5 Coexistence of traffic states

The last chapter has shown that the BL model is able to capture the main microscopic characteristics of traffic, and especially is able to reproduce the three empirically observed traffic states even on a microscopic level. However, empirical observations have revealed that synchronized traffic is mainly observed in the vicinity of onramps. Furthermore, 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 [73]. Although in the last few years several model approaches have been suggested to reproduce the three empirically observed traffic phases (for an overview, see chapter 2.2 and [18, 44, 46]) and much progress has been made in understanding topological effects in highway traffic [45, 90, 92, 108, 134, 137], so far only the coexistence has been observed [44, 45].

In chapter 4 has been mentioned that the BL model [80, 81] reproduces all three traffic phases already on a single-lane road without any inhomogeneities. Here, it will further be shown that in the presence of onramps the coexistence of the phases can be obtained, and a wide moving jam can pass through free flow and synchronized traffic. Thus, the model is able to pass this most sensitive test.

One of the main advantages of the cellular automaton approach for traffic flow is the fact that the driving behavior of a single vehicle is imitated by a set of a few rules. The interpretation of these minimal driving strategies may therefore shed some light on the complex psychology of human behavior. In this chapter it will furthermore be demonstrated that the desire for smooth and comfortable driving is directly responsible for the occurrence of synchronized states 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. The essential demand of drivers for smooth and comfortable driving has been taken into account 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 of jam formation.

(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 what may cut a chain of braking over-reactions which 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 which can lead to an avalanchelike amplification of the velocity fluctuations upstream and finally to the formation of jams.

(iii) Timely braking: Finally timely braking suppresses another mechanism of jam forma-

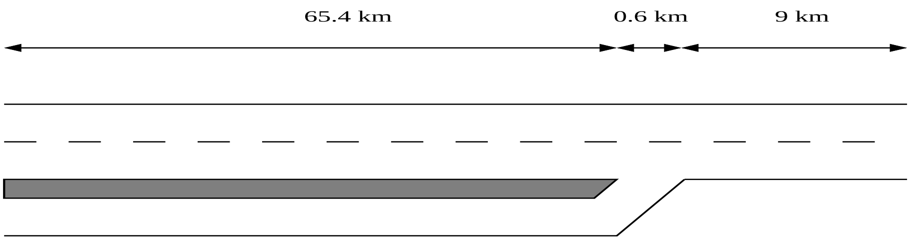

Figure 5.1: Schematic plot of the highway section modeled throughout this chapter. The total length of the highway is 75 km or 50 000 cells per lane. The merging zone of the onramp is of length 600 m, i.e., 400 cells. Fluid traffic on the onramp with an average velocity of $\sim$ 80 km/h is simulated.

tion: 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, the BL model avoids this artificial mechanism to form a jam, the drivers adjust their speed to the vehicles ahead.

5.1 Wide moving jams in coexistence with synchronized traffic

For the comparison with the empirical data, a two-lane segment with an onramp (Fig. 5.1) is simulated [1]. For the sake of simplicity, symmetric lane changing rules are applied. The lane changing rule set of [123] is used and modified by including anticipation effects for the calculation of an effective gap to the predecessor on the destination lane. In addition, the safety distance to the successor on the destination lane is weakened to the velocity of the successor. The lane changing rules of the onramp are formulated less stringent, in the sense that incoming cars accept smaller gaps for lane changes. A vehicle is allowed to change to the highway if it has an effective gap of 5 cells to the predecessor and a gap of 5 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, the incentive criterion is dropped. The results, however, do not depend on the details of the applied set of rules.

Analogously to the empirical setup, the simulation data are evaluated by a virtual inductive loop, i.e., the number of vehicles passing a given link of the lattice is counted, and their speed is measured. 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 [45], due to local perturbations. For the sake of simplicity, only one type of cars is used 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

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[1] The calibration of the microscopic driving behavior resulted in the following model parameters: $v_{max} = 18$, $p = 0.1$, $p_b = 0.95$, $p_0 = 0.5$, $h = 8$, $d_{\text{safety}} = 3$. The cell length is 1.5 m, a car has a length of 5 cells.

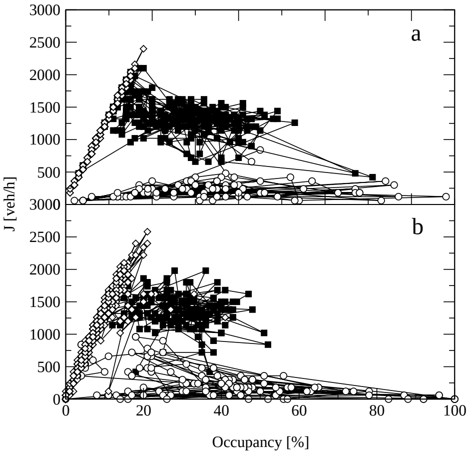

Figure 5.2: Comparison between empirical results (b) for the flow-density relation (fundamental diagram), and time-traced simulation results (a). Each data point corresponds to an average over an one-minute interval. Consecutive measurements are connected by lines. Part (a) shows that the three empirically observed phases of highway traffic are recovered: 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).

comparable to free flow but with a velocity considerably below the free flow velocity and which can, therefore, be identified as synchronized traffic (Fig. 5.3).

The simulations show that the empirical results for the fundamental diagram can quantitatively (see Fig. 5.2) be recovered. 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 reveals large correlations of the velocity time-series between the lanes 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 inductive loop. Thus, the agreement with the empirical fundamental diagram is not only valid for the average values but also concerns 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 5.3 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 demonstrates that the different traffic states can be superposed as observed empirically [73]. 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

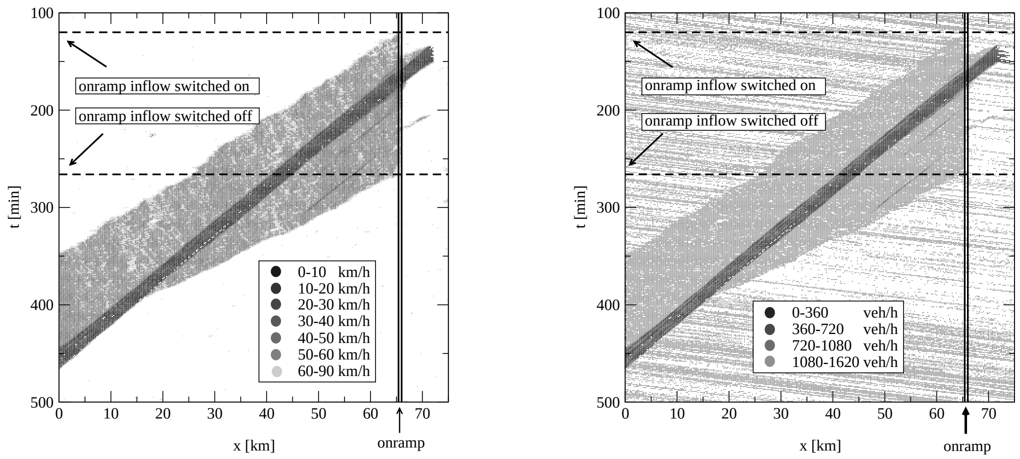

Figure 5.3: Coexistence of wide moving jams and synchronized states. Space/time evolution of the velocity (left) and of the flow (right). The figures show how a traveling jam wave crosses a region of synchronized traffic, that is pinned at the onramp. Downstream the onramp a jam has been generated that 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.

disturbed.

At this point it is important to stress the fact that the observed phenomena are a consequence of the individual behavior of the drivers (see chapter 4 for the calibration of the model). None of the microscopic model parameters has been changed throughout the simulations in order to optimize the agreement 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 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 sidesteps another important question in traffic dynamics, i.e., the origin of phase transitions. The 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 [18, 44, 46]. In addition, the robustness of the empirical observations give strong evidence that traffic states themselves 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 [69, 70].

5.2 Conclusion

From a theoretical point of view, the 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 facilitates the application of phenomenological approaches [65, 66]. 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 [1, 9, 115] for approaches of this kind).

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

Summarizing, it could be 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, that are equally well observed in periodic systems.