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ENHANCING HIGHWAY CAPACITY BY HOMOGENIZING TRAFFIC FLOW

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This paper studies the capacity of a highway with an on-ramp, using a cellular automaton (CA) model. This CA model is in the framework of three phase traffic theory and can reproduce the first order phase transition from the free flow to synchronized flow (Jiang and Wu, 2005, *European Physical Journal B*, **46**, 581-584). It is shown when some special homogeneous boundary conditions are used, the capacity of the on-ramp system is greatly enhanced because the strong interactions of main road vehicles and on-ramp vehicles, which occur under inhomogeneous boundary conditions, are avoided. Based on this finding, we propose a new design of road section upstream of on-ramp, i.e., to split the main road into several branches and then the branches merge together. With the help of traffic light control, the inhomogeneous vehicles are homogenized. Accordingly, the capacity is enhanced.

KEYWORDS: Traffic flow, highway capacity, on-ramp

1. INTRODUCTION

Freeway traffic is a complex dynamic process, in which complex spatiotemporal congested patterns are observed. The systematic investigation of traffic flow has a quite long history (see, e.g., Banks, 2002; Chowdhury et al., 2000; Daganzo, 1997; Helbing, 2001; Kerner, 2004; May, 1990) and it is found the transition from free flow to congested flow usually occurs near the inhomogeneities (also referred to as bottlenecks) on the roads. The inhomogeneities include on-ramp, off-ramp, speed limit, reduction of the width of road etc. Among these inhomogeneities, the on-ramp is of particular interest and has been widely studied (Cassidy and Rudjanakanoknad, 2005; Jiang et al., 2002; Li et al., 2007; Gupta and Katiyar, 2006; Ciamarra, 2005; Huang, 2006, Ngoduy, 2006; Albanese et al., 2003).

To enhance the capacity of highway with an on-ramp, various kinds of methods have been proposed. For example, the ramp metering method has been widely studied and applied in real traffic (Papageorgiou and Kotsialos, 2002; Kerner, 2005; Xin et al., 2004; Sun and Horowitz, 2006; Shen and Chang, 2007; Hegyi et al., 2005). Recently, a cooperative merge strategy is investigated by Davis (2006a, 2006b, 2007) and Jiang and Wu (2006). Furthermore, Jiang et al. (2006) has proposed to use a loop structure at the merge region of the on-ramp, and they show from simulations that the capacity could be enhanced.

In this paper, the highway capacity with an on-ramp is further studied using a cellular automaton (CA) model. The model is in the framework of three phase traffic theory and can reproduce the first order phase transition from free flow to synchronized flow (Jiang and Wu, 2003, 2004, 2005). Moreover, the spatial-temporal patterns at an isolated on-

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ramp are also investigated and it is shown that the patterns are qualitatively consistent with empirical observations.

Our studies show the highway capacity could be greatly enhanced if the traffic flow is homogeneous upstream of the merge region. Based on this, we propose a new design of road section upstream of on-ramp to homogenize traffic flow. As a result, the highway capacity is enhanced.

The paper is organized as follows. In Section 2, the CA model used is briefly reviewed and the setup of the on-ramp is presented. In Section 3, the simulation results are presented and the new design is introduced. The conclusions are given in Section 4.

2. MODEL, BOUNDARY CONDITIONS AND SETUP OF ON-RAMP

For the sake of the completeness, we briefly recall the CA model (Jiang and Wu, 2003, 2004, 2005). The parallel update rules of the model are as follows:

(1) Determination of the randomization parameter $p_n(t+1)$:

$$p_n(t+1) = p(v_n(t), b_{n+1}(t), t_{h,n}, t_{s,n})$$

(2) Acceleration:

if $((b_{n+1}(t) = 0 \text{ or } t_{h,n} \geq t_{s,n}) \text{ and } (v_n(t) > 0))$ then: $v_n(t+1) = \min(v_n(t)+2, v_{\max})$

elseif $(v_n(t) = 0)$ then: $v_n(t+1) = \min(v_n(t)+1, v_{\max})$

else: $v_n(t+1) = v_n(t)$

(3) Braking rule:

$$v_n(t+1) = \min(d_n^{\text{eff}}, v_n(t+1))$$

(4) Randomization and braking:

