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Instantaneous information propagation in free flow, synchronized flow, stop-and-go waves in a cellular automaton model*

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Recently, a number of efforts are underway to investigate inter-vehicle communications (IVC). This paper studies the instantaneous information propagation behaviours based on IVC in three different traffic situations (free flow, synchronized flow and stop-and-go waves) in a cellular automaton model. It is shown that different behaviours appear in stop-and-go waves from those in free flow and synchronized flow. While the distribution of Multi-hop Communication Distance (MhCD) is either exponential or uniform in free flow and synchronized flow, the distribution of MhCD is either exponential or with a single peak in stop-and-go waves.

Keywords: traffic flow, inter-vehicle communications, cellular automaton model
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1. Introduction

Recently the traffic flow problem has attracted the interest of physicists and engineers and many models have been presented to simulate various driving behaviours.[1−10] With the rapid progress of communication technology, more comfort and convenience could be provided by using, e.g., adaptive cruise control system and wireless communication technologies.

The rapid development of wireless communication technologies, now makes feasible the exploration of traffic information systems which decentralizes the tasks of collecting and disseminating traffic information. A number of efforts are currently underway to investigate inter-vehicle communications (IVC) based on mobile ad hoc networking technology as a means of developing the 'internet on the road' (e.g., Refs.[11–13]).

This paper focuses on a fundamental issue regarding performance of such a system, i.e., how far can information be expected to propagate in a traffic system under certain traffic conditions, penetration rate of equipped cars, and transmission range of wireless units? By providing some general answers to this question, we hope to help guide specification of appropriate communication devices, routing protocols, and database management schemes that would be required in order to have the most important information collected and distributed, and to determine the range of applications for which a mobile, ad hoc traffic information system might be effective.

In previous work, Hartenstein *et al*[14] simulated the process of information propagation by using the cellular automaton (CA) model, presenting results on the probability that two equipped vehicles could establish connection through IVC under different transmission ranges. In Ref.[15], IVC was simulated with Paramics, a microscopic traffic simulator, and the maximum information propagation distance was evaluated against transmission range and penetration rate for unidirectional roads, bi-directional roads, and road networks. In Ref.[16], propagation of travel time information was studied in a grid road network through information exchange between vehicles travelling in opposite directions. Jin and Recker[17] developed an analytical model of the probability that a message can travel beyond a point in a traffic stream on a link.

The empirical observations show that in real traffic, there exist complex traffic phenomena such as synchronized flow, stop-and-go waves etc. As noted in Ref.[17], traffic patterns have significant influences on

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the distribution of the locations of equipped vehicles and therefore on the performance of IVC. However, in the previous studies, the information propagation behaviours were only studied for very simple scenarios of uniform or piecewisely uniform traffic streams, but not identified for stop-and-go waves or synchronized flow.

In this paper, the problem is investigated by using a CA traffic flow model. Recently, modelling road traffic behaviour using CA has become a well-established method to model, analyse, understand, and even forecast the behaviour of real road traffic.[18,19] We study the dependence of Multi-hop Communication Distance (MhCD), i.e., the distance a piece of information propagates, on the transmission range R and the penetration rate of equipped vehicles μ in free flow, synchronized flow and in stop-and-go waves. As in Ref.[17], we assume that (i) the transmission range R is constant for each hop; (ii) the traffic stream is static, as compared to the information propagation (i.e., instantaneous information propagation behaviours).

In Section 2, the CA model used in this paper is introduced. It is shown that free flow, synchronized flow and stop-and-go waves can be induced by speed limit bottleneck (of different limit speed $v_{\rm lim}$). In Section 3, the instantaneous information propagation behaviours for various traffic patterns are investigated. The conclusions are given in Section 4.

2. Cellular automaton simulation

2.1. A CA model

In this section, the CA model used for simulation is introduced. In the CA models, the roads are classified into cells, a cell is either occupied by a vehicle or empty. The vehicles move with velocity 0, 1, 2, ..., $v_{\max}$, where $v_{\max}$ is an integer representing the maximum velocity of the vehicles.

Recently, the authors have introduced a CA model, which can reproduce the empirical traffic situation quite satisfactorily.[20−22] In the model, the parallel update rules of the model are as follows.

