Lane-changing behavior on highways

Ding-wei Huang
Department of Physics, Chung Yuan Christian University, Chung-li, Taiwan
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We study the lane-changing behavior in multilane highway modeling by a cellular automaton. We analyze the effects of speed limit and stochastic noise. A new parameter is introduced to allow vehicles not to change lanes even when the environmental criteria are met. Without stochastic noise, the lane-changing rate vanishes in the stationary states of a homogeneous highway. With stochastic noise, vehicles change lanes frequently even when there are no slow vehicles to overtake. The lane-changing rate reflects the intrinsic fluctuations much more than the inhomogeneity of the highway. Aggressive vehicles which change lanes at every opportunity will only keep a speed slightly larger than others.

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I. INTRODUCTION

Recently the traffic behavior on highways has attracted much attention of physicists [1–3]. Various models had been proposed to characterize the traffic patterns from free flow to congestion. Most observations can be well understood within the single-lane models. The success of the single-lane models implies that the traffic patterns are mainly determined by the appropriate response of a vehicle to the motion of the preceding one. However, the real highway often consists of more than a single lane. The distinct characteristic of multilane traffic is the phenomenon of lane changing. Basically there are two types of lane-changing behavior. The first one is related to the specific destination pursued by each vehicle. Vehicles change lane in order to continue the journey. This kind of lane-changing behavior is often observed around the on/off ramps and the interchanges. The other type of lane-changing behavior is related to overtaking a slow vehicle. When passing is forbidden, a slow vehicle will easily block the traffic and leave a long queue behind. Then lane changing provides a maneuver for a fast vehicle to pass a slow vehicle, which can be observed everywhere on the highway. The effects of slow vehicles had been the focus of previous studies [4–7]. From one's daily experience, changing lanes to pass the preceding vehicle is not always as promising as it seems to be. Some aggressive drivers change lanes frequently but they may not drive much faster than the others. In this paper, we focus on such unpromising lane-changing behavior, which is understood as lane changing without overtaking or driving faster. We study the phenomenon of lane changing in a homogeneous highway system. The effects of inhomogeneity from ramps, interchanges, and the existing slow vehicles are all excluded. The model is described in the following section. The effects of stochastic noise and speed limit are explored separately. Discussions and some comments on our daily experience are presented in Sec. III.

II. MODEL

To focus on the phenomenon of lane changing, we adopt a simple configuration of a two-lane highway without ramps. The periodic boundary conditions are employed. The system is then specified by the highway length L and the vehicle number N. As long as L is large enough to disregard the finite size effects, the vehicle density $\rho = N/(2L)$ is a good parameter to study the underlying dynamics. Vehicles are restricted to move in one direction only. Their behaviors are prescribed by the following rules: (1) acceleration if the speed is less than the speed limit, it increases by one unit; (2) braking if the speed is larger than the headway, it reduces to the headway; (3) stochastic noise if the speed is not zero, it reduces by one unit stochastically; (4) forward moving, the vehicle moves forward according to the speed determined by the preceding three rules; (5) lane changing, the vehicle changes to the other lane when the environmental criteria are fulfilled, which will be specified later. Basically the first two rules make the vehicle drive as fast as possible, as long as it keeps a safety headway and is not speeding. The third rule introduces the stochastic noise, which is an important ingredient for modeling the highway traffic. The last two rules prescribe the motion of a vehicle along the driveway and the opportunity to change lane. Without the fifth rule, the other four rules are also known as the Nagel-Schreckenberg model [8,9]. There are two parameters: the speed limit v_{max} and the probability of stochastic braking p, which are in effect the first rule and the third rule, respectively. The real traffic on a single-lane highway can be well reproduced by setting $v_{max} = 5$ and $p = 0.5$, which corresponds to a speed limit of 139 km/h.

The lane-changing rules for a vehicle can be further specified as follows: (a) the headway in the current lane is not larger than the speed, (b) the headway in the target lane is larger than that in the current lane, (c) an empty site right in the next lane is available, (d) the headway of the following vehicle in the target lane is larger than its speed. The conditions (a) and (b) are known as the incentive criteria, which imply that the vehicle can drive faster in the target lane. The conditions (c) and (d) are known as the safety criteria, which imply that the lane changing will not cause the following vehicle to brake. When these criteria are satisfied, a new stochastic probability q is assigned to the vehicle to change to the target lane. In contrast to previous works, the vehicles are not forced to change lanes even when the environmental criteria are met. A probability of $(1-q)$ is prescribed for a vehicle to stay in the current lane.

