17th International Conference on the Application of Computer
Science and Mathematics in Architecture and Civil Engineering
K. Gürlebeck and C. Könke (eds.)
Weimar, Germany, 12–14 July 2006

DECENTRALIZED APPROACHES TO ADAPTIVE TRAFFIC CONTROL AND AN EXTENDED LEVEL OF SERVICE CONCEPT

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Keywords: Traffic simulation, adaptive cruise control, traffic and driver assistance systems, inter-vehicle communication, self-organized traffic light control, quality and level of service

Abstract. *Traffic systems are highly complex multi-component systems suffering from instabilities and non-linear dynamics, including chaos. This is caused by the non-linearity of interactions, delays, and fluctuations, which can trigger phenomena such as stop-and-go waves, noise-induced breakdowns, or slower-is-faster effects. The recently upcoming information and communication technologies (ICT) promise new solutions leading from the classical, centralized control to decentralized approaches in the sense of collective (swarm) intelligence and ad hoc networks.*

An interesting application field is adaptive, self-organized traffic control in urban road networks. We present control principles that allow one to reach a self-organized synchronization of traffic lights. Furthermore, vehicles will become automatic traffic state detection, data management, and communication centers when forming ad hoc networks through inter-vehicle communication (IVC). We discuss the mechanisms and the efficiency of message propagation on freeways by short-range communication.

Our main focus is on future adaptive cruise control systems (ACC), which will not only increase the comfort and safety of car passengers, but also enhance the stability of traffic flows and the capacity of the road ("traffic assistance"). We present an automated driving strategy that adapts the operation mode of an ACC system to the autonomously detected, local traffic situation. The impact on the traffic dynamics is investigated by means of a multi-lane microscopic traffic simulation. The simulation scenarios illustrate the efficiency of the proposed driving strategy. Already an ACC equipment level of 10% improves the traffic flow quality and reduces the travel times for the drivers drastically due to delaying or preventing a breakdown of the traffic flow. For the evaluation of the resulting traffic quality, we have recently developed an extended level of service concept (ELOS). We demonstrate our concept on the basis of travel times as the most important variable for a user-oriented quality of service.

1 INTRODUCTION

Traffic congestion is a severe problem on freeways in many countries. According to a study of the European Commission [1], its impact amounts to 0.5% of the gross national product and will increase even up to 1% in the year 2010. Since in most countries, building new transport infrastructure is no longer an appropriate option, there are many approaches towards a more effective road usage and a more "intelligent" way of increasing the capacity of the road network and thus to decrease congestion. Due to the potential benefits and the expected technological progress, there is considerable research in the area of intelligent transport systems (ITS) [2, 3]. Examples of centralized traffic management and control systems are, e.g., ramp metering, adaptive speed limits, or dynamic and individual route guidance.

However, the recently upcoming information and communication technologies (ICT), including cheap optical, radar, video, or infrared sensors and mobile communication technologies promise new solutions. For example, future adaptive cruise control systems (ACC) will not only increase the comfort and safety of car passengers, but also enhance the stability of traffic flows and the capacity of the road. We call this "traffic assistance" [5]. Vehicles will become automatic traffic state detection, data management, and communication centers when forming ad hoc networks through inter-vehicle communication (IVC) [6].

These concepts lead from the classical, centralized control to decentralized approaches in the sense of collective (swarm) intelligence and ad hoc networks. Such concepts reduce the problem of data flooding by restricting to the locally relevant information only and reach more adaptiveness, flexibility, resilience and robustness with respect to local requirements and temporary failures. Another interesting application field is adaptive traffic control in urban road networks. Recently, control principles have been formulated that allow one to reach a self-organized synchronization of traffic lights.

For the evaluation of the resulting traffic quality, we have recently developed an *extended level of service concept (ELOS)*. In contrast to the standard concept of six levels of service (LOS) [7, 8], which is purely based on density classes, it pursues a multi-criteria approach, taking into account a wider range of traffic-related properties and the subjective quality of traffic flow conditions. Our *quality of service concept* considers impacts on individual road users, society, and environment. Multi-criteria ELOS information is suitable for traffic planning that is not only oriented at traffic capacity, but also at traffic quality. Moreover, ELOS information about the actual or forecasted traffic situation could be broadcasted to drivers. The individual driver could use this information to identify the optimal route under given traffic conditions.

Our paper is organized as follows: First, we introduce an extended level of service concept (ELOS). In Sec. 3, we present different approaches for decentralized adaptive traffic control. In Sec. 4, we go into detail and model a driving strategy for a "traffic assistance" system as extension of today's ACC systems. The impact on the traffic dynamics is investigated by means of a multi-lane microscopic traffic simulation. We conclude with a summary and outlook.

2 A MULTI-CRITERIA CONCEPT FOR AN EXTENDED LEVEL OF SERVICE

The growing demand for mobility and its consequences such as traffic jams pose a major social, economic, and environmental challenge. To guide the driver in route-choice decisions ant trip start times, or to assess the impacts of traffic congestion, an accurate measure for the level of service on given sections of the primary and secondary road network is essential. In contrast to the standard concept of six levels of service (LOS) of the *Highway Capacity Manual* (HCM) [8], which is based on density classes, our proposed *extended level of service* (ELOS) pursues a multi-criteria approach, which takes into account a wider range of traffic-related properties and the subjective quality of traffic flow conditions. It could also be called a *quality of service concept*, as it considers impacts on individual road users, society, and environment. This includes travel times, driving comfort, safety, the ability to change lanes freely, fuel consumption, and emissions, or the degree to which traffic quality is affected by road works or an increased percentage of trucks.

The focus of the multi-criteria ELOS concept is on the individual road user rather than on the operators of the infrastructure. From the various level of service variables, an ELOS *index* can finally be defined. The new index distinguishes unstable and congested traffic situations (classes 'E' and 'F' in the HCM scheme) in much greater detail. This is highly relevant, as, for example, a 10 km long road section of congested traffic may result in a travel time increase by only 5 minutes (relatively mild congestion), or by 20 minutes (more severe), cf. Sec. 4. Nevertheless, in the LOS concept of the HCM, both traffic situations are categorized in the same category 'F', which is obviously not differentiated enough. This shortcoming has been identified by other researchers as well [9, 10].

