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Cooperative bypassing algorithm for connected and autonomous vehicles in mixed traffic

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Abstract: Connected and autonomous vehicles (CAVs) have the capability to acquire real-time information from each other while human-driven vehicles (HVs) are standalone in the vehicle roadway navigation system. The information asymmetry poses significant challenges in managing and controlling vehicles in mixed traffic. To address such challenges, this study first customises the intelligent driver model to describe the car-following behaviour of CAVs. Furthermore, to raise the traffic efficiency of the mixed traffic flow, a new lane-changing decision support algorithm is proposed, which incorporates the interaction between CAVs and HVs by controlling the speed and locating the lane of CAVs. In addition to the common indexes of outflow and travel time to be used to measure the travel efficiency, new parameters such as platoon intensity and single rate are defined to evaluate the CAV platooning capability. Through simulation tests, the proposed controlling framework is implemented for a two-lane (per direction) freeway segment under different CAV penetration rates and input volumes. The simulation results indicate that, at all the CAV penetration levels, the proposed controlling algorithm provides significant performance improvements to the whole mixed traffic flow in terms of outflow, travel time, and the number of CAV platoons.

1 Introduction

Connectivity and automation in vehicles provide high potentials for the transportation system to reduce traffic congestion, energy consumption, and travel delays and improve road capacity and safety. With the introduction of connected and autonomous vehicles (CAVs), both of the driver behaviours and interactions with ambient vehicles are expected to change. A 100% deployment of CAVs, will significantly increase highway capacity on the existing infrastructures, due to smaller time headways between consecutive CAVs. However, there is still a long transition time from human-driven vehicles (HVs) to totally CAVs. According to estimates, most new vehicles will have some form of connectivity until 2025 [1], and 75% of vehicles will be autonomous until 2040 [2]. During the transition period, how to incorporate the relatively uncontrollable, random, and uncertain HVs with intelligent CAVs, and keep the mixed traffic flow operating in an efficient and smooth level is a crucial problem.

One of the efficient manners for the problem is to reduce the interference of HVs with dedicated lane use separating CAVs from HVs, which exerts a great impact on both road capacity and safety. However, dedicated lane use is an expensive strategy and only suitable when the CAV penetration reaches to a certain degree [3–5]. In other words, if the CAV penetration is at a relatively low level, allocating a dedicated lane for CAVs is wasteful and may incur traffic congestion in regular lanes. Another alternative is CAV platooning, where several CAVs closely follow a leading CAV. Because of the closer spacing, it is expected that the road capacity can be improved as a result of the higher traffic density and the cooperative behaviour of CAVs within a platoon [6]. Nevertheless, the movement of CAV platoons may be hindered by HVs, and the efficiency of CAV platoons will be greatly reduced. Therefore, for the mixed traffic to improve flow efficiency, a well-developed platooning and lane-changing management protocol is needed to arrange operations of two different types of vehicles.

Toward this objective, a cooperative adaptive cruise control (CACC) framework for CAV car-following and lane-changing in a mixed traffic environment is developed in this study. This study makes the following contributions. First, we consider the headway time of CAVs in the intelligent driver model (IDM) to model CAV drivers' acceleration behaviour, distinct from the car-following model for HVs. Secondly, a novel lane-changing algorithm for CAV platoons to bypass HVs is proposed, so as to improve travel efficiency for CAVs without sacrificing the speed of HVs. Thirdly, through the simulation experiment based upon VISSIM and COM interface using Python coding, the proposed CACC framework is tested and proved to reduce the system travel time and improve the freeway outflow and CAV platooning performance.

This paper is organised as follows. After the introduction part, Section 2 provides a review of the related literature about longitudinal and lateral controls for HVs and CAVs. We then present car-following and lane-changing models for CAVs in a mixed traffic environment in Section 3. Two new measurement indexes for evaluating the network performance under different CAV penetrations are further proposed in Section 4. Then, a case study is developed to implement the proposed models in VISSIM, and simulation results are presented and analysed. Finally, we conclude the paper with a summary of findings and a brief discussion of future research directions.

2 Literature review

The introduction of CAVs would result in a change in the driving environment due to the difference in driving behaviour between CAVs and HVs. Unlike CAVs whose movements can be well communicated and manipulated by the CACC system, HVs usually do not follow control laws, and their movements involve high levels of uncertainty and randomness. Therefore, in the mixed environment of CAV and HV, it is essential to carefully consider how the traffic flow should be controlled to achieve higher traffic efficiency.

A reasonable manner to address the mixed traffic flow is separating CAVs from HVs through dedicated lanes [7]. However, a certain degree of CAV penetration is an essential prerequisite to the dedicated lane method. Chen *et al.* [3] provided a theoretical framework for a two-lane (per direction) highway and claimed that

Table 1 Comparison of lane-changing strategies in a mixed environment

	Lane change method	Objective	Allow platoon change	Independent of CAV penetration
Shi *et al.* [9]	PAL and FAL	promote CAV platooning.	no	no
Liu *et al.* [25]	anticipatory lane-changing algorithm	enable CACC vehicles to merge into the managed lane.	no	yes
Wang *et al.* [26]	Q-learning	CAVs pursue higher speed via lane changing.	no	yes
Lin *et al.* [27]	transferable utility game	trade or transfer utility between vehicles.	no	yes
this study	bypassing algorithm	CAVs pursue longer distance to accelerate via bypassing HVs.	yes	yes

a dedicated lane for CAVs achieves the maximum capacity when CAV penetration exceeds about 0.66. Talebpour *et al*. [4] announced that reserving a lane for autonomous vehicles was only beneficial at CAV penetration above 50% for the two-lane (per direction) highway and 30% for the four-lane (per direction) highway. Ye and Yamamoto [5] also derived that the benefit of setting a CAV dedicated lane can only be obtained within a medium density range. Another way to improve the efficiency of mixed traffic flow is leveraging CAV platooning strategies, which enables CAVs in a platoon to maintain a smaller headway and follow closely at a reasonably high speed. However, the presence of HVs may bring a negative impact on the CAV platooning efficiency [8, 9]. Through the analytical formulation of the Markov chain model, Ghiasi *et al.* [8] revealed that, under the mixed traffic circumstance, CAV platooning may not always help improve highway capacity. If the sum of HV following HV and CAV following CAV headway time is larger than twice of HV following CAV headway time, vehicle platooning intensity hurts traffic capacity. Furthermore, several simulation experiments also found that CAV platooning and platoon size have little effect on the mixed traffic capacity [9, 10]. Although Mena-Oreja *et al*. [11] claimed a positive impact of platooning on traffic flow when platoon size increases from 2 to 4, there was almost no distinction in traffic flow between platoon sizes of 4 and 8. It may be reasonable that under a mixed traffic environment, the interference of HVs, to some extent, limits CAVs' driving efficiency and throughput, even if a platooning scheme is applied. How to take full advantage of CACC technology to reduce the negative impact of HVs on travel efficiency in mixed traffic flow is still a challenge to be studied.

