Original research paper

Simulation and analysis of the carrying capacity for a road network

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Abstract

The number of vehicles that a road network can carry is limited. When the limit is exceeded, the network system is not able to function effectively. In this paper, an updated cellular automaton model for urban two-way-four-lane network systems with all-way stop control intersections is proposed to simulate the network level critical density and carrying capacity under different conditions, which essentially indicates the limit number of vehicles that the network can handle before going into gridlock. In the proposed model, two update rules, including lane changing and the longitudinal location update, are adopted to represent vehicle movements on road sections according to the driving condition on the road and the vehicle's direction in the downstream intersection. The vehicle's movements in intersection areas are prioritized based on vehicle's position, so as to prevent collisions within the intersection area. The simulation results show that an increase in network size is able to expand the carrying capacity of a road network, whereas the expansion rate is less than the change rate in the network size. The carrying capacity is also associated with the structure of the road network. The carrying capacity is inversely proportional to the number of intersections, and proportional to the length of the road in the network. Besides, Optimizing the O-D distribution also can increase the carrying capacity, speed and efficiency of the urban road network.

Keywords:

carrying capacity; urban road network; congestion; critical density; cellular automata model

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1 Introduction

Capacity of a road network ought to be an essential part of any urban traffic planning and management. The capacity of an urban road network indicates the maximum attainable throughput of the given network (Yang et al., 2000), which is highly associated with various factors, such as the road lay out, right of way, type of intersection, control method, road section capacity, intersection spacing, origin-destination (O-D) distribution pattern, route choice and the Level Of Service (LOS).

The primary objective of a network capacity problem is to determine the maximum attainable flow that a network can carry (Chen et al., 2002). For a simply network with single O-D, the network capacity is defined as the maximum flow and minimum cut problem, i.e., the maximum flow between two nodes r and s in a network is equal to the capacity of the minimum cross section in all cut sets that separate such the two nodes r and s (Ford and Fulkerson, 1956; Ahuja et al., 1993). However, the maximum flow minimum cut theorem can only describe the maximum flow problem of one O-D pair, and cannot solve the maximum flow problem with multiple origin-destinations (O-Ds). When the O-D demand pattern is fixed and only the route choice behavior is considered, the maximum capacity of the road network can be obtained by a traffic assignment method (Lam and Zhang, 2000). On the other hand, when all or part road users can choose their own destinations, the O-D demand pattern becomes uncertain. A nonlinear programming method can be used to estimate the maximum attainable flow in the road network with the uncertain O-D demand pattern (Kasikitwiwat and Anthony, 2005; Zhu and Zhang, 2008). Similar research includes the studies on reserve capacity (Gao and Song, 2002; Wong, 1996; Wong and Yang, 1997; Zhang et al., 2010; Miandoabchi and Farahani, 2011), and capacity reliability (Soltani-Sobh et al., 2016). In addition, a number of studies have been conducted to optimize the road network capacity from the perspectives of design variables, routing behavior models, demand characteristics, and design objective functions (Yang and Bell, 1998; Farahaniet al., 2013; Chen et al., 2011; Sohn, 2011; Xu et al., 2016).

Most of the methods mentioned above focused on the maximum demand that the network can handle without traffic degradation. However, the results from these methods cannot indicate how many vehicles the road network can support, carrying capacity. The term carrying capacity is borrowed from biology, where it is defined as the maximum number of members of a species that can survive indefinitely in a given environment, given the space and resources available (Angus and Butler, 2011). It can be used as a new network performance index to estimate how many vehicles the urban road network can support. In this paper, the carrying capacity of a road network is defined as the maximum vehicles that can move indefinitely (at most 10^7 seconds) without traffic degradation (gridlock) in a given road network.