An essential feature of our ELOS index is the commensurability of all level of service criteria. To this end, we formulate all factors in terms of *generalized costs*. For example, we convert travel times into monetary units by appropriate "time-is-money" relationships to compare them with the costs by fuel consumption with the actual costs. The environmental costs of emissions could be quantified in terms of the prices traded, e.g., on European markets for CO_2 emission certificates. Other aspects such as the driving comfort or the subjective costs for increased stress when driving along sections with road works can be compared to travel times by *thought experiments* describing typical decision processes. In evaluating the subjective costs determining the outcome of such decisions, recent results from empirical psychological studies in the field of *behavioral finance* [11] have been taken into account by us.

In order to obtain the actual ELOS index for a certain road segment, all of the above mentioned costs are summed up to yield the overall generalized costs. Applying a monotonous nonlinear function to these costs finally distinguishes ten different quality levels of the proposed ELOS index.

The ELOS criteria are formulated in terms of measurable quantities of traffic flow such as velocity, traffic flow, truck percentage, occupancy, and variations thereof. Depending on their availability, stationary detector data for the measurement of velocity or occupancy, floating-car data, and trajectory data can be included. From these data, the spatiotemporal traffic dynamics [12], travel times [13], and measures for the driving comfort and safety [14] are derived. Further input quantities include infra-structural properties such as positions and lengths of building sites and possible reductions in lane numbers and narrowings of lanes in these sections. From this information, the reduction of the ELOS by road works is calculated. Finally, the ELOS concept includes a model for the fleet-averaged instantaneous fuel consumption as a function of velocity and acceleration.

The new ELOS variables can serve several purposes. First, the generalized costs underlying the ELOS concept can be used to estimate the total costs to society imposed by traffic, in particular, by congested traffic. Moreover, multi-criteria ELOS information about the actual or forecasted traffic situation could be broadcasted to drivers. On the level of individual drivers, this information could be used to identify the optimal route for given traffic conditions. Even individual preferences, e.g., for the time-is-money conversion factor, could be set. In this way, a more accurate analysis of individual travel behavior may become possible as well.

In the following, we will focus on decentralized strategies in order to improve the traffic efficiency and the capacity of the road network. For their assessment, the ELOS index can be used as a quality measure and benchmark, which takes into account the impacts on individual road users, the society, and environment. In Sec. 4.6 we will, therefore, evaluate the ELOS index on the basis of travel times as the most important variable for a user-oriented quality of service.

3 DECENTRALIZED APPROACHES TO ADAPTIVE TRAFFIC CONTROL

3.1 Adaptive Cruise Control (ACC)

The recent development and availability of *adaptive cruise control* systems (ACC) extends earlier cruise control systems, which were designed to maintain a selected speed. An ACC system is able to detect and to track the vehicle ahead, measuring the actual distance and speed difference to the vehicle ahead by a radar sensor. Together with the own vehicle speed, these input data allow the system to calculate the needed acceleration or deceleration to maintain a selected safe time headway. The update time for the data is typically $0.1\,\mathrm{s}$, i.e., much shorter that the reaction time of human drivers of about $1\,\mathrm{s}$ [15]. In commercially available ACC systems, the time headway can be adjusted by the user typically in the range between $1\,\mathrm{s}$ and $2\,\mathrm{s}$. Additionally, the user is able to select the desired velocity. These systems offer a gain in comfort in applicable driving situations on freeways, but they are still restricted to free traffic and high speed regimes due to their limited speed and acceleration range. The next generation of ACC is constructed to operate in all speed ranges and most traffic situations on freeways including stop-and-go traffic. Furthermore, ACC systems have the potential to prevent actively a rear-end collision and, thus, to achieve also a gain in safety. Nevertheless, it should be emphasized that ACC systems control only the longitudinal driving task. Merging, lane changes or gap-creation for other vehicles still need the intervention of the driver. So, as the driver still takes the entire responsibility, he or she has always to be able to override the system.

3.2 Extending ACC towards a "Traffic Assistance System"

Let us now present an *automated driving strategy* for vehicles equipped with ACC systems [5]. The motivation is that a vehicle-based driving strategy might help to increase the road capacity and thus decrease traffic congestion. In contrast to the short-time response of the ACC system to the local traffic environment by means of acceleration and braking maneuver, we will denote by the term "strategy" adaptations to the overall traffic situations on a longer time scale (typically minutes) aimed to improve the traffic performance, i.e., both capacity and stability of traffic flow. To this end, we consider a driving strategy, which adapts its specific driving style to the current, local traffic situation. Our driving strategy distinguishes between the following traffic situations:

- The default driving strategy implements a normal, comfortable ACC driving style comparable to human driving behavior. This default driving state applies for the predominant number of driving situations.

- The most important strategy aims to avoid or, at least, delay a traffic breakdown. This does not only reduce travel times, but also increases traffic performance, since traffic breakdowns lead to significant *capacity drops* [16]. Stationary bottlenecks, i.e., freeway entrances, exits, or construction sites, are typically the locations where traffic initially breaks down [17]. To maintain free flow conditions, we implement an attentive driving style with a slightly reduced time headway when passing a stationary bottleneck section. This behavior leads to a dynamic homogenization of traffic flow, since even a slightly increased capacity can compensate for the capacity-reducing property of many bottlenecks.

- The second important traffic situation is related to congested traffic conditions. Once traffic has broken down, increasing the outflow at the downstream jam front is the only possible strategy to reduce traffic congestion. An increased acceleration in combination with keeping a small gap to the vehicle ahead is an appropriate driving style while passing the downstream front of the traffic jam.

- Furthermore, our strategy adapts to the situation, when a driver approaches the upstream front of a traffic jam, by more timely and smoother braking in order to increase the safety of a driver and the followers. On average, this driving style can have a positive impact on capacity, because the risk of accidents is reduced.

An important feature of the proposed decentralized driver assistance system is the autonomous adaptation of the driving style according to the proposed strategy of the equipped vehicles in the mixed traffic flow of human and ACC-controlled vehicles. The identification of the aforementioned traffic states requires a *detection model* as additional system component, which is based on the locally available floating car data, i.e., the data that are provided by the radar sensor of the ACC system. Furthermore, the identification of stationary bottlenecks requires information about the infrastructure, because bottlenecks are typically associated with modifications in the freeway road design such as on-ramps, off-ramps, lane blocking, or uphill gradients (cf. Fig. 1). We assume that this information is provided by a digital map database in combination with a positioning device (GPS receiver). The positioning device provides the vehicle position and the digital map contains the position of a bottleneck. Similar applications of driver assistance systems using advanced digital maps are, e.g., curve speed or speed limit assistance.

