Chapter

Connected and Autonomous Vehicle Platoons and Traffic Bottlenecks: Effects on Recurrent and Non-Recurrent Congestion in Mixed Traffic Conditions

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Abstract

Connected and autonomous vehicles (CAVs) are expected to play a transformative role in highway traffic, particularly through platooning strategies. Specifically, they are expected to enhance operational conditions at bottlenecks by reducing the propagation of congestion and the emergence of safety-critical conflicts. In these contexts, CAV platoons might increase flow capacity by operating with shorter headways, while they could enhance safety by adopting more coordinated maneuvers. While existing research has shown the potential of CAVs to enhance traffic performance, significant gaps remain regarding how platoons behave under bottleneck conditions, especially in mixed traffic with both CAVs and human-driven vehicles (HDVs). This chapter explores the impacts of CAV platoons on highway traffic performance under mixed traffic conditions, focusing on their role at bottlenecks. Two cases are considered: (i) a recurrent bottleneck in a highway merging area, where the interaction between entering and mainline flows typically generates congestion, and (ii) a non-recurrent bottleneck produced by a vehicle breakdown, causing temporary capacity reduction. Using microsimulation-based analyses, this study investigates how platoon size and CAV market penetration rate (MPR) influence traffic capacity, travel times, and environmental impacts. Results show that CAV platoons may reduce congestion in recurrent situations and improve resilience under non-recurrent disruptions: specifically, in highway merging areas, platooning increases flow capacity and reduces travel times, while in the case of vehicle breakdowns, platoons help mitigate capacity drops and limit delays, particularly at higher MPRs and moderate platoon sizes. These findings contribute to a deeper understanding of the opportunities and challenges of CAV platoon deployment.

Keywords: connected and autonomous vehicles (CAVs), platooning, mixed traffic, highway bottlenecks, on-ramp merging, vehicle breakdown

1. Introduction

In recent years, connected and autonomous vehicles (CAVs) have attracted growing attention for their potential to transform road transportation by improving safety, operational efficiency, and environmental performance. By integrating advanced sensing, control, and communication technologies and exchanging real-time information with other vehicles and the infrastructure, CAVs can coordinate their movements more effectively, leading to increased road capacity and optimized energy consumption [1–3]. At the same time, CAVs may enhance road safety by minimizing human errors, maintaining safer following distances, and responding more effectively to potential hazards [4, 5]. However, it is expected that, in the foreseeable future, CAVs and conventional human-driven vehicles (HDVs) will coexist in mixed traffic conditions [6, 7]. This mixed environment introduces additional complexity, as the effects of automated traffic depend not only on CAV performance but also on their interactions with conventional vehicles.

The potential of CAV could be relevant on highways, where relatively uniform traffic conditions and higher speeds amplify the benefits of coordinated vehicle behavior; particularly, CAV platooning has received significant attention [8]. Platooning refers to groups of vehicles traveling in a coordinated manner, maintaining short inter-vehicle distances and synchronized speeds enabled by vehicle-to-vehicle (V2V) communication. This coordinated behavior may increase road capacity, improve flow stability, and reduce fuel consumption due to lower aerodynamic drag [9, 10]. These features make platooning an effective strategy for enhancing the benefits associated with the gradual introduction of CAVs into highway systems. Beyond improving traffic flow under stable conditions, the potential of CAV platoons can be especially relevant when the highway network is subject to congestion. The highway system is often characterized by the presence of bottlenecks, that is, critical points in the network where traffic demand exceeds the available capacity, generating congestion, queues, delays, environmental impacts, and safety risks. These bottlenecks can be: (i) recurrent, such as those that form in on-ramp or off-ramp areas, where the interaction between entering flows and mainline traffic reduces overall capacity, or (ii) non-recurrent, associated with unexpected or temporary events such as accidents, vehicle breakdowns, or road works. In both cases, the occurrence of a bottleneck and the resulting reduction in effective capacity not only worsen local traffic conditions but can also trigger spillback along upstream segments, amplifying congestion. In these situations, CAV platoons might provide significant benefits in mitigating disturbances. In fact, by maintaining short and steady headways, adjusting speeds consistently, and reacting faster and more uniformly than human drivers, CAV platoons may help reduce disturbances, limit delays, and support a faster recovery of traffic flow, thereby improving the overall resilience of the highway system [11]. However, the actual potential of CAV platooning is not obvious: depending on factors such as platoon size and market penetration rate, they may either improve traffic performance or, in some cases, worsen local congestion at bottlenecks.

The literature has shown that CAVs can alleviate congestion both at recurrent bottlenecks and under non-recurrent disturbances. Most previous works have examined merging areas, where CAVs are generally found to improve capacity and flow efficiency [12]. However, the majority of studies analyze the behavior of individual CAVs rather than the dynamics of full platoons. Studies specifically addressing platoons often concentrate on cooperative control strategies – such as gap opening, platoon splitting or coordinated merging – which assume that platooned vehicles actively adjust their configuration to facilitate ramp entries or respond to critical events [13, 14]. These approaches are useful for illustrating the maximum potential of platooning, but they rely on control capabilities that may not be available in the short to medium term, when CAV platoons are more likely to operate on the mainline without dedicated mechanisms for interacting with on-ramp traffic. Moreover, the literature is still limited in comparing platoon performance across different operational contexts. For example, a platoon configuration that proves effective at a recurrent bottleneck may perform very differently – and in some cases even worsen congestion – during a non-recurrent disturbance such as a vehicle breakdown. This context-dependence of platoon performance remains largely underexplored, despite being a key factor for assessing the feasibility of large-scale platoon deployment in real mixed-traffic conditions.

This chapter examines the effects of CAV platoons on highway traffic performance in the presence of bottlenecks under mixed traffic conditions. Two representative cases are considered:

1. A recurrent bottleneck, corresponding to a highway on-ramp merging area, where the interaction between entering vehicles and the mainline flow reduces capacity and generates congestion;

2. A non-recurrent bottleneck, generated by a vehicle breakdown, leads to a temporary capacity reduction and traffic disturbance.

For both scenarios, the analysis explores how market penetration rate (MPR) and platoon size affect traffic performance in the two bottleneck scenarios by assessing their effects in terms of capacity, travel times, and environmental impacts. The analysis relies on a microsimulation-based approach, which allows detailed modeling of vehicle interactions and the evaluation of different penetration levels and platoon configurations. The results provide a quantitative basis for evaluating the effects of CAV platoons and enable the identification of platoon configurations that are most effective for the different bottleneck scenarios, providing insight into how their performance evolves under varying disturbance conditions. This is particularly relevant in mixed traffic environments, as understanding how CAVs and HDVs interact at highway bottlenecks provides the basis for developing traffic management strategies that can fully exploit the benefits of platooning.

