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RESEARCH ARTICLE

Influence of Bus Bay on Heterogeneous Traffic Flow Consisting of Human Driving and Autonomous Vehicles

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ABSTRACT With the deployment of autonomous vehicles (AV), it can be assumed that a heterogeneous flow consisting of human driving and autonomous vehicles will appear in urban road networks. Numerous studies have shown that bus stops tend to have great influence on the nearby traffic flow, but few insightful researches have been conducted on the influence of bus bays in the context of heterogeneous traffic flow consisting of human driving vehicles and autonomous vehicles. In this paper, a new KKSW (Kerner-Klenov-Schreckeneberg-Wolf)-BB (bus bay)-AVHDV (autonomous vehicles and human driving vehicles) CA (cellular automata) model is proposed to study the influence of bus bays on heterogeneous traffic flow based on the well-known KKSW CA model. Through numerical simulations, the flow characteristics, congestion patterns and speed characteristics in the heterogeneous traffic flow are studied. The frequency and severity of rear-end collisions are analyzed to study the influence of the bus bay on traffic safety. The results show that bus bays may have a significant impact on traffic flow efficiency and traffic safety. The introduction of AVs in the heterogeneous traffic flow could significantly improve traffic efficiency and safety near the bus bay, especially under the condition of heavy traffic flow.

INDEX TERMS Bus bay, bus interference, three-phase traffic theory, cellular automata model, heterogeneous traffic flow, human driving and autonomous vehicles, traffic conflict techniques.

I. INTRODUCTION

Autonomous vehicle (AV), an emerging mobile robot technology, has developed rapidly in recent years, showing great potential in reducing traffic congestion and reducing the number of traffic accidents caused by human errors [1], [2]. However, AVs are still far from completely replacing human driving vehicles (HDV), technology wise and public trust wise [3]. Hence, in the foreseeable future, a heterogeneous flow consisting of human driving vehicles and autonomous vehicles is expected in urban road networks. To ensure traffic efficiency and safety with the introduction of AV, it is necessary to understand the characteristics of the heterogeneous traffic flow and the potential impacts.

Many studies have been done on the characteristics of the heterogeneous flow consisting of AVs and HDVs on freeways [4], [5], and at intersections [6], [7]. However, in the context of AVs, few studies have been conducted focusing on bus stops, which are also a crucial component in urban road networks. Bus stops can influence the efficiency and safety of the heterogeneous traffic flow nearby [8], and the introduction of AVs could in turn impact the performance of public transportation. As bus bay is one of the most common types of bus stops in urban areas in countries such as China, to ensure a smooth traffic flow movement, it is necessary to study the influence of bus bay on the heterogeneous traffic flow. Besides, bus bay has also been utilized in the infrastructure of real-world autonomous bus solution [9]. Therefore, it is also instructive to explore bus bay specific rules for AVs, in addition to the existing AV technologies.

As an efficient microscopic simulation tool, cellular automata (CA) model offers the possibility to study traffic flow characteristics by modelling interactions among HDVs and AVs. Many studies have utilized CA models to study

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FIGURE 1. A typical bus bay on urban roads in China.

the impacts of AVs on the heterogeneous flow, while building new rules to make the CA models more realistic, both to simulate the driving behaviors of HDVs and to project the self-driving rules of AVs. Among various types of CA models, the well-known Kerner-Klenov-Schreckenberg-Wolf (KKSW) CA model could capture the tendency of speed synchronization of human drivers and accurately simulate the phase transitions of traffic flow, based on the three-phase traffic theory proposed by Kerner and the calibration using a great number of traffic data on German highways. To study the influence of bus bays, Hu et al proposed the KKSW-BB (bus bay) CA model, and recalibrated some of the parameters for urban roads [10]. Based on these works, the primary objective of this study is to incorporate rules of AVs into the KKSW CA model, and to extend rules of buses of the KKSW-BB CA model. We propose a new KKSW-BB-AVHDV (autonomous vehicles and human driving vehicles) CA model, and study the influence of the bus bay on the heterogeneous traffic flow consisting of manual cars, manual buses, autonomous cars and autonomous buses, under different stopping bus and AV penetration rate conditions.

The remaining parts of the paper are organized as follows. Section II presents the literature reviews covering the impacts of autonomous vehicles and bus bays on traffic flow efficiency and traffic safety. Section III proposes the new KKSW-BB-AVHDV CA model. Then, simulation results and analysis are discussed in Section IV. The conclusions are summarized in the last section of the paper.

II. LITERATURE REVIEW

A. THE IMPACT OF AUTONOMOUS VEHICLES ON TRAFFIC FLOW AND TRAFFIC SAFETY

With the development of autonomous vehicles and connected autonomous vehicles, the performance of the heterogeneous traffic flow consisting of both human driving vehicles and autonomous vehicles has drawn scholars' attention. Based on the analysis of traffic flow characteristics, the impact of the introduction of AV is mainly studied in terms of efficiency and safety. Talebpour et al. studied the potential impact of AVs on traffic flow, and the results showed that the introduction of AV would increase the throughput of highway facilities and improve the stability of the traffic flow [2]. Identifying the differences among three types of car-following modes in the heterogeneous flow, Jiang et al. found that the congestion is greatly reduced when the penetration rate of AV reaches 0.8 [11]. Dresner et al. found that as the number of autonomous vehicles on the road increases, a massive decline in traffic delays and congestions could be observed [12]. Similar conclusion was drawn when introducing both autonomous and human driving buses into the heterogeneous traffic flow [13]. However, some researchers hold quite different views. Kerner made a probabilistic analysis of the effect of AVs on a mixed traffic flow consisting of AVs and HDVs, and the results pointed out that low penetration of AVs in the mixed traffic flow might cause the deterioration of the performance of the traffic system [14]. Calvert et al. used an empirically calibrated and validated simulation experiment to estimate the effect of AVs on traffic flow, and found that low penetration of AVs in mixed traffic would initially have a negative impact on traffic flow and road capacities [15].

For traffic safety, most previous research conclude that the introduction of AVs could lead to improvement. Ye et al. studied the mixed traffic flow with human driving vehicles and connected autonomous vehicles (CAV), and revealed that the condition of traffic safety is greatly improved as the CAV penetration rate increases [16]. Papadoulis et al. found that number of conflicts on motorways is reduced by more than 80% and 90% for 75% and 100% CAV penetration rates, respectively [17].

B. THE IMPACT OF BUS BAYS ON TRAFFIC FLOW

Existing literature indicate that bus stops have a negative effect on the traffic flow nearby. Among the common types of bus stops, it is found that bus bays with inboard bike lane have the least impact on bicycle and vehicle operations, while occupying the most road space [18]. Most of the existing researches focus on the influence of bus bays on the right lane (the lane adjacent to the bus bay). Kwami et al. established a statistical relationship between the time duration of bus impacting the traffic and bus arrival frequency [19]. Xu et al. further analyzed the drop of the lane capacity, with and without bus overflow [20]. Considering the probability of lane blockage caused by bus overflow, Luo et al. proposed a model to estimate the capacity of the bus bay and the adjacent lane [21]. Hu et al. studied the influence of the bus bay with a CA model, based on Kerner's three-phase traffic theory, and found that both traffic efficiency and safety are negatively impacted by buses entering and exiting the bus bay [10]. While the influence of the bus bay on the right lane has been analyzed and quantified, these studies all make the assumption that buses would only approach the bus bay on the right lane, and that the influence of the bus bay on the other motor lanes (if any) is not significant. Besides, in the context of bus bays, the influence of the buses on a heterogeneous traffic flow consisting of HDVs and AVs remains to be studied. Therefore, in this paper, we aim to propose a model with a heterogeneous traffic flow consisting of human driving vehicles and autonomous vehicles, to study the influence of the bus bay on the traffic flow characteristics of a two-lane road section, and evaluate the impacts on traffic efficiency and traffic safety.