3.3 Inter-vehicle communication

The aforementioned detection model is exclusively based on *local information*. For a more advanced vehicle-based traffic state estimation, non-local information can be additionally incorporated in order to improve the detection quality (cf. Fig. 1). For example, a short-range communication between vehicles (inter-vehicle communication, IVC) is a reasonable extension providing up-to-date information about *dynamic* up- and downstream fronts of congested traffic, which cannot be estimated without delay by local measurements only [6, 18]. In contrast to the conventional communication channels, which operate with a centralized broadcast concept via radio or mobile-phone services, IVC is designed as a local service. Vehicles equipped with a short-range radio device broadcast messages, which are received by all other equipped cars

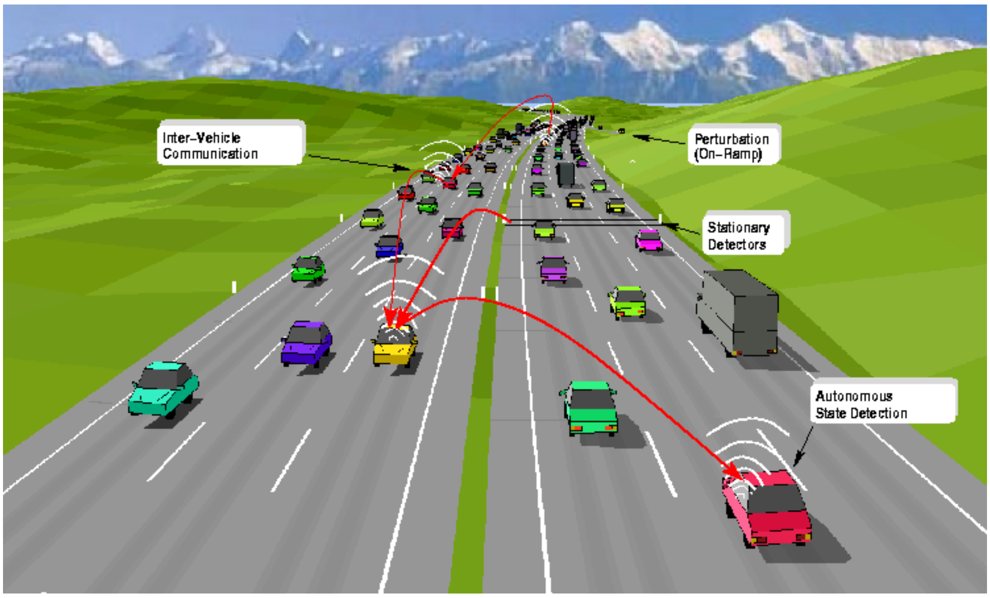


Figure 1: Illustration of different information sources for a vehicle-based detection of the current traffic situation: (i) The radar sensor of the ACC system provides local floating-car data. (ii) A positioning device (GPS receiver) in combination with a digital map allows for a detection of stationary bottlenecks due to inhomogeneities of the road infrastructure such as on-ramps, off-ramps, uphill gradients, etc. Non-local information can be communicated by local broadcast services whether (iii) by stationary senders resp. detectors, or (iv) by inter-vehicle communication.

within the limited broadcast range. The message transmission is not controlled by a central station, and, therefore, no further communication infrastructure is needed. Wireless local-area networks (WLAN) have already shown their suitability for IVC with typical broadcast ranges of 100–300 m. In addition, the short-range broadcast technology allows also for a roadside-to-vehicle communication, e.g., while passing a stationary sender.

In the context of freeway traffic, messages normally have to travel upstream in order to be valuable for their receivers. In general, there are two strategies, how a message can be transported upstream via IVC as displayed in Fig. 2: Either the message hops from an IVC car to a subsequent IVC car within the same driving direction (“longitudinal hopping”), or the message hops to an IVC-equipped vehicle of the other driving direction, which takes the message upstream and delivers it back to cars of the original driving direction (“transversal hopping”). A problem of the longitudinal hopping process is that it may not work properly for low equipment rates due to the short broadcasting range. However, the latter mechanism with vehicles of the opposite driving direction serving as relay stations is operational for a reliable and fast information propagation in case of low equipment levels of some percent of the vehicle fleet. For example, even for an equipment rate of 5% only, a traffic-information message will be passed 1 km upstream with a probability of 50% within 36 seconds [6].

3.4 Adaptive control of traffic signals

Decentralized approaches can also be applied to the adaptive control of traffic signals at intersections in urban road networks [19, 20]. When the arrival flows of vehicles are low, it is known that the first-in-first-out principle or the right-before-left principle without any further traffic regulation work well. For moderate flows, rotary traffic has shown to be efficient, reach-

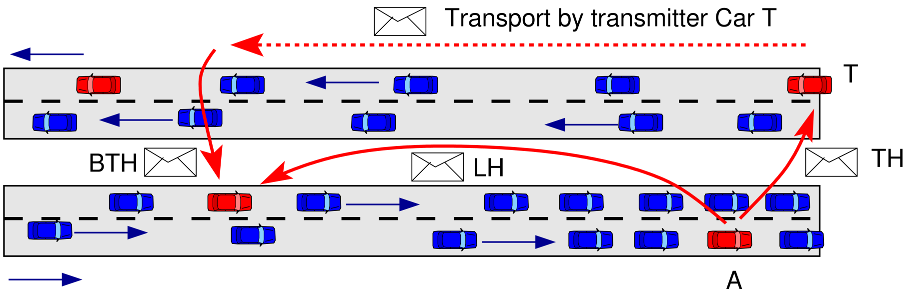


Figure 2: Transport of a traffic-related information message: The car *A* enters a traffic jam and broadcasts a corresponding message. The message is either received by a subsequent car via longitudinal hopping (*LH*) or by an equipped transmitter car *T* of the other driving direction via transversal hopping (*TH*). The message can travel with the transmitter vehicle further upstream until the message hops back to the original driving direction (*BTH*). The transversal hopping process is much more efficient for a fast and reliable message propagation in upstream direction.

ing only small delays in travel times. However, for high traffic volumes, it is better to bundle cars with the same or compatible directions and to serve them group-wise rather than one by one. This implies an oscillatory mode of service, since it saves clearance times to serve many cars with the same direction.

