Vehicle Trajectory Effects of Adaptive Cruise Control

ANDREAS TAPANI
Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden, and Linköping University, Department of Science and Technology (ITN), Norrköping, Sweden

Adaptive cruise control (ACC) can potentially improve quality-of-service and safety and reduce the environmental effect of the road traffic system. This article uses vehicle trajectories from traffic simulation to study effects of ACC on vehicle acceleration and deceleration rates. The analysis is based on traffic simulations with car-following models including ACC functionality and driver behavior in ACC-equipped as well as standard nonequipped vehicles. The simulation results show that ACC can improve the traffic situation in terms of reduced acceleration and deceleration rates even though macroscopic traffic properties may remain uninfluenced. This supports the hypothesized positive road safety and environmental effects of ACC. It is also established that the results are largely dependent on the assumptions made regarding driver behavior in ACC-equipped and standard vehicles. It is consequently crucial to include appropriate assumptions regarding driver behavior in traffic simulation–based analyses of ACC.

Keywords Adaptive Cruise Control; Acceleration Noise; Traffic Simulation; Driver Behavior

INTRODUCTION

The past decade has seen an increase in the interest in intelligent transportation systems (ITS) to improve quality-of-service and safety and to reduce the negative environmental effect of road traffic. One category of ITS that is expected to have substantial effect on future road traffic is in-vehicle Advanced Driver Assistance Systems (ADAS; Berghout, Versteegt, van Arem, Naomi, & Bootsma, 2003). The first generation of ADAS that is currently commercially available includes standalone systems such as adaptive cruise controls (ACCs), speed limiters, and lane-keeping assistants. Cooperative systems based on vehicle-to-vehicle communication are expected to be introduced in the future.

Possible benefits provided by ADAS are determined by the properties of the ADAS-equipped driver/vehicle unit and its interactions with the surrounding traffic. Traffic microsimulation models that consider individual vehicles in the traffic stream are consequently useful tools for traffic system effect analysis of ADAS. These models allow inclusion of ADAS functionalities and the induced driver behavior in driver/vehicle submodels of the simulation. Traffic effects of the considered ADAS can then be estimated through simulations including ADAS-equipped vehicles (e.g., Hoogendoorn & Minderhoud, 2002; Liu & Tate, 2004; Tapani, 2008).

ACC is among the most studied ADAS. Several driver behavioral studies of driving with ACC have been performed (Dragutinovic, Brookhuis, Hagenzieker, & Marchau, 2005; Funcher et al., 1998; Saad et al., 2004; Viti, Hoogendoorn, Alkim, & Bootsma, 2008). ACC has also been the subject of many traffic simulation experiments (Broqua, Lerner, Mauro, & Morello, 1991; Davis, 2004, 2007; Hoogendoorn & Minderhoud, 2002; Kesting, Treiber, Schönhof, & Helbing, 2007; Kesting, Treiber, Schönhof, Kranke, & Helbing, 2007; Minderhoud & Bovy, 1999; van Arem, Hogema, & Smulders, 1996; van Arem, van Driel, & Visser, 2006). Most traffic simulation studies of ACC effects have focused on macroscopic capacity and quality-of-service effects of the distance-keeping functionality of the ACC. ACC has, however, also been hypothesized to have potential to improve safety and to reduce the environmental effect of road traffic. These aspects of traffic are dependent on the movements of individual vehicles in the traffic stream. Large acceleration
Individual vehicle movements can be described by position, speed, and acceleration time series. Such time series are commonly referred to as vehicle trajectories. The aim of this article is to use vehicle trajectories from traffic simulation to quantify potential effects of ACC on vehicle acceleration and deceleration rates. The analysis is based on traffic simulations of mixed traffic including ACC-equipped and standard vehicles. Car-following models that include ACC system functionality and driver behavior in ACC-equipped as well as standard vehicles are used in the simulations. We also investigated how the results are dependent on driver behavior in terms of desired speeds, desired following gaps, and reaction times. The purpose of this work is not to evaluate a specific ACC system but to provide knowledge of potential vehicle trajectory effects of the ACC distance-keeping functionality and driver behavioral adaptations related to ACC.

