Influence of bus stop with left-turn lines between two adjacent signalized intersections*

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Based on the symmetric two-lane Nagel–Schreckenberg (STNS) model, a three-lane cellular automaton model between two intersections containing a bus stop with left-turning buses is established in which model the occurrences of vehicle accidents are taken into account. The characteristics of traffic flows with different ratios of left-turn lines are discussed via the simulation experiments. The results indicate that the left-turn lines have more negative effects on capacity, accident rate as well as delay if the stop is located close to the intersections, where the negative effect in a near-side stop is more severe than that in a far-side one. The range of appropriate position for a bus stop without the bottleneck effect becomes more and more narrow with the increase of the ratio of left-turn bus lines. When the inflow is small, a short signal cycle and a reasonable offset are beneficial. When the inflow reaches or exceeds the capacity, a longer signal cycle is helpful. But if the stop position is inappropriate, the increase of cycle fails in reducing the negative effect of left-turning buses and the effectiveness of offset is weakened.

Keywords: cellular automata (CA) model, bus stop, left-turn bus line, vehicle accident

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1. Introduction

As an important part of public transport networks, bus stops provide the basic conditions for the buses to load and unload passengers.[1] They are crucial for urban public transport. However, the set bus stops have some negative influence on road traffic systems.[2,3] The traffic flow on a roadway is affected when a bus enters in and departs from a stop, for the driving behaviors of other vehicles near the bus have to be changed. Inappropriate position for a bus stop, especially located close to an intersection, magnifies the negative influence, which frequently causes traffic congestion and acts as a bottleneck for the road.[2–8] Moreover the road capacity drops and some traffic accidents may happen. These have been proved by plenty of theoretical studies about the influence of bus stops for roadway traffic and engineering practice, particularly by using the cellular automata (CA) model in the last decade, which is discrete in both space and time.[2–8] For instance, the capacity-drop phenomenon was analyzed, and the combined effect of the signalized intersections and its nearby bus stops was discussed by using a two-lane CA model by Song and Zhao,[2] and Zhao *et al.*[5,6] Qian *et al.* studied the influences of public transit and the harbor-shaped bus stop on traffic flow by using a one-lane CA traffic model.[9] Tian investigated lane-changing and dwelling behaviors in a two-lane mixed traffic for different proportions of buses over the whole flow.[8] According to Kinematic wave theory,[10] Gu *et al.* developed models and studied vehicle delays and optimization measures when a bus stop was located at a short distance from a signalized intersection.[3,4] These studies lay the foundation for further studying the influence of bus stops. However, there are some limitations.

Firstly, the case in which the bus stop has left-turn lines has not been studied, and the influence of left-turning buses has not been discussed either.[3–8] In fact, left-turning buses have to change lanes to the left-turn lane after they have departed from the stop and before they reach the forbidden lane-changing segment at the downstream intersection. Conflicts between left-turning buses and through or right-turning vehicles may occur if the road length for left-turning buses is short and the flux is large with a long queue. This is the main reason why traffic congestion happens and makes the segment a bottleneck, thereby triggering possible traffic accidents.

Secondly, the occurrence of vehicle accident has not been discussed in these models. All drivers are rational, and the safety distance can be met at all times, which does not conform to the actual road traffic case obviously.[11–16] Especially when a left-turning bus changes lane to the left-turn lane after it has departed from the stop, the through or right-turning vehicles at a relatively high speed might collide with it.[13–15] As a result, a rear-end accident may occur.

Thirdly, the coordinated signal timing scheme between two intersections has not been studied. Although some researches discussed that the capacity can be maximized by adjusting both the stop position and the cycle, the influence of offset between the two intersections has not been involved.

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According to these concerns, we extend the research object to a road between two signalized intersections containing a bus stop with left-turn lines. A three-lane CA model with the detailed lane-changing rules is presented, where vehicle accidents occur when the necessary conditions are satisfied simultaneously. The influences of bus stop position on capacity, accident rate, and delay are discussed and the performances of cycle time and offset between two intersections are analyzed.

2. CA model with vehicle accident

As shown in Fig. 1, a road between two signalized intersections containing a bus stop with left-turn bus lines, is used as the research object. The road is composed of three lanes, named left lane, middle lane, and right lane. The section is divided into five segments denoted as Segments A, B, C, D, and E respectively. Segment A starts from the upstream intersection (stop line of the intersection on the reverse street) where the inflow enters. Segment B is located at the upstream of the stop, where the buses have to change lanes to the right lane in order to enter into the stop. The stop with one lane is located in segment C, where each bus has to spend a certain amount of time on entering in and departing from the stop, and dwelling. Segment D is the part between the stop and the downstream intersection. Sub-segment D1 is the channelized part of the downstream intersection where lane groups are designed, the left lane acts as an exclusive left-turn lane, the middle lane acts as a through lane and the right lane acts as a shared through and right-turn lane. The left-turning buses have to change lanes to the left lane after they have departed from the stop and before they reach D1. Segment E is located at the downstream intersection, which is set for more easy understanding.

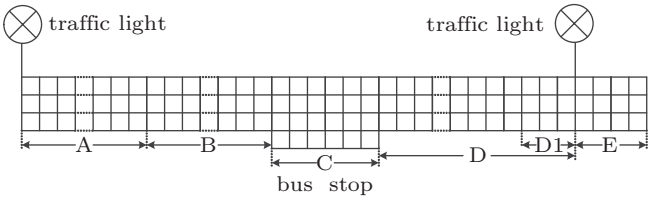


Fig. 1. Studied object.

In order to describe the traffic flow processing of the studied object, we establish an extended three-lane CA model based on a symmetric two-lane Nagel–Schreckenberg (STNS) model with taking into account the occurrences of vehicle accidents. The road is divided into cells. The length of each cell is 1 m for the purpose of simulating the lane-changing behaviors in a more precise way. Each cell may be either empty or occupied by one vehicle with an integer velocity v between zero and the maximal speed limit $v_{\max}$, where we use $v_{\max 1}$ in place of $v_{\max}$ for a car and $v_{\max 2}$ in place of $v_{\max}$ for a bus. $x(i,t)$ and $v(i,t)$ denote the position and velocity of vehicle i at discrete time step t, respectively. The first vehicle is numbered as 1, and the following vehicles as 2, 3, ..., i. Here $d(i,t) = x(i,t) - x(i-1,t) - l$ is the empty cells between vehicle i and its predecessor at time t, with l representing the number of cells occupied by one vehicle where l is 6 for a car and 12 for a bus, $d(i,t)_{\text{front}}$ and $d(i,t)_{\text{back}}$ denoting the empty cells between vehicle i and its predecessor and its successor on its destination lane, respectively. Let d_{safe} denote the safe distance between a vehicle and its preceding one. Considering the complexity of the studied problem, we set d_{safe} to be $v_{\max}$ in normal vehicle driving motion, and to be 1 m if the speed of the predecessor is zero and the vehicle has to queue for waiting. If the leading vehicle in each lane before the downstream intersection is vehicle i and the signal light of its direction is red, the gap will be calculated as $d(i,t) = x_{\text{light}} - x(i,t)$, where x_{light} is the position of the stop line at the downstream intersection.