A large amount of effort has been spent on optimizing traffic light control in the past. The classical approaches require vast amounts of data collection and processing as well as huge processing power. Centralized control concepts, therefore, imply a tendency of overwhelming the control center with information, which cannot be fully exploited online. Furthermore, today's control systems have difficulties responding to exceptional events, accidents, temporary building sites or other changes in the road network, failures of information channels, control procedures, or computing centers, natural or industrial disasters, catastrophes, or terrorist attacks. These weaknesses could be overcome by a decentralized, adaptive approach, which can utilize local information better. The independence from a central traffic control center promises a greater robustness with respect to localized perturbations or failures and a greater degree of flexibility with respect to the local situation and requirements. A decentralized control approach reduces the computational complexity and the sensitivity to far remote traffic a lot. As there is usually only one globally optimal solution, but a large number of nearly optimal solutions, the idea is to find the one which fits the local situation and demand best.

In a pending patent [21], we have described an autonomous adaptive control based on a traffic-responsive self-organization of traffic lights, which leads to reasonable operations, including synchronization patterns such as green waves. In particular, our principle of self-control [22] is suited for irregular (i.e. non-Manhattan type) road networks with counter flows, with main roads (arterials) and side roads, with varying inflows, and with changing turning or assignment fractions. This distinguishes our approach from simplified scenarios investigated elsewhere [23, 24, 25].

Our approach to the problem was inspired by pedestrian flows at bottlenecks [26, 27, 19]: One can often observe oscillatory changes of the passing direction, as if the pedestrian flows were controlled by a traffic light. Therefore, we extended this principle to the self-organized control of intersecting vehicle flows. Oscillations are an organization pattern of conflicting flows which allows to optimize the overall throughput under certain conditions [28]. In pedestrian flows (see Fig. 3), the mechanism behind the self-induced oscillations is as follows: Pressure

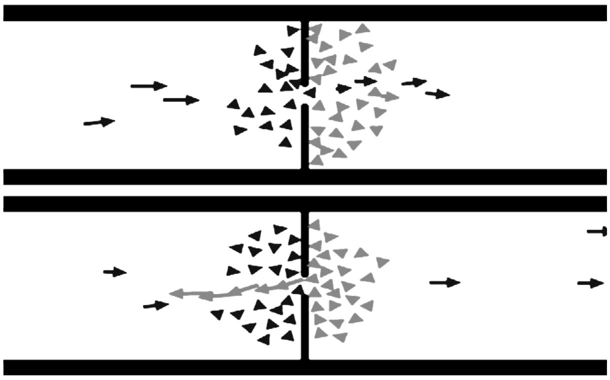


Figure 3: Alternating pedestrian flows at a bottleneck. These oscillations are self organized and occur due to a pressure difference between the waiting crowd on one side and the crowd on the other side passing the bottleneck (after [26]).

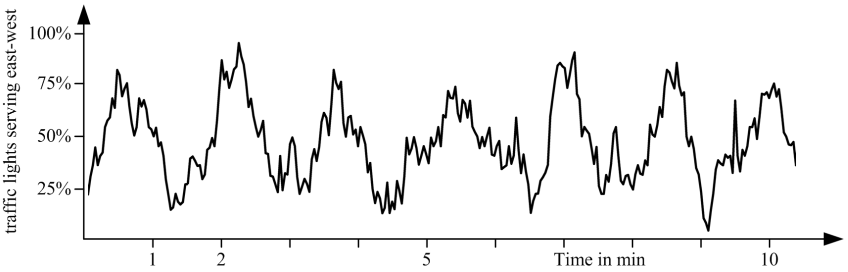


Figure 4: The fraction of traffic lights in a regular road network serving a particular direction oscillates irregularly. The travel direction of green waves is permanently changing in order to adapt to the local traffic demands. A movie on our website [22] demonstrates this effect.

builds up on that side of the bottleneck where more and more pedestrians have to wait, while it is reduced on the side where pedestrians can move ahead and pass the bottleneck. If the pressure on one side exceeds the pressure on the other side by a certain amount, the passing direction is changed. Transferring this self-organization principle to urban vehicle traffic, we define red and green phases in a way that considers “pressures” on a traffic light by road sections waiting to be served and “counter-pressures” by subsequent road sections, when these are full and green times cannot be effectively used. Generally speaking, these pressures depend on delay times, queue lengths, or potentially other quantities as well. The proposed control principle is self-organized, autonomous, and adaptive to the respective local traffic situation. It provides reasonable control results (see Fig. 4).

Our proposed autonomous, decentralized control strategy for traffic flows has certain interesting features: Single arriving vehicles always get a green light. When the intersection is busy, vehicles are clustered, resulting in an oscillatory and efficient service (even of intersecting main flows). If possible, vehicles are kept going in order to avoid capacity losses produced by stopped vehicles. This principle bundles flows, thereby generating main flows (arterials) and subordinate flows (side roads and residential areas). If a road section cannot be used due to a building site or an accident, traffic flexibly re-organizes itself. The same applies to different demand patterns in cases of mass events, evacuation scenarios, etc. Finally, a local dysfunction of sensors or control elements can be handled and does not affect the overall system. A large-scale harmonization of traffic lights is reached by a feedback between neighboring traffic lights based on the vehicle flows themselves, which can synchronize traffic signals and organize green waves. In summary, the system is self-organized based on local information, local interactions, and local processing, i.e. decentralized control.

4 MICROSCOPIC MULTI-LANE TRAFFIC SIMULATIONS

4.1 Modeling human and ACC driving behavior

Most microscopic traffic models describe the acceleration and deceleration of each individual "driver-vehicle unit" as a function of the distance and velocity difference to the vehicle in front and on the own velocity [4, 29]. Some of these car-following models have been successful in reproducing the characteristic features of macroscopic traffic phenomena such as traffic breakdowns, the scattering in the fundamental diagram, traffic instabilities, and the propagation of stop-and-go waves or other patterns of congested traffic. While these collective phenomena can be described by macroscopic, fluid-dynamic traffic models as well [30], microscopic models are more suited to cope with the heterogeneity of mixed traffic, e.g., representing different driver-vehicle classes such as cars and trucks by different parameter sets or even by different models. The microscopic modeling approach also allows for a detailed modeling of vehicles equipped with ACC. Furthermore, the heterogeneity of human and ACC-equipped vehicles can be taken into account by microscopic simulation.

