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Combined bottleneck effect of on-ramp and bus stop in a cellular automaton model*

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The combined bottleneck effect is investigated by modeling traffic systems with an on-ramp and a nearby bus stop in a two-lane cellular automaton model. Two cases, i.e. the bus stop locates in the downstream section of the on-ramp and the bus stop locates in the upstream section of the on-ramp, are considered separately. The upstream flux and downstream flux of the main road, as well as the on-ramp flux are analysed in detail, with respect to the entering probabilities and the distance between the on-ramp and the bus stop. It is found that the combination of the two bottlenecks causes the capacity to drop off, because the vehicles entering the main road from the on-ramp would interweave with the stopping (pulling-out) buses in the downstream (upstream) case. The traffic conflict in the former case is much heavier than that in the latter, causing the downstream main road to be utilized inefficiently. This suggests that the bus stop should be set in the upstream section of the on-ramp to enhance the capacity. The fluxes both on the main road and on the on-ramp vary with the distance between the two bottlenecks in both cases. However, the effects of distance disappear gradually at large distances. These findings might give some guidance to traffic optimization and management.

Keywords: cellular automaton model, combined bottleneck, bus stop, on-ramp

PACC: 0550, 0520, 0570F

1. Introduction

In the past few decades, a number of traffic dynamic models, including the car-following model, gas-kinetic model, continuum model, and cellular automaton (CA) model, have been developed to understand traffic nature and investigate various traffic issues.[1−8] One of the most important issues in traffic research is the traffic bottleneck, e.g. intersection, on-ramp, off-ramp, bus stop, speed limitation zone, etc., which cause congestion, capacity drop, and many other complex phenomena. Kerner *et al*[9] empirically investigated the bottleneck effect of the on-ramp, and found different traffic patterns. Using the CA model, Jiang and Jia simulated the interaction between main road and ramp.[10−13] Brockfeld *et al*[14] coupled the NaSch model[15] with BML model[16] to simulate a traffic light controlled cross intersection. Li *et al*[17] simulated an uncontrolled T-shape intersection in a CA model. Huang *et al*[18] investigated the influence of tollbooth on highway traffic. Furthermore, the problem of combined bottlenecks, i.e. several neighbouring bottlenecks coexist on a road, is also attractive to some researchers. Zhao *et al*[19,20] studied the capacity drop-off caused by the combined effect of the intersection and its nearby bus stop. They found that the capacity could be maximized by adjusting the traffic light cycle, the location of the bus stop and adding a special stop lane for bus stopping.

Inspired by the previous works of Zhao, Jia and Jiang,[10,11,19] we consider the combined bottleneck effect between an on-ramp and its nearby bus stop in the present study. The traffic system composed of a main road, an on-ramp, and a bus stop is modeled to find solutions to the following questions: how the interaction between the two different bottlenecks influences the traffic characteristics? where the bus stop should be set to optimize the capacity, in the downstream section or in the upstream section of the on-ramp? how the capacity varies with the distance between the bus stop and the on-ramp? The paper is organized as follows: the model is presented in Section 2. Simulation results are analysed in Section 3. Finally, we draw some conclusions from the present study in Section 4.

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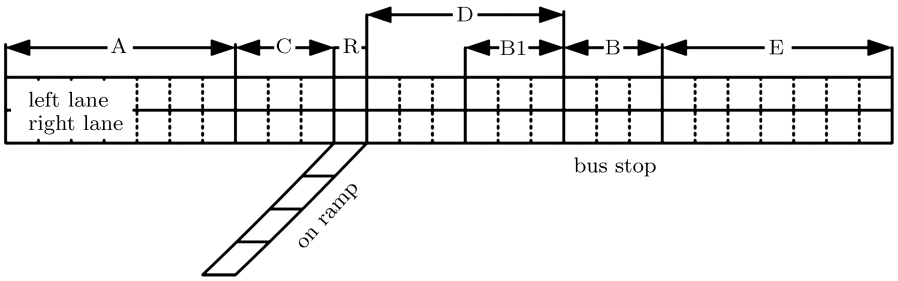
2. Models

