1 Introduction

The phases of traffic are matters of everyday experience: going as fast as you can on a freeway, poking along in a crowd of cars moving roughly in unison, sticking in a jam for hours. Empirical observations [73] support this everyday life experience and suggest that one can distinguish three traffic phases: free flow, synchronized traffic and wide jams.

The characteristics of free flow traffic and wide jams are obviously clear. While in free flow an undisturbed movement is possible, in a traffic jam vehicles come to a halt. Usually, traffic jams arise in the vicinity of on- and offramps. These structures are not pinned at a bottleneck but moving in upstream direction, leading to the well-known stop-and-go behavior. One possible explanation for the formation of jams are overreactions of the drivers which induce an avalanchelike cascade of braking maneuvers.

The understanding of synchronized traffic is far behind that of traffic jams. In synchronized traffic, although traffic is dense, the vehicles keep on moving with a small velocity leading to a considerable high flow. In contrast to jams, the downstream front of a synchronized region is fixed at an on- or offramp while in the upstream region small jams can be formed. Several empirical studies [38, 67, 69, 70, 73] describe the properties of synchronized traffic, and various model approaches have been proposed [18, 44, 46] which try to reproduce the basic characteristics. However, most of the empirical analyses focus on the macroscopic characterization of traffic states but do not provide information on the microscopic driving behavior giving rise to them. In addition, most of the present modeling approaches do not allow the reproduction of all the traffic states, especially on a microscopic level of description. Thus, a complete description of synchronized traffic is still missing, and especially the effects of human driving behavior leading to the synchronized state are still far from being understood.

From a traffic engineer's point of view, free flow is the most desirable traffic state because the individual travel-times of the vehicles are optimal. The synchronized state, however, is the most important traffic state since the largest amount of vehicles can drive on the road without large jams and, moreover, high flows are still observable. Unfortunately, its stability is very weak so that perturbations of the flow can cause wide jams. The understanding of the mechanisms leading to the synchronized state may therefore help to stabilize traffic and to increase the throughput of a road, thus, to improve the efficiency of the road-infrastructure. In particular, theoretical observations [56] have demonstrated that the travel-time of vehicles on a highway and on the corresponding onramp can be optimized at a finite injection rate of the onramp. The variation of the onramp flow allows the adjustment of the vehicle interactions and, thus, the stabilization of the synchronized state. As a result, the perturbations are minimized, and the performance of the highway is optimized. The benefits of these ramp-metering systems are confirmed by several empirical studies [124].

From a physicist's point of view, the fundamental understanding of traffic in general as a complex system of many interacting particles driven far from equilibrium, and especially the complex dynamics of the synchronized state leading to collective behavior, is a challenging task. In contrast to many physical systems, the dynamics of traffic cannot be described by well-known physical laws since the details of the microscopic interactions are not fully known. An increased understanding of the microscopic interactions of the vehicles in the various traffic states can be obtained by the analysis of a large amount of empirical traffic data with methods of statistical physics. The aim of a physicist is to describe the general characteristics of traffic by model approaches comprising only the essential parts of the driving dynamics. Thus, the system is assumed to behave randomly according to a set of a few probabilistic dynamical rules. Here, the methods of statistical physics become indispensable for the study of the system's properties. Unfortunately, although much progress has been made in the last few years for the exact solution of such stochastic processes, the analytical treatment of realistic models is still not possible [18].

One approach towards traffic flow that has been widely accepted in recent years are cellular automaton models. The basic ideas of cellular automata were developed by Ulam and von Neumann [139] in the early 1950s for the study of self-reproduction in biological systems. However, it was about years later, the first systematic analysis was carried out by Wolfram [145]. Cellular automaton models are by design well suited for computer simulations. Since the behavior of a system is described in discrete time and space, and the evolution of the system is governed by a set of a few simple update rules, very efficient implementations are possible.

The first cellular automaton models for traffic flow were proposed by Cremer [22] and Nagel and Schreckenberg [106]. Despite its simplicity, the stochastic model of Nagel and Schreckenberg is able to reproduce the basic phenomena of traffic flow like the spontaneous emergence of jams, and it also shows typical stop-and-go patterns. Thereby the model of Nagel and Schreckenberg is a minimal model in the sense that every further simplification of the dynamics leads to a loss of realism. This quite simple model already gives reasonable results in modeling large scale traffic networks like the inner city of Duisburg [29], the Dallas/Forth-Worth area [122] and the highway traffic in North-Rhine Westfalia [62]. However, in order to improve the fidelity of these approaches, more sophisticated models are necessary that consider the vehicle not only as an interacting particle, but also focus on basic psychological aspects of the drivers' decision processes. The model's rules may therefore be related to the human driving behavior and give a microscopic explanation for the stability of synchronized traffic.

Thus, a more realistic model and a more careful re-analysis of existing and new data in the light of recently developed concepts is required (cf. [18]). The objective of this thesis is therefore to analyze single-vehicle data in order to obtain more insight into the driving dynamics in the various traffic states and to develop a microscopic model based on the Nagel and Schreckenberg cellular automaton which is able to give a satisfactory description of the three traffic states, especially of synchronized traffic.

The outline of the thesis is as follows:

In chapter 2 a short review of the empirical facts and modeling approaches is presented: The measurement techniques and observables required for the description of the empirical characteristics of the traffic states are provided. In addition, results from recent empirical observations on highway traffic are given. The traffic states appearing in reality are described, and their transitions are characterized. Moreover, the microscopic properties of the various states are emphasized. Finally, empirical multi-lane characteristics of highway traffic are summarized, and an overview of the modeling approaches and their success in reproducing the traffic states is presented.

The following chapter concentrates on an extended analysis of empirical single-vehicle data. Existing results [110] are verified, and the driving behavior of a vehicle in the traffic states is described in order to formulate a microscopic model that reproduces synchronized traffic.

Based on the comparison with empirical results, the limitations of various prominent cellular automaton models for traffic flow regarding the degree of realism in modeling traffic states are analyzed in chapter 4, and an extension of the Nagel and Schreckenberg cellular automaton model is presented which allows the reproduction of synchronized traffic. The basic properties of the proposed model are analyzed, and its parameters are calibrated. The validation of the model on a microscopic level is based on empirical single-vehicle data.

As a next step for the evaluation of the model, in chapter 5 a two-lane highway segment with an onramp is considered. The propagation of a wide jam through synchronized traffic, which is an objective criterion for the distinction of these phases [73], is shown. In addition, the model properties are related to the human driving behavior.

Although these results do not depend on the lane changing rules, a realistic two-lane extension of the model is presented in the next chapter, and the microscopic origin of the empirically observed lane-usage inversion is clarified.

Since empirical [124] and theoretical [56] studies reveal that ramp-metering systems are promising for the optimization of traffic flow on a highway, in chapter 7 an extended analysis of empirical data of the highway network of North-Rhine-Westfalia is presented. The coverage of the network with inductive loops allows to identify and characterize its bottlenecks and helps to judge its optimization potential. It is clarified whether the bottlenecks are of topological nature or if they are constituted by on- and offramps.

The work concludes with a brief summary and outlook in chapter 8.

Finally, in appendix A is described a method how to calculate the correlations of a time-series that is unevenly sampled. This method becomes useful for the analysis of empirical traffic data. In appendix B the effects of the discretization of the Nagel and Schreckenberg model on the traffic dynamics is discussed.