2.1. Forward rules

At each discrete time step $t \to t+1$, the system is updated by the following rules.

Rule 1 Acceleration, $v(i,t+1) = \min(v(i,t)+1, v_{\max})$, indicating that the driver of vehicle i expects to maintain the maximal speed.

Rule 2 Deceleration, $v(i,t+1) = \min(v(i,t+1), d(i,t) - d_{\text{safe}})$, indicating that the driver decelerates the vehicle so as to maintain a safe distance and avoid crashing with its preceding one.

Rule 3 Randomization, $v(i,t+1) = \max(v(i,t+1) - 1, 0)$ with randomization probability P_1, indicating that the vehicle should be decelerated for uncertain factors.

Rule 4 Motion, $x(i,t+1) = x(i,t) + v(i,t+1)$, indicating that the vehicle should continue to move forward with the updated speed.

2.2. Lane-changing rules

2.2.1. Lane-changing probability

In normal lane-changing rules of a CA mode for a vehicle, the lane-changing probability P is set as a fixed value. But in the study, only partial lane-changing probability with a fixed value is used.[17–19] Here P_{LC} and P_{RC} denote the probabilities for a car changing to its left-side lane and changing to its right-side lane if the lane-changing rules are met, respectively. P_{LB} and P_{RB} denote the probabilities for a bus changing to its left-side lane and changing to its right-side lane if the lane-changing rules are met, respectively.

(i) P_{LC} and P_{RC} in the segments except D1. Here Segment D1 contains L_{D1} cells. P_{LC} for a left-turning car and P_{RC} for a right-turning car in the section except D1 are defined as two linear-increase functions in the process of approaching the downstream intersection, i.e., $P_{\text{LC}} = P_{\text{RC}} = x(i,t)/(x_{\text{light}} - L_{\text{D1}})$, which shows that P_{LC} or P_{RC} increases as the left-turning car or the right-turning car approaches to the stop line. P_{LC} and

P_{RC} for other cars in the segments except D1 are set as a fixed value P_2.

(ii) P_{LB} and P_{RB} in the segments except D1. Segment A contains L_A cells, and P_{RB} in the segment is defined as a linear-increase function, i.e., $P_{RB} = x(i,t)/L_A$. P_{LB} in Segment A is set to be 0. P_{RB} in Segment B is set to be 1 and P_{LB} is 0. P_{LB} for left-turning buses in Segment D except D1 is set to be 1 and P_{RB} is 0. P_{LB} for a right-turning bus in Segment D is 0. P_{LB} and P_{RB} for a through bus in the Segment D except D1 are both set as a fixed value P_2.

(iii) Lane-changing probability in Sub-segment D1. All vehicles are prohibited to change lanes after they have reached sub-segment D1, meaning that P_{LC}, P_{RC}, P_{LB}, and P_{RB} are all 0.

2.2.2. Lane-changing rules

The different lane-changing rules of a vehicle in different segments are as follows.

i) For Segments A and E, $d(i,t) < \min(v(i,t)+1, v_{max})$, indicating that vehicle i cannot travel at the expected speed, $d(i,t)_{front} > d(i,t)$, indicating that the driving condition in the neighboring lane is better than that in its lane, $d(i,t)_{back} > d_{safe}$, indicating that when changing lanes, vehicle i cannot collide with its successor on its destination lane for the safety distance is met.

The vehicle will change lanes with its probability, if the above three conditions are met.

ii) Segment B. A car may change lanes by the lane-changing rules described in Segment A with its probability. For a bus in the left lane or middle lane, when two conditions, $d(i,t)_{front} > v(i,t)$, and $d(i,t)_{back} > d_{safe}$, are satisfied simultaneously, it will change to its right-side lane so that it can enter into the stop. If a bus cannot change to the right lane, it will slow down to find the next opportunity to change to the right lane before reaching Segment C. There will be a scene of relatively small traffic jams.

iii) Segment C. The maximal number of buses in the stop with one-lane is two.

For the waiting bus outside the stop, if stop2 $= 1$, $x(i,t+1) = x(i,t)$, meaning that the waiting bus has to stop in the right lane of Segment B, for the latter part of the stop is occupied by the other bus, where stop2 denotes the latter part of the stop and 1 denotes that the part is occupied by the other bus. If stop2 $= 0$, $x(i,t+1) = x(i,t) + v(i,t+1)$, meaning that the waiting bus changes lanes and enters into the stop, for the latter part of the stop is empty.

For the entering bus, which occupies the latter part of the stop, if stop1 $= 1$, $x(i,t+1) = x(i,t)$, meaning that the bus has to stop at the position for loading and unloading passengers, for the first part of the stop is occupied by the other bus, where stop1 denotes the first part of the stop. If stop1 $= 0$, $x(i,t+1) = x(i,t) + v(i,t+1)$, meaning that the entering bus should continue to move forward and stop in the first part for loading and unloading passengers, for the first part of the stop is empty.

For the bus, which occupies the first part of the stop and is ready to depart from the stop, if $d(i,t)_{front} > v(i,t)$ and $d(i,t)_{back} > d_{safe}$, meaning that a bus departs from the stop and enters into the right lane.

The cars may change lanes by the lane-changing rules described in Segment A with its probability.

iv) Segment D. For a left-turning bus, it will continue to change lanes to the left lane with probability P_{LB} before it reaches Sub-segment D1. Other vehicles may change lanes with their probabilities. All vehicles are prohibited to change lanes after they have reached Sub-segment D1.

2.3. Rules of entering, dwelling and departing from the stop

The maximal velocity of bus in the stop is set to be v_{max22}, and $v_{max22} < v_{max2}$. The rules for a bus to enter into, move forward and depart from the stop are described in Subsection 2.2. It is impossible to overtake for there is only one lane. When a bus stops in the stop, meaning that its speed is zero, its dwelling time T_s is generated randomly, which follows a normal distribution with a mean value of 30 s according to the Transit Co-operative Research Program (TCRP) Report 19(1996).[5,6]

2.4. Signal control rules

The coordinated signal timing schemes with four-phase are used, where T is the cycle time and G is offset between the two intersections. For each intersection, the timing scheme includes through and right-turn phase with green time T_{TR1} and left-turn phase with green time T_{L1} in the east–west direction, through and right-turn phase with green time T_{TR2} and left-turn phase with green time T_{L2} in the north–south direction.

2.5. Criteria rules for a vehicle accident

Considering that the conditions of traffic accidents proposed by Boccara *et al.*,[13] are applied to the continuous traffic flow road, on which a vehicle can move at a high speed and the gap between two vehicles is large, we adjust the first condition $d(i,t) \le v_{max}$ to $d(i,t) \le v(i,t)$ for the reality of urban roads with a low speed and small gap. The other conditions of Boccara *et al.* remain unchanged.[13] The modified conditions are as follows.