Lanes are divided into cells with the same lengths. There are two lanes on the main road and one lane on the on-ramp. As illustrated in Fig.1, the main road is partitioned into several sections. Sections A and E are the beginning part and the ending part of the main road, respectively. Section B on the right lane is the bus stop. The upstream section of the bus stop is denoted by B1. Section R including only one cell (also called the cell R) connects the main road and the on-ramp, with its upstream section denoted by C. In addition, the road between the bus stop and the on-ramp is section D. Two cases are considered,

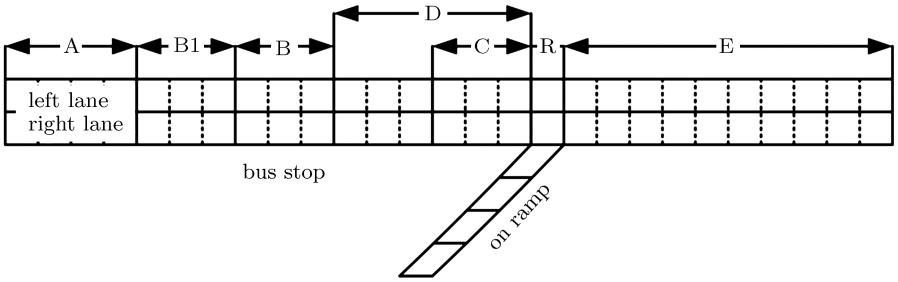
(i) Case a (Fig.1(a)). The bus stop locates in the downstream section of the on-ramp.

(ii) Case b (Fig.1(b)). The bus stop locates in the upstream section of the on-ramp.

Assume that there are two types of vehicles in the system, i.e. buses with two-cell length and cars with one-cell length. The mixture probability of buses is $P_{\rm mix}$. Buses will stop at the bus stop with probability $P_{\rm s}$ and stay for $T_{\rm s}$ time steps. For simplicity, buses run only on the main road. The updating rules of vehicle motion include lane changing and forward motion.



(a) Case a, the bus stop locates in the downstream section of the on-ramp.



(b) Case b, the bus stop locates in the upstream section of the on-ramp.

Fig.1. Configurations of the road system.

2.1. Lane changing rules

For a vehicle that is running neither in section B nor in section B1, it will change to the other (neighbouring) lane, if the following condition is satisfied,

$$d_n < \min\{v_n + 1, v_{\max}\} \quad \text{and} \quad d_{n,\text{other}} > d_n \quad \text{and} \quad d_{n,\text{back}} > v_{\text{other,back}}, \tag{1}$$

where v_n is the velocity of the n-th vehicle, $v_{\max}$ is the maximum velocity, d_n ($d_{n,\text{other}}$) is the gap between the n-th vehicle and its preceding one on the current (the other) lane, $d_{n,\text{back}}$ is the gap between the n-th vehicle and its corresponding rear vehicle on the other lane with velocity $v_{\text{other,back}}$. Condition (1) means that a vehicle will change to the other lane, when the gap on the current lane does not allow it to be accelerated, the gap on the other lane is larger, and it is safe to change the lane without collision.

In section B1, stopping buses are willing to run on the right lane in order to conveniently approach the bus stop. Thus, a stopping bus on the left lane will change to the right lane, if the following condition is satisfied,

$$[d_{n,\text{other}} \geq v_{\max} \quad \text{or} \quad (d_{n,\text{other}} \geq 0 \text{ and}$$

$$d_n - d_{n,\text{other}} \leq 2)]\text{and} \quad d_{n,\text{back}} > v_{\text{other,back}}, \quad (2)$$

which implies that the gap on the other lane is sufficient to drive at the maximum speed, or the situation on the current lane is not much better than on the other lanes, meanwhile the safety condition is fulfilled. In section B, if a stopping bus is still on the left lane, it will change to the right lane under the following condition,

$$d_{n,\text{other}} \geq 0 \quad \text{and} \quad d_{n,\text{back}} > v_{\text{other,back}}. \quad (3)$$

A stopping bus will stop and wait for changing the lane until condition (3) is satisfied, when it reaches the last cell of section B but is still on the left lane. Stopping buses on the right lane are forbidden to change the lane in sections B1 and B.