In total, there are three parameters: speed limit v_{max}, stochastic braking p, and stochastic lane changing q. In the following, we study the lane-changing rate ξ defined as the average lane-changing frequency per vehicle. With naive expectation, the rate ξ is proportional to the parameter q. And one also expects $\xi=0$ at the densities $\rho=0$ and $\rho=1$, where the lane changing becomes either motiveless or impossible. Thus the function $\xi(\rho)$ is expected to have a maximum at the intermediate density. It would be interesting to clarify the correlation between the maximum lane-changing rate and the maximum traffic flow. Also the dependence of the speed limit v_{max} and the stochastic noise p will be examined.

A. $v_{max}=1$

We start with the simplest case of $v_{max}=1$ and $p=0$, which is also known as the asymmetric simple exclusion process. At each time step, a vehicle moves forward to the next site as long as it is empty. It is interesting to observe that the lane-changing rate ξ vanishes in the stationary state, regardless of the density ρ and the stochastic lane changing q. We prepare the system to start with a configuration of vehicles randomly distributed on the highway. In the preparation stage, the system is updated with rules (1)–(4), i.e., lane changing is forbidden. A long period is assigned to this preparation stage to disregard the dependence of the initial configuration. Then the system is updated with rules (1)–(5) and we record the lane-changing rate as time evolves. Initially, vehicles change lanes frequently. However, the lane-changing rate drops rapidly as time evolves. In the stationary state, lane changing can no longer be observed. Such a result is interesting. On the one hand, the two lanes are decoupled. Vehicles stay in their current lanes. The distribution is exactly the same as in a single-lane highway, which can be correctly described by the mean-field theory [10]. On the other hand, the two lanes are strongly correlated. By lane changing, vehicles adjust their relative positions to discourage further lane changing. Thus after a transition period, the lane changing becomes impossible. We also notice that the initial lane-changing rate can be correctly described by the mean-field theory of a single-lane highway, which implies that the two lanes are uncorrelated initially.

With stochastic noise, i.e., in the case of $v_{max}=1$ and $p>0$, a nonvanishing lane-changing rate in the stationary state is observed. The typical results are shown in Fig. 1. Again the lane-changing rate decreases dramatically once the system is open to lane-changing behavior. However, a finite lane-changing rate is still observed in the stationary state. As the density increase from 0 to 1, the lane-changing rate increases in the low density region, reaches the maximum around a density of 0.2, and then decreases in the high density region. We notice that the maximum traffic flow occurs at $\rho=0.5$ in the case of $v_{max}=1$. The maximum of the lane-changing rate occurs at a much smaller density. As shown in Fig. 1, the mean-field theory of a single-lane system describes the initial lane-changing rate correctly. The drop from the initial rate to the stationary rate can be qualitatively captured by a phenomenological factor of $2p(1-p)$, which is motivated by the conjecture that the stationary rate reflects the stochastic noise on the highway. The factor also correctly prescribes the vanishing of the stationary rate in the case of $p=0$.

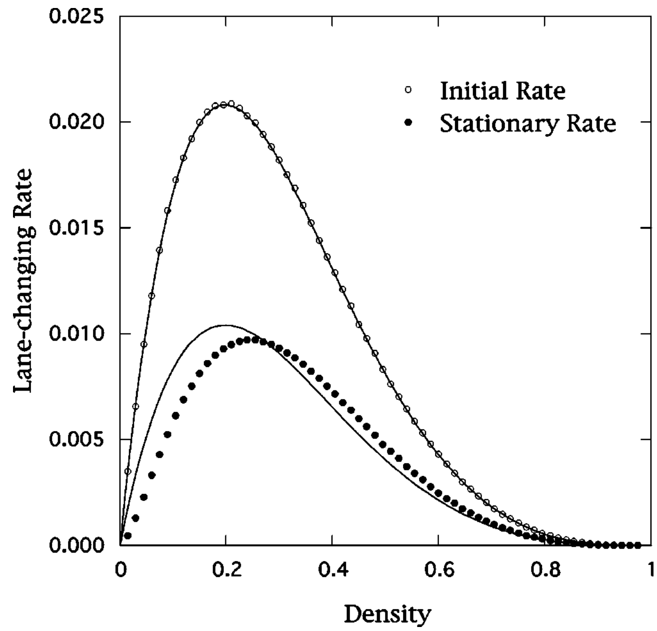

FIG. 1. Lane-change rate as a function of density in the case of $v_{max}=1$, $p=0.5$, and $q=0.5$. The data of initial rate are shown by the open circles; the data of stationary rate are shown by the closed circles. The results of mean-field theory are shown by solid lines.

