Extending Adaptive Cruise Control to Adaptive Driving Strategies

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An adaptive cruise control (ACC) strategy is presented in which acceleration characteristics, that is, driving styles, automatically adapt to different traffic situations. The three components of the concept are the ACC itself, implemented in the form of a car-following model; an algorithm for the automatic real-time detection of the traffic situation based on local information; and a driving strategy matrix to adapt the driving characteristics—that is, the parameters of the ACC controller—to the traffic conditions. As an option, intervehicle and roadside-to-car communication can be used to improve the accuracy for determining the local traffic states. The complete concept was simulated microscopically on a road section with an on-ramp bottleneck by using real loop-detector data for an afternoon peak period as input for the upstream boundary. A small percentage of traffic-adaptive ACC vehicles, a relatively modest local change in the maximum free flow, improves traffic stability and performance significantly. Although the traffic congestion in the reference case was completely eliminated when a proportion of 25% of ACC vehicles was simulated, travel times for the drivers were reduced in a relevant way for much lower penetration rates. The presented results are largely independent of details of the model, the boundary conditions, and the type of road inhomogeneity.

Traffic congestion is a severe problem on freeways in many countries. In most countries, building new transport infrastructure is no longer an appropriate option. Therefore, considerable research in the area of intelligent transport systems (ITS) is undertaken with a view toward more effective road usage and a more intelligent way to increase the capacity of a road network, and thus decrease congestion. Examples of advanced traffic control systems are ramp metering, adaptive speed limits, and dynamic and individual route guidance. The latter examples are based on a centralized traffic management, which controls the operation and the system's response to a given traffic situation. On the other hand, automated highway systems (AHSs) have been proposed as a decentralized approach based on automated vehicles (*1*). The concept of fully automated vehicle control allows for small time gaps and platoon driving, which is a key to greater capacity. However, such systems need adapted infrastructure and dedicated lanes, which can be justified only if the percentage of automated vehicles is sufficiently high. This would make this scenario appear unlikely for the foreseeable future (*2*).

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Nevertheless, partly automated driving is already commercially available for essential driving tasks such as accelerating and braking by means of adaptive cruise control (ACC). In fact, ACC systems are the first driver assistance systems with the potential to influence traffic flow characteristics. But as typical representatives of driver assistance systems, present implementations of ACC systems are designed exclusively to increase driving comfort, and its influence on the surrounding traffic has not yet been considered. This is justified as long as the number of ACC-equipped vehicles is negligible. However, the expected growing penetration rate of these devices makes the question of their impact on traffic flow more pressing. It is therefore important to understand the effects of ACC on capacity and stability of traffic flow at an early stage, so that their design can be adjusted before adverse traffic effects are widely manifested.

In the literature, the effects of emerging driver assistance systems such as ACC on traffic dynamics has been addressed by means of traffic simulation, because large-scale field tests are not feasible. In particular, the microscopic modeling approach allows for a natural representation of the heterogeneous traffic stream consisting of ACC vehicles and manually driven vehicles (*3–9*). However, there has been no clarity about the meaning of these effects. Some investigations predict a positive effect (*4, 6*), whereas others are more pessimistic (*7, 10*). For realistic estimates of the impact of ACC on the capacity and traffic stability, the models must capture the driving dynamics of ACC vehicles and manually driven vehicles and the relevant interactions between them. The findings thus depend on the model fidelity, the modeling assumptions, and, mainly, on the setting for the time gap, because the maximum capacity is approximately determined by the inverse of the average time gap T of the drivers.

This paper proposes an ACC-based traffic-assistance system intended to improve traffic flow and road capacity and thus to decrease traffic congestion while retaining driving comfort. To this end, a driving strategy layer, which controls the settings of the driving parameters of the ACC system, is introduced. Whereas the ACC operational control layer calculates the response to the input sensor data by means of accelerations and decelerations on a short time scale of seconds, the automated adaptation of the ACC parameters happens on a longer time scale, typically of minutes. To resolve possible conflicts between objectives—between comfort and road capacity—an intelligent driving strategy that adapts the ACC driving characteristics according to the local traffic situation is proposed. A finite set of five traffic situations that are associated with a specific set of ACC driving parameters is considered. These traffic states have to be detected autonomously by each ACC-equipped vehicle.

For concrete model formulation and implementation, the proposed system components are investigated within a microscopic, multilane traffic simulator. The simulator generates surrounding traffic that is required as input for the autonomous detection model based on locally available information. Because of the inherent complexity, the interplay of the individual adaptation of each ACC-equipped vehicle and the impact on the resulting traffic dynamics can be considered only within a simulation framework. Moreover, the simulation tool also allows for an investigation of the effect of a given proportion of intelligent ACC vehicles. A positive impact of the proposed traffic assistance system on the collective benefits for low market penetration rates is an important precondition for the success of the proposed vehicle-based optimization strategy.

