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An improved cellular automaton model with the consideration of a multi-point tollbooth

Y.S. Qian*, X.M. Shao, J.W. Zeng, M. Wang

School of Traffic and Transportation, Lanzhou Jiaotong University, Lanzhou, 730070, China

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ABSTRACT

Based on the classical Nagel–Schreckenberg model, we in this paper propose an improved cellular automaton (CA) model to study the influences of a multi-point tollbooth on traffic flow. The numerical results show that the multi-point tollbooth can be looked at as a bottleneck and that it can improve the road capacity compared with other tolling stations, which shows that the proposed model is more effective than other traffic flow models. In addition, the results can help readers to better understand the effects of a multi-point tollbooth on traffic flow and help traffic engineers to reasonably design the tolling station.

1. Introduction

Most expressways are built through loan in China, so drivers should pay tolling if they use the expressway. But since traffic demand is higher than the expressways' supply, so the expressways are often very congested though tolling exists. So, it is necessary to develop a reasonable tolling technology to improve the road capacity.

Most Chinese highways use Manual Toll Collection (MTC), MTC is a traditional toll, it is paid by hand at a toll gate. Although payments may still be made in cash, it is more common now to pay by credit card but this tolling mode will make vehicles stop to pay the tolling and produce queues at the upstream of the tolling stations. Recently, researchers found that Electronic Toll Collection (ETC) system can improve the road capacity since the vehicles do not stop to pay tolling. ETC gantries are at entrances and exits, or at strategic locations on the mainline of the road. However, the ETC is affected by many objective and subjective factors, so the MTC mode is the main tolling mode on the Chinese highways.

In China, many tolling stations use road expansion and multi-point tollbooths, which can save spatial resources, but the tolling mode needs multi tolling devices on the road. The tolling devices should be switched on or off based on the traffic states, so the road can simultaneously accommodate multiple vehicles at the tolling station, which indicates that this tolling mode can save land resources, reduce the related costs and negative influences of the tolling station and improve the road capacity.

As for the influences of bottlenecks (e.g., interruption) on traffic flow, researchers have developed a few traffic flow models to study some complex traffic phenomena resulted by bottlenecks [1–29]. However, the models cannot be used to study the impacts of a tolling station on traffic flow because they do not explicitly consider this factor. To explore the impacts of a tolling station on traffic flow, Huang et al. [30] investigated the role of the tolling station on a single-lane highway traffic by use of the cellular automaton (CA) model and found that tolling station can be regarded as a bottleneck; Tang et al. [31] proposed a macro traffic model with static bottleneck; Zhu et al. [32] proposed a CA model with ETC; Shen and Yang [33] explored traffic phenomena on a freeway with dynamic tolling and ramp control; Lee et al. [34] studied the design and implementation of the vehicle positioning system based on the ETC system; Komada et al. [35] studied the traffic states

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* Corresponding author. Tel.: +86 13993116951.
E-mail address: qianyongsheng1@sina.com (Y.S. Qian).

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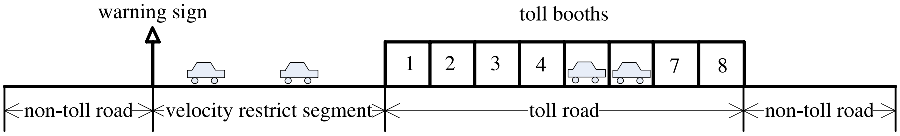

Fig. 1. The scheme of multi-point tollbooths in a single-lane traffic system.

on a two-lane road with electronic and manual tollgates; Komada and Nagatani [36] studied the traffic states on a road with multi-lane tollgates; Jou et al. [37] proposed a conceptual framework to investigate the factors affecting the driver's intention towards the ETC service.

However, little effort is made to explore the impacts of a multi-point tollbooth on traffic flow. In this paper, we propose a CA model to explore the effects of the vehicle's maximum speed, dwell time (on an open toll system, all vehicles stop at various locations along the highway to pay a toll), the number of tollbooths and the configuration of a tolling station on traffic flow.