if $(rand() < p_n(t+1))$ then: $v_n(t+1) = \max(v_n(t+1)-1, 0)$

(5) The determination of $b_n(t+1)$:

if $(v_n(t+1) < v_n(t))$ then: $b_n(t+1) = 1$

if $(v_n(t+1) > v_n(t))$ then: $b_n(t+1) = 0$

if $(v_n(t+1) = v_n(t))$ then: $b_n(t+1) = b_n(t)$

if $v_n(t+1) \geq v_c$ and $t_{f,n} \geq t_{c1}$, then: $b_n(t+1) = 0$

(6) The determination of $t_{st,n}$:

if $v_n(t+1) = 0$ then: $t_{st,n} = t_{st,n} + 1$

if $v_n(t+1) > 0$ then: $t_{st,n} = 0$

(7) The determination of $t_{f,n}$:

if $v_n(t+1) \geq v_c$ then: $t_{f,n} = t_{f,n} + 1$

if $v_n(t+1) < v_c$ then: $t_{f,n} = 0$

(8) Car motion:

$$x_n(t+1) = x_n(t) + v_n(t+1).$$

Here x_n and v_n are the position and velocity of vehicle n (here vehicle $n+1$ precedes vehicle n), d_n is the gap of the vehicle n, b_n is the status of the brake light (on(off)$\rightarrow b_n = 1(0)$). The two times $t_{h,n} = d_n / v_n(t)$ and $t_{s,n} = \min(v_n(t), h)$, where h determines the range of interaction with the brake light, are introduced to compare the

time $t_{h,n}$ needed to reach the position of the leading vehicle with a velocity dependent interaction horizon $t_{s,n}$. $d_n^{\text{eff}} = d_n + \max(v_{\text{anti}} - gap_{\text{safety}}, 0)$ is the effective distance, where $v_{\text{anti}} = \min(d_{n+1}, v_{n+1})$ is the expected velocity of the preceding vehicle in the next time step and gap_{safety} controls the effectiveness of the anticipation. $rand()$ is a random number between 0 and 1, $t_{st,n}$ denotes the time that the car n stops, $t_{f,n}$ denotes the time that car n is in the state $v_n \geq v_c$. The randomization parameter p is defined:

$$p(v_n(t), b_{n+1}(t), t_{h,n}, t_{s,n}) = \begin{cases} p_b & : \text{ if } b_{n+1}=1 \text{ and } t_{h,n}<t_{s,n} \\ p_0 & : \text{ if } v_n=0 \text{ and } t_{st,n}\geq t_c \\ p_d & : \text{ in all other cases} \end{cases} .$$

Here v_c, t_c and t_{c1} are parameters.

Next we present the setup of the on-ramp. We assume the main road is a single lane road and its length is L. The on-ramp is assumed to be from L_1 to L_2 and the length of the merge section is L_m (see Figure 1). In the merge region, the on-ramp vehicle changes lane to the main road, provided the following conditions are met:

$$x_n - x_n^- - d > \lambda v_n^- , \tag{1}$$

$$x_n^+ - x_n - d > \lambda v_n . \tag{2}$$

Here superscripts + and – denote the preceding vehicle and the trailing vehicle in the target lane, respectively; λ reflects the personality of the driver, d is the vehicle length. We would like to point out the merge behaviors could affect system capacity. Although it is believed rules (1) and (2) are qualitatively correct, we need to find out realistic freeway merge behaviors in future study (Sarvi and Kuwahara, 2007; Sarvi et al. 2007).

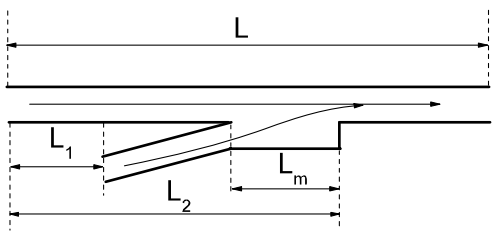

FIGURE 1: The sketch of the on-ramp

The open boundary conditions are adopted as follows. In the exit, when the first vehicle goes beyond L, it is removed from the system and the second vehicle becomes the new leading vehicle and it moves without hindrance. At the entrance of the main road, if the last vehicle is beyond x_{in}, then a new vehicle is inserted at $\min(x_{\text{last}} - x_{\text{in}}, x_{\text{in}})$ with maximum velocity $v_{\max}$ with probability α_{A}. Here x_{in} is a parameter controlling inflow rate, x_{last} is the position of the last vehicle on main road. At the entrance of the on-ramp, if the last vehicle is beyond $L_1 + x_{\text{in}}$, then a new vehicle is inserted at $\min(x_{\text{on,last}} - x_{\text{in}}, L_1 + x_{\text{in}})$ with maximum velocity $v_{\max}$ with probability α_{B}. Here $x_{\text{on,last}}$ is the position of the last vehicle on on-ramp.

