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Human behavior as origin of traffic phases

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It is shown that the desire for smooth and comfortable driving is directly responsible for the occurrence of synchronized traffic in highway traffic. This desire goes beyond the avoidance of accidents, which so far has been the main focus of microscopic modeling and that is mainly responsible for the other two phases observed empirically, free flow and wide moving jams. These features have been incorporated into a microscopic model based on stochastic cellular automata by means of event-driven anticipation. The results of computer simulations are compared with empirical data. It turns out that anticipation effects are responsible for the stabilization of the traffic phases and even reproduce the empirically observed coexistence of wide moving jams with both free flow and synchronized traffic.

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The empirical observation of highway traffic has shown the existence of very complex spatiotemporal structures [1,2]. So it is now widely believed [3] that three traffic states exist, i.e., (i) free flow, (ii) synchronized traffic, and (iii) wide moving jams. The characteristics of free flow [4] and wide moving jams [5] are intuitively clear. For a long time it was believed that these states are the only stable traffic states. This commonly accepted picture was enhanced by establishing a second stable congested state, i.e., synchronized traffic. Synchronized traffic [2], which is typically observed at on and offramps, is characterized by a large variance in flow and density measurements and a velocity that is significantly lower than in free-flow traffic. The origin of the notation ‘‘synchronized traffic’’ is the fact that the time series of measurements on different lanes are highly correlated. But more important is the apparent absence of a functional flow-density form, i.e., the measurements of the flow, density, and velocity of the traffic are distributed over a wide area [6]. This observation has been confirmed quantitatively [7] by means of vanishing cross correlations between these two quantities.

Synchronized traffic and wide moving jams differ also in their behavior at bottlenecks. If synchronized flow is generated at a bottleneck its downstream front is pinned there. In contrast, the downstream front of wide moving jams propagates with constant velocity in upstream direction. This velocity (about 15 km/h) is only determined by the density inside a wide jam and the delay time between two vehicles leaving the jam [8]. Therefore, the velocity does not depend on the traffic state they cross and is even unchanged if they pass a bottleneck. This property is an objective criterion for the identification of wide jams and is responsible for the coexistence of wide moving jams and synchronized traffic [3]. The final characteristic feature are the phase transitions between the different states [2]. In general they are of first order [9], e.g., the phase transition free flow to synchronized traffic is characterized by a discontinuous change of the velocity.

Several model approaches have been suggested in the last few years to reproduce the three empirically observed traffic phases (for an overview, see [10–12]). In addition, much progress has been made in understanding topological effects in highway traffic [13,14]. However, one of the most puzzling points for any model is to reproduce the empirically observed coexistence of stable traffic states and especially the upstream propagation of wide moving jams through both free flow and synchronized traffic with constant velocity and without disturbing these states [3]. So far, only the coexistence has been observed [14,12]. We recently have shown that the model [15] used here reproduces all three traffic phases already on a single-lane road without any inhomogeneities. Here, we will further show that in the presence of onramps the coexistence of the phases can be obtained and a wide moving jam can pass free flow and synchronized traffic. Thus, the discussed model is able to pass this most sensitive test.

The used model [15] is based on the cellular automaton model of Nagel and Schreckenberg [16] and incorporates a desire for smooth and comfortable driving. This essential demand of drivers has been incorporated in the model by the introduction of ‘‘brake lights’’ for a timely adjustment of the velocity when approaching slow upstream traffic and ‘‘anticipation’’ by estimating the velocity of the leading vehicle. This leads to the following driving behavior.

(i) Velocity anticipation. At the onramp the anticipation of the leaders velocity avoids abrupt braking of the traffic behind and, therefore, reduces the probability to form jams.

(ii) Retarded acceleration. Comfortable driving also implies that cars do not accelerate immediately in case of a larger gap ahead if they observe slow downstream traffic. On one hand, this leads in some sense to a suboptimal gap usage, because the velocity is smaller than the headway allows. On the other hand, larger gaps in a dense region reduce the car-car interactions and may cut a chain of braking over-reactions that is responsible for the formation of jams. These over-reactions are a direct consequence of the delayed human behavior in adapting the velocity to the headway that can lead to an avalanchelike amplification of the velocity fluctuations upstream and finally to the formation of jams.