The dependence of the stochastic probability q is shown in Fig. 2. Basically, the rate ξ increases with the increase of q. But the expected linear dependence is only approximately valid in the stationary state. As q increases, the stationary rate ξ increases less than expected and the maximum shifts slightly toward a higher density. In contrast, the initial rate depends linearly on the parameter q exactly.

The dependence of the stochastic probability p is shown in Fig. 3. As the stationary lane-changing rate vanishes in the

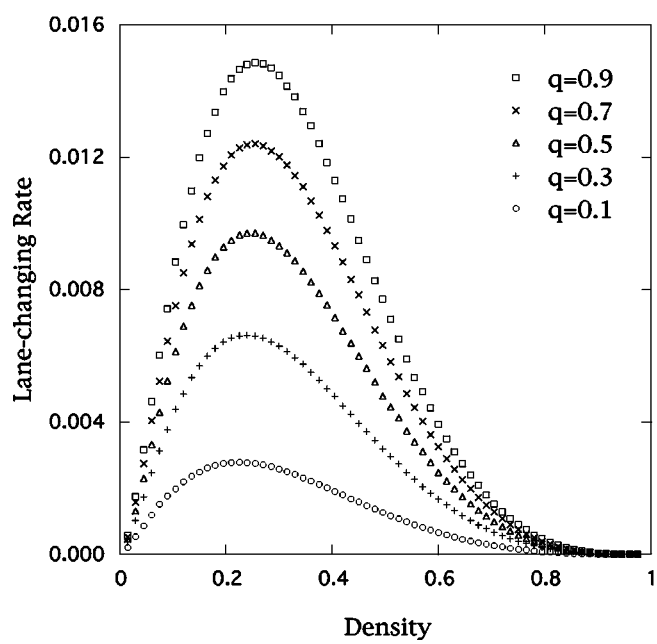

FIG. 2. Stationary lane-change rate as a function of density for various values of q. The parameters are $v_{max}=1$ and $p=0.5$.

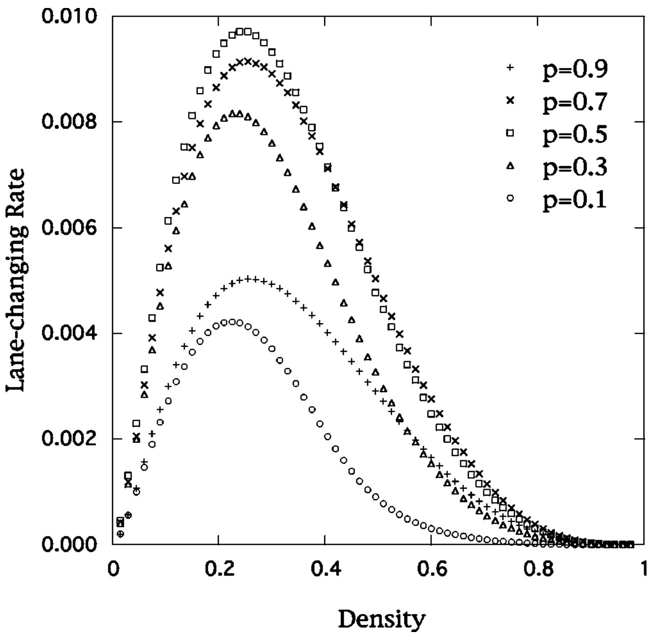

FIG. 3. Stationary lane-change rate as a function of density for various values of p. The parameters are $v_{max}=1$ and $q=0.5$.