A possible solution to reduce the influence of HVs on travel efficiency is cooperative CAV lane changing. In contrast to abundant efforts on the car-following behaviour of CAVs [12–21], there are few studies on the lane-changing behaviour of CAVs [22–24] and even fewer research studies on the lane change problem of mixed CAVs and HVs. To the best of our knowledge, existing studies devoted to lane-changing strategies in the mixed environment are listed in Table 1. Shi *et al.* [9] introduced a partial CAV lane change (PAL) for low CAV penetrations and full CAV lane change (FAL) for high CAV penetrations. Liu *et al.* [25] introduced an anticipatory lane change criterion to depict the interactions among CAVs and HVs, with which a quadratic increase of pipeline capacity to CAV penetration was obtained. The Q-learning algorithm from the family of reinforcement learning was applied to develop the CAV lane-changing strategy, which aimed to gain higher speeds of CAVs [26]. Lin *et al*. [27] treated lane changing as transferable utility games with side payments, and vehicles could exchange right-of-way for money. Results showed that vehicles with low and high values of travel time derived benefit from the proposed approach.

Motivated by the research scarcity in mixed traffic flow, this study seeks to develop a new lane-changing algorithm to deal with the interactions between CAVs and HVs under various CAV penetrations. By comparing the existing studies and this study in Table 1, it is observed that different lane change methods pursue different objectives, and this paper encourages CAV platoons to bypass HVs to obtain greater acceleration. In this study, we first put some effort into building an IDM to model CAV following behaviours. Secondly, an innovative bypassing algorithm is proposed for CAVs within a platoon to change lanes simultaneously in a mixed environment when approaching an HV. The bypassing algorithm aims to maximise the CAV driving efficiency through bypassing HVs in a safe distance. Thirdly, several evaluation indicators are introduced to measure the performance of the proposed bypassing algorithm. Finally, based on the comparison of simulation results in a two-lane (per direction) freeway, the bypassing algorithm is tested to be an efficient strategy to deal with the mixed environment under different CAV penetration levels, especially to reduce CAV travel time.

3 Microscopic model for CAVs in mixed traffic

Just like the microscopic model of the conventional (or HV) traffic flow, the microscopic model of CAV flow is also divided into two parts: a car-following model and a lane-changing model.

3.1 CAV following model

For CAVs, the commonly used collision-free model IDM is employed to describe the acceleration and deceleration behaviours [12]. The expression of IDM acceleration is shown in (1)

$$\text{IDM\_}ac_u = a\left[1 - \left(\frac{v_u}{v_0}\right)^{\delta} - \left(\frac{s^*(v_u, \Delta v_u)}{\Delta x_u - l}\right)^2\right] \tag{1}$$

$$s^*(v_u, \Delta v_u) = s_0 + \max\left(0, v_u h + \frac{v_u \cdot \Delta v_u}{2\sqrt{ab}}\right) \tag{2}$$

In (1), $(v_u/v_0)^{\delta}$ ensures a positive acceleration for vehicle u when its velocity is below the desired speed, otherwise a negative acceleration. $((s^*(v_u, \Delta v_u))/(\Delta x_u - l))$ is designed to preclude crashes by forcing vehicle u with a preceding gap $(\Delta x_u - l)$ shorter than the desired gap $s^*(v_u, \Delta v_u)$ to decelerate. In (2), s_0 is the jam between vehicle spacing, which is only active in stationary traffic; $v_u h$ corresponds to the distance that vehicle u travels before responding to any changes of its preceding vehicle; $((v_u \cdot \Delta v_u)/(2\sqrt{ab}))$, designed to stabilise the platoon in terms of vehicle speed, is positive only when the current speed of vehicle u is larger than that of the preceding vehicle. The notations and values used in this study in (1) and (2) are listed in Table 2 to depict the car-following behaviours of CAVs [20, 25].

3.2 Bypassing algorithm with lane change operations

The most important innovation of the study is the development of the bypassing algorithm. An algorithm-based lane-changing model is developed to guide the interactions between CAVs and HVs. The basic idea of the bypassing algorithm is that when a CAV platoon approaches an HV, the CAV platoon splits into sub-platoons seeking a longer following space in another lane. If there's a longer space in another lane (also called target lane), the sub-platoons will change the lane, which allows the sub-platoon to travel at a higher speed. The notations that appear in the bypassing algorithm are listed in Table 3.

For easy presentation of the bypassing algorithm, Fig. 1 is drawn to show the concepts intuitively. As seen in Fig. 1, the CAV platoon in lane 2 is made up of a leader i and a follower set F_i that includes followers $j = 1, 2, \ldots, n$, thus the CAV platoon size is

Table 2 Notations and values used in this study for IDM

Notation	Explanation	Value used in this study for CAVs
a	maximum acceleration	2 m/s^2
b	maximum deceleration	3 m/s^2
l	vehicle length	4 m
s_0	jam spacing	2 m
v_0	desired speed	30 m/s
h	headway time	0.5 s
δ	acceleration exponent	4
v_u	the current speed of vehicle u	—
Δx_u	the bumper-to-bumper distance of vehicle u to the preceding vehicle	—
Δv_u	speed difference of vehicle u with the preceding vehicle	—
$s^*(v_u, \Delta v_u)$	the desired distance of vehicle u from the preceding vehicle	—
$\mathrm{IDM\_}ac_u$	acceleration of vehicle u	—