**ACC AND CAR FOLLOWING**

ACC was one of the first ADAS to be introduced on the market. ACC extends the functionality of traditional fixed speed cruise control with a distance controller. If there are no vehicles within following distance in front of the ACC-equipped vehicle, then ACC works as a fixed-speed cruise control and adjusts the vehicle’s speed toward a desired speed that is set by the driver. In situations with a slower vehicle within following distance of the ACC-equipped vehicle, the distance controller of the ACC system regulates the distance to the leader vehicle. A fixed time strategy is commonly adopted; that is, the driver sets a desired time gap to the leader vehicle and the ACC updates the vehicle’s acceleration/deceleration to maintain this desired time gap. When driving with the ACC system active, the driver remains responsible for the drive and may resume control at any time. The operation of many early ACC systems is limited to speeds corresponding to free-flow traffic conditions. The acceleration/deceleration used by the ACC is also commonly restricted to a subrange of the vehicle’s capability. ACC systems applicable to all speeds, including stop-and-go traffic, are expected in the near future. The ACC system functionality can, on the basis of the given description, be described as a distance and speed controller.

Improved driver comfort is the main reason for the development and introduction of ACC. It has, however, been hypothesized that ACC could have an effect on road safety and quality-of-service (Golias, Yannis, & Antoniou, 2002). The reasoning behind these hypotheses is that as the ACC distance controller has a potential to be a more efficient regulator than a human driver, the number of rear-end collisions can be reduced and vehicles can travel closer together at higher speeds and thereby increase the capacity of the road. There may also be environmental gains to be made from increased ACC usage. More efficient following distance control facilitates the use of lower acceleration and deceleration rates, which, in turn, reduces fuel consumption and vehicle emissions.

ACC is one of the most studied ADAS in terms of the system’s effects on driver behavior. Driver behavior studies in real traffic and in driving simulators have been performed. From the results of an early field study, Fancher et al. (1998) concluded that ACC can improve driver comfort. However, high deceleration rates were observed when drivers took over control from the ACC. In a recent field study, Viti et al. (2008) showed that the drivers’ ACC headway setting were related to their manual driving behavior. It was also found that drivers did not use the ACC system as much in dense traffic conditions as in free-flow traffic conditions. Many driving simulator studies have focused on concerns raised about driver behavioral adaptation in relation to driving with ACC. There are apprehensions about whether the reduction in driver workload may reduce attention to the driving task. The driver’s ability to deal with the limitations of the ACC system and to resume control in critical situations has also been frequently discussed. The results of driving simulator studies have confirmed that drivers react later to critical situations when driving with ACC (Saad et al., 2004). The observed delays were attributed to either reduced attention or overreliance on the ACC. A reduction in driver workload has also been established (Dragutinovic et al., 2005). Commonly observed changes in the continuous driving behavior in ACC-equipped vehicles are changes in speeds and car following–time headways.

Numerous traffic simulation studies of ACC can also be found in the literature (Broqua et al., 1991; Davis, 2004, 2007; Hoogendoorn & Minderhoud, 2002; Kesting, Treiber, Schönhof, & Helbing, 2007; Kesting, Treiber, Schönhof, Kranke, & Helbing 2007; Minderhoud & Bovy, 1999; van Arem et al., 1996; van Arem et al., 2006). Traffic simulation has traditionally been applied for quality-of-service analysis of proposed changes in traffic management or road network design. Most traffic simulation studies of ACC are for this reason focused on macroscopic quality-of-service effects, such as changes in road capacity and effects on average speeds. Driver behavioral adaptations are also usually not considered. This simplification may be justified for analyses on the basis of macroscopic quality-of-service indicators. Changes in driver behavior can, however, be crucial for analyses that rely on representative vehicle trajectories. There is consequently a need for analysis of the sensitivity of traffic simulation–based vehicle trajectories to the assumptions made regarding driver behavior.

An ACC system influences the longitudinal movements of the equipped vehicle. Longitudinal vehicle movements are in a traffic simulation model governed by a car-following model. It is therefore necessary to modify the car-following model to allow simulation of ACC vehicles. Many commonly applied car-following models are in essence controllers that determine acceleration/deceleration rates given distance and speed difference to the immediate leader (Janson Olstam & Tapani, 2003). Hence, car-following models and models of ACC systems have
the same input data. ACC system functionality can therefore straightforwardly be taken into account by changing parameters or functional form of the car-following model. The car-following model should also include parameters controlling speeds and car-following headways to allow modeling of observed driver behavioral changes. Delayed reactions in situations when the driver need to resume control of the longitudinal driving task should also be modeled if such situations are to be studied. The importance of this aspect is, however, likely to decrease as stop-and-go ACC systems are introduced.

More important for the analysis of future effects of ACC is probably the modeling of nonequipped vehicles in simulations of mixed traffic. The most obvious difference between ACC and human driving is the longer reaction time of human drivers. Human drivers are also likely to estimate the position and speed of the leader vehicle with less accuracy than that of an ACC system’s sensors. Limited perception capabilities are compensated for by the drivers through anticipation of future traffic situations. This anticipation can, to be more precise, be described as consideration of multiple vehicles ahead and accounting for future speeds and positions.

The aforementioned aspects need to be considered in detailed car-following modeling of human drivers. However, Treiber, Kesting, & Helbing (2006) showed that macroscopic traffic dynamics resulting from simulations with a detailed car-following model, including the human limitations discussed earlier, were equal to the conditions resulting from simulations with a simpler, and more ACC-like, car-following model. This result indicates that, when considering macroscopic traffic flow dynamics, anticipation and human limitations cancel out. It is consequently appropriate to use a car-following model with less modeling detail for macroscopic quality-of-service analysis. There will be differences in the underlying vehicle trajectories for simulations using different levels of car-following modeling detail. These differences, which may prove to be important for detailed analyses on the basis of entire vehicle trajectories, are investigated in the remainder of this article.

**TRAFFIC SIMULATION OF ACC-EQUIPPED AND STANDARD VEHICLES**

This article presents results of traffic simulations including ACC-equipped and standard vehicles. The car-following and lane-changing models applied for these simulations are described in this section. The objective of the simulations is to study effects of ACC on vehicle acceleration and deceleration rates. The utilized indicator of vehicle acceleration trajectory smoothness is also presented in this section.

All simulations were performed using the Rural Traffic Simulator (RuTSim) framework presented by Tapani (2005). RuTSim is a stochastic simulation model and simulation runs based on different random number generator seed will consequently give different results. For this reason, all results are given as confidence intervals on the basis of repeated simulation runs using five different random number generator seeds. This number of repetitions was found to give reasonably narrow confidence intervals for most of the simulated situations. The use of an equal number of random number generator seeds for all simulations also allows for differences in the stochasticity of the resulting traffic conditions to be studied through the confidence interval widths. The simulation update time was set to 0.1 s.

**The Simulated Road and Traffic Condition**

The simulated road is a one-directional open traffic system including a 500-meter-long one-lane section followed by a 1,000-meter-long two-lane section completed by a lane drop and a 500-meter-long one-lane section. This road was modeled to allow studies of simulated vehicle trajectories under the influence of a lane drop bottle neck. The sequence of 1–2–1 lanes is also of interest because it is a basic element of Swedish three-lane highways with a cable barrier between the oncoming traffic lanes. Figure 1 contains a schematic picture of the simulated road. The speed limit of the road was set to 90 km/hr.

All simulated traffic flows contained 100% passenger cars. The basic desired speeds of all cars in the simulations were determined according to a Gaussian distribution ($M = 113$ km/hr, $SD = 10.8$ km/hr).

**Modeling of ACC and Human Drivers**

The basic car-following model used to model ACC and standard vehicles is the intelligent driver model introduced by Treiber, Hennecke, & Helbing (2000). The model determines a vehicle’s acceleration rate at time $t$ according to the following:

$$a(t) = a_0(1 - (v(t)/v_0)^4) - (s*(v(t), \Delta v(t))/s(t))^2),$$

(1)

where $v(t)$ and $v_0$ are the current and desired speed, respectively, of the considered vehicle, $\Delta v(t)$, $s(t)$ and $s*(v(t), \Delta v(t))$ are the approach speed, the current gap and the desired gap to the vehicle in front, respectively, and $a_0$ is a parameter that determine maximum acceleration. The desired gap is given by the following equation:

$$s*(v(t), \Delta v(t)) = s_0 + v(t)T_d + \frac{v(t)\Delta v(t)}{2\sqrt{a_0b}},$$

(2)

where $s_0$ is the minimum distance between vehicles, $T_d$ is the desired steady-state time gap and $b$ is a parameter that correspond to the desired maximum deceleration rate. In the simulations, parameter values presented by Kesting, Treiber, Schönhof, & Helbing (2007) have been used for all vehicles; that is, $T_d = 1.5$ s, $a_0 = 1.4 m/s^2$, $b = 2 m/s^2$, and $s_0 = 2 m$. 

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**Figure 1** The simulated road section.
For standard vehicles, limited perception and reaction capabilities and anticipation to compensate for these limitations have been taken into account by extending the intelligent driver model with the human driver model—presented by Treiber et al. (2006)—a meta-model that allows modeling of delayed reactions, perception inaccuracies and anticipation of the future traffic situation. The ACC system response time was also taken into account.

The reaction delay, $T'$, is in the human driver model modeled by evaluating the left hand side of Eq. 1 at time $t$ and the right hand side at time $t - T'$; that is, one reaction delay time earlier. The reaction delay has been set to 1.2 s for standard cars and to 0.1 s for ACC cars.

The human driver model takes into account inaccuracies in a driver’s estimation of the approach speed and the distance to the leader. Imperfect estimation of the approach speed to the lead vehicle are modeled by assuming that the uncertainty of the estimation of $\Delta v$ is proportional to the distance $s$, that is, drivers estimate the time-to-collision, $s/\Delta v$, with constant uncertainty. This assumption is supported by empirical observations. Persistence of the estimation errors are accounted for by modeling the error as a Wiener process. Then, the estimated approach speed can be expressed as follows:

$$(\Delta v)^{\text{est}}(t) = \Delta v(t) + s(t)r_c w_{\Delta v}(t),$$

where $r_c$ is the inverse of the average estimation error of time-to-collision and $w_{\Delta v}(t)$ is a Wiener process with unit variance and correlation time $\tau$. The uncertainty in the estimation of the distance to the leader is defined in a relative way by assuming a constant variation coefficient, $V_s$. As for the estimation error for the approach speed, the error is modeled as a Wiener process with correlation time $\tau$. The estimated distance to the leader can be expressed as follows:

$$s^{\text{est}}(t) = s(t)e^{V_s w_s(t)}$$

where $w_s(t)$ is a Wiener process with unit variance and correlation time $\tau$. The Wiener processes $w_{\Delta v}(t)$ and $w_s(t)$ are independent. Simulation of the Wiener processes was conducted using the numerical scheme proposed by Treiber et al. (2006). The human driver model’s driver perception error parameters were also set to the values presented by Treiber et al. (2006):

$r_c = 0.01 \text{s}^{-1}$, $V_s = 5\%$ and $\tau = 20 \text{s}$.

The human driver model also takes into account driver anticipation to compensate for the reaction delay. A constant acceleration heuristic is adopted for the anticipation of the future speed, $v'(t)$. The future speed is obtained with the following equation:

$$v'(t) = v(t - T') + T' a(t - T').$$

Other vehicles acceleration is known to be difficult to estimate for human drivers. A constant speed heuristic is therefore adopted for the anticipation of the future distance, $s'(t)$, and approach speed, $\Delta v'(t)$, to the leader. We obtain the following:

$$s'(t) = s^{\text{est}}(t - T') - T' \Delta v^{\text{est}}(t - T')$$

and

$$\Delta v'(t) = \Delta v^{\text{est}}(t - T').$$

The anticipated future speed, distance and approach speed given by Eq. 3–5 are used as input to the intelligent driver model in Eq. 1.

The final aspect of human driving considered in human driver model is spatial anticipation by considering multiple vehicles ahead. This is accomplished by separating the right hand side of Eq. 1 into free driving acceleration:

$$a_{\text{free}} = a_{\text{free}} [1 - \left( \frac{v(t)}{v_0(t)} \right)]^4$$

and interaction acceleration

$$a_{\text{int}} = -a_{\text{free}} \left( \frac{s^{\text{est}}(v(t), \Delta v(t))}{s(t)} \right)^2.$$  

Interaction with $n$ leaders are modeled by summation of the interaction accelerations between the considered vehicle, $i$, and the nearest $n$ vehicles. Then, the acceleration rate of vehicle $i$ can be expressed as follows:

$$a_i(t) = a_{\text{free}} + \sum_{j=i+n}^{i-1} a_{\text{int}}.$$  

where $a_{\text{free}}$ is given by Eq. 6 and $a_{\text{int}}$ is given by Eq. 7 where $i$ is the considered vehicle and $j$ is the leader that is taken into account. Drivers in standard cars have been assumed to consider three vehicles in front in car-following situations; that is, we set $n = 3$. Car-following models including three leaders have been found to fit empirical data better than models including fewer vehicles in front (Hoogendoorn, Ossen, & Schreuder, 2006).

The human driver model and the underlying intelligent driver model become equal if $T' = 0$, $n = 1$ and $V_s = r_c = 0$ in the human driver model. It is therefore possible to describe the accelerations of ACC-equipped cars and standard cars using the human driver model with different parameter values. The basic

### Table 1: Basic human driver model parameter values for ACC-equipped and standard vehicles.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard cars</th>
<th>ACC cars</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_d$</td>
<td>1.5 s</td>
<td>1.5 s</td>
</tr>
<tr>
<td>$a_0$</td>
<td>1.4 m/s²</td>
<td>1.4 m/s²</td>
</tr>
<tr>
<td>$b$</td>
<td>2 m/s²</td>
<td>2 m/s²</td>
</tr>
<tr>
<td>$s_0$</td>
<td>2 m</td>
<td>2 m</td>
</tr>
<tr>
<td>$T'$</td>
<td>1.2 s</td>
<td>0.1 s</td>
</tr>
<tr>
<td>$r_c$</td>
<td>0.01 s⁻¹</td>
<td>0 s⁻¹</td>
</tr>
<tr>
<td>$V_s$</td>
<td>5%</td>
<td>0%</td>
</tr>
<tr>
<td>$\tau$</td>
<td>20 s</td>
<td>-</td>
</tr>
<tr>
<td>$n$</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

*Note. ACC = adaptive cruise control.*
parameter values of the human driver model for ACC-equipped and standard cars are shown in Table 1.

The standard lane-change model implemented in RuTSim was used for all vehicles in the simulation. In this model, vehicles change lane to pass slower vehicles in front. The right lane is the preferred lane, vehicles stay in, or return to, the right lane if there are no slower vehicles in front.

Lane-change decisions are governed by the length of the two-lane section, the surrounding traffic and the vehicle’s ability to pass a slower vehicle in front. Vehicles start to merge to the right and no lane changes to the left are allowed when there are 350 meters left of the two-lane section. The desired gap function of the car-following model, Eq. 2, is used to calculate the gap needed in the adjacent lane to allow a lane change. The lane-changing model is consequently consistent with the car-following model. Upstream of lane-drop bottlenecks, vehicles in the right lane recognize merging vehicles in the adjacent lane to the left as a leader vehicle to follow. Right lane vehicles will thereby extend the gap to the merging vehicle to allow a lane change before the lane drop.

An Indicator of Vehicle Trajectory Smoothness

Exhaust emissions are correlated with vehicle accelerations and decelerations (e.g., Pandian, Gokhale, & Ghoshal, 2009). Vehicle accelerations and decelerations have also shown to be a useful traffic accident predictor (af Wåhlberg, 2006).

In this work, acceleration noise is used as a performance indicator of vehicle accelerations and decelerations. Leutzbach (1988) suggested acceleration noise as a good indicator of the smoothness of the traffic flow. Acceleration noise has also been used as a basis for modeling of vehicle emissions (Greenwood, Dunn, & Raine, 2007).

For a single vehicle, acceleration noise is defined as the standard deviation of acceleration according to the following:

\[
ACN_i = \sqrt{\frac{1}{T} \int_0^T [a(t) - \bar{a}]^2 dt},
\]

where \( T \) is the travel time over which \( ACN_i \) is calculated, \( a(t) \) is the vehicle’s acceleration rate at time \( t \) and \( \bar{a} \) is the average acceleration computed as follows:

\[
\bar{a} = \frac{1}{T} \int_0^T a(t) dt.
\]

We apply \( ACN_i \) as an indicator of the smoothness of the simulated vehicle trajectories. Large values of \( ACN_i \) indicate large changes in acceleration and deceleration, which in turn may decrease road safety and increase the environmental effects of traffic. In contrast, low values of \( ACN_i \) indicate a smoothly travelling vehicle. \( ACN_i \) is an individual vehicle indicator. In the simulation we use \( ACN \) defined as the average of \( ACN_i \) over all vehicles as an indicator of the collective situation.

Congested traffic implies larger and more frequent acceleration and deceleration changes. \( ACN_i \) will consequently increase with increasing traffic flow. Figure 2 shows the resulting \( ACN \) from simulations with varying input traffic flows. All simulated flows contained only standard passenger cars.

As can be seen in the figure, \( ACN \) is increasing with increasing traffic flow. This is in accordance with the expectation. Increasing stochasticity caused by more vehicle interactions in higher flows gives rise to larger differences between different simulation runs as indicated by the wide confidence interval for the highest flow. Simulations of traffic flows close to the capacity of the lane-drop bottleneck; that is, 1,400 to 1,500 veh/hr, confirm these observations. \( ACN \) grows fast with increased flow, and the corresponding confidence intervals become wide. A total flow of 1,000 veh/hr was chosen for the remaining simulations on the basis of these observations. This flow results in significant vehicle interactions without increasing the stochasticity of the traffic flow. Resulting confidence intervals will consequently be narrow enough to allow conclusions to be drawn with a reasonable number of repetitions of the simulations.

Effects of ACC, Human Limitations and Driver Behavior

Effects of driver behavioral adaptation to ACC and the effects of detailed car-following modeling of human limitations are in this section studied through traffic simulations of a road section with a mix of standard and ACC-equipped cars.

The modeled ACC system is assumed to be operative at all speeds and drivers in ACC-equipped vehicles are assumed to use the ACC at all times. System limitations and driver acceptance of the ACC are consequently not considered. In addition, drivers in ACC-equipped and standard vehicles are as a starting point of the analysis assumed to have equal desired following-time gaps and desired speeds. Consequences of this assumption are investigated as part of the subsequent analysis.

Vehicle Trajectory Effects of ACC

The difference in the applied car-following modeling of standard and ACC cars are the following. Human reaction delays, perception inaccuracies, and anticipation are taken into account in the human driver model used for standard cars and a short system response time is assumed in the intelligent driver model used for ACC-equipped cars. The effects of these aspects on \( ACN \) have been studied through simulations of mixed traffic including varying percentages of ACC vehicles. Simulations of traffic with varying ACC penetration rate also allowed analysis of changes in traffic conditions as the percentage of ACC-equipped vehicles grows. One expects that the faster and more accurate response of the ACC system will result in smoother trajectories for ACC cars. This was also confirmed by the simulation results as shown in Figure 3.
A tendency toward decreased ACN and smoother trajectories for standard and ACC cars with increased percentages of ACC cars could also be observed. This effect is likely due to the fact that a standard vehicle behind an ACC-equipped vehicle will have more time to adjust its speed in response to changes in speed of vehicles in the downstream traffic. A certain percentage of ACC vehicles in the traffic stream could therefore prevent and reduce the severity of shock waves. This conclusion has also been drawn from the traffic simulation–based capacity and quality-of-service studies of ACC referred to earlier in this paper.

**Figure 2**: Average ACN for varying traffic flows, 95% confidence intervals (color figure available online).

Sensitivity of the Results to Changes in Driver Behavior

The aim of this article is to use traffic simulation–based vehicle trajectories to quantify effects of ACC on vehicle acceleration and deceleration rates and to investigate the influence of the assumed driver behavior on the results. Observed behavioral adaptations of drivers in ACC-equipped vehicles include changes in following-time gaps and speeds. Effects of these changes have been studied by simulations of traffic including 20% ACC cars. Positive effects of ACC can to a large extent be contributed to the faster reaction of the ACC system compared with a human driver. The effect of the delayed reactions of drivers in standard cars has also been investigated. The first experiment is concerned with the effect of changed following-time gaps for ACC-equipped vehicles. Reduced following-time gaps can be expected to lead to increased acceleration and deceleration rates. Following-time headways in the intelligent driver model are controlled by the desired steady-state time gap, $T_d$. ACN from simulations with varying $T_d$ for ACC cars are shown in Figure 4. The desired following-time gaps of standard cars have been kept constant at 1.5 s in the simulations.

As expected, reduced desired following-time gap starting from 1.5 s for ACC cars lead to increased ACN. This effect is small, and nonequipped standard cars seem to be uninfluenced. However, for the shortest time gap setting, 0.5 s, the trajectories of the standard cars become unstable. The corresponding large ACN and wide confidence interval does not fit the scale of the other results and are therefore not included in the figure. This instability is likely caused by the reduction of the time and space available for reactions when travelling behind an ACC car that travels close to its leader. Note that, for the shortest
time gap setting, the reaction time of standard cars is 2.4 times longer than the desired steady-state time gap of the ACC cars. The effect of increased desired following-time gaps for ACC cars starting from 1.5 s is smaller than the effect for reduced following-time gaps. This is likely due to that as the following-time gaps increase the influence on ACN of vehicle-to-vehicle interactions during car-following decrease. The second experiment is concerned with the effect of changed desired speeds of drivers in ACC-equipped vehicles. ACC and standard cars have in the previously described simulations been assigned desired speeds from RuTSim’s default desired speed distribution for cars; that is, a Gaussian distribution with a mean of 113 km/hr ($SD = 10.8$ km/hr). Simulations with varying desired speeds of the ACC cars have been performed to study the effect of changes in speed when driving with ACC. Modification of the desired speeds of ACC cars has been carried out by horizontal translation of the basic desired speed distribution. The distribution mean has been shifted and the variance is kept constant; that is, only the mean of the basic Gaussian distribution is changed. The results of these simulations are shown in Figure 5.

Vehicles with lower desired speed can be assumed to interact less with vehicles in front. Less interaction implies less accelerations and decelerations and thereby lower ACN. This is confirmed by the simulation results in Figure 5. In contrast, vehicles with higher desired speeds will be constrained by slower vehicles more often and therefore accelerate and decelerate more. This can also be observed in the results for positive shifts of the desired speed distribution for ACC cars. Shift of the desired speed distribution of ACC cars with 1.5 m/s results in inseparable ACN for standard and ACC cars. It is also possible to conclude that an ACC system will result in less positive vehicle trajectory effects the higher the desired speeds of the equipped vehicles. The third experiment is concerned with the effect of the delayed reactions of drivers in standard cars. The purpose of this experiment is to investigate the importance of the slower reaction time of human drivers for the observed differences in acceleration noise. Positive traffic system effects of ACC can to large extents be related to the faster reaction of the ACC system compared with a human driver. It can be expected that reduced driver reaction times will lead to smoother vehicle trajectories. Figure 6 shows the results of simulations with varying reaction times of standard cars.

The results confirm that reduced driver reaction times lead to decreased ACN. A reaction time of 0.4 s was found to result in inseparable ACN for standard and ACC cars. The assumed ACC system response time is 0.1 s.
It is therefore possible to conclude that the modeled human driver behavior in standard cars correspond to a hypothetical, reduction in reaction time of approximately 0.3 s. The modeled human driver behavior aspects consist of anticipation, which can be expected to increase trajectory smoothness, and estimation inaccuracies, which will have a negative effect on trajectory smoothness. Anticipation of the future traffic situation can therefore compensate for more than 0.3 s longer reaction time. Detailed analyses of effects of driver anticipation and inaccuracies on vehicle trajectory smoothness are interesting topics for further research.