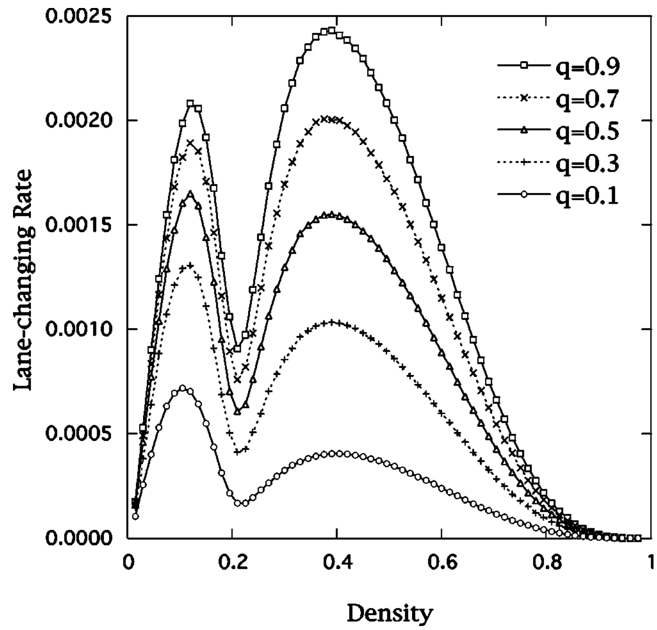

FIG. 4. Stationary lane-change rate as a function of density for various values of q. The parameters are $v_{max}=3$ and $p=0.1$.

deterministic limit, $\xi(\rho)=0$ is expected in both the limits $p=0$ and $p=1$. Thus, as p increases from 0 to 1, the stationary rate is expected first to increase and then to decrease. Such expectation is behind the phenomenological factor $2p(1-p)$ in describing the drop from the initial rate to the stationary rate. In contrast, the initial rate increases monotonically with the increase of p.

B. $v_{max}>1$

Next, we consider the effects of speed limit. The most distinct feature of $v_{max}>1$ is the dip in the distribution $\xi(\rho)$, see Fig. 4. With the two fixed points of $\xi=0$ at $\rho=0$ and $\rho=1$, the distribution $\xi(\rho)$ presents two distinct maxima, which invites the interpretation of superposing two different structures. In contrast, only one structure is presented in the case of $v_{max}=1$. As expected, $\xi(\rho)$ increases with the increase of q. It is interesting to observe that the peak in the high density region enhances much more significantly than that in the low density region does. Thus, when q is small, most of the lane-changing behavior is observed in the low density region; when q is large, the lane-changing behavior in the high density region becomes dominant.

As v_{max} increases, the dip moves toward a lower density. The peak in the low density region shrinks and that in the high density region enhances, see Fig. 5. When v_{max} is large enough, the structure in the high density region becomes dominant over the entire density region. As the peak moves toward the low density region, a scaling relation is observed in the high density region. When the density is high, vehicles cannot drive at high speed, which results in scaling with respect to the variation of v_{max}. It is interesting to note that the scaling relation cannot be extended to the case of $v_{max}=1$. The peak in the high density region can only be attributed to the effects of $v_{max}>1$. In Fig. 6, we show yet another scaling relation observed in the low density region, which does include the case of $v_{max}=1$. When the density is very low, the lane-changing behavior becomes motiveless. The scaling implies that the increase of speed limit will have no effect on stimulating the lane-changing behavior. However, we notice that such scaling is applied only to the low density peak and limited to the very low density region when the speed limit is large. As the two peaks result from different dynamics, no scaling relation is expected to cover both of them. When the high density peak extends to the low density region as v_{max} increases, the rate $\xi(\rho)$ in the low density

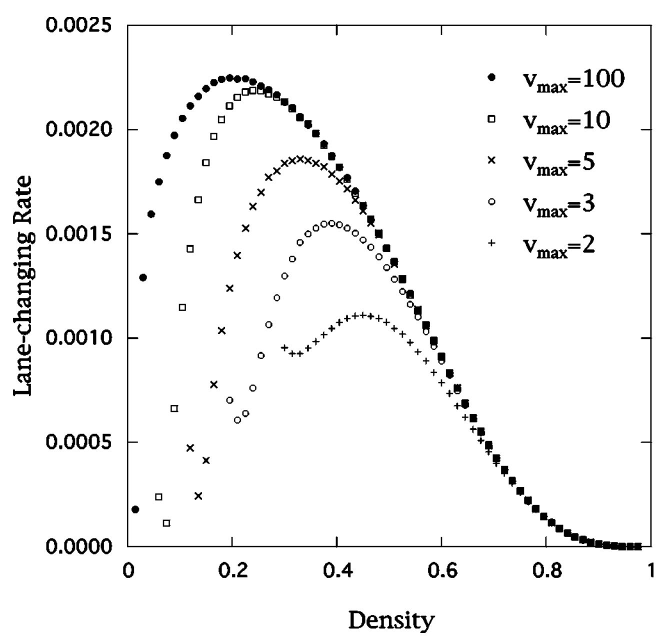

FIG. 5. Stationary rate $\xi(\rho)$ in the high density region for various values of v_{max}. The parameters are $p=0.1$ and $q=0.5$.