Cars and non-stopping buses in sections B1 and B will change the lane under condition (1) if there is no stopping bus in frontage. Otherwise, cars and non-stopping buses on the right lane will change to the left one under condition (3). If they cannot change to the left lane until they have reached the last cell of section B1, they will stop and wait for condition (3) to be satisfied. For cars and non-stopping buses on the left lane, lane changing is prohibited.

2.2. Forward motions

The NaSch model[15] is used to describe vehicle forward motions. Each cell is empty, or occupied by a car (or half of a bus), with an integral velocity from zero to $v_{\max}$, where $v_{\max}$ is also denoted as v_{mb} (for buses) or v_{mc} (for cars). From time t to $t+1$, the updating procedure is carried out as follows: (i) acceleration, $v_n = \min\{v_n + 1, v_{\max}\}$; (ii) deceleration, $v_n = \min\{v_n, d_n\}$; (iii) randomization, $v_n = \max\{v_n - 1, 0\}$ with probability p; (iv) motion, $x_n = x_n + v_n$. Particularly, bus approaching the bus stop is controlled by NaSch rules with $d_n = X_{\text{B}} - x_n$, where X_{B} is the location of the last cell on section B.

2.3. Behaviours at the on-ramp

The method proposed by Jiang *et al*[10,11] is used here. On the right lane of the main road, let Lead1 denote the leading vehicle in the upstream section of the cell R, and Last denote the last downstream vehicle. The leading vehicle on the on-ramp is denoted by Lead2. x_{Lead1}, x_{Lead2}, and x_{Last} are the corresponding positions in front of vehicle. $x_{\text{Last}} \to x_{\text{Last}} - 1$ if the last is a bus. The time t_1 for Lead1 and t_2 for Lead2 to reach X_{R} (location of the cell R) are computed from

$$t_1 = \frac{X_{\text{R}} - x_{\text{Lead1}}}{\min\{v_{\max}, x_{\text{Last}} - x_{\text{Lead1}} - 1, v_{\text{Lead1}} + 1\}},$$
$$t_2 = \frac{X_{\text{R}} - x_{\text{Lead2}}}{\min\{v_{\max}, x_{\text{Last}} - x_{\text{Lead2}} - 1, v_{\text{Lead2}} + 1\}}. \quad (4)$$

Lead1 and Lead2 may interfere with each other when $t_2 \leq 1$. If $t_1 < t_2$, Lead1 will move at velocity $\min\{v_{\max}, x_{\text{Last}} - x_{\text{Lead1}} - 1, v_{\text{Lead1}} + 1\}$ without being influenced, while Lead2 will slow down at velocity $X_{\text{R}} - x_{\text{Lead2}} - 1$. If $t_1 > t_2$, Lead2 will enter into the main road at velocity $\min\{v_{\max}, x_{\text{Last}} - x_{\text{Lead2}} - 1, v_{\text{Lead2}} + 1\}$, meanwhile Lead1 will move under the NaSch rules, regarding Lead2 as its preceding vehicle. If $t_1 = t_2$, the vehicle closer to the cell R takes the priority to pass. If $t_1 = t_2$, and $x_{\text{Lead1}} = x_{\text{Lead2}}$, the priority is given to Lead1.

2.4. Boundary conditions

The following simulations are carried out under open boundary conditions.

At the exit boundary: The leading vehicle will be removed if the position of the leading vehicle x_{Lead} on the main road exceeds L (the length of the main road), and its follower becomes the new leading vehicle.

At the entrance boundary: A vehicle will enter the lane with probability P_{em} if the position of the last vehicle $x_{\text{Last}} > v_{\text{mc}}$. The new vehicle will be a bus with probability P_{mix}. If the new vehicle is a bus, it will enter into the cell $\min\{v_{\text{mb}}, x_{\text{Last}} - v_{\text{mb}}\}$ with velocity v_{mb}, and be set as a stopping bus with probability P_{s}. Otherwise it will enter into the cell $\min\{v_{\text{mc}}, x_{\text{Last}} - v_{\text{mc}}\}$ with velocity v_{mc}. Similarly, cars enter into the on-ramp with probability P_{er}.