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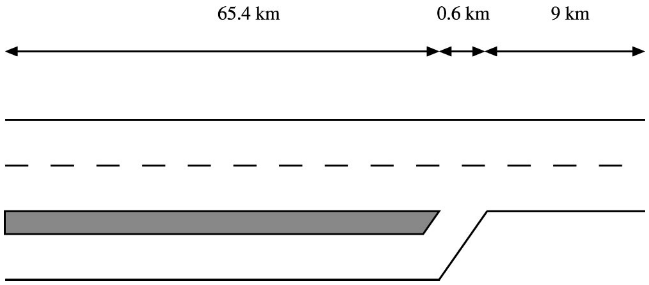

FIG. 1. Schematic plot of the highway section modeled throughout this work. The space has been discretized such that each lattice site corresponds to 1.5 m in reality. The total length of the highway is 75 km or 50 000 cells per lane. The merging zone of the onramp is of length 600 m, i.e., 400 cells. Lane-changing rules as presented in [17,18] have been used. The results, however, do not depend on the details of the applied set of rules. We simulate fluid traffic on the onramp with an average velocity of ~80 km/h. In addition, the incoming cars accept smaller gaps for lane changes [19].

(iii) Timely braking. Finally timely braking suppresses another mechanism of jam formation: When the velocity adjustment is only based on the distance to the next car ahead, jams often emerge in the layer between free flow and synchronized traffic. In these models the jam formation arises from cars approaching a slow-moving cluster with high speed that leads to a compactified region. In contrast, our approach avoids this artificial mechanism to form a jam, the drivers adjust their speed to the vehicles ahead.

For comparison with the empirical data, we simulate a two-lane segment with an onramp (Fig. 1). Analogously to the empirical setup the simulation data are evaluated by a virtual induction loop, i.e., we counted the number and measured the speed of vehicles passing a given link of the lattice. This allows to calculate minute averages of the velocity, the flow and the density that is given by the occupancy of the detector.

The simulation protocol emulates a few hours of highway traffic including the realistic variations of the number of cars that are fed into the system. A large input rate of the onramp in combination with a large flow on the highway generates synchronized flow on the highway segment. In contrast, at low input rates small jams are expected to form in the vicinity of the onramp [14,20] due to local perturbations. For the sake of simplicity, we used only one type of cars in the simulations that leads to a smaller variance of the data points in the free-flow regime compared with the empirical data.

The additional input of cars triggers a dense traffic region behind the onramp with a flow comparable to free-flow but with a velocity considerable below the free flow velocity and which can, therefore, be identified as synchronized traffic (Fig. 3).

The simulations show that we can recover the empirical results for the fundamental diagram quantitatively (see Fig. 2). The flow and density measurements of the synchronized region cover a two-dimensional region in the fundamental diagram. Moreover, the analysis of the traffic data for both lanes shows large correlations of the velocity time series that can directly be related to a synchronization of the velocity on both lanes. In addition, the measurements of the wide moving jam can be characterized by a triangular shape that is a consequence of the event-driven measurement process of the induction loop. Thus, the agreement with the empirical fundamental diagram is not only for the average values but also concern the statistical properties of the results. This is mandatory for traffic forecasting, e.g., in order to calculate upper limits of individual travel times as well. But, as mentioned above, also the stability of the synchronized traffic state is described correctly. In order to verify this a jam was generated by an obstacle at the downstream end of the highway section. Figure 3 illustrates how the jam wave travels through the free-flow region with constant velocity and also passes the section where the synchronized traffic is localized. This shows that we can superpose the different traffic states as observed empirically [3]. Thus, the model is able to reproduce the three traffic phases since synchronized traffic is fixed at the onramp and the jam propagates with a constant velocity and passes the free flow, onramp and synchronized regions without being disturbed.

