Doctoral Thesis Summary

Microscopic Modeling of Human and Automated Driving: Towards Traffic-Adaptive Cruise Control

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Mikroskopische Verkehrsmodellierung menschlichen und automatisierten Fahrverhaltens: Verkehrsadaptive Strategie für Geschwindigkeitsregler

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Efficient transportation systems are essential to the functioning and prosperity of modern, industrialized societies. Mobility is also an integral part of our quality of life, sense of self-fulfillment and personal freedom. Our traffic demands of today are predominantly served by individual motor vehicle travel which is the primary means of transportation. However, the limited road capacity and thus traffic congestion has become a severe problem in many countries. On the one hand, traffic demand can only be affected indirectly by means of policy measures. On the other hand, an extension of transport infrastructure is no longer an appropriate or desirable option in densely populated areas. Moreover, construction requires high investments and maintenance is costly in the long run. Therefore, engineers are now seeking solutions to the questions of how the capacity of the road network could be used more efficiently and how operations can be improved by way of intelligent transportation systems (ITS).

Achieving this efficiency through automated vehicle control is the long-standing vision in transport telematics. With the recent advent of advanced driver assistance systems, at least partly automated driving is already available for basic driving tasks such as accelerating and braking by means of *adaptive cruise control* (ACC) systems. An ACC system extends earlier cruise control to situations with significant traffic in which driving at constant speed is not possible. The driver cannot only adjust the desired velocity but also set a certain safety time gap determining the distance to the leading car when following slower vehicles. The task of the ACC system is to calculate the appropriate acceleration or deceleration as a function of the input quantities and the driver's settings. Therefore, the actual distance and speed difference to the vehicle ahead is measured by means of a long-range radar sensor.

The thesis is composed of two main parts. The first part deals with a microscopic traffic flow theory. Models describing the individual acceleration, deceleration and lane-changing behavior are formulated and the emerging collective traffic dynamics are investigated by means of numerical simulations. The models and simulation tools presented provide the methodical prerequisites for the second part of the thesis in which a novel concept of a traffic-adaptive control strategy for ACC systems is presented. The impact of such systems on the traffic dynamics can solely be investigated and assessed by traffic simulations.

Microscopic Model Calibration and Validation

The Intelligent Driver Model (IDM)[1], a microscopic car-following model, is the starting point of the thesis. It is well-known from the literature that the IDM is able to reproduce all essential traffic dynamic phenomena observed on freeways. Furthermore, the IDM features a small number of parameters which are easy to interpret and therefore allow for a intuitive characterization of different driver-vehicle classes (e.g., cars and trucks) but also heterogeneous

[1] M. Treiber, A. Hennecke, D. Helbing, *Congested traffic states in empirical observations and microscopic simulations*, Physical Review E 62, 1805 -1824 (2000).

driving behavior. A basic understanding of the properties of the IDM is obtained by the in-depth investigation of the single-vehicle dynamics, the equilibrium characteristics and the emergence of collective instabilities.

In the literature, the IDM has been calibrated using macroscopic quantities derived from empirical speed and flow data. In the thesis, a microscopic calibration and validation framework for car-following models is presented which aims to minimize deviations between the observed driving dynamics and the simulated trajectory when following the same leading vehicle. For the numerical solution of this nonlinear optimization problem, a genetic algorithm has been developed. Three different objective functions were formulated to assess the reliability and robustness of the calibration results. The IDM was able to reproduce the driving behavior reflected in the empirical trajectories. The calibrated model parameters are in the expected range whilst the errors obtained are between 10% and 30% which is consistent with errors typically found in previous studies for other models. The results indicate that dynamic adaption processes of the drivers (*intra-driver variability*) rather than varying driving characteristics of different drivers (*inter-driver variability*) account for a large part of the calibration errors.

Model for the Human Driving Behavior

As shown in the calibration study, the Intelligent Driver Model is able to describe the human driving behavior on a microscopic level to a satisfactory extent. With respect to obvious operational differences between a human driver and a simplistic car-following model which simply reacts instantaneously to the immediate vehicle ahead, it is important to ask for a theoretical justification. This is not only of fundamental scientific interest but also relevant to the underlying modeling assumptions in the second part of the thesis.