III. MODEL

In this study, a new KKSW-BB-AVHDV CA model is proposed to simulate the heterogeneous traffic flow consisting of manual cars (MC), manual buses (MB), autonomous buses (AB) and autonomous cars (AC) near a bus bay. Based on the KKSW CA model and KKSW-BB CA model, new rules for both HDVs (MC and MB) and AVs (AC and AB) are incorporated. Specially, bus bay specific rules are added to simulate the action of buses, including forward and lane changing motions to enter or exit the bus bay. As the bicycle lanes are assumed to be physically separated from motor lanes near bus bays, non-motor vehicles are not considered in the model. The road in this heterogeneous system consists of three lanes, including a left lane as fast lane, a right lane as slow lane and a specified stop lane for the bus bay. In order to accurately reflect the characteristics of traffic flow, each cell is defined as 1.5 m [22]. The length of the motor lane is set as 6000 cells (9000 m), and the specified stop lane is set as 45 cells (67.5 m), as shown in Fig. 2.

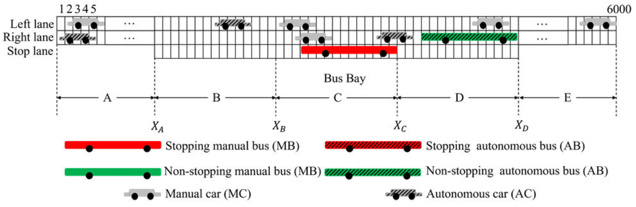


FIGURE 2. **Schematic plot of a bus bay road section with heterogeneous traffic flow.**

The length of cars is 5 cells and the length of buses is 12 cells. In the heterogeneous traffic flow, the penetration rate of buses is denoted as P_b. The penetration rate of AC among cars is denoted as P_{ac}. The penetration rate of AB among buses is assumed to be equal to P_{ac}. Some manual buses that must halt at the bus bay are called stopping buses, and the other buses are called non-stopping buses. The notation P_s indicates the percentage of stopping buses among buses. T_{dwell} denotes the desired dwelling time of stopping buses at the bus bay.

In addition, the heterogeneous traffic system is split into five sections, Sections A, B, C, D, and E. The lengths of the sections are set as $L_{\mathrm{A}} = 3978$, $L_{\mathrm{B}} = 15$, $L_{\mathrm{C}} = 15$, $L_{\mathrm{D}} = 15$, and $L_{\mathrm{E}} = 1977$ cells, respectively. Section A is the entrance region and Section E is the exit region. The bus bay with one berth is located in Section C, where each stopping bus must spend a certain time loading and unloading passengers. Section B and Section D are the upstream part and downstream part of the bus bay, respectively. The approaching buses can change to the special stop lane when they enter Section B to pull into the bus bay on the stop lane in Section C. If there is a dwelling bus in Section C, the trailing bus is allowed to dwell in Section B. Once Section B is occupied by a bus, the next stopping bus must wait at position x_{A} on the right lane. After dwelling, the stopping bus will pull out and change back to the right lane in Sections C or D.

In the KKSW-BB-AVHDV CA model, the following notations for the major variables and vehicle parameters are used: $n = 0, 1, 2, \ldots$ is the number of time steps; $\tau = 1$s is time step; $\delta_x = 1.5$ m is space step; x_{n} and v_{n} are the position and speed of the vehicle; $v_{\max}$ is the maximum speed in the lanes; the lower index l is used to mark variables related to the preceding vehicle; $g_n = x_{l,n} - x_n - d_l$ is the space gap between two adjacent vehicles, with d being vehicle length and d_l thus representing the length of the preceding vehicle. In the situation of lane changing, when a vehicle changes to its target lane, the superscripts "+" and "-" are used to denote the variables and functions related to the preceding and trailing vehicles on the target lane, respectively; in particular, $g_n^+ = x_n^+ - x_n - d^+$ is the space gap between the vehicle and the preceding vehicle at x_n^+ on the target lane, and $g_n^- = x_n - x_n^- - d$ is the space gap between the vehicle and the trailing vehicle at x_n^- on the target lane. For buses, T_B denotes the time duration that a bus is on the stop lane. The movement of autonomous vehicles and human driving vehicles include lane-changing motion and forward motion. With the notations described above, the rules of vehicle movements are defined as follows.

(a) Lane changing on motor lanes:

Except for stopping buses that are trying to enter or exit the bus bay as described in rule (b), (c) and (o), with a probability p_{lc} of for MC and MB, a vehicle can make a lane change if:

$$R \rightarrow L: \quad v_n^+ \geq v_{l,n} + \delta_1 \text{ and } v_n \geq v_{l,n}, \tag{1}$$

$$(bus): \quad \text{and } v_{l,n} < v_{max} - \delta_0, \tag{2}$$

$$L \rightarrow R: \quad v_n^+ \geq v_{l,n} + \delta_2 \text{ or } v_n^+ \geq v_n + \delta_2, \tag{3}$$

$$(bus): \quad \text{or } v_n^+ \geq v_{max} - \delta_0, \tag{4}$$

If the subject vehicle is an MC or MB:

$$g_n^+ \geq min\,(v_n \cdot \tau, g_c), \tag{5}$$

$$g_n^- \geq min\,(v_n^- \cdot \tau, g_c), \tag{6}$$

where g_c is a constant for general safety space gap for lane-changing.

If the subject vehicle is an AC or AB:

$$g_n < min\,(v_n + 1, v_{max}) \cdot \tau, \tag{7}$$

$$g_n^+ > g_n, \tag{8}$$

If the trailing vehicle on the target lane is an AV within the detection range:

$$g_n^- \geq \left(v_n^- - v_n\right) \cdot \tau + d_{safe}^0, \tag{9}$$

where d_{safe}^0 is a constant for safety distance gap.

otherwise:

$$g_n^- \geq v_n^- \cdot \tau, \tag{10}$$

(b) Bus lane changing upstream the bus bay:
For a stopping bus on the left lane, if $x_A - L_a \leq x_n \leq x_A$ (L_a is a look-ahead constant), it changes to the right lane, to further enter the bus bay for dwelling, if the following conditions are met:

$$g_n^+ \geq min\ (v_n \cdot \tau, g_c), \tag{11}$$

$$g_n^- \geq min\ (v_n^- \cdot \tau, g_c), \tag{12}$$

(c) Bus exiting bus bay after dwelling:
For MB, it changes from the stop lane to the right lane if:

$$T_B \geq T_{dwell}, \tag{13}$$

$$g_n^+ \geq min\ (v_n \cdot \tau, g_c), \tag{14}$$

$$g_n^- \geq min\ (v_n^- \cdot \tau, g_t), \tag{15}$$

$$g_t = max\ (g_{t,min}, g_{t,max} - ceil\left(\frac{T_B - T_{dwell}}{5}\right)) \tag{16}$$

For AB, it changes from the stop lane to the right lane if:

$$T_B \geq T_{dwell}, \tag{17}$$

When the leading vehicle on the right lane is an AV within the detection range,

$$g_n^+ \geq (v_n - v_n^+) \cdot \tau + d_{safe}^0, \tag{18}$$

otherwise,

$$g_n^+ \geq v_n \cdot \tau, \tag{19}$$

When the trailing vehicle on the right lane is an AV within the detection range:

$$g_n^- \geq \left(v_n^- - v_n\right) \cdot \tau + d_{safe}^0, \tag{20}$$

otherwise,

$$g_n^- \geq v_n^- \cdot \tau, \tag{21}$$

If the bus fails to change to the right lane, skip rules (d)-(l), and update the speed by rule (m).

(d) Calculation of safety space gap:
If the subject vehicle and the leading vehicle are both AV within the detection range:

$$g_{safe,n} = d_{safe}^0, \tag{22}$$

Otherwise,

$$g_{safe,n} = v_n \cdot T_{react} + \frac{v_n^2 - v_{l,n}^2}{2B}, \tag{23}$$

where T_{react} is reaction time.

(e) Comparison of vehicle gap with the synchronization gap:
For MC and MB, if

$$g_n \leq G(v_n), \tag{24}$$

then follow rules (f) and (g), and skip rule (h);
else if

$$g_n > G(v_n), \tag{25}$$

then skip rules (f) and (g), and follow rule (h).

