ENHANCING PLATOON DYNAMICS: CACC IN HOMOGENEOUS VEHICLE GROUPS VIA TORCS SIMULATION

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In the realm of autonomous vehicle mobility within urban settings, platoon driving has emerged as a highly promising approach, not only for the optimization of fuel consumption but also for the enhancement of road safety and traffic flow.The command structure of Cooperative Adaptive Cruise Control (CACC) encompasses both longitudinal and lateral control of a collective of intelligent autonomous vehicles, where optimizing the inter-vehicle distance stands out as a paramount challenge crucial for ensuring platoon stability. This study is dedicated to the comprehensive exploration of the design, analysis, and validation of control systems tailored for automated and cooperative vehicles. The devised algorithms have been rigorously implemented and tested within The Open Racing Car Simulator (TORCS), employing 3D vehicle models in simulations that faithfully replicate real-world scenarios.

Keywords: Autonomous Vehicle, The Open Racing Car Simulator, Platoon drinving, Cooperative Adaptive Cruise Control.

1. Introduction

Many studies on Connected and Autonomous Vehicles (CAVs) have been conducted to identify practical answers to this issue using intelligent transportation methods. Both connection and automation are built into CAVs, enabling them to communicate with one another via Vehicle-to-Vehicle (V2V) communications [8]. Different types of communication are possible due to advancements such as the dedicated short-range communication (DSRC) [1]. In addition to being able to drive on their own using onboard sensing sensors, one of the most promising CAV technologies is cooperative adaptive cruise control (CACC), which extends adaptive cruise control (ACC) through coordinated maneuvers by CAVs.

The V2V connections used in CACC systems allow CAVs to independently share their own settings with other CAVs in the network without the need for centralized management [7]. Different works and studies in the real world have been completed by optimizing driving safety [16]. Among the first research projects launched in this field, we can mention the SARTRE project

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(Safe Road Trains for the Environment). Launched in 2009 and supported by Volvo, the idea of SARTRE is to improve the safety and fluidity of traffic while reducing polluting emissions. Each vehicle is equipped with electronic devices (cameras, sensors) that monitor the preceding vehicle and the immediate environment. These sensor systems maintain a distance of 6 meters between vehicles, and the entire train travels at 85 km/h [3].

The main goal behind cooperative adaptive cruise control is to maintain a safe distance between the vehicles, thereby ensuring platoon stability and passenger comfort [14]. In this field, many control laws and platoon models are suggested. For example, authors of [10] implemented a linear controller on a second-order model, while [11] have tried to implement an MPC controller to ensure the stability of the platoon along its travel. Our contribution lies in the specific application of PID to vehicle convoy control, particularly in the context of maintaining stability under varying operational conditions.

Based on TORCS as a simulation tool, the main objective of this work is to ensure the control of a platoon composing two to ten vehicles traveling at different speeds while maintaining a Constant Time Headway (CTH). To achieve this, it is essential to select a model for the vehicle in order to obtain control parameters and ensure the platoon's stability. Additionally, using the Leader Predecessor-Following (LPF) communication protocol, the proposed control law must guarantee both the time and distance that may occur within the system.

This article is organized as follows. Section 2 presents the longitudinal and lateral controllers and the communication between the vehicles of the platoon. Section 3 provides a description of the TORCS simulator and the experimental part of our controllers on one, two, and ten vehicles. Finally, in section 4, we conclude with some remarks and perspectives.

2. **Longitudinal and Lateral Control in CACC**

Modeling involves describing the motions and forces acting on the vehicle as it travels. This includes factors such as speed, acceleration, rolling resistance, aerodynamic drag and engine power. Models are used to simulate vehicle performance and design control systems [12]. Linear models are most commonly used to solve treatable problems. The single integrator model, the second-order model, the third-order model, and the Single Input Single Output (SISO) model are the most commonly used models in the literature.