1) $d(i,t) \le v(i,t)$, indicating that the empty cells between vehicle i and its predecessor are not larger than current velocity and could reach the position of its predecessor by the next time step.

2) $v(i+1,t) > 0$, indicating that vehicle $i+1$ will move forward at time t.

3) $v(i+1,t+1)=0$, indicating that vehicle $i+1$ will stop abruptly at time $t+1$.

If the three conditions are met, a rear-end accident or a conflict is calculated. Obviously the above three conditions for the occurrences of car accidents hold true under the assumption of neglecting time correlations.[13] Although the future traffic state, i.e., $v(i+1,t+1)$, cannot be known at current time in real traffic, the accident rate in the numerical simulation can be calculated when the simulation is all finished, which means that we have obtained all the sequences of space and time data and know all the states in the simulation period. Here the accident rate is just a numerical parameter in evaluating the influence on traffic safety.

The accident occurrence number $N_{\rm ac}$ is increased by 1 if these necessary conditions are satisfied. The accident probability $P_{\rm ac}$ is defined as $N_{\rm ac}/N$, where N is the total number of vehicles.

2.6. Delay statistics

A statistical approach is proposed to calculate the delays experienced by vehicles, including average control delay and delay incurred by bus interference near the stop. Specifically, it is assumed that the cars would travel through the road with maximal speed $v_{\max}$ in the absence of a control facility of the intersection. At each time step, vehicles move forward a length of current speed v, thus we calculate the difference between speed v and $v_{\max}$ at each time step for each vehicle on the road in the stimulation period TT. The delay D is defined as

$$\frac{1}{N}\sum_{t=1}^{TT}\sum_{i=1}^{N}(v_{\max}-v(i,t))/v_{\max}.$$

2.7. Boundary conditions

The boundary conditions are open.

2.7.1. Inflow boundary condition

The vehicles generated randomly on the stop lines of the upstream intersection pass through the intersection according to the signal control rules, where partial vehicles reach Segment A and become the real inflow of the studied object. In order to simplify the studied problem, the signalized intersections are not included into the studied object. But we use some relatively simple rules to map the relation between the signal control rules of the upstream intersection and the inletting flow. In each green-light period, the total entering probability is distributed to each lane of the subject street segment. $P_{\rm e}$ denotes the entering probability for each inletting lane of the upstream intersection. Values of 20 percent for right turns and 20 percent for left turns are assumed to be a percentage of the total approaching traffic in each cycle time T in this model. Let t_1, t_2, t_3, t_4, and t_5 denote the travel times of vehicles on the eastbound through lane, eastbound through and right-turn lane, westbound left-turn lane, northbound through and right-turn lane, southbound left-turn lane from their stop lines of the upstream intersection to Segment A if the signal lights of their directions are green, respectively. Obviously the inflow in Segment A that does not possess the characteristics of continuous traffic flow consists of the vehicles from the five lanes after t_i time delayed and corresponding to signal lights.

(I) Vehicle generation. In each step, when the update of vehicles on the roadway is finished, a random number $\text{rand}_{1i}()$ for each of the five lanes before the stop line of the upstream intersection is generated. If $\text{rand}_{1i}() < P_{\rm e}$, order $l_{1i}(t+1)=l_{1i}(t)+1$, meaning the number of vehicles in lane i plus one, where $l_{1i}(t)$ denotes the number of queuing vehicles in lane i.

(II) Traffic flow generation ahead of Segment A. The vehicles approaching Segment A are divided into three parts, corresponding to three lanes on the studied road. Here $l_{2j}(t)$ $(j=1,2,3)$ denotes the number of vehicles in the queue ahead of lane j, where $j=1$ for the left lane, $j=2$ for the middle lane, and $j=3$ for the right lane.

Case 1 For $k\times T =< t < k\times T+T_{\rm TR1}$ at step t, indicating that the signal lights of the west-east direction are green during the k-th signal cycle.

1) If $l_{11}(t)>0$, $l_{22}(t+t_1)=l_{22}(t+t_1-1)+1$ and $l_{11}(t+1)=l_{11}(t)-1$, indicating that the first vehicle in the eastbound through lane is added to the queue ahead of middle lane (lane 2) after t_1 step.

2) If $l_{12}(t)>0$, $l_{12}(t+1)=l_{12}(t)-1$, and if $\text{rand}_{22}() > P_{\rm RT}$, $l_{23}(t+t_2)=l_{23}(t+t_2-1)+1$, indicating that the first vehicle in the eastbound through and right-turn lane is removed. If it is a through vehicle, we have the number of vehicles in the queue ahead of lane 3 plus 1 after t_2 step. $P_{\rm RT}$ denotes the right-turn probability for a vehicle in this lane.

Case 2 For $k\times T+T_{\rm TR1} =< t < k\times T+T_{\rm TR1}+T_{\rm L1}$ at step t, if $l_{13}(t)>0$, $l_{13}(t+1)=l_{13}(t)-1$, and if $\text{rand}_{23}() < P_{\rm LU}$, $l_{21}(t+t_3)=l_{21}(t+t_3-1)+1$, indicating that the first vehicle in the westbound left-turn lane is removed. If it is a U-turn vehicle, we have the number of vehicles in the queue ahead of lane 1 plus 1 after t_3 step. $P_{\rm LU}$ denotes the U-turn probability for a vehicle in this lane.

Case 3 For $k\times T+T_{\rm TR1}+T_{\rm L1} =< t < k\times T+T_{\rm TR1}+T_{\rm L1}+T_{\rm TR2}$ at step t, if $l_{14}(t)>0$, $l_{14}(t+1)=l_{14}(t)-1$, and if $\text{rand}_{24}() < P_{\rm RT}$, $l_{23}(t+t_4)=l_{23}(t+t_4-1)+1$, indicating that the first vehicle in the northbound through and right-turn lane is removed. If it is a right-turning vehicle, we have the number of vehicles in the queue ahead of lane 3 plus 1 after t_4 step.

Case 4 For $k\times T_s+T_{\rm TR1}+T_{\rm L1}+T_{\rm TR2} =< t < k\times T+T_{\rm TR1}+T_{\rm L1}+T_{\rm TR2}+T_{\rm L2}=(k+1)\times T$ at step t, if $l_{15}(t)>0$, $l_{15}(t+1)=l_{15}(t)-1$, and If $\text{rand}_{25}() > P_{\rm LU}$, $l_{21}(t+t_5)=$

$l_{21}(t+t_5-1)+1$, indicating that the first vehicle in the southbound left-turn lane is removed. If it is a left-turning vehicle, we have the number of vehicles in the queue ahead of lane 1 plus 1 after t_5 step.