The chapter is structured as follows. Section 2 presents a review of the literature on platooning, with emphasis on bottleneck-related studies, while Sect. 3 outlines the methodological framework adopted in this study. Section 4 describes the simulation setup and reports the findings for the two case studies, and Sect. 5 discusses their implications. Finally, Sect. 6 summarizes the conclusions.

2. Literature review

A growing body of research has examined the potential of CAVs to improve the efficiency, safety, and stability of highway traffic flow. Studies consistently indicate that CAVs, thanks to real-time communication and coordinated longitudinal control, can maintain more regular headways, react more smoothly to disturbances [15, 16], and reduce the formation and propagation of stop-and-go waves [17, 18]. These mechanisms are generally recognized as key enablers of both improved operational performance and enhanced safety in highway environments.

Within this context, vehicle platooning has attracted increased research interest, examining how groups of CAVs can travel cooperatively through communication and coordinated longitudinal control, enabling significantly shorter headways than those maintained by human drivers. The literature shows that platooning can significantly increase lane capacity [19] and improve flow stability [1, 20], while also enhancing safety [21]. Several studies on both truck and passenger-car platoons report higher throughput and lower emissions, the latter mainly resulting from lower aerodynamic drag and the mitigation of stop-and-go oscillations [22–24]. These advantages have been found to be particularly relevant in highway environments, where coordinated maneuvers and smoother trajectories can substantially enhance overall traffic performance [25, 26]. Although quantitative estimates vary across modeling approaches, the literature generally agrees that capacity gains become more substantial as cooperative automation increases [27, 28].

A growing number of modeling and simulation studies have also explored how CAV market penetration rates and platoon size influence mixed-traffic conditions [29]. Most work suggests that the benefits of CAVs emerge even at moderate penetration rates, although the magnitude of such benefits depends strongly on behavioral interactions with HDVs and on platoon configuration [30]. Behavioral heterogeneity between CAVs and HDVs is frequently identified as a central factor, especially in low-penetration scenarios where mixed-traffic instabilities may still occur [31, 32]. Using cellular automata models [33] demonstrates that fixed-length platoons can already enhance flow efficiency and reduce congestion [22]. This line of research is extended through a hybrid cellular automaton framework integrating both autonomous platoons and human-driven vehicles. Several simulation and analytical studies indicate that at low CAV penetration, very long platoons can even introduce additional disturbances if not properly managed, and improvements in capacity are limited. For instance, [8] reports that at 50% CAV penetration, platoons of around 20 vehicles increase capacity by only about 2% and tend to generate additional lane-changing interactions in predominantly human-driven traffic. Several studies indicate that moderate platoon sizes achieve higher capacity while keeping inter-vehicle dynamics stable [28, 34]. Beyond efficiency, several studies have investigated the safety and environmental implications of platooning. The main findings consistently point to fewer abrupt maneuvers, smoother speed adaptation, and potential reductions in collision risks [35], travel time [22], fuel consumption, and emissions [24].

In relation to freeway bottlenecks, most research has focused on on-ramp merging areas, where vehicles must negotiate right-of-way and where recurrent congestion typically arises. In these critical zones, CAV platooning has shown considerable potential to mitigate the capacity drop and delays usually associated with merges [36]. The literature on merging often centers on cooperative control strategies, such as adaptive gap policies or platoon reconfiguration, designed to facilitate smoother interactions with entering traffic [37]. Indeed, several cooperative merging algorithms have been proposed to improve lane-use efficiency during merging [38, 39]. For instance, [40] shows that employing cooperative merging control in on-ramp conditions enhances traffic flow stability and throughput relative to conventional merging, and [14] proposes a platoon-split merging strategy for mixed traffic. Other works investigate cooperative lane-changing and trajectory-planning approaches, demonstrating that CAV coordination of lane and speed adjustments can increase merge capacity, smooth the flow, and reduce fuel consumption [41]. A second line of research quantifies the capacity gains achievable through platooning, generally considering CAVs operating on both the mainline and the on-ramp. The greatest benefits are consistently observed for the ramp flow: shorter inter-vehicle gaps reduce the effective length of merging vehicle strings, allowing a larger number of vehicles to clear the merge point within the same time interval [25]. A macroscopic model was developed showing that optimizing platoon length as a function of demand and CAV penetration can substantially increase the throughput of a freeway merge. However, it has been noted that, without adaptive gap management, tightly spaced platoons can restrict the gaps available to on-ramp vehicles, causing safety issues and degrading merge performance [42, 43]. It was observed that short intra-platoon gaps can form a "moving wall" that hinders merging, leading to late and risky lane changes, whereas slightly larger gaps increased merge success rates and reduced conflicts.

Beyond everyday bottlenecks, some studies have also examined the effects of non-recurring events such as accidents or vehicle breakdowns. Existing evidence suggests that CAV platooning can improve traffic performance during incidents by enabling faster recovery and reducing the severity of congestion [44, 45]. These benefits become more pronounced as penetration increases, with several studies reporting faster recovery and reduced secondary disturbances after an incident [46–48]. Reports indicate that under accident-induced bottlenecks, CACC-enabled platoons maintain higher throughput than human-driven traffic due to shorter safe gaps, with upstream congestion progressively diminishing as CAV penetration increases [49]. Researchers investigate platoon breakdowns and find that the sudden disablement of a platoon leader can temporarily reduce capacity, although higher CAV penetration considerably mitigates this effect. Their findings also show that very long platoons exacerbate delay and safety risks when forced to dissolve near an incident, leading the authors to recommend limiting operational platoon sizes to around four vehicles. Related research in lane-closure and work-zone contexts offers similar indications, reinforcing the idea that cooperative longitudinal control is particularly valuable under non-recurrent, capacity-reducing disturbances [50].