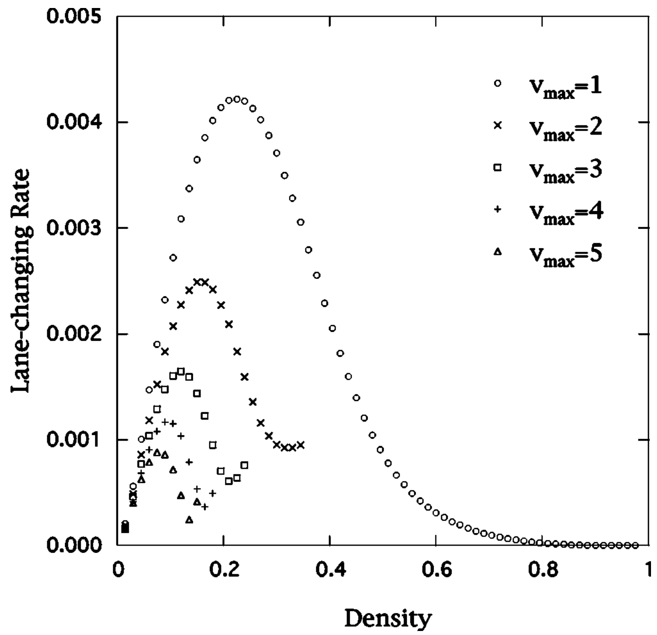

FIG. 6. Stationary rate $\xi(\rho)$ in the low density region for various values of v_{max}. The parameters are $p=0.1$ and $q=0.5$.

region does increase with the increase of v_{max}. The observed scaling also indicates that the distribution $\xi(\rho)$ in the case of $v_{max}=1$ results from the same dynamics behind the low density peak in the case of $v_{max}>1$.

As p increases, the dip becomes a shoulder structure and then disappears, see Fig. 7. Basically the same as in the case of $v_{max}=1$, as the stochastic noise p increases, the rate ξ first increases and then decreases. However, the dip is not restored as the parameter p approaches 1. The structure of the two peaks is also observed in the initial lane-changing rate,

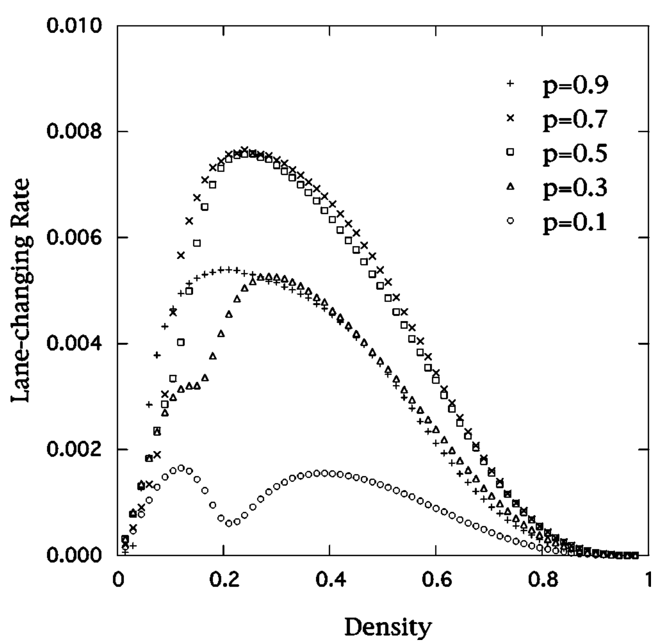

FIG. 7. Stationary lane-change rate as a function of density for various values of p. The parameters are $v_{max}=3$ and $q=0.5$.

which is significantly larger than the stationary lane-changing rate as expected. It is interesting to note that the high density peak enhances with the increase of p as in the case of $v_{max}=1$. However, the behavior of the low density peak is quite on the contrary. In the low density region, the initial lane-changing rate decreases with the increase of p.