MODELING ACC-BASED AND HUMAN DRIVING BEHAVIOR

The recent development and availability of ACC systems extends earlier cruise control systems, which were designed to reach and maintain a certain speed preset by the driver. The ACC system extends this functionality to situations with significant traffic in which driving at a constant speed is not possible. The driver not only can adjust the desired velocity but also can set a certain safety time gap, determining the gap to the leader when following slower vehicles (typically in the range between 0.9 s and 2.5 s). The task of the ACC system is to determine the appropriate acceleration or deceleration as a function of the traffic situation and the driver settings. To do this, the system can detect and track the vehicle ahead, measuring the actual distance and speed difference to the vehicle ahead by means of radar or infrared sensors.

Current ACC systems offer a gain in comfort in most driving situations on freeways. Nevertheless, it should be emphasized that present-day ACC systems operate only above a certain velocity threshold and are limited in their acceleration range. The next-generation ACC will be designed to operate in all speed ranges and in most traffic situations on freeways, including stop-and-go traffic. In addition, future ACC systems will have the potential to prevent a rear-end collision actively and, thus, to achieve a gain in safety. ACC systems control only longitudinal driving. However, merging, lane changes, or gap creation for other vehicles still need the intervention of the driver. So, as the driver retains the entire responsibility, he or she can always override the system.

Remarkably, the input quantities of an ACC system—that is, the vehicle's own speed, the distance to the car ahead, and the velocity difference—are exactly those of many time-continuous car-following models. Because the ACC response time, which is of the order of 0.1 to 0.2 s, is generally negligible compared with the human reaction time of about 1 s (*11*), suitable ACC models give the instantaneous acceleration $\dot{v}(t)$ of each vehicle in terms of a continuous function of the velocity $v(t)$, the net distance $s(t)$, and the approaching rate $\Delta v(t)$ to the leading vehicle. To be a suitable candidate for simulating ACC systems, car-following models must meet the following criteria:

- The car-following dynamics must be accident free, if physically possible.
- The dynamics should correspond to a natural and smooth driving style.
- Adaptations to new traffic situations (for example, when the predecessor brakes, or another vehicle cuts in) must be performed without any oscillations.
- The model should have few parameters. Each parameter should have an intuitive meaning and plausible values after calibration. Ideally, the parameter list should include the desired velocity v_0 and the desired time gap T, which are preset by the driver.
- By varying the remaining parameters, it should be possible to model different driving styles, such as experienced versus inexperienced or aggressive versus relaxed, as well as vehicle-based limitations, such as finite acceleration capabilities.
- Calibration should be easy and lead to good results.

These criteria are met by the intelligent driver model (IDM) (*12*). Moreover, the IDM algorithm recently served as base for an ACC implementation in a test car from Volkswagen within the German project (*13*). In the following simulations, ACC vehicles are represented by this model. The IDM acceleration $\dot{v}$ is given by

$$\dot{v}(s, v, \Delta v) = a\left[1 - \left(\frac{v}{v_0}\right)^4 - \left(\frac{s^*(v, \Delta v)}{s}\right)^2\right] \quad (1)$$

This expression combines the acceleration $\dot{v}_{\text{free}} = a\lfloor 1 - (v/v_0)^4 \rfloor$ on a free road with a braking term $\dot{v}_{\text{brake}}(s, v, \Delta v) = -a(s^*/s)^2$, which is dominant if the current gap $s(t)$ to the preceding vehicle becomes smaller than the effective desired minimum gap.

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

The minimum distance s_0 in congested traffic is significant for low velocities only. The dominating term of Equation 2 in stationary traffic is vT, which corresponds to following the leading vehicle with a constant safety time gap T. The last term is active only in nonstationary 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.

Although the simple car-following approach is perfectly suited to model the dynamics of ACC-controlled vehicles, the human driving style differs in essential points, such as the following:

1. The finite reaction time of humans results in a delayed response to the traffic situation.
2. Imperfect estimation capabilities result in perception errors and limited attention spans.
3. Human drivers scan the traffic situation several vehicles ahead, whereas the ACC sensors are restricted to the immediate predecessor.
4. Furthermore, human drivers anticipate future traffic situations by making use of further clues (such as brake lights) and by forming plausible hypotheses, such as assuming constant accelerations of all neighboring vehicles in the next few seconds.

In view of these differences, the question arises of why the simple car-following approach is also able to capture many aspects of human driving, particularly regarding the collective macroscopic dynamics (*12*), but also on a microscopic level (*14*). This question becomes more pressing as one can show that for realistic human reaction times of the order of the time gaps, the destabilizing influences of Points 1 and 2 alone would lead to traffic instabilities and accidents. Obviously, the stabilizing effects of spatial and temporal anticipation of Points 3 and 4 are essential for human driving.