In our study, we opted for the third-order model which provides an additional state compared to the second-order model. The additional state is used to simulate the input/output behavior of the powertrain dynamics, which reduces the control input to the engine torque and/or braking torque [19]. The majority of approximations use either the feedback linearization approach [6] or the lower layer control technique [21], resulting in a state space model [13] given by equation (1):

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) \tag{1}$$

$$x_i(t) = \begin{pmatrix} q_i \\ v_i \\ a_i \end{pmatrix}; A_i = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau_i} \end{pmatrix}; B_i = \begin{pmatrix} 0 \\ 0 \\ \frac{1}{\tau_i} \end{pmatrix};$$

Where, $x_i(t)$ is the state vector of the vehicle i; q_i is the rear bumper position; v_i is the velocity; a_i is the acceleration; and $u_i(t)$ is the desired acceleration of vehicle i.

Third-order models are better suited for simulating and predicting the behavior of systems with multiple interacting components. They can provide more accurate forecasts and insights into how the system will respond to changes or inputs, and they can provide a better understanding of the underlying dynamics, making it easier to design and implement control strategies.

2.1. Longitudinal control

The main objective of longitudinal control in vehicle dynamics is to regulate the speed and distance between vehicles. The aim is to keep the distance between the vehicles consistent, as shown in Fig. 1, commonly referred to as the "headway" or "following distance", and to ensure that all vehicles in a platoon maintain the same speed. This is important for safety and to prevent collisions, as well as to increase the efficiency of the overall system by reducing the energy consumed and minimizing fuel consumption [5]. The distance

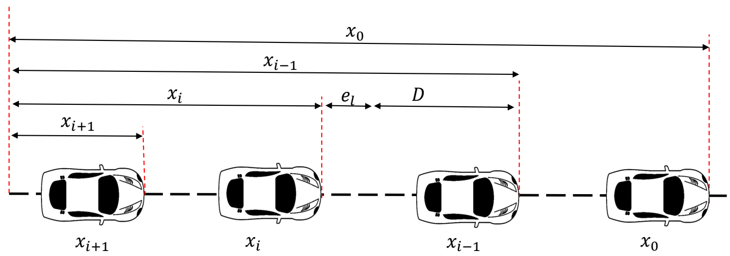


Figure 1. Inter-vehicle distance scheme and longitudinal error.

can be expressed in either cartesian or curvilinear coordinates, depending on the specific application and requirements. The control system uses sensors, such as radar or cameras, to measure the distance and speed between vehicles and then adjusts the throttle, brakes, or other actuators to regulate the speed and maintain the desired headway. The control algorithms used for this purpose can vary, ranging from simple proportional-integral-derivative (PID) [18] controllers to more advanced techniques such as model predictive control (MPC) [9] or reinforcement learning [15]. The command to correct the longitudinal error in a PID controller is given by equation (2):

$$u_i = K_p e_{li}(t) + K_i \int e_{li}(t)\, dt + K_d \frac{d\, e_{li}(t)}{dt} \tag{2}$$

Where, u_i is the control signal or command and $e_{li}(t)$ represents the error between the desired and actual longitudinal distance.

$$e_{li}(t) = d_{i-1,i} - d_{ri} \tag{3}$$

Here, $d_{i-1,i}$ is the distance desired between vehicle $i-1$ and vehicle i,

$$d_{i-1,i} = t_h v_i + d_0 \tag{4}$$

With, t_h is the time headway; d_0: is the distance security; and d_{ri} is the distance measured between vehicle $i-1$ and vehicle i;

$$d_{ri} = q_{i-1} - q_i - L \tag{5}$$

Here, L is the longueur of vehicle and v_i is the velocity of vehicle i;

$$v_i = \frac{\left(\frac{V_{i-1}+V_i}{2}\right) + V_L}{2} \tag{6}$$

With,V_{i-1}, V_i, and V_L represent the velocity of vehicles $i-1$, i and Leader; and K_p, K_i, and K_d are the gain parameters of the PID controller.

The gain determines the behavior of the controller and can be adjusted to achieve the desired performance. The proportional gain K_p controls the magnitude of the correction and the immediate response of the system to the error. The integral gain K_i corrects for any sustained error and eliminates steady-state error. The derivative gain K_d improves the stability of the system and reduces overshoot.