III. DISCUSSIONS

In this paper, we study the lane-changing behavior numerically within a model system. Under the assumption of homogeneity, each individual vehicle behaves just like the others. As we do not introduce any slow vehicles into the system, all the lane-changing behaviors observed are unpromising. With respect to overtaking a slow vehicle, such lane-changing behavior is not necessary. Owing to the fluctuations in highway traffic, a vehicle will not always keep at a constant speed. The incentive criterion is then met frequently even when there is no slow vehicle ahead. Thus the lane-changing behavior reflects the intrinsic fluctuations on the highway, instead of the encounter of a slow vehicle. The enhancement to the traffic flow is marginal. Similar results have been related to the psychological effects of human perception [13]. In contrast, such human psychology has not been included in this work. The lane-changing criteria involve mainly the headway, both in the current lane and in the target lane. The perception of vehicular speed in the target lane has not been included specifically. However, as strong correlation between the speed and headway is expected, the fluctuations will also result in an illusion that the vehicle in the target lane is moving faster.

We analyze the effects of the three parameters: v_{max}, p, and q. The parameter v_{max} is the speed limit subjected to all vehicles. To model the typical highway traffic, a setting of $v_{max}=5$ is appropriate. For urban traffic, v_{max} is expected to have a smaller value. The parameter p measures the intrinsic fluctuations among the vehicles. The setting for highway traffic is around $p=0.5$. For urban traffic, a much larger uniformity is expected, which leads to a smaller value of p. The parameter q represents the tendency to change lanes when the environmental criteria are satisfied. With naive expectation, the lane-changing rate $\xi(\rho)$ is proportional to q. In this work, nonlinear effects are observed. With the increase of q, the increase of $\xi(\rho)$ is less than expected.

Unrelated to the presence of slow vehicles, this unpromising lane-changing behavior reflects the stochastic fluctuations in the traffic. Thus, $\xi(\rho)=0$ is observed in the deterministic limit $p=0$. As p increase from 0, the stochastic fluctuations enhance and the lane-changing rate enhances accordingly. As p approaches 1, the stochastic fluctuations diminish and the lane-changing rate reduces as well. A special feature is observed in the cases of $p\sim 0$ and $v_{max}>1$: a dip in the distribution $\xi(\rho)$, where the lane-changing behavior is scarcely observed. As the lane-changing behavior is unpromising, the location of the dip presents the most desirable situation on the highway. A large uniformity is observed among the vehicles $(p\sim 0)$, and all the vehicles drive at high speed $(v_{max}>1)$. The unnecessary lane-changing behavior is reduced effectively. The corresponding examples on the real

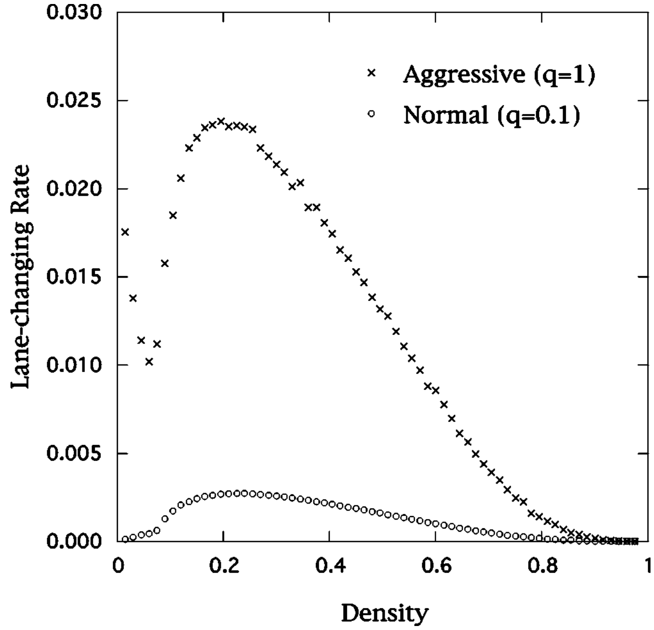

FIG. 8. Stationary lane-change rate as a function of density for different kinds of driving. For normal vehicles, the parameters are $v_{max}=5$, $p=0.5$, and $q=0.1$; for the aggressive vehicle, they are $v_{max}=\infty$, $p=0.5$, and $q=1$.