3. Simulation results and discussion

Each cell 7.5-m long, and each time step is 1 s. $L = 500$, $X_{\text{R}} = 250$, $v_{\text{mb}} = 2$, $v_{\text{mc}} = 3$, $p = 0.3$, $P_{\text{mix}} = 0.05$. Let $P_{\text{s}} = 1$, which means all buses are going to stop. $T_{\text{s}} = 30$. The lengths of section B, B1, C, and D are L_{B}, L_{B1}, L_{C}, and L_{D}. $L_{\text{B}} = 6$. In Case a, $X_{\text{B}} = X_{\text{R}} + L_{\text{D}} + L_{\text{B}}$, $L_{\text{C}} = 8$, and $L_{\text{B1}} = \min\{L_{\text{D}}, 8\}$. In Case b, $X_{\text{B}} = X_{\text{R}} - L_{\text{D}} - 1$, $L_{\text{C}} = \min\{L_{\text{D}}, 8\}$, and $L_{\text{B1}} = 8$. L_{D} is fixed to be 10 at first. The total evolution time is 150000, and data in the last 100000 time steps are collected to calculate the average flux.

Virtual detectors are placed on sections A and E, and on the on-ramp for counting the flux. $Q_{\rm u}$ ($Q_{\rm d}$) is the upstream (downstream) flux on the main road. $Q_{\rm r}$ is the on-ramp flux.

The relationships between the flux and entering probabilities are shown in Fig.2. $Q_{\rm u}$ increases with $P_{\rm em}$ and then reaches its saturation (i.e. the capacity) in both cases. $Q_{\rm u}$ does not vary with $P_{\rm er}$, which implies that the on-ramp has little impact on the upstream traffic flow of the main road. $Q_{\rm r}$ increases with $P_{\rm er}$ until it reaches the capacity. The capacity of $Q_{\rm r}$ drops off with $P_{\rm em}$ and then keeps a constant, because vehicles cannot run into the main road from the on-ramp conveniently when the main road becomes congested at large $P_{\rm em}$.

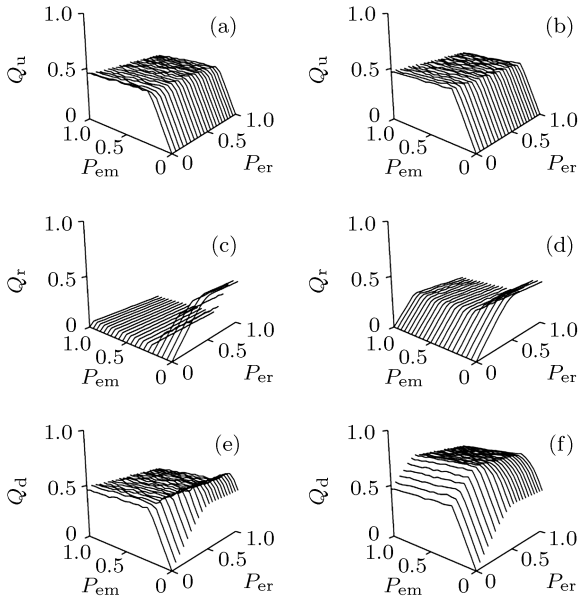


Fig.2. Upstream flux on the main road ($Q_{\rm u}$), on-ramp flux ($Q_{\rm r}$) and downstream flux on the main road ($Q_{\rm d}$) versus entering probabilities $P_{\rm em}$ and $P_{\rm er}$. (a), (c), (e) for Case a; (b), (d), (f) for Case b.

The fluxes versus $P_{\rm em}$ with $P_{\rm er} = 1$ are shown in Fig.3. The values of $Q_{\rm u}$ vary similarly in both cases, while the value of $Q_{\rm u}$ is slightly higher in Case a. This indicates that the bus stop has a slight influence on the upstream flow of the main road, no matter whether the bus stop locates in the downstream or the upstream section of the on-ramp. $Q_{\rm r}$ drops off more sharply in Case a than in Case b, and the stationary level of $Q_{\rm r}$ is much lower in the former case than in the latter. $Q_{\rm d}$ is equal to the sum of $Q_{\rm u}$ and $Q_{\rm r}$, and it is also much lower in Case a than in Case b. This suggests that the combined bottlenecks with the on-ramp and the bus stop greatly reduce the capacity of the on-ramp and the downstream main road. Furthermore, the negative effect is much greater in the case where the bus stop locates on the downstream section of the on-ramp.