Table 3 Notations in bypassing algorithm

Notation	Explanation
C	the set of CAVs in a link.
H	the set of HVs in a link.
$\mathrm{IDM\_}ac_i$	the acceleration of CAV i, obtained by IDM.
M	the set of lane ID, $M = \{1, 2\}$ for a two-lane segment.
F_i	the CAV follower set led by the CAV leader i within a CAV platoon.
T	timestamp.
fd_i	the following distance of CAV leader i. If there is no vehicle in front of CAV leader i, fd_i is a big number (250 m in this study).
$ff_{i,j}$	the following distance between CAV leader i and its follower j in a CAV platoon, where $j \in F_i$.
fo_u	the vehicle in front of vehicle u in the current lane, $u \in \Phi$.
i	the index of CAV leaders, where $i \in \Omega$.
j	the index of CAV followers, $j \in F_i$, $\forall i \in \Omega$
lane_u	the lane of vehicle u, $u \in \Phi$.
$lf_{i,m}$	the longitudinal distance between CAV leader i and its front vehicle (CAV or HV) in lane m, where $m \neq \mathrm{lane}_i$.
$lt_{i,m}$	the longitudinal distance between leading CAV i and its immediately following vehicle (CAV or HV) in lane m, where $m \neq \mathrm{lane}_i$.
m	the index of lane, $m \neq M$.
pos_u	the longitudinal position of vehicle u. If vehicle u is at the starting point of the link, $\mathrm{pos}_u = 0$.
sd_u	the safety distance of vehicle u, $u \in \Phi$.
speed_u	the speed of vehicle u, $u \in \Phi$.
ta_u	the immediately following vehicle of vehicle u in the current lane, $u \in \Phi$.
u	vehicle index, $u \in \Phi$
v_0	desired speed.
Ω	the set of CAV leaders of all platoons in a link, where $\Omega \subseteq C$.
Φ	the set of all kinds of vehicles in a link, where $\Phi = C \cup H$.
Δt	the time step for updating vehicle states (the value is set as 1 s in this study)

$(n + 1)$. The minimum platoon size is 1 when there is only one isolated single CAV.

There are generally two scenarios in lane-changing operations of a CAV platoon:

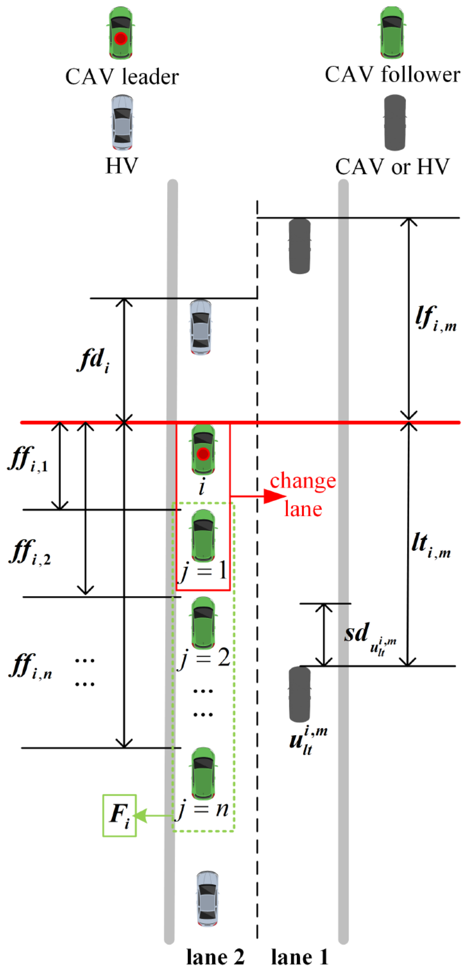

Fig. 1 *Lane-changing operations of CAV platoon*

(i) The first CAV i, acting as the platoon leader, accelerates until the desired speed is achieved, if the distance from leader i to the preceding HV (fd_i) is larger than both of the safety distance of leader i (sd_i) and the longitudinal distance to the front vehicle in another lane $(lf_{i,m})$. As the leader accelerates, each of the followers $(j = 1, 2, \ldots, n$ belonging to the CAV follower set $F_i)$ maintains a dynamic response to the preceding vehicle, yielding a close following distance within the CAV platoon. The accelerations for the CAV leader and followers are modelled by the IDM. The pseudocode for realising the car-following behaviour of a CAV platoon is detailed as follows (See Fig. 2).

(ii) When the CAV platoon leader i approaches a preceding CAV in the current lane, the CAVs can form a larger platoon. However, if the preceding vehicle is an HV, and there is more forward space in another lane, then a split operation of the CAV platoon is triggered. Ideally, the maximum CAV sub-platoon seeks to change lanes when the safety distance of the following vehicle $(lf_{i,m})$ in the target lane permits. As Fig. 1 shows, vehicle i leads a CAV platoon $(j = 1, 2, \ldots, n)$ getting closer to an HV in lane 2, if the forward gap in the target lane $(lf_{i,m}, m = 1)$ is larger than that in the current lane (fd_i), and the backward gap in the target lane $(lf_{i,m}, m = 1)$ allows the addition of two vehicles without breaching the safety distance required for the following vehicle $(sd_{u_{lt}^{i,m}})$, then vehicle i and vehicle $j = 1$ as a sub-platoon will simultaneously change to the target lane (lane 1), and vehicle $j = 2$ then becomes the new leader of the remaining sub-platoon $(j = 2, 3, \ldots, n)$ in the original lane. The pseudocode for realising the lane-changing strategy is detailed as follows (See Fig. 3).

The whole algorithm to realise the system operation for a mixed traffic flow is as follows (See Fig. 4).

If $fd_i > sd_i, fd_i > lf_{i,m}, m \neq lane_i$:
  Use constraint (1) to calculate IDM_ac_i;
  $speed_i = speed_i + IDM\_ac_i \cdot \Delta t$;
For j in F_i:
  Use constraint (1) to calculate IDM_ac_j;
  $speed_j = speed_j + IDM\_ac_j \cdot \Delta t$;

Fig. 2 *Sub-Algorithm 1: Car-following for the CAV platoon led by leader $i, i \in \Omega$*

If $lt_{i,m} > sd_{u_{lt}^{i,m}}, fd_i < lf_{i,m}$:
  $lane_i = m$;
  For j in F_i:
    If $ff_{i,j} < lt_{i,m} - sd_{u_{lt}^{i,m}}$:
      $lane_j = m$;

Fig. 3 *Sub-Algorithm 2: Lane changing for the CAV platoon led by leader $i, i \in \Omega$*