(III) Inflow generation. In each step, when the update of vehicles on the roadway is finished, the positions x_{last} of the last vehicles in lane j ($j = 1, 2, 3$) in Segment A are checked. If $x_{\text{last}} > v_{\max}$ and $l_{2j}(t) > 0$, a vehicle with velocity $v_{\max}$ enters at the cell $\min\{v_{\max}, x_{\text{last}} - v_{\max}\}$. If $\text{rand}_3() < P_{\text{bus}}$, the entering vehicle is a bus, otherwise it is a car. If $x_{\text{last}} < v_{\max}$ and $l_{2j}(t) > 0$, a vehicle would not be generated for the basic entering condition cannot be satisfied.

2.7.2. Outflow boundary condition

At each time step, the leading vehicle in each lane of the downstream intersection is removed, if its position $x_{\text{first}} > L_{\text{R}}$. Here L_{R} denotes the length of the road. Then its following vehicle becomes the new leader.

3. Simulation results and discussion

3.1. Simulation condition and signal timing scheme

The road described in Section 2 is simulated, where the total length L_{R} is 1200 m meaning that there are 1200 cells and the downstream intersection is located at the 1000th cell. Section C contains $L_{\text{C}} = 50$ cells, section D1 contains $L_{\text{D1}} = 30$ cells, and section E contains $L_{\text{E}} = 200$ cells. L denotes the distance between the stop and the downstream intersection. The ratio of the left-turning car is 0.2. Four bus lines are set. Other parameters are set as follows: $v_{\max 1} = 14$, $v_{\max 2} = 11$, $v_{\max 22} = 5$, $P_1 = P_2 = 0.3$, $P_{\text{LC}} = P_{\text{RC}} = x(i,t)/(1000 - L_{\text{D1}})$, $t_1 = t_2 = 5$ s, $t_3 = 3$ s, $t_4 = 4$ s, $t_5 = 6$ s. $P_{\text{LT}} = P_{\text{RT}} = 0.2$, and $P_{\text{LU}} = 0.01$. Bus arrival follows a Poisson distribution and the average arrival rate is 1/60. Each time step corresponds to 1 s. The first 10^4 time steps are eliminated to avoid transient behaviors. The flow is averaged by 2×10^4 time steps. The final result is an average of 10 simulation results in order to reduce stochastic influence.

The coordinated signal timing schemes with four phases are used. The control parameters of the two intersections are set to be the same, for there is no difference in basic condition between the intersections. At the same time, we adopt different timing strategies by the traffic states in order to obtain the optimal control parameters. The fixed timing control is used for saturated flow, and actuated signal control is used for unsaturated flow.[20] Then the concrete control method and parameters are optimized for each simulation experiment. For example, three methods including the most famous and typical TRRL (Webster) model and its two improved methods, namely the Australian Road Research Bureau (ARRB) model and the stop-line method, are used to calculate the parameters of each signal timing scheme when the traffic state is saturated flow.[18–20] By comparing the simulation results of signal timing schemes, the method and its parameter values are determined. Table 1 shows the calculated parameter values and their simulated results of a case, where inflow volume is 1150 veh/h, $L = 200$ m, the ratio of left-turning bus lines is 50%, and offset is 60s. Obviously the control effect using the ARRB model is best. The optimal control parameters by the ARRB model are applied to the case.

Table 1. Comparison among three timing methods.

	Cycle time/s	$T_{\text{TR1}} - T_{\text{L1}} - T_{\text{TR2}} - T_{\text{L2}}$/s	Flux/veh·h^{-1}	D/s·veh^{-1}
ARRB	130	36-25-36-25	1115	75
TRRL	120	34-22-34-22	1075	86
Stop-line method	124	34-24-34-24	1090	78

3.2. Influence of left-turning bus line

Figure 2 shows the comparison of the flux, P_{ac} and D of simulation results between case 1 without left-turn bus line (shown in Fig. 2(a)) and case 2 with a 50% ratio of left-turn bus lines (shown in Fig. 2(b)), where the values of L are 50 m, 75 m, 100 m, and 150 m, respectively. The achieved findings are as follows.

I) The traffic volume increases with the inflow increasing until it reaches a saturated value. There is a critical point of the inflow above which the traffic on the studied road transforms from free flow to saturated flow. The saturated flow describes the capacity of the road. At the same time, the accident probability P_{ac} decreases slightly before the inflow reaches the saturated flow and then increases markedly after the saturated flow. There is no difference in D before the saturated flow and then increases markedly after the saturated flow. This is because there are fewer vehicles on the road when the state is free flow. P_{ac} and D are very low and there is no great difference. When a jamming state occurs, the disorder phenomenon becomes more and more serious with the increase of inflow. Then P_{ac} and D increases markedly.

II) The influences of L are different. The smaller the value of L, the greater the influence is, if the bus stop is located close to the downstream intersection. The results are again proved

that inappropriate bus stops have a negative effect on traffic flow.[5,6]

III) The negative effect with 2 left-turn bus lines is more serious than that without a left-turn line when the inflow exceeds the saturated flow, L is a small value, i.e., 100 m, and the other conditions are the same. The road capacity with 50% left-turn lines is obviously lower than that without a left-turning bus line. Moreover P_{ac} and D with 50% left-turn bus lines increase more markedly and their values are larger than those without a left-turn bus line if the entering flow exceeds the saturated flow. These more clearly show the great influence of left-turning buses on traffic flow. If a bus stop with left-turn lines is set close to a downstream intersection, the left-turning buses have some difficulties in changing lanes to the left-turn lane after departing from the stop and before reaching Segment D1. The conflicts between the left-turning buses and the through or right-turning vehicles may occur. That explains the drop in capacity and the fact that the increase in P_{ac} and D with left-turn bus lines are much greater than those without a left-turn line.

In order to fully understand these negative effects of left-turn buses, figure 3 shows the time–space evolution diagrams on the three lanes and the bus stop for case 3 without left-turn line (shown in Fig. 3(a)) and case 4 with 2 left-turn lines (shown in Fig. 3(b)). Here $L = 100$ m and the inflow is 1150 veh/h. The negative effect can be observed when the buses enter into the stop. If a bus fails to change to the right lane or enter into the stop after reaching Segment C shown in Figs. 3(a2) and 3(a4), it has to stop to wait. Then a queue behind it, marked with a blue point, will appear, which results in a negative influence on both safety and delay. However, the negative effects become more serious as shown in Figs. 3(b2), 3(b3), and 3(b4) when a left-turning bus departs from the stop and changes to the left-turn lane before it reaches Segment D1 if L is a small value. In Fig. 3(b), the queue phenomena appear before the stop line. There are limited spaces for a left-turning bus. Some buses have to stop to change lane, thereby incurring queues behind them. Under extreme circumstances shown in Figs. 3(b2), 3(b3), and 3(b4) with time steps from 1.06×10^4 to 1.07×10^4 around position 970, the middle lane and right lane are blocked by the waiting left-turning buses and cars have to spend several cycles on passing the intersection.