Determination of the randomization parameter p_n(t+1), which takes into account the different behavioural patterns of the individual drivers, especially nondeterministic acceleration as well as overreaction while slowing down,

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

Acceleration:

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

Braking rule:

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

Randomization and braking:

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

Determination of $b_n(t+1)$:

if $((v_n(t+1) > v_n(t))$ or $(v_n(t+1) \geq v_{\rm c}$ and $t_{f,n} > t_{\rm c1}))$
then: $b_n(t+1) = 0$,
else if $(v_n(t+1) < v_n(t))$ then: $b_n(t+1)=1$,
else $(v_n(t+1) = v_n(t))$ then: $b_n(t+1) = b_n(t)$.

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: $t_{st,n} = 0$.

Determination of $t_{f,n}$:

if $v_n(t+1) \geq v_{\rm c}$ then: $t_{f,n} = t_{f,n} + 1$,
if $v_n(t+1) < v_{\rm c}$ then: $t_{f,n}$=0.

Car motion: $x_n(t+1) = x_n(t) + v_n(t+1)$.

Here $x_n(t)$ and $v_n(t)$ are the position and velocity of vehicle n at time instant t (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 $t_{s,n} = \min(v_n(t)\ (\delta t)/(\delta v),\ h)$, 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 $t_{s,n}$, $d_n^{\rm eff} = d_n + \max(v_{\rm anti} - {\rm gap}_{\rm safety}, 0)$ is the effective distance, where $v_{\rm anti} = \min(d_{n+1}, v_{n+1})$ is the expected velocity of the preceding vehicle in the next time step and ${\rm gap}_{\rm safety}$ 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 $v_n \geq v_{\rm c}$. The randomization parameter p is defined as

$$p(v_n(t), b_{n+1}(t), t_{h,n}, t_{s,n}) = \begin{cases} p_{\rm b} : \text{if } b_{n+1} = 1 \ \text{ and } \ t_{h,n} < t_{s,n}, \\ p_0 : \text{if } v_n = 0 \ \text{ and } \ t_{st,n} \geq t_{\rm c}, \\ p_{\rm d} : \text{in all other cases.} \end{cases}$$

Here δt=1, δv=1, t_c=7, t_{c1}=30 and v_c=18 are parameters.

2.2. Simulation set-up

In the simulations, the open boundary conditions are used. In one time step, when the update of the cars on the road is completed, we check the position (the first cell) of the last car and that of the leading car on the road, which are denoted as x_{last} and x_{lead}, respectively. If $x_{\text{last}} > v_{\max}$, a car with velocity $v_{\max}$ is injected with probability α at the cell $\min(x_{\text{last}}-v_{\max}, v_{\max})$. Near the exit of the road, the leading car is removed if $x_{\text{lead}} > L$ (L denotes the position of the right most cell on road) and the following car becomes the new leading car and it moves without any hindrance. The length of the test single-lane road is L=30000 cells. Initially there is no car on the road. From t=0 on, the cars drive into the road with probability α. We assume that there is a speed limit region from x=24900 to x=25000 cells, in which the maximum velocity of vehicles is v_{lim}.

In the simulations, the parameter values are $v_{\max}$=20 (corresponding to 108km/h), $p_d = 0.1$, $p_b = 0.94$, $p_0 = 0.5$, $h = 6$, $\text{gap}_{\text{safety}} = 7$. Each cell corresponds to 1.5m and a vehicle has a length of five cells. One time step corresponds to 1s.

2.3. Three phases of traffic flow

Recently, based on his empirical observations, Kerner developed a three phase traffic theory.[19] In the theory, traffic can be either free or congested, and congested flow is further classified into synchronized flow and jams. While the jams are characterized by constant mean velocity of the downstream jam front, the downstream front of synchronized flow is often fixed at a bottleneck. Moreover, the onset of congestion is usually associated with a phase transition from free flow to synchronized flow and jams can merge spontaneously in synchronized flow.

In Fig.1, we show typical free flow, synchronized flow, and stop-and-go waves induced by the speed limit bottleneck of different v_{lim}. In all three figures, we have a free flow region downstream to the bottleneck. In Fig.1(a), since the capacity of the speed limit region is higher than the demand level at the entrance, free flow with density and speed at 15.5 vehicles/km and 107km/h respectively is maintained upstream to the bottleneck. In Fig.1(b), the capacity of the speed limit region is lower than the demand level at the entrance, as a result, the congestion, i.e., synchronized flow with density and speed at 33.9 vehicles/km and 50km/h respectively, appears. When v_{lim} is very small, the stop-and-go waves occur (Fig.1(c)). But note that, near the speed limit region, synchronized flow exists. In the next section, we shall investigate the instantaneous information propagation behaviours in the three different kinds of traffic situations, respectively.