In the next section, the simulations are carried out. In the simulations, the parameter values are $t_c = 7$, $t_{c1} = 30$, $v_c = 18$, $v_{\max} = 20$, $p_d = 0.1$, $p_b = 0.94$, $p_0 = 0.5$, $h = 6$, $gap_{\text{safety}} = 7$, $\lambda = 1.0$, $L = 30000$, $L_1 = 15000$, $L_2 = 16000$, $L_m = 300$ unless otherwise mentioned. Each cell corresponds to 1.5 m and a vehicle has a length of five cells. One time step corresponds to 1 s.

3. SIMULATION RESULTS

In this section, the simulation results are presented. We assume initially there is no vehicle on the road. From $t = 0$ the vehicles enter the main road with probability α_A and enter the on-ramp with probability α_B. The simulation lasts for 10 800 time steps (3 hours). In Figure 2, the typical traffic patterns found in empirical observation are reproduced.

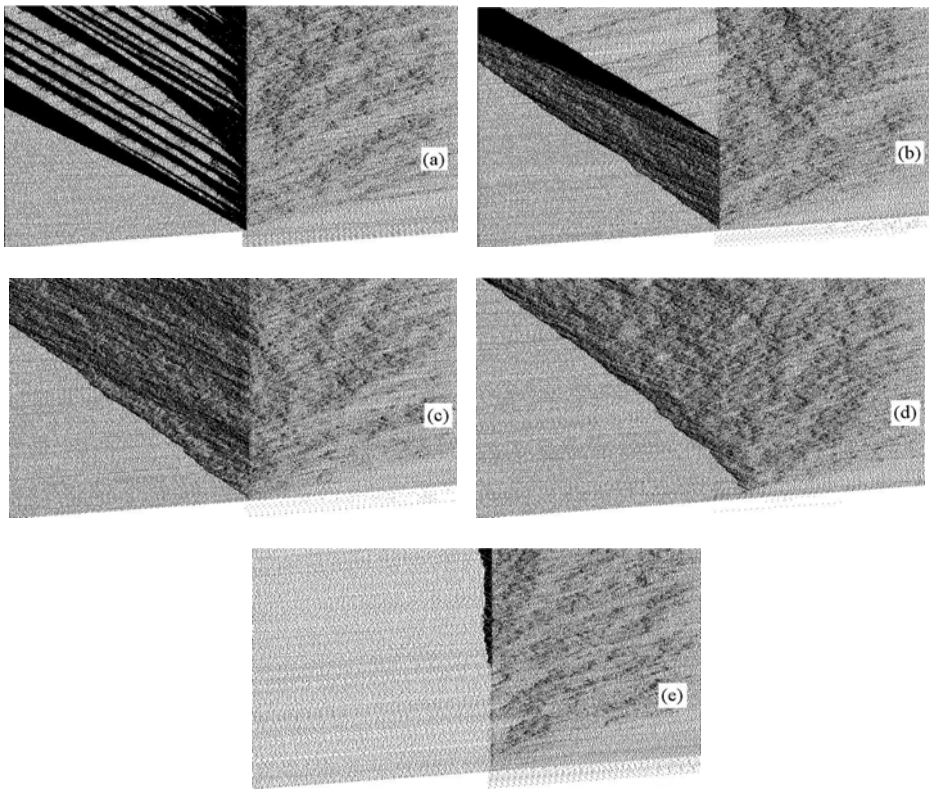

FIGURE 2: The typical traffic patterns induced by the on-ramp. The parameter $x_{\text{in}} = 30$. (a) GP, $\alpha_A = 0.6$, $\alpha_B = 0.5$; (b) DGP, $\alpha_A = 0.6$, $\alpha_B = 0.06$; (c) WSP, $\alpha_A = 0.6$, $\alpha_B = 0.04$; (d) ASP, $\alpha_A = 0.6$, $\alpha_B = 0.01$; (e) LSP, $\alpha_A = 0.36$, $\alpha_B = 0.15$. Here traffic moves from left to right and the time is increasing in up direction. Each point on the plot represents a vehicle on the location *x* at time *t*. Therefore, the darker the area is, the larger the density is.