Step 0: T=0, $\Delta t = 1$. Attain link information.
Step 1: Update vehicle information in Ω at time T.
  1.1 Update Φ, H, C, pos_u, $lane_u$, $speed_u$, sd_u and IDM_ac_u.
  1.2 Update Ω.
    $\Omega = \emptyset$;
    For each lane m in M:
      For each vehicle u in C :
        If fo_u in H and ta_u in C:
          $\Omega = \Omega \cup u$;
  1.3 Update F_i, $\forall i \in \Omega$, and $ff_{i,j}$.
    For each leading CAV i in Ω:
      $F_i = \emptyset$;
      $fd_i = pos_{fo_i} - pos_i$;
      $u = ta_i$;
      While u in C:
        $F_i = F_i \cup u$;
        $ff_{i,j} = pos_i - pos_j$;
        $u = ta_i$;
  1.4 Update $lf_{i,m}$, $lt_{i,m}$.
    For each leading CAV i in Ω:
      For each vehicle u in lane $m\,(m \neq lane_i)$:
        If $pos_{fo_u} \geq pos_i$ and $pos_i \geq pos_u$:
          $lf_{i,m} = pos_{fo_u} - pos_i$;
          $lt_{i,m} = pos_i - pos_u$;
          $u_{lt}^{i,m} = u$;
Step 2: Update the speed and lane state of each CAV.
  For each CAV platoon led by leader i, $i \in \Omega$;
    Call Sub-Algorithm 1 to update the speed of each platoon member.
    Call Sub-Algorithm 2 to update the lane state of each platoon member.
Step 3: $\mathrm{T} = \mathrm{T} + \Delta t$, go back to step 1.

Fig. 4 *Whole algorithm to realise the system operation for a mixed traffic flow*

4 Performance indexes for mixed traffic

The outflow and travel time are adopted as two performance indexes to assess the travel efficiency of the road system and to evaluate the effectiveness of the bypassing algorithm in dealing with the mixed traffic flow. Moreover, we propose two other indexes: platoon intensity and single rate to represent the CAV platooning ability.

CAV platoon intensity reflects the strength of CAV clustering in the mixed traffic. For a certain CAV penetration rate, platoon intensity determines the probability that the following vehicle is of the same type as the preceding one. Different controlling and management strategies have a momentous effect on how CAVs are platooned and split, and hence a different value of platoon intensity. For example, 5 CAVs moving together in the form of a platoon yield a platoon intensity of 5, but the 5 CAVs travelling independently and separately will generate 5 platoons with size 1 in each platoon, and the average platoon intensity is only 1. In general, a higher platoon intensity exerts a more stable traffic flow. Therefore, controlling algorithms to encourage CAV platooning have gained more attention recently.

Here we define the CAV platoon intensity as the average number of CAVs in a formed CAV platoon during the whole simulation process, which is calculated as in (3)

$$I = \frac{1}{T}\sum_{t=1}^{T}\left(\frac{n_{\mathrm{CAV}}^{t}}{\sum_{i=1}^{\max}\mathrm{platoon}_i^t}\right) \tag{3}$$

where I represents the average CAV platoon intensity, T is the total number of time steps during simulation, n_{CAV}^{t} denotes the total number of CAVs at time t, and $\mathrm{platoon}_i^t$ stands for the number of CAV platoons of size i at time t. We keep track of the number of CAVs and the number of CAV platoons of size i at each time step, hence the platoon intensity can be calculated by averaging the sizes of platoons over time.

However, the platoon intensity is not the larger, the better. Bujanovic and Lochrane [28] pointed out that the capacity of freeways that restrict platoons to no more than five vehicles is comparable to the capacity of freeways that allow larger platoons. With the proposed bypassing algorithm, a CAV platoon is encouraged to split first when encountering an HV, and then a sub-platoon changes lane in order to bypass the HV. Under this context, the bypassing algorithm could not present many advantages in terms of platoon intensity. Therefore, the platoon intensity index alone is not enough to measure the CAV platooning capability of the bypassing algorithm and other related/similar algorithms. In this study, the single rate, defined as the proportion of single CAVs among the CAV platoon system by (4), is also considered as one of the measurements to evaluate the platooning performance of the proposed bypassing algorithm. The lower the single rate, the stronger the platooning capability

$$S = \frac{1}{T}\sum_{t=1}^{T}\left(\frac{\mathrm{platoon}_1^t}{\sum_{i=1}^{\max}\mathrm{platoon}_i^t}\right) \tag{4}$$

where S represents the single rate of CAVs, T is the total number of time steps during simulation, $\mathrm{platoon}_i^t$ is the number of platoons of size i at time t, thus $\mathrm{platoon}_1^t$ stands for the number of CAV platoons of size 1 (single CAVs).

The indexes of platoon intensity and single rate can be further illustrated by the above example, shown in Fig. 5. Here we only consider the two indexes at one time step ($T = 1$). In Fig. 5*a*, 10 CAVs mixed with 8 HVs travel on the road forming five isolated single CAV platoons ($\mathrm{platoon}_1^t = 5$) and one CAV platoon with size 5 ($\mathrm{platoon}_5^t = 1$). Therefore, the platoon intensity is $10/(5+1) = 1.67$, the single rate is $5/(5+1) = 0.83$. In Fig. 5*b*, 10 CAVs mixed with 8 HVs form four isolated single CAV platoons ($\mathrm{platoon}_1^t = 4$) and two CAV platoons with size 3 ($\mathrm{platoon}_3^t = 2$). The platoon intensity is calculated as $10/(4+2) = 1.67$, and the single rate is $4/(4+2) = 0.67$. By comparing the results, we find that the platoon intensities in Figs. 5*a* and *b* are the same, while Fig. 5*b* has a lower single rate

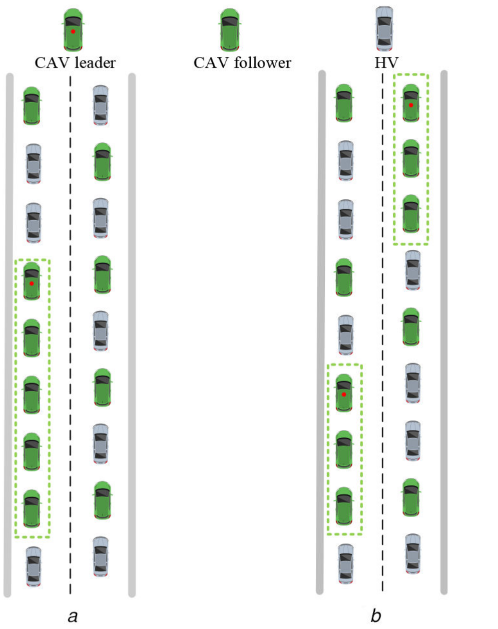

Fig. 5 *Example for the explanation of platoon intensity and single rate*
(a) Scenario 1, ***(b)*** Scenario 2