This has been investigated by using the recently proposed human driver model (HDM) (*15*), which extends the car-following modeling approach to include the listed points. It turns out that the destabilizing effects of reaction times and estimation errors can be quantitatively compensated for by spatial and temporal anticipation. As an important result, one obtains essentially the same longitudinal dynamics when including all four effects compared to the simulations with the car-following model, where none of these effects is incorporated.

Therefore, one may conclude that although the mode of operation is fundamentally different, ACC-equipped vehicles and manually controlled vehicles exhibit a similar effective driving behavior for collective properties such as stability of traffic flow, traffic performance (measured as capacity), or the emergence and propagation of congestion. Since this contribution investigates the influence of ACC on macroscopic properties of traffic flow, it is justified to simulate human drivers with simple car-following models such as the IDM, instead of using more complex models such as the HDM. The advantage of using simple models for both human-driven and automated vehicles lies in the reduced number of parameters that need to be calibrated.

ACC-BASED TRAFFIC ASSISTANCE SYSTEM WITH ADAPTIVE DRIVING STRATEGY

The ACC concept is generalized here to a traffic assistance system, in which intelligent vehicles automatically adapt their ACC parameters, with the aim of improving traffic flow and road capacity and thus decreasing traffic congestion while retaining driving comfort. To resolve possible conflicts of objective between comfort and road capacity, a driving strategy is proposed that adapts the ACC driving characteristics according to the local traffic situation. A finite set of five traffic situations is considered: free traffic, approaching congestion (upstream front), congested traffic, leaving congestion (downstream front), and infrastructural bottleneck sections (such as road works or intersections). These traffic situations have to be detected autonomously by each ACC-equipped vehicle. Since autonomous detection alone is possible only with delays, the local information is supplemented by roadside-to-car and intervehicle communication between the equipped vehicles (*16–18*).

The proposed traffic-assistance system consists of several system components: the main operational layer is still the ACC system calculating the acceleration $\dot{v}(t)$. The new feature of the proposed system is the strategic layer, which implements the changes in the driving style in response to the local traffic situation by changing some parameters of the ACC system. To this end, a detection algorithm determines which of the five traffic situations applies best to the actual traffic situation. The user adjusts the driving characteristics individually by setting the desired velocity and the time gap. In contrast to conventional ACC systems, the driving behavior of this traffic-assistance system, that is, acceleration, is determined in a two-step process.

On the strategic level, the traffic situation is determined locally and the driving style is adapted accordingly by changing some ACC parameters. The parameter settings related to the detected traffic state changes typically on time scales of minutes and in a range of typically a few hundred meters. This is analogous to manual changes of the desired velocity or the time gap in conventional ACC systems by the driver, which, of course, is possible in the proposed system as well.

The operational level consists of responding to changes of the ACC input quantities s, v, and Δv. The time scale is of the order of seconds, and the spatial range is limited to the immediate predecessor. Notice that this is the only level of conventional ACC systems. The following subsections discuss the system components for a traffic-adaptive ACC system in more detail.

General Considerations for Comfortable and Efficient Driving Strategy

The design of an ACC-based traffic assistance system is subject to several, partly contradicting, objectives. On the one hand, the resulting driving behavior has to be safe and comfortable to the driver. This implies comparatively large gaps and low accelerations. On the other hand, the performance of traffic flow is enhanced by lower time gaps T and higher accelerations, which can be seen when considering the main aspects of traffic performance: the static road capacity C defined as the maximum number of vehicles per time unit and lane is strictly limited from above by the inverse of the time gap, $C < 1/T$. Moreover, simulations show that higher accelerations increase both the traffic stability and the dynamic bottleneck capacity, that is, the outflow from congested traffic at the bottleneck, which, typically, is lower than the free-flow capacity (*3*). The present approach to solving this conflict of goals is based on the following observations:

- Most traffic breakdowns are initiated at some sort of road inhomogeneities or infrastructure-based bottlenecks, such as on ramps, off ramps, and sections of road works (*19–21*)
- An effective measure to avoid or delay traffic breakdowns is to homogenize the traffic flow.
- Once a traffic breakdown has occurred, the further dynamics of the resulting congestion are uniquely determined by the traffic demand (which is outside the scope of this investigation), and by the traffic flow in the immediate neighborhood of the downstream boundary of the congestion (*22*). In many cases, the downstream boundary is fixed and located near a bottleneck, as found in empirical investigations (*19*).
- Traffic safety is increased by reducing the spatial velocity gradient at the upstream front of traffic congestion, that is, by reducing the risk of rear-end collisions.

In the context of the ACC-based traffic assistance system, one can make use of these observations by only temporarily changing the comfortable settings of the ACC in specific traffic situations. The selected situations must be determined autonomously by the equipped vehicles, and they must allow for specific actions to improve the traffic performance. To this end, the following discrete set of five traffic situations and the corresponding actions are proposed:

1. Free traffic. This is the default situation. The ACC settings are determined solely for maximum driving comfort. Since each driver can set the parameters for the time gap and the desired velocity individually, this may lead to different settings of the ACC systems.
2. Upstream jam front. Here, the objective is to increase safety by decreasing velocity gradients. Compared to the default situation, this implies earlier braking when approaching slower vehicles. Notice that the operational layer always ensures a safe approaching process independent of the detected traffic state.
3. Congested traffic. Since drivers cannot influence the development of traffic congestion in the bulk of a traffic jam, the ACC settings are reverted to their default values.
4. Downstream jam front. To increase the dynamic bottleneck capacity, accelerations are increased and time gaps are temporarily decreased.
5. Bottleneck sections. Here, the objective is to locally increase the capacity, that is, to dynamically fill the capacity gap, which is the defining property of bottlenecks. This implies a temporal reduction of the time gap.

Drivers typically experience the sequence of these five traffic states when traveling through congested traffic. It is emphasized that the total fraction of times in which the ACC settings deviate from the default state is only a few percent in most situations. Moreover, the following section shows that even a small percentage of equipped vehicles driving according to the preceding strategy substantially decrease the size and duration of congestion and thus the travel time. This means that despite a temporary deviation from the most comfortable ACC settings, the drivers of such systems will profit overall.

Implementation of ACC Driving Strategy

This section implements the concept for an ACC based on the IDM (*12*). Three of the five IDM parameters listed in Table 1 correspond directly to the different aspects of the adaptation strategy: the acceleration parameter a gives an upper limit for the acceleration $\dot{v}(t)$ of the ACC-controlled vehicle. Consequently, this parameter is increased when leaving congestion, that is, when the downstream-front state has been detected. The comfortable deceleration b characterizes the deceleration when approaching slower or standing vehicles. Obviously, to be able to brake with lower decelerations, one has to initiate the braking maneuver earlier, corresponding to higher levels of anticipation. Since this smooths upstream fronts of congestion, the parameter b is decreased when the upstream-front state has been detected. Notice that irrespective of the value of b, the ACC vehicle brakes stronger than b if this is necessary to avoid collisions. Finally, the time gap parameter T is decreased if either the bottleneck or the downstream-front state is detected.

To be acceptable to drivers, the system parameters must be changed in a way that preserves the individual settings and preferences of different drivers and also the driving characteristics of different vehicle categories, such as cars and trucks. Particularly, the preferred time gap T can be changed both by the driver and by the event-oriented automatic adaptation. This can be fulfilled by formulating the changes in terms of multiplication factors λ_a, λ_b, and λ_T defined by the relation

$$a^{(s)} = \lambda_a^{(s)} a$$

$$b^{(s)} = \lambda_b^{(s)} b$$

and

$$T^{(s)} = \lambda_T^{(s)} T \qquad (3)$$

where the superscript (s) denotes one of the five traffic states to which the respective value is applicable. Furthermore, a, b, and T denote the default values of the IDM parameters as given in Table 1. In summary, this implementation can be formulated succinctly in terms of a strategy matrix, as depicted in Table 2. Of course, all changes are subject to restrictions by legislation (lower limit for T) or by vehicle type, such as an upper limit for a, particularly for trucks. (See www.traffic-simulation.de for an interactive simulation of IDM.)

TABLE 1 Model Parameters of IDM Used in Simulations

Traffic Situation	λ_T	λ_a	λ_b	Driving Behavior
Free traffic	1	1	1	Default–comfort
Upstream front	1	1	0.7	Increased safety
Congested traffic	1	1	1	Default–comfort
Bottleneck	0.7	1.5	1	Breakdown prevention
Downstream front	0.5	2	1	High dynamic capacity

TABLE 2 Driving Strategy Matrix

Model Parameter	Car	Truck
Desired velocity v_0	120 km/h	85 km/h
Safe time gap 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

Traffic-State Detection Model

A detection model for an automated, vehicle-based identification of the local traffic situation is required for the proposed driving strategy. The detection model is based on the locally available floating-car time series data. The controller area network of the vehicle provides the vehicle's own speed, whereas the velocity of the leader is measured by the radar sensor of the ACC system. Both velocities can be used in a weighted average, but for simplicity, the focus here is on the own velocity. Because of short-term fluctuations, the time series data require a smoothing in time to reduce variation. The present traffic simulator uses an exponential moving average (EMA) for a measured quantity $x(t)$,

$$x_{\text{EMA}}(t) = \frac{1}{\tau}\int_{-\infty}^{t} dt' e^{-(t-t')/\tau} x(t') \qquad (4)$$

with a relaxation time of $\tau = 5$ s. The EMA allows for an efficient real-time update by using an explicit integration scheme for the corresponding ordinary differential equation

$$\frac{d}{dt} x_{\text{EMA}} = \frac{x - x_{\text{EMA}}}{\tau} \qquad (5)$$

The following criteria are defined for identification of the proposed five traffic states. The free traffic state is characterized by a high average velocity,

$$v_{\text{EMA}}(t) > v_{\text{free}} \qquad (6)$$

with a typical value for the threshold of $v_{\text{free}} = 60$ km/h. In contrast, the congested traffic state is characterized by a low average velocity,

$$v_{\text{EMA}}(t) < v_{\text{cong}} \qquad (7)$$

with a threshold of $v_{\text{cong}} = 40$ km/h. The detection of an upstream or downstream jam front relies on a change in speed compared to the exponentially averaged past of the speed. Approaching an upstream jam front is therefore characterized by

$$v(t) - v_{\text{EMA}}(t) < -\Delta v_{\text{up}} \qquad (8)$$

whereas a downstream front is identified by an acceleration period,

$$v(t) - v_{\text{EMA}}(t) > \Delta v_{\text{down}} \tag{9}$$

Both thresholds are of the order of $\Delta v_{\text{up}} = \Delta v_{\text{down}} = 10$ km/h.

The identification of the bottleneck state requires information about the infrastructure, because bottlenecks typically are associated with spatial modifications in the freeway road design, such as on ramps, off ramps, lane closures, and construction sites. It is assumed that this information is provided by a digital map database containing the position of a bottleneck (x_{begin}, x_{end}) in combination with a positioning device (GPS receiver), which provides the actual vehicle position $x(t)$. This information allows for an identification of the bottleneck state by the spatial criteria

$$x(t) > x_{\text{begin}} \quad \text{and} \quad x(t) < x_{\text{end}} \tag{10}$$

The proposed criteria offer the possibility that no criterion is fulfilled or, conversely, multiple criteria are met simultaneously. To this end, an heuristic is needed for the discrete choice problem. From the visualized traffic simulations (see Figure 1), it was found that the following decision order is the most adequate: downstream front → bottleneck → traffic jam → upstream front → free traffic → no change. This order reflects the relevance of the driving strategy associated with these traffic states for an efficient traffic flow. A more sophisticated heuristics would consist of a dynamic adaptation of the thresholds used in the criteria of Equations 6 through 9.

Inclusion of Intervehicle and Roadside-to-Car Communication

So far, the detection model is exclusively based on local information that is provided autonomously by the floating-car data, the ACC sensor data, and the positioning device. This approach has principal limitations. An autonomous detection in real time has to struggle with the time delay caused by the exponential moving average, that is of the order of τ. This fact limits the timing of the traffic state identification. Particularly, the adaptation toward a smooth deceleration behavior when approaching a dynamically propagating upstream front requires the knowledge of the jam front position at an early stage to be able to switch to the new driving strategy in time. For a more advanced vehicle-based traffic state estimation, nonlocal information can be incorporated to improve the detection quality (*23*). For example, a short-range intervehicle communication (*16–18*) is a reasonable extension providing up-to-date information about dynamic upstream and

FIGURE 1 Screenshot of traffic simulator showing on-ramp scenario. Two simulation runs are displayed. In upper simulation, 100% vehicles are equipped with ACC-based traffic assistance system. Vehicle color indicates locally detected traffic state. Reference case without ACC equipment (gray vehicle) displayed in lower simulation run shows congested traffic at bottleneck. In both simulations, same time-dependent upstream boundary conditions have been used; see Figure 2.

downstream fronts of congested traffic, which cannot be estimated without delay by only local measurements. Furthermore, in case of a temporary bottleneck such as a construction site that is not attributed in the digital map database, the information about the location could be provided by the communication with a stationary sender (roadside unit) upstream of the bottleneck (roadside-to-car communication). Intervehicle communication is not used for direct control of ACC. Rather, additional, nonlocal information sources are incorporated for an improved traffic-state estimation.

MICROSCOPIC FREEWAY SIMULATIONS

Now traffic simulations can be used to evaluate the impact of the proposed ACC-based traffic assistance system. The microscopic modeling approach allows for a detailed specification of the parameters and proportions of cars and trucks, as well as ACC and manually controlled vehicles. As introduced earlier, the IDM (*12*) is used with the parameter sets for cars and trucks given in Table 1. The vehicle length has been set to 4 m for cars and 12 m for trucks. Furthermore, lane changing is a required ingredient for realistic simulations of freeway traffic and merging zones. The lane-changing decision was modeled by the MOBIL (minimizing overall braking induced by lane changes) algorithm that is based on the expected (dis)advantage in the new lane in terms of the difference in the acceleration (*24*). The ACC system controls only the longitudinal driving task. For this reason, the lane-changing parameters for ACC and manually controlled vehicles are not differentiated.

