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Analysis of the influence of occupation rate of public transit vehicles on mixing traffic flow in a two-lane system*

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Based on the existing classical cellular automaton model of traffic flow, a cellular automaton traffic model with different-maximum-speed vehicles mixed on a single lane is proposed, in which public transit and harbour-shaped bus stops are taken into consideration. Parameters such as length of cellular automaton, operation speed and random slow mechanism are re-demarcated. A harbour-shaped bus stop is set up and the vehicle changing lane regulation is changed. Through computer simulation, the influence of occupation rate of public transit vehicles on mixed traffic flow and traffic capacity is analysed. The results show that a public transport system can ease urban traffic congestion but creates new jams at the same time, and that the influence of occupation rate of public transit vehicles on traffic capacity is considerable. To develop urban traffic, attention should be paid to the occupation rate of public transit vehicles and traffic development in a haphazard way should be strictly avoided.

Keywords: public transit vehicles, cellular automata, capacity, average velocity
PACC: 8220F

1. Introduction

Urban public transportation systems play a very important role in urban transportation systems.[1] Yang *et al* studied the cellular automaton model of pedestrian movement with consideration of pedestrian behaviour.[2] However, because public transportation vehicles feature fixed travel lines, arrival and departure times, fixed bus stations, big vehicle types, low speeds and so on, their effects on urban traffic flow are very clear. A phenomenon that bus stations become road section traffic bottlenecks appears often. As the cellular automaton has particular features, i.e. simple in structure, rich in dynamic behaviour and so on, the use of the cellular automaton theory to study the issue has some advantages.[3]

At present, in the two-lane cellular automaton model of traffic flow the effect of harbour-shaped bus stops on traffic flow is not taken into consideration.[4−7] In order to better reflect the real traffic conditions, in the present paper a two-lane mixed traffic flow cellular automaton model under periodic boundary conditions is proposed and the effects of buses and bus bays are also considered. Through computer simulation, the effect of the average time for a bus to stop at a station stop on traffic flow is also investigated in this paper.

2. Model

We regard the road as two one-dimensional separate grid point chains where the lanes on the left and the right are parallel to each other and their lengths are L, each grid point is empty at every moment or is occupied by a vehicle, the lane on the right side is defined as the first lane (bus lane), the lane on the left side is defined as the second lane (fast lane). On the assumption that there are only buses and cars on the road, the cellular length is 4 m, a car takes 2 cellules, and a bus takes 4 cellules. A bus bay takes 4 cellules too. We assume that buses and cars have the same rate of random slowdown.[8,9]

The status of the k-th vehicle at the moment t

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is represented by its upper limit speed $V_k(t)$, $V_k(t) \in [0, V_{\max}]$. If the k-th vehicle is a bus then $V_{\max} = 3$, corresponding to a practical speed of 40.5 km/h; if the k-th vehicle is a car, then $V_{\max} = 5$, corresponding to a practical speed of 67.5 km/h. We denote $X_k^1(t)$ and $V_k^1(t)$ as the position and the speed of the k-th vehicle at the moment t on the 1st lane respectively and $X_k^2(t)$ and $V_k^2(t)$ as the position and the speed of the k-th vehicle at the moment t on the 2nd lane, respectively. Then at the moment t the distance between the k-th vehicle and the most neighbouring vehicle in front on the 1st lane is $D_k^{1-1}(t)$, i.e. $D_k^{1-1}(t) = X_{k+1}^1(t) - X_k^1(t) - 1$. The distance between the k-th vehicle and the most neighbouring vehicle in front on the 2nd lane is $D_k^{2-2}(t)$, i.e. $D_k^{2-2}(t) = X_{k+1}^2(t) - X_k^2(t) - 1$, at the moment t. The distance between the k-th vehicle on the 1st lane and the most neighbouring vehicle in front on the 2nd lane is $D_k^{1-2}(t)$; the distance between the k-th vehicle and the most neighbouring vehicle in the rear is $B_k^{1-2}(t)$; the distance between the k-th vehicle on the 2nd lane and the most neighbouring vehicle in front on the 1st lane is $D_k^{2-1}(t)$; the distance between the k-th vehicle and the most neighbouring vehicle in the rear is $B_k^{2-1}(t)$.

2.1. Rule of bus operation in a bus bay

When a bus arrives at the front of the entrance of a bus bay, it must be first judged whether any vehicle has stopped in the bus bay. If there are vehicles stopping in the bus bay, the bus must wait at the entrance. If not, the bus enters the bus bay, and waits for passengers to get on and off. When the prescribed time for the bus to stay in the bus bay is over, a signal of leaving the bus bay is sent. When the exit of the bus bay and the three cellules behind are empty, the bus speeds up and leaves at a speed of $V_k(t) = 1$.