One way to understand the carrying capacity of an urban road network is to run a micro-simulation of traffic movements in the network based on relevant micro-simulation models such as the cellular automata (CA) model. CA is a discrete model studied in computability theory, mathematics, physics, complexity science, theoretical biology, microstructure modeling, and transportation modeling. The CA model is an effective tool to simulate road network due to its characteristics of simplicity, flexibility and immediacy. The first traffic CA model was proposed by Wolfram in 1983 (Wolfram, 1983). Then, the one-dimensional CA traffic model (NaSch) (Nagel and Schreckenberg, 1992) and the two-dimensional CA traffic model (BML) (Biham et al., 1992) were proposed. In 1999, an “unified” CA model of city traffic named Chowdhury-Schadschneider(Chsch) model was developed based on the NaSch model and the BML model (Chowdhury and Schadschneider, 1999). A CA model of vehicular traffic in a Manhattan-like urban system studied the influences of advanced traveler information system and adaptive traffic lights (Li et al., 2011; Jiang et al., 2016). Zhang et al. (2013) proposed a stochastic cellular automaton model for urban traffic flow to study and compare Macroscopic Fundamental Diagrams (MFDs) of arterial road networks governed by different types of adaptive traffic signal systems. Recently, a new CA model simulated the traffic dynamics in urban two-way road network systems to investigate network fundamental diagram and the effect of the randomization probability and the maximum vehicle speed on network traffic mobility (Shi et al., 2014).

In this paper, the CA model is further updated with the rules of the two-way-four-lane all-way stop control intersection and the practicality of the CA model is improved accordingly. In the proposed model, vehicles on roads follow the rules of turning for lane changing, overtaking lane changing, and longitudinal location update. To reduce vehicle conflicts and improve traffic efficiency, the vehicles within an intersection are assumed to have the priority over the vehicles in the cells outside the intersection, and the vehicles in the cells outside the intersection have the priority over the vehicles in the cells nearby the intersection, and an additional rule is developed to avoid the ‘gridlock’ phenomenon in the intersection. Simulations were carried out to investigate the effects of the road network scale, the road network structure, and the O-D demands distribution pattern on the road network carrying capacity.

The rest of the paper is organized as follows: In section 2, an updated CA model is proposed for urban two-way-four-lane networks. In Section 3, the simulation results are presented and discussed. Finally, the conclusions are drawn in Section 4.

2 Updated CA model

As shown in Fig. 1, an urban road network with $S \times S$ roads is constructed. Each road has 2 lanes, and each lane is divided into L cells, and the length of each cell is 7.5 m, and each vehicle occupies one cell. Vehicles drive on the right-hand side of the road. Each vehicle can turn left, right, or go through at intersections, but driving in the reverse direction is not allowed. All-way stop control is applied to all intersections, which means vehicles need to stop and wait for a safe gap before proceeding into the intersection. The total number of the cells (N_{cell}) in the road network is the sum of the number of cells in roads and intersections, as expressed in Eq. 1.

$$N_{cell} = 8 \times S \times (S+1) \times L + 16 \times S^2 \quad (1)$$

The network density is defined as the percentage of the total number of cells occupied by the vehicle, while the network speed is the average of instantaneous speed of all vehicles in the road network (Shi et al., 2014).

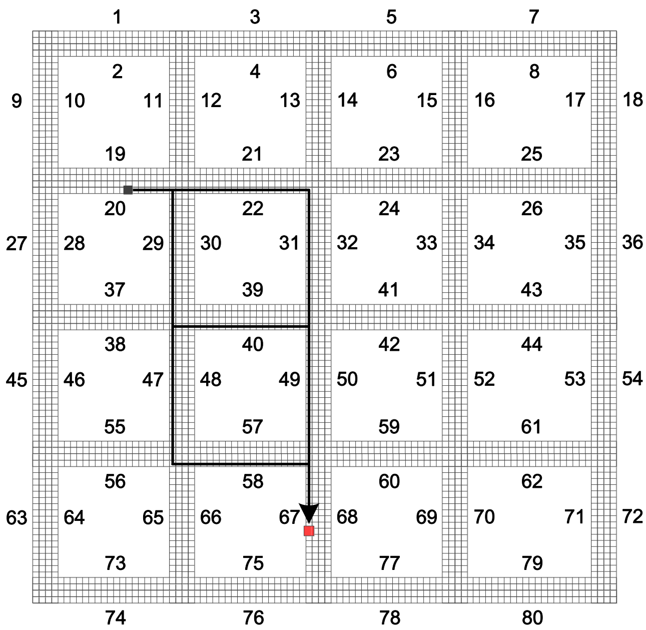

Fig. 1 Diagram of the urban two-way-four-lane network, $S=5$, $L=20$.