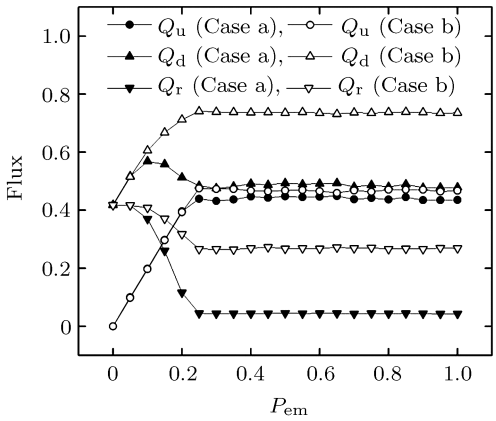


Fig.3. Curves for $Q_{\rm u}$, $Q_{\rm r}$ and $Q_{\rm d}$ versus $P_{\rm em}$, with $P_{\rm er} = 1$.

The space-time diagrams over 500 time steps are drawn in Fig.4 with $P_{\rm em} = P_{\rm er} = 1$. In Case a (see Fig.4 (a1–a3)), traffic jams propagate on the whole on-ramp, because vehicles can hardly enter into the main road from the on-ramp. Traffic jams propagate backward on the upstream section of the main road. At the same time, some blank zones appear on the downstream section of the main road, especially on the right lane, implying that the downstream section of the main road cannot be utilized sufficiently. It can be explained as follows. Buses staying at the bus stop stand in the way of other vehicles from the upstream sections of both the main road and the on-ramp, thus only a few of vehicles can pass through, consequently creating blank zones on the right lane on the downstream section of the main road close to the bus stop. While in Case b (see Fig.4 (b1–b3)), traffic jams seldom occur on the upstream sections of both the main road and the on-ramp, also a few blank zones appear on the downstream section of the main road. The reason is that cars from the on-ramp can easily enter into the main road, for the on-ramp is just located in the blank zones. Hence in Case b the traffic situation on the on-ramp is much better, and the downstream section of the main road can be used efficiently.