In Figure 2a, the flow rates on both main road and on-ramp are high. As a result, the general pattern (GP) is observed. GP remains when on-ramp flow rate decreases. However, when on-ramp flow rate is small, the outflow rate of the jam is smaller than the capacity of the on-ramp system, free flow will form between the location of the on-ramp and the downstream front of the jam. As a result, the dissolving general pattern (DGP) is observed (Figure 2b). When the on-ramp further decreases, the jam will not spontaneously occur in the synchronized flow and the widening synchronized flow pattern (WSP) appears (Figure 2c). When the on-ramp flow is very small, the main road flow is perturbed by the on-ramp flow and consequently the synchronized flow is induced. However, the on-ramp flow will not become a bottleneck to the main road flow. In this way, the alternations of free and synchronized flow (ASP) is observed (Figure 2d). Between the region of GP and free flow, the localized synchronized flow pattern (LSP) exists (Figure 2e).

We investigate the capacity of the on-ramp system. Here for simplicity, we only consider the case that both main road flow and on-ramp flow are high. Our simulations show that when GP occurs, the capacity is approximately 1700 veh/h, which is essentially independent of α_A and α_B because congestion occurs on both main road and on-ramp. The contribution of the main road is 890 veh/h and that of the on-ramp is 810 veh/h.

Next we adopt a different boundary condition for the on-ramp. A new car is inserted at $x = 1$ at time step $3m + 1$ on main road with maximum velocity, and a new car is inserted at $x = L_1$ at time step $3m + 2$ on on-ramp with maximum velocity. Here m is an integer $0, 1, 2, \ldots$. The parameters used are $L = 14400$, $L_2 = 400$, $L_1 = 50$. Initially there is no vehicle on the road. Under such boundary condition, the capacity is 2400 veh/h, much higher than 1700 veh/h. The contributions of both main road and the on-ramp are 1200 veh/h.

Let us have a look at the distribution of the vehicles in the merge region. It is found that the headways of vehicles on on-ramp to the vehicle ahead (on target lane) and vehicle back (on target lane) slightly fluctuate around 30. In other words, when the first vehicle (suppose it is from main road) reaches $x = x_1$, the second vehicle (which is from on-ramp) reaches $x \approx x_1 - 30$, the third vehicle (which is from main road again) reaches $x \approx x_1 - 60$, and so on. Therefore, the on-ramp vehicles always have the chance to change lane to main road far before they reach the end of the merge region. Moreover, when the vehicle on on-ramp changes lane to main road, it does not brake and the back vehicle on target lane does not brake, either. In other words, the strong interactions of main road vehicles and on-ramp vehicles, which occur under inhomogeneous boundary conditions, are avoided. As a result, the high capacity is maintained.

In real traffic, the entry of vehicles is always inhomogeneous. For example, we consider the following traffic situations: the vehicles enter the main road with probability $\alpha_A = 0.5$ and $x_{in} = 30$ and enter the on-ramp with probability $\alpha_B = 0.4$ and $x_{in} = 30$, which implies main road inflow rate $q_{in} \approx 1680$ veh/h and on-ramp inflow rate $q_{on} \approx 1390$ veh/h. Under normal on-ramp setup as shown in Figure 1, the capacity is approximately 1700 veh/h as shown before.

Next we propose a new design of road section upstream of on-ramp, which homogenizes the vehicles and accordingly enhances the capacity. The design is shown in Figure 3. Both the main road and on-ramp expand into two roads and then the two roads

merge into one again just upstream of the merge region. Note that this method is widely used at tollbooth system on highways (Jiang et al, 2004; Huang and Huang, 2002). When the vehicles approach the diverge, the drivers select a branch, which has enough space for a vehicle (i.e., the last vehicle on the branch should be beyond $x_{\text{div}}+10$ with x_{div} the position of diverge point), with the same probability. If none of the branches has enough space for a vehicle, then the drivers select the branch on which the last vehicle is the farthest.