Longitudinal control ensures speed control, i.e. the vehicle speed converges towards the desired speed. In the simulation, we will control the speed of the model with a PID controller as shown in Fig. 2. The control law for

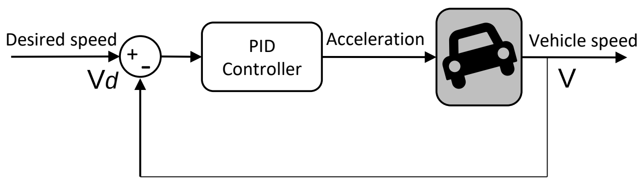


Figure 2. Demonstrative diagram of PID controller.

speed is presented by the equation (7):

$$u = K_p(V_d - V) + K_d \frac{d(V_d - V)}{dt} + K_i \int (V_d - V)dt \tag{7}$$

Where, u is the control input (the acceleration request); V represents the vehicle speed; V_d is the desired speed; and K_p, K_i, and K_d are the setting parameters of the PID corrector.

This equation takes into account the desired speed, the current speed, and the error between them. The control law can be implemented using the PID controller. To ensure that the vehicles in a platoon stay under control, it's important to integrate both longitudinal and lateral controls.

2.2. Lateral control

The objective of lateral control is to keep each element of the platoon on its reference path. Two strategies can be considered:

- Lateral control from near to near, where the lateral set point for each element of the platoon is the path taken by the vehicle in front of it;
- Global lateral control, where the reference trajectory is the same for all elements of the platoon.

The advantage of the first approach is that it only requires relative location sensors. Inter-vehicle communications are not required. However, this strategy suffers from the accumulation of lateral errors between two consecutive vehicles, even if they are small, the errors accumulate from the head to the tail of the platoon, and consequently, the last vehicle of the platoon risks describing a trajectory far from that of the head vehicle, and even possibly leaving the platoon. The second approach requires vehicles to be equipped with an absolute location system. The reference trajectory is then either known in advance or defined in real time by the path of the lead vehicle. In this case, communication from the lead vehicle to all the elements of the platoon is necessary, and no errors accumulate. For these reasons, the second approach has been proposed [20]. The main objective of the lateral controller is to eliminate

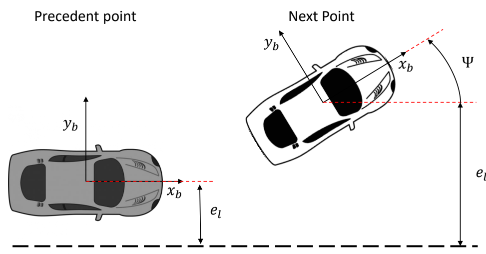


FIGURE 3. Demonstrative diagram on the lateral error.

lateral and heading errors to ensure that the required path is followed. The output of the lateral controller is the steering angle. The different errors are shown in Fig. 3.

- e_l Lateral error: the distance between the center of the reference frame associated with the vehicle and the trajectory tangent to be followed;
- Ψ Heading error: this is the angle between the vehicle's reference frame and the parallel of the path to be followed.

Lateral control provides trajectory tracking, i.e. keeping the car on the road. In the simulation, we control the steering angle with a PID type controller. The control law is presented in equation (8):

$$u = K_p\Psi + K_d\frac{d\Psi}{dt} + K_i\int \Psi dt - k\tan^{-1}\frac{e_l + P}{2L} \tag{8}$$

Where, u is the steering angle; Ψ is the course error, the angle between the axe of the road and the axe of the vehicle; e_l is the lateral error; P: is constant for positioning; L is a car length; K_p, K_i, and K_d are the adjustment parameters of the PID controller; and k is the control constant to give more importance to the lateral error.

2.3. Communication between vehicles

Communication among vehicles within a platoon is a dynamic process that can unfold through various means. This communication plays a pivotal role in safeguarding control and upholding stability within the platoon. Whether through advanced radio systems, synchronized protocols, or visual cues, the exchange of information between vehicles enables them to operate in a coordinated manner. By sharing vital data such as speed, direction, and road conditions, vehicles can adjust their movements, maintain appropriate spacing, and respond swiftly to changes in the platoon's environment [4]. This seamless communication network fosters a heightened level of control, ensuring that the platoon operates as a cohesive unit and minimizing the potential for disruptions or accidents. Ultimately, this effective communication framework proves to be instrumental in maintaining the desired levels of control and stability within the platoon.

In our work, we place our emphasis on leader predecessor-following communication (PLF) [17]. This communication paradigm implies that each vehicle receives information from both the leading vehicle and the preceding vehicle, as shown in Fig. 4. Maintaining constant inter-vehicle spacing over

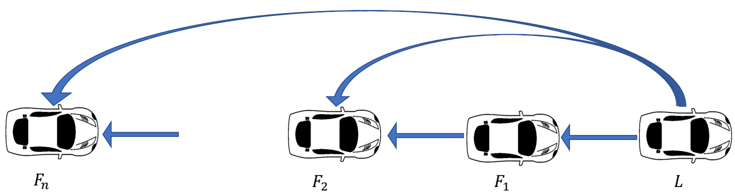


FIGURE 4. Topology of communication between vehicles (leader predecessor-following).

a consistent period of time is important for ensuring the smooth operation of the platoon. By adhering to a predefined spacing, driving systems can create a safe buffer that allows for appropriate reaction time and maneuverability.

This becomes particularly crucial in high-density traffic scenarios or during platoon operations, where maintaining consistent spacing is vital for synchronized movement.

In our work, we use the Constant Time Headway (CTH) [2]. Despite the potential for large inter-distances with variable spacing, its advantages have prompted researchers to work towards reducing the spacing to make this control strategy more appealing. The control method that keeps the inter-vehicle distance proportional to the car speed with a constant time has become a benchmark in the field of variable spacing strategies, as shown in equation (4).

3. Simulation and Results

To assess the efficiency and robustness of our proposed controller with PLF communication, we conducted a series of evaluations in The Open Racing Car Simulator (TORCS).

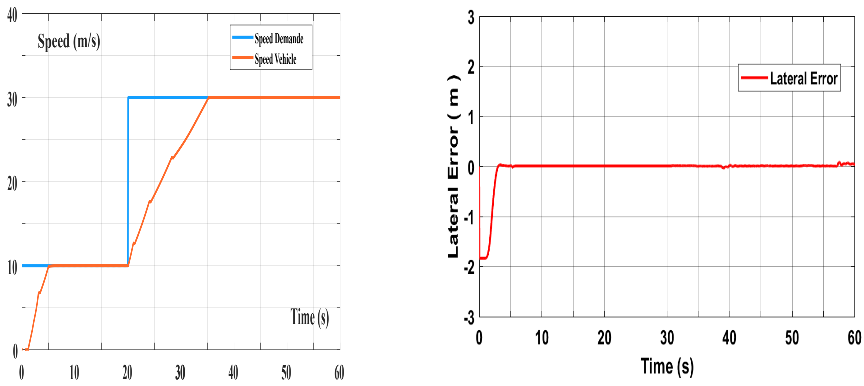
TORCS is a highly portable cross-platform car racing simulator. It can be used as an ordinary racing game, an AI racing game or a research platform. The simulator runs on Linux, FreeBSD, OpenSolaris, MacOSX, and Windows. TORCS source code is licensed under the GPL Torcs, the open racing car simulator. TORCS features a variety of cars, different tracks, and numbers of opponents that can compete. The graphics feature lighting, smoke, skid marks, and lighted brake discs. The software allows different racing scenarios, from simple training sessions to championships.

The TORCS simulator has an interface with Matlab and Simulink called TORCSlink. This means that controllers can be developed for TORCS using Matlab.

To assess the effectiveness of our approach in Torcs, we elaborate three scenarios: the first involves a single vehicle to evaluate the controller in different circuits, the second involves two vehicles to assess the distance space, and the third includes ten vehicles to evaluate inter-vehicle communication.

3.1. Single vehicle simulation

The focus of this section is on the control of a vehicle in both its longitudinal and lateral directions. Longitudinal control refers to the regulation of the forward motion of the vehicle, including aspects such as speed, acceleration, and deceleration. Lateral control, on the other hand, refers to the control of the lateral movement of the vehicle, including aspects such as steering, lane keeping, and lateral stability. **Discussion** In the provided scenario, the vehicle initiates its motion by accelerating to reach a velocity of 10 m/s, and then maintaining this speed for a predetermined duration 15 seconds. After that, the vehicle increases its speed until it reaches a peak velocity of 30 m/s. This progressive convergence of the vehicle's speed toward the target speed underscores the effectiveness of the implemented control system, as illustrated in Fig. 5a.