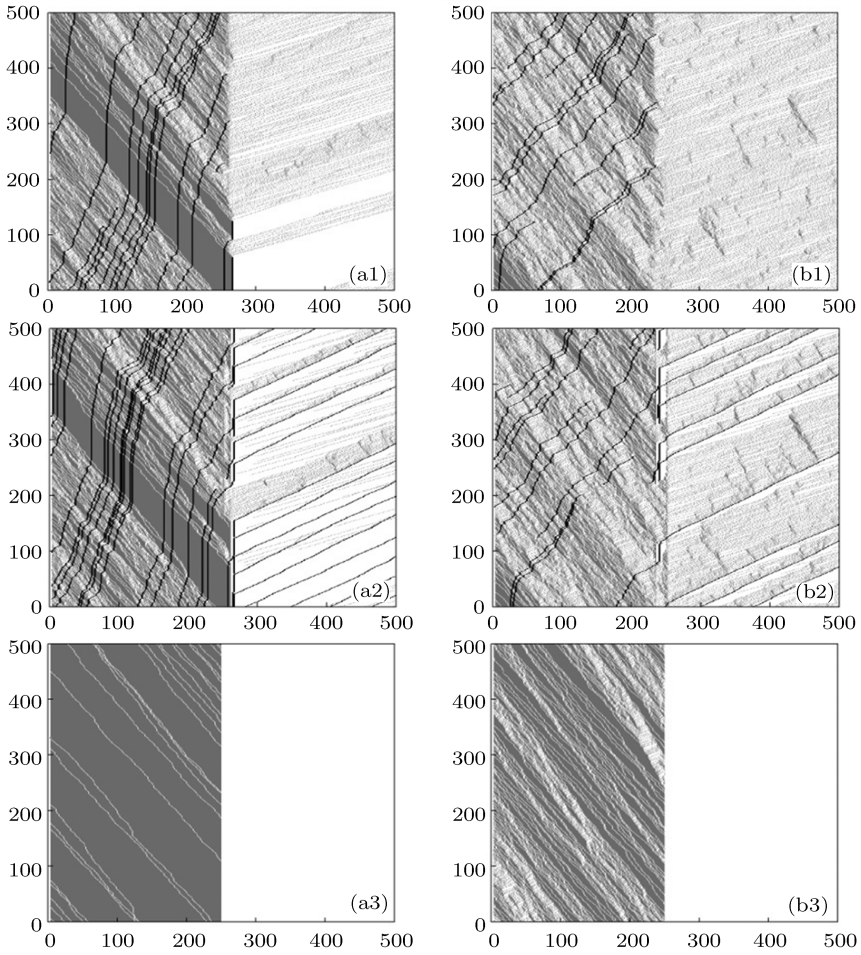


Fig.4. Space-time diagrams over 500 time steps. Horizontal axis is for position and vertical axis is for time. Black points and gray points are for the trajectories of buses and cars respectively. (a1) ((a2)) is for the left (right) lane of main road, and (a3) is for the on-ramp in Case a. (b1)–(b3) are for Case b, with $P_{\rm em} = P_{\rm er} = 1$.

Moreover, the ($P_{\rm em}$, $P_{\rm er}$) phase diagrams are drawn to describe the traffic states (see Fig.5). The space is divided into several regions. Traffic flows both on the main road (both on upstream section and on downstream section) and on the on-ramp are free in region I. The flow on the main road is congested, while that on the on-ramp is free in region II. The flows both on the main road and on the on-ramp are congested in region III. The flow on the main road is free, while that on the on-ramp is congested in region IV. Particularly, in Case a

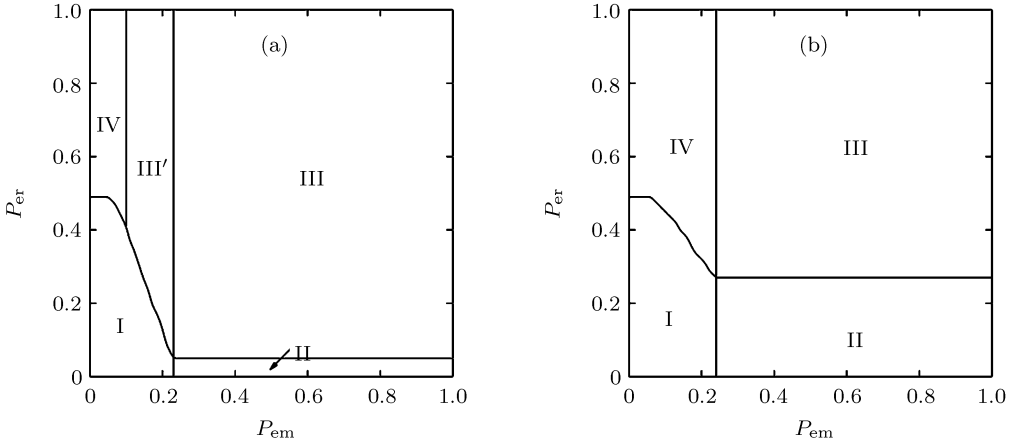


Fig.5. Phase diagrams in ($P_{\rm em}$, $P_{\rm er}$) for (a) Case a and (b) Case b.

there exists a special region III′, where the upstream section of the main road is free, while the flows both on the downstream section of the main road and on the on-ramp are congested. It can be seen that the area of free flow region is larger in Case b. In addition, the flux differences, $\Delta Q_{\rm u} = Q_{\rm u}^{\rm (b)} - Q_{\rm u}^{\rm (a)}$, $\Delta Q_{\rm r} = Q_{\rm r}^{\rm (b)} - Q_{\rm r}^{\rm (a)}$, $\Delta Q_{\rm d} = Q_{\rm d}^{\rm (b)} - Q_{\rm d}^{\rm (a)}$, are all equal to or greater than zero (see Fig.6). These results suggest that the traffic situation would be good when an upstream bus stop locates near the on-ramp compared with a downstream one.