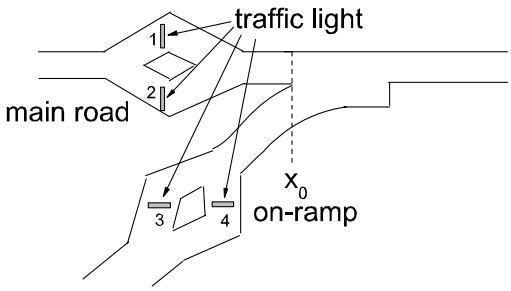

FIGURE 3: The sketch of the new design of road section upstream of on-ramp

On each of the four branches, a traffic light is set. Suppose traffic light 1 is at $x = x_1$, then traffic light 2 is at $x_2 = x_1$, traffic light 3 is at $x_3 = x_1 - 10$, traffic light 4 is at $x_4 = x_1 - 10$. Traffic light 1 is switched to green on time step $6m+1$ to allow one vehicle to pass, and then is switched to red. Similarly, traffic light 2 is switched to green on time step $6m+4$; traffic light 3 is switched to green on time step $6m+2$; traffic light 4 is switched to green on time step $6m+5$. For the first vehicle upstream of the traffic light, the gap between the vehicle and the stop line is used when the signal is red (Spyropoulou, 2007). We suppose that when the traffic light switches to green, the vehicle accelerates with constant acceleration $a = 1$ before it reaches the maximum velocity, then it moves according to CA model used in this paper. In this way, the vehicles enter the merge region homogeneously and high capacity 2400 veh/h is maintained [6]. One each branch, the flow rate is 600 veh/h.

Figure 4 shows the spatio-temporal plot of the main road. Here the length of the expansion region is 300 and it ends at x_0, the position of the traffic light 1 is at $x_1 = x_0 - 200$. One can see that the lane expansion and the traffic lights homogenize the vehicles. In Figures 4b and 4d, the details near the traffic lights are shown. One can see that homogeneous free traffic forms (on each branch) downstream of the traffic lights. The vehicles on the four branches almost do not interact with each other when they enter the merge region area.

We need to point out the density of the queue between the traffic lights and diverge point is larger than the density upstream of the diverge. The queue results in low speed and large time delay in this road section. However, by reducing the length of this road section, the influence of the queue could be greatly suppressed. As for traffic flow upstream of the diverge point, the congestion is even more serious if no control method

[6] Note under interrupted traffic contexts, such as signalized highways or intersections, capacity is less than highest flow rate, in which some adjustment factors normally apply. In this paper, we simply define capacity of the new design on-ramp system as highest flow rate.

is adopted, because the flow rate is lower without control method (c.f. Figure 2a and Figure 4a).

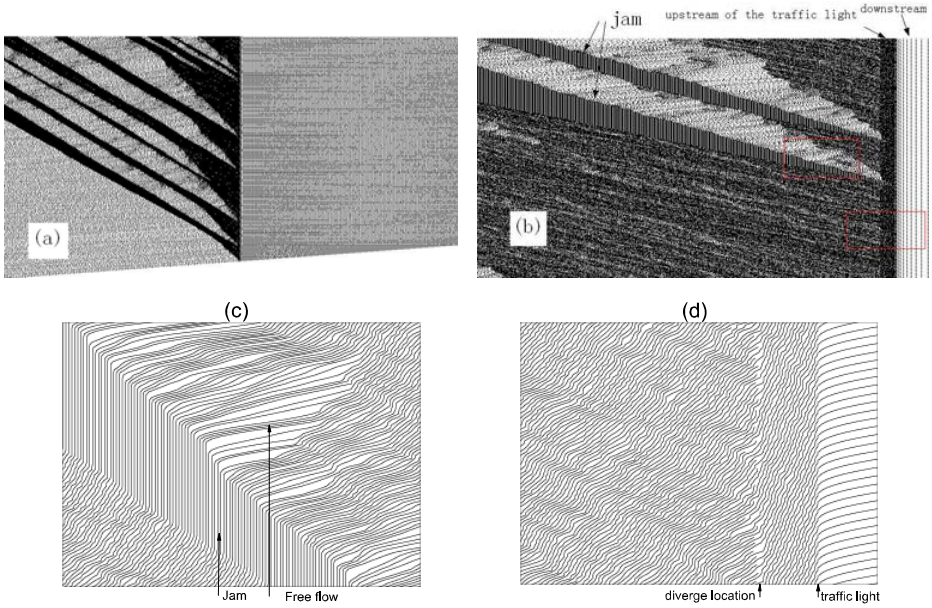

FIGURE 4: The spatio-temporal plot of the main road under new design. Note only the traffic situations on one branch are shown and those on other branch are similar. (a) shows the full picture and (b) shows the details near the traffic lights. (c) and (d) show the details in the red square area in (b). The cars are moving from left to right and the time in increasing in up direction.