In a simulation run, a given proportion of vehicles is equipped with ACC. Each ACC vehicle determines the local traffic situation dynamically by evaluating the autonomously available floating-car data according to the presented detection model. According to the detected traffic state, the individual ACC parameters T, a, and b are changed by the multipliers of the driving strategy matrix given in Table 2. (For example, $\lambda_T = 0.5$ denotes a reduction of the default time gap T of 50% in the bottleneck situation.) As indicated in Figure 1, the current traffic state of each ACC vehicle is displayed by a changing color, allowing for a direct, visual assessment of the implemented detection criteria. In contrast, non-ACC vehicles are displayed in gray. The parameters of the strategy matrix can be changed interactively by the user to test new strategies directly. The driving adaptations influences the traffic dynamics of the overall system as intended for an improved traffic flow. The impact of the proportion of ACC vehicles, the driving strategies, and the boundary conditions on the capacity and stability of traffic flow is evaluated by means of numerical simulations in the following subsections. For a direct evaluation of the effects of the proposed adaptive driving strategy of ACC vehicles, the same default parameter is set for human drivers and ACC-equipped vehicles, which is in line with earlier principal considerations.

Spatiotemporal Dynamics for Various ACC Proportions

A traffic scenario is now proposed with open boundary conditions and an on-ramp that is typical for a stationary bottleneck. The simulated three-lane freeway section is 13 km long. The on-ramp merging zone of length $L_{\text{rmp}} = 250$ m is located symmetrically around $x = 10$ km. As an upstream boundary condition, empirical detector data from the eastbound A8 autobahn from Munich, Germany, to Salzburg, Austria, are used. Figure 2 shows the 1-min data of the lane-averaged traffic flow and the proportion of trucks during the evening peak period between 3:30 and 8:00 p.m. Moreover, a constant ramp flow of 750 vehicles per hour with 10% trucks is assumed. The parameters in Table 1 are calibrated to reproduce qualitatively the empiric traffic breakdown further downstream at a bottleneck (*12*).

Several simulations with varying proportion of vehicles equipped with ACC were carried out to investigate the impact of the proposed traffic assistance system on the traffic dynamics. The resulting spatiotemporal dynamics for ACC penetrations of 0%, 5%, 15%, and 25% are shown in Figure 2. For a better illustration, the lane-averaged mean velocity was plotted inversely. Thus, a decrease in the speed due to the increase of the inflow as well as congested traffic are clearly displayed. The simulation scenario without ACC vehicles shows a traffic breakdown at $t \approx$ 5:00 p.m. at the on ramp caused by the increasing incoming traffic at the upstream boundary during the peak period. The other three diagrams of Figure 2 show simulation results for an increasing proportion of ACC-equipped vehicles. An increasing proportion of ACC vehicles reduces traffic congestion significantly. Already a proportion of 5% ACC vehicles improves the traffic flow, demonstrating the efficiency of the proposed automated driving strategy and its positive effect on capacity for small penetration levels. An equipment level of 25% ACC vehicles avoids the traffic breakdown in this scenario completely. Simulations with uniformly distributed time gaps T and desired velocities v_0 also were considered to represent individual differences between the drivers, but no qualitative difference was found.

Instantaneous and Cumulated Travel Times

Now consider the travel time as the most important quantity for a user-oriented quality of service (*25*). Whereas the instantaneous 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 that can be associated with the economic costs of traffic jams. The instantaneous travel time is defined by

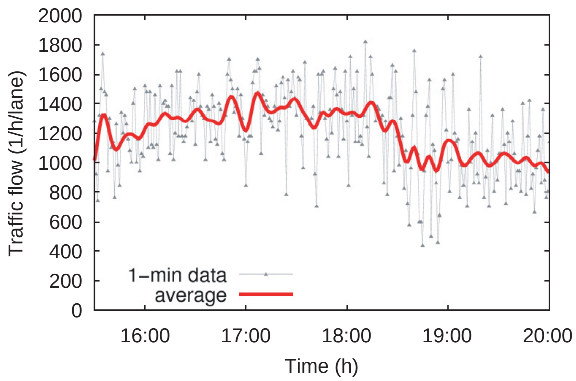
$$\tau_{\text{inst}}(t) = \int_{x_{\text{start}}}^{x_{\text{end}}} \frac{dx}{V(x,t)} \tag{11}$$

In a microscopic simulation, the average velocity $V(x, t)$ can be approximated from the velocities v_i and gaps $\Delta x_i = x_{i-1} - x_i$ of all vehicles i according to