Remarkably, the input quantities of car-following models are exactly those of an ACC system. The ACC controller unit calculates the acceleration as a function of the distance and the relative velocity with a negligible response time. One might even state that many car-following models neglecting reaction times and fluctuations due to imperfect driver reactions, describe ACC systems more accurately than human drivers.

Thus, the question arises, how to take into account the *human* aspects of driving for a realistic description of the traffic dynamics. The nature of human driving is apparently more complex. First of all, the *finite reaction time* of humans results in a delayed response to the traffic situation. Furthermore, human drivers have to cope with imperfect estimation capabilities resulting in *perception errors* and *limited attention spans*. These destabilizing influences alone would lead to a more unsafe driving and a high number of accidents, if the reaction time reached the order of the time headway.

This suggests that human drivers achieve additional stability and safety by scanning the traffic situation *several vehicles ahead* and by *anticipating* future traffic situations. The question is, how this behavior affects the overall driving behavior and performance in combination with the ACC-like driving mimicked by car-following models. Do the stabilizing effects (such as anticipation) or the destabilizing effects (such as reaction times and estimation errors) dominate, or do they effectively cancel out each other? The recently proposed *human driver model* (HDM) [31] extends the car-following modeling approach by explicitly taking into account reaction times, perception errors, spatial anticipation (more than one vehicle ahead) and temporal anticipation (extrapolating the future traffic situation). It turns out that the destabilizing effects of reaction times and estimation errors can be compensated for by spatial and temporal anticipation. One obtains essentially the same longitudinal dynamics, which explains the good reproduction of

IDM Parameter	**Car**	**Truck**
Desired velocity v_0	120 km/h	85 km/h
Safe time headway T	1.5 s	2.0 s
Maximum acceleration a	1.4 m/s^2	0.7 m/s^2
Desired deceleration b	2.0 m/s^2	2.0 m/s^2
Jam distance s_0	2 m	2 m

Table 1: Model parameters of the *intelligent driver model* (IDM) for cars and trucks. The vehicle length has been set to 4 m for cars and 12 m for trucks. The vehicles equipped with ACC adapt their parameters T, a, and b to the detected traffic situation summarized in the "driving strategy matrix" in Fig. 5. The website `http://www.traffic-simulation.de` provides an interactive simulation of the IDM in combination with the lane-change model MOBIL.

real traffic situations by the simpler, ACC-like car-following models.

4.2 Intelligent driver model (IDM)

Motivated by the considerations in the previous section, we describe both human drivers as well as ACC-equipped vehicles with the same microscopic model. For our simulations, we use the *Intelligent Driver Model* (IDM) [32], which has been successfully applied to describe real world traffic phenomena [32]. The IDM acceleration of each vehicle α is a continuous function of the velocity v_α, the net distance gap s_α, and the velocity difference (approaching rate) Δv_α to the leading vehicle:

$$\dot{v}_\alpha = a\left[1 - \left(\frac{v_\alpha}{v_0}\right)^4 - \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha}\right)^2\right]. \tag{1}$$

The deceleration term depends on the ratio between the effective "desired minimum gap"

$$s^*(v, \Delta v) = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}} \tag{2}$$

and the actual gap s_α. The minimum distance s_0 in congested traffic is significant for low velocities only. The dominating term in stationary traffic is vT, which corresponds to following the leading vehicle with a constant safe time headway T. The last term is only active in non-stationary traffic and implements an accident-free, "intelligent" driving behavior including a braking strategy that, in nearly all situations, limits braking decelerations to the "comfortable deceleration" b. Notice that the IDM guarantees crash-free driving. The parameters for the simulations are given in Table 1.

4.3 The lane-changing model MOBIL

Complementary to the longitudinal movement, lane-changing is a required ingredient for simulations of multi-lane freeway traffic. When considering a lane change, a driver typically makes a trade-off between the expected own advantage and the disadvantage imposed on other drivers. For a driver considering a lane change, the subjective utility of a change increases with the gap to the new leader on the target lane. However, if the velocity of this leader is lower, it may be favorable to stay on the present lane despite of the smaller gap. A criterion for the utility including *both* situations is the difference of the accelerations after and before the lane change. This is the core idea of the lane-changing algorithm MOBIL [33, 34] that is based on the expected (dis-)advantage in the new lane in terms of the difference in the acceleration, which are calculated with an underlying microscopic longitudinal traffic model, e.g., the IDM.

For the lane-changing decision, we consider a safety constraint and an incentive to change lanes. In order to avoid accidents by the follower on the prospective target lane, the safety criterion