Since usually the on-ramp flow is not so high as main road flow, we may split the main road into three roads and the on-ramp does not split. In this way, the flow rate on main road can reach 1800 veh/h. Let us discuss the dependence of highway capacity on the on-ramp flow rate q_{on} and main road flow rate q_{in} under this situation. (i) When $q_{\text{on}} > 600$ and $q_{\text{in}} > 1800$, the capacity is 2400 veh/h; (ii) When $q_{\text{on}} < 600$ and $q_{\text{in}} > 1800$, the capacity is $q_{\text{on}} + 1800$ veh/h; (iii) When $q_{\text{on}} > 600$ and $q_{\text{in}} < 1800$, the capacity is $q_{\text{in}} + 600$ veh/h; (iv) Finally, when $q_{\text{on}} < 600$ and $q_{\text{in}} < 1800$, the capacity is $q_{\text{in}} + q_{\text{on}}$. The capacity is smaller in cases (ii)-(iv) than in case (i).

When $q_{\text{in}} + q_{\text{on}}$ is small and free flow could exist on the road even under normal setup of on-ramp, the new design is not needed. For the case, only one branch is needed and the traffic light on the branch needs to be switched off and all other branches need to be closed.

If we split the main road into four roads, then a higher capacity can be reached. In this case, suppose traffic light 1 is at $x = x_1$, then traffic light 2 is at $x_2 = x_1 + 12$, traffic light 3 is at $x_3 = x_1 + 4$, traffic light 4 is at $x_4 = x_1 + 16$, traffic light 5, which is on on-ramp, is at $x_5 = x_1 + 8$. The traffic lights are switched to green in the following way: Traffic light 1 is on time step $7m$, traffic light 2 is on time step $7m + 2$, traffic light 3 is

on time step $7m+3$, traffic light 4 is on time step $7m+5$, traffic light 5 is on time step $7m+6$. The spatial arrangement of traffic lights ensures the vehicles enter the merge region homogeneously with headway 28. As a result, the capacity 2570 veh/h is reached. One each branch, the flow rate is 514 veh/h.

Free flow with high flow rate (e.g., 2700 veh/h) cannot be maintained for a long time due to the intrinsic fluctuation and it will transit into congested flow spontaneously, even if the entrance boundary condition is homogeneous. Therefore, there is no need to discuss cases with more than 5 branches.

To demonstrate the benefit of the design is not artificial effect of the CA model, we have reproduced the result with a modified optimal velocity car-following model (Bando et al., 1995):

$$\frac{\mathrm{d}v_n}{\mathrm{d}t} = \min\left(\kappa[V(\Delta x) - v_n], a^+\right). \tag{3}$$

Here V is optimal velocity, x and v are position and velocity of vehicles, $\Delta x = x_{n+1} - x_n$ is headway between vehicle n and vehicle $n+1$, a^+ is maximum acceleration of vehicles. In the simulations, the optimal velocity function

$$V(\Delta x) = \begin{cases} V_\mathrm{f} & \text{if } \Delta x > x_\mathrm{c} \\ \dfrac{q_\mathrm{max}}{1/x_\mathrm{j} - 1/x_\mathrm{c}}\left(\dfrac{\Delta x}{x_\mathrm{j}} - 1\right) & \text{if } \Delta x < x_\mathrm{c} \end{cases} \tag{4}$$

is used. Here V_f is maximum velocity, q_max is maximum flow rate, x_j is the minimum headway, x_c is headway corresponding to the maximum flow rate. The fundamental diagram corresponding to the optimal velocity function is shown in Figure 5. The merging strategy shown in equations (1) and (2) is adopted. We carry out the simulations with the parameters $V_\mathrm{f} = 30$ m/s, $q_\mathrm{max} = 2400$ veh/h, $x_\mathrm{j} = 7.5$ m, $x_\mathrm{c} = 45$ m, $a^+ = 3$ m/s^2, $\kappa = 1.8$ s^{-1}, $\lambda = 0.8$ s. Our simulations show the capacity is approximately 1833 veh/h under normal on-ramp setup and it could reach maximum flow rate 2400 veh/h under the new design.