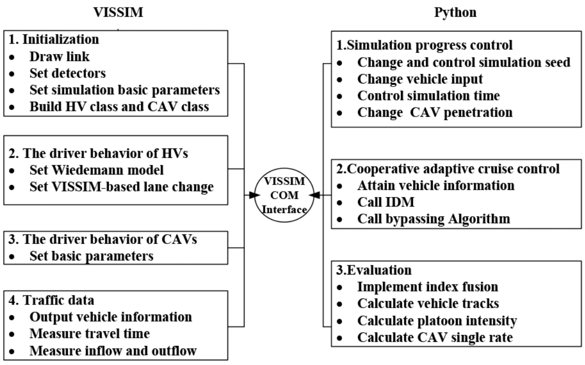

Fig. 6 *Simulation process in VISSIM*

than Fig. 5*a*, indicating a better platooning performance of CAVs in Fig. 5*b*.

5 Case study for freeway segments

The capability of the proposed modelling framework has been demonstrated in a two-lane (per direction) freeway, which is a 2-km segment created in PTV VISSIM simulation. The proposed bypassing algorithm is implemented in Python using a Dell XPS15 9560 laptop with 16 GB RAM. During the simulation, VISSIM and Python communicate with each other via the COM interface of VISSIM. With the COM interface, Python has access to all the traffic data inside VISSIM and controls driver behaviours of CAVs. Under the assumption that a CAV can only receive real-time information from the surrounding CAVs, and HV information is unable to be obtained neither by CAVs nor HVs, we only control the CAV driving behaviours in the VISSIM platform. Therefore, CAVs and HVs, driven by robots and humans, respectively, have different driving behaviours. The communication between VISSIM and Python in the simulation process is shown in Fig. 6.

In the simulation process, to keep with the real-world CAV communication and environment, we update the CAV/HV information and call the bypassing algorithm per simulation second. For simulating a 2-km segment, completing one simulation second takes 0.2 real-time seconds when the inflow is 500 veh/h and CAV penetration is 0.0. However, the simulation time and computation time will increase with the number of CAVs, because the bypassing algorithm enumerates all CAVs on the road. When the inflow and CAV penetration reach 3500 veh/h and 1.0, respectively, running one simulation second requires almost 1.0 real-time second.

5.1 Simulation settings

The detail car-following, lane-changing models, and the corresponding parameters for CAVs have been described in Section 3, while the psychological–physiological car-following model developed by Wiedemann [29] is employed to describe HV following behaviours.

The concept of the Wiedemann model is that a fast-moving HV approaching a slower preceding vehicle will start to decelerate once reaching its own individual safety perception threshold. Then, the speed may become smaller than the lead vehicle as a result of the driver's imperfection in the estimation of the lead vehicle speed [30]. Due to disparate physical characteristics, each HV has different perception thresholds of safety distance, desired speed, and speed difference [31]. The Wiedemann car-following model is preset in VISSIM, and the default values are used in this study to model HV following behaviours. For example, at a given speed v (m/s), the safety spacing distance $\mathrm{d}x\_\mathrm{safe}$ is calculated by the equation $\mathrm{d}x\_\mathrm{safe} = d_0 + h \cdot v$ where the desired standstill distance between two HVs (d_0) is set as 1.5 m, and the headway time h is 0.9 s. Furthermore, the longitudinal oscillation for HVs is expected to be 4 m, speed difference during the 'following' state ranges from −0.35 to 0.35.

The lane-changing behaviours of HVs are also described by the preset strategies in VISSIM: free lane changing and necessary lane changing. When the desired safety distance to the trailing vehicle on the target lane is satisfied, free lane changing is allowed for an HV to reach its desired speed through bypassing slower vehicles. Necessary lane changing happens when an HV is going to reach the next waypoint on its route. The default lane-changing parameters in VISSIM are used to model the aggressiveness of lateral maneuvers for HVs.

5.2 Visualisation of bypassing algorithm

On the VISSIM simulation platform, the vehicle type, location, time, lane position, and following distance of each vehicle are collected in real-time. With the same simulation seed, the vehicle track, lane-changing behaviours, and car-following distances are depicted in Figs. 7–9 under the input flow of 1500 veh/h and CAV penetration rate of 50%.

As seen in Fig. 7*a*, most of the CAV position-time curves with the bypassing algorithm are steeper than those without the bypassing algorithm. The slope of the position-time curve represents the vehicle speed, and the steeper the slope, the higher the speed. Thus, it is obvious that with the bypassing strategy, the moving speeds of CAVs become faster. Interestingly, the speeds of HVs are slightly increased as well, as shown in Fig. 7*b*, some slopes of HV tracks with the CAV bypassing algorithm are steeper than that without the CAV bypassing algorithm. For clarity, four HV tracks extracted from Fig. 7*b*, the origins of which are marked as blue circles, are plotted in Fig. 7*c*. We can see clearly from Fig. 7*c* that for the same HV, its speed will be improved in the environment where the CAV bypassing algorithm is applied. In theory, the bypassing strategy is designed only for CAVs, no matter whether with or without the bypassing strategy, the driver behaviour models of HVs should be the same. A possible reason to explain the improvement of HV speeds is that in the mixed environment, not only HVs influence CAVs, but CAVs affect HVs as well. When a preceding CAV moves faster, the following HV will have a larger following distance, which allows a higher acceleration. Therefore, the proposed CAV bypassing algorithm is verified to benefit not only CAVs but also HVs in travel speed.