At the initial time, N vehicles (here all vehicles are assumed to be cars) are randomly distributed to the network. Each vehicle is randomly assigned with an origin and a destination. Besides the cells in intersections, all other cells can be selected as origins and destinations by vehicles. The distance is adopted to reflect the different impedance between each road section pairs, and assume vehicles travel along the shortest path in terms of their distance to relevant destinations. Then, the Dijkstra's algorithm can be used to generate the shortest path tree between road sections (Dijkstra, 1959). For example, in Fig. 1, there are 3 shortest paths from origin (road section 20) to destination (road section 67). Among these three shortest paths, each vehicle randomly selects one to finish its trip. Once the vehicle arrives at this destination, a new destination will be assigned. In this way, vehicles in the network keep moving and the number of vehicles in the road network is constant, which is a condition for further study of the urban road network traffic flow under different traffic densities.

Assume that the critical density in the urban road network is $\rho_c(N)$. When the density is less than such critical density, vehicles can travel at a higher speed without congestion. On the contrary, the congestion will occur and eventually lead to gridlock after running for a period of time. The carrying capacity of urban road network is defined as the maximum number of vehicles running within the critical density, i.e., the product of the total number of cells and the critical density, which is estimated by Eq.

2.

$$N(p) = N_{cell}(k) \times N_c \quad (2)$$

Starting from section 2.1, the rules of vehicle movement in the network will be discussed in details. As the movement of a vehicle traveling through an intersection is quite different from that on the mainline of a road, the discussion of the rules on the mainline section and the intersections are arranged in different sections.

2.1 Update rules of road sections

In Fig. 2, Let x_n and v_n indicate the position and speed of the n^{th} vehicle on a given road section, respectively. Each vehicle has a maximum speed $v_{\max}$, and $v_n = 0, 1, \cdots, v_{\max}$. The distance between the n^{th} vehicle and its leading vehicle is denoted as d_n, and can be calculated by Eq. 3.

$$d_n = x_{n+1} - x_n - 1 \quad (3)$$

and, when the n^{th} vehicle is the first vehicle in the mainline section, it is estimated by Eq. 4.

$$d_n = L - x_n \quad (4)$$

where L is the length of the mainline section.

The distance between the n^{th} vehicle and the downstream intersection is S_n, the calculation of which is similar to d_n as is shown in Eq. 5.

$$S_n = L - x_n \quad (5)$$

Let d_{back} and d_{other} represent the distance between the n^{th} vehicle and its following vehicle and leading vehicle in the adjacent lane, respectively. The length of prohibitions against changing lanes is indicated as d_{avoid}, while the lane number of the n^{th} vehicle is K_n. where k_n is either 1 or 2, with 1 indicating that the vehicle is driving on the innermost lane, and 2 indicating driving on the outermost lane. The direction of the n^{th} vehicle on the next intersection is represented by F_n. The value of F_n could be 1, 2, and 3 for left turning, through movement, and right turning, respectively. Let Δt indicates a time step. At each Δt, the speed and position of each vehicle on a road section is updated in parallel according to the designed lane changing rule and the longitudinal location update rules.

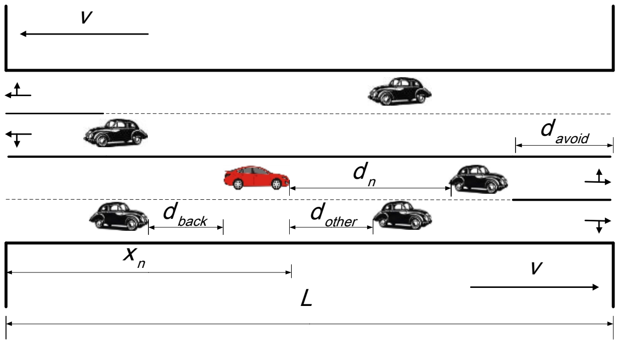

Fig.2 The sketch of the road.

2.1.1 Lane changing rule

(1) Turning lane changing

A vehicle entering a road section from the upstream intersection will change its lane according to the direction to the downstream intersection, with a condition that the gap provided on the adjacent lane is safely acceptable.

If the n^{th} vehicle meets all the following conditions, the vehicle will change its lane to the adjacent lane.