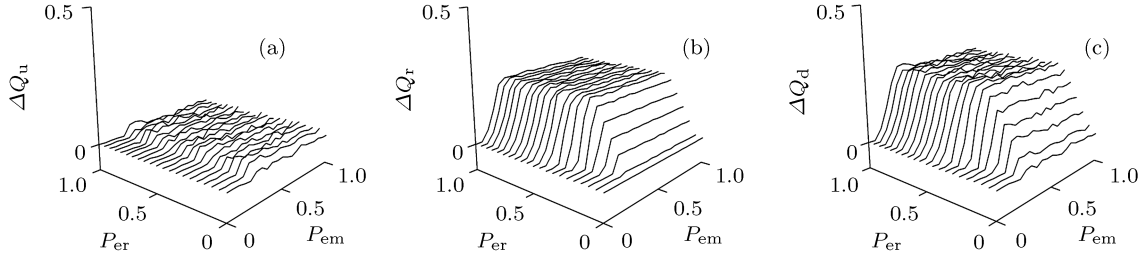


Fig.6. (a) $\Delta Q_{\rm u} = Q_{\rm u}^{\rm (b)} - Q_{\rm u}^{\rm (a)}$ versus $P_{\rm em}$ and $P_{\rm er}$, (b) $\Delta Q_{\rm r} = Q_{\rm r}^{\rm (b)} - Q^{\rm r(a)}$ versus $P_{\rm em}$ and $P_{\rm er}$, and (c) $\Delta Q_{\rm d} = Q_{\rm d}^{\rm (b)} - Q_{\rm d}^{\rm (a)}$ versus $P_{\rm em}$ and $P_{\rm er}$.

Furthermore, the effects of $L_{\rm D}$ are shown in Fig.7 with $P_{\rm em} = P_{\rm er} = 1$. In both cases, $Q_{\rm u}$ increases with $L_{\rm D}$, and then keeps constant at large values of $L_{\rm D}$. This can be explained as follows. The stopping buses on the upstream section of the bus stop tend to change to the right lane, while cars from the on-ramp try to enter into the main road through the cell R on the right lane. Thus, they would seriously interweave in the zone between the bus stop and the cell R, if the bus stop is on the downstream section of the on-ramp (Case a). Differently, the cars entering into the on-ramp would interweave the pulling-out buses, if the bus stop is on the upstream section of the on-ramp (Case b). However, the conflicts gradually diminish with $L_{\rm D}$ increasing in both cases.