The simulation duration time in the case study is set at 3600 s to process all the vehicles. For visualisation, we show the time series from 200 to 400 s. Fig. 8 exhibits the lane positions of CAV IDs from 24 to 163 over the time range of 200–400 s. A CAV ID in the y-axis is the unique key for each vehicle determined in the order of input time in VISSIM. For example, the CAV of ID 24 is input to the simulated freeway prior to that of ID 25. In addition, the blank

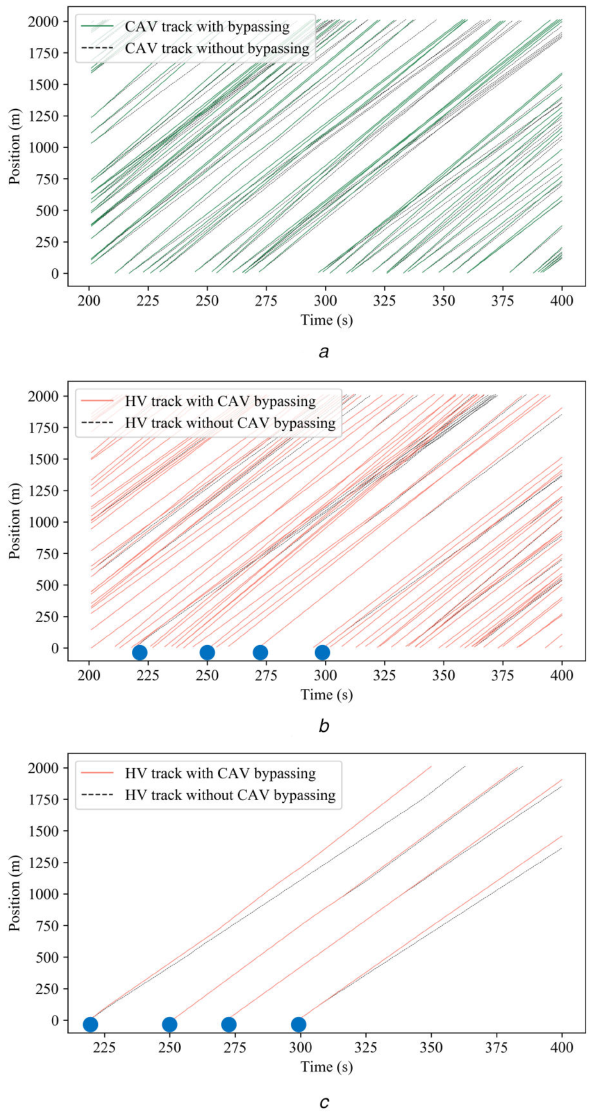

Fig. 7 *Track comparison of CAVs and HVs with and without bypassing algorithm*
(a) CAV tracks, ***(b)*** HV tracks, ***(c)*** Examples of four HV tracks that speed up with CAV bypassing algorithm

space in the *y*-axis means HV. For instance, vehicles of IDs 100, 99, and 98 are HVs, but vehicles of IDs 97 and 95 are CAVs. Compared to Fig. 8*a*, most of the CAVs in Fig. 8*b* keep in the same lanes within the observed 200 s. It is concluded that the CAVs with bypassing strategy experience more lane changes than those without bypassing strategy.

Relating Fig. 8*a* with Fig. 7*a*, CAVs with IDs 95 and 97 are input to the freeway at time 226 and 230 s, respectively. CAV 97 moves forward at a slightly higher speed to approach CAV 95 until grouping a platoon. Then, the CAV platoon of size two changes from the right lane to the left lane at the same time (309 s). After 2 s at time 311 s, the CAV platoon split, only CAV 97 changes lanes by itself. This phenomenon coincides with the behaviours proposed by the bypassing algorithm, with which CAVs form platoons when approaching each other, split into sub-platoons when approaching an HV, and the CAV sub-platoon could change lanes simultaneously.

Fig. 9 shows the following distance of each CAV with and without the bypassing algorithm. The change of CAV following distance in Fig. 9 is in accordance with the lane-changing decision in Fig. 8, Fig. 9*a* corresponds to Fig. 8*a* and Fig. 9*b* corresponds to Fig. 8*b*. For example, in the dotted box in Fig. 8*a*, CAV 117 travels on the left lane while CAV 118 moves on the right lane until time 330 s, CAV 118 makes a lane change to the left lane in front of CAV 117. This lane-changing behaviour is also reflected in the dotted box in Fig. 9*a*, where before time 330 s, CAV 118 follows a

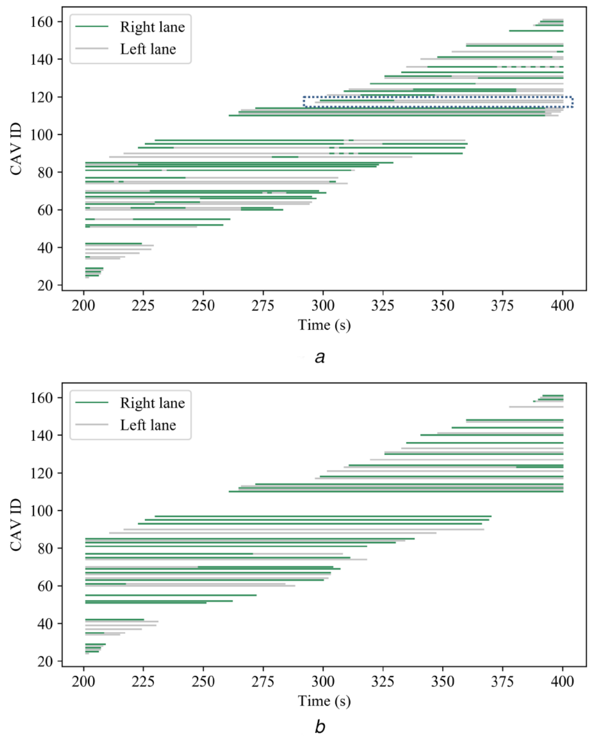

Fig. 8 *Comparison of CAV lane-changing behaviours*
(a) With bypassing algorithm, ***(b)*** Without bypassing algorithm

vehicle in a small distance and CAV 117 has a large space in front, however, after changing lanes, CAV 118 gains a much longer following distance while CAV 117 follows closely behind CAV 118. It is not difficult to find that, compared to Fig. 9*b* in which each CAV keeps a relatively single following distance, there are more gradient colours in Fig. 9*a*. The comparison result suggests that, with the bypassing strategy, CAVs travel in a more flexible way, changing lanes according to the following distance.

5.3 Comparison of traffic evaluation indexes

To test the performance of the presented controlling algorithm under different travel demands, the input volume increases from 500 to 3500 veh/h with an increment of 500 veh/h. Different CAV penetration rates are also considered in the study, increasing from 0 to 100%, with an increment of 10%. The 0% penetration indicates full of HVs on the freeway, and 100% means all the vehicles on the road are CAVs. The characteristics of the mixed traffic flow are analysed under different CAV penetrations and input flows. Furthermore, three different random seeds are implemented in simulations.