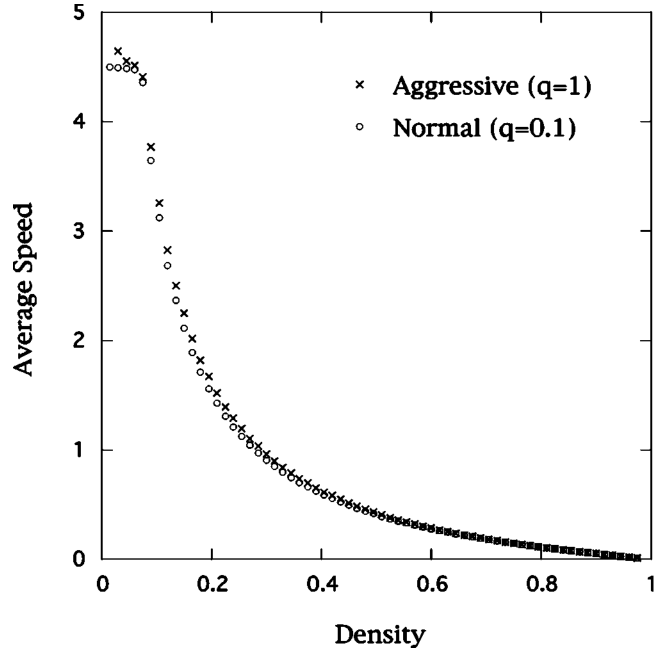

FIG. 9. Average speed as a function of density for different kinds of driving. The parameters for normal and aggressive vehicles are the same as in Fig. 8.

highway can be the synchronized traffic state observed recently [11,12]. Besides, reducing the unnecessary lane-changing behavior will provide a much safer driving condition, as many traffic accidents occur while the vehicle changes lanes. However, the lane-changing behavior becomes necessary in some other situations, e.g., near the lane merge, or where specific destinations are assigned to different lanes. Then the location of the dip will present a very difficult situation for the drivers and should be avoided by all means.

Finally we would like to comment on our daily experience of highway traffic. For most drivers, the lane-changing behavior provides a maneuver to overtake a slow vehicle. Afraid of being blocked by slow vehicles, some aggressive drivers expect to be able to drive faster by exerting lane-changing behavior much more frequently than others. However, the naive expectation is only an illusion. In the following simulation, one of the vehicles is designated as the aggressive one, who secures every opportunity to change lanes whenever the incentive and safety criteria are both fulfilled, i.e., the parameter q is set to 1 for the aggressive vehicle; for other vehicles, a value of $q=0.1$ is applied. Furthermore, the speed limit for the aggressive vehicle is lifted; for other vehicles, a value of $v_{max}=5$ is applied. The stochastic noise of the aggressive vehicle is expected to be the same as the others. A setting of $p=0.5$ is then applied to all vehicles. As expected by a factor of 10, the aggressive vehicle changes lanes much more frequently than others do, see Fig. 8. However, the average speed of the aggressive vehicle is basically the same as other vehicles, see Fig. 9. Even when the vehicles are scarce on the highway, the aggressive vehicle can only keep a speed slightly larger than others.

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[1] D. Helbing and M. Treiber, Science **282**, 2001 (1998).
[2] D. Chowdhury, L. Santen, and A. Schadschneider, Phys. Rep. **329**, 199 (2000).
[3] D. Helbing, Rev. Mod. Phys. **73**, 1067 (2001).
[4] P. Wagner, K. Nagel, and D.E. Wolf, Physica A **234**, 687 (1997).
[5] K. Nagel, D.E. Wolf, P. Wagner, and P. Simon, Phys. Rev. E **58**, 1425 (1998).
[6] D. Helbing and B. Huberman, Nature (London) **396**, 738 (1998).
[7] W. Knospe, L. Santen, A. Schadschneider, and M. Schreckenberg, Physica A **265**, 614 (1999).
[8] K. Nagel and M. Schreckenberg, J. Phys. I **2**, 2221 (1992).
[9] M. Schreckenberg, A. Schadschneider, K. Nagel, and N. Ito, Phys. Rev. E **51**, 2939 (1995).
[10] A. Schadschneider, Eur. Phys. J. B **10**, 573 (1999).
[11] B.S. Kerner and H. Rehborn, Phys. Rev. Lett. **79**, 4030 (1997).
[12] B.S. Kerner, Phys. Rev. Lett. **81**, 3797 (1998).
[13] D.A. Redelmeier and R.J. Tibshirani, Nature (London) **401**, 35 (1999).