$$\dot{v}_{\text{follow}} \geq -b_{\text{safe}} \tag{3}$$

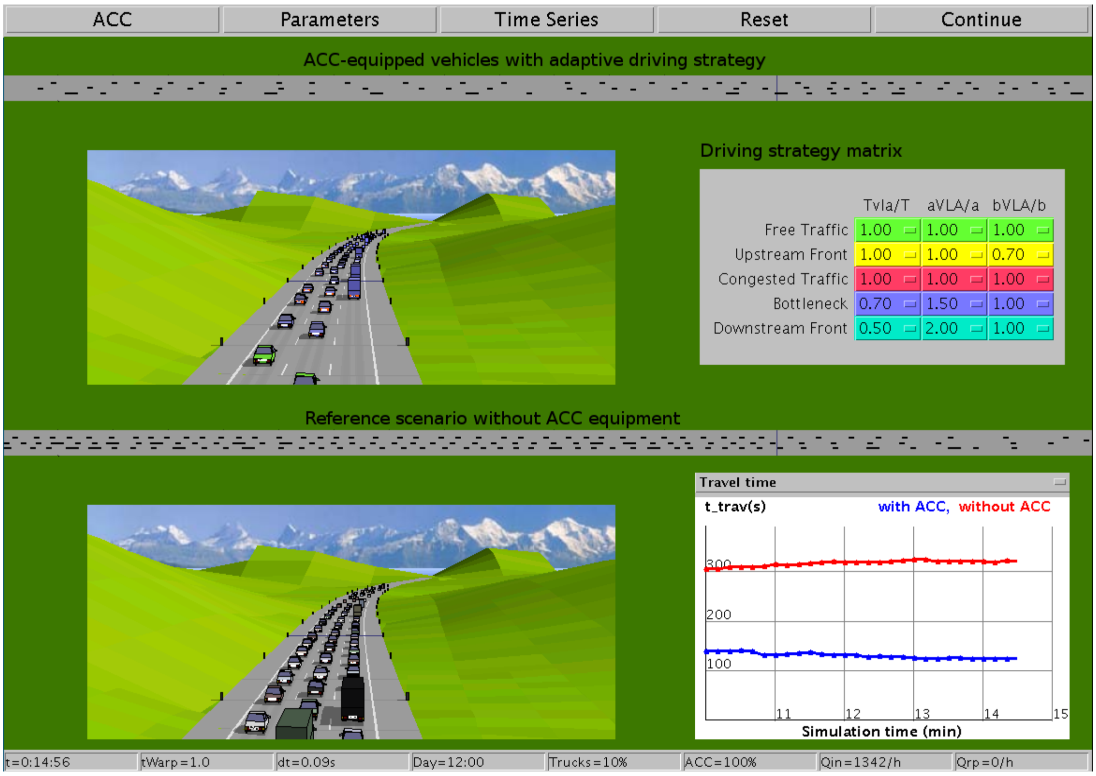
guarantees that, after the lane change, the deceleration of the successor $\dot{v}_{\text{follow}}$ on the target lane does not exceed a safe limit $b_{\text{safe}} \simeq 4\,\text{m/s}^2$. Although formulated as a simple inequality, this condition contains all the information provided by the longitudinal car-following model via the acceleration $\dot{v}_{\text{follow}}$. In particular, if the longitudinal model has a built-in sensitivity with respect to *velocity differences*, such as the IDM, this dependence is transfered to the lane-changing decisions. In this way, larger gaps between the following vehicle in the target lane and the own position are required to satisfy the safety constraint, if the following vehicle is faster than the own speed. In contrast, lower values for the gap are allowed if the back vehicle is slower. Moreover, by formulating the criterion in terms of safe braking decelerations of the longitudinal model, crashes due to lane changes are *automatically* excluded as long as the longitudinal model itself guarantees a crash-free dynamics. Notice that, for realistic longitudinal models, b_{safe} should be well below the maximum possible deceleration b_{max} (about $9\,\text{m/s}^2$ on dry road surfaces).

The incentive criterion for a lane change is also formulated in terms of accelerations. A lane change is executed, if the sum of the own acceleration and those of the affected neighboring vehicle-driver units is higher in the prospective situation than in the current local traffic state.

The innovation of the MOBIL model is that the immediately affected neighbors are considered by the "politeness factor" p. For an egoistic driver corresponding to $p = 0$, this incentive criterion simplifies to $\dot{v}_{\text{new}} > \dot{v}_{\text{old}}$. However, for $p = 1$, lane changes are only carried out if this increases the combined accelerations of the lane-changing driver and all affected neighbors, i.e., each driver contributes to reaching a system optimum, at least locally. This strategy can be paraphrased by the acronym *"Minimizing Overall Braking Induced by Lane Changes"* (MOBIL). We found that realistic lane-changing behavior results for politeness parameters in the range $0.2 < p < 1$. Furthermore, extensions of the concept allow one to incorporate driving rules that are required by legislation. For example, the "keep-right" directive for most European countries is implemented by adding a bias to the incentive criterion equation. A "keep-lane" behavior is modeled by an additional constant threshold when considering a lane change.

4.4 Simulation scenario with a bottleneck caused by an uphill gradient

In order to evaluate the impact of the proposed traffic-adaptive driving strategy implemented by ACC vehicles (cf. 3.2), we have investigated a traffic scenario with an uphill gradient as typical representative for a stationary and flow-conserving bottleneck. We have carried out a simulation of a three-lane freeway section of total length 13 km with open boundary conditions (cf. Fig. 5). The inflow at the upstream boundary is the natural control parameter for the open system. As upstream boundary condition, we used empirical detector data from the German freeway A8 East from Munich to Salzburg. Figure 6 shows the 1-min cross-section data of



Driving strategy matrix

	Tvla/T	aVLA/a	bVLA/b
Free Traffic	1.00	1.00	1.00
Upstream Front	1.00	1.00	0.70
Congested Traffic	1.00	1.00	1.00
Bottleneck	0.70	1.50	1.00
Downstream Front	0.50	2.00	1.00

t=0:14:56
tWarp=1.0
dt=0.09s
Day=12:00
Trucks=10%
ACC=100%
Qin=1342/h
Qrp=0/h

Figure 5: The screenshot of our traffic simulator shows the uphill scenario investigated in Sec. 4.5. In the upper simulation run, the ”traffic assistance” strategy of the ACC-equipped vehicles avoids the traffic breakdown. The reference case without ACC equipment displayed in the lower simulation run shows congested traffic at the bottleneck due to the uphill gradient. In both simulations, the same time-dependent upstream boundary conditions have been used (cf. Fig. 6).

the lane-averaged traffic flow and the proportion of trucks during the evening rush-hour between 15:30h and 20:00h. Notice that traffic further downstream of the detector was congested between 17:00h and 19:30h due to an on-ramp and an uphill gradient (cf. Fig. 14 of [32]).

Besides a high traffic demand, a bottleneck is a necessary condition for the majority of traffic breakdowns. At a bottleneck, perturbations are triggered and potentially grow in the course of time. Stationary bottlenecks on freeways are, e.g., merging zones like construction sites, on-ramps and exits. As example for a flow-conserving bottleneck, we have modelled the uphill region with a gradient slope by locally increasing the safe time headway parameter by 30% for all vehicles in a range of 500 m around the bottleneck location at $x = 10$ km and smooth linear transitions around.

Each vehicle equipped with ACC has incorporated the driving strategy proposed in Sec. 3.2. While passing the uphill road section, the detection model identifies the stationary bottleneck by means of its digital map. At the front of the bottleneck, the time headway parameter of the ACC system is dynamically decreased by 50%. A similar driving strategy also applies when the ACC vehicle detects the passage of the downstream front of any traffic jam. The relative parameter change of the time headway T, the maximum acceleration a, and the comfortable deceleration b are summarized in the “driving strategy matrix” displayed in the screenshot of our traffic simulation software in Fig. 5.