5.3.1 Traffic outflow: A detector is set up at the end of the 2-km freeway to collect the outflow information in every 200 s. The outflows under a variety of input volumes ranging from 500 to 3500 veh/h are compared to capture the effectiveness of the proposed CAV controlling strategy.

From the result shown in Fig. 10, it is worth noting that, under low input flows, there is a very little distinction drawn between the outflow with and without the bypassing lane-changing strategy. This phenomenon may be linked to the reason that the low input volumes have not reached the two-lane freeway capacity, so that all the input vehicles can be discharged without latency. However, as inflow continues to increase from 1500 veh/h, the superiority of the bypassing algorithm is becoming more and more obvious. We thus conclude that the proposed bypassing algorithm exhibits the superiority in outflow, especially in the case of relatively high input flow. In addition, in terms of freeway outflow, no matter how the CAV penetration changes, the proposed bypassing strategy outperforms the default controlling algorithms in VISSIM. Fig. 10 also reveals an overall growing tendency, with the bypassing algorithm, of the freeway outflow as CAV penetration rate

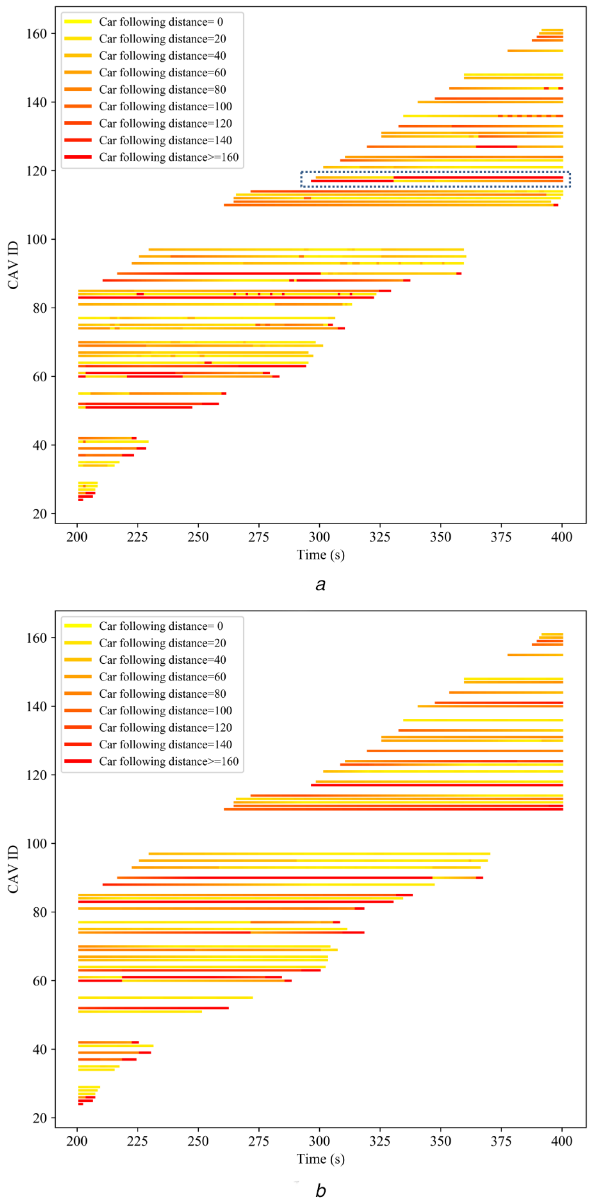

Fig. 9 *Comparison of CAV following distance*
(a) With bypassing algorithm, ***(b)*** Without bypassing algorithm

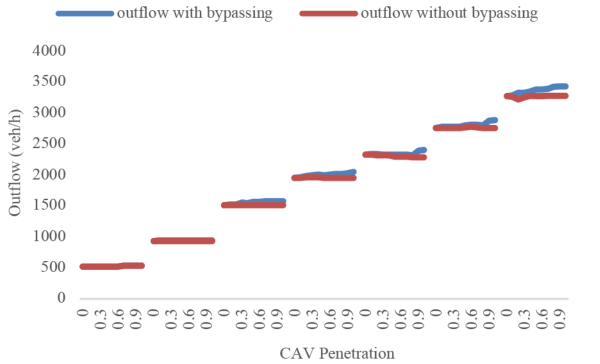

Fig. 10 *Outflow under different input volumes and different CAV penetrations*

increases, while increment of CAV penetration makes little difference to the freeway outflow without the bypassing algorithm. Therefore, without the bypassing algorithm, the CAV technology would not help in improving the freeway outflow performance.

5.3.2 Travel time: In addition to the outflow performance, the proposed lane-changing strategy is particularly advantageous in improving system travel time, no matter whether the input volume is low or high. As Fig. 11 shows, without the bypassing strategy, CAV penetration shows an insignificant effect on travel time, especially when the input flow is low. Although as the CAV penetration rate increases, there are more CAVs, and accordingly less HVs travelling on the road, the system travel time reduces by at most 1.5 s. As mentioned before, the randomness and uncertainty of HVs bring limitations to the operations of mixed traffic flow, and therefore the addition of CAV penetration serves little in performance improvement. Therefore, external controlling algorithms are needed to leverage the benefits of CAVs in a mixed environment.

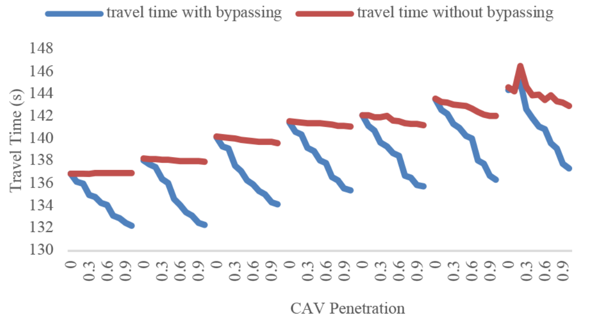

Fig. 11 *Travel time under different input volumes and different CAV penetrations with and without bypassing algorithm*

In Fig. 11, under input volumes from 500 to 3500 veh/h, the proposed bypassing algorithm exhibits paramount effectiveness in reducing travel time. For example, when the CAV penetration increases from 0 to 100% under the input volume of 3000 veh/h, the travel time of implementing the proposed bypassing strategy reduces from 143.6 to 136.4 s, while the same penetration increase without the bypassing strategy saves only 1.5 s. That is because, in relatively smooth traffic flow, when a CAV platoon is blocked by an HV in front, the platoon will be prompted by the bypassing algorithm to change lanes and bypass the HV. With this bypassing algorithm, CAV platoons travel faster and more flexible.