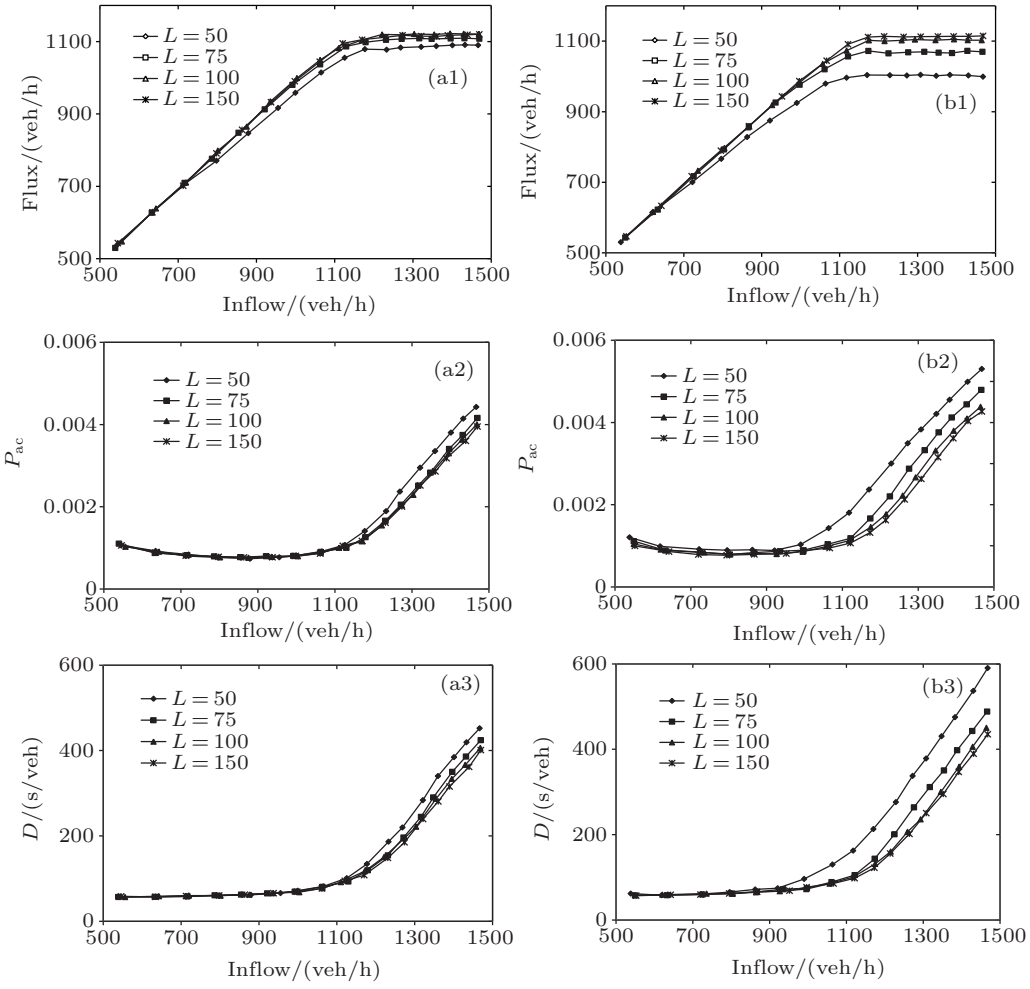


Fig. 2. Relationships between the flux and inflow, P_{ac} and inflow, D and inflow for different values of L. Panel (a) denotes case 1 without left-turn bus line and panel (b) refers to case 2 with 50% ratio of left-turn bus lines (2 left-turn bus lines).

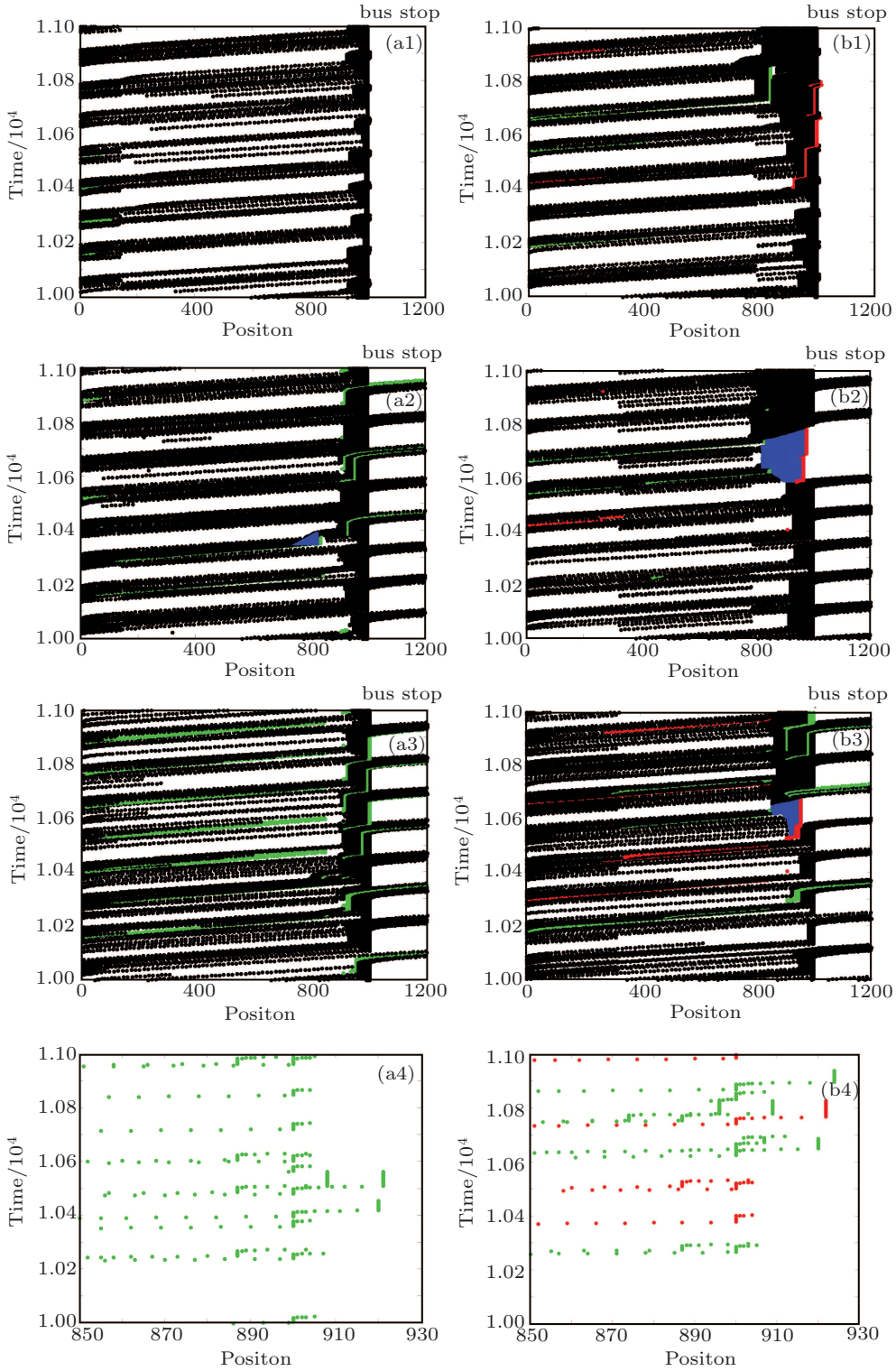


Fig. 3. (color online) Time-space plots. Black points denote cars, green and red points represent buses among which the red one refers to the left-turning bus. Blue points denote the queuing vehicles incurred by waiting buses. $L = 100$. Panels (a1) and (b1) refer to the left lane, (a2) and (b2) the middle lane, (a3) and (b3) the right lane, and (a4) and (b4) the time-space plot of the bus stop.