① $x_n \le L - d_{avoid}$, the n^{th} vehicle is in the front of prohibitions against changing lanes;

② ($F_n = 1$ and $K_n = 2$) or ($F_n = 3$ and $K_n = 1$), the n^{th} vehicle is not on the correct lane;

③ $d_{back} > v_{\max} \times \Delta t$, the n^{th} vehicle's lane changing will not affect the vehicle at the back of it on the adjacent lane.

(2) Overtaking lane changing

Within a fleet, if a leading vehicle suddenly stops or slows down and the driving speed in the adjacent lane is relatively faster with acceptable safe gaps, part of the following vehicles would select to change to the adjacent lane, while the rest might still remain in the original lane.

Thus the n^{th} vehicle will change to its adjacent lane with the probability p_{change}, if the following conditions occur.

① $\min(v_n+1, v_{max}) > d_n$, the speed of the n^{th} vehicle is higher than the distance between it and the leading vehicle;

② $d_{other} > d_n$, the adjacent lane has a better driving condition;

③ $d_{back} > v_{max} \times \Delta t$, the n^{th} vehicle's lane changing will not affect the vehicle at the back of it in the adjacent lane.

2.1.2 The longitudinal location update

Step 1: Acceleration. $v_n \rightarrow \min(v_n+1, v_{max})$;

Step 2: Deceleration. If ($F_n = 1$ or $K_n = 1$) or ($F_n = 3$ or $K_n = 2$) or $F_n = 2$, then $v_n \rightarrow \min(v_n, d_n, s_n)$, otherwise $v_n \rightarrow \min(v_n, d_n, s_n - d_{avoid})$.

Step 3: Randomization. $v_n \rightarrow \max(v_n-1, 0)$ with probability p_{slow}.

Step 4: Vehicle movement. $x_n \rightarrow x_n + v_n$.

2.2 Update rules of the vehicles in intersection areas

As shown in Fig. 3, there are three types of cells related to each intersection: (i) cells outside the intersection (i.e., Cells 1-12), (ii) cells inside the intersection (i.e., Cells 13-16), and (iii) cells nearby the intersection (i.e., Cells 17-32). Vehicles of different directions travel through an intersection with different trajectories. Using the eastbound movement as an example, the left-turning vehicles travel to the north through Cells 17, 12, 13, 14, 15, 8, and 29, the through movement vehicles travel to the east through Cells 17, 12, 13, 14, 5 and 25 (the left lane) or Cells 18, 1, 2, 3, 4 and 26 (the right lane), and the right-turning vehicles travel to the south through Cells 18, 1, and 32. The movements of vehicles in the remaining three approaches follow the same patterns. The speed of the vehicle in an intersection is assumed to be either 0 or 1. Hence, vehicles must travel through the cells one by one along its trajectory in the intersection areas.

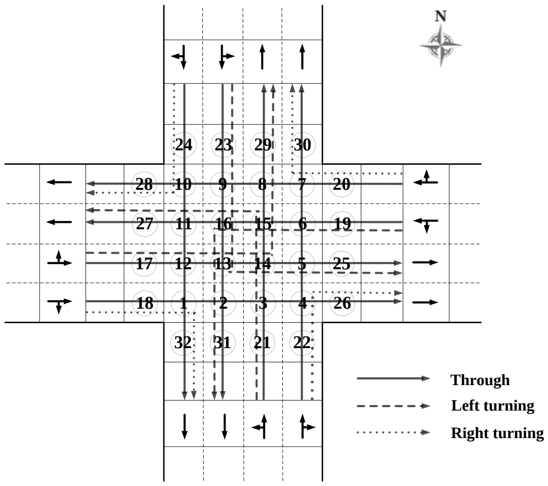

Fig.3 Cell representation of an intersection.

To prevent vehicle collisions, the vehicles in the cells inside an intersection are assumed to have the priority over the vehicles in the cells outside the intersection, and the vehicles in the cells outside the intersection have the priority over the vehicles in the cells nearby the intersection. The following four rules are applied to the vehicles in intersection areas:

(1) Updated rules for vehicles in the cells inside the intersection: If the next cell along its trajectory is empty, the vehicle moves forward the next cell at the end of the step; otherwise, the vehicle will stand still. This rule is adopted for all vehicles in Cells 13-16.

