Combining traffic simulation and driving simulator analyses for Advanced Cruise Control system impact identification

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ABSTRACT

The objective of this research is to combine microscopic traffic simulation and driving simulator pilot tests of vehicles equipped with Advanced Cruise Control (ACC) systems, aiming to identify traffic and safety impact of the introduction of this technology. The relevant outputs of two microscopic traffic simulation and driving simulator experiments were analysed and the similarities between their experimental designs were identified. Relevant outputs were cross-tabulated and analysed, and qualitative results were extracted. Indicators selected for the purposes of this research include average speed, minimum and desired headways, and Time-To-Collision (TTC). The analysis indicates that the impact of ACC on the average speed is minimal, while headways and time-to-collision distributions are decreased. While these findings indicate positive traffic impacts, shorter headways and TTC values could have negative safety implications. Our findings have resulted in conclusions for the future development of ACC systems but also illustrated the usefulness for extracting a more complete assessment through the combination of traffic simulation results with respective results from driving simulators.

Keywords: traffic simulation, driving simulators, Advanced Cruise Control, traffic impacts, safety impacts

1. INTRODUCTION

1.1 Background

Cars have long become an indispensable part of everyday life for most people. Increasing car use, however, has several adverse impacts, including congestion (leading to excess delays, unnecessary fuel consumption and pollution) and a large number of fatalities resulting from accidents. As a consequence, a great deal of research is being performed by academics, federal agencies and related industries, in a coordinated effort to face some of the problems resulting from the rapid motorization of the last decades. Advanced Driver Assistance Systems (ADAS) are one of the areas that are being actively researched as it is believed by many that their wide-spread deployment may help in the alleviation of a multitude of traffic-related issues.

After a long period of system research and development, a number of systems have reached the deployment stage, while many more will be ready in the foreseeable future. An important activity is now the determination of the actual expected impact of such systems and thus the preparation of strategies to maximize the benefits from their deployment. Within this objective, a number of experimental and methodological studies focus today on the quantification of this impact.

Braban-Ledoux et al. (2000) propose a set of microscopic indicators for characterising driver behaviour and describe a methodology for the assessment of Dynamic Speed Adaptation on driver behaviour. Duynstee et al. (2000) present the preliminary results of a research aiming at estimating the effects of Intelligent Speed Adaptation on driving behaviour, based on experimental results. Ishida et al. (2000) present experimental results of an evaluation of ADAS impacts on driver's workload that they performed, using an equipped vehicle. Regan et al. (2000) present an experimental trial and evaluation of an integrated suite of eight in-vehicle intelligent transport systems, focussed on safety and behavioural aspects. Misener et al. (2000) describe the adaptation of a microscopic simulator, SmartAHS, for the evaluation of ADAS and present simulation results for an Adaptive Cruise Control and Stop-and-Go system. An analysis of Adaptive Cruise Control impact on the fuel consumption of equipped vehicles is presented in Neunzig et al. (2000). Even though several aspects of ADA impact are explored, none of the above research efforts has addressed in a specific way the impacts that ADA systems and related driver behaviour changes may have on network traffic conditions.

Some of these studies use traffic simulation software to simulate the expected impact of these systems, while others rely on experiments using human drivers on driving simulators (Kikuchi et al., 2003). Both approaches have advantages and disadvantages, as each is more suitable to capture different types of ADAS impacts. Certainly, the combination of both approaches in comparable experiments could lead to more complete conclusions.

1.2. Scope of the analysis

The objective of this research is the comparative analysis of the findings obtained from the microscopic simulation of traffic of vehicles equipped with Advanced Cruise Control (ACC) systems with the findings obtained from the driving simulator pilot tests of vehicles equipped with ACC systems, both aiming to identify traffic and safety impact.

This research has been undertaken within the scope of the ADVISORS European Union project, which aimed at assessing the impact of Advanced Driver Assistance Systems (ADAS) in a very broad context, including legal issues, user acceptance issues, willingness to pay, as well as traffic, safety and environmental impacts (SWOV, 2003). Two of the tasks that were undertaken within the ADVISORS project focused on the determination of the expected traffic and safety impacts of the introduction of selected ADAS using traffic simulation and traffic simulators respectively.

While each task looked at different ADA systems, including Advanced Cruise Control (Oei, 1998a) and Variable Speed Limiters (Oei, 1998b) and used different scenarios and methodologies (chosen to best fit the task at hand), there are considerable overlaps that allow validation and cross-analysis of the obtained results to infer more general conclusions.

The first challenge in this process is the identification of a comparable set of situations, for which meaningful comparisons can be made. While the traffic simulation effort focused on simulating the impacts of ADAS in network efficiency and environmental conditions (covering also relevant topics, such as safety), the driving simulator experiments had a different focus and attempted to provide insight in many human-related aspects of the potential impacts of ADAS. Examples of such topics, not covered within the scope of the traffic simulation task, include driver workload, willingness-to-pay, and user acceptance. Furthermore, while microscopic traffic simulation models provide output in the form of aggregate information on all vehicles in the network, driving simulator tests focus on detailed observations from a discrete number of specimens.

The comparative analysis of the output of the microscopic simulation and driving simulator experiments had been included as a consideration during the planning stage of the two tasks. Furthermore, the teams that designed and performed the experiments were in close cooperation during their execution. Thus, the two tasks were coordinated to be as compatible as possible within the limits of each experiment. It should be noted, however, that both efforts did not focus on providing quantitative results, but aimed to the development of a robust ADAS assessment framework. Thus, while quantitative results were used to support this comparative analysis, this synthesis was geared mostly towards presenting qualitative comparison results.

The methodology that was used for the comparison of the results can be summarized in three steps. First, the two experiments were analysed in detail and the similarities between their experimental designs were identified. The relevant outputs were then cross-tabulated and analysed, and qualitative results were extracted. Based on this comparative analysis, a discussion was performed to draw more general conclusions and illustrate the actual significance of the obtained results.

This paper is structured in the following way. Section 2 describes the two experiments and provides the background for the comparative analysis. Section 3 presents the comparative analysis of the results obtained from the two approaches, while a synthesis of the analysis can be found in Section 4. Finally, Section 5 presents some overall conclusions and identifies key directions for further research in this area.

2. THE TWO EXPERIMENTS

This section describes the tools that were used for each of the two experiments, from which this research draws most of its data, as well as the experimental design. The emphasis of this presentation is on those situations that are common to the two experiments and can thus be used in the subsequent analysis.

2.1 Microscopic traffic simulation models

Two microscopic traffic simulation models were used. The following paragraphs provide useful background information on these models, to support the reader's understanding of the following material. Supplementary references are also provided, from which additional information can be obtained. Furthermore, a more detailed description of these experiments can be find in the relevant project deliverable (Golias et al., 2001).

The Dutch simulation model, SIMONE (Minderhoud, 1999, and Minderhoud and Bovy, 1999) from the TRAIL/University of Delft, is designed to analyse traffic flow impacts of a wide variety of driver support system compositions of the vehicle fleet under various roadway configurations and traffic demand conditions. SIMONE has concentrated on modelling two critical situations of inter-urban traffic, specifically an on-ramp (3+1) and a lane drop situation (3 to 2). Critical traffic speeds are 86-96 km/h and flow is 2000 vehicles/hour/lane.

The British model, SISTM (Stevens et al., 2000) of the Transport Research Laboratory (TRL), can be used to evaluate qualitatively and quantitatively the effect of different layouts or operating conditions on a length of motorway. In particular, relative to the ADVISORS scope, SISTM can simulate lanes reserved for specific vehicle types or for vehicles making certain Origin-Destination (OD) movements, different levels of traffic demand and changes in vehicle characteristics (e.g. incorporation of ADAS). SISTM has been used to investigate a simple geometry consisting of 10km of 3-lane motorway with a 2-lane entry slip road located 2km along the section, and a more complex geometry with entry and exit slip roads and road gradients. Both networks yielded essentially the same results. The model was also run to investigate the blocking of one lane, but again essentially the same relative effects were observed. Traffic speeds were 80-90 km/h and flow rates investigated were between 1200 and 2000 vehicles per hour per lane.

2.2 Driving simulator tests

A number of driving simulator tests were performed within the scope of the ADVISORS project, using different configurations and testing the impact of various systems (Nielsson et al., 2002). The driving simulator test performed by the Swedish National Road and Transport Research Institute (VTI) for the assessment of the impacts of Advanced Cruise Control has been selected as the most relevant for this comparison. The TRL driving simulator test also considers a longitudinal ADAS (comprising ACC and stop-and-go (S&G) functionality), but by considering an urban setting it diverges from the conditions simulated within the microscopic traffic simulation experiments. The other driving simulator tests are either focused on the evaluation of lateral ADAS, or systems that relate mostly to behavioural aspects. Similarly, while several ADA systems have been simulated in the microscopic traffic simulation models, only the ACC-related output was used for this comparison, as no equivalent to the other systems has been tested in the driving simulator tests.

In the considered experiment, the ACC system was assessed in the VTI driving simulator (a detailed presentation of the experiment setup, execution and results can be found in Tornros et al., 2002). The simulator has a moving base system, a wide-angle visual system, a vibration-generating system, a sound system, and a temperature-regulating system. All systems are controlled and interact in a way that gives the driver an impression very much that of real driving. The car mock-up used in the pilot was a front wheel drive Volvo 850 with an automatic gearbox. Twenty-four drivers participated in the driving simulator tests, equally split between female and male drivers. The drivers' age ranged between 23 and 55 years (mean age was 40 years) and they owned a driver's license between 5 and 37 years (mean value: 19 years). Driver experience was also measured by the kilometers driven by each driver. In particular, the drivers had driven (in their entire life) between 20.000 and 1.500.000 km (mean value: 302.000 km). Furthermore, they annually drive between 2.000 and 55.000 km (mean value: 15.100).

The ACC system simulated in the pilot had two operative modes: speed control and distance control. Within the first mode the ACC worked as an ordinary cruise control, i.e. kept the speed chosen and set by the driver. In the second mode (in case of a vehicle ahead) it controlled the host-vehicle's speed in order to keep a fixed distance to the vehicle ahead on the trajectory, based on a minimum headway value chosen by the experiment leader (according to the experimental design). Both modes of the ACC were imitated in the simulator, and a mock-up interface was provided for the driver to interact with.

When approaching another vehicle from behind, the ACC applied a constant brake force of 1 m/s^2 until the set minimum time headway was reached. If the car in front started braking during this manoeuvre, the ACC car decelerated harder, up to 2.5 m/s^2. If this was not sufficient to keep the minimum time headway, a beep warning sound was emitted and a red lamp was lit on the dashboard. When speed got below 50 km/h, a sound signal was emitted, different in pitch from the warning signal described above, informing the driver that the speed level was out of the operative range of the ACC.

The participants drove a route consisting of four sections: two identical rural road sections with one lane in each direction and traffic appearing in both direction (speed limit 90 km/h), and two identical two-lane motorway sections (speed limit 110 km/h). One section on each of the two road types was driven with ACC support and the other without ACC support. The length of each of the four road sections was 30 km. Along the route "normal driving" as well as "more critical" situations occurred. The participants were exposed to other traffic – they were overtaken by other cars on all four road sections and encountered oncoming traffic on the rural road sections.

2.3 Experimental design

In terms of network set-up motorway sections were selected as the basis of the comparative analysis, as they were simulated by both types of experiments.

The main functional characteristics of the simulated ACC systems (at the traffic simulations and the driving simulator test) are presented in Table 1. Speed range indicates the range of speeds for which the system is operational. Acceleration and deceleration ranges indicate the system-controlled ranges for these measures, while driver controlled acceleration/deceleration is not limited to these values. Minimum time headway values represent alternative scenarios selected for the investigation of the impact of this variable in the system performance. Finally, for the microscopic simulators penetration rates indicate different rates that were considered in separate microscopic simulator runs. While not all penetration levels are common to both experiments, comparisons can be made for the base case (no ACC), low penetration (10%), medium penetration (50%), and high penetration (90-100%). Given the nature of the driving simulator experiments (where the focus is on a single driver), the concept of system market penetration becomes more difficult to capture.

3. COMPARATIVE ANALYSIS

A diverse set of indicators has been used across the various tests. However, for the purposes of this qualitative comparative analysis it was necessary to identify a subset of common indicators. After careful consideration, the following indicators, provided by the two microscopic traffic simulations and the driving simulator tests were finally selected for the purposes of this analysis:

- Average speed.
- Minimum and desired headways.
- Time-To-Collision (TTC).

Speeds and headways provide insight into the traffic impact of the introduction of Advanced Cruise Control systems, while all three measures can be used to infer potential impact on safety.

3.1 Average speed

One observation, on which there is general consensus from both experiments, is the fact that the introduction of Advanced Cruise Control systems did not have a significant impact on average driving speed.

In the driving simulator experiments, the average speed was 105 km/h in both situations: unsupported driving and presence of ACC. The average speed without other traffic was 116 km/h and –again– remained unaffected by the introduction of ACC.

Similarly, microscopic traffic simulation results indicate that while at low penetrations and traffic flows the impact of ACC on average speed is minimal, as either of these measures increase, average speed increases. For example, simulations using the British model SISTM suggest that the effects of ACC on speed are broadly neutral, except for a 7% increase with a complex geometry, high flows and high penetration rate. Overall the average speed drops as the flow increases, from 99 km/h at low flows and no ADAS to 95 km/h at medium flows. This can be attributed to the fact that without ADAS, the average speed is already less than the legal limit; there are sufficient drivers traveling at less than the limit to prevent a large proportion of drivers exceeding the limit by a significant amount.

Several observations about speed measures are worth noting. Driving simulator experiments found that with the introduction of ACC and under certain (low traffic) conditions, the intra-individual variation in driving speed was reduced (compared to the observed variation without ACC). When the entire session was analyzed, the intra-individual variation in driving speed in the motorway was 25 km/h, irrespective of the use of ACC. However, for those sections that no other traffic was present, effects of ACC support appeared. While in unsupported driving the average intra-individual variation in driving speed was 6 km/h, with ACC support the speed variation was reduced to 4 km/h.

Furthermore, the average maximum driving speed was reduced in most situations. In unsupported driving, the maximum driving speed was 133 km/h, when data for the whole session were analyzed. With ACC support the maximum driving speed was reduced to 123 km/h. Similar effects were observed for the sections where no other traffic was present. With the introduction of the ACC system, the average maximum speed dropped from 129 km/h to 120 km/h. This reduction can be attributed to the fact that the drivers' desired speeds (as expressed in the experiments without ACC) were higher than the speed limit.

Furthermore, traffic simulations using the SIMONE model found that speed at capacity (so-called critical speed) is higher for the ACC scenarios, probably as a result of improvement of traffic stability. For example, in a lane drop bottleneck (from 3 to 2 lanes), critical speed increased from 90 km/h (without ACC) to 101 km/h when all vehicles were equipped with ACC. Figure 1 illustrates the critical speed as a function of the ACC market penetration for this situation. Further analysis showed that this is mainly caused by changes in the use of the respective roadway lanes, which result from the deployment of ACC.

3.2 Headway distribution

Driving simulator tests indicated that in certain situations the observed headways were shortened significantly in response to the introduction of ACC. The average distance headway was 51 m without ACC support and 31 m with ACC support.. Furthermore, the average preferred headway (on the motorway) was between 1.4 and 2.8 s without ACC and between 1.5 and 2.5s with ACC.

The results obtained from the microscopic traffic simulations were at the same direction. Comparing the headway distributions obtained from SIMONE, it turns out that the headway distribution is more uniform at higher ACC penetration levels. Figure 2 shows the headway distribution by lane without ACC and Figure 3 shows the headway distribution when 25% of the vehicles are equipped with ACC. This is a reasonable and expected result, since the increase in the penetration rate suggests that more vehicles follow the system-dictated headway. The resulting headway pattern suggests lower variability and therefore arguably higher traffic stability. Based on the SISTM simulation results, at low flows, there is a small increase (1% - 2%) in the observed headways at low and medium penetration levels, reducing to virtually no change at high penetration levels. At medium flows, all scenarios have little effect at low penetration, produce about a 2% reduction at medium penetration and a reduction of 5% or slightly more when almost all vehicles are equipped.

Clearly, a reduction in average headway affords the driver less time to respond to unforeseen events and so must be associated with an increase in the frequency and severity of accidents. In a number of European countries (e.g. the UK and Germany) recommendations or rules are in effect concerning a "2-second headway". However, surveys of actual headway distributions on motorways show that this rule is widely ignored. Indeed, on busy inter-urban routes a 2s headway may be viewed as "deviant behaviour" by other drivers who will overtake and cut in front of the lawful driver. Another factor is the variability in headway. Although capacity is not affected unless the average headway is changed, homogeneity is expected to increase the safety of traffic.

3.3 Time to collision

Average minimum time to collision (TTC) was calculated for most driving simulator scenarios. For several situations the minimum TTC was significantly shorter with ACC support than without it. For example, in the scenario where the vehicles were approaching queues the TTC fell from 17 seconds to 10 seconds. However, due to the magnitude of these TTC values, this decrease is not expected to negatively impact traffic safety. For other scenarios small increases in the time-to-collision were observed. For example, in the pulling out scenario time-to-collision increased from 2.35 seconds to 2.52 seconds.

Decreases in time-to-collision are also observed in the microscopic traffic simulations. In the SISTM simulations, for example, the measure that is used for reporting is the proportion of vehicles with TTC of less than 10 seconds, and respectively the proportion with TTC of less than 1 second. SISTM reports reduction in the proportion of these smaller TTC values after the introduction of ACC, thus implying improvement in terms of safety. When the flow is low, the maximum decrease in TTC less than 10s is more than 20% when all vehicles are equipped with ACC. At high flows, this decrease becomes 35%. Furthermore, the decrease in TTC less than 1s is minimal for low flows, and exceeds 15% for high flows.

SIMONE reports proportions of TTC values less than 3s (representing "uncomfortable" situations) and TTC <1.5s (representing "dangerous" situations) and provides mixed results. For ACC and lane drop situations, SIMONE reports reductions in "dangerous" TTC measurements (from ~15% without ACC to less than 10% when all vehicles are equipped) but increases in "uncomfortable" TTC measurements (from ~30% without ACC to 35-40% when all vehicles are equipped). For the on-ramp situation both TTC measures imply decreases in safety.

4. SYNTHESIS OF RESULTS

The aim of the two types of experiments examined in this section was to evaluate the expected impact of the introduction of an Advanced Cruise Control system. While further research is necessary before conclusive and quantitative results can be obtained, a number of observations can be made based on the available results. A first observation is that the introduction of a complicated ADA system is a multifaceted task that must be well planned and implemented. The functional characteristics of such a system (e.g. short headways, lower speed variability, decreased time-to-collision) do provide some traffic stability characteristics; however, they may also lead into compromises in traffic safety.

The quantitative results of the previous section are summarized in Table 2. Furthermore, these results have been converted into qualitative indications in Table 3. Thus, Table 3 allows for the overall qualitative comparison of the results obtained from both microscopic traffic models and the results obtained from the driving simulator tests. A zero ("0") indicates no impact from the introduction of the considered ADA system. A plus sign ("+") indicates that there was some positive *traffic* impact observed, while a plus sign in parenthesis implies that this impact was small. It should be noted, that while - for example - a decrease in average headways or time-to-collision values would be ranked as having a positive impact from a traffic efficiency point of view, it can be argued that it would result in unsafe (i.e. short headway/time-to-collision) situations, deserving thus a negative safety ranking.

The impact of ACC on the average speed is generally minimal. However, under particular scenarios simulated in the microscopic traffic models, it was found that speed increased with the introduction of ACC. Furthermore, the decreases observed in the average headways would also have a positive traffic effect. Time-to-collision values generally reduce as a result of the introduction of ACC. This would have positive traffic implications (and thus gets marked by a plus sign in the table). However, shorter TTC values might have negative safety implications. This observation is somewhat mitigated by the fact that, even though average TTC values reduce after the introduction of ACC, occurrences of very small (and thus dangerous) values are decreased.

Traffic simulation models and driving simulator experiments reached generally similar conclusions about the impact of ADA systems. However, there are situations where they diverge. For example, in the driving simulator experiments maximum speeds decreased, while in the traffic simulations they stayed the same or increased. The reasons for this apparent disagreement should be sought at the special characteristics and setup of each exercise. In particular, in the microscopic traffic simulation experiments, the maximum desired speed by the drivers was above the speed limit and was thus limited by the ADA system. On the contrary, speeds at the traffic simulators were generally below the speed limit (and thus unaffected from the speed limiting feature) while they gained from the increased traffic stability (and consequently showed an increase).

5. CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

The findings of two methodologies that had the common task of identifying the impact of ACC are presented, compared and analysed in this paper. Comparisons between traffic simulation models (including those used in the presented research) and experiments using driving simulators (again, like those used here) are a challenging task and the results should be treated with due caution, depending on the level of detail of the comparison results. A key difference between the two approaches is that while driving simulators may capture drivers' reactions to alternative scenarios directly, traffic simulation is limited to using models of driver behaviour. The situation is often further complicated by the fact that the data that was used for the calibration of these behavioural models may not include situations identical to the ones modelled, as is the case with the ADA systems scenarios modelled within the scope of the ADVISORS project.

On the other hand, microscopic traffic simulation packages simulate the entire driver population and can thus assess more complicated interactions between vehicles. Driving simulators deal with individual drivers and their immediate environment (i.e. only surrounding vehicles) and thus simulating conditions, such as the effect of ADAS market penetration, is not straightforward. The differences in the quantitative results (Table 2