(A) Speed of the vehicle (B) Lateral error

FIGURE 5. Single vehicle simulation

In addition, the lateral error is gradually decreases over time to eventually become negligible after approximately 3s, as illustrated in Fig. 5b. This convincingly demonstrates the effectiveness of the side controller, which guides the vehicle properly along its intended route.

3.2. Simulation of two leader-follower vehicles

After controlling the leader vehicle, in this section, we shift our focus to controlling the follower vehicle. The primary goal of the control law is to maintain the inter-vehicle distance equal to a desired value. The purpose of this section is to control the speed of the follower vehicle. To maintain the desired distance, we keep the lateral controller unchanged from the previous part. The problem is depicted as shown in Fig. 6. Where, V_f is the speed of

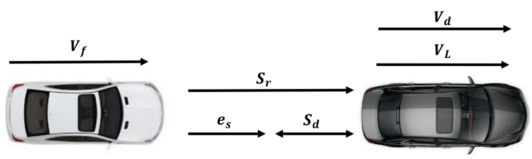


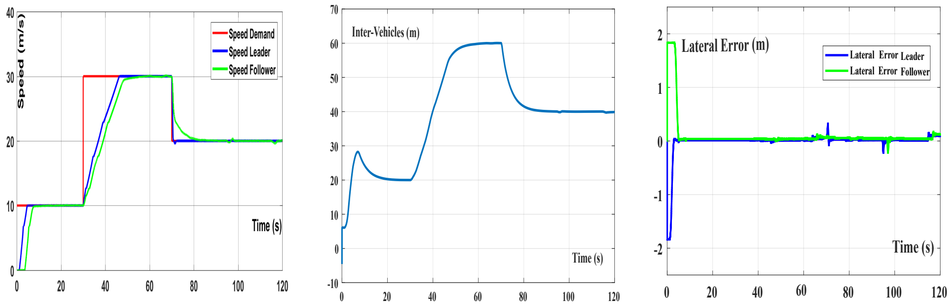
FIGURE 6. Distance between two vehicles in a platoon.

the following vehicle, S_r is the real spice between vehicles, S_d is the desired spice between vehicles, e_s is the error spice, V_L is the speed of the leader vehicle and V_d is the desired speed

Various criteria exist for establishing the desired safety distance, and in this context, we will define the desired distance utilized in the simulation, as outlined in the following equation (9). The selection of an appropriate safety distance involves a careful consideration of multiple factors, including vehicle speed and reaction times. In the subsequent simulation, the defined distance in the equation serves as a fundamental parameter, influencing the overall safety and efficiency of the system under examination.

$$S_d = D_{MIN} + K * V_F \tag{9}$$

Where, D_{MIN} is the minimum distance and K is a regulation constant (Its choice is in accordance with the safety distance). **Discussion** In this situation,



(A) Longitudinal speed (B) Spacing results (C) Lateral error

FIGURE 7. Simulation of two leader-follower vehicles

we watch two vehicles closely as they try to reach a set speed. At the beginning, they are 7 meters apart. When the first vehicle speeds up to 10 m/s, the gap between the two vehicles naturally gets bigger. The first vehicle stops changing its speed. At that point, the second vehicle keeps speeding up until it reaches the desired speed and the desired inter-vehicle distance. They end up 20 meters apart.

Later on, after the 30 s, we change the desired speed Fig. 7a. The first vehicle speeds up to 30 m/s, and the second vehicle follows to keep the distance between them at 60 meters. This whole process shows that the control system is clever at adjusting the speeds of both vehicles to keep the desired gap, even when the speed changes. This adaptability can be seen in Fig. 7b.
In Fig. 7c, you can see that the sideways error for both vehicles gets smaller over time until it's almost gone. This gradual decrease shows how good the control system is at keeping both vehicles on the right path.