(2) Updated rules for vehicles in cells outside the intersection: If the next cell along its trajectory is empty and there is no vehicle in any cells inside the intersection attempting to occupy this cell, the vehicle moves forward to this cell at the end of the step; otherwise, the vehicle will stand still. For example, if Cell 16 is occupied by a westbound left-turning vehicle, or a southbound through movement or left-turning vehicle, the vehicle in Cell 12 will be forbidden to drive into Cell 13. If there is at least one of Cell 13 and Cell 16 being occupied by a southbound through movement vehicle, the vehicle in Cell 1 will be forbidden to drive into Cell 2. This rule is adopted for all vehicles in Cells 1-12.

(3) Updated rules for vehicles in cells nearby the intersection: If the next cell is empty and there are no vehicles in cells outside the intersection attempting to occupy this cell, the vehicle moves forward to this cell at the end of the step; otherwise, the vehicle will stand still. For example, if there is at least one of Cell 10 and Cell 11 being occupied by a through movement vehicle from the north, the vehicle in Cell

17 will be forbidden to drive into Cell 12. If there is at least one of Cells 10, 11, and 12 being occupied by a through movement vehicle from the north, the vehicle in Cell 18 will be forbidden to drive into Cell 1. This rule is adopted for all vehicles in Cells 17-24.

(4) An additional rule for vehicles avoiding 'gridlock' phenomenon: the 'gridlock' phenomenon can occur for a special case when Cells 13-16 are empty, and Cells 3, 6, 9, and 12 are, respectively, occupied by a through movement or left-turning vehicle. In this case, if the four vehicles in Cells 3, 6, 9, and 12 simultaneously move forward to the same cell, Cells 13-16 will all be occupied at the next step and the four vehicles can never move forward. To avoid the 'gridlock' phenomenon, one vehicle in Cells 3, 6, 9, and 12 would be selected randomly to stand still, and the other three vehicles move forward for one cell.

3 Simulation results

3.1 Parameter settings

The variables of the proposed CA model are preset for five network scales to investigate the change in the capacity of the two-way-four-lane road network. Specifically, the scale of network changes from 3×3 to 7×7 with increment of 1 road. The cell number of each road sections is 20 (i.e., 150 m), and the values of $v_{\max}$, d_{avoid}, p_{slow} and p_{change} are 3, 3, 0.3, and 0.2, respectively. The network density ranges from 0.005 to 0.9 with an increment of 0.005. Each simulation runs for 10^7 time steps until gridlock happens and all vehicles stop. If the gridlock does not take place, the network density would increase by 0.005. Otherwise, the network density is the critical density of the road network ($\rho_c(N)$).

3.2 The effect of the road network scale

Table 1 shows the network carrying capacity estimation from the simulation results for the five networks with five scales (K is assumed as the number of lanes in one road). The influence of the road network scale on carrying capacity is illustrated in Fig. 4. One can observe that there are some relationships between the road network scale and carrying capacity are stated in the following paragraphs.

(1) There is a specific critical density and road network carrying capacity in different scales of road network. For example, the critical density of the 3×3 road network is 0.135, and the network carrying capacity is 149. When the road network changes to 5×5, the critical density and the carrying capacity of the road network become 0.085 and 306, respectively. If the traffic flow in the road network exceeds the road network carrying capacity and the operation time is long enough, congestion will be formed, leading to gridlock.

(2) The critical density decreases with the increase in the network scale. The critical density $\rho_c(N)$ would be higher when the network scale is smaller. When the road network scale is large and thus the density is low, the local deadlocks would possibly occur if most vehicles are concentrated on a particular region, such as a Central Business District (CBD). This also explains that why big cities are more prone to traffic congestion even though the average road area per vehicle is the same. The present simulation results are not yet determined to convergent to a critical value, or converge to 0 when the road network scale tends to infinity.

(3) The carrying capacity of the road network is proportional to the road network scale, but the carrying capacity is less sensitive to the change in the network scale. For example, the 7×7 road network has 7,504 cells, which is 6 times more than the 3×3 road network (1,104 cells). Nevertheless, the road network carrying capacity only increases less than 3 times, from 149 to 488. This implies that, even if the expansion of the road network matches the growth of the traffic demand, the urban road network will still be even more congested.

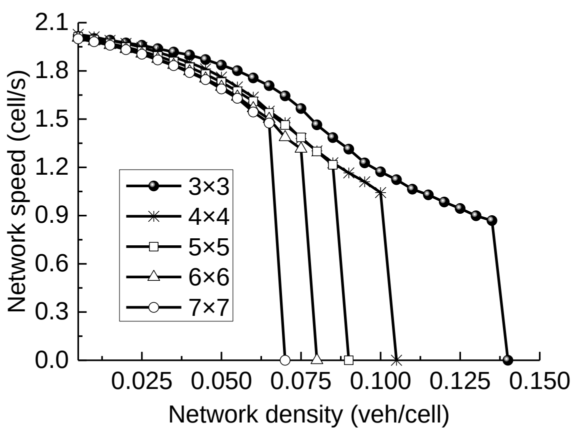

Fig.4 The influence of the road network scale on carrying capacity.

Table1 Estimated indicators of road network based on CA model simulation

Scale	K	L	N_{cell}	$\rho_c(N)$	$N(\rho_c)$
3×3	2	20	1,104	0.135	149
4×4	2	20	2,176	0.1	218
5×5	2	20	3,600	0.085	306
6×6	2	20	5,376	0.075	403
7×7	2	20	7,504	0.065	488

3.3 The effect of the road network structure

The road network structure is a comprehensive concept, including the functional structure, hierarchical structure and layout structure of the road network. In practice, two road networks with the same scale may have quite different capacities due to the different configurations of the road network. Three road networks with different structures to simulate and analyze the influence of the road network structure on road network carrying capacity are shown in Table 2.

The influences of the road network structure on carrying capacity are plotted in Fig. 5. One can observe that there are some relationships between the road network structure and carrying capacity.

(1) Road widening can improve the road network carrying capacity, but the increase in carrying capacity is less than the increase in the number of lanes. For example, the critical density of a 5×5 two-way-two-lane road network is 0.11, and the carrying capacity is 187. Assuming that the road length and scale of the network are constant. The two-way-two-lane roads are changed to two-way-four-lane roads, and then the total number of cells is changed from 1,700 to 3,600. Here, the road width is doubled and the total area of the road network is increased by 1.1 times, but the road network carrying capacity is only increased to 306 (0.6 times). This means simply widen roads cannot induce the same effect in the growth of road network carrying capacity.

(2) The carrying capacity of the road network is inversely proportional to the number of intersections and proportional to the road length. For example, there are two different road networks with two-way-four-lane. The one is a 5×5 network with 20 cells in the road length and 25 intersections. Another one

is a 4×4 network with 35 cells in the road length and 16 intersections. The total number of cells of the two-road network are 3,600 and 3,616, respectively. Table 2 shows that the critical density of the 5×5 road network is 0.085, the carrying capacity is 306, and the critical density of the 4×4 road network is 0.09, and the carrying capacity is 325. This means the decrease in the number of intersections and the increase in the length of the road are beneficial to improve the carrying capacity of the road network.

Table 2 Network carrying capacity estimations based on simulation results

Scale	K	L	N_{cell}	$\rho_c(N)$	$N_c(\rho)$
5×5	2	20	3600	0.085	306
5×5	1	20	1700	0.11	187
4×4	2	35	3616	0.09	325

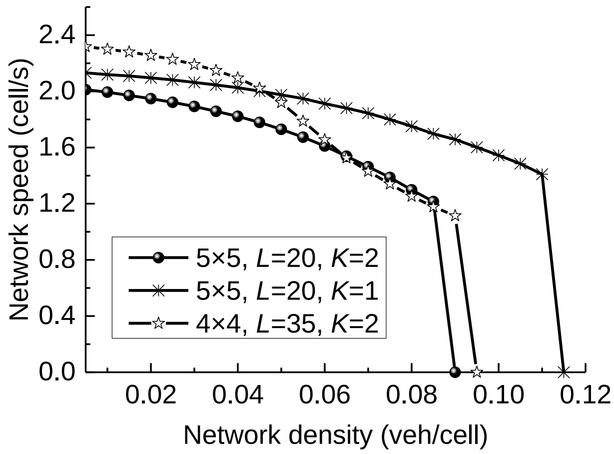

Fig.5 The influence of the road network structure on carrying capacity.

