



Towards an understanding of adaptive cruise control

Greg Marsden ^{*}, Mike McDonald ¹, Mark Brackstone

*Department of Civil and Environmental Engineering, Transportation Research Group, University of Southampton,
Highfield, Southampton SO17 1BJ, UK*

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Abstract

Adaptive cruise control (ACC) provides assistance to the driver in the task of longitudinal control of their vehicle during motorway driving. The system controls the accelerator, engine powertrain and vehicle brakes to maintain a desired time-gap to the vehicle ahead. This research describes the results of a detailed microscopic simulation investigation into the potential impacts of ACC on motorway driving. In addition to simulation, real vehicle driving profiles, obtained from instrumented vehicle experiments in three European countries, have been used to compare real following behaviour with that of a simulated ACC equipped vehicle. This new approach has shown that following with an ACC system can provide considerable reductions in the variation of acceleration compared to manual driving. This indicates a potential comfort gain for the driver and environmental benefits. A number of critical situations in which ACC does not perform well have also been identified. The research also highlights the limitations of microscopic simulation in modelling the impacts of ACC because of the lack of understanding of the interaction between the driver and the ACC system relative to the traffic conditions. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Daily traffic congestion is a severe problem on European motorways. Fixed infrastructure advanced transport telematics systems such as variable speed limits (Hardman, 1996) and ramp metering (Papageorgiou et al., 1997), are seeing widespread deployment within Europe. These

^{*} Corresponding author. Tel.: +44-23-8059-5000; fax: +44-23-8059-3152.

E-mail addresses: grm@soton.ac.uk (G. Marsden), mm7@soton.ac.uk (M. McDonald).

¹ Tel.: +44-23-8059-2192; fax: +44-23-8059-3152.

systems help to reduce congestion and smooth traffic flow-patterns and are installed by network operators as traffic control tools.

Other developments that will influence traffic performance have focussed on in-vehicle driver assistance such as collision warning (CW) and adaptive cruise control (ACC) devices. ACC performs the longitudinal following control task for a driver, within limited acceleration ranges. The systems have been designed by vehicle manufacturers and tiered suppliers to increase the quality of the driving experience and, therefore, vehicle sales. Daimler Chrysler announced the launch of the DISTRONIC ACC system at the Paris motor show in October 1998 and Jaguar have more recently launched their system. It has been hypothesised that such systems may also provide an improvement in traffic safety, efficiency and capacity due to a more stable time-gap control than a driver is able to apply (Sala and Pressi, 1994; Zwaneveld and van Arem, 1998). However, it is not certain that the characteristics of ACC systems are the same, as those required improving traffic capacity more generally.

This article examines the compatibility of the driver support role of ACC with the efficiency improvements desired by network operators. It begins with a review of driver behaviour and user acceptance issues relating to ACC to provide a background to driving conditions most suited to ACC use. The results of a review of previous simulation studies of ACC and the assumptions, results and implications are examined. A fuzzy-logic based driver simulation model is then introduced to expand the discussion to consider limitations of the way in which human behaviour is represented in the context of ACC. The collection of driver behaviour data using an instrumented vehicle is then described as an alternative method for assessing the impacts of ACC. The effects of ACC for drivers following a vehicle with the same speed profile as the instrumented vehicle are presented and comparisons made between the performance of manual driving and assisted driving. More general conclusions are drawn regarding the expected impacts of ACC on motorway operations.

2. Driver behaviour and user acceptance

An ACC system attempts to maintain a desired speed (set by the driver) whilst keeping a minimum time-gap between the vehicles, typically measured by a radar (Tribe et al., 1995). The functionality of the systems varies (e.g. engine braking or engine and active braking) as does the control algorithm for managing the inter-vehicular separation. The driver is able to over-ride the system at any time by activating the brake or accelerator pedal and can switch it on or off at different stages of the journey. In common with all 'real' ACC systems, that being studied within this research is fully autonomous (not requiring any vehicle to roadside or vehicle to vehicle communication) and assumes that the driver has control of the steering of the vehicle at all times.

The first stages of deployment of ACC will be on 'top of the range' vehicles, offering improved driver support with personal comfort as a prime advantage. Such ACC systems may not fully meet the requirements of a system designed to enhance the efficiency of traffic flow. For example, more gentle approaching behaviour and larger inter-vehicular distances, if selected by drivers, could reduce capacity. The systems will only operate in high-speed motorway driving conditions, which have been assumed to be more than 40 km/h for this study. Traffic characteristics below this speed are such that a separate algorithm would be required to perform a comfortable and

acceptable distance control function (Blosseville et al., 1998) although work is on-going in this area (Hayward, 1999).

User acceptance is of fundamental importance for vehicle manufacturers to achieve rapid market penetration and widespread use of ACC in traffic networks. Understanding user acceptance and the implications of ACC use in a traffic stream is also of great importance to network operators who are charged with improving capacity and safety of the road network. A review of the state-of-art of user acceptance issues can be found in Brackstone and McDonald (2000). The key issues however, are identified below:

- Is the system safe?
- When will the drivers use the system?
- What characteristics should the system have?
- What are the Human-Machine Interface issues?
- How much will the consumer pay?
- What effect does demographics have?
- What effects do national driving characteristics have?
- What are the long-term effects of the system?

The safety of ACC has been addressed in a number of studies e.g. Chira-Chavala and Yoo (1994), Najm and Burgett (1997), Nilsson (1995), Takubo (1995), DIATS (1998a), Touran et al. (1998). These assessments examine the potential for ACC to reduce accidents in an emergency-braking situation in two ways. The first approach involves the development of a probabilistic model that can analyse the response of a platoon of vehicles to a variety of lead-vehicle braking manoeuvres. The second approach involves simulator investigation into the ability of drivers to take control from the ACC when entering an emergency situation. The concluding evidence is unclear. Some studies highlight the benefits to safety of an improvement in driver reaction time, brought about from the accelerator and braking feedback from the ACC system. Other studies highlight the degradation of driver performance due to a lack of involvement in this primary driving task (Brookhuis and de Waard, 1999). However, it is clear that the safety concerns have not been significant enough to delay deployment in Europe beyond 1999.

The main evidence on driver willingness to use an ACC system has come from a field operational test in USA (Fancher and Baraket, 1998; Fancher et al., 1998; Hagan et al., 1997). This project evaluated the responses of over 100 drivers who used ACC for a period of two or five weeks in their natural driving environment (the systems were post fitted to 1996 Chrysler Concorde sedan vehicles). The ACC system braked using the engine and powertrain only, producing a maximum deceleration capability of 0.07 g. A large data set of driver behaviour was collected, indicating when drivers will use ACC and how they use ACC in conjunction with manual driving. The results suggest that drivers will not use the systems in dense traffic conditions. Results showed that drivers chose to engage the ACC in about half of all miles travelled above 35 mph and for 39% of the time it was available. The above results are supported by a stated preference study, DIATS (1998b) in which drivers expressed a willingness to use the system in low-density traffic. The priority situations for using the system from this study were found to be:

1. driving in fog;
2. driving at night on an unlit motorway;
3. driving for 4 h instead of 1 h;
4. driving in low density traffic;

5. driving at night on a well-lit motorway;
6. driving on an unknown road network.

There is increasing evidence from a number of studies that current ACC systems are not suitable for use in high-density traffic conditions. Results from instrumented vehicle measurements in the UK appear to support this. Tests conducted on the M3 motorway 20–40 miles SW of London as part of this research found that only 35% of the following events measured during the morning peak were at speeds above the assumed ACC minimum operating threshold of 40 km/h.

Other evidence from the US trials (Fancher et al., 1998) suggested that a vehicle changing to the lane immediately in front of the ACC equipped vehicle caused the drivers to resume manual control in many cases. Such manoeuvres are inevitably more prevalent at high flows. One potential solution to this problem has been proposed by Godbole et al. (1999), who suggested that if the ACC lane can be separated from normal traffic and merging performed by co-ordinating the merging vehicles with the mainstream traffic (using communication between vehicles on the on-ramp and in the nearside lane) then ACC can achieve >98% usage when the system has a deceleration capability of 2 m/s². However, spatial restrictions in Europe make this approach an unlikely near future scenario. Other solutions for handling cut-in scenarios will also be developed, including prediction of cut-in manoeuvres to augment ACC performance.

Manufacturers have addressed the central issues regarding system characteristics through a number of studies. Becker et al. (1994) as part of PROMETHEUS demonstrated that ACC without brake activation was acceptable but that a large proportion of drivers thought brake activation was desirable. Kopf and Nirschl (1997) found that the supervisory role of an ACC system with a deceleration level of 3 m/s² was more clearly understandable than one with a deceleration level of 1.5 m/s² where more manual interventions were required from the driver to keep an acceptable time-gap. The most important evidence from all of the investigations into system requirements was from the American business assessment of ACC provided by Ervin et al. (1997), which found that actuated braking in addition to engine braking is inevitable as a first or future application, following interviews with manufacturers. As the system is being implemented on luxury cars first, the consumer will require a high degree of functionality that will include both braking methods. Indeed, the Mercedes DISTRONIC system will automatically activate its brakes when required to do so. The Jaguar system will also activate braking to a level of about 2 m/s² (Richardson, 1999).

BMW have carried out investigations into the selection of following time-gaps with a user variable system. Reichart et al. (1997) found that six out of eight subjects chose to drive with a time-gap of less than 1.3 s. Fancher et al. (1998) in the US FOT trial showed that younger drivers preferred a short time-gap whilst older drivers preferred time-gaps of more than 1.4 s. The stated preference survey from the DIATS project DIATS (1998b), found the following groups of people to be more interested in ACC and CW:

- people describing the way they drive as 'careful';
- people with children under the age of 15 in their household;
- people who are 50 yr old or more;

This may imply that more careful drivers, likely to select larger time-gaps, are more likely to use the system. This finding is supported to some extent by the US FOT where some aggressive drivers turned the system off when it impeded their progress. However, it should be noted that all drivers

showed a tendency for larger time-gaps under ACC relative to manual control (Fancher et al., 1998). The DISTRONIC system allows time-gaps between 1 and 2 s to be selected by the user.

3. Simulation studies

The principal concern of vehicle manufacturers is to produce an ACC system that will support driver comfort, have no negative impact on safety and add to the selling qualities of the vehicle. However, the impacts of such new systems on safety and traffic capacity are primarily the concern of the network operator. Many simulation studies have tried to quantify the change in traffic flow characteristics that ACC will bring. It is not possible to perform a direct comparison of the results of these simulation studies as each study has employed different ACC models and different driver behaviour models but some common trends are evident. This section reviews these studies and examines some of the key issues through a further simulation investigation.

Early studies such as the DOMINC project (Broqua et al., 1991) estimated gains in throughput of 13% with only 40% of vehicles equipped with ACC when the target time-gap of the system was 1 s. More recent work by van Arem et al. (1996) and Minderhoud and Bovy (1998, 1999) has found some potential problems from the introduction of ACC. In particular, both studies have found a decrease in average speed caused by a collapse of speed in the fast lane. This is particularly noticeable for ACC target time-gaps of 1.4 s and above. Minderhoud and Bovy (1999) also performed a range of simulations with ACC target time-gaps as low as 0.8 s from which they found that current expected ACC systems can achieve capacity gains of 4% assuming a net time-gap setting of 1 s. No large or significant changes or trends were observed with time-gap settings of 1.2 s.

The occurrence of large speed fluctuations in the outside (i.e. faster/overtaking) lanes of motorways for target time-gaps above 1.2 s is a source of potential concern for the motorway operators. As time-gap settings will be user dependent, it is unlikely that all drivers will select time-gaps of 1.2 s and below. Indeed, user acceptance studies have indicated that this would be unlikely for cautious and older drivers. However, in determining guidelines for the use of ACC systems it is important to understand why the speed fluctuations occurred in the outside lane for the larger target time-gaps. A simulation investigation was therefore undertaken to examine the mechanism for flow breakdown in the outside lane.

The FLOWSIM microscopic simulation model (Wu et al., 1998) was selected for use in this study. FLOWSIM uses fuzzy logic (Zadeh, 1965) to represent driver decision-making processes, which “allows the introduction of a quantifiable level of uncertainty into the modelled process to reflect ‘natural’ or subjective perception of real variables” (Wu et al., 1998).

The fuzzy inference model for car following is based on two variables. The first, distance divergence, is the ratio of vehicle separation to desired vehicle separation. This parameter varies significantly between driving subjects. The second variable is the relative speed of the driver’s vehicle to the lead vehicle. There are five overlapped fuzzy sets for each input variable.

There are two distinct lane changing fuzzy models reflecting the difference between motivations to overtake and to lane change to a slower lane. Lane changing to overtake has two input variables relating to the speed benefit that would be gained by overtaking and the opportunity to overtake. Lane changing to a slower lane is motivated by pressure from a following vehicle and

the availability of a suitable gap in the slower lane. A complete description of the fuzzy sets for both car following and lane changing is provided in Wu et al. (1998). FLOWSIM offers a user defined up-date rate and applies accelerations instantaneously based on the decision of the fuzzy model.

A fuzzy logic based model offers clear advantages over traditional mechanistic models that do not incorporate all of the inconsistency and uncertainty found within a single driver's normal driving behaviour. ACC systems try to minimise longitudinal following instability and a good identification of benefits requires a base line driver model representative of real performance against which to assess ACC.

For this simulation, an ACC algorithm based on a manufacturer prototype was selected. The acceleration rate adopted by the ACC equipped vehicle during a given period is related to the following variables:

- mass of vehicle;
- the gap headway;
- the rate of change of gap headway;
- velocity of the equipped vehicle.

No detailed models of ACC system use by the driver have yet been developed. Although a number of driving simulator studies have been undertaken, these have necessarily focussed on safety critical aspects of ACC use (e.g. Nilsson, 1995). Very few studies exist on how drivers incorporate the functionality of ACC into his/her driving cycle (Saad and Villame, 1996). The US FOT has collected a considerable database about ACC usage from over 100 drivers using one ACC system (Fancher et al., 1998) but no generalised model regarding usage has been developed. For the purposes of this research, it has therefore been assumed that if the ACC system can be used, it is used. However, if the driver takes over manual control from the ACC system then the system can not re-engage in the following 10 s.

As highlighted previously, the US FOT trials indicated that ACC was used for over 50% of all miles driven at speeds of above 35 mph (typical of the simulation runs). In addition, usage rates for individuals varied between 20% and 100% (Fancher et al., 1998). It is acknowledged therefore that the assumption on ACC usage produces an artificially high proportion of equipped vehicles using the system. However, the purpose of the simulation runs is to examine the most extreme usage scenarios to define the range of effects that could potentially be found.

The maximum deceleration of the ACC equipped vehicle when under distance control mode is limited to 1.5 m/s^2 whilst the maximum acceleration under ACC is 1 m/s^2 within the main simulations. A vehicle is not allowed to enter ACC mode unless the next acceleration calculation will determine a value between these two limits.

A simple scenario of a three-lane motorway section, 3 km long, with no entry and exit slips was established. This geometry is typical of many inter-urban stretches of motorway in the UK and avoided adding further variables relating to merge and demerge behaviour to the analysis. The demand profile employed for the study is shown below in Fig. 1. The demand profile was chosen, as it would result in an overloading of motorway capacity during the middle 20 min of the simulation. Significant inter-vehicle interaction is present throughout the simulation. The scenarios were designed to highlight whether or not ACC could maintain a higher capacity through more stable driving and a reduction in small flow breakdown events.

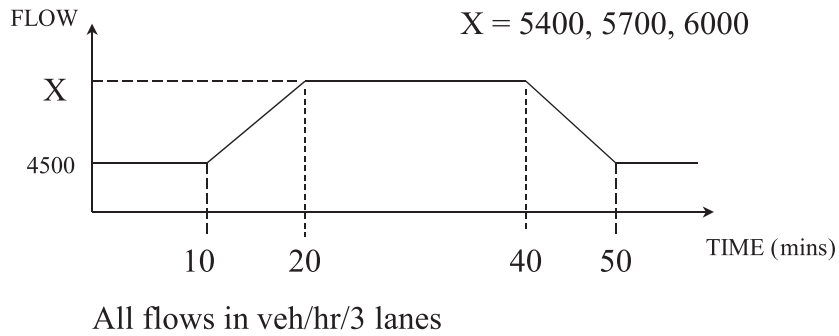


Fig. 1. Demand flow profile for ACC scenarios.

Three model runs were performed at each demand level for each of five different ACC penetration rates: 0%, 10%, 20%, 40% and 70%. The scenarios were run for ACC system target time-gap values of 1.2 and 1.5 s (i.e. a total of 120 simulation runs). Information concerning all of the vehicles on the section was collected every 0.5 s on a lane by lane basis for the whole 3 km-section. Information included average speed, standard deviation of speed, acceleration, time-gap, journey time, lane changing, density and flow.

Figs. 2 and 3 show the average journey times over the 3 km-section for the different target time-gaps with different levels of penetration.

It is clear from Fig. 2 that increasing the percentage of vehicles equipped with ACC increases the average journey time, particularly for the two highest demand scenarios. This trend was less evident from Fig. 3 where the target time-gap for the ACC system was 1.2 s, although at the highest demand scenario there is an increase in average journey time with increasing equipped ACC vehicles. This is in agreement with the findings of van Arem et al. (1996) and Minderhoud and Bovy (1999).

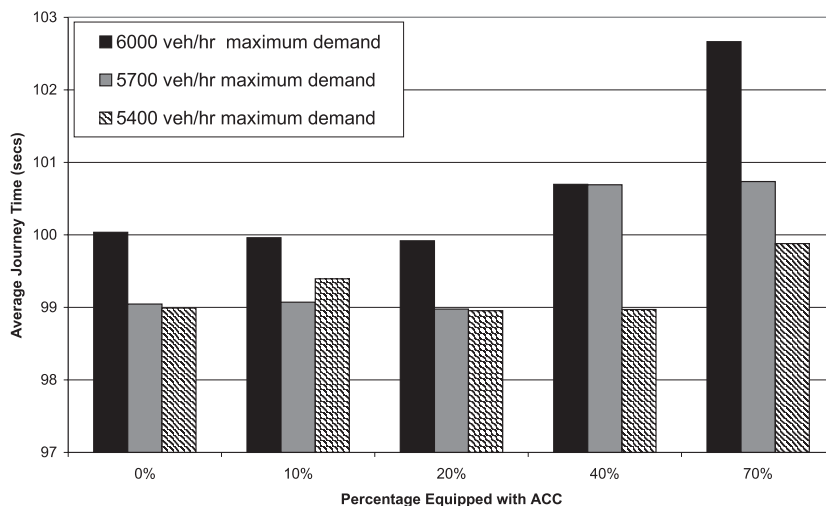


Fig. 2. Average journey time against percentage equipped for ACC target time-gap of 1.5 s.

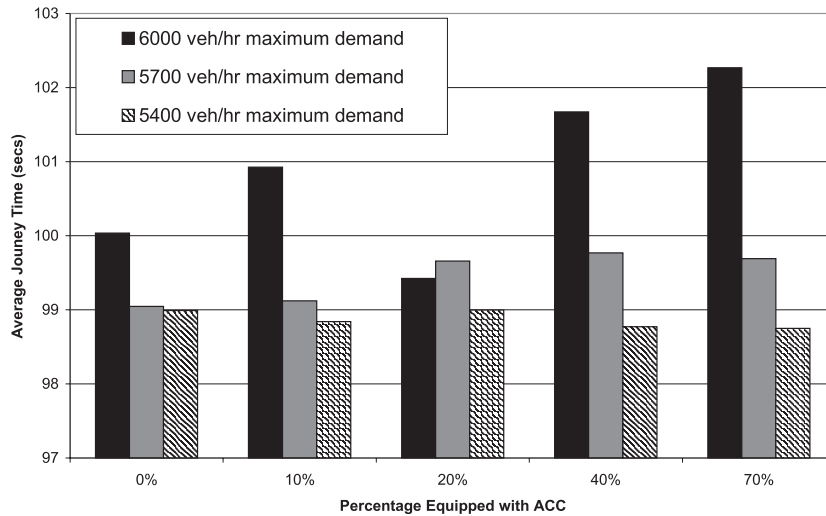


Fig. 3. Average journey time against percentage equipped for ACC target time-gap of 1.2 s.

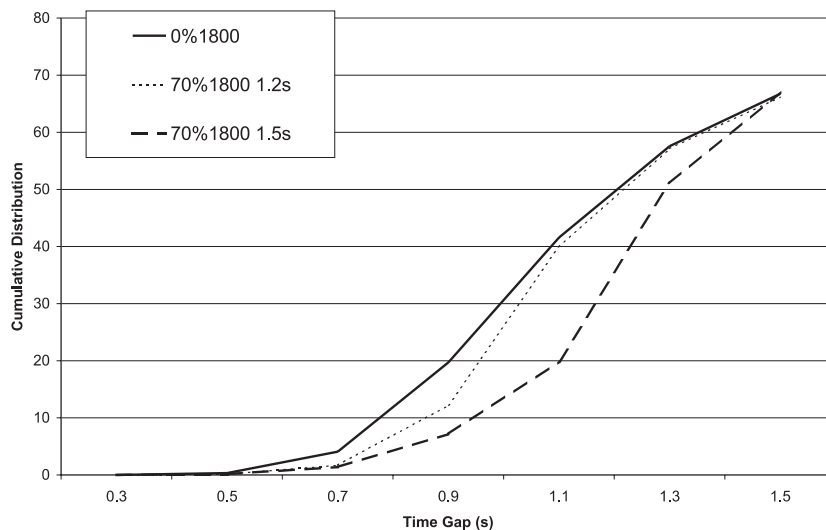


Fig. 4. Time gap cumulative distribution for 70% vehicles equipped compared to 0% equipped (flow 5400 veh/h).

A sample comparison of the effects of ACC on the time-gap distributions is shown in Fig. 4. The figure compares the cumulative time-gap distributions for the scenario with 5400 veh/h with 0% and 70% equipped at both target time-gaps. The results show a reduction in time-gaps of 1 s or less of 7.5% (time-gap 1.2 s) and 12.5% (time-gap 1.5 s). The distributions intersect at the time-gap distribution bin of 1.4–1.6 s. The ACC systems are having the expected effect of shifting the time-gap distributions towards the target time-gap.

Further investigation has concentrated on determining where and why the flow is disturbed causing the journey time to increase. Figs. 5–7 show the average speed on lane 1 (nearside or slow lane), lane 2 (middle lane) and lane 3 (offside or fast lane).

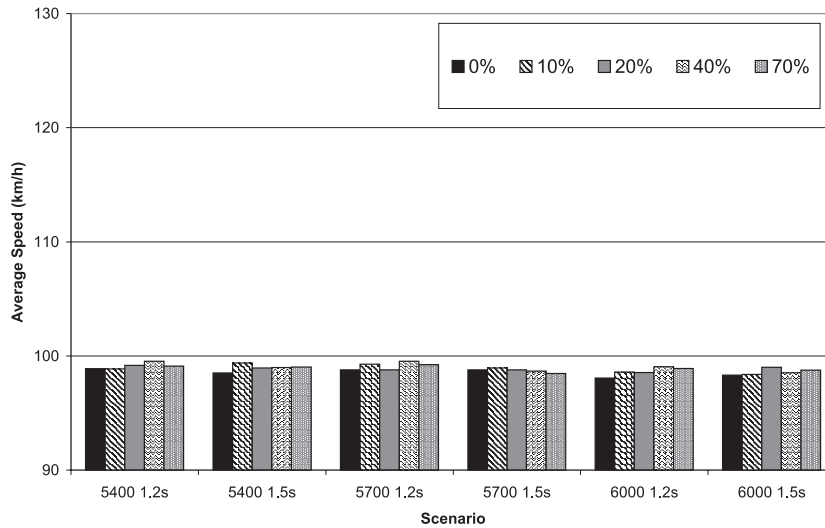


Fig. 5. Average speed against percentage of vehicles equipped – lane 1.

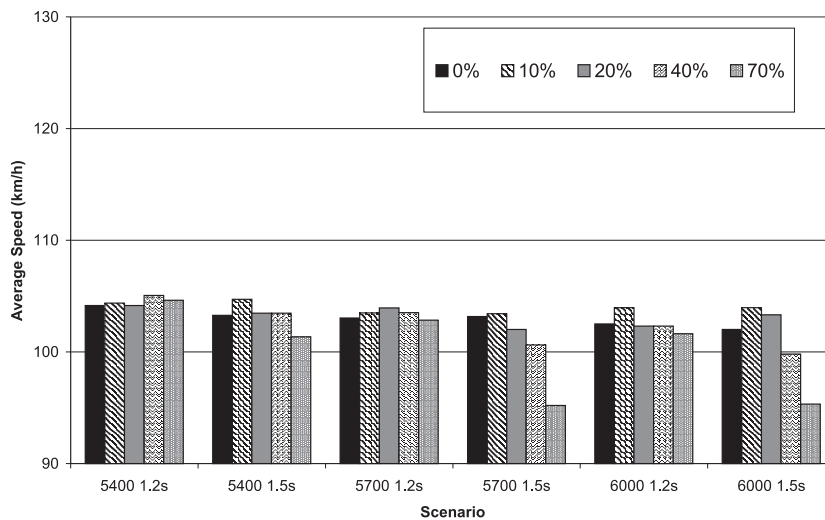


Fig. 6. Average speed against percentage of vehicles equipped – lane 2.

Fig. 5 shows very little effect on traffic in lane 1 from an increasing proportion of vehicles equipped with ACC, independent of the target time-gap chosen. This effect is due to the large percentage of heavy goods vehicles (HGV) (15% of total traffic) operating in the nearside lane. The presence of such numbers of HGV on UK motorways is typical. Car drivers using the nearside lane will frequently encounter HGV with lower speeds than their desired speed and will have to overtake.

A small, but statistically significant decrease in average speed in lane 2 may be seen in Fig. 6 when 70% of vehicles are equipped with ACC for the target time-gap of 1.5 s when the maximum

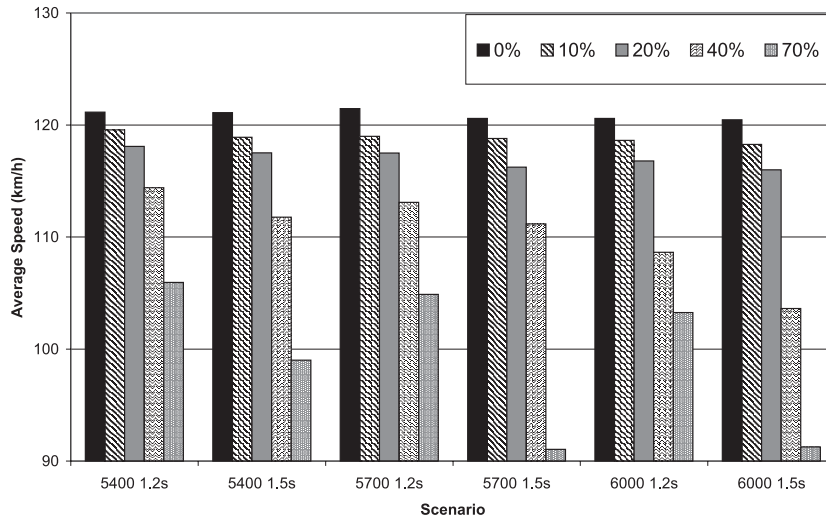


Fig. 7. Average speed against percentage of vehicles equipped – lane 3.

flow level is 5700 or 6000 veh/h ($P_{0.95}T \leq t = 0.00008$, $P_{0.95}T \leq t = 0.00015$, respectively). T -tests show no statistically significant change in average speed on lane 2 for target time-gaps of 1.2 s.

It may be seen in Fig. 7 that there is a clear decrease in the average speed as the percentage of vehicles equipped with ACC increases and for both target time-gaps. However, the effects are more pronounced with a target time-gap of 1.5 than 1.2 s. The standard deviation of speed in lane 3 is shown in Fig. 8.

An increase in standard deviation of speeds in lane 3 as the percentage of vehicles equipped with ACC increases may be seen in Fig. 8. The effects are generally larger for a target time-gap of

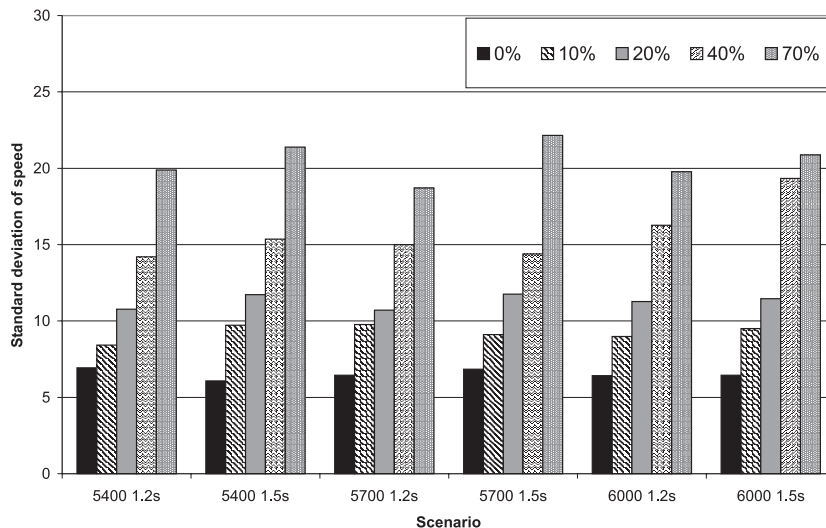


Fig. 8. Standard deviation of speed against percentage of vehicles equipped – lane 3.

1.5 s but are also evident for the smaller target time-gap of 1.2 s. This supports the theory that there are a number of flow disturbances occurring on lane 3. Extensive observation of the simulation model and the data collected suggests the following mechanism to be responsible for the flow disturbances in lane 3.

The desired speed of a driver with and without ACC has been assumed to be unchanged within the FLOWSIM logic, as has the overtaking decision making process. Whilst the FOT found that ACC usage induced some elevation in speed, no firm conclusion of whether this was due to improvements in speed maintenance, driver motivation or both was provided. The offside lane of the motorway carries some 40–45% of flow during the high demand scenarios described above (McDonald et al., 1994). As the percentage of ACC vehicles equipped increases, so does the use of ACC in lane 3. Lane 1 is dominated by unequipped HGV and lane 2 has limited ACC use due to lane changing effects from lanes 1 and 3. Platoons of ACC equipped vehicles with constant time-gap spacing are therefore, naturally formed in lane 3.

ACC systems with a maximum deceleration of $0.07g$ used in the US FOT trials were found to be capable of performing the majority of simple following control. However, with a target time-gap of 1.5 s and, to a lesser extent, 1.2 s, vehicles from lane 2 are able to cut-in between two vehicles in any following process. The ACC algorithm modelled in this study is unable to adapt to the new vehicle in front and manual control is resumed. This usually includes a period of sharp deceleration (more than 1.5 m/s^2) to resume the driver's desired time-gap. This deceleration response is greater than the ACC system can adapt to and drivers further down the platoon therefore also take manual control of their vehicles. In this way, a shockwave passes down the platoon of ACC equipped vehicles and reduces the average speed of lane 3. This process is illustrated in Fig. 9.

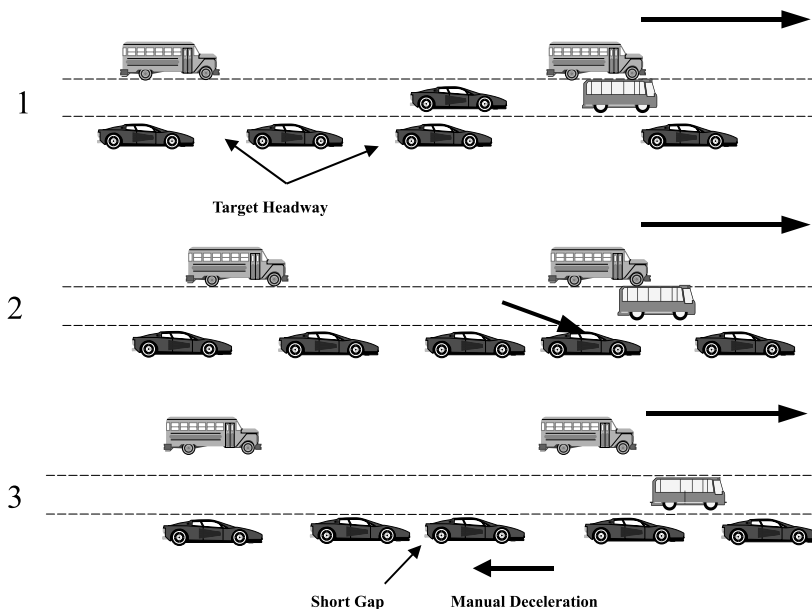


Fig. 9. Mechanism for flow breakdown in lane 3.

Experimental data from US (e.g. Mclaughlin and Serafin, 1999; Fancher et al., 1998) provides evidence that drivers do wait to see if the ACC will cope with the situation and then react later with a strong deceleration if the system does not recover the time-gap sufficiently. The time-gap distribution shown in Fig. 4 supports the hypothesis that there are more gaps suitable for vehicles to cut-in to, although the distributions are aggregated over all lanes. Fancher et al. (1998) demonstrate empirical evidence about cut-in rates found from the FOT that suggest that the reduction in very small time-gaps found from the modelling exercise here would indeed provide greater opportunity for cut-in manoeuvres.

Minderhoud and Bovy (1999) suggests that such effects are not observed with ACC systems where the target time-gap is set to below 1.2 s. It seems likely that this is a result of small inter-vehicular separations that do not allow vehicles to cut-in. In this modelling exercise, the assumption was made that drivers will select ACC at all times if it is possible to do so. It seems unlikely however, that drivers would indeed select ACC if, as is suggested, recurrent manoeuvres such as lane changing require the driver to resume manual control as ACC should be used to enhance driver comfort.

However, the results do raise the question of whether it will be in the interest of the network operator to encourage large informal platoons of vehicles operating in time-gaps below 1.2 s. The US FOT implemented a small scale investigation of the stability of strings of ACC equipped vehicles (Fancher et al., 1998) to address this issue. The results showed that exaggerated deceleration responses were found when the lead vehicle performed a deceleration. This was identified as an issue of future concern. Vehicles using ACC will have different operational characteristics and probably different ACC algorithms. Following at such short distances will present a potential safety hazard in the case of an emergency scenario such as an incident ahead or vehicle failure if the magnitude of deceleration increases along a platoon of ACC vehicles. Godbole et al. (1999) present some ideas on damping these effects for ACC and such concerns have also been addressed during the development of the automated highway concept (de Vos et al., 1997) but further research and demonstration is required.

Modelling of the impacts of ACC without a comprehensive understanding of the effects of ACC on driver behaviour has provided knowledge about the boundaries of the expected impacts on traffic flow, such as platoon stability effects, but further application is limited. Traffic models developed for normal motorway driving have lane-changing models based on factors such as expected gain in speed and pressure from vehicles behind. Driving with ACC will inevitably alter a driver's desire to change lane and probably their stimuli for doing so (Saad and Villame, 1996). The lack of a driver behavioural model for ACC use makes the results dependent on the mechanics of the traffic models. Further practical understanding of driver interaction with ACC is still required.

Large scale field trials such as the US FOT trial must be encouraged as ACC moves from a research project to the market. As the next stages of in-vehicle technology arrive on the market, an imperfect understanding of the modelling requirements for existing technologies could be a major shortcoming. One method of assessing the performance of new technologies such as ACC that avoids some of the modelling problems described above is a comparison of the microscopic behaviour of a normal driver and that of a vehicle using the new technology system. To date, a few examples exist of this methodology e.g. Godbole et al. (1999) and Neunzig et al. (1998) where real velocity profiles, measured by instrumented vehicles have been used. The data provides realistic

conditions under which the performance of the new technology is assessed. The next section describes a study of driver performance in the UK, France and Germany and how this data has been used to assess the potential impacts of ACC.

4. Instrumented vehicle assessment of ACC

An instrumented vehicle, developed at the University of Southampton, described in Brackstone and McDonald (1997), was used to collect driver following behaviour data in three countries. The instrumented vehicle is equipped with a number of sensors and video cameras. In particular, a ground speed measuring device provides information on the instrumented vehicle speed, whilst a radar measures distance and relative velocity to targets at either the front or rear of the vehicle. For this study, the radar was located at the rear of the vehicle, measuring the performance of anonymous, random drivers following the instrumented vehicle. Table 1 provides the details of the trials.

Driver behaviour varies between sites within any country and throughout the day as well as between drivers. The measurements taken are therefore only able to supply an indicative rather than a definitive statement on the differences between driver behaviour in the three countries. Some of the work comparing following time-gaps has been reported in McDonald et al. (1998). However, the value of the data set is that it allows an assessment to be made of three very different roads with different types of drivers.

The research described here examines two aspects of ACC performance. Firstly, the experiments examined how equipping the following vehicles with an ACC device would have changed their following behaviour. Secondly, situations where the ACC algorithm was unable to adapt to the acceleration responses experienced by the instrumented vehicle during normal driving were observed. Only those cases where the speed of the instrumented vehicle remained above the minimum operating speed for the ACC system (40 km/h) were examined. Following events were only processed if the duration was greater than 1 min.

The FLOWSIM model was adapted to model two vehicles. The lead vehicle was progressed through the model using the vehicle speed profile provided by the instrumented vehicle every 0.125 s. Modelling the performance of the ACC system at 0.125 s intervals was felt to be more

Table 1
Details of instrumented vehicle trials

Date	Site	Number of following events	Average duration of following (s)
14/10/97	A1 – Lille, France	12	177
16/10/97	A1 – Lille, France	35	141
22/10/97	M3 – SW London, UK	17	194
23/10/97	M3 – SW London, UK	19	111
23/10/97	M3 – SW London, UK	18	151
02/06/98	A1 – Hamburg, Germany	21	129
03/06/98	A1 – Hamburg, Germany	47	161
04/06/98	A1 – Hamburg, Germany	53	202
05/06/98	A1 – Hamburg, Germany	39	178

realistic than the 0.5 s and greater intervals used by most simulation models. The following vehicle was given speed and distance data for the real following vehicle at the beginning of the following sequence and then allowed to follow using the ACC algorithm. The experiment was run three times for each event studied with target time-gaps of 1, 1.5 and 2 s. Table 2 summarises the number of events in which ACC was able to operate without driver intervention at each site.

The measurements were all taken during morning and evening peak driving periods. This limited the number of following events in which the speed remained above 40 km/h, and therefore the potential to use an ACC system. This was particularly the case at the UK test site. That the system was unable to cope with all of the acceleration responses of the instrumented vehicle does not necessarily correlate with the driver's choosing not to use the system. However, manual intervention in braking situations will lessen driver comfort and confidence in the system.

The speed and acceleration profiles of the instrumented vehicle for the single following event on the UK motorway when the modelled driver intervened are shown in Fig. 10. The acceleration profile for the following vehicle is also shown.

Table 2
ACC operation statistics

Location	Number of events	Number of events >40 km/h	Number unable to use ACC throughout following sequence			% events suitable
			Target headway 1 s only	Target headway 1 and 1.5 s	Target headway 1, 1.5 and 2 s	
Lille	47	43	4	2	6	66
SW London	47	19	1	0	0	38
Hamburg	160	138	5	5	2	79

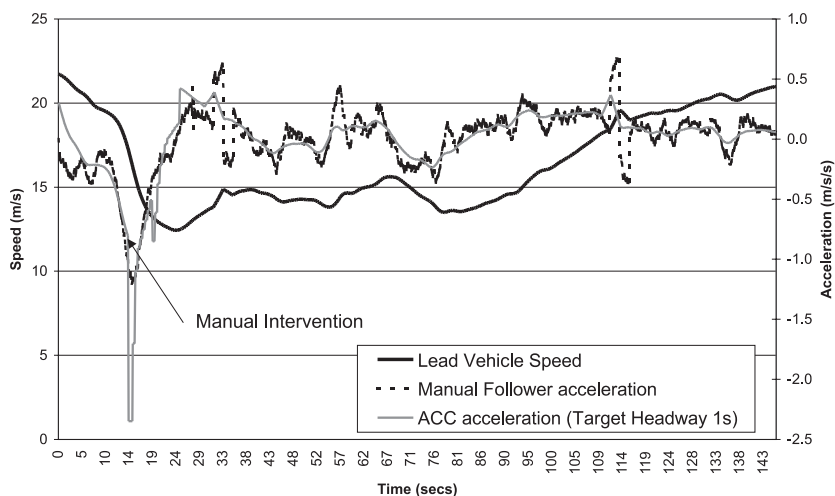


Fig. 10. Speed and acceleration profiles for manual intervention event – UK.

An analysis of the video recordings taken at the points when the model estimated manual intervention to be required was performed. Some common traffic conditions that were found just prior to the intervention point included vehicles pulling out in front of the instrumented vehicle, driving round curves, approaching slower moving traffic and changing lane then encountering a slower lead vehicle.

The combination of a number of short following events, events where vehicle speed fell under 40 km/h and events highlighted above where the ACC system is unable to respond to sufficiently to prevent driver intervention make it likely that ACC would only have limited use during the peak periods. However, such an assessment is limited to the ACC system under investigation here. The modelled driver intervened before the system achieved maximum braking (1.5 m/s^2) which indicates that a stronger system reaction could be incorporated to mitigate such interventions or that a modification to the driver model is required based on empirical ACC use data. Such data is not currently available for application to a UK driver model.

Another interesting observation can be made from consideration of the results in Fig. 10. Apart from the period where the ACC system was switched off, the acceleration profile for the following vehicle is smoother than that for the instrumented vehicle. Whilst some of the variation on the instrumented vehicle profile will be due to the data being field measurements, the overall trend of acceleration is considerably more peaked than for the ACC driver. A further example of this can be seen in Fig. 11 with data from the Hamburg test site.

The standard deviation of acceleration for at least 10 following events at each site when no interruption in ACC operation was observed is shown in Table 3. The results show a reduction of between 44% and 52% in the standard deviation of acceleration. This confirms that the ACC is providing a support to the driver and is controlling the acceleration task of the driver with less variation. The magnitudes of the difference between human performance and ACC system performance suggest that considerable fuel consumption savings will be made through the use of ACC.

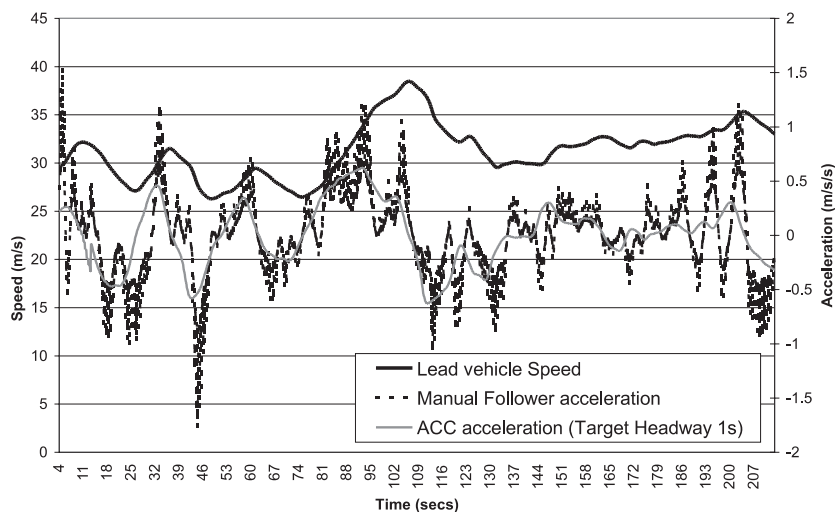


Fig. 11. Speed and acceleration profiles – Hamburg follower.

Table 3
Standard deviations of accelerations from test site measurements

Location	Number of events	Standard deviation of acceleration measured	Standard deviation of acceleration ACC 1 s ^a	Standard deviation of acceleration ACC 1.5 s ^a	Standard deviation of acceleration ACC 2 s ^a
Lille	13	0.24	0.13 (-46)	0.11 (-51)	0.12 (-52)
SW London	10	0.42	0.22 (-48)	0.22 (-48)	0.22 (-47)
Hamburg	31	0.35	0.19 (-46)	0.19 (-45)	0.20 (-44)

^a Figures in brackets denote % change from measured data.

The results in Table 3 also show that the reduction in acceleration is equally high for all three of the target time-gaps selected. *T*-tests comparing the standard deviations for all three of the target time-gap settings showed no statistically significant differences in the reduction in standard deviation of acceleration between target time-gaps at each of the three sites.

5. Conclusions

In-depth investigation of the effects of introducing vehicles equipped with ACC systems into microscopic traffic simulations has been completed. Several conclusions have been reached.

Large scale modelling results presented in this research and by other independent research teams have linked traffic capacity and speed to ACC system target time-gap and penetration rates. One conclusion that has been drawn through this research is that these modelling studies are limited by their assumptions about ACC use. Limited evidence was found to support the modelling findings that platoons of ACC vehicles will form in the offside lane. Such platoons were subject to increased platoon instability compared with manual driving. This was attributed to a significant deceleration obtained when the lead driver resumes control over the ACC system to compensate for the short inter-vehicular distance produced when a vehicle cuts in at the head of the platoon of ACC vehicles. This deceleration propagates along the platoon and causes a mini shockwave to form. However, what is less certain, is whether drivers will choose to engage their ACC systems during the most congested driving conditions and, once performing a manual intervention, whether they will choose to re-engage the system. Evidence from the US FOT indicates that most drivers will not. This in turn implies that ACC will have no impact on maximum road capacity.

Current microscopic simulation models have reached the limits of their usefulness in assessing the impacts of ACC on motorway efficiency. It is possible that ACC will fundamentally alter the way in which we drive and our motivations during normal driving. Further understanding of the human decision making processes when using ACC is necessary to ensure that the traffic simulation modelling tools are able to adequately represent network performance as future in-vehicle systems are introduced.

Further work has used driving profiles collected by an instrumented vehicle in the UK, France and Germany to compare real driver following behaviour with that, had the rear vehicle been equipped with an ACC device. The driving profiles were collected during peak periods where

speed fluctuations and lane changing occurred regularly. The results indicated that the ACC systems may be switched off during the following sequence and are perhaps unsuitable for dense driving conditions. It may be considered ironic that the ACC system might not be used in those traffic conditions in which the driver needs greatest assistance. However, ACC systems rely on data from one fixed external sensor whilst a human operator has many more sensors at their disposal to deal with a greater range of uncertainties.

ACC performance during long following sequences however, showed reductions in the standard deviation of acceleration of the following vehicle of between 44% and 52%. This again highlights that ACC has been developed for driver comfort. Considerable benefits to the driver and network operator from a reduction in fuel consumption will be an additional result of the reduction in acceleration variation. However, no short-term changes to traffic efficiency during peak conditions can be deduced from these results.

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