(f) Speed adaption within the synchronization gap:
For MC and MB,

$$v_{n+1} = v_n + sgn(v_{l,n} - v_n), \tag{26}$$

(g) Over-acceleration through random acceleration within the synchronization gap:
For MC and MB, if $v_n > v_{l,n}$ then with probability p_a,

$$v_{n+1} = min\ (v_{n+1} + 1, v_{max}), \tag{27}$$

(h) Acceleration:
If the subject vehicle is an AV, and the leading vehicle is also an AV within the detection range:

$$v_{n+1} = min(v_n + 1, v_{max}, g_n/\tau + v_{l,n+1} - g_{safe,n}), \tag{28}$$

Otherwise:

$$v_{n+1} = min(v_n + 1, v_{max}), \tag{29}$$

(i) Deceleration:
For MC and MB,

$$v_{n+1} = min\ (v_{n+1}, g_n/\tau), \tag{30}$$

(j) Deceleration within safety distance gap:
If $g_n < g_{safe,n}$,

$$v_{n+1} = min\ (v_n, g_n/\tau), \tag{31}$$

(k) Deceleration upstream the bus bay:
For a stopping bus on the motor lane, if $x_A - L_a \leq x_n \leq x_A$,

$$v_{n+1} = min\ (v_{n+1}, (x_A - x_n)/\tau), \tag{32}$$

(l) Randomization with probability p:
For MC and MB, with r being a random value distributed uniformly between 0 and 1, if:

$$p_a \leq r < p_a + p, \tag{33}$$

then:

$$v_{n+1} = max\ (v_{n+1} - 1, 0), \tag{34}$$

(m) Moving along the stop lane:
For a bus on the stop lane that has finished dwelling,

$$v_{n+1} = min\ (1, (x_D - x_n)/\tau, g_n/\tau), \tag{35}$$

(n) Motion:

$$x_{n+1} = x_n + v_{n+1} \cdot \tau, \tag{36}$$

(o) Bus entering bus bay for dwelling:

If a stopping bus is on the right lane, and $x_n = x_A$, it will try to enter the bus bay.

If both Section B and Section C of the stop lane are vacant, the bus will change to the stop lane and begin its dwelling at Section C.

$$x_{n+1} = x_C, \tag{37}$$

$$v_{n+1} = 0, \tag{38}$$

If Section B of the stop lane is vacant but Section C is occupied by another bus, the bus will change to the stop lane and begin its dwelling at Section B.

$$x_{n+1} = x_B, \tag{39}$$

$$v_{n+1} = 0. \tag{40}$$

Otherwise, the bus will stay in the current position on the right lane.

In rule (a), δ_0, δ_1 and δ_2 are determined according to [23]. In rule (e), the synchronization gap $G(v_n)$ is calculated based on (16) and (20) in [10]. The probability p_a in rule (g) is calculated using (15) in [10]. The probability p in rule (l) is calculated using (17) - (19) in [10].

Whereas built based on the KKSW-BB CA model in [10] and the KKSW CA model in [23], the KKSW-BB-AVHDV CA model proposed in this study differs from these earlier works with the following features.

First, the model expands the KKSW-BB CA model to two lanes, and utilizes the lane changing rules from the KKSW CA model. In rule (a), truck-specific lane-changing conditions in [23] are applied on buses, to represent the difference of lane changing decisions between buses and cars.

Secondly, speed updating rules within safety distance gap is introduced into the KKSW CA model. One unique feature of KKSW CA model is that it models the synchronization behavior of human drivers. Calibrated with highway data, in [23], the synchronization gap $G(v_n)$ is calculated as below:

$$G(v_n) = \begin{cases} k_1 v_n \cdot \tau, & if\ v_n > v_{pinch} \\ k_2 v_n \cdot \tau, & if\ v_n \leq v_{pinch} \end{cases} \tag{41}$$

where k_1, k_2 and v_{pinch} are set as 3, 2 and 6, respectively.

On urban links with bus bay stations, as the speed of the traffic is lower than that on highway, in [10], the parameters k_1, k_2 and v_{pinch} are recalibrated as 2, 1 and 4, respectively. However, parameters with such small values could lead to a synchronization gap shorter than the safety distance gap, in which case, drivers should stop accelerating to keep a safety distance, instead of synchronizing the speed. In [10], this case is not considered, as the safety distance gap is set as $v_n \cdot \tau$, which tends to be short. To deal with this case, in this study, the safety distance gap is calculated by rule (d), based on [11]. If the subject vehicle and the leading vehicle are both AV, the safety distance gap is a small constant d^0_{safe}. Otherwise, the safety distance gap is the sum of two terms, a distance for reaction time and a distance for emergency break considering the speed difference. Then, according to rule (j), when the gap to the leading vehicle is smaller than the safety distance gap, the speed will be updated by (31), which overwrites the speed updating results by the steps before it.

Thirdly, autonomous cars and autonomous buses are introduced, with rules (a), (d) and (h). According to rule (a), the lane changing conditions of AVs have several differences from HDVs. The safety conditions in (8) - (10) are defined based on a modified version of the MOBIL (Minimizing Overall Braking Induced by Lane changes) model, whose principle is a trade-off between the motivation of gaining a higher speed by changing lane and the courtesy of causing the least possible inconvenience to the adjacent vehicles [24]. According to (7), an AV would only change lanes when the gap to the leading vehicle is small enough to prevent it from reaching a higher speed or the maximum speed. In the MOBIL model, the subject vehicle needs the gap to the trailing vehicle on the target lane, g_n^-, to be at least $v_{max} \cdot \tau$ [24]. Considering that AVs can accurately detect the speed of the trailing vehicle, this condition of MOBIL model is too conservative, compared with the rules for HDVs in (6). Therefore, in the model proposed in this study, the condition is changed to (9) and (10). According to rule (9), if the trailing vehicle on the target lane is an AV within the detection range, the subject AV would allow a smaller g_n^- for lane changing, as the two AVs are assumed to be connected and update speeds simultaneously. Otherwise, as in (10), the subject AV would allow $v_n^- \cdot \tau$ for g_n^-.

If the leading vehicle is an HDV, an AV updates its speed by (29), subject to the checking of safety distance gap in rule (j). If the leading vehicle is an AV, the subject vehicle updates its speed by (28), to form a platoon with the leading vehicle as soon as possible [11].

Finally, bus bay specific rules are defined for stopping buses. According to rule (k), when approaching the bus bay, a stopping bus would slow down to reach the position of x_A. According to rule (b), if the bus is on the left lane, it would try to change to the right lane upstream the position of x_A. If it fails to do so, it would stay at x_A to wait for a chance. Similarly, according to rule (o), a stopping bus at x_A on the right lane would try to enter the bus bay on the stop lane. Based on site observations, if Section B and Section C are both vacant, a bus would dwell at Section C, which is the standard position of the bus stop. If Section C is occupied by another bus, and Section B is vacant, the bus would dwell at Section B instead. Otherwise, the bus cannot enter the bus bay and would wait at x_A on the right lane.

After dwelling, a bus changes back to the right lane, if the conditions in rule (c) are met. Compared to the lane changing in rule (a), the motivation criterion of speed difference in (1) - (4) are removed, as the motivation for this lane changing is to get back to the motor lane after dwelling, not for overtaking. For an MB, in (15), instead of using a constant g_c as in (6), a variable g_t is used for the condition of g_n^-. After dwelling, g_t gradually decreases as T_B increases, to show that drivers become less patient as they are delayed, and tend to force their way into the traffic. For an AB, in (18) and (20), similar to (9), it allows d_{safe}^{0} for the gap of the lane changing, considering the speed difference of the leading / trailing AV within the detection range. According to rule (m), if the bus cannot change to the right lane, it would slowly move forward inside the bus bay, to make room for buses behind, with a speed of 1 cell/s (5.4 km/h), until it reaches the position of x_D.

TABLE 1. Model parameters of the KKSW-BB-AVHDV CA model used in simulations.

Parameters for forward motions

$d = 5$ (7.5m) for MC and AC,
$d = 12$ (18 m) for MB and AB,
$v_{max} = 11$ (59.4km/h) for MC and AC,
$v_{max} = 10$ (54km/h) for MB and AB,
Detection range = 80 (120m) for AC and AB,
$d_{safe}^{0} = 1$,
$T_{react} = 2$ for MC and MB; $T_{react} = 1$ for AC and AB,
$B = 3$.

Parameters for lane-changing

$p_{lc} = 0.3$,
$\delta_1 = 1$, $\delta_2 = 3$ for cars, $\delta_1 = 3$, $\delta_2 = 1$ for buses,
$\delta_0 = 4$,
$g_c = 10$ (15m), $L_a = 100$ (150m),
$g_{t,max} = 10$ (15m), $g_{t,min} = 1$ (1.5m) for MB,
$T_{dwell} = 10$.