3.4 The effect of the O-D demand pattern

In the model, the destination of the vehicle is randomly selected. Therefore, the O-D matrix is position-independent and the spatial distribution of the O-D demand is balanced, while the attracted traffic and generated traffic on each road section is balanced. Table 3 shows the probability of being selected for 80 mainline sections within the 5×5 road network from the relatively shortest path sets. the traffic flow of each mainline section is positively related to the probability of what are selected from the shortest path set. This means that, the higher the probability of being selected, the heavier the traffic flow would be. Here, the position-independent O-D matrix pattern is changed to the position-dependent one, which means the probability that the mainline section is selected as an origin or a destination is negatively related to the probability of being selected from the shortest path set, so as to simulate the effect of the O-D demands distribution pattern on the road network carrying capacity.

Table 3 The probability of being selected in the shortest path set.

Road section number	Proportion (%)
1 , 7 , 9 , 18 , 63 , 72 , 74 , 80	6.0
2 , 8 , 10 , 17 , 64 , 71 , 73 , 79	7.2
3 , 5 , 27 , 36 , 45 , 54 , 76 , 78	7.3
11 , 16 , 19 , 25 , 56 , 62 , 65 , 70	9.0
4 , 6 , 28 , 35 , 46 , 53 , 75 , 77	9.4
12 , 15 , 20 , 26 , 55 , 61 , 66 , 69	9.9
13 , 14 , 37 , 38 , 43 , 44 , 67 , 68	10.3
21 , 23 , 29 , 34 , 47 , 52 , 58 , 60	12.6
22 , 24 , 30 , 33 , 48 , 51 , 57 , 59	13.8
31 , 32 , 39 , 40 , 41 , 42 , 49 , 50	14.4
Total	100

The effect of the O-D demand distribution pattern on the road network carrying capacity is displayed in Fig. 6. One can observe that the critical density is 0.085 when the O-D demand distribution pattern is position-independent, while the critical density is 0.09 when the O-D demand pattern is position-dependent. As can be seen, changing the O-D demands distribution pattern may change the road network carrying capacity. In addition, changing O-D demands distribution pattern would affect the network speed. This implies that the optimization of O-D demands distribution would improve the road network efficiency.

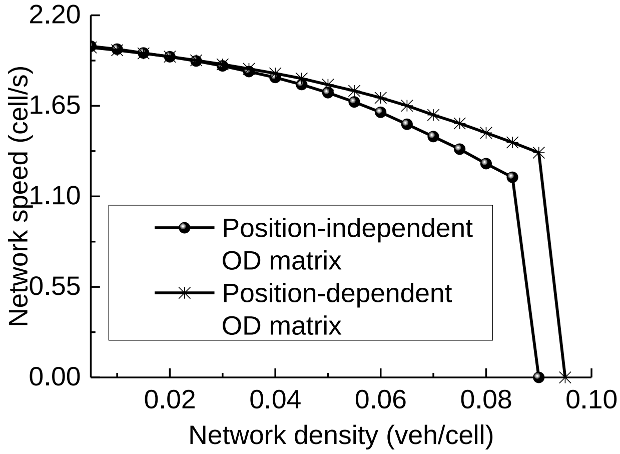

Fig.6 The effect of O-D demands distribution pattern on the road network carrying capacity.

4 Conclusions

In this paper, an updated CA model for urban two-way-four-lane network systems with all-way stop control intersections was proposed to investigate the effect of the road network scale, the road network structure, and the O-D demand pattern on the road network carrying capacity. The main findings are summarized below.

(1) The critical density and road network carrying capacity in different scales of road network are different.

(2) The critical density decreases with the increase in the network scale.

(3) The carrying capacity of the road network can be expanded by increasing the road network scale, but the increase in the carrying capacity of the road network is less than the increase in the road network scale.

(4) Road widening can improve the road network carrying capacity, but the increase in carrying capacity is less than the increase in the number of lanes.

(5) The carrying capacity of the road network decreases with the increase in the number of intersections and the decrease in the road length.

(6) Changing the O-D demand distribution pattern can affect the network carrying capacity, speed and efficiency.

Since the updated CA model has not been validated by field tests, more factors will be considered in the future to simulate the realistic road network, such as signal control, reasonable traffic demand distribution, diverse routing choice, and so on. In addition, the road network design problem should be considered, such as adaptive signal control, connected vehicle, and route guidance to optimize the carrying capacity of urban road networks.

Acknowledgments

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