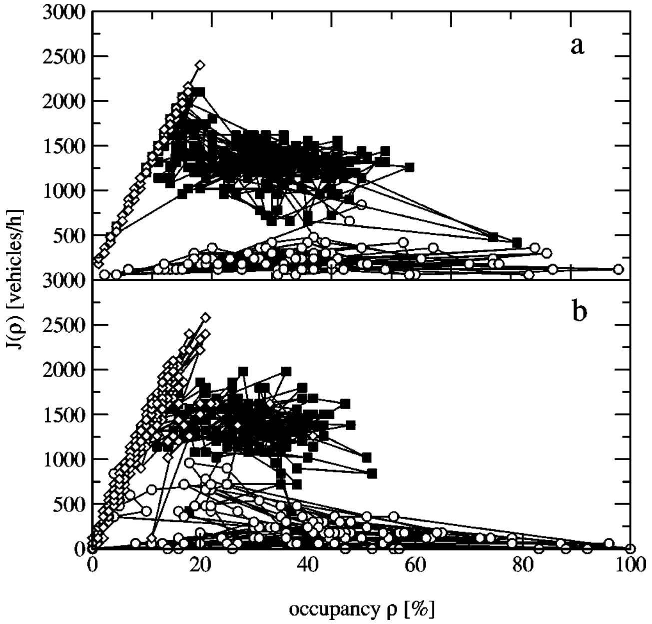

FIG. 2. Comparison between empirical results (b) for the flow-density relation (fundamental diagram), and time-traced simulation results (a). On the abscissa the density (the number of vehicles per kilometer) and on the ordinate the flow (number of cars passing the detector extrapolated to one hour) is shown. Each data point corresponds to an average over a one-minute interval. Consecutive measurements are connected by lines. Part (a) shows that we recover the three empirically observed phases of highway traffic: free flow (diamonds), synchronized traffic (squares), and wide jams (circles). The empirical data are one-minute averages of detector data from the German freeway A40 near Moers junction at 2000-12-12 (synchronized state) and near Bochum-Werne junction at 2001-02-14 (wide moving jam of about 2-h duration). The density is given by the occupancy, which gives the percentage of the measurement time a detector is covered by cars. This has the advantage that the occupancy can directly be measured by an inductive loop and the simulation data can be related to the empirical data.

At this point, we stress the fact that the observed phenomena are a consequence of the individual behavior of the driv-