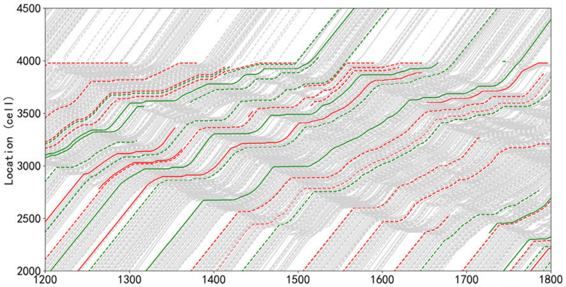
IV. SIMULATION RESULTS AND ANALYSIS

A. MODEL PARAMETERS

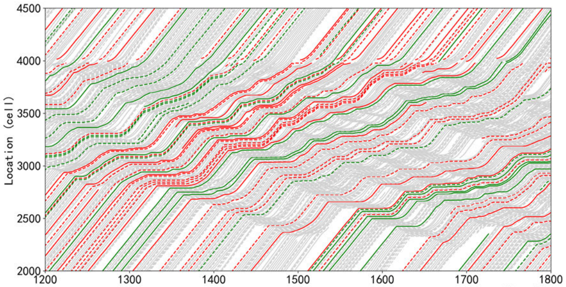
Parameters of the KKSW-BB-AVHDV CA model used in simulations are presented in Table 1. The maximum speed of MC and AC is set as 11 cell/s (about 60 km/h), which is approximately the speed limit in many urban areas, and the maximum speed of AB and MB is set as 10 cells/s (about 54 km/h), which is the speed limit for safe bus driving in some cities in China. The values of p_{lc} and L_a are determined by Kerner's KKSW CA model in [23]. The values of g_c and g_t are determined according to the characteristics of human driving vehicles and traffic conditions on urban roads in China. In [23], the value of g_c is 20, which is slightly smaller than the value of highway free flow speed (25 cell/s). Similarly, in this paper, in the context of urban links, the value of g_c is set as 10, which is slightly smaller than the speed limit of 11. The safety distance gap between AVs is assumed to be 1 cell. For human drivers, reaction time is set as 2 seconds. For AVs, reaction time is set as 1 second, based on value of the processing time of the on-board sensing system [11] and the response time of ACC (Adaptive Cruise Control) controller [25]. In the calculation of safety distance gap, the deceleration rate B is set as 3 (4.5 m/s^2).

The simulation is carried out under the open boundary condition, using the boundary and initial conditions defined in [26]. q_{in} denotes the flow rate of the incoming traffic, for which six different values are considered ($q_{in} = 300$, 600, 900, 1200, 1500 and 1800 veh/h/lane).

Two different values of P_b are used in simulations ($P_b = 0.05$ and 0.10), based on field observations of bus volumes at a bus bay in Hangzhou, China, as shown in Fig. 1. To simplify the calibration process, big vehicles, such as buses and trucks, are all counted as buses and the bus stopping probability P_s is calculated accordingly. Four different values of P_s are considered ($P_s = 0$, 0.3, 0.5 and 0.8), and the bus dwell time T_{dwell} is set as 10 s in simulations based on field observations. Each simulation iterates 2000 time steps and the result of each simulation is obtained after discarding the first 1000 time steps as warm-up time. The simulation is run 10 times for each set of parameters.



(a) Left lane



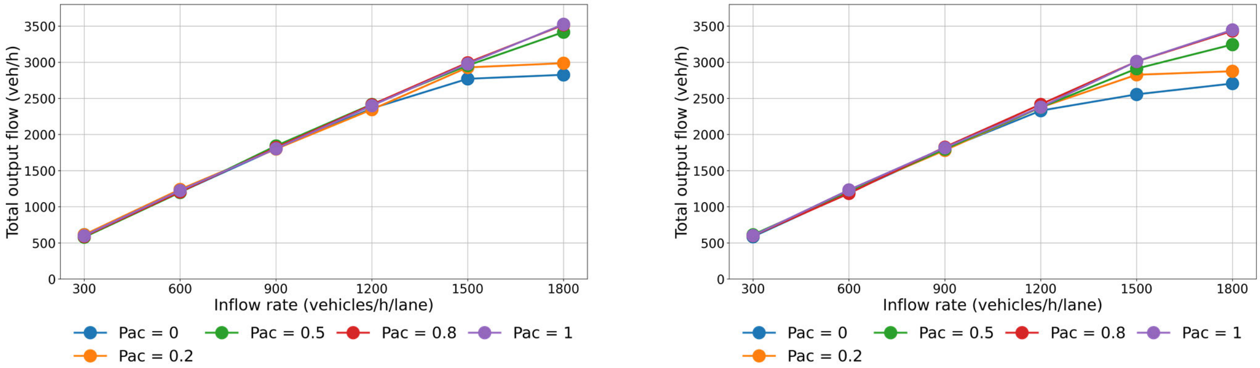
(b) Right lane

FIGURE 3. Spatiotemporal diagrams of the left lane and the right lane, with $q_{in} = 1500$, $P_b = 0.1$, $P_s = 0.5$.

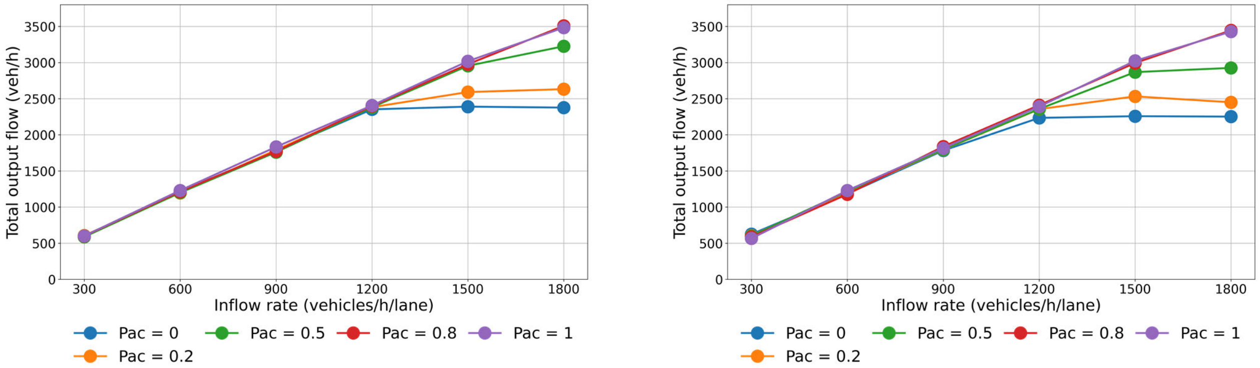
B. FLOW CHARACTERISTICS IN THE HETEROGENEOUS TRAFFIC FLOW

To investigate the impact of the bus bay on the heterogeneous traffic flow, a series of simulations are conducted. Fig. 3 shows the spatiotemporal diagrams near the location of the bus bay, with $q_{in} = 1500$ veh/h/lane, $P_b = 0.1$, $P_s = 0.5$. In the figure, stopping buses, non-stopping buses and cars are shown in red, green, and grey, respectively. HDVs are shown with solid lines and AVs are shown with dashed lines.

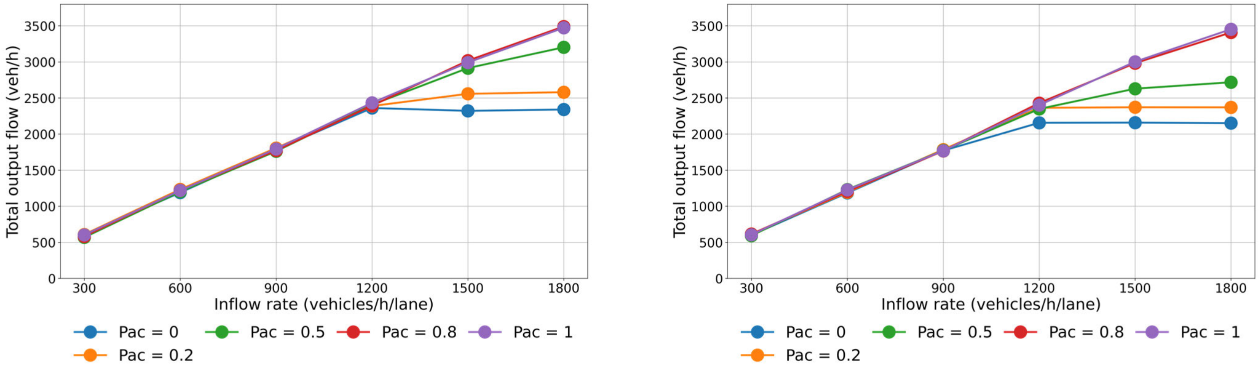
In the heterogeneous traffic system, the maximum speed of buses is lower than that of cars, so MCs and ACs trailing behind buses tend to change lane to overtake the preceding buses. According to (1) - (4) in rule (a), the conditions to change from the right lane to the left lane are stricter on buses than cars, whereas it is easier for buses to change from the left lane to the right lane. Besides, stopping buses must change to the right lane to enter the bus bay in rule (b). As a result, buses are mostly concentrated on the right lane.