2. Model

For convenience, we give the following assumptions:

(1) The road is divided into a number of 1-dimensional cells whose length is L; each cell may be occupied by a vehicle or empty.
(2) $V_{\max}, V^*_{\max}$ are the maximum speed and limited maximum speed on the non-toll road, respectively; $v_i \in \{0, 1, 2, \ldots, V_{\max}\}$, x_i are the ith vehicle's speed and location, respectively; p is the random deceleration probability; $d_i = x_{i+1} - x_i - l$ is the number of empty cells between the ith and $(i+1)$th vehicles, where l is the vehicle's length.

From Fig. 1, we can conclude that, if the vehicles that will pass the multi-point tolling station are the same type, the vehicles should decelerate in the speed restricted region since the warning sign is set at a certain distance in front of the tolling station. Here, we give the following notations: M is the number of the multi-point tollbooths and their locations are $X_{toll} = \{toll_1, toll_2, \ldots, toll_M\}$; $toll_{active}$ are the valid tollbooths at the service position.

In the tolling segment, a vehicle should pay the fee when it reaches the first tolling station and the dwell time is T_w. The vehicle tolled does not pay the fee when it passes the other tollbooths. When one vehicle enters the non-toll segment, it can accelerate to its ideal speed and leave the toll station.

Thus, we can define the movement rules at the multi-point toll station as follows:

(1) Speed evolution:
    If $X_{warn} \le x_i(t) < toll_1$, then
  (a) Deterministic acceleration: $v_i(t+1/3) = \min\left(v_i(t)+1, V^*_{\max}\right)$;
  (b) Deterministic deceleration: $v_i(t+2/3) = \min\left(v_i(t+1/3), d_i(t)\right)$;
  (c) Random deceleration: $v_i(t+1) = \max\left(v_i(t+2/3)-1, 0\right)$;
  If $toll_1 \le x_i(t) \le toll_{\mathrm{M}}$, then
    if $x_i(t) = toll_{charge}$ && $t_s < T_w$, $v_i(t+1) = 0$; $t_s = t_s + 1$;
    else
  (a) Deterministic acceleration: $v_i(t+1/3) = \min\left(v_i(t)+1, V^*_{\max}\right)$;
  (b) Deterministic deceleration: $v_i(t+2/3) = \min\left(v_i(t+1/3), d_i(t)\right)$;
  (c) Random deceleration: $v_i(t+1) = \max\left(v_i(t+2/3)-1, 0\right)$;
  else
  (a) Deterministic acceleration: $v_i(t+1/3) = \min\left(v_i(t)+1, V_{\max}\right)$;
  (b) Deterministic deceleration: $v_i(t+2/3) = \min\left(v_i(t+1/3), d_i(t)\right)$;
  (c) Random deceleration: $v_i(t+1) = \max\left(v_i(t+2/3)-1, 0\right)$;
(2) Location update: $x_i(t+1) = x_i(t) + v_i(t+1)$;
(3) Time feedback: If $x_i(t+1) > toll_{\mathrm{M}}$, then $t_s = 0$;

where X_{warn} is the warning sign's location, $toll_{charge}$ is the tollbooth's location, t_s is the cumulative waiting time at the tolling station.

3. Numerical tests

Vehicles are randomly distributed on the ring; each cell's length is 7.5 m; the initial number of vehicles is N on the road; the toll station is the road's midpoint. Other related parameters are defined as follows:

$$L = 200 \text{ cell}, \qquad l = 1 \text{ cell}, \qquad X_{\text{warn}} = toll_1 - 20,$$
$$V_{\max} = 5 \text{ cell/s}, \qquad V^*_{\max} = 1 \text{ cell/s}.$$

We assume that the vehicles passing the multi-point tolling station consist of MTC and ETC vehicles and that the ratio of MTC vehicles is R. Fig. 2 is the flux–density curves under different R. From Fig. 2, we have: