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 complex spatio-temporal structures (“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 which 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 and the results of computer simulations are compared with empirical data. The simple structure of the model allows for very fast implementations of realistic networks. The level of agreement with the empirical findings opens new perspectives for reliable traffic forecasts.

The empirical observation of highway traffic has shown the existence of very complex spatio-temporal structures \[\textsuperscript{[1]}\]. Therefore it was questioned if it is possible to find a model which can reproduce the various observed phenomena and which is able to relate the origin of these phenomena to the human driving behavior. Compared to the analysis of a conventional liquid the difficulties in modeling traffic are already in describing the “microscopic” interactions between the vehicles. These do not follow the fundamental laws of nature but are rather complex decisions taken individually by each driver. Therefore any successful microscopic description has to extract the essentials of the human behavior in different traffic situations, which is clearly a difficult task. 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\[\textsuperscript{[2]}\]. Much progress has been made in recent years in understanding topological effects in highway traffic \[\textsuperscript{[3]}\]. It became clear that e.g., a change of the activity of an on-ramp may induce a phase transition on the highway. The observed phase transitions are between stable traffic states, i.e., the generated traffic states dissolve only if the external conditions change again. 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.

Below we will show that it is possible to overcome 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 second essential demand of drivers has been incorporated in a recent traffic model\[\textsuperscript{[4]}\], which introduces “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 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 which is crucial to overcome the difficulties in describing the empirically observed phases and their transitions\[\textsuperscript{[5]}\]. Like any other theoretical approach traffic models have to be compared with empirical results. Here one has the difficulty that one cannot perform experiments but is restricted to pure observation of a given situation. Nevertheless much progress has been made in recent years by analyzing large data sets in different environments. So it is now widely believed that at least three traffic states exist, i.e., (i) free-flow (ii) synchronized traffic and (iii) wide moving jams \[\textsuperscript{[6]}\]. The characteristics of free-flow \[\textsuperscript{[7]}\] and wide moving jams \[\textsuperscript{[8]}\] 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 \[\textsuperscript{[9]}\], which is typically observed at on- and off-ramps, is characterized by a large variance in flow and density measurements and a velocity which 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 \[\textsuperscript{[10]}\]. This observation has been confirmed quantitatively 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 at the bottleneck. In contrast the downstream front of wide moving jams propagates with constant velocity in upstream direction. Their velocity does not depend on the traffic state they cross and is even unchanged if they pass a bottleneck. The final characteristic feature are the phase transitions between the dif-
ferent states. In general they are of first order, e.g., the phase transition free-flow to synchronized traffic is characterized by a discontinuous change of the velocity.

![FIG. 1. Schematic plot of the highway section modeled throughout this work.](image)

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 on-ramp is of length 600 m, i.e., 400 cells. Lane-changing rules as presented in [13,14] have been used. The results, however, do not depend on the details of the applied traffic rules. We simulate fluid traffic on the on-ramp with an average velocity of \( \sim 80 \text{ km/h} \). In addition the incoming cars accept smaller gaps for lane-changes [15].

Already the correct reproduction of synchronized traffic on a quantitative level is a difficult task, but the most puzzling point for any model is to reproduce stable synchronized traffic in coexistence with the other two traffic states. The discussed model is able to pass this most sensitive test.

The model is based on the cellular automaton model of Nagel and Schreckenberg and incorporates the desire for smooth and comfortable driving by anticipating the velocity of the leading vehicle and the introduction of "brake lights". For comparison with the empirical data we simulate a two-lane segment with an on-ramp (fig. 1). The additional input of cars triggers a dense traffic region behind the on-ramp which can be identified as synchronized traffic. Our simulations clarify how the synchronized state is related to the human factors in driving.

(i) Velocity anticipation: At the on-ramp 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 the one hand, this leads in some sense to a sub optimal 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 what may cut a chain of braking overreactions which is responsible for the formation of jams. These overreactions are a direct consequence of the delayed human behavior in adapting the velocity to the headway which can lead to an avalanche like amplification of the velocity fluctuations upstream and finally to the formation of jams.

(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 which 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.

![FIG. 2. Comparison between empirical results (b) for the flow-density relation (fundamental diagram), and time-traced simulation results (a).](image)

At this point we stress the fact that the observed phenomena are a consequence of the individual behavior of the drivers (See [4,12] 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 shows the existence of synchronized traffic and wide moving jams. In this simulation the boundary con-
ditions 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 on-ramp 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.

The simulation protocol emulates a few hours of highway traffic including the realistic variations of the number of cars which are fed into the system. A busy on-ramp in combination with high flow generates in general synchronized flow on the highway segment. For the sake of simplicity we used only one type of cars in the simulations which leads to a smaller variance of the data points in the free flow regime compared with the empirical data.

The simulations show that we can recover the empirical results for the fundamental diagram quantitatively (see Fig. 2). The agreement 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 were the synchronized traffic is localized. This shows that we can superpose the different traffic states as observed empirically. The fact that the jam propagates with a constant velocity and passes the free-flow, on-ramp and synchronized regions without being disturbed is typical for wide moving jams.

Our simulation results have far reaching consequences for the theory of traffic flow as well as for practical applications. From a theoretical point of view, it is 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. This stability allows for the application of phenomenological approaches. 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 [16] for approaches of this kind).

From a practical point of view, our simulation results open the door the desire for smooth and comfortable driving allows for more realistic simulations and opens the door for a forecast of highway traffic which should outperform knowledge based approaches. Models of this type have already been used for fast microsimulations of large traffic networks. Here the simple structure of the model, i.e., its discreteness and the local rules, is of great importance.

Summarizing, we have shown that a rather simple cellular automaton model is able to reproduce the empirically observed phases of traffic flow even quantitatively. The model parameters can be related directly to the human behaviour, especially to the desire for smooth and comfortable driving. This desire turns out to be responsible for the occurrence of complex spatio-temporal structures, like the so-called synchronized traffic phase.
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 on-ramp. Downstream the on-ramp a jam has been generated which 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 on-ramp.

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

[7] 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 which implies that their characteristic parameters agree.

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