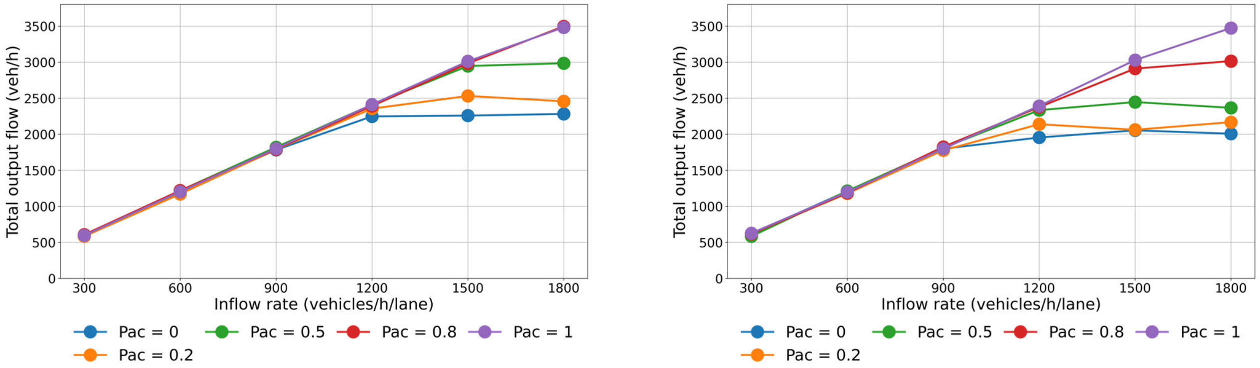
(a) $P_b = 0.05$, $P_s = 0$ (b) $P_b = 0.10$, $P_s = 0$



(c) $P_b = 0.05$, $P_s = 0.3$ (d) $P_b = 0.10$, $P_s = 0.3$



(e) $P_b = 0.05$, $P_s = 0.5$ (f) $P_b = 0.10$, $P_s = 0.5$



(g) $P_b = 0.05$, $P_s = 0.8$ (h) $P_b = 0.10$, $P_s = 0.8$

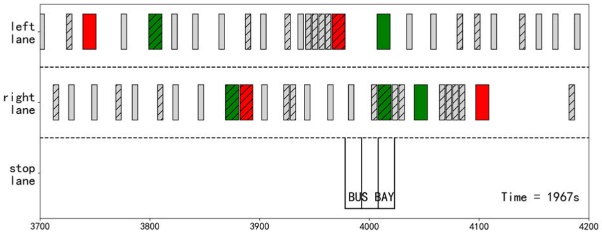
FIGURE 4. **Total output flow rates under different conditions.**

In the diagram, it is clear to see that the bus bay could exert negative influence on the heterogeneous traffic flow, causing a wide moving jam (WMJ) moving upstream. To quantify the impact of the bus bay, Fig. 4 shows the total output flow rate of the two lanes, under different stopping bus and AV penetration rate conditions.

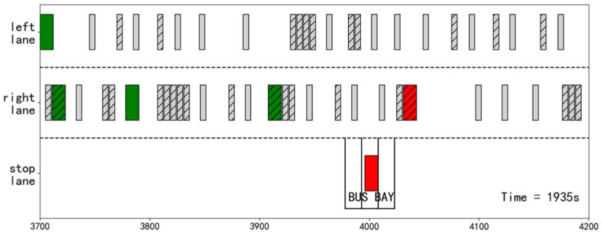
When there is no stopping bus, the bus bay has no impact on the traffic flow. With $q_{in} \leq 1200$ veh/h/lane, the output flow rate is nearly equal to the inflow rate, as traffic move in a free flow state. With $q_{in} \geq 1500$ veh/h/lane, when the penetration of AV is low, the output flow rate can no longer match the inflow rate, as the capacity of the system is reached. As an example, in Fig. 4 (a), with $P_{ac} = 0$ and $q_{in} = 1800$ veh/h/lane, the output flow rate is around 1400 veh/h/lane, namely, a headway of 2.57 s. This value could be explained by a rough estimation of the headway in a synchronized HDV platoon, which is given as the sum of the reaction time T_{react} in (23), and a term of d/v_{max}. This result is also consistent with values reported by field measurements in some previous researches, such as [27], where the mean headway is around 3.3 s and 2.5 s during morning peak on two different urban links in Beijing, China.

With low penetration of AV, as the percentage of stopping bus increases, the output flow rate drops significantly. In Fig. 4 (h), with $P_b = 0.1$ and $P_s = 0.8$, the road capacity drops to as low as 1000 veh/h/lane. This demonstrates the huge negative impact of bus bay on the heterogeneous traffic. In Fig. 3 (a), it has be shown that, the left lane is frequently blocked by a stopping bus. Even though most buses tend to drive on the right lane according to rule (a) and (b), under high flow rate conditions, it is still possible that a stopping bus remains on the left lane when approaching the bus bay, as the lane changing conditions of (5) – (12) could not be met. In this case, the bus would stop at the position of x_A, waiting for a chance to switch to the right lane. As a result, vehicles behind the bus have to stop, and a queue is formed on the left lane. At the same time, some vehicles on the left lane upstream the queue would choose to switch to the right lane, which increases the volume on the right lane and makes it even more difficult for the bus on the left lane to make the lane change. Therefore, a 'vicious cycle' is formed, and the performance of the traffic is severely impacted. This process is further shown with a snapshot of the simulation run in Fig. 5 (a).

In all cases, the negative impact of the bus bay on the heterogeneous traffic flow under high inflow rate conditions is reduced as the penetration of AV increases. When $P_{ac} \geq 0.5$, the increase in the output flow rate becomes more significant. Interestingly, it is found that except for Fig. 4 (h), which has the most stopping buses, the output flow rate of the heterogeneous flow with $P_{ac} = 0.8$ is nearly equal to that of the flow with no human drivers ($P_{ac} = 1$). This could be explained as follows. With high penetration of AV, the average headway among the traffic flow is small, and thus the overall capacity is high. In Fig. 5 (b), it is clear to see the difference in the headway of platoons formed by purely AVs and platoons containing HVs. When $P_{ac} \geq 0.8$, the system has adequate capacity to handle the disturbance of stopping buses, which leads to the output flow rate being equal to the inflow rate in most cases.



(a) Left lane blockage by a stopping bus



(b) Vehicle platoons

🟥 Stopping MB ▨ Stopping AB ▯ MC

🟩 Non-stopping MB ▨ Non-stopping AB ▨ AC

FIGURE 5. **Snapshots of the simulation.**

C. CONGESTED PATTERNS AND SPEED CHARACTERISTICS IN THE HETEROGENEOUS TRAFFIC FLOW

In [10], it has been shown that the bus bay section could be regarded as an effectual bottleneck in the adjacent lane. In this study, as the KKSW-BB-AVHDV CA model expands the KKSW-BB CA model in [10] from one lane to two lanes, bus maneuvers at the bus bay disturb the heterogeneous traffic flow in four ways:

(i) Bus changing lanes, causing the trailing vehicle on the target lane to decelerate.

