Lane Management Strategies to Enhance Traffic Performance in Mixed Traffic Environments with Platoons of Connected Autonomous Vehicles

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1 INTRODUCTION

The rapid development of Connected Autonomous Vehicles (CAVs) is attracting global research attention, with significant potential to enhance traffic stability, safety, efficiency, and environmental benefits (Chakraborty, S. *et al.*, 2021; Sala, M. and Soriguera, F., 2021; Moode, S.N. and Soriguera, F., 2023). While CAVs are increasingly present in today's infrastructure, Regular Vehicles (RVs) remain dominant, and a complete transition to autonomous systems will take time. As a result, mixed traffic where CAVs and RVs share the road will continue to shape our transportation networks for the foreseeable future (Chen, B. *et al.*, 2020).

To optimize CAV performance within these mixed environments, lane management strategies are essential, especially those that leverage the connectivity of CAVs through *platooning*. Researchers are exploring various strategies, such as dedicated and mixed lanes for CAV platoons on freeways (Zhang, F. 2023; Wang, Y. *et al.*, 2024). However, current platoon car-following algorithms often rely on traditional car-following models, which may not fully realize the potential benefits in terms of traffic throughput. This study investigates how innovative lane management strategies with novel CAV Platoon-based car following algorithm can enhance traffic performance in mixed-traffic settings.

2 METHODOLOGY

In this research, we simulate different lane management strategies for CAV platoons using the AimsunNext simulation tool. This research outlines a three-phase process for platooning: (i) platoon formation, (ii) platoon driving, and (iii) platoon splitting. The formation and driving phases will be discussed in more detail later, while platoon splitting involves a CAV changing lanes to exit the platoon lane. For the RVs that are not part of a CAV platoon, we apply the Gipps car-following model (Gipps, P.G., 1981) as defined in Aimsun. Meanwhile, a novel car-following model proposed by Moode, S.N. and Soriguera, F., 2023, is used to simulate the behavior of CAV platoons specifically, helping us assess how different lane management strategies affect overall traffic throughput in a mixed-traffic environment.

2.1 Platoon Formation

CAV platoon formation phase starts when a CAV designated as the follower detects another CAV in front, known as the leader, within a specific formation range. The leader can either be a standalone

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CAV or the last vehicle in an existing platoon. The follower CAV attempts to join the platoon by pursuing the leader using the cooperative adaptive cruise control (CACC) model (Van Arem, B. et al., 2006), as outlined in Equation 1:

$$a_{follower} = k_1 a_{leader} + k_2 e_v + k_3 e_x \text{ where, } k_1, k_2, k_3 > 0 \tag{1}$$

Where: $a_{follower}$ is acceleration of the follower, a_{leader} is acceleration of the leader, e_v is relative speed; e_x is space-gap error. k_1, k_2, k_3 are control gain coefficients.

2.2 Platoon Driving

CAVs aim to maintain a desired space gap during platoon driving mode, denoted as g_i^*. This minimum space gap is designed to enhance traffic flow throughput while ensuring safety in the event of a sudden braking by any vehicle. Considering the advanced driving capabilities of CAVs, the minimum space gap required to ensure safety between two consecutive vehicles in the platoon, i and $i-1$ is defined in Equations 2 and 3 and the acceleration is from the solution of Equation 4 (Moode, S.N. and Soriguera, F., 2023).

$$g^*{}_{i,t} = g_{min} - \frac{1}{2}\frac{\left(v_{i,t} + a_{i,t}\delta^*\right)^2}{a_{min\_e}} + \frac{a_{i,t}\delta^{*2}}{2} + v_{i,t}\delta^* + \frac{1}{2}\frac{\left(v_{i-1,t-\delta} + a_{i-1,t-\delta}\delta^*\right)^2}{a_{min\_e}} \tag{2}$$

$$\delta^* = \delta - \frac{v_{max}}{a_{min\_e}}\left(\frac{\beta}{1-\beta}\right) \tag{3}$$