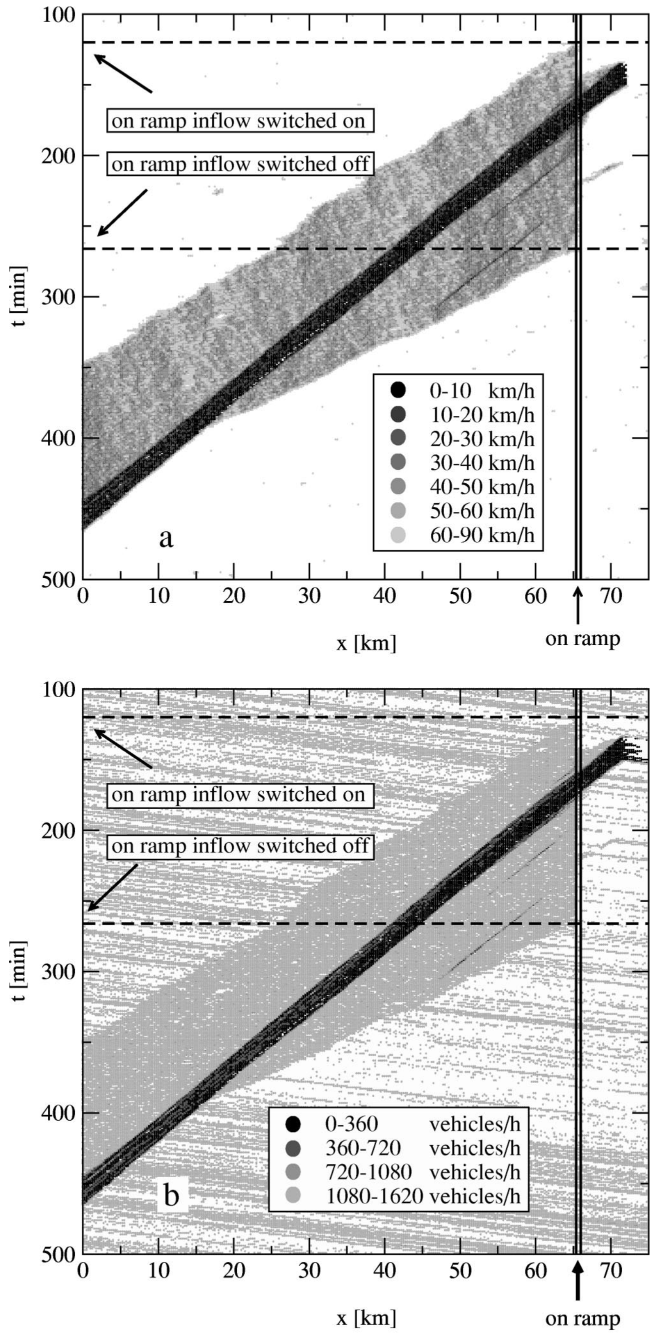

FIG. 3. Coexistence of wide moving jams and synchronized states. Space/time evolution of the velocity (a) and of the flow (b). The figures show how a traveling jam wave crosses a region of synchronized traffic which is pinned at the onramp. Downstream the onramp a jam has been generated that moves in upstream direction and passes the segment with free flow and synchronized states. One clearly observes that the synchronized state is recovered directly after the jam has passed the onramp.

ers (see [15,21] for the calibration of the model). None of the microscopic model parameters has been changed throughout the simulations in order to optimize the accordance with the empirics. Already the single-lane model on a periodic street without bottlenecks [15] shows the existence of synchronized traffic and wide moving jams. In this simulation the boundary conditions are used only to induce the transitions to these traffic states. By contrast, the excellent agreement with the empirics was obtained simply by applying the correct inflow at the upstream end and the onramp of the highway section. This side steps another important question in traffic dynamics, i.e., the origin of phase transitions. Our simulation results support the view that the transitions are mostly induced by obstacles rather than by a spontaneous breakdown of the traffic stream.

In addition, the results clarify how the synchronized state is related to the human factors in driving. Most present modeling approaches concentrate on the fact that drivers want to avoid accidents. This has been implemented by adjusting the velocity according to differences in speed and/or the distances to the other cars. Traffic models based on this interaction only have been able to reproduce various observed phenomena but fail to give a complete description of the empirical results [10–12]. In addition, the robustness of the empirical observations give strong evidence that traffic states itself are a consequence of the human driving behavior rather than a response to different topological situations.

It is possible to overcome some of the problems in modeling traffic if one takes into account that people like to have a comfortable journey, i.e., they try to avoid strong accelerations and abrupt braking. This approach goes far beyond the consideration of velocity differences since acceleration changes become visible and allows for an event-driven anticipation of velocity reductions. These two features lead to a stabilization of the flow in dense traffic that is crucial to overcome the difficulties in describing the empirically observed phases and their transitions [2].

From a theoretical point of view our simulation results have shown that the desire for smooth and comfortable driving is the origin of synchronized traffic and wide moving jams and is responsible for the stability of the different traffic phases. The analysis of the empirically observed coexistence of traffic states allows the identification of all three traffic phases. This stability allows for the application of phenomenological approaches [22]. In particular, the motion and formation of jam waves, which is most interesting for any traffic forecast, should be predictable within these approaches with high accuracy (see [23] for approaches of this kind).

From a practical point of view, our simulation results allow for more realistic simulations and opens the door for a forecast of highway traffic that should outperform knowledge based approaches.

Summarizing, we have shown that a rather simple cellular automaton model is able to reproduce the empirically observed phases of traffic flow and their coexistence even quantitatively. While synchronized traffic with a large flow and a small velocity can be found in the vicinity of the onramp, a wide jam passes both free flow and synchronized traffic with a constant velocity. The features of the model can be related directly to the human behavior, especially to the desire for smooth and comfortable driving. It turns out that this need is responsible for the occurrence of the observed complex spatio-temporal structures as stable bulk states of the model. This implies that the role of the boundaries is restricted to a *selection* of the different steady states of the model, which are equally well observed in periodic systems.

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[1] F.L. Hall, B.L. Allen, and M.A. Gunter, Transp. Res., Part A **20**, 197 (1986).