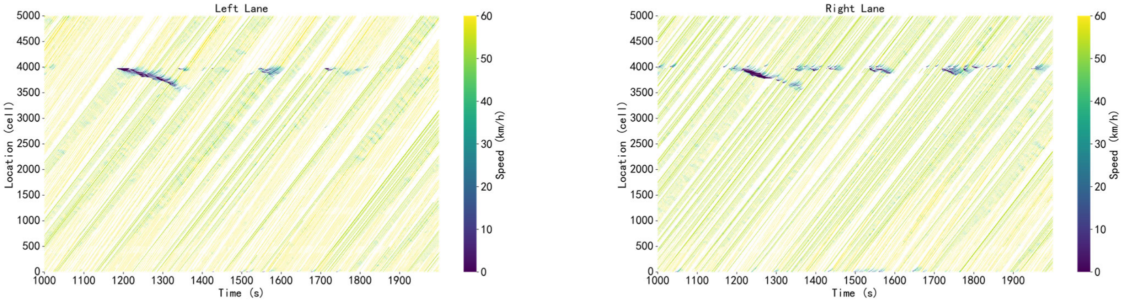
(ii) Bus slowing down on the right lane when entering the bus bay.

(iii) Bus stopping on the right lane to wait for a vacant place in the bus bay.

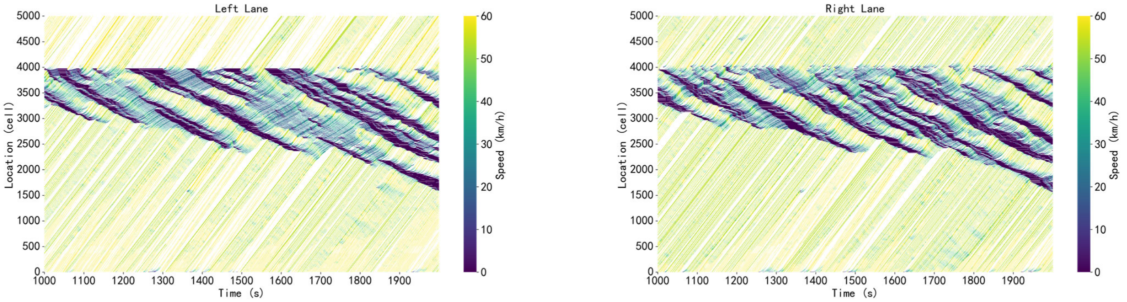
(iv) Bus stopping on the left lane to wait for a chance for lane changing.

To better understand the congested patterns caused by the influence of the bus bay, Fig. 6 shows the spatiotemporal diagrams of the two lanes under different inflow rate, stopping bus percentage and AV penetration conditions, with a heat map of the speed.

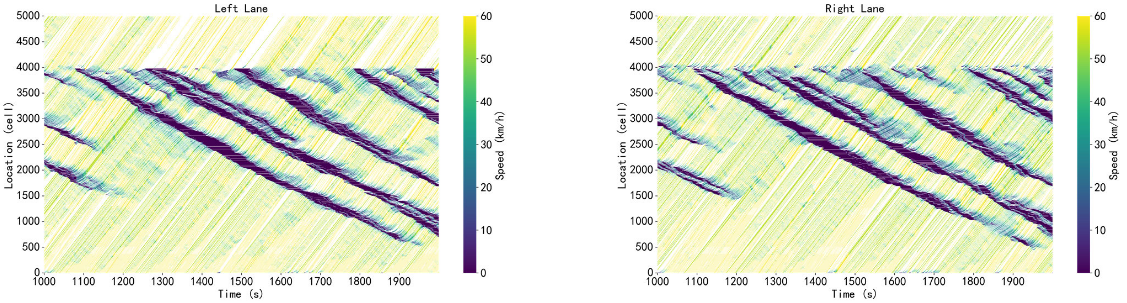
In Fig. 6 (a) and (b), with a low inflow rate of 1200 veh/h/lane and $P_{ac} = 0.5$, traffic moves in a free flow state upstream and downstream the bus bay, with occasional speed disturbance due to randomization in speed updating rules. Near the bus bay, the disturbance of stopping buses entering and exiting the bus bay causes transition from free flow phase to synchronized flow phase (F→S transition, as defined in [26]), and leads to multiple localized synchronized patterns (LSP) on both lanes, whose upstream and downstream fronts are localized at



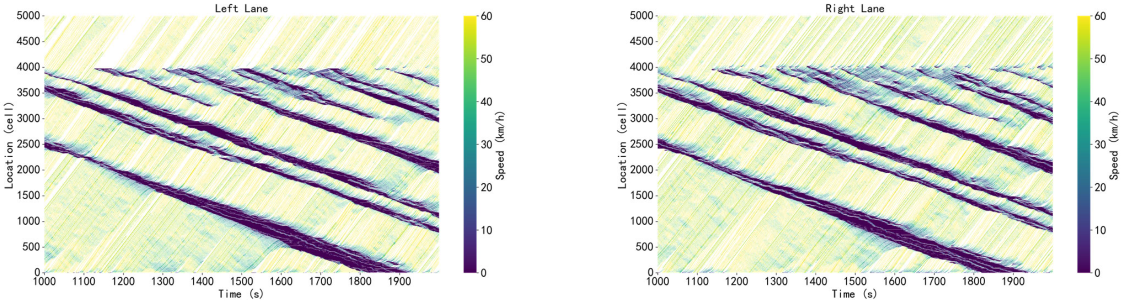
(a) q_{in} = 1200 veh/h/lane, P_{ac} = 0.5, P_b = 0.1, P_s = 0.5 (b) q_{in} = 1200 veh/h/lane, P_{ac} = 0.5, P_b = 0.1, P_s = 0.5



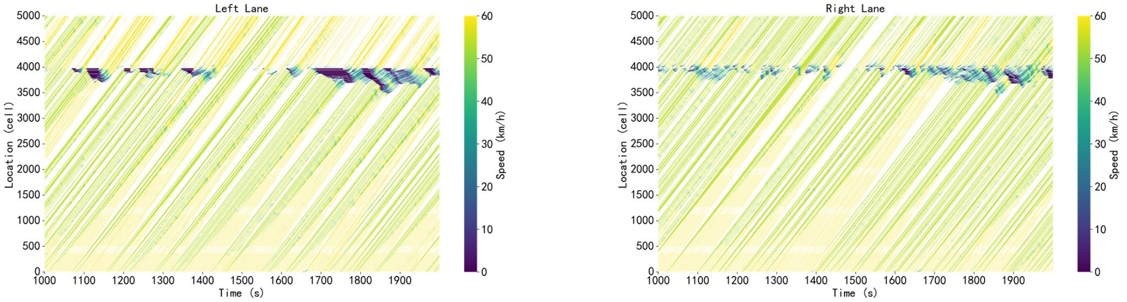
(c) q_{in} = 1500 veh/h/lane, P_{ac} = 0.5, P_b = 0.1, P_s = 0.5 (d) q_{in} = 1500 veh/h/lane, P_{ac} = 0.5, P_b = 0.1, P_s = 0.5



(e) q_{in} = 1800 veh/h/lane, P_{ac} = 0.5, P_b = 0.1, P_s = 0.5 (f) q_{in} = 1800 veh/h/lane, P_{ac} = 0.5, P_b = 0.1, P_s = 0.5



(g) q_{in} = 1800 veh/h/lane, P_{ac} = 0.2, P_b = 0.1, P_s = 0.5 (h) q_{in} = 1800 veh/h/lane, P_{ac} = 0.2, P_b = 0.1, P_s = 0.5



(i) q_{in} = 1800 veh/h/lane, P_{ac} = 0.8, P_b = 0.1, P_s = 0.5 (j) q_{in} = 1800 veh/h/lane, P_{ac} = 0.8, P_b = 0.1, P_s = 0.5

FIGURE 6. Spatiotemporal diagrams of traffic flow under different conditions.

some distance upstream the bus bay bottleneck [28]. Because of the big time gaps among the platoons, these LSPs cannot propagate far upstream over time and dissipate quickly.

By contrast, in Fig. 6 (c) - (h), with $q_{in} \geq 1500$ veh/h/lane, the speed disturbances caused by stopping buses have a more severe impact on the heterogeneous traffic flow. On the right lane, in Fig. 6 (d), (f) and (h), moving synchronized flow patterns (MSP) are induced near the bus bay, with a speed significantly lower than the speed limit v_{max}. While these MSPs propagate upstream the bus bay, most grow into wide moving jams (WMJ). Compared with Fig. 6 (d), in Fig. 6 (f), as the inflow rate is higher, WMJs could propagate farther upstream, and the WMJ regions are also wider (in the longitudinal direction). In Fig. 6 (h), with a lower AV penetration, the influence of the bus bay becomes even more obvious, with many wide WMJs induced, spreading upstream all the way to the entry point of the road section.