2.2. Rule of car operation in a bus bay

When a car arrives at the front of the entrance of a bus bay, it must be first known whether the signal for the bus to leave the bus bay is on. If not, it can operate normally. When the bus-bay-leaving signal is on, the car must slow down and stop to wait for the bus to leave the bus bay or move into the other lane.

2.3. Rule of vehicle lane changing

In this paper, the rule of greedy lane changing based on gaps is used. The condition of lane changing on the 1st lane is as follows:
K is a car and $V_k^1(t) > D_k^{1-1}(t)$ and $B_k^{1-2}(t) + V_k^1(t) > V_{\max}$ and $D_k^{1-2}(t) > V_k^1(t)$.
The condition of lane changing on the 2nd lane is as follows:
$V_k^2(t) > D_k^{2-2}(t)$ and $B_k^{2-1}(t) + V_k^2(t) > V_{\max}$ and $D_k^{2-1}(t) > V_k^2(t)$.
If the vehicle satisfies the condition of lane changing, then it may change lane.
The rule of lane changing on the 1st lane is as follows:
$V_k^2(t+1) = V_k^1(t)$, and $X_k^2(t+1) = X_k^1(t) + V_k^1(t)$.
The rule of lane changing on the 2nd lane is as follows:
$V_k^1(t+1) = V_k^2(t)$, and $X_k^1(t+1) = X_k^2(t) + V_k^2(t)$

2.4. Rule of vehicles' state evolution

For the cars outside the station, their speeds and locations are updated in parallel according to the NS model evolution rule. For the cars inside the station, their speeds and locations are first updated in parallel according to the NS model evolution rule, and then amended according to the rule of vehicle operation in the bus bay.
Acceleration:
If $V(t) \le D_k(t)$ then $V(t+1) = V_{\max}$;
Deterministic deceleration process:

If $V(t) > D_k(t)$ then $V(t+1) = D_k(t)$;
Stochastic deceleration process with probability p:
If $V(t) = V_{\max}$ then $V(t+1) = (p, V_{\max} - 1)$;
Update the location: $X(t+1) = X(t) + V(t+1)$.

3. Data analysis and discussion

For a concrete analysis of the kinetic property of the traffic flow system, we define the vehicle density on the two lanes as ρ, the density of vehicles on lane 1 (bus lane) at a certain moment as ρ_1, the density of vehicles on lane 2 (fast lane) at a certain moment as ρ_2, the average speed of cars as $\overline{V_c}(t)$, and the average speed for buses as $\overline{V_b}(t)$. Then

$$\rho = \rho_1 + \rho_2,$$

$$\rho_1 = \frac{N_c^1 + N_b}{L'}, \quad \rho_2 = \frac{N_c^2}{L'},$$

$$\overline{V_c}(t) = \frac{1}{N_c^1 + N_c^2}\left(\sum_{k=1}^{N_c^1} V_k(t) + \sum_{k=1}^{N_c^2} V_k(t)\right),$$

$$\overline{V_{\rm b}}(t) = \frac{1}{N_{\rm b}} \sum_{k=1}^{N'_{\rm b}} V_k(t),$$

where $N_{\rm c}^1$ is the total number of cars on lane 1, $N_{\rm c}^2$ is the total number of cars on lane 2, $N_{\rm b}$ is the total number of buses, $N'_{\rm b}$ is the total number of buses on the road, except for buses in the bus bay, L' is the corresponding actual length in km, $V_{\rm c}(t)$ is the operating speed of the k-th car at moment t, $V_{\rm b}(t)$ is the operating speed of the k-th car at moment t, and Q is the traffic flow Q that refers to the total number of vehicles passing through a cellule in a period. In order to consider the mixed extent, namely the occupancy rate of a bus, we introduce the bus possession ratio coefficient

$$f = \frac{N_{\rm b}}{N_{\rm b} + N_{\rm c}} 0 \le f \le 1,$$

$N_{\rm c} = N_{\rm c}^1 + N_{\rm c}^2$, the bus station distance s and the average bus station stopping time $t_{\rm bs}$.

In the present paper we use a periodic boundary condition in simulation, and $L = 2000$. At the initial moment, these two types of vehicles distribute on lanes according to a certain percentage of the mixture factor f. Each evolution runs for 10000 steps. We record the speed in every step from step No.6000 to step No.9600. From the recorded data, we can obtain the average speed at every step. Then we average the 3600 speed values and obtain the average speed in this evolution.