Overall, the literature strongly supports the capacity and safety advantages of CAV platooning under ideal or near-ideal conditions, such as high CAV adoption, tight coordination, and homogeneous traffic. In mixed traffic, however, existing findings also show that the magnitude of these benefits depends critically on factors such as market penetration and platoon size, indicating that platoon performance is highly sensitive to the operating conditions. Despite this, important gaps remain regarding how different platoon configurations perform across distinct bottleneck types. Most studies analyze platooning either in recurrent merging scenarios or in non-recurrent disruptions, but they rarely assess whether a given configuration performs consistently across both conditions. Consequently, there is limited evidence on whether configurations that prove beneficial in one type of bottleneck may become less effective when the congestion mechanism changes. Building on this gap, the present study examines how the effectiveness of CAV platoons varies across two fundamentally different types of freeway bottlenecks within a common modeling framework. In detail, this chapter investigates whether operational characteristics such as market penetration or platoon size can lead to different outcomes depending on whether congestion originates from routine merging interactions or from an unexpected incident, thereby contributing to a clearer understanding of how platoons behave under heterogeneous traffic conditions and which configurations are more appropriate for each context.

3. Methodology

To address the research objectives, this study combines established microscopic traffic models with simulation experiments to analyses HDV and CAV behavior under bottleneck conditions. For longitudinal movement, different models are applied depending on the vehicle type. The car-following behavior of HDVs is simulated using the intelligent driver model (IDM) [51], which captures essential aspects such as acceleration, deceleration, and the management of safe distances typical of human drivers. For CAVs, the cooperative adaptive cruise control (CACC) and adaptive cruise control (ACC) models [52] are used to reflect their cooperative behavior and adaptive responses to surrounding traffic. For both CAVs and HDVs, lane-changing behavior is modeled using the LC2013 model [53], which effectively represents how vehicles decide to change lanes and execute these maneuvers in mixed traffic conditions. To model merging operations, it is assumed that shorter lane-changing gaps are accepted [54]. A highway segment is recreated in the simulation, incorporating realistic geometric and traffic flow characteristics. Two distinct scenarios are modeled: a non-recurrent bottleneck caused by a vehicle breakdown and a recurrent bottleneck generated by an on-ramp merging area. To assess the impact of these conditions, several key performance indicators are considered, focusing on traffic flow efficiency and environmental impacts. The overall architecture is depicted in **Figure 1**.

3.1 HDVs longitudinal movement model

HDVs' longitudinal navigation is modeled using the intelligent driver model (IDM), a standard car-following model widely adopted for representing human

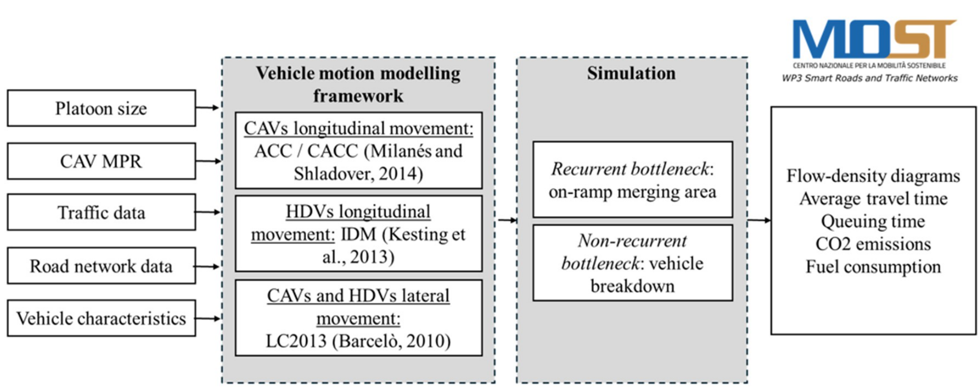

Figure 1.
Overview of the methodology.

driving behavior in microscopic simulations. IDM is used here because it captures typical acceleration, deceleration, and gap-keeping tendencies of human drivers, providing a reliable baseline for mixed-traffic conditions. Furthermore, it has been proven to be particularly suitable for microscopic simulations involving mixed traffic flows [55]. The IDM defines a vehicle's acceleration based on the current speed, the speed difference with the leading vehicle, and the space gap between them. The acceleration of a vehicle is given by:

$$a_{IDM} = a_m \left[1 - \left(\frac{v}{v_0} \right)^{\delta} - \left(\frac{s^*(v, \Delta v)}{s} \right)^2 \right] \tag{1}$$

$$s^*(v, \Delta v) = s_0 + \max\left(0, vT + \frac{v\Delta v}{2\sqrt{a_m b}} \right) \tag{2}$$

where a_m is the maximum HDV acceleration, v is the speed of the following vehicle, v_0 is the desired speed, s is the space gap between the leading and following vehicles, Δv is the speed difference between the leading and following vehicles, δ is a parameter characterizing how the acceleration decreases with the speed, $s^*(v, \Delta v)$ is the minimum desired space gap, s_0 is the minimum inter-vehicular distance at standstill, T is the safe time headway and b is the desired comfortable deceleration.

3.2 CAVs longitudinal movement model

CAVs are modeled as operating in platoons, each comprising a group of n vehicles. Within each platoon, the first vehicle is designated as the leader, while the others act as followers. This platoon-based structure reflects the coordinated behavior enabled by vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies. The motion dynamics of CAV platoons are modeled by applying distinct control strategies to the leading and following vehicles. The longitudinal motion of the platoon leader is governed by an ACC model, which regulates the vehicle's behavior based on on-board perception systems (e.g., radar, LiDAR) to maintain a safe headway relative to the preceding traffic. In contrast, follower vehicles in the platoon are modeled using a CACC strategy, which integrates local sensor data with information received through V2V communication. The CACC framework enables the followers to access not only their immediate leader's state but also information from other platoon members, allowing for reduced time headways and improved responsiveness of the platoon.

For modeling the ACC and CACC behavior, a simplified version of the cooperative controller implemented in commercial CACC-equipped vehicles is employed, following the formulation proposed by [52]. The longitudinal control of the platoon leader under the ACC model is represented by a car-following scheme aiming to maintain a desired time headway t_{hw} with respect to the preceding vehicle. The acceleration a_i commanded by the ACC controller is given by:

$$a_i = k_1(x_{i-1} - x_i - t_{hw}v_i) + k_2(v_{i-1} - v_i) = k_1 e_i + k_2(v_{i-1} - v_i) \tag{3}$$

Where x_i, v_i and a_i are the current position, speed and acceleration of the i–th CAV vehicle; x_{i-1} and v_{i-1} are the current position and speed of the preceding vehicle; e_i is the gap error of the i–th vehicle, representing the difference between the desired gap and the actual gap between the vehicle and its preceding one. k_1 and k_2

are the gain coefficients on both the spacing and speed differences, respectively, acting as tuning parameters that determine the ACC controller's responsiveness to variations in traffic conditions.