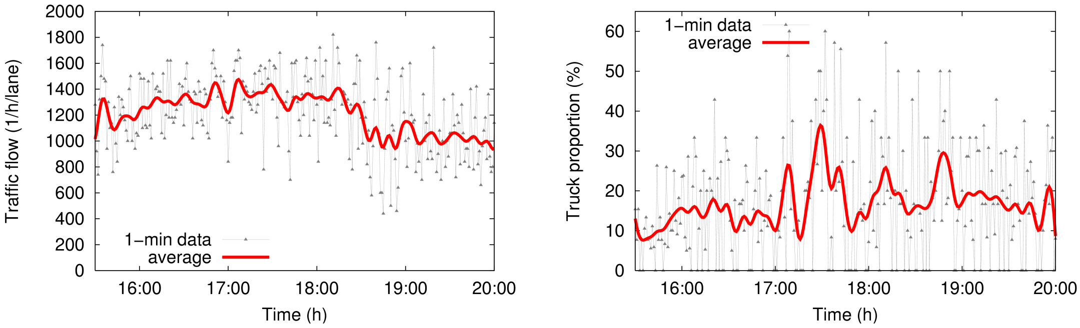


Figure 6: Time series of the 1-min loop detector data of the lane-averaged traffic flow and truck proportion used as upstream boundary conditions for the traffic simulations. The data show the afternoon rush-hour peak of the German Autobahn A8 from Nuremberg to Munich. The average values (red thick lines) are only plotted for a better overview over the strongly fluctuating 1-min data points.

4.5 Simulation results

Figure 7 shows the spatiotemporal dynamics of the traffic density for various proportions of ACC vehicles. The simulation scenario without ACC vehicles shows a traffic breakdown at $t \approx$ 16:20 h at the uphill bottleneck at $x = 10$ km due to the increasing incoming traffic at the upstream boundary during the rush-hour (cf. Fig. 6). The other three diagrams of Fig. 7 show the simulation results with an ACC proportion of 10%, 20%, and 30%. Increasing the proportion of ACC vehicles incorporating the traffic-adaptive ACC driving strategy reduces the traffic congestion significantly. An equipment level of 30% ACC vehicles avoids the traffic breakdown practically completely. Already a proportion of 10% “intelligent” ACC vehicles improves the traffic flow, demonstrating the efficiency of the proposed ACC driving strategy. The improvement of the traffic efficiency essentially scales non-linearly with the proportion of ACC vehicles, i.e., a gradual increase of ACC vehicles in the mixed traffic flows has a positive impact on the capacity, and, thus, on the traffic flow efficiency. The strong sensitivity of the scaling function at small equipment levels is essential for a successful market introduction of traffic assistance systems.

4.6 Impact of ACC systems on the quality of service (ELOS)

For matters of illustration, let us now consider the travel time as the most important variable for a user-oriented quality of service. While the travel time as a function of simulation time reflects mainly the perspective of the drivers, the cumulated travel time is a performance measure of the overall system. The latter quantity can be associated with the economic costs of traffic jams. As indicated in Fig. 8, traffic flow breakdowns have a strong effect on the travel times. For example, the cumulated travel time without ACC vehicles amounts to about 3800 h, whereas the scenario with a fraction of 30% ACC vehicles results in approximately 2500 h. Therefore, the traffic breakdown leads to an increase of the overall travel time by 50% compared to free flow conditions. In comparison, the travel time of individual drivers at the peak of congestion ($t \approx$ 18:45 h) is even tripled compared to the uncongested situation. Increasing the proportion of ACC vehicles reduces the travel times significantly due to the reduction in the lengths of the traffic jam.

Let us now calculate the quality of service index presented in Sec. 2. In general, we define

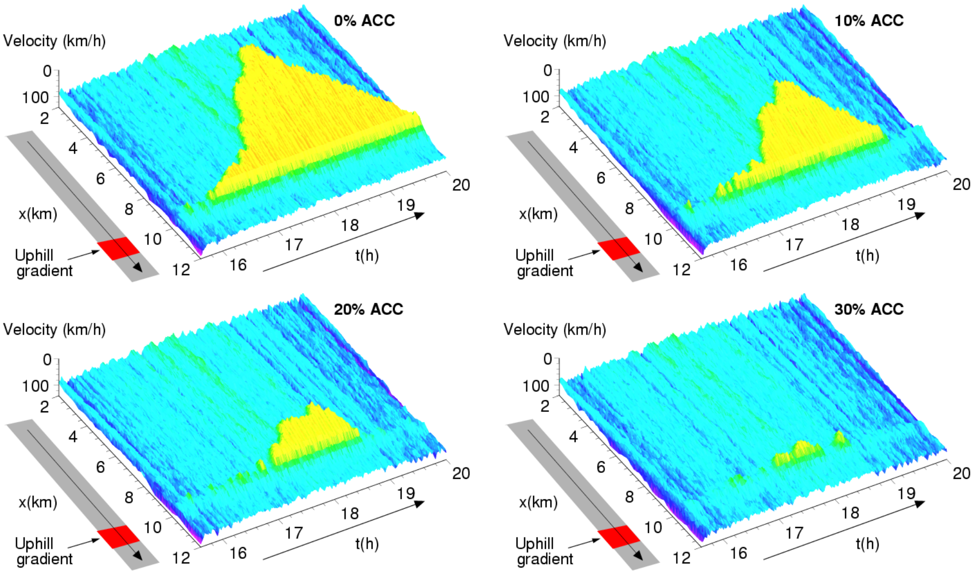


Figure 7: Spatiotemporal dynamics of the simulation of a three-lane freeway with an uphill gradient located at $x = 10\,\mathrm{km}$, which produces a bottleneck effect. The diagrams display the lane-averaged (inverse) velocity as a function of space and time for different proportions of ACC vehicles. The simulations show the impact of the driving strategy of the ACC-equipped vehicles.