Increased driver reaction times were, in accordance with the expectation, found to increase ACN. The trajectories of standard cars become unstable for reaction times over 1.4 s. This result is natural given that the assumed desired following-time gap is set to 1.5 s. A consequence of this instability are very large ACN that are outside the scale of the other results. These large values are therefore not shown in Figure 6. An effect on the trajectories of ACC cars can also be established. The effect seems to increase as the reaction time of standard cars increase. This can be explained as a consequence of interactions between standard and ACC cars in the traffic stream. As the accelerations and decelerations of standard cars increase, ACC cars are also forced to use increased acceleration and deceleration rates in order to prevent collisions. Noticeable is the bounded ACN of ACC cars. This indicates that the trajectories of ACC cars remain stable when the trajectories of standard cars become unstable. ACC will therefore have a stabilizing effect on the traffic stream. Further analysis of this effect could be conducted through simulations of varying driver reaction times in traffic with different percentages of ACC cars.

**CONCLUSIONS**

This article aimed to use trajectories from traffic simulation to study the effects of the ACC distance-keeping functionality on vehicle acceleration and deceleration rates. The analysis is based on simulations of traffic including ACC-equipped and standard cars. As a basic scenario, the simulated ACC system was assumed not to have any influence on drivers’ desired speeds or following-time headways. Such an ACC system has previously been found to have no effect on macroscopic road capacity (Minderhoud & Bovy, 1999). In addition, Treiber et al. (2006) showed that simulations with an ACC-like car-following model resulted in equal macroscopic traffic dynamics as simulations with a more complex human driver model. However, the results of this work show that ACC-equipped vehicles use lower acceleration and deceleration rates than standard nonequipped vehicles. This indicates that ACC may have positive consequences for safety and the environmental effect of road traffic even though the macroscopic traffic conditions remain unchanged. Moreover, nonequipped standard vehicles were found to be positively influenced by increasing percentages of ACC vehicles in the traffic stream.

We have also shown that the effects of ACC are to large extents dependent on the assumptions made regarding driver behavior. This finding was established through simulations with varying desired following-time gaps and desired speeds of ACC-equipped vehicles. Changes in desired speeds and following-time gaps are commonly reported from driver behavioral studies of ACC (Dragutinovic et al., 2005; Saad et al., 2004). Simulations with varying reaction times of standard vehicles were also performed. These simulations confirmed that the positive effects of ACC can largely be contributed to the faster reaction of the ACC system compared with a human driver. The results reported on in this article show that it is crucial to include appropriate assumptions on driver behavior in the analysis. It is notable that this aspect has usually not been taken into account in previous traffic simulation–based studies of ACC.

The experiments presented in this article can be supplemented by additional traffic simulation tests. For example, ACC can be hypothesized to affect not only the mean of the desired speed distribution but also the distribution variance. Effects of such effects on driver behavior can be studied using the same methodology as the experiments presented in this article. It is also of interest to study the effects of ACC on additional performance indicators. The results presented in this article are entirely based on traffic simulation experiments. A validation study using real traffic data collected in a field operational test of ACC-assisted driving is consequently an important topic for further work.

Further research related to the work presented in this article also include quantification of environmental and road safety effects of ACC. The presented findings on properties of simulated vehicle trajectories will provide a basis for this work. There is, however, a general need to relate traffic simulation–based performance indicators other than macroscopic quality-of-service measures to empirically observed effects. It is also of interest to investigate the effect of the lane-changing modeling on the smoothness of traffic simulation–based vehicle trajectories. Last, as indicated by the results presented in this article, human driver’s anticipation can to some extent compensate for perception errors and reaction time. Further research on this topic may facilitate development of improved driver behavior models for microscopic traffic simulation.

**REFERENCES**