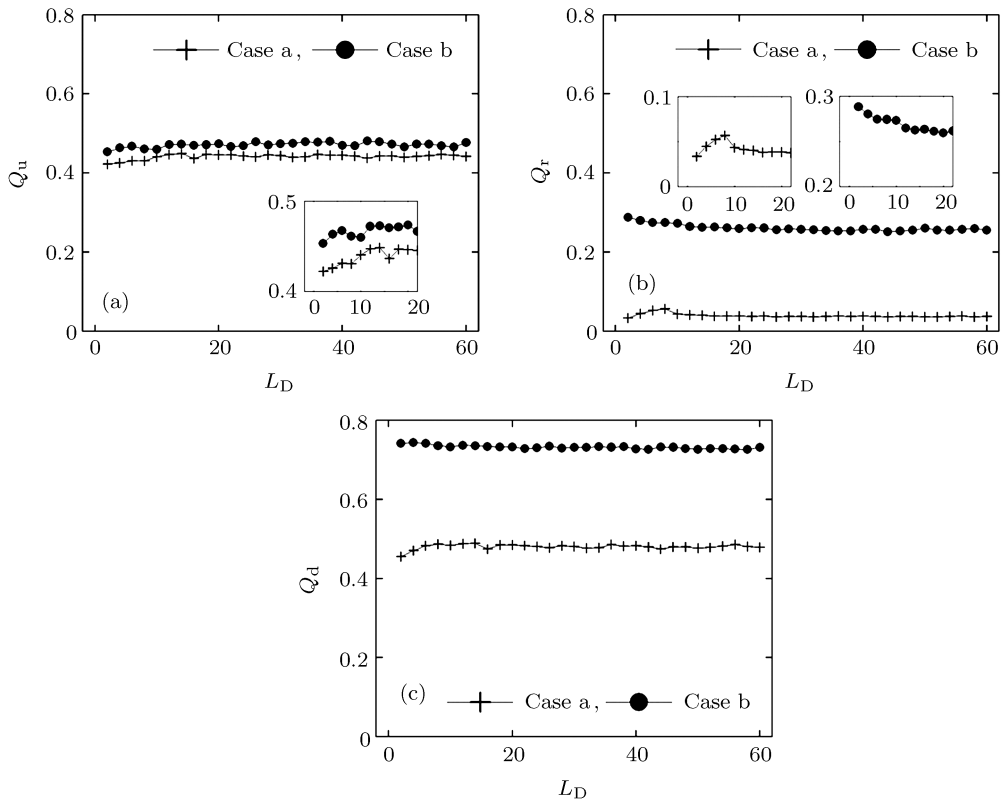


Fig.7. Dependences of (a) $Q_{\rm u}$, (b) $Q_{\rm r}$, (c) $Q_{\rm d}$ on the distance between the bus stop and the on-ramp, $L_{\rm D}$, in Case a and Case b, with $P_{\rm em} = P_{\rm er} = 1$.

In Case a, $Q_{\rm r}$ increases with $L_{\rm D}$ increasing to the maximum (at $L_{\rm D} = 8$) and then drops off. This can be understood as follows. When $L_{\rm D}$ is small ($L_{\rm D} \leq 8$), it is favourable for cars to run into the main road from the on-ramp, since the on-ramp is just within the upstream section of the bus stop, where cars are forbidden to run on the right lane during buses stopping. However, the convenience is very limited, and no longer exists when $L_{\rm D} > 8$. In Case b, $Q_{\rm r}$ decreases with $L_{\rm D}$ increasing. This can be explained as follows. Downstream blank zones on the right lane of the main road might gradually disappear as the on-ramp goes far from the bus stop. Thus cars from the on-ramp can enter into the main road easily if $L_{\rm D}$ is small, but difficultly as $L_{\rm D}$ increases.

Determined by the variations of both $Q_{\rm u}$ and $Q_{\rm r}$, $Q_{\rm d}$ increases with $L_{\rm D}$ in Case a, while it almost keeps constant in Case b. Besides, $Q_{\rm u}$, $Q_{\rm r}$ and $Q_{\rm d}$ in Case b are larger than those in Case a. This also indicates that setting the bus stop in the upstream section of the on-ramp (i.e. Case b) is helpful for enhancing the capacity.

4. Conclusions

The traffic characteristics of a combined bottleneck with an on-ramp and its nearby bus stop are studied based on a two-lane cellular automaton model. Two cases, i.e. the bus stop locates in the downstream section (Case a) and the bus stop locates in the upstream section (Case b) of the on-ramp, are considered separately. Simulation results on flux are discussed with respect to the main road entering probability ($P_{\rm em}$), the on-ramp entering probability ($P_{\rm er}$), and the distance between the on-ramp and the bus stop ($L_{\rm D}$). In both cases, traffic flow transits from free flow to congested flow at corresponding critical entering probabilities. The combination of the bus stop and the on-ramp causes the capacity to drop off, due to the interweavement of entering vehicles from the on-ramp with the stopping buses in Case a (or the pulling-out buses in Case b). Especially, the traffic conflict in Case a is much more serious than in Case b. Thus in Case a, the capacities both on the main road and on the on-ramp are lower, and the downstream section of the main road cannot be utilized efficiently. The upstream flux on the main road increases first and then keeps constant in both cases, with the increase of the distance between the two bottlenecks. The on-ramp flux is maximized at $L_{\rm D} = 8$ in Case a, while it decreases first and then reaches a constant in Case b. The distance effects disappear as the distance increases. Moreover, the fluxes both on the main road and on the on-ramp in Case b are much greater than those in Case a. These results suggest that setting the bus stop in the upstream section of the on-ramp is helpful for enhancing the capacity and improving the road efficiency.

These conclusions may provide some suggestions for traffic management and optimization. However, only qualitative results can be given due to the simplicity and ideality of the model. For instance, a stop lane for buses is neglected. Besides, other combinations of bottlenecks are also commonly found in reality, which are to be taken into consideration in the future work.

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