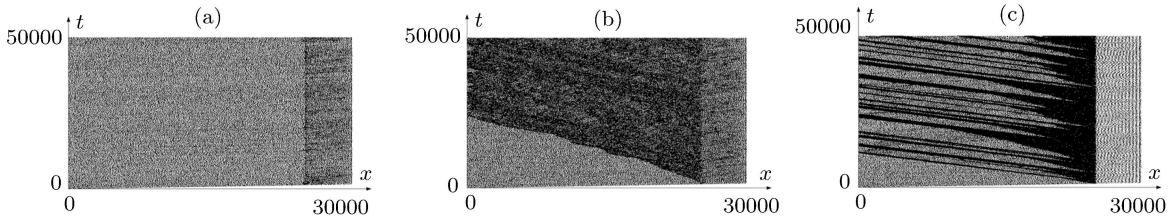


Fig.1. Typical free flow (a), synchronized flow (b), and stop-and-go waves (c) induced by the speed limit bottleneck. In (a) α=0.46, v_{lim}=15; (b) α=0.5, v_{lim}=15; (c) α=0.46, v_{lim}=4.

3. Instantaneous information propagation behaviours

3.1. Free flow

Firstly, we investigate instantaneous information propagation behaviours in free flow shown in Fig.1(a). We focus on the MhCD, i.e., the distance a piece of information propagates, of the first equipped vehicles upstream of the speed limit region. Here we only consider information propagation in the opposite direction of traffic flow. Figure 2 shows the probability distribution of MhCD at various distances in the free flow for different market penetration rate. The probability distribution is obtained from 150000 samples and each data point on the curve denotes the probability that

MhCD is in the range $200M \leq \text{MhCD} < 200(M+1)$, with M=0, 1, 2, ...: i.e., we study the probability $P(M)$ with $\int_0^{+\infty} P(M)\mathrm{d}M = 1$. One can see that the curve is nearly a straight line (with some fluctuations) in the semi-log plane, which means that the MhCD obeys an exponential distribution. With the increase of penetration rate μ, the slope (absolute value) decreases.

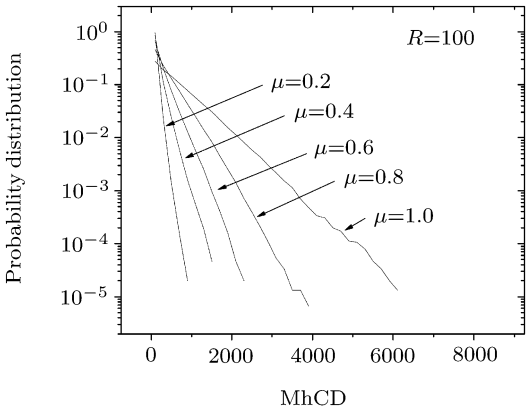


Fig.2. Probability distribution of MhCD in free flow. The transmission range R=100.

Figure 3 shows the probability distribution of MhCD in the free flow where the transmission range R is larger (R=200 cells). One can see that for μ=0.2, 0.4, and 0.6, the exponential distribution of MhCD exists as in Fig.2. However, when μ=0.8 and 1, the information could propagate to the entrance of the road section, i.e., the maximum MhCD is larger than the length of the study area. Therefore, the peak of the distribution curve at MhCD≈25000 means the probability that the information could propagate to the entrance of the road section.

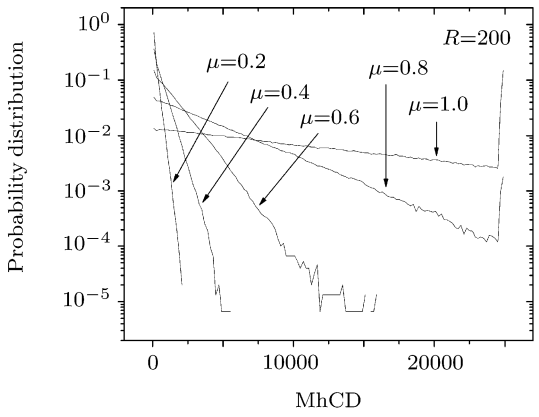


Fig.3. Probability distribution of MhCD in free flow. The transmission range R=200.