$$\begin{aligned} 0 = {} & \left[\frac{-\delta^{*2}}{2a_{min\_e}}\right] a_{i,t}^2 + \left[\frac{\delta^{*2}}{2} - \frac{v_{i,t}\delta^*}{a_{min\_e}}\right] a_{i,t} \\ & + \left[g_{min} - g^*{}_{i,t} - \frac{v^2{}_{i,t}}{2a_{min\_e}} + v_{i,t}\delta^* + \frac{1}{2}\frac{\left(v_{i-1,t-\delta} + a_{i-1,t-\delta}\delta^*\right)^2}{a_{min\_e}}\right] \end{aligned} \tag{4}$$

Where, $a_{i,t}$ is acceleration to apply for the vehicle i at time t, $v_{i,t}$ is known speed of vehicle i at time t, $v_{i-1,t-\delta}$ is known speed of vehicle $i-1$ at time $t-\delta$, δ is latency of communications between CAVs, a_{min_e} is max. braking capabilities of the vehicle, β is maximum differential braking capabilities of CAVs [fraction of unit], v_{max} is maximum platoon travelling speed, g_{min} is the minimum safety space-gap when the vehicles are stopped.

The dynamics of car-following in platooning are established as follows: (i) If the difference between the current space-gap g_i and the desired safe space-gap g_i^* is greater than 10% of g_i^*, the vehicles' accelerations will be governed by the CACC model outlined in Equation 1; (ii) conversely, if the difference is less than or equal to 10% of g_i^*, the accelerations that dictate the car-following behavior will be calculated by solving for $a_{i,t}$ in Equation 4.

3 SIMULATION SCENARIO AND EXPERIMENTS

The AIMSUN Next traffic micro-simulation software along with a Python-coded API to control vehicles based on car-following and platooning strategies have been used for simulation. Non-CAV vehicles follow AIMSUN's default lane-changing rules and use the Gipps car-following model (Gipps, P.G., 1981). Table 1 outlines the simulation specifications, covering vehicle characteristics, traffic demands, highway structure, and other parameters designed to closely reflect reality with safe maneuvers. Real-world values are used for average vehicle lengths and human driver reaction times, while other parameters have been obtained from the literature or after calibration.

Table 1: *Summary of Simulation Specifications and Parameter Values*

Simulation Feature	**Description and parameter values**
Vehicles	▪ CAVs: 4 m long, 2.8 m wide ▪ Regular Vehicles: Average 5 m, Max 5.5 m, Min 4.5 m

	▪ Human driver reaction time: 1.0 s ▪ Non-platooned CAV reaction time: 0.8 s ▪ CAV latency of communications: $\delta = 0.1$ s ▪ Max. braking capabilities of CAVs: $a_{min\_e} = -3$ m/s^2 ▪ Max. differential braking capabilities of CAVs: $\beta = 0.2$
Platooning	▪ Max. platoon travelling speed: $v_{max} = 30.56$ m/s ▪ Speed limit acceptance: 1.1 ▪ Platoon max. length: 20 Cars ▪ Platoon formation range: 75 Meters ▪ CACC Control gain coefficients: $k_1 = 1$, $k_2 = 0.3$, $k_3 = 0.1$ ▪ Min. space-gap when the vehicles are stopped: $g_{min} = 0.5$ m ▪ CAV is in platoon when $g_{i,t} \in \left[0.5 g^*_{i,t}, 1.5 g^*_{i,t}\right]$ ▪ CAVs try to split courteously from the platoon at 1 km from their exit off-ramp ▪ CAV force platoon split when the ramp is 400m away
Infrastructure layout	▪ 3 Lane ring road highway; one direction ▪ 1.5 km length; 100 m ramps (1 on-ramp and 1 off-ramp) ▪ Off-ramp flow: 10% of circulating flow
CAV penetration rate	▪ 0%, 10%, 25%, 50%, and 75% of the demand
Simulation time step	▪ 0.1 s
Statistics aggregation period	▪ 5 min intervals

3.1 Platoon Management Strategies and Simulation Scenarios

In this paper, we propose to analyze several platoon management scenarios in order to dynamically manage the formed platoons. The following scenarios are defined:

Scenario 1. Dedicated Platoon Lane

- The highway usage structure will feature the leftmost lane as a CAV-only lane where CAVs are able to platoon. Regular vehicles cannot enter the leftmost lane under any circumstances.