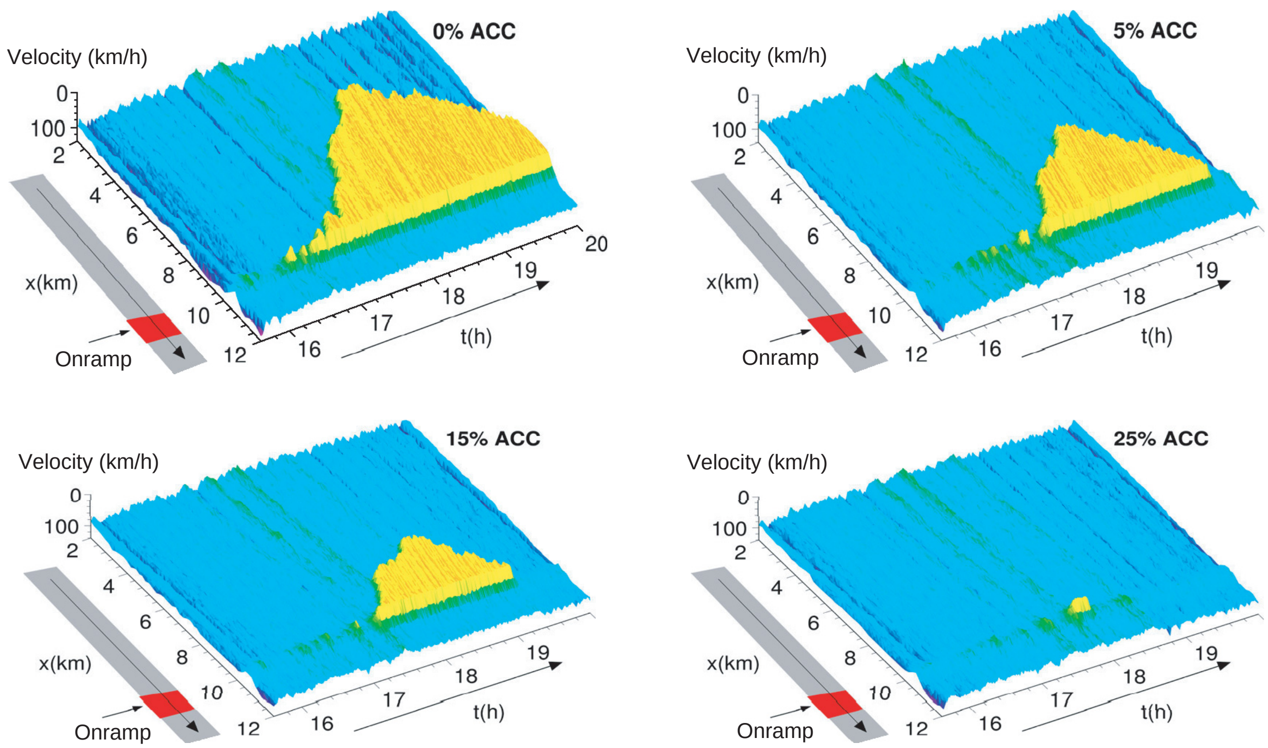
$$\tau_{\text{inst}}(t) = \sum_i \frac{\Delta x_i}{v_i(t)} \tag{12}$$

Moreover, the cumulated travel time is simply the discretized integral over time of the vehicles in the simulation.

Figure 3 shows the instantaneous and cumulated travel times for the simulation runs in Figure 2. Obviously, the breakdown of the traffic flow has a strong effect on the travel time. For example, the cumulated travel time without ACC vehicles amounts to about 4,000 h, whereas the scenario with a fraction of 25% ACC vehicles results only in approximately 2,500 h. Therefore, the traffic breakdown leads to an increase of the overall travel time by 60% compared to free-flow conditions. In comparison, the travel time of individual drivers at the peak of congestion ($t \approx$ 6:45 p.m.) is even tripled compared to the situation without congestion. The time series of the



(a)



(b)

FIGURE 2 Graphs in (a) show time series of 1-min loop detector data of lane-averaged traffic flow and truck proportion used as upstream boundary conditions in traffic simulations. Data show afternoon peak on German Autobahn A8 from Munich to Salzburg. Moving average values (thick lines) are plotted for better overview over strongly fluctuating quantities. Spatiotemporal dynamics are displayed in (b) as lane-averaged velocity of three-lane freeway with on ramp located at x = 10 km for different proportions of ACC vehicles. Simulations show positive effect of proposed traffic assistance system for ACC-equipped vehicles.

instantaneous travel times indicates that an increased ACC proportion delays the traffic breakdown. For 5% ACC vehicles, the traffic breakdown is shifted by 20 min compared to the traffic breakdown at $t \approx$ 5:00 p.m. in the scenario without ACC vehicles.

The results in Figure 3 demonstrate that both the instantaneous and the cumulated travel time are sensitive measures for the impact of traffic congestion and, thus, the quality of service. In contrast to other macroscopic quantities such as traffic flow or average velocity, the travel time sums up over all vehicles in the simulation and weights their influence directly in terms of the travel time. As shown in these simulations, a slightly increased capacity caused by the adaptive driving strategy of a small fraction of traffic-assisted vehicles can have a significant positive effect on system performance.

Discussion and Outlook

ACC systems are available on the market, use of these systems will grow, and the next generation of ACC systems is expected to extend their range of applicability to all speeds. This offers a realistic perspective for a decentralized traffic optimization strategy based on ACC-equipped vehicles.