On the right lane, stopping bus disturb the heterogeneous traffic flow mainly by lane changing and slowing down when approaching the bus bay. In [10], it is found that long dwell time of the stopping buses could lead to upstream buses waiting on the right lane and thus inducing WSPs and WMJs. In this study, since the dwell time is relatively short (10 s), and buses could dwell at both Section B and Section C, the bus bay has enough capacity to serve the stopping buses, considering the values of q_{in}, P_b, and P_s. Therefore, in our simulations, buses rarely have to stop on the right lane to wait for a vacant place for dwelling.

Different from the right lane, on the left lane, as some stopping buses stop at the position of x_A to change the lane, transitions of F→S and even F→J (free flow phase to wide moving jam phase) are formed. Similar to the findings in [10], the WMJs not only emerge spontaneously among synchronized flow, but could also be directly induced by a large disturbance caused by a stopped bus. Whereas past researchers have focused on the influence of the bus bay on the right lane caused by bus queueing and blockage [19], [20], [21], the results in this study show that under certain conditions, the influence on the left lane could be significant too. Besides, it is found that the MSPs and WMJs on the left lane demonstrate high degree of synchronization with those on the right lane. This is because, in this study, the most severe influence of the bus bay comes from the stopping buses delayed on the left lane that block the lane. As these buses make the lane change, they also introduce disturbance to the upstream traffic flow on the right lane. Indeed, in Fig. 6 (c) – (h), such synchronized disturbance on the two lanes could be found near the bus bay, with the right lane showing slightly narrower and less occurrences of WMJs than the left lane.

Once the stopping bus on the left lane changes to the right lane successfully, the WMJs begin to dissipate. During the process of WMJ dissipation, a J→S (wide moving jam phase to synchronized flow phase) transition occurs, and then MSPs occur. Both the WMJs and MSPs on the left lane can propagate upstream the bus bay, and the vehicle speed inside MSPs is significantly lower than the speed limit v_{max} but higher than that within WMJs.

In Fig. 6 (i) and (j), with a high AV penetration of 0.8, the influence of the bus bay is significantly reduced. Multiple synchronized patterns occur on the right lane, which are mostly localized. On the left lane, WMJs caused by stopping buses still exist, but they dissipate quickly and cannot propagate far upstream. As aforementioned, with high AV penetration, the capacity of the system is high, and the transition to the free flow phase could be achieved among the platoons.

To summarize, due to the speed disturbance caused by stopping buses entering and exiting the bus bay, LSPs could occur among the heterogeneous flow under the condition of low inflow rates. Under high inflow rate conditions, both WMJs and MSPs could be induced, showing high degree of synchronization on the two lanes. The most severe disturbance is caused by stopping buses stopped on the left lane, which greatly reduces the capacity of the system. With the introduction of AVs, the impact of the bus bay is significantly reduced, and it becomes easier for the heterogeneous traffic flow to recover the free flow state.

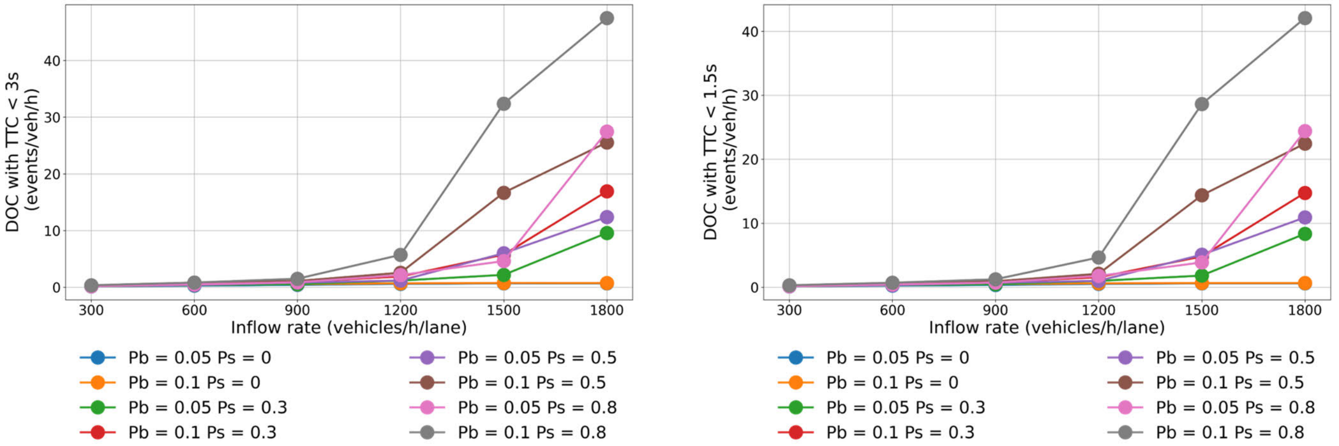
D. ANALYSIS OF TRAFFIC CONFLICTS IN THE HETEROGENEOUS TRAFFIC FLOW

According to the three-phase traffic theory, the major reason of F→S phase transition is the sudden speed reduction occurring in free flow, which could easily lead to rear-end conflicts. Therefore, a rear-end conflict analysis is made to evaluate traffic safety in this section.

This study uses the Traffic Conflict Technique (TCT) to assess traffic safety near the bus bay. A traffic conflict situation is defined as when two or more road users approach each other in time and space to such an extent that a collision is imminent if their movements remain unchanged [29]. The rear-end conflict analysis includes the frequency and severity under different percentages of stopping bus and different percentages of AVs.

In this paper, we use a proxy indicator, namely deceleration occurrences caused by conflicts (DOC) [30], to estimate the occurrences of vehicle conflicts, and use the surrogate safety indicator time-to-collision (TTC) to distinguish serious and non-serious conflicts, which is defined as the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained [31]. In each simulation, the velocity and position of each vehicle, as well as occurrence of vehicle's deceleration (DOC) are recorded, with which TTC can be computed. A serious conflict is said to have occurred when the TTC value is less than 1.5 s [29]. Therefore, we use DOC with TTC smaller than 3 s to measure the frequency of conflicts and use DOC with TTC smaller than 1.5 s to measure the severity of conflicts.

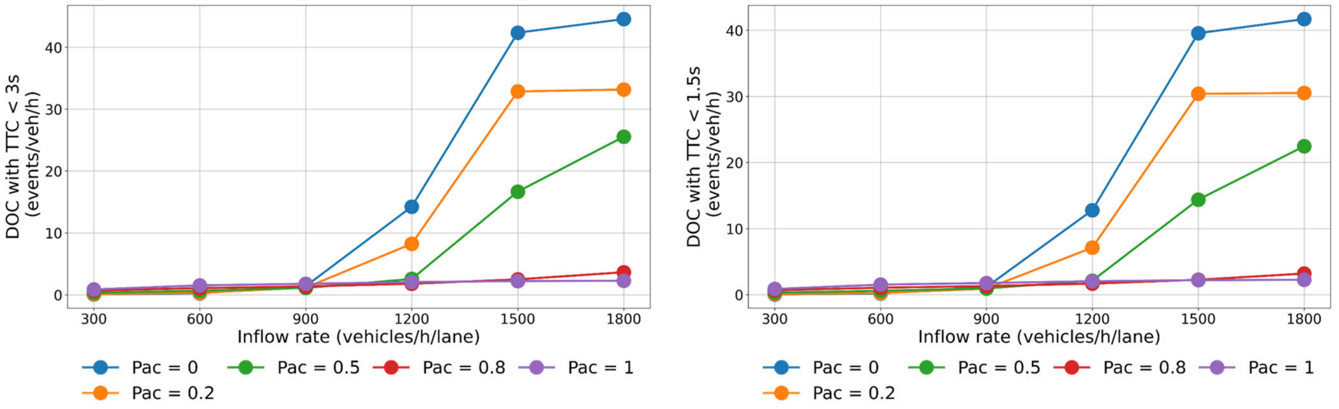
Fig. 7 (a) shows the distribution of DOC per vehicle per hour with TTC smaller than 3s under different stopping bus percentage and inflow rate conditions, with the penetration rate of AV being 0.5. It could be seen that when there is no stopping bus, the number of conflicts remains small. In this case, the disturbance of buses entering or exiting



(a) Conflict frequency shown by DOC with TTC < 3

(b) Conflict severity shown by DOC with TTC < 1.5

FIGURE 7. **Conflict frequency and severity distributions under different stopping bus percentage and inflow rate conditions.**



(a) Conflict frequency shown by DOC with TTC < 3

(b) Conflict severity shown by DOC with TTC < 1.5

FIGURE 8. **Conflict frequency and severity distributions under different AC percentage and inflow rate conditions.**

bus bay does not exist. When the inflow rate is no greater than 900 veh/h/lane, vehicles move in a free flow state, and the impact of stopping buses cannot lead to large number of conflicts, as the disturbance of stopping buses quickly dissolves. When the inflow rate is larger than 900 veh/h/lane, the number of conflicts increases drastically with the inflow rate and the penetration rate of stopping buses. The increase of the number of conflicts coincides with the occurrence of WMJs, as shown in Fig. 6 (c) - (f), which demonstrates the huge negative impacts of bus bay on the heterogeneous traffic. Fig. 7 (b) shows the distribution of DOC per vehicle per hour with TTC smaller than 1.5 s. Similar to the result of conflict frequency, it is found that when $q_{in} \geq 900$ veh/h/lane, the negative impact on conflict severity by stopping buses becomes more significant.