3.3. Influence of bus stop position

The relations between the capacity and L, P_{ac}, and L with the different ratios of left-turning bus lines are shown in Figs. 4 and 5, respectively. It is clear that as L increases, the capacity first grows until it approaches to a maximum Q_{cmax} at a smaller critical value L_{BC1}. At the same time, P_{ac} first drops until it approaches to a minimum P_{acmin}. Then they maintain their values with mediate value L_{BC}. Finally the capacity drops and P_{ac} grows when L reaches a larger critical value L_{BC2}. The results prove again that the bottleneck effects exist only when the distance between the stop and the intersection is small. The negative effect at a near-side stop is more severe than that in

a far-side one when left-turn bus lines exist. The critical values for different types of stops are different. With the increase of left-turn bus lines, L_{BC1} becomes large and L_{BC2} becomes small. The range of appropriate position for bus stop without bottleneck effect becomes smaller and smaller with the increase of the ratio of left-turn bus lines.

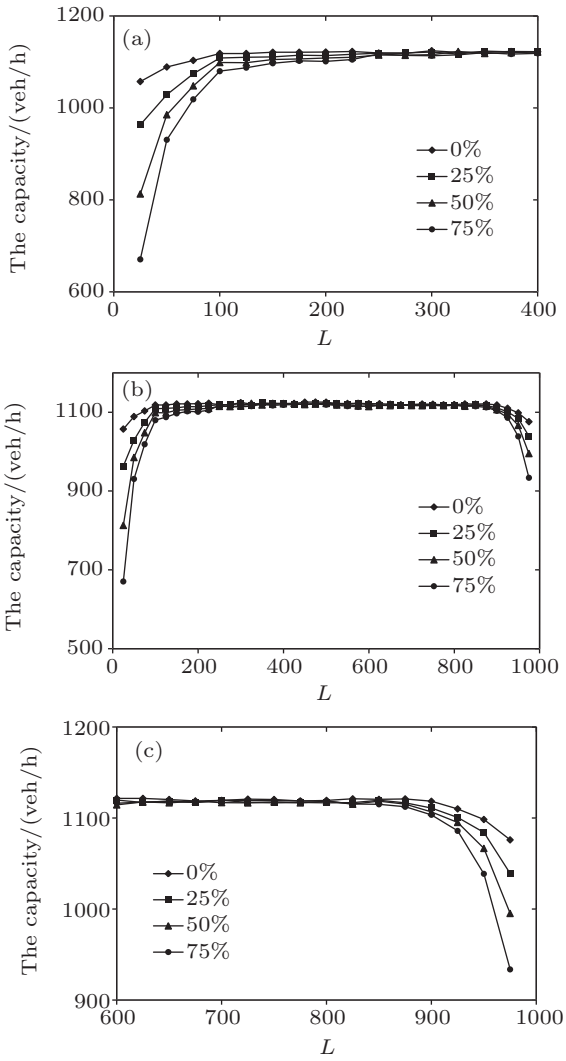


Fig. 4. Relationships between the capacity and L for different ratios of left-turn bus lines with values of L being in the ranges $[0,400]$ (a), $[0,1000]$ (b), and $[600,1000]$ (c).

Figure 6 shows the phase diagrams in (inflow, L) space, including the case without left-turn bus line and the case with 2 left-turn bus lines. For each case, the space can be categorized into three regions. The system is in free flow state in region I, for the inflow in this region is smaller than the capacity of the road. Although the traffic flow is in a saturated state in both regions II and III, the capacity in region II is smaller than that in region III due to the negative effect caused by a bus stop located in the vicinity of signalized intersections.

At the same time, the area of region II with no left-turn bus line is smaller than that with 2 left-turn bus lines. The area of region III with no left-turn bus line is larger than that with 2 left-turn bus lines. This is because the negative effects caused by left-turning buses are more serious if the stop is close to the intersection. With the increase of the left-turn bus lines, L_{BC1} becomes large and L_{BC2} becomes small. The range of mediate value L_{BC} without a bottleneck effect becomes smaller. So the area of region III becomes smaller. Moreover the expanded area of region II in the left of Fig. 6 is more than that in the right. It indicates that the negative effect caused by a left-turning bus in a near-side stop is more serious when in saturate

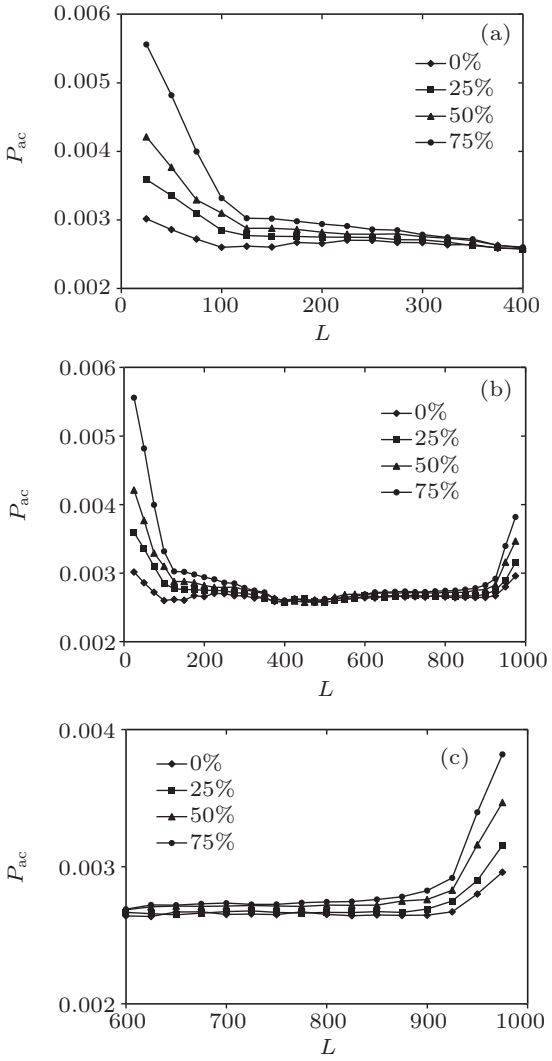


Fig. 5. Relationships between P_{ac} and L for different ratios of left-turn bus lines with the values of L being in the ranges $[0,400]$ (a), $[0,1000]$ (b), and $[600,1000]$ (c).