For follower vehicles operating under the CACC model, a cooperative control law is applied and the desired speed v_i for a follower vehicle is computed based on information received from the platoon leader (or other upstream vehicles), according to [52]:

$$v_i = v_{i,\,prev} + k_p e_i + k_d \dot{e}_i \tag{4}$$

Where $v_{i,\,prev}$ is the speed of the i–th follower vehicle at previous time step; k_p and k_d are control gains associated to the time gap error.

3.3 CAVs and HDVs lateral movement model

For both HDVs and CAVs, lateral vehicle behavior is modeled using the LC2013 lane-changing framework [56]. The model distinguishes among three types of lane change motivations: strategic, cooperative and tactical. A strategic lane change is initiated to avoid reaching a dead-end or an unusable lane and is classified as a mandatory maneuver. A cooperative lane change occurs when a vehicle adjusts its speed or position to facilitate the lane change of another vehicle. A tactical lane change is performed voluntarily to optimize travel conditions, such as improving speed, following traffic rules (e.g., returning to the right lane after overtaking) or maintaining lane discipline. Once a lane change is deemed necessary or desirable, the vehicle evaluates the feasibility of the maneuver through a gap acceptance process, where it assesses the available gaps in the target lane relative to its own speed and position. If a suitable gap is identified, the vehicle may initiate the maneuver; otherwise, it may postpone the lane change and adapt its behavior to create favorable conditions. To model bottleneck conditions, it is assumed that vehicles temporarily accept shorter lane-changing gaps than under normal conditions, reflecting the increased urgency to complete the maneuver before the end of the lane [54]. Specifically, a reduction of approximately 20% in the acceptable gap size is considered, based on empirical observations [57]. Following the lane change, vehicles gradually restore their headways to typical values within a short recovery period, consistent with the relaxation phenomenon described by [58].

3.4 CAV platoon behavior at bottlenecks

In the presence of a bottleneck, whether recurrent or non-recurrent, the behavior of CAVs within platoons is modified based on the approach developed by [49]. A CAV detects a bottleneck when the speed of its preceding vehicle remains at zero for more than 2 seconds and the distance to that vehicle is less than 60 m. The 60 m threshold corresponds to the typical stopping distance at highway speeds and is consistent with values reported in the literature [59]. When these conditions occur, it is assumed that the CAV "recognizes" that it has entered the influence area of a bottleneck and triggers a dedicated control logic.

The platoon that includes the detecting CAV is dissolved by modifying the control logic described in Sect. 3.2, specifically through the activation and deactivation of ACC and CACC modes, consistent with the approach proposed in [60]. For all follower CAVs in the platoon, the CACC mode is deactivated, and their control is switched to ACC. The platoon leader already operates under ACC and, therefore, remains in ACC mode. At this point, all CAVs behave as independent vehicles rather than as members of a coordinated platoon. The choice to model platoon dissolution near bottlenecks is driven by the need to ensure sufficient gaps to perform lane changes. In fact, if the platoon is kept intact, coordinated maneuvers would require gaps that could accommodate the entire formation. Such gaps grow rapidly with platoon size and may not be available in congested conditions, potentially leaving the platoon stuck in the tail for long periods. Platoon dissolution avoids this problem by allowing each CAV to act independently and use smaller, individually acceptable gaps, thus improving maneuverability. More advanced cooperative lane change or platoon-splitting strategies are not considered, as they require coordinated interactions that cannot be guaranteed in mixed traffic, especially in cases of low CAV penetration. For this reason, platoon dissolution has been adopted here as the most effective default behavior in bottleneck regions.

In ACC mode, each CAV adapts its speed to the vehicle ahead and, at the same time, monitors the neighboring lane. If the lane-changing criteria (safety gaps and incentive conditions) are satisfied, the CAV initiates a lane change to bypass the obstacle or the queue forming upstream of the bottleneck. The flowchart of the proposed platoon control algorithm in the presence of bottlenecks is shown in **Figure 2**. After passing the bottleneck and once local traffic conditions return to normal (i.e., no stopped vehicles ahead within the detection distance and speeds compatible with free-flow or near free-flow), CAVs return to their lane. If other CAVs are available in the same lane and within the required distance, platoons are re-formed by reactivating CACC mode for follower vehicles, following the logic described in Sect. 3.2. In practice, platoons dynamically dissolve in the vicinity of bottlenecks and re-establish once the congested area has been cleared. HDVs are modeled using the IDM car-following model and perform lane changes to avoid the stopped vehicle according to the LC2013 lane-changing model described earlier.

3.5 Traffic performance indicators

The system's performance is assessed through a set of indicators, each addressing different dimensions, including operational efficiency and environmental impacts.

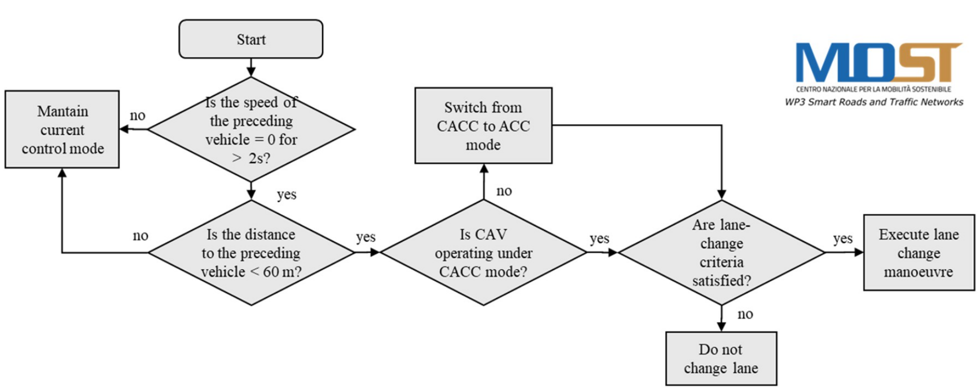

Figure 2.
Control logic in the presence of a bottleneck.