Figure 4 shows the distribution of MhCD in the free flow where the transmission range R=400. One can see that when μ=0.8 and 1, the distribution of MhCD is nearly uniform for MhCD<MhCD_m ≈24500. Note that the uniform distribution of MhCD means that the success rate of information propagation is linearly decreasing with the information propagation distance. With the increase of μ, the appearance probability of MhCD smaller than MhCD_m decreases.

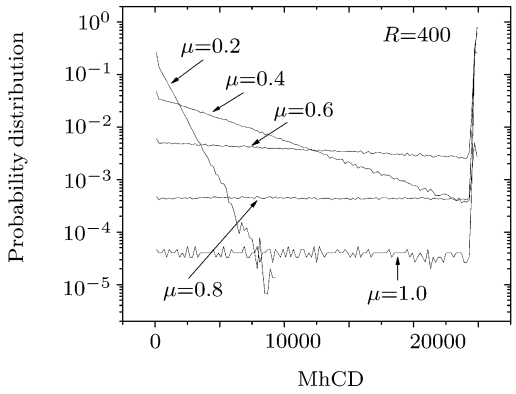


Fig.4. Probability distribution of MhCD in free flow. The transmission range R=400.

Figure 5 shows the distribution of MhCD in the free flow in a larger system where L=60000. The speed limit region is from x=54900 to x=55000. Comparing Fig.5 with Fig.4, one can see that the distributions are the same for MhCD<MhCD_c as shown by the dashed line. Based on this, we argue that in an infinite system, the distribution of MhCD is either exponential or uniform (for not so large R and/or μ).

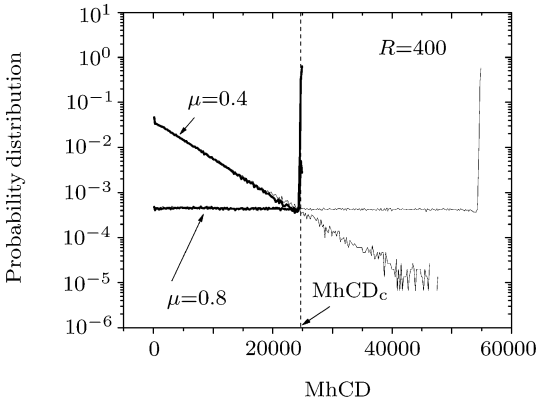


Fig.5. Probability distribution of MhCD in free flow in system of L=30000 (thick lines) and L=60000 (thin lines).

When R and/or μ are large enough, the uniform probability becomes zero and the information can propagate to infinity. Our simulations found that for the free flow shown in Fig.1(a), the maximum headway between two consecutive vehicles is approximately 520 cells. Therefore, when $R > 520$ and μ=1,

the information can always propagate to the entrance of the system, no matter how large the system is.

3.2. Synchronized flow

We investigate the instantaneous information propagation behaviours in synchronized flow (Fig.1(b)). Figure 6 shows the distribution of MhCD in the synchronized flow. One can see that similar to that in free flow, the distribution of MhCD is exponential when penetration rate μ is not so large (Fig.6(a)). For very large μ, the distribution becomes uniform (Fig.6(b)). With the decrease of R, the transition from exponential distribution to uniform distribution occurs at a larger penetration rate μ.

In Fig.7, we compare the average MhCD and the variance of MhCD in free flow and in synchronized flow. One can see that both are larger in synchronized flow. This is because the density is larger in synchronized flow. Therefore, the average distance between two consecutive vehicles is smaller, which is better for the information to propagate.