Scenario 2. Mixed Platoon Lane

- The platooning lane is located in the leftmost lane, and the leftmost lane allows regular vehicles and CAVs indistinctly.

Scenario 3. Mixed Double Platoon Lane

- Both the middle and the leftmost lanes will serve as platooning lanes. Regular vehicles and CAVs can enter into both platooning lanes indistinctly.

In addition, two traffic management strategies at the vehicular level are implemented in order to avoid undesirable outcomes from the previously defined platooning lane management scenarios:

Strategy 1. Platooning lane speed limits

- If average speed in the middle lane < 85 km/h, then platooning lane speed limit is the speed in middle lane + 10 km/h.

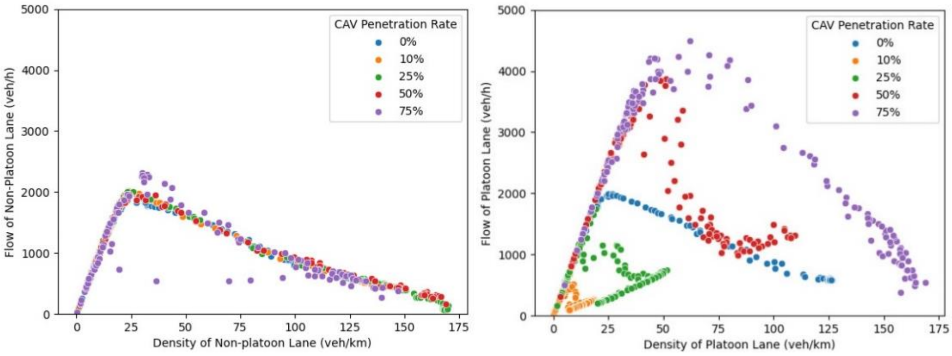
Strategy 2. Platoon lane desirability

- CAVs, by default, desire to enter the platoon lane.
- If platoon lane speed < middle lane speed AND density of the platoon lane > 40 veh/km, desirability is off, and CAVs do not aim to move to the platooning lane.

4 RESULTS AND DISCUSSIONS

This section presents the main results and insights obtained for the management scenarios proposed. The primary result focused on the dedicated platooning lane.

Figure 1 illustrates the key challenges in managing CAV traffic within a dedicated platooning lane (Scenario 1). At CAV penetration rates of up to 50%, traffic in non-platooning lanes behaves typically, with a capacity of about 2000 vehicles per hour (veh/h) and a jam density of 175-180 vehicles per kilometer (veh/km). However, when CAV penetration reaches 75%, the dedicated lane becomes oversaturated, leading to irregular flow patterns that force some CAVs into adjacent middle lanes, causing congestion.



(a) Non-platooning lane (b) Dedicated platooning lane

Figure 1. *Fundamental diagram for the platooning lane for different CAV penetration rates*

While high CAV penetration can increase the dedicated lane's capacity to 4500 veh/h due to platooning, at lower penetration rates (10%-50%), this lane remains underutilized, while adjacent lanes experience congestion. Furthermore, a speed-limit management strategy, designed to prevent unsafe speed differences between CAVs and regular vehicles, further limits the effectiveness of the platooning lane by capping its speed to that of congested lanes.

These issues suggest that the dedicated lane approach is inefficient, particularly at low CAV penetration rates. To address these challenges, exploring alternative strategies like mixed platoon lanes and double mixed platoon lanes could be beneficial. Such strategies would allow for more flexible lane usage, potentially reducing congestion and enhancing traffic flow by better integrating CAVs with regular vehicles, leading to smoother transitions and improved overall traffic performance.

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