[2] B.S. Kerner, J. Phys. A **33**, L221 (2000); Phys. World **8**, 25 (1999).

[3] B.S. Kerner, Networks, and Spatial Economics **1**, 35 (2001).

[4] Free-flow traffic is characterized by a high average velocity of the vehicles, e.g., close to the eventually applied speed limit.

[5] Wide moving traffic jams are upstream moving structures consisting of two fronts separated by a region of negligible velocity and flow. They can be characterized by the upstream propagation velocity, their density and the outflow from the jam. These parameters of the jam are quite robust: Empirically it has been observed that two jams can move in parallel through the system that implies that their characteristic parameters agree [3].

[6] B.S. Kerner and H. Rehborn, Phys. Rev. E **53**, 4275 (1996).

[7] L. Neubert, L. Santen, A. Schadschneider, and M. Schreckenberg, Phys. Rev. E **60**, 6480 (1999).

[8] B.S. Kerner, Phys. Rev. Lett. **81**, 3797 (1998).

[9] The notation *first-order transition* is borrowed from the terminology of thermodynamic phase transitions. The analogy is simply in the discontinuous change of the velocity signal, which is in analogy to the behavior of the order parameter in a thermodynamic first-order transition.

[10] D. Chowdhury, L. Santen, and A. Schadschneider, Phys. Rep. **329**, 199 (2000).

[11] *Traffic and Granular Flow'99*, edited by D. Helbing, H.J. Herrmann, M. Schreckenberg, and D. Wolf (Springer, Berlin, 2000).

[12] D. Helbing, e-print cond-mat/0012229.

[13] H.Y. Lee, H.W. Lee, and D. Kim, Phys. Rev. Lett. **81**, 1130 (1998); E. Tomer, L. Safonov, and S. Havlin, *ibid.* **84**, 382 (2000); P. Nelson, Phys. Rev. E **61**, R6052 (2000); M. Treiber, A. Hennecke, and D. Helbing, *ibid.* **62**, 1805 (2000); H.Y. Lee, H.W. Lee, and D. Kim, *ibid.* **62**, 4737 (2000).

[14] D. Helbing, A. Hennecke, and M. Treiber, Phys. Rev. Lett. **82**, 4360 (1999).

[15] W. Knospe, L. Santen, A. Schadschneider, and M. Schreckenberg, J. Phys. A **33**, L477 (2000).

[16] K. Nagel and M. Schreckenberg, J. Phys. I **2**, 2221 (1992).

[17] M. Rickert, K. Nagel, M. Schreckenberg, and A. Latour, Physica A **231**, 534 (1996).

[18] We modified the symmetric lane-changing rule set of Ref. [17] by including anticipation effects for the calculation of an effective gap to the predecessor on the destination lane and weakened the security criterion for the distance to the successor on the destination lane to the velocity of the successor.

[19] Lane-changing rules of Ref. [17] are applied. A car is allowed to change the lane if it has an effective gap of five cells to the predecessor and a gap of five cells to the successor on the destination lane. Anticipation of the velocity of the predecessor on the destination lane increases the gap and leads to an effective gap. Additionally, we dropped the incentive criterion.

[20] W. Knospe, L. Santen, A. Schadschneider, and M. Schreckenberg (unpublished).

[21] The calibration of the microscopic driving behavior resulted in the following model parameters: $v_{\max}=18$, $p_d=0.1$, $p_b=0.95$, $p_0=0.5$, $h=8$, and $gap_{\text{security}}=3$. The cell length is 1.5 m, a car has a length of five cells (see Ref. [15] for a detailed discussion of the rules and model parameters).

[22] B.S. Kerner, H. Rehborn, and H. Kirschfink, German Patent No. DE 196 47 127 (1998); U.S. Patent No. US 5861820 (1998); B.S. Kerner and H. Rehborn, Germany Patent No. DE 198 35 979 A1 (2000).

[23] V. Popkov, L. Santen, A. Schadschneider, and G.M. Schütz, J. Phys. A **34**, 45 (2001); C. Appert and L. Santen, Phys. Rev. Lett. **86**, 2498 (2001); R. Barlovic, A. Schadschneider, and M. Schreckenberg, Physica A **294**, 525 (2001).