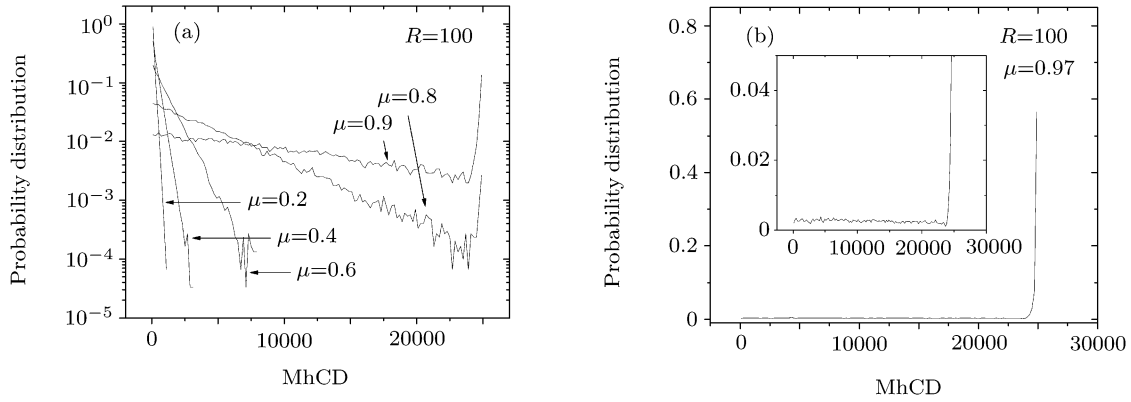


Fig.6. (a) Probability distribution of MhCD in synchronized flow in system of L=30000. (b) The inset shows the details of the uniform distribution.

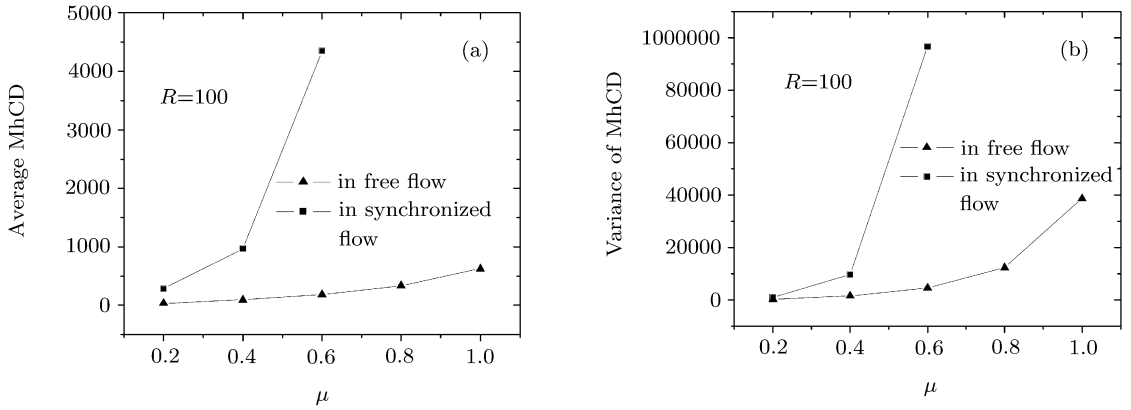


Fig.7. Comparison of average MhCD and variance of MhCD in free flow and synchronized flow.

Similarly as in free flow, when R and/or μ are large enough, the uniform probability becomes zero and the information can propagate to infinity. Our simulations found that for the synchronized flow shown in Fig.1(b), the maximum headway between two consecutive vehicles is approximately 110 cells. Therefore, when $R > 110$ and $\mu = 1$, the information can always propagate to the entrance of the system, no matter how large the system is.

3.3. Stop-and-Go waves

Finally we investigate the instantaneous information propagation behaviours in stop-and-go waves (Fig.1(c)). Figure 8 shows the distribution of MhCD in the stop-and-go waves. When the transmission range R and the penetration rate μ are small, the information cannot propagate far. Since near the speed limit region, the synchronized flow exists, the

distribution of MhCD is exponential (μ=0.2 and 0.3, Fig.8(a)). When μ increases, the information can propagate into the stop-and-go region. As a result, the distribution of MhCD is not exponential (μ=0.4, Fig.8(a)): a peak begins to appear (μ=0.6, Fig.8). If μ continues increasing, the distribution expands and