Figures 1(a) and 1(b) separately give the relationship between flux and density and the relationship between speed and density on the fast lane when $s = 200$, $t_{\rm bs} = 20$ s, $p = 0.2$, $f = 0$, $0.05 \ldots 0.45$. From Fig.1(a),we can see that when the bus occupancy ratio f changes from 0 to 0.45, the flux is significantly affected by the bus occupancy ratio. When $f = 0$, the model is equivalent to the two-lane NS model of $V_{\max} = 5$. The largest flux can reach up to 3005 veh/h. With the gradual increase of f, the flux significantly reduces. When f=0.45, the largest flux is only 1,492 veh/h. As the density increases, the impact of $f$on flux increases gradually. But as to the critical density, with the continuous increase in density, the effect of f on flux weakens gradually. From Fig.1(b) we can see that there are three significant states in the speed-density curve. The first state is an irrelevant state in which the density is not related to speed when the density is small. The second state is the stable state in which the speed changes linearly with density. The third state is the obstruction state in which as density changes, the speed changes a little. The effect of bus occupancy ratio on speed is very clear. The greater the value of f is, the shorter the irrelevant state is. It is easier to enter into the stable state. When $f = 0.05$ and ρ varies from 0 to 80 veh/km·h, it is an irrelevant state. When ρ varies from 0 to 80 veh/km·h, it is a stable state. When $\rho > 80$ veh/km·h it is an obstruction state. When $f = 0.45$ and ρ varies from 0 to 10veh/km·h, it is an irrelevant state. When ρ varies from 10 to $\rho = 40$veh/km·h, it is a stable state. When $\rho > 40$ veh/km·h, it is an obstruction state. This shows that when mixed vehicles run on the two-lane road, the effect of bus occupancy ratio on the flux and speed of the entire system is very significant. When the density reaches a critical density, the effect arrives at the maximum.

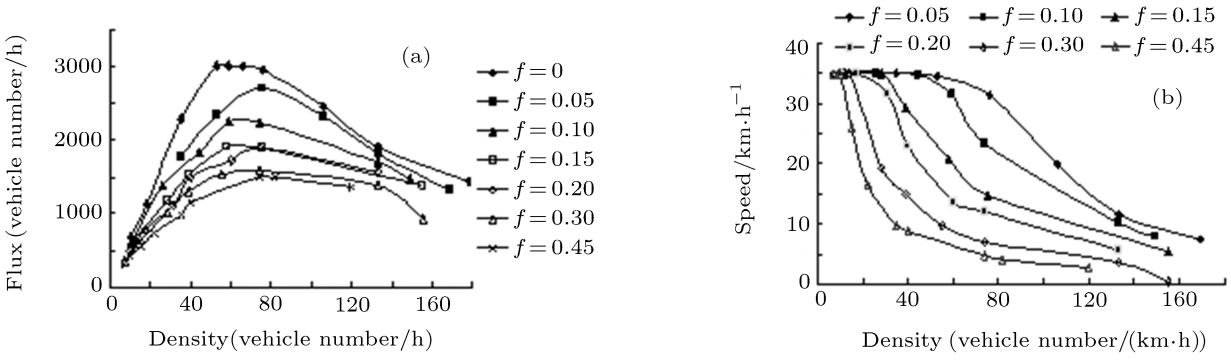


Fig.1. Effects of bus occupancy ratio on flux for different values of f and $p = 0.2$, showing the relation between flux and density (a) and the relation between speed and density (b).

Figure 2(a) is for the NS model when $\rho = 63$, $p = 0.2$, $R = 0.235$ and $f = 0.0$. Figure 2(b) is for the mixed

vehicle model when $s = 200$, $f = 0.05$, $\rho = 63$, $R = 0.235$, $p = 0.2$ and $t_{\rm bs} = 20$ s. The two figures show the evolution from $t = 8000$ to $t = 8370$ for L=500–1000. The horizontal axis represents vehicle location. Vehicles move from left to right. The vertical axis represents the time. The black spots denote the positions of the vehicles. The white spots refer to space points. From Figs.2(a) and 2(b), we can see that the NS model and the mixed vehicle model both indicate a partial block. In contrast, the NS model obstruction region is more random. The road utilization rate is significantly higher than that obtained from the mixed vehicle model. As the mixed vehicle model is affected by buses and bus stations, we can see the marked blank area from the figure in lane 1. It is because buses have a low speed. During travelling, the interval between the car and the front car gradually augments. But the backside vehicle cannot directly take up this interval. It needs to switch lane. But the vehicles travel according to the rule of lane changing if they can travel normally; they would not make up for the interval on the bus lane so some section capability goes to waste. As some of the vehicles on lane 2 switch to lane 1, it makes the blocking probability on lane 2 increase. After the blocking probability increases, it makes some vehicles on lane 2 switch to lane 1 to travel. Although this makes up for some part of the vacancy on lane 1, it reduces the utilization rate in some parts of sections on lane 2. From all the analyses above, we can see that buses are an important factor in making city traffic jams. So in the organizing and the planning of traffic, we should try our best to separate buses from cars. In particular, we should build a lane for buses if possible.