A complex microscopic traffic model is formulated which comprises essential aspects of human driver behavior not captured by simple car-following models. In the first place, there is a finite reaction time, the mathematical formulation of which leads to delay-differential equations. It is known from the literature that human reaction times are of the order of one second leading to very unstable modeled driving behavior. Stability is further reduced by limited human perception and estimation capabilities which are treated by Wiener processes leading to stochastic model elements. For a stabilization of the microscopic driving behavior, two anticipation mechanisms are considered: First, the modeled driver reacts not only to the immediate leader but also (with decreasing weights) to the vehicles further ahead ("spatial" or multi-anticipation). In this respect, the proposed model goes well beyond the usual car-following approximation. As the driver knows about his or her reaction time while perceiving the vehicles in front we moreover assume a heuristic that extrapolates the actual traffic situation on the scale of the reaction time ("temporal" anticipation).

The three characteristic time constants that influence the collective dynamics and stability of traffic flow are: (i) The delay caused by the finite reaction time of the drivers, (ii) the time lag due to a finite velocity adaptation time needed to accelerate to a new desired velocity, and (iii) the numerical update time[2]. In the proposed model, these effects are incorporated by independent parameters. By means of numerical simulations, we investigate how these times are interrelated and act to influence the local and collective mechanisms for instability in a platoon of vehicles. The long-wavelength string instability is mainly driven by the velocity adaptation time (due to the vehicles' limited acceleration capabilities) whilst short-wavelength local instabilities arise by sufficiently high reaction and/or update times. Furthermore, we investigate the relationship between large update time steps and finite reaction times, both of which introduce delays in the reaction to the traffic situation. Remarkably, the numerical update time is dynamically equivalent to about half the reaction time which clarifies the meaning of the time step in models formulated as iterated maps such as the Newell and the Gipps models. With respect to stability, we found an *optimal* adaptation time (corresponding to moderate vehicle accelerations) as a function of the reaction time.

Furthermore, we simulate the emerging macroscopic traffic dynamics in the presence of finite reaction times and driver anticipation in a complex scenario with a flow-conserving bottleneck (e.g., a lane closure or roadworks) in the open system with a time-dependent inflow as upstream boundary condition. It is shown that various spatiotemporal patterns of congested traffic can be reproduced by varying intrinsic model parameters such as reaction times and multi-anticipation. Moreover, we show that the destabilizing effects of reaction times and estimation errors can essentially be compensated for by spatial and temporal anticipation. Remarkably, the anticipation allows accident-free smooth driving in complex traffic situations even if reaction times exceed typical safety time gaps. Within the proposed modeling framework, these findings are able to explain why the simplified car-following models are capable of quantitatively describing the empirically observed traffic phenomena.

Modeling Lane-Changing Decisions

In addition to the acceleration and deceleration behavior of the drivers in the lane, a fully multi-lane simulation framework is needed for a realistic microscopic description of freeway traffic as only the possibility of passing slower vehicles allows for a consideration of effects that are caused by heterogeneous driver types and different vehicle classes. In addition, realistic on-ramp bottlenecks require the explicit modeling of the merging decision to the main road.

[2]As well as the numerical necessity for a finite time discretization to solve differential equations by means of numerical integration, the update time can be interpreted as representing *finite attention to the traffic*: Only at times that are a multiple of the update step do drivers look at the traffic situation and instantaneously adapt their acceleration to the new situation. Because of the intuitive meaning of this update procedure in the context of traffic, the explicit integration scheme is sometimes considered as an explicit model parameter rather than as a numerical approximation. Popular examples of such *coupled maps* include the models by Newell and Gipps.

The general model MOBIL ("Minimizing Overall Braking Induced by Lane Change") is proposed to derive lane-changing rules for discretionary and mandatory lane changes for a wide class of car-following models. Both the utility of a given lane and the risk associated with lane changes are determined in terms of longitudinal accelerations calculated with microscopic traffic models. This determination in terms of a "meta model" allows for the formulation of compact and general safety and incentive criteria for both symmetric and asymmetric passing rules. Moreover, anticipative elements and the crucial influence of velocity differences of these car-following models are automatically transferred to the lane-changing rules. Although the safety criterion prevents critical lane changes and collisions, the incentive criterion takes into account the respective advantages and disadvantages of all drivers via a "politeness factor" which rise out of a lane change. This novel feature allows one to vary the motivation for changing lane from purely egoistic to more cooperative driving behavior. Firstly, the politeness parameter prevents lane changes for a marginal advantage if other drivers are obstructed. Secondly, it induces a lane change by a slower driver ahead if an aggressive driver in the same lane is approaching quickly. The latter phenomenon is common for asymmetric passing rules with a dedicated lane for passing. Simulations of an open system result in realistic lane-changing rates as a function of traffic density.