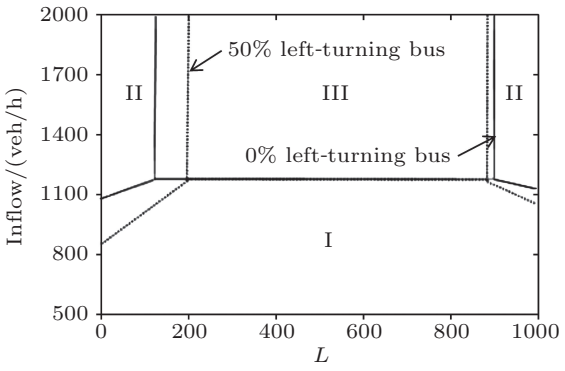


Fig. 6. Phase diagram in (inflow, L) space.

state. If the stop is located close to the upstream intersection, the left-turning buses have a longer distance to change lanes to the left-turn lane. The negative effect is small relatively.

Thus, for a bus stop that contains left-turn lines, a far-side stop is preferred to a near-side one, and a near-side stop should keep a longer distance from the downstream intersection to ease the negative effect caused by the left-turning bus in its lane-changing process.

3.4. Influence of signal control

Figure 7 shows the relationships between the flux and inflow, P_{ac} and inflow, D and inflow for different values of signal cycle T, where there are 2 left-turn bus lines and the stop is located at 100 m in case a, 200 m in case b from the downstream intersection. The achieved findings are as follows.

F1 The flux increases with the inflow increasing until it reaches a saturated value in Figs. 7(a1) and 7(b1). The capacity grows with the increase of T. It means a longer cycle corresponding to a higher capacity in a certain range. The capacities for different values of T in Fig. 7(a1) are all smaller than their counterparts in Fig. 7(b1) due to the more serious negative effect of small L.

F2 Before the inflow reaches the saturation flow, P_{ac} (Figs. 7(a2) and 7(b2)) and D (Figs. 7(a3) and 7(b3)) are very small, where P_{ac} keeps a slow decline and D keeps a slow increase with the increase of inflow if the signal cycle is relatively short, i.e., $T = 80$, 100, and 120 s. But P_{ac} is large and keeps a fast decline with the inflow increasing if T is relatively long, i.e., $T = 160$ and 200 s. In general, P_{ac} in the case with a longer cycle time is larger than that in the case with a shorter cycle time when in free flow state. However, when the inflow reaches the capacity, P_{ac} and D in the case with a shorter cycle time increase more dramatically with the increase of inflow, while in the case with a longer cycle time, P_{ac} and D rise much more slowly. It means that a longer cycle time corresponds to a lower accident rate and delay when in a saturated state.

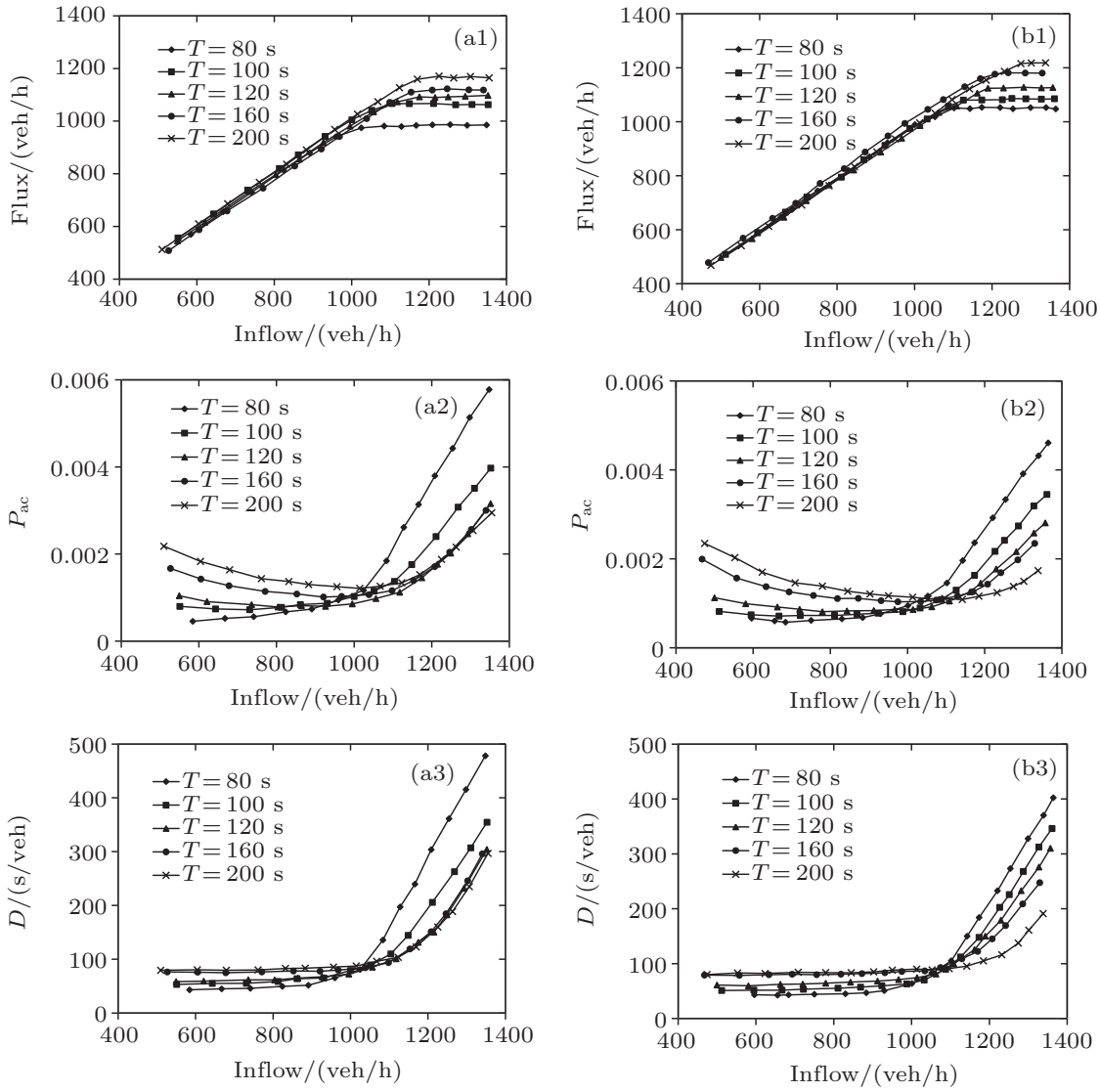


Fig. 7. Relationships between the flux and inflow, P_{ac} and inflow, D and inflow for different signal cycles. (a1)–(a3): $L = 100$ m, (b1)–(b3): $L = 200$ m.

