Definition of strategies to optimize the platooning of connected automated vehicles on freeways

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1 INTRODUCTION

Recent advancements in vehicle technology and communication systems, among others, are paving the way for the deployment of innovative transportation solutions aimed at reducing traffic-related externalities such as congestion, accidents and environmental pollution. In the context of highway traffic management, one promising strategy is the platooning of connected automated vehicles (CAVs), where CAVs travel relatively fast and close together, akin to a road train, without compromising safety. While the concept of platooning is not new, its practical implementation has become increasingly feasible with the advent of CAVs.

The present paper focuses on the impact of CAV platooning in multilane mixed traffic flows, where CAVs share the road with regular vehicles (RVs). It is anticipated that introducing platoons could increase maximum traffic throughputs by reducing the average vehicular headway (Zhou and Zhu, 2020; Sala and Soriguera, 2021; Martínez-Díaz et al., 2024). Still, adequate traffic management strategies in order to make the most of CAVs platooning are to be proposed and assessed. This involves analyzing if platooning lanes need to be dedicated or not (or when), how many and which lanes should allow CAV platooning or if the platoon length must be limited. With this objective, the paper adopts a simple platooning algorithm for multilane highways, and implements it in the Aimsun Next microsimulation software. Different scenarios are run to assess the effect of platooning on traffic flows in mixed environments, and the adequacy of the management strategies proposed.

2 PLATOON DRIVING

Consider platoons of CAVs as strings of homogeneous connected automated vehicles that cooperate using V2V communications. This cooperation allows maintaining short distances between the front and rear bumper of each pair of consecutive vehicles (i.e., short space gaps) while travelling at high speeds and without compromising safety. Platooning comprises three different phases, namely: i) joining the platoon or platoon formation; ii) platoon driving; and iii) leaving the platoon or platoon split. Platoon formation occurs when one CAV is travelling behind another CAV or behind an already formed platoon. Then, the CAV approaches its immediate predecessor using a classical cooperative adaptive cruise control (CACC) scheme, trying to reach the platooning desired space gap. The desired space gap balances the enhanced throughput achieved with narrower gaps and high speeds against the necessary gap to ensure safety during platoon driving and specifically in emergency conditions. This means that vehicle, i (i.e. the follower) should be able to brake up to full-stop without colliding with its predecessor, vehicle $i-1$, even in case of a sudden incident. This safety condition allows defining the desired space gap of vehicle i at time t, $g_{i,t}^{*}$ as in Equation 1, given its travelling speed, $v_{i,t}$, and the time delay in the followers' speed adaptation, δ. Other factors such as possible errors in communications, errors in sensor measurements or vehicle differential braking capabilities are accounted for by the dimensionless safety factor $\gamma, \gamma > 1$. In Equation 1, g_{min} represents the minimum space gap while travelling at low speeds or stopped.

$$g_{i,t}^{*} = \max\left(g_{min}, \delta v_{i,t} \gamma\right) \tag{1}$$

Once the desired space gap is reached (i.e. in practice this means that the actual space gap is within the range $\left[0.9 g_{i,t}^{*}, 1.1 g_{i,t}^{*}\right]$), vehicle i is said to drive in platooning mode. This driving mode is characterized by all the n followers in the platoon maintaining their platooning desired space gaps and adapting it to any speed change of the platoon leader (i.e. $i = 0$). This speed adaptation is performed according to Equation 2:

$$v_{i,t} = \min\left(v_{i-1,t-\delta} + \frac{\left(g_{i,t-\delta} - g_{i,t-\delta}^{*}\right)}{\delta}, v_{max}\right) \qquad i = 1, \dots, n \tag{2}$$

Note from Equation 2 that the speed of the follower, $v_{i,t}$, is adapted with a time delay, δ, with respect to the observed inputs at time $t - \delta$. The time delay, δ, includes the latency of communications (whose role is comparable to that of the reaction time for the case of human-driven vehicles, but whose magnitude is much shorter), as well as the time required to adapt to the new speed. v_{max} represents the speed limit of any vehicle within the platoon.

At some point (e.g. when approaching the destination off-ramp), one or several CAVs may need to leave the platoon by performing a lane change. The aggressiveness and gap acceptance to perform this maneuver will depend on the necessity of the CAV in leaving the platoon (e.g. the intended off ramp approaching). If density on the target lane is high and the lane change is impeded, at the end CAVs may reduce their speed and force a sufficient gap, leading to a long split process and even to the division of the platoon into two.

3 SIMULATION SCENARIOS

Platooning scenarios depend, among others, on the CAVs' features and penetration rate, the highway layout, the existing traffic conditions and the platooning management strategies. Table 1 summarizes the main parameters used and the simulation scenarios analyzed in the present paper. Parameters included in Table 1 are those usually found in reality or validated in the related literature. For example, $\delta = 0.1\ s$ or a V2V communications range of 25 m are quite conservative values considering the advances in communication technologies, whereas $\gamma = 1.1$ accepts that CAVs sensors will perform quite accurately. Overall, the approach turns out to be optimistic in the CAV performance, but cautious in the platooning management. In turn, opting for a time delay equal to the simulation time step was a pragmatic choice, well-suited at the present stage of implementation.

The simulation layout is defined to reproduce multi-lane traffic features and support a wide range of traffic states on a finite road length and with short computational times. It consists of a circular three-lane highway of approximately 1.5 km, with one on-ramp and one off-ramp. Several on-ramp input flows, $f(t)$, were considered, leading to different circulating flows, $q(t)$, on the main. In stationary conditions, Equation 3 holds, being α the exit ratio at the off-ramp.

$$q(t) = \frac{1}{\alpha} f(t) \tag{3}$$

α plays a key role, as it determines the average trip length on the ring-road. It has to be small enough so that i) high flows on the main trunk can be achieved; ii) the off-ramp is able to hold the outflows (i.e., $\alpha q(t)$); and iii) very short average trip lengths (which would prevent the formation of long platoons) are avoided. The chosen $\alpha = 0.1$, is a realistic value which fulfills these conditions. Variable input demands yielding a wide range of traffic densities and the whole spectrum of CAV penetration rates have been considered.