Traffic-adaptive Driving Strategy extending ACC Systems

In the second part of the thesis, the focus is on future adaptive cruise control (ACC) systems and their potential applications in the context of vehicle-based intelligent transportation systems. Present implementations of ACC systems are exclusively designed to increase driving comfort and the influence on the surrounding traffic is neither considered nor optimized. This is justified as long as the number of ACC-equipped vehicles is negligible but the growing market penetration of these devices makes the question of their impact on traffic flow more pressing. Therefore, it is important to understand the effects of ACC systems on the capacity and stability of traffic flow at an early stage so that their design can be adjusted before adverse traffic effects can widely manifest themselves.

In order to ensure that ACC systems are implemented in ways that improve rather than degrade traffic conditions, the thesis proposes an extension of ACC systems towards *traffic-adaptive cruise control* by means of implementing an actively jam-avoiding driving strategy.

The newly developed *traffic assistance system* introduces a *driving strategy layer* which modifies the driver's individual settings of the ACC driving parameters depending on the local traffic situation. Whilst the conventional operational control layer of an ACC system calculates the response to the input sensor data in terms of accelerations and decelerations on a short time scale, the automated adaptation of the ACC driving parameters happens on a somewhat longer time scale of, typically, minutes. By changing only temporarily the comfortable parameter settings of the ACC system in specific traffic situations, the driving strategy is capable of improving the traffic flow efficiency whilst retaining the comfort for the driver. The traffic-adaptive modifications are specified relative to the driver settings in order to maintain the individual preferences.

The proposed system consists of three components: (i) the ACC system itself, (ii) an algorithm for the automatic real-time detection of the traffic situation based on local information, and (iii) a "strategy matrix" that associates the autonomously detected traffic situation with different parameter settings of the underlying ACC system, that is, it implements different driving characteristics. In order to do this, a finite set of five "traffic situations" is considered, each of which is associated with a specific set of ACC driving parameters:

- Moving in *free traffic* is the default situation. The ACC settings are determined solely with regard to the individual driving comfort. Since each driver adjusts his or her ACC parameter settings individually, this may lead to different settings for each ACC system.
- When *entering a traffic jam* (approaching an upstream congestion front) the driving strategy aims at reducing velocity gradients in order to reduce the risk of rear-end collisions, thus increasing collective safety. Compared to the default situation, this implies earlier braking when approaching slow vehicles which also increases the driving comfort. Note that the operational layer of the ACC system always assures a safe individual approaching process independent of the detected traffic state.
- Since drivers *moving in congested traffic* cannot influence the development of traffic congestion in the bulk of a traffic jam, the ACC settings revert to the individual parameter values of the driver again.
- Once traffic flow has broken down, the dynamics of the evolving congestion is determined first by the inflow (the externally given traffic demand) and second by the outflow from the traffic jam at the downstream congestion front. When *passing the downstream congestion front*, accelerations are therefore increased and time gaps temporarily decreased in order to raise that dynamic capacity.
- It is known that most traffic breakdowns are initiated at some sort of road inhomogeneities or infrastructure-based bottlenecks such as on-ramps, off-ramps or sections of roadworks. When passing these infrastructural *bottleneck sections*, the objective is to locally increase the capacity, that is, to *dynamically "fill" the capacity gap*. This requires a temporary modest reduction of the parameter value for the time gap.

Note that drivers typically experience the full sequence of these five traffic states when traveling through congested traffic. In free flow conditions, only the default and the bottleneck state are relevant. Therefore, the cumulative time period during which the ACC settings deviate from the default state is usually only a few percent.