F3 If the inflow exceeds road capacity and the signal cycle is short, P_{ac} and D increase faster when $L = 100$ m than when $L = 200$ m. This is because only a small fraction of vehicles can pass Segment D within one cycle and a large number of vehicles have to queue at the downstream intersection. The probability of interference with the queuing vehicles for the left-turning buses when $L = 100$ m is larger than when $L = 200$ m. That explains the increases in P_{ac} and D when $L = 100$ m are much greater than when $L = 200$ m.

F4 Obviously, signal cycle has significant influences on capacity, P_{ac} and D. When the inflow is small, a short signal cycle would be helpful in reducing both accident rate and delay. When the inflow reaches or exceeds the capacity, a longer signal cycle is helpful in enhancing capacity, reducing accident rate and delay. But if the stop position is inappropriate, i.e., $L = 100$ m, the increase of cycle fails to reduce the negative effect of left-turning buses.

Figure 8 shows the flux with respect to the inflow and offset between the two intersections (Figs. 8(a1) and 8(b1)), P_{ac} with respect to the inflow and offset between the two intersections (Figs. 8(a2) and 8(b2)), and D with respect to the inflow and offset between the two intersections (Figs. 8(a3) and 8(b3)), where the ratio of left-turn bus lines is 50% and $L = 100$ m in case a and 200 m in case b. The offset in the simulation is set as a series of values with an interval of 10 s. The achieved findings are as follows.

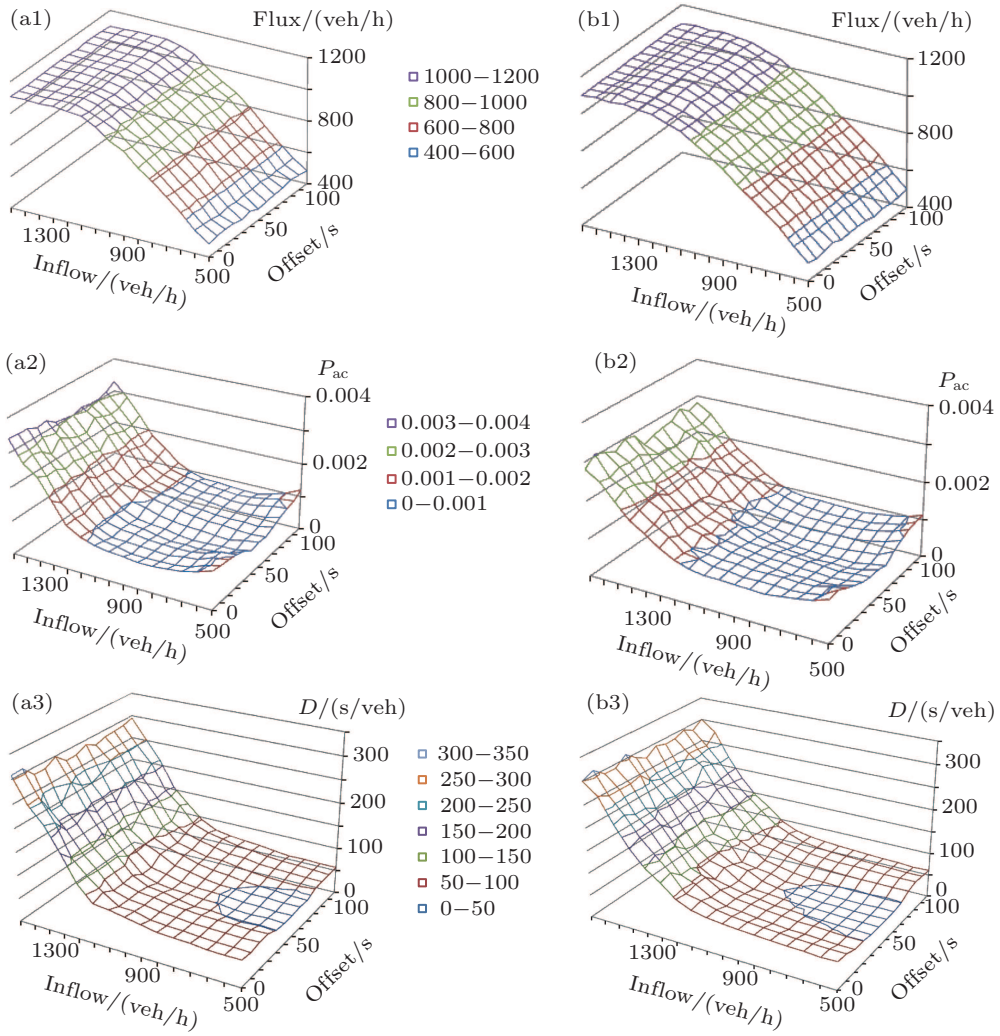


Fig. 8. (color online) Influences of offset between the two intersections. (a1)–(a3): $L = 100$ m, (b1–b3): $L = 200$ m.

FF1 Although the capacity when $L = 100$ m is smaller than when $L = 200$ m (Figs. 8(a1) and 8(b1)) due to the negative effect of the short distance between the stop and the intersection, there are little differences in the flux among the different offsets if L is a fixed value and the inflow condition is the same.

FF2 A reasonable offset is helpful in reducing accident rate and delay when the inflow has not reached a saturated value from the presented curves in Figs. 8(a2) and 8(b2), 8(a3), and 8(b3)). The effect is not obvious when in the saturated state, for there is no regularity about the parts of the curves. This is because many vehicles have to interweave with left-turning buses and spend more than one cycle on passing through the downstream intersection when the inflow exceeds

a saturated volume. It is difficult to play the advantages of green wave control and the effectiveness of offset is weakened.

FF3 Comparing Fig. 8(a2) with Fig. 8(b2), and Fig. 8(a3) with Fig. 8(b3), we can find that the weakened degree of effectiveness for offset when $L = 100$ m is more serious than when $L = 200$ m. This is because the conflicts between the left-turning buses and the through or right-turning vehicles and the disorder phenomenon when $L = 100$ m are more serious than when $L = 200$ m. The vehicles have to spend more time on passing through the downstream intersection. So the probability of vehicle accident and the delay with a small L are larger than with a large one.

4. Conclusions and perspectives

The influences of bus stop with left-turn lines between two adjacent signalized intersections on capacity, accident rate and delay are studied by using a three-lane CA model. The results of the simulations suggest that the left-turning buses in a near-side stop have more negative effects. The range of appropriate position for bus stop with no bottleneck effect becomes smaller and smaller with the left-turn bus lines increasing. When the inflow reaches or exceeds the capacity, a longer signal cycle is helpful. But if the stop position is inappropriate, the increase of cycle fails to reduce the negative effect of a left-turning bus and the effectiveness of offset is weakened. These findings may provide some reference values for setting bus stop and traffic management.

Some relatively simple rules are used to map the relation between the signal control rules of the upstream intersection and the inletting flow. The inflows from different directions are set to be the same. Vehicle accident does not really occur in the simulation and these dangerous situations are only calculated and considered to be the signals of accidents occurring. Future work will concentrate on these problems.

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