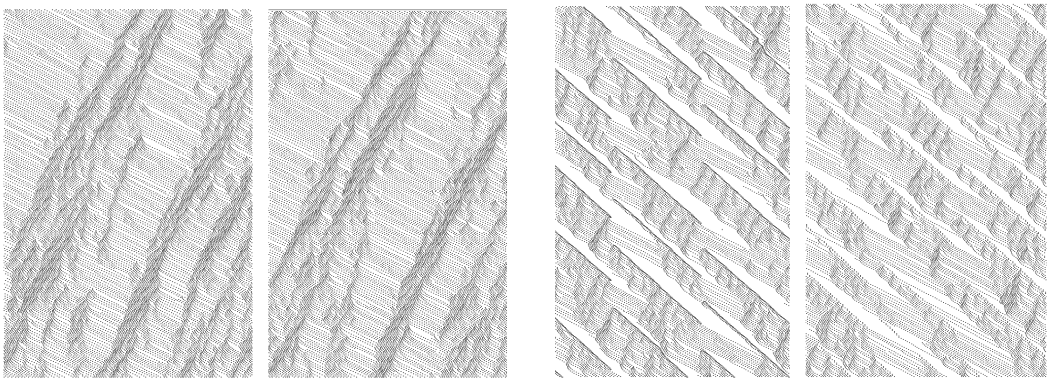


Fig.2. Space–time evolution pattern for (a) $f = 0$, $R = 0.235$, $\rho = 63$ and (b) $f = 0.05$, $R = 0.235$, $\rho = 63$.

4. Effect of bus occupancy ratio on road capacity

Through the discussion of the simulation results, we can see that the bus occupancy ratio has a great effect on the other vehicles on the road. Thereby it affects the capacity of the road. When we study the effect of a bus on flux in this paper, we presume that the length of the bus is 15 m. The conversion coefficient between buses and cars is 2.5. When we set up the model, we assume the speed of a car to be 67.5 km/h and the average speed of a bus to be 40.5 km/h. According to the analysis of car following, we can have the capacity of mixed traffic flow to ensure safe braking. By the use of the car following model, we can calculate the capacity of mixed traffic flow to make up for cars and buses. We assume the bus proportion to be p, and the critical safety following distances between vehicles and cars and between vehicles and buses to be l and L respectively. With comprehensive consideration of the car following model and of the probability of various car following models, we can obtain the weighted average time headway of the total mixed traffic flow as

$$h = \sum t_{ij} * p_{ij},$$

where t_{ij} is time headway; p_{ij} is the probability of various car following models; i, j respectively denote the types of forward vehicle and backward vehicle.

By the weighted average time headway, we can have the capacity of mixed traffic flow C

$$C = 1/h = v/\{[T \cdot p + t\,(1-p)] \cdot v + p \cdot L + (1-p) \cdot l + p \cdot (1-p) \cdot s\,(v)\}.$$

where $s\,(v) = v_{\text{big}}^2/2A - v_{\text{small}}^2/2a$; T and t are the brake response times of a bus and a car respectively, and they are in units of s; l and L respectively represent the critical safety following distances between vehicles, and they are in units of m; A and a refer to the decelerations of a bus and a car when braking, and they are in units of m/s^2; v_{big} and v_{small} respectively denote the speeds of the bus and the car, and they are in units of km/h. After analysis, we can obtain the results as shown in Table 1.

Table 1. Capacities of mixed traffic flow for different bus occupancy ratios.

bus occupancy ratio						
0	0.05	0.1	0.15	0.2	0.3	0.45
3005	2892	2587	2327	2340	2380	2457

According to Table 1,we can see that the bus occupancy ratio has a great effect on the mixed traffic flow. Buses can at best reduce the capacity of the mixed traffic flow down to 23 percent.

5. Conclusion

According to our computer simulations, we can find that the flux and speed of mixed traffic flow are greatly affected by the bus occupancy ratio on a two-lane road. The larger the bus occupancy ratio is, the smaller the capacity of the road will be and the lower the average speed will be. At the same time, as the density of traffic flow gradually increases, the effect of buses on flux and speed also increases. When the density reaches a critical value, the effect of the bus occupancy ratio on traffic flow reaches a maximum. Buses have a great effect on mixed traffic flow. The bus occupancy ratio has a great effect on the capacity of buses. Bus systems can ease the traffic jams caused by car flow, but form a bus congestion. Buses are one of the important factors leading to urban traffic flow jams. So, in actual planning and operation, the bus occupancy ratio should be controlled in order to ensure the smooth flow of urban road traffic.

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