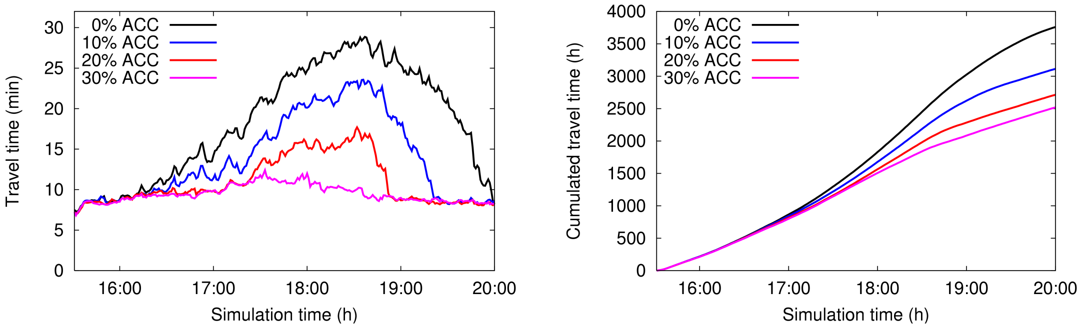


Figure 8: The current and the cumulated travel time for different ACC equipment levels. The diagrams show the strong impact of a traffic breakdown on the travel times as the most important quantity for the vehicle drivers. In the peak of the traffic congestion, the travel time is approximately tripled compared to the travel time of approximately 8 min under free flow conditions. The cumulated travel time indicates the impact of congestion on the overall system. An ACC proportion of 30% prevents the traffic breakdown completely.

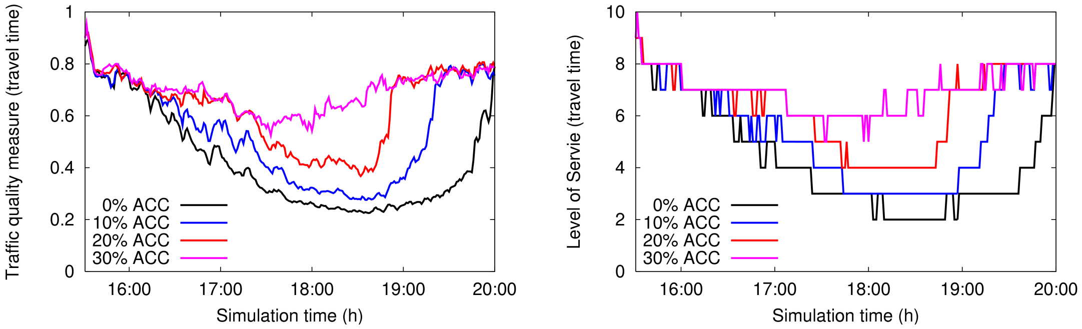


Figure 9: Time series of the quality of service y based on the travel time and resulting extended level of service index (ELOS). The reduction of traffic congestion by vehicles equipped with the proposed ”traffic assistance system” leads to a considerable better traffic quality compared to the scenario without ACC-equipped vehicles.

the extended level of service y from several quality measures y_i by a weighted harmonic mean:

$$\frac{1}{y} = \sum_{i=1}^{n} \frac{w_i}{y_i}. \tag{4}$$

In order to allow for a natural comparison, the y_i are to be defined in a range between 0 and 1. For matters of illustration, we only discuss consider the travel time τ as the most important quantity for a user-defined level of service here (the fully elaborated quality of service concept will be published elsewhere). The desired velocity $v_0 = 120\,\text{km/h}$ of car drivers (see Table 1) together with the length of the considered road section of $\Delta x = 13\,\text{km}$ determine the reference travel time $\tau_0 = 6.5\,\text{min}$. Therefore, the quality measure is given by

$$y = \frac{\tau_0}{\tau}. \tag{5}$$

We define the resulting index value by rounding Ny to integer values in a range from 1 to $N = 10$, where 10 indicates the best quality value. Figure 9 shows the time-dependant quality of service $y(t)$ and the resulting discrete index for different proportions of vehicles equipped with the ACC system presented in Sec. 3.2.

5 SUMMARY AND OUTLOOK

We have presented two decentralized, vehicle-based approaches of traffic control: adaptive cruise control (ACC) and self-organized traffic light control. In this paper, we have focused on the impact of an automated driving strategy that adapts the operation mode of an ACC system to the autonomously detected, local traffic situation. This vehicle-based detection can be extended by information propagation based on inter-vehicle communication (IVC). The impact of a given percentage of vehicles equipped with our ”traffic assistance system” on traffic dynamics has been studied by means of microscopic multi-lane traffic simulations. Already an equipment level of 10% improves the traffic flow quality and reduces the travel times for the drivers drastically due to delaying or preventing a breakdown of the traffic flow. The simulation scenarios illustrate the efficiency of the proposed driving strategy.

Furthermore, the understanding of human driving behavior, the calibration of traffic models, and their improvement is still a lively research area. For example, it is known that human drivers adapt his or her driving style to the local traffic conditions [35, 36]. One observes a "frustration effect" while traveling in congested traffic for a longer time, which leads to a distinct capacity drop [37]. Recently, we have also discovered an adaptation of the time headways in car-following behavior as a function of the local velocity variance, which is a measure of the inhomogeneity of traffic flows. In the corresponding variance-driven time headway model [38], the desired safety time headway increases with the local velocity variance, which explains the capacity drop, the wide scattering of congested flow-density data, and the platooning of vehicles under free flow conditions. Again, the distinct increase of the time headways after a traffic breakdown facilities vehicle-based strategies to increase traffic performance and stability by means of ACC systems. With our presented driving strategy for varying the time headways of ACC systems as a function of the traffic situation, imperfections of the human driving behavior can be partially compensated for.

The implications of our adaptive traffic light control are manifold. Signal control is adapting to local traffic demands instead of dominating it by pre-determined traffic light schedules. This is the key for a more effective usage of the network capacities and also implies reduced travel times for the individual drivers. Our traffic light operation distinguishes several regimes: (i) At low traffic demand, each vehicle gets a green light upon arrival. (ii) At higher demand, conflicts become more likely and delay times are unavoidable. These delays, however, impose a bundling effect resulting in a more efficient usage of the green times. Moreover, suitably delayed green phases give rise to the emergence of "green waves". (iii) If the demand exceeds capacity, some turning directions will be prohibited. This leads to an even more efficient service at the intersections, although some routes become a little longer. (iv) In extreme cases, where the demand is considerably above capacity and heavy congestion is unavoidable, our control generates "green waves" for gaps. The goal of this operation scheme is to balance the load equally in the road network.

Acknowledgments: The authors would like to thank Hans-Jürgen Stauss for the excellent collaboration and the Volkswagen AG for partial financial support within the BMBF project INVENT. D.H. and S.L. kindly acknowledge partial financial support from the DFG project He 2789/5-1.

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