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Perimeter control for urban traffic system based on macroscopic fundamental diagram

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HIGHLIGHTS

- MFD has different shape for the system and for the core area.
- Parameters of perimeter control should be determined by the MFD of core area.
- Perimeter control can reduce gridlock and increase the critical density.

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ABSTRACT

In this paper, we study the application of perimeter flow control by simulation of cellular automaton model on urban traffic system. We find that the relation of traffic flow and vehicle density (Macroscopic Fundamental Diagram, MFD) will have different shapes for the core area and the peripheral area. The MFD shows free-flow state, saturate flow state and congestion state. But the magnitude of maximal flow and the position for congestion transition are different for the whole system and the core area. We suggest to realize the perimeter control strategy by assigning a special prohibiting phase to the perimeter traffic lights for the roads entering the core area. The strategy is controlled by two critical densities ρ_1 and ρ_2, which are determined by the MFD of the core area. Simulations show that both the average arrival rate and the average flow will be greatly improved with the perimeter flow control strategy. In addition, the perimeter flow control strategy can increase the critical density of traffic congestion. The probability of system-wide gridlock will decrease, and the system can perform well under both close and open boundary conditions. All the results indicate that the perimeter flow control strategy can effectively improve the performance of the traffic system.

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1. Introduction

With the development of economy, traffic systems in most cities become increasingly aggravated and the efficiency of transportation drops substantially in rush hours. This creates a major challenge for researchers trying to get a clear view of the reasons for traffic congestion and the corresponding traffic control measures. Studies have been done over the years on many aspects of urban traffic, varying from microscopic car-following behavior and intersection signaling to macroscopic traffic network characteristics [1–8]. A primary tool for graphically displaying information of urban traffic system is the

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Macroscopic Fundamental Diagram (MFD), which depicts the global traffic properties of the system by means of flow-density relation [9–12]. With MFD, researchers can explore the relationship between flow and density of traffic. The existence of urban-scale MFD in real urban traffic system was first validated by the taxi-trip data in Yokohama [9]. After that, the studies of MFD have attracted wide attention in the traffic field [13–16].

Since MFD can picture the properties of traffic system clearly as a whole, it is usually used to predict the capability of a road system. Based on MFD, macroscopic control strategies have been proposed to improve the performance of traffic systems, including perimeter control [17–21], cooperative control [22], hierarchical control [23], robust control [24,25], gating control [26], etc. The main aims of these control strategies are to maximize the number of trips that reaching their destinations and increase the stability of traffic network. Among the various control strategies, the perimeter control strategy is deemed an convenient way to improve the traffic efficiency. In this strategy, an urban-traffic system is usually partitioned to two regions. One is the core area of the urban system, which often has heavy traffic loads. The other roads with low traffic load form another area. The perimeter control strategy mainly focus on the control of the accesses to the core area of the urban-traffic system. Perimeter control is supposed to improve the mobility of core area in saturated traffic conditions.

However, most of previous studies of perimeter control are carried out theoretically based on a presupposed MFD model, which usually takes a triangular or trapezoid shape. The MFD is also assumed to have identical shape for different regions of the system. Moreover, only the performance of the core area is considered, while the performance of outer area are neglected. It has been reported that traffic signals and control strategies can change the shape of MFD and the critical densities for congestion [13–15]. The performance of a control strategy should be examined by the overall traffic of the urban system. It is also necessary to simulate the perimeter control strategy in traffic networks closer to the real traffic system.

In this paper, we study this problem with a urban-network traffic model based on microscopic Nagel–Schereckenberg (NaSch) cellular automaton model [27]. This kind of urban traffic model has been developed recently as an efficient way to analyze urban traffic system by reflecting various aspects of real world traffic environment and drivers' behavior [13,28–33]. For example, Zhang et al. used a grid lattice network to examine the impact of adaptive traffic signal systems on the MFD [13,30]. Li et al. and Chen et al. used a Manhattan-like network to study the effect of feedback information in advanced traffic information systems [28,29]. Jiang et al. adopted a similar model to study the network operation reliability (NOR) of the traffic system [32]. Here we further extend the model to incorporate more detailed driving behavior in reality, especially the intersection-traversing and route-choice behavior, in the cellular automaton rules. Particularly, the intersection-traversing movement is modeled as a cellular automaton model of turning tracks. The route-choice behavior is also incorporated in the rule with the vehicle's lane-changing movement before entering the intersections. Furthermore, we proposed a realization method of perimeter control strategy by adjusting the phases of some particular traffic lights surrounding the focused area. The realization method does not need to install new traffic lights, and thus can be adopted in real urban systems. In the perimeter control strategy, the controlling parameters are selected based on the simulated flow-density relation or MFD of the core area. It is shown that the strategy can greatly improve the performance of the whole system, especially when the vehicles tend to enter the core area.

The rest of this paper is organized as follows. Section 2 describes the traffic model and the setup of simulation experiment, including the perimeter control strategy. Section 3 shows the simulation results of perimeter control and the corresponding discussion. Concluding remarks are reported in Section 4.

2. Model

2.1. Controlling equation for urban regions

For the implementation of perimeter control, the urban traffic system is usually divided into two parts: the core area and the peripheral area. Denote N_c as the number of vehicles within the core area, N_p as the number of vehicles in the peripheral area. The controlling equation for vehicles in the core area can be formulated as follows:

$$\frac{\delta N_c}{\delta t} = I_c(k) - Q_{ca}(k) + J_{in}(k) - J_{out}(k), \tag{1}$$

where δt is the discrete sample time step, k is the index for time step, $I_c(k)$ is the inflow of vehicles entering the system within the core area, $Q_{ca}(k)$ is the outflow of vehicles arriving at their destinations within the core area, $J_{in}(k)$ is the inflow of vehicles from the peripheral area to the core area, and $J_{out}(k)$ is the outflow of vehicles from the core area to the peripheral area. Eq. (1) depicts the state variation during the time interval $[k\delta t, (k+1)\delta t]$.

For the peripheral area, the control equation is formulated as:

$$\frac{\delta N_p}{\delta t} = I_p(k) - Q_{pa}(k) - J_{in}(k) + J_{out}(k), \tag{2}$$

where $I_p(k)$ is the inflow of vehicles entering the system within the peripheral area, $Q_{pa}(k)$ is the outflow of vehicles arriving at their destinations in the peripheral area.

For the whole system, the conservation equation is formulated as follows:

$$\frac{\delta N}{\delta t} = I_c(k) + I_p(k) - Q_{ca}(k) - Q_{pa}(k), \tag{3}$$

where $N = N_c + N_p$ denotes the total number of vehicles in the system.

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