The proposed system requires an autonomous real-time detection of the five traffic states by each ACC-equipped vehicle. The formulated algorithm is based on the evaluation of the locally available data such as the vehicle's velocity time series and its geo-referenced position (GPS) in conjunction with a digital map. It is assumed that the digital map is complemented by information about stationary bottlenecks as most of the observed traffic flow breakdowns occur at these fixed locations. By means of a heuristic, the algorithm determines which of the five traffic states mentioned above applies best to the actual traffic situation. Optionally, inter-vehicle and infrastructure-to-car communication technologies can be used to further improve the accuracy of determining the respective traffic state by providing non-local information.

Evaluation by means of Microscopic Traffic Simulations

The effects of upcoming driver assistance systems on the collective traffic dynamics can only be evaluated by means of traffic simulations. In order to study the proposed traffic-assistance system we have implemented the proposed components within a microscopic multi-lane traffic simulator which considers both "human drivers" as well as which fraction of vehicles are equipped with the traffic-adaptive cruise control system. As the autonomous traffic state detection requires real-time traffic data, the simulations first serve as "proof of concept" of the system components. Depending on the detected local traffic situation, the corresponding driving strategy is realized by the underlying ACC system. From a formal point of view, this corresponds to a car-following model with an automatic, event-driven choice of parameters which therefore become time-dependent. Furthermore, we simulated a road section with an on-ramp bottleneck using empirical loop-detector data for an afternoon rush-hour as inflow at the upstream boundary.

By means of simulation, we found that the automatic traffic-adaptive driving strategy improves traffic stability and increases the effective road capacity. Depending on the fraction of ACC vehicles, the driving strategy "passing a bottleneck" effects a reduction of the bottleneck strength and therefore delays (or even prevents) the breakdown of traffic flow. Changing to the driving mode "leaving the traffic jam" increases the outflow from congestion resulting in reduced queue lengths in congested traffic and, consequently, a faster recovery to free flow conditions. The current travel time (as most important criterion for road users) and the cumulated travel time (as an indicator of the system performance) are used to evaluate the impact on the quality of service. While traffic congestion in the reference scenario was completely eliminated when simulating a proportion of 25% ACC vehicles, travel times were significantly reduced even with much lower penetration rates. Moreover, the cumulated travel times decreased consistently with the increase in the proportion of ACC vehicles.

For a systematic analysis of the impact of a given proportion of ACC vehicles on capacity, we varied external parameters such as the proportions of trucks and ACC-equipped vehicles and also the parameterization of the proposed driving strategy. First, we considered the maximum capacity in free flow determining the maximum throughput up to the breakdown of traffic flow.

As a dynamic quantity depending on collective stability properties, the maximum capacity has to be distinguished from the static road capacity. For the purpose of clarification, the stochastic nature of a traffic flow breakdown has been demonstrated by considering multiple simulation runs. The variance of the maximum free capacity (treated as a random variable) depends on the heterogeneity of the driver-vehicle composition. Furthermore, it has been shown that the consideration of different vehicle classes has a stronger impact on the arithmetic mean than the consideration of statistically distributed model parameters within a driver-vehicle class.

Finally, the simulations allow the identification of limitations to the autonomous traffic-state detection. In particular, the adaptation when approaching a dynamically propagating front (e.g., a stop-and-go wave) requires knowledge of the jam front position at an early stage in order to be able to switch to the new driving strategy in time. It has been shown that propagating jam fronts cannot be detected reliably enough on the basis of the vehicle's local information. In order to improve the accuracy of determining the traffic states the detection algorithm is extended by adding non-local information that can be provided by inter-vehicle or infrastructure-to-car communication. As concerns inter-vehicle communication, a simulation study has demonstrated the whole cycle of information generation, propagation, reception, processing and autonomous on-board estimation of the upcoming traffic situation. The simulations demonstrate that the "store and forward" strategy (that is, vehicles in the opposite driving direction serving as intermediate stations keeping information and sending messages at a later point in time to other equipped vehicles in the considered driving direction) allows for a sufficient connectivity resulting in the effectual propagation of information even in the case of a limited broadcast range and a low percentage of equipped vehicles.

The efficiency of the proposed driving strategy even with a low market penetration is a promising result for the successful application of future driver assistance systems. In addition to the application for traffic-adaptive cruise control, the detection, interpretation and prediction of local traffic situations in combination with future communications technologies can be used for the development of future driver information systems.