Fig. 8 (a) shows the distribution of DOC per vehicle per hour with TTC smaller than 3 s under different AC percentage and inflow rate conditions, with P_b and P_s being 0.1 and 0.5, respectively. It could be seen that when $q_{in} \geq$ 900 veh/h/lane, the number of conflicts is reduced significantly as P_{ac} gets larger. Specially, with $P_{ac} \geq 0.8$, the number of conflicts remains at a low level, and demonstrates insensitivity to flow rates. In this case, with AV dominating the traffic flow, the impact of disturbance of stopping buses dissipates quickly. As a result, with few occurrences of WMJs, as shown in Fig 6 (i) and (j), the risk of rear-end collision is greatly reduced. Contrary to this finding, it could be seen that, when $q_{in} \leq 900$ veh/h/lane, conflicts occur slightly more frequently when the penetration rate of AV is high. This is caused by the short gap allowed between AVs. According to the rules of the KKSW-BB-AVHDV CA model, AVs have a short reaction time and can update speed simultaneously with the leading AV. Therefore, in the case of high AV penetration, as most conflicts occur on AVs, the chance of rear-end collision is actually low, compared with conflicts on human drivers, to whom reaction time is critical.

Fig. 8 (b) shows the distribution of DOC per vehicle per hour with TTC smaller than 1.5 s. Similar to the result of conflict frequency, the number of serious conflicts is also greatly reduced with the introduction of ACs with $q_{in} \geq 900$ veh/h/lane.

Through the analysis above, it may be concluded that bus maneuvers at the bus bay can exert negative impacts on traffic safety, causing rear-end conflicts. As the percentage of stopping buses in the heterogeneous traffic flow increases, the impact of bus bay on traffic safety becomes more frequent and severe. Introducing AVs into the heterogeneous traffic flow can alleviate such impacts and significantly reduce the frequency and severity of traffic conflicts.

V. DISCUSSION

A. SUGGESTIONS

Based on the analysis above, it has been seen that bus maneuvers at the bus bay have significant impact on the heterogeneous traffic flow, especially under high flow rate conditions. By introducing AVs into the heterogeneous traffic flow, the impact of stopping buses is significantly reduced and traffic congestion near the bus bay is alleviated.

However, as no yield-to-bus rule is established in the KKSW-BB-AVHDV CA model, under high flow rate conditions, buses still experience delay for lane changing, which results in blockages of the left lane, despite high penetration of AVs. Indeed, in Fig. 6 (i), multiple WMJs can be found upstream the bus bay, and the blockage of the left lane is still obvious.

To eliminate the possibility of left lane blockage, one simple method is to forbid stopping buses to drive on the left lane far upstream the bus bay. However, this management may not always be effectual in real-world traffic, due to heavy traffic demand or road network layouts. Therefore, to minimize the disturbance of stopping buses, for cars and non-stopping buses, three yield-to-bus rules are proposed below:

(i) If a bus is trying to exit the bus bay, a vehicle on the right lane should decelerate or stop to yield to the bus, if possible.

(ii) If a bus is trying to change from the left lane to the right lane to enter the bus bay, a vehicle on the right lane should decelerate or stop to yield to the bus, if possible.

(iii) If a bus is trying to change from the left lane to the right lane to enter the bus bay, or if a bus is trying to exit the bus bay, a vehicle within a certain range upstream on the left lane should not change to the right lane.

For human drivers, the application of the first and the second rules above may be achieved as driving courtesy or Yield-To-Bus (YTB) laws. In fact, YTB programs have been tested on human drivers in some areas, such as Florida, USA, but the effect was not found to be significant [32]. The difficulty in implementation and enforcement of the YTB laws makes it ineffectual to apply to human drivers in general.

For autonomous vehicles, on the other hand, it could potentially be much more feasible to implement YTB rules. With simple data communication technologies, such as RFID (Radio Frequency Identification), a stopping bus (AB or MB) could make a call when it is trying to enter or exit the bus bay. When an upstream AV receives the call, it follows the three rules above to yield. The rules utilize vehicle-to-vehicle communication, which allows AVs to make decisions in advance, so that buses could enter or exit the bus bay as soon as possible.

In short, the principle of the three rules above is to ensure bus priority when it comes to the usage of the right lane. The shorter buses are delayed on the motor lanes, the less their negative impact is on the traffic. Such bus priority management at the bus bay could further enhance the performance of public transportation, in addition to the congestion alleviation thanks to AV.

B. CONCLUSIONS

This study proposed a KKSW-BB-AVHDV CA model, extending the research scope of the KKSW-BB CA model, based on the KKSW CA model in the framework of Kerner's three-phase traffic theory. The model can reflect the features of a heterogeneous traffic flow composed of human driving vehicles and autonomous vehicles near a bus bay. The proposed model is utilized to study the influence of bus bay on the efficiency and safety of the heterogeneous traffic flow.

Based on the numerical simulation and analysis, the following conclusions are obtained: (1) The maneuvers of stopping buses entering and exiting the bus bay have a significant impact on traffic efficiency in the heterogeneous traffic system. The introduction of AVs in the heterogeneous traffic flow can significantly improve the efficiency of the heterogeneous flow, especially under heavy flow conditions. In some cases, the performance of the heterogeneous flow with a high AV penetration of 0.8 shows no significant difference from that of a pure AV traffic flow. (2) Under low inflow rate conditions, localized synchronized flow patterns (LSP) could occur near the bus bay on both lanes. Under high inflow rate conditions, moving synchronized flow patterns (MSP) could occur near the bus bay, and wide moving jams (WMJ) could emerge spontaneously in the synchronized flow. The WMJs and MSPs in the heterogeneous traffic system can propagate upstream the bus bay, demonstrating high degree of synchronization on the two lanes, and the corresponding vehicle speed is significantly lower than that of free flow. (3) The most severe disturbance comes from the stopping buses stopped on the left lane, in which case, the lane is blocked and a WMJ is directly induced. (4) The bus bay can exert negative influence on traffic safety, causing rear-end conflicts to be more frequent and serious as the percentage of stopping buses in the heterogeneous traffic flow increases. The frequency and severity of the conflicts could be significantly reduced by the introduction of AVs in the heterogeneous traffic flow.

In conclusion, the KKSW-BB-AVHDV CA model presents a method to study the traffic characteristics of the heterogeneous flow on multiple lanes in the context of bus bay. In this study, by introducing AVs into the heterogeneous traffic, the impact of the bus bay is alleviated mainly by taking the advantage of the high road capacity resulted from short headways among AVs. However, the problem of left lane blockage by stopping buses is still not completely solved. In future studies, in order to fully explore the capability of AVs, yield-to-bus rules could be applied, and experiments could be conducted with even higher inflow rates, to better understand the potential of AVs in this context. More complex models, such as game theory, could also be utilized for the modelling of AVs, so that an optimization at the system level could be reached, instead of individual rule-based decisions. Besides, based on the KKSW-BB-AVHDV CA model, more complicated cases can be studied, such as multi-berth stations and no-lane-changing rules near the bus bay. In comparison with bus bays, it would also be interesting to apply the model on curbside stops, which are also common in urban areas.

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