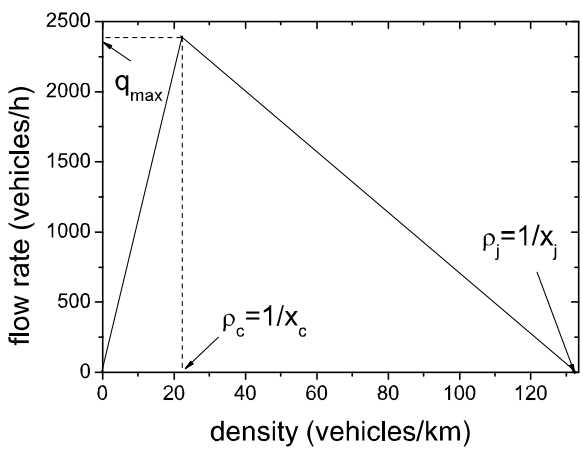

FIGURE 5: The fundamental diagram corresponding to the optimal velocity function

In real traffic, the heterogeneous vehicles and drivers may bring some problems to the design. Firstly, we discuss the response time to traffic lights. It is found the result is unchanged if the response time of drivers equals to each other. However, if the response time of drivers differs greatly from each other (for example, response time of some drivers is one second while it is two seconds for others), then the homogenization effect disappears. Similarly, if the acceleration of vehicles differs greatly from each other, then the homogenization effect also disappears. When the difference of acceleration and response time of different vehicles is small, the homogenization is still valid.

Next we discuss the different merge behaviors. This is fulfilled by giving different values of λ to different drivers. Our simulations show the result is unchanged provided the maximum of λ is not very large ($\lambda < \lambda_c \approx 1.25$ for four branches case shown in Figure 3). Otherwise, the vehicle will not be able to merge into main road and have to stop in merge region.

Finally, some vehicles have large maximum velocity, some trucks are much longer. Therefore, it is important to limit the maximum velocity of the vehicles near the merge region. Otherwise, the homogeneous boundary conditions will be violated. When a long truck is detected passing the light, we may stop the next traffic light from switching to green for one time. In this way, the headway between the truck and its follower will be large enough and the follower does not need to brake.

4. CONCLUSIONS

In this paper, we have studied the traffic flow in a CA model with an on-ramp in the open boundary conditions. This CA model is in the framework of three phase traffic theory, it can reproduce the synchronized flow quite satisfactorily and can reproduce the first order phase transition from the free flow to synchronized flow.

The simulations show that the typical traffic patterns found in empirical observation can be reproduced under inhomogeneous boundary conditions. Furthermore, we found that when homogeneous boundary conditions are used, the capacity of the on-ramp system is greatly enhanced because the strong interactions of main road vehicles and on-ramp vehicles, which occur under inhomogeneous boundary conditions, are avoided. Next we propose a new design of road section upstream of on-ramp, i.e., to split the main road into several branches and then the branches merge together. With the help of traffic light control, the inhomogeneous vehicles are homogenized. Accordingly, the capacity increases.

The heterogeneity of vehicles and drivers (e.g., different response time to traffic light, different acceleration) may violate the homogenization effect. Therefore, how to minimize the heterogeneity of vehicles and drivers in expansion region is an important task to ensure the performance the proposed design[7].

In real traffic, the main road usually has two lanes or three lanes. Actually, our preliminary study has found for a multi-lane on-ramp system, the capacity could be enhanced by forbidding lane changing between the rightmost lane and other lanes near the on-ramp. In this way, the rightmost lane and the on-ramp constitute a one-lane freeway on-ramp system, as discussed in our paper. Therefore, we believe our proposed

[7] One possible choice is moving guide system, in which an object moves along the roadside from stop line when the traffic light turns into green. It starts from zero velocity and accelerates with constant acceleration, and maintains constant velocity after maximum velocity is reached. The vehicles just follow the movement of the object before they enter merge region.

design is still in effect for multi-lane on-ramp system. Of course, more investigations are needed in the future work.

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