Despite being relatively unstable when compared to low or medium input volumes, the bypassing algorithm still has positive impacts on travel time when the input volume reaches 3500 veh/h. At a high input volume, the unstable relationship between travel time and CAV penetrations should be attributed to the congested traffic environment, where CAV platoons barely have space to change lanes.

5.3.3 CAV platoon intensity: Platoon intensity means the average size of a CAV platoon. When the CAV penetration is 0, there is no CAV in the road system, as a result, the platoon intensity is 0. The comparison of CAV platoon intensities between the proposed bypassing algorithm and the VISSIM-default model is displayed in Fig. 12. It shows almost no difference in CAV platoon intensity between the proposed bypassing strategy and the VISSIM-default model. We can therefore conclude that the proposed bypassing algorithm for CAV lane-changing serves no positive effect on CAV platoon size. Although at the same platoon intensity, as we understand from the above observations, the bypassing algorithm functions well in improving travel efficiency. Another interesting phenomenon that can be articulated is that there exist exponential relationships between platoon intensity and CAV penetration, with shape parameters in connection with input flows. At the same CAV penetration, the higher the inflow is, the larger the CAV platoon intensity would be.

5.3.4 CAV single rate: Fig. 13 depicts the impact of the bypassing strategy on the single rate of CAVs. With the proposed bypassing strategy, we expect to have a lower single rate of CAVs among all the CAV penetrations. That means, compared to VISSIM-default lane-changing strategy, there are lower single rates of CAVs on the road with the bypassing algorithm, correspondingly more CAVs moving in the form of platoons. Through the comparison of Fig. 12 with Fig. 13, the bypassing

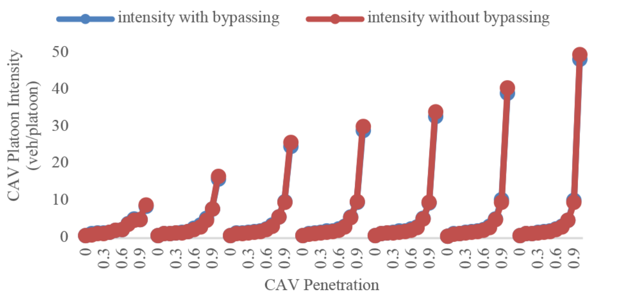

Fig. 12 *Platoon intensity under different inflows and different CAV penetrations*

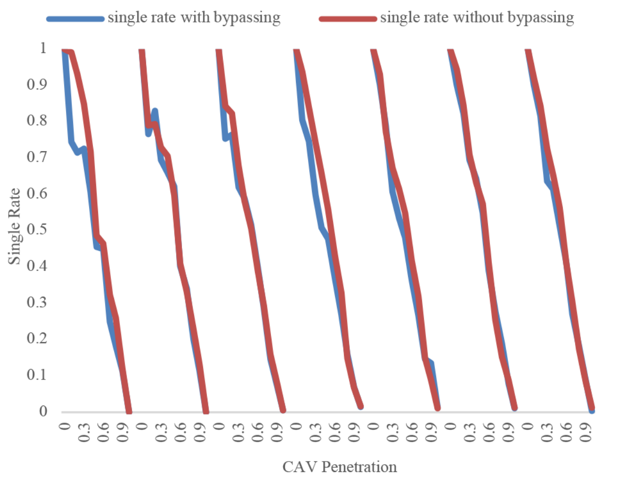

Fig. 13 *Single rate under different inflows and different CAV penetrations with and without bypassing algorithm*

strategy is observed to have the same CAV platoon intensities but lower CAV single rates than the VISSIM-default models. Therefore, the proposed lane-changing algorithm is proved to have the ability to increase the number of CAV platoons rather than expanding the size of a CAV platoon. This observation is in line with the design idea of the bypassing algorithm, where CAV platoons split into sub-platoons when bypassing an HV is needed. There would not be many long CAV platoons to travel smoothly for all the time, but lots of short CAV platoons bypass preceding HVs and can move more efficiently.

6 Conclusions

In this study, we present an effort to propose a cooperative controlling algorithm for dealing with the complicated environment in which connected autonomous vehicles and human vehicles mix together, and furthermore, investigate how the controlling algorithm would influence drivers' behaviours and the system operation. A microscopic simulation framework is developed in VISSIM for a two-lane per direction freeway segment, where different car-following and lane-changing models are incorporated for CAVs and HVs. First, the VISSIM preset models, including the Wiedemann model and a rule-based lane-changing strategy, are used to simulate HVs. In addition, an IDM is customised to determine the CAV acceleration, and an innovative lane-changing strategy is proposed to control the interactions between CAVs and HVs. The lane-changing strategy motivates CAV platoons to move forward until approaching a preceding HV, then change lanes to bypass the HV if allowed, and move on until approaching another HV in front. The proposed lane-changing strategy is therefore called bypassing algorithm, and the algorithm codes are publicly available at https://doi.org/10.5281/zenodo.3258685.

Through a case study with a freeway created in VISSIM, the capabilities of the developed controlling framework in forming CAV platoons, splitting platoons into sub-platoons, and changing lanes to bypass HVs, are tested in simulations. The bypassing algorithm is proved to not only benefit CAVs but also HVs in travel speed. In addition, the simulation results show the predominance of the bypassing algorithm in improving system performance for the mixed traffic flow. Specifically, under different input flows and CAV penetrations, the proposed bypassing algorithm can efficiently reduce the system travel time, improve freeway outflow performance, and increase the number of CAV platoons. In comparison, the CAV technology without a bypassing algorithm has no effect in outflow performance and helps little in reducing travel time.

In theory, the bypassing algorithm can be adapted to multi-lane circumstances, and we will continue to improve and test the algorithm for multi-lanes. In future work, we will also research the application of the proposed bypassing algorithm to traffic merging points and urban traffic intersections under a mixed environment.

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