Table 1 – *Platooning scenarios analyzed*

Factor	Description
Vehicles	• CAVs penetration rate: from 0% to 100% • Average reaction time: 0.8 s for RVs; 0.1 s for CAVs • Delay of speed adaptation, δ: 0.1 s (includes latency of V2V communications)
Platooning	• Platooning lane: Only leftmost; Leftmost & middle lane; Only rightmost. • Dedicated vs Non-dedicated platooning lanes. • Free flow speed in the platooning lane ≤ speed limit • No platoon length limit vs Platoon length limit of 20 CAVs • Platooning V2V communications range: 25 m • Split if CAV wants to exit within 1 km. Forced split if within 400 m. • Safety factor in the platooning desired space gap, γ: 1.1 (dimensionless) • Minimum space-gap when vehicles are stopped, g_{min}: 0.5 m
Infrastructure	• 3-lane ring-road. 1.5 Km in length. 1 on-ramp and 1 off-ramp • Speed limit, $v_{max} = 27.8$ m/s
Traffic demand	• On-ramp flows: varying input flows, from 300 veh/h to 1,100 veh/h • Off-ramp flows: 10% of the circulating flow (exit ratio $\alpha = 0.1$)
Others	• Simulation time step Δt of 0.1 s • Simulation software: Aimsun Next

Regarding the tested platooning management strategies, we can group them into the following aspects: i) Platoon length: limiting the platoon length or not; ii) Number of platooning lanes: allowing platoon driving in one or two lanes; and iii) Mixed vs dedicated platooning lanes: allowing non-platooned vehicles to share the platooning lane or not. These aspects will affect the traffic performance in the presence of platoons, still without conclusive results in the related literature. Note that not limiting the platoon length could lead to higher traffic throughputs, but also could create disturbances to other vehicles and might raise safety concerns. This is also related to the selection of the platooning lane/s. The leftmost lane, the farthest from ramps and waving sections, is set as the primary platooning lane. However, for high penetration rates of CAVs and high flows, it could be advisable also using the middle lane. Another important management decision is if the primary platooning lane (e.g., the leftmost lane), should be dedicated or not, or in which cases (e.g. dynamically dedicated platooning lane). The microsimulation software used to test the former scenarios has been Aimsun Next. Its default car-following and lane-changing algorithms, which apply for the non-platooned vehicles, are based on the Gipps models (Gipps, 1981; Gipps, 1986a; Gipps 1986b). In turn, the developed platooning algorithm and the management strategies have been coded in Python and implemented into AIMSUN through an API.

4 RESULTS

Results below correspond to a first case study where platoons only drive on the leftmost lane, which is not dedicated. Penetration rates of CAVs from 0% to 50% are tested for all range of traffic demand.

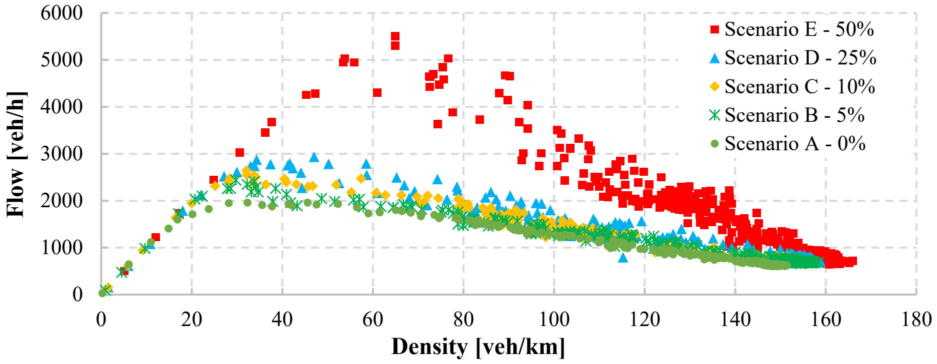

Figure 1 – *Flow - density diagram on the platooning lane for different CAV penetration rates*

Figure 1 shows that platooning allows a capacity increase in the platooning lane. The higher the CAVs penetration rate, the higher the maximum flows achieved, with increasing marginal gains. For example, for a share of 50% of CAVs, the baseline capacity increases around 150%, as does the critical density. In turn, flows in the middle and rightmost regular lanes do not present remarkable changes. Improvements on the traffic throughput for CAV penetration rates higher than 50% can not be taken for granted. In this scenario note that all CAVs would try to drive on the leftmost lane, leading to over optimal traffic densities and to many disturbances due to the necessary lane changes. Dedicating this leftmost lane to CAV platoons only or allowing platooning in the middle lane could be an appropriate solution. This and other scenarios will be assessed as next steps in this research.

5 CONCLUSIONS

This paper explores the management of CAV platoons so that they can safely enhance traffic flow on highways. It proposes algorithms to model CAV platooning, focusing on key factors that affect traffic efficiency. Results are achieved through simulation in a three-lane ring-road, and demonstrate significant increases in traffic throughput with CAV penetration rates exceeding 25%. At a 50% penetration rate and with a single platooning lane, the capacity of the infrastructure more than doubles compared to that in baseline conditions. Next steps comprise the introduction of other strategies such as the platooning dynamic management or the limitation in the platoon lengths.

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