3.3. Simulation of a platoon of ten vehicles

After successfully controlling the two vehicles, our focus shifts to controlling the entire platoon. Figure 8 illustrates the initial configuration of the vehicles on the track within the TORCS environment. The primary objective is to maintain the inter-vehicle distance, which depends on the speed, and to make the vehicles run at the same speed while ensuring the stability and safety of the platoon, i.e. the inter-vehicle distance errors do not increase when they propagate along the platoon. We use a local control architecture in both longitudinal and lateral. Table 1 presents the PID parameters setting.

Discussion the desired speed is 10 m/s and maintain this speed for 55 seconds. Initially, the distance between the vehicles was 15 meters. As the

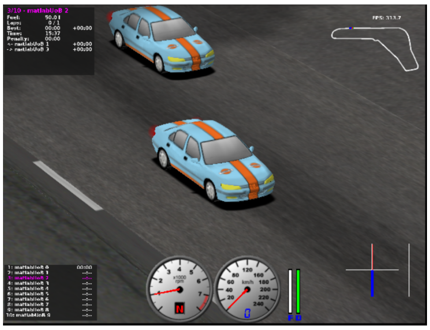
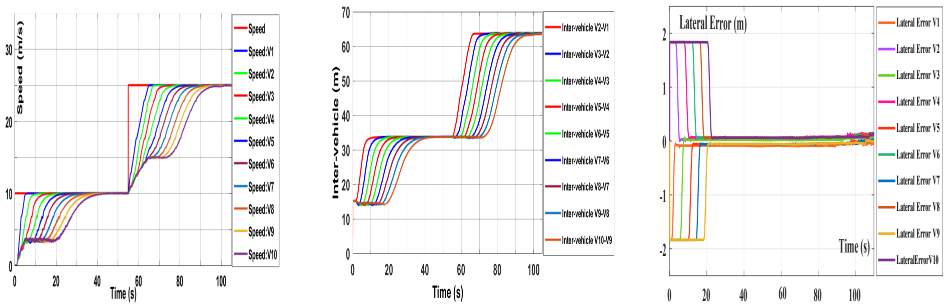


FIGURE 8. Initial configuration of the vehicles.

TABLE 1. Qualitative comparison of different SFs.

PID Parameters	Type	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
K_p	longitudinal	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
K_d	longitudinal	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
K_i	longitudinal	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
K_p	lateral	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
K_d	lateral	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
K_i	latera	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05



(A) Longitudinal speed (B) Spacing results (C) Lateral error

FIGURE 9. Simulation of two leader-follower vehicles

speed of the leader increases, the distance increases. Once the leader's speed becomes constant, the following vehicles continue to accelerate until they reach the desired speed, and the distance is maintained at 33 meters, as shown in Fig. 9a.

We increase the desired speed, the leading vehicle accelerates until it reaches a speed of 25m/s, and beyond that, the followers would increase their speeds as well to reach the desired speed and keep the inter-vehicle distance equal to 63 meters, as shown in Fig. 9b.

Vehicle speeds converge to the desired speed; the distances between vehicles are in accordance with the safety distance specified in the Algerian Highway Code.

The graphs in Fig. 9c demonstrate the efficiency of the proposed control laws, with the lateral error decreasing until it reaches zero.

4. Conclusion

The proposed approach in this paper focuses on the implementation of a platoon of vehicles by developing two control types: longitudinal and lateral control. A simulation was carried out to evaluate the performance of the control. The first section of the paper discusses the problem and its positioning within the current state of the art and previous works, as well as the description of the simulation software, TORCS. The software accurately simulates the behavior of a real platoon and accounts for various forces acting on the vehicle. The simulation was first performed for a single vehicle and then expanded to two vehicles, with the first serving as the Master and the second as the Slave. Finally, the simulation was generalized to a platoon of vehicles while ensuring the control of ten vehicles. The simulation utilized a PID controller, and the results demonstrated its efficiency in terms of speed, convergence, and accuracy.

In future work, we aim to develop adaptive algorithms and customized vehicle control strategies that enhance our approach to heterogeneous platoons. By focusing on the unique characteristics of different vehicle types, we seek to extend the applicability of our methods across a broader range of real-world scenarios.

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