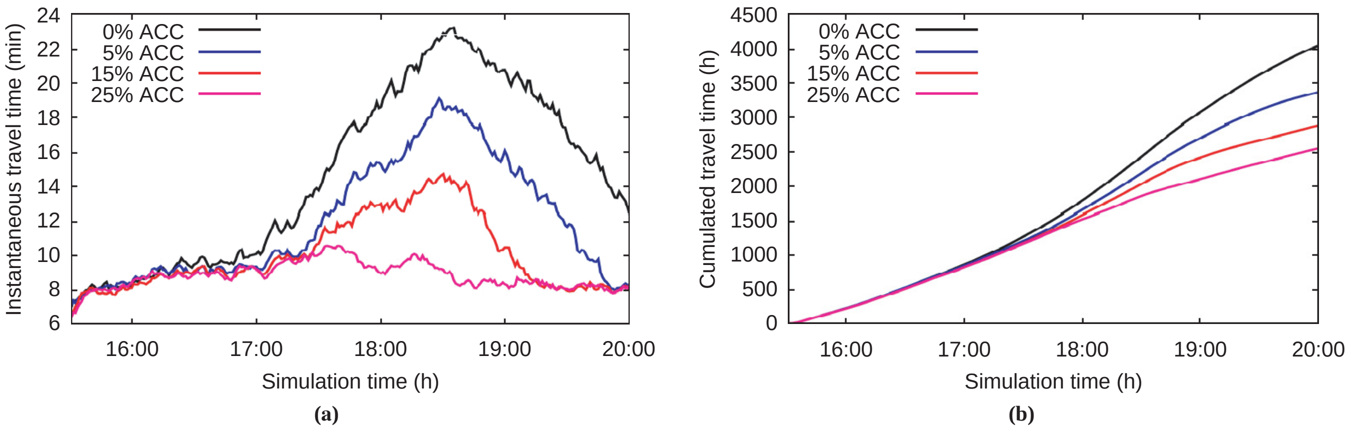


FIGURE 3 Instantaneous and cumulated travel times for different ACC equipment levels: (*a*) strong effect of traffic breakdown on resulting travel times and (*b*) impact of congestion on overall system.

Previously, ACC systems were optimized only for the user's driving comfort and safety. In fact, current ACC systems may have a negative influence on system performance when their market penetration increases. To ensure that ACC systems are implemented in ways that improve, rather than degrade, traffic conditions, an ACC-based traffic assistance system implementing an actively jam-avoidance strategy is proposed. The main innovation of this concept is that ACC vehicles implement variable driving strategies and choose a specific driving strategy according to the actual traffic state. On the basis of local information, each vehicle detects autonomously the traffic situation and adapts automatically the parameters of the ACC system accordingly. The local traffic state detection can be improved by infrastructure-to-car and intervehicle communication, which offer an interesting field for applications of communication technologies.

A concrete model specification of the traffic assistance system was presented, and the components within a microscopic simulation framework were implemented. The simulations served as a test of a driving strategy matrix based on a finite set of five traffic states in order to resolve conflicting objectives between driving comfort and road capacity. Traffic simulations of a freeway, with an on ramp serving as a bottleneck, showed that the temporary reduction of the time gap in the bottleneck state and the downstream front state of congested traffic is sufficient for an improvement in traffic flow efficiency. As a bottleneck is defined by a capacity reduction, the reduction of the time gap at a bottleneck to fill the capacity gap is a general approach applicable to other kinds of bottlenecks as well (*26*).

Furthermore, the simulations of the afternoon peak on the German autobahn showed that a small percentage of intelligent ACC vehicles, that is, a relatively modest change in maximum free flow can significantly improve traffic performance. The breakdown of the traffic flow is delayed (or avoided), which (together with an increased dynamic capacity) results in reduced queue lengths in congested traffic. The simulations demonstrate that an ACC equipment level of 5% improves the traffic flow quality and reduces the travel times for the drivers in a relevant way. The presented results are largely independent of details of the model, the upstream boundary conditions, or the type of road inhomogeneity. A positive impact of the proposed jam-avoidance assistance system for gradual market penetration is important for the success of such a system.

The simulations were based on the assumption that only a small fraction of ACC vehicles adapt their parameters according to the proposed jam-avoiding driving strategy, whereas the manually controlled vehicles applied a time-independent driving style. On the other hand, human drivers may adapt their driving style as well (*27, 28*). It is an interesting research problem to identify empirically the character of human adaptations, their sign, and magnitude on the scale of the microscopic driving behavior.

The presented work was developed in cooperation with a car manufacturer. A real-world implementation of an ACC based on the IDM was recently presented as part of the German research project INVENT (*13*). The authors' current research focuses on implementation of the presented driving strategies and the transition between them in test vehicles (*29*).

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