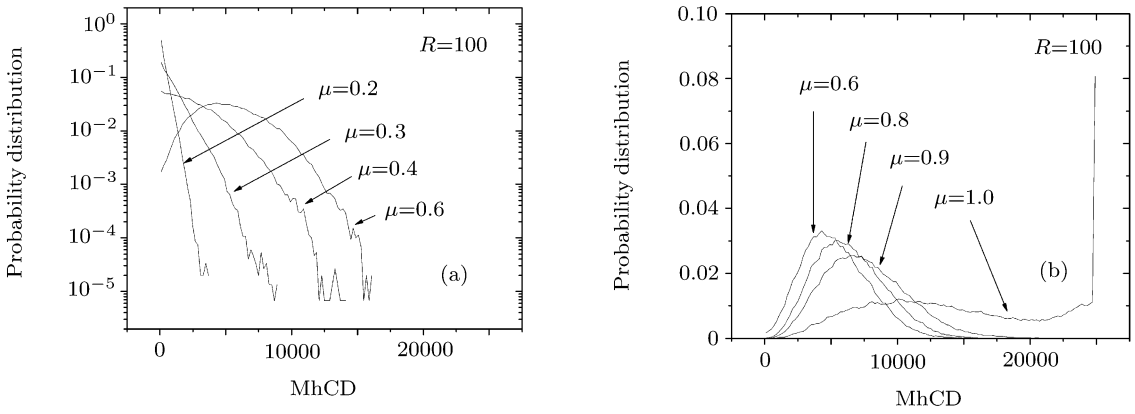


Fig.8. Probability distribution of MhCD in stop-and-go waves in system of L=30000. The transmission range R=100.

the peak decreases and shifts right. When μ=1, the information could propagate to the entrance of the road section, accordingly another peak of the distribution curve appears at MhCD≈25000.

Figure 9 shows the distribution of MhCD in the stop-and-go waves where the transmission range R is larger. Similar results are obtained. Based on this, we argue that in an infinite system, the distribution of MhCD is with a single peak when R and/or μ are in intermediate range. When R and/or μ are large enough, the information can propagate to infinity as in free flow and synchronized flow.

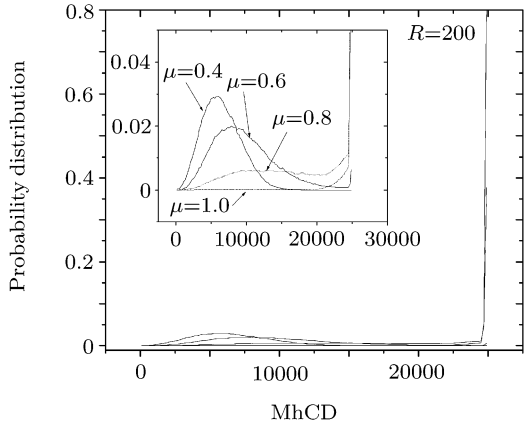


Fig.9. Probability distribution of MhCD in stop-and-go waves in system of L=30000. The transmission range R=200. The inset shows the details of the peak of the distribution. μ=0.4, 0.6, 0.8, and 1 from top to bottom in inset.

4. Conclusion

IVC is widely regarded as a promising concept for the transmission of traffic-related information.[13] Comparing with centralized advanced traffic information system (ATIS) systems, we find that a decentralized system offers some significant advantages: (1) the IVC components of the system require no capital investment on the part of the transportation agencies, and can evolve to a full system gradually; (2) the system is much more resilient to disruption, particularly in the event of such disasters as major earthquakes. Apart from the drivers appreciating reliable and up-to-date traffic information, the whole traffic system may benefit from IVC as well.[13]

This paper focuses on how far information can be expected to propagate in a traffic system under different traffic conditions. To this end, a CA model which can describe free flow, synchronized flow and stop-and-go waves is used.

Our simulations show that different behaviours appear in stop-and-go waves from that in free flow and synchronized flow. In free flow and synchronized flow, the distribution of MhCD is exponential when the transmission range R and penetration rate μ are small. However, with the increase of R and/or μ, the slope of the distribution (absolute value) decreases. When R and/or μ are large enough, the distribution becomes uniform. The uniform probability decreases with the further increase of R and/or μ.

In stop-and-go waves, the distribution of MhCD is still exponential when the transmission range R and penetration rate μ are small. However, with the increase of R and/or μ, the distribution transits into one with a single peak. Then the distribution expands and the peak decreases and shifts right with the further increase of R and/or μ. We believe that the difference is caused due to the existence of synchronized flow near the bottleneck in stop-and-go waves.

In our future work, the investigation will be extended to bi-directional traffic and to network (which is a dynamically changing ad hoc network). We will consider that the network dynamics strongly influences message propagation, which is done by the movement of nodes (vehicles) and by hops between nearby nodes.

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