Specifically, the selected metrics include traffic capacity, vehicle travel time, CO_2 emissions, and queuing time. Traffic capacity is derived by calibrating the flow-density (q–k) relationship using experimental data, employing a triangular flow diagram [61]:

$$q(k) = \begin{cases} v_f k & for\, k < k_c \\ w(k_j - k) & for\, k > k_c \end{cases} \tag{5}$$

where q is the traffic flow; k is traffic density; v_f is the free-flow speed; w is the shockwave speed; k_j is the jam density; k_c is the density at capacity (critical density). The maximum flow q_{max} (capacity) occurs at k_c and is equal to $v_f k_c$. Average travel time is employed as a performance indicator of the overall efficiency of the network and it is computed by averaging the individual travel times of all vehicles in the network. Queuing time is used to quantify the delay experienced by vehicles during congested conditions. It is computed as the total time during which a vehicle speed falls below 0.1 m/s, which corresponds to stopped or near-stop motion. Two complementary indicators are considered: the average queuing time per vehicle, which reflects the typical delay experienced by individual users, and the total queuing time per 5-minute interval, used to capture the temporal evolution of congestion formation and dissipation along the network. Environmental impacts are evaluated in terms of CO_2 emissions (mg/vehicle). Emissions are estimated using the HBEFA4 emission model, which computes pollutant production for each vehicle based on its instantaneous kinematic state (speed and acceleration). For each scenario, the total CO_2 emitted along the highway segment is aggregated across all vehicles and the corresponding average emission per vehicle is used to compare environmental performance across different market penetration rates and platoon sizes. These indicators are calculated across various scenarios under varying levels of MPR and platoon size and compared to evaluate the impacts of CAV platooning on traffic efficiency and safety.

4. Simulation experiments

4.1 Simulation setup

The simulation is carried out using the Python-SUMO platform on a three-lane highway segment. The simulated section is 3 km long, with a lane width of 3.75 m and a speed limit of 130 km/h. Two scenarios are implemented to analyze both a non-recurrent bottleneck (vehicle breakdown) and a recurrent bottleneck (on-ramp merging area). The first scenario (**Figure 3a**) represents a freeway segment without ramps, reproducing undisturbed flow upstream of a non-recurrent event. The breakdown is modeled by stopping an HDV in the left lane at 2 km. The stopped vehicle remains in place for 15 minutes, during which approaching vehicles slow down and perform lane changes to bypass the lane blockage. CAV behavior follows the obstacle-avoidance logic described in Sect. 3.4: once the bottleneck is detected, platoons dissolve, follower vehicles switch from CACC to ACC mode, and all CAVs operate as independent units while executing lane changes based on safety and incentive rules. After removal of the obstacle, the resulting queue gradually dissipates until normal operating conditions are restored. The second scenario (**Figure 3b**) represents an on-ramp merging area. The acceleration lane is 200 m

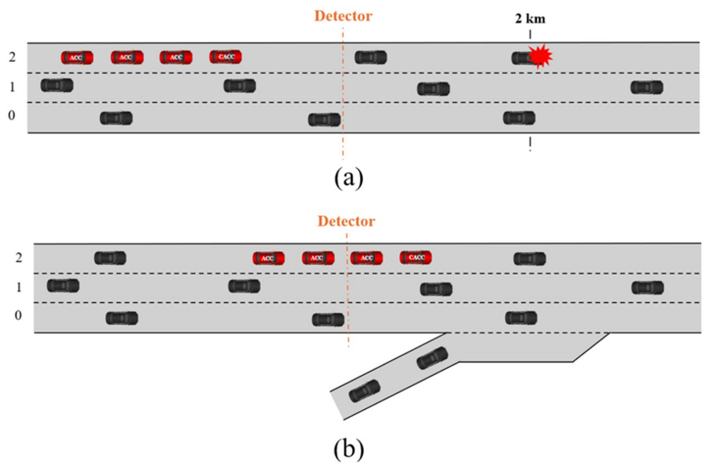

Figure 3.
Simulated highway segment and bottleneck configurations: (a) Non-recurrent incident scenario; (b) Recurrent on-ramp merging scenario.

long, and entering vehicles, composed exclusively of HDVs, merge into the mainline. The on-ramp flow is fixed at 600 veh/h. In both scenarios, the mainline flow consists of mixed traffic, with the proportion of CAVs determined by the market penetration rate; CAVs travel in platoons and may use all lanes.

Parameter values for car-following and lane-changing models follow established values in the literature [52, 62] and are summarized in **Table 1**. A set of experiments is conducted to evaluate how MPR and platoon size affect traffic performance. CAV market penetration is varied across 0%, 20%, and 40%, representing plausible medium-term adoption levels. For each penetration level, platoons of 2, 4, 6, and 8 vehicles are simulated. Total traffic demand is varied at several levels of congestion conditions, across 1,000, 1,350, 1,650, and 2,000 veh/h/lane, the latter representing highly congested conditions. Each simulation runs for 3,600 s, preceded by a 600 s warm-up period excluded from the analysis. To account for stochasticity, three random seeds are used for each configuration. Performance is evaluated in terms of flow capacity, operational efficiency, and environmental impacts, using the indicators described in Sect. 3.5.

Parameter	Value	Parameter	Value
k_j (maximum density)	160 veh/km/lane	Platoon inter-vehicle distance	5 m
δ (HDV free acceleration exponent)	4	t_{hw} (CACC desired time gap)	1.1 s
b (desired deceleration)	2 m/s^2	t_{hw} (ACC desired time gap)	0.6 s
a_m (max. acceleration)	1 m/s^2	k_1 (gains on positioning errors)	0.23 s^2
v_0 (desired speed)	33 m/s	k_2 (gains on speed errors)	0.07 s^2
T (safe time headway)	1.6 s	k_p (gains on time-gap)	0.45
s_0 (min. gap at standstill)	1 m	k_d (gains on time-gap)	0.25

Table 1.
Parameters used in the simulation.

4.2 Results

Figure 4 shows the results for the vehicle breakdown scenario: **Figure 4a-d** describe the effects of different market penetration rates (*MPR* = 0.20 and 0.40) and platoon sizes (*n* = 0, 2, 4, 6, 8) under high-demand conditions (2,000 veh/h/lane); **Figure 4e** presents the flow-density relationships observed upstream of the incident. Traffic data are collected at a simulated detector located 50 m upstream of the breakdown (see **Figure 3a**) and averaged across the three lanes for each MPR. For every condition, a triangular fundamental diagram is fitted to the aggregated data to estimate the free-flow speed (v_f), critical density (k_c), and maximum flow (q_{max}); calibration uses the Nelder–Mead optimization method [63], with the jam density fixed at 160 veh/km/lane.

Overall, the introduction of CAV platoons markedly improves traffic performance compared with the all-HDV baseline. Travel times (**Figure 4a**) decrease substantially even at moderate penetration levels, and their variability is significantly reduced. At *MPR* = 20%, travel times already show a notable reduction: for *n* = 2, the median decreases by roughly 25–30%, and for *n* = 4, by about 20–25%

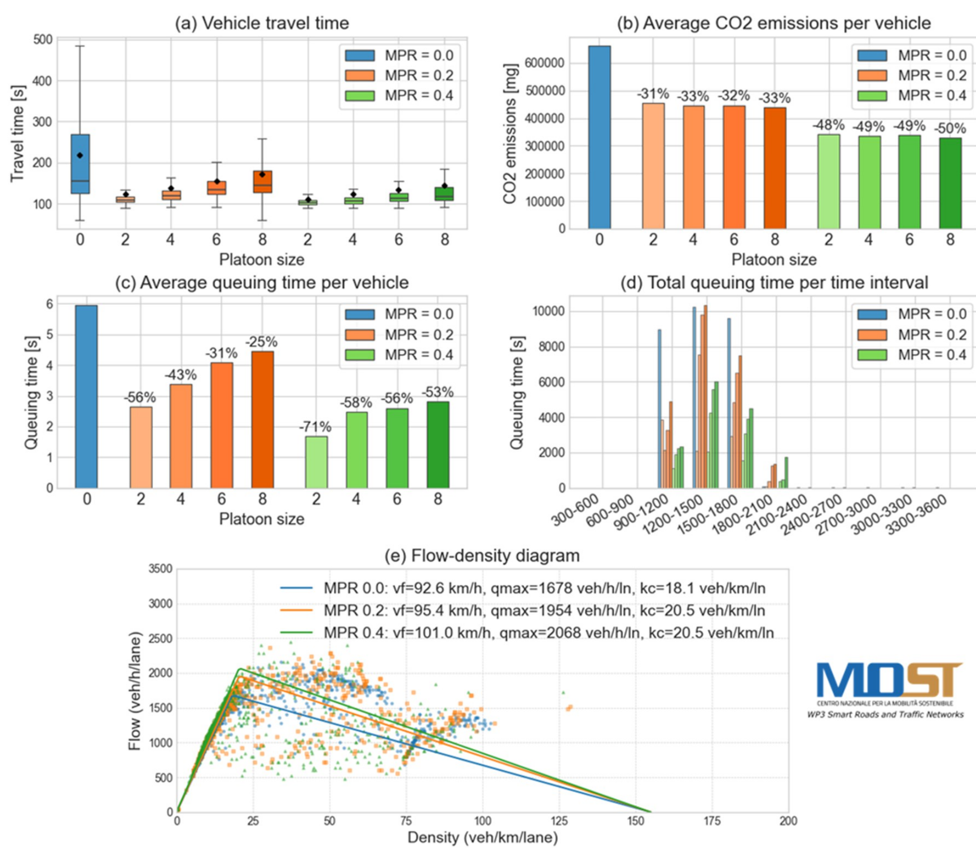

Figure 4.
Indicators under different market penetration rates (MPR) and platoon sizes for the breakdown scenario: (a) Vehicle travel-time; (b) Average CO_2 emissions per vehicle; (c) Average queuing time per vehicle; (d) Total queuing time per 5-minute interval; (e) Flow-density diagrams.

relative to the HDV case. The improvement becomes even more pronounced at *MPR* = 40%, where reductions of approximately 40–45% (*n* = 2) and 35–40% (*n* = 4) are observed, together with a marked contraction of the interquartile range. However, increasing platoon size does not continue to improve performance. For both penetration levels, larger platoons (*n* = 6 and *n* = 8) lead to increased travel times relative to smaller formations. The flow-density diagram in **Figure 4e** further quantifies the positive effects of CAV MPR on the macroscopic traffic characteristics. As MPR increases, the scatter of flow-density observations is reduced, and the estimated maximum flow shows a moderate but consistent improvement relative to the all-HDV case, indicating that CAVs can enhance overall throughput even when HDVs remain the majority of the fleet. In particular, maximum flow increases by approximately 16% at *MPR* = 20% and by about 23% at *MPR* = 40% compared with the HDV baseline. Although the gain between 20% and 40% penetration is moderate, the upward shift in both critical density and maximum flow indicates that CAVs improve the ability of the traffic stream to sustain higher densities before the onset of congestion. Queue-related indicators provide additional insight into the system's response to the breakdown (**Figure 4c, d**). Average queuing times decrease substantially with the introduction of CAVs. At *MPR* = 20%, reductions of approximately 56% (*n* = 2) and 43% (*n* = 4) are observed relative to the HDV case, while at *MPR* = 40%, the decrease reaches about 72% and 55% for the same platoon sizes. These improvements are also reflected in the temporal distribution of delays across the simulation horizon, which becomes smoother in the presence of CAVs: in the all-HDV scenario, queuing concentrates in sharp peaks associated with rapid queue formation, whereas with CAVs, the peaks are smaller and more evenly distributed. Therefore, queues build up more gradually and dissipate more quickly once the obstacle is removed. Emissions-related indicators show a similar pattern. Average CO_2 emissions per vehicle (**Figure 4b**) decrease markedly with the introduction of CAVs: reductions of about 31–33% are observed at *MPR* = 20% and approximately 45–50% at *MPR* = 40%. As with queuing times, the largest benefits occur for smaller platoon sizes (*n* = 2–4), while larger formations offer more limited improvements. **Table 2** summarizes the percentage improvements in average travel time, CO_2 emissions, and queuing time for the breakdown scenario.

The results for the merging scenario (**Figure 5**) reveal patterns that are broadly consistent with those observed in the incident case, but with differences in both

Platoon size		**n = 2**	**n = 4**	**n = 6**	**n = 8**
Average travel time [Δ%]	MPR = 0.2	−43.98	−37.15	−29.38	−21.29
	MPR = 0.4	−49.15	−43.73	−39.01	−33.42
Average CO_2 emissions [Δ%]	MPR = 0.2	−31.08	−32.86	−32.47	−33.49
	MPR = 0.4	−48.42	−49.09	−48.63	−50.24
Average queuing time [Δ%]	MPR = 0.2	−55.66	−43.26	−31.32	−25.36
	MPR = 0.4	−71.49	−58.24	−56.24	−52.51

Table 2.
Percentage reductions in travel time, CO_2 emissions, and queuing time relative to the all-HDV case for the breakdown scenario.

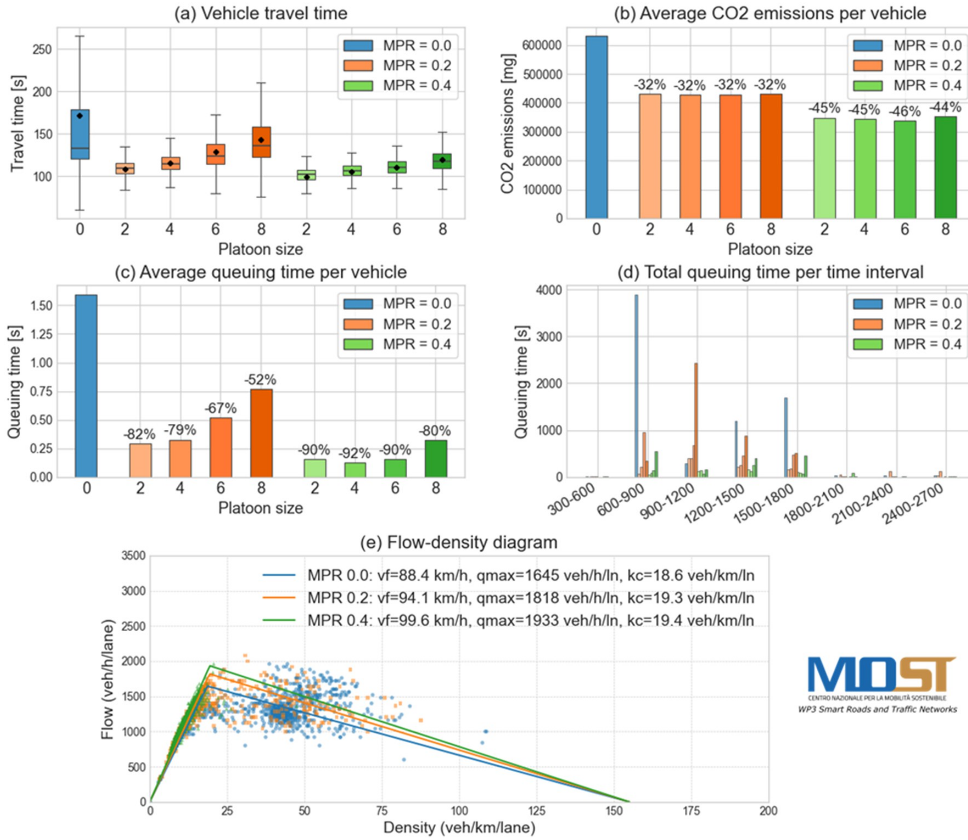

Figure 5.
Indicators under different market penetration rates (MPR) and platoon sizes for the merging scenario: (a) Vehicle travel-time; (b) Average CO_2 emissions per vehicle; (c) Average queuing time per vehicle; (d) Total queuing time per 5-minute interval; (e) Flow-density diagrams.

magnitude and pattern. As in the breakdown scenario, the introduction of CAVs reduces travel times (**Figure 5a**), queuing (**Figure 5c, d**) and emissions (**Figure 5b**) relative to the all-HDV baseline, and these improvements become more pronounced as MPR increases. However, in this case, reductions in travel and queuing times are smaller than those observed during the incident. For example, at MPR = 20%, median travel times decrease by roughly 10–15% for small platoons (n = 2–4), and at MPR = 40%, the reduction rises to approximately 20–25%. Platoon-size effects also differ. While small platoons (n = 2–4) again provide the best performance, the penalty associated with larger formations is less severe than in the breakdown scenario. For instance, moving from n = 4 to n = 8 at MPR = 40% increases median travel time by only 5–8%, whereas the same increase in platoon size during the incident caused travel-time penalties exceeding 15–20%.

Macroscopic flow patterns confirm these trends. The flow-density diagrams in **Figure 5e** – derived from data collected at the detector positioned 50 m upstream of the on-ramp (see **Figure 3b**) – show a moderate upward shift in both critical density and capacity with increasing MPR, similar in direction to the incident scenario but smaller in magnitude. Maximum flow increases from the HDV baseline to

Platoon size		n = 2	n = 4	n = 6	n = 8
Average travel time [Δ%]	MPR = 0.2	−36.78	−32.67	−25.04	−16.91
	MPR = 0.4	−42.30	−38.59	−35.62	−30.53
Average CO_2 emissions [Δ%]	MPR = 0.2	−31.73	−32.34	−31.98	−31.67
	MPR = 0.4	−44.76	−45.42	−46.46	−43.89
Average queuing time [Δ%]	MPR = 0.2	−81.58	−79.50	−67.43	−51.69
	MPR = 0.4	−90.22	−92.20	−89.99	−79.85

Table 3.
Percentage reductions in travel time, CO_2 emissions, and queuing time relative to the all-HDV case for the merging scenario.

approximately +10% at *MPR* = 20% and +17% at *MPR* = 40%. CO_2 emissions follow the same qualitative pattern as in the incident scenario, decreasing by roughly 30–33% at *MPR* = 20% and 45–47% at *MPR* = 40% for *n* = 2–4, but again with more modest gains relative to the incident case. **Table 3** provides percentage variations in average travel time, queuing time, and CO_2 emissions for the on-ramp merging scenario.

5. Discussion

The results obtained from the two bottleneck scenarios provide a comprehensive view of how CAV platoons influence traffic performance under bottleneck conditions. Overall, during an incident, CAV platoons act as “shock absorbers,” mitigating the abrupt disturbance generated by the lane blockage. The coordinated behavior within platoons limits sharp decelerations, reduces lane-change pressure upstream, and accelerates the transition back to uncongested flow. The benefits of platooning materialize across a wide range of performance indicators (capacity, travel time, queuing time, emissions), but the extent and nature of these benefits depend strongly on the type of disturbance affecting the traffic stream. This context-dependence is critical for understanding the real-world applicability of CAV platoons, especially in mixed traffic, where interactions between automated and human-driven vehicles introduce additional variability.

In the incident scenario, where an unexpected lane blockage abruptly reduces available capacity, CAV platoons generate significant improvements. The substantial reductions in travel time and queuing time, together with lower emissions and fuel consumption, show that platoons help normalize traffic behavior during both the formation and the dissipation of the queue. The flow-density relationships reinforce this interpretation: compared with fully human-driven traffic, even moderate CAV penetration produces denser and more compact flow regimes that can sustain higher densities before congestion emerges. These improvements stem from the coordinated deceleration and acceleration inherent in platooned CAVs, which limit the propagation of abrupt speed changes and maintain smoother trajectories upstream of the obstruction. In this scenario, therefore, platooning acts primarily as a stabilizing mechanism, reducing the severity of the disturbance and enabling a more efficient recovery of the traffic stream.

In contrast, in the merging scenario, benefits are still present but less pronounced. This is consistent with the fundamentally different nature of the bottleneck: whereas an incident induces a sudden and sharply localized reduction in capacity, merging turbulence arises from continuous interactions between entering vehicles and the mainline flow. Since the CAV platoons in this study do not perform explicit cooperative maneuvers, such as gap-opening or platoon splitting to accommodate merging traffic, the residual conflicts at the merge persist even at higher penetration levels. The improvements observed – lower travel times, reduced emissions and more compact flow-density patterns – result primarily from the smoother longitudinal behavior of CAVs on the mainline rather than from an active facilitation of merging maneuvers. As a result, the gains are more incremental and do not eliminate the inherent competition for space at the merge.

The analysis also highlights the central role of the market penetration rate. Across both scenarios, performance improves consistently as CAV penetration increases from 0% to 40%. This is evident in all key indicators: travel time, fuel consumption, emissions, and delay. These improvements at moderate penetration levels confirm that the benefits of platooning are accessible even in the early phases of deployment, when fleets are far from full automation. Importantly, however, the magnitude of the benefits differs between scenarios, confirming that the penetration rate interacts with the specific congestion mechanism at play.

Perhaps more importantly, the study reveals that platoon size has a non-trivial and context-dependent impact on performance. Contrary to earlier findings suggesting that medium-sized platoons (e.g., four vehicles) offer an optimal balance between capacity and stability, our results show that when platoons occupy all lanes, larger platoons tend to hinder lane-changing flexibility. This is particularly evident in both scenarios: long platoons act as moving barriers, reducing the opportunities for human-driven vehicles to execute evasive or merging maneuvers. In the incident scenario, this manifests as delayed lane changes upstream of the blockage, while in the merging scenario, it exacerbates competition for gaps at the merge. In both cases, smaller platoons – typically two vehicles – lead to better performance. This finding underscores the importance of considering lane distribution when determining optimal platoon configurations: what is optimal when platoons are confined to one lane may be suboptimal when they are distributed across all lanes. It is worth noting, however, that our findings on platoon size are linked to the demand conditions considered in this study. The simulations focus on traffic levels close to congestion, a regime in which density is high and acceptable gaps tend to be limited. Under these circumstances, it is plausible that long platoons reduce maneuverability and therefore perform worse. This mechanism may not operate in the same way under different demand levels: under low-demand conditions, larger gaps may be available, which could reduce the disadvantages associated with longer formations or even make them preferable in some situations. These considerations suggest that the advantage of small platoons observed here refers to highly congested conditions.

Together, these insights highlight the complexity of deploying CAV platoons in real-world mixed traffic. The performance of a given platoon configuration cannot be generalized across bottleneck types or roadway contexts. Instead, effective deployment strategies will likely require adaptive or context-specific settings – adjusting platoon size, gap policy, and possibly even lane allocation according to the nature of the bottleneck and prevailing traffic conditions. In other words, platooning strategies may need to adapt dynamically to the operational environment and to the type of bottleneck encountered. This observation has direct implications for future CAV control algorithms and traffic management policies, suggesting that "one-size-fits-all" platooning strategies may be insufficient to deliver consistent benefits across the highway network.

6. Conclusions

This study examined the impact of CAV platoons on highway traffic performance under mixed-traffic conditions, focusing on two representative bottlenecks: an incident-induced lane blockage and an on-ramp merging area. By evaluating identical platoon configurations across these two distinct operational environments, the analysis provides insights into the conditions under which CAV platooning yields measurable performance gains in mixed-traffic scenarios.

The findings show that CAV platoons can provide substantial benefits, leading to reductions in travel time, queueing times, and environmental emissions. However, the magnitude of these benefits varies with the nature of the bottleneck and therefore depends on the operational context. During an incident, platoons help absorb the sudden disturbance caused by the lane blockage: they reduce abrupt braking, limit the propagation of shockwaves, and allow traffic to recover more quickly. In contrast, in the merging scenario, the improvements are smaller because the bottleneck is created by continuous interactions between mainline and ramp vehicles, and platoons can only smooth these interactions rather than eliminate them.

A central result of the analysis is that the "optimal" platoon size is not a fixed property of the system but varies with the type of bottleneck. While prior studies often assume an optimal platoon size – typically around four vehicles – our results demonstrate that this assumption does not generalize to multi-lane, mixed-traffic environments. When platoons operate across all lanes, larger groups can restrict lane-changing maneuvers, particularly in zones where such maneuvers intensify (as in both incident avoidance and merging). In these conditions, smaller platoons consistently perform better. This highlights that the effectiveness of a given platoon size is inherently context-dependent, shaped by the interplay between platoon structure, lane-changing needs and the disturbance driving the congestion. Overall, the findings suggest that effective real-world deployment of CAV platoons will likely require adaptive and dynamic strategies – allowing platoon size, headways, or lane-use patterns to change according to the type of bottleneck encountered and the prevailing traffic conditions. Such context-aware approaches could help ensure that platooning delivers the expected improvements in efficiency, reliability, and environmental performance.

Although there are some encouraging results, this study has some limitations. First, no cooperative merging or lane-changing mechanisms were implemented for CAVs: vehicles do not generate gaps, coordinate trajectories, or perform platoon-splitting operations but rely on standard gap-acceptance rules. Second, platoon lane allocation is fully flexible, with no dedicated lanes or priority policies, whereas some studies advocate lane restrictions for platoons. Third, the analysis relies on ACC/CACC longitudinal controllers; more advanced approaches, such as RL– or MPC-based cooperative control, increasingly discussed in recent literature, are not considered. These assumptions should be taken into account when interpreting the results and considered in future extensions of this work. Moreover, in this study, platoons are always dissolved near bottlenecks, which is suitable for high-demand levels, but future research should verify whether this strategy is appropriate in all demand conditions. The advantage of dissolution may, in fact, depend on travel demand: while it appears beneficial under congestion, in low-demand conditions, larger gaps may be available, and keeping the platoon intact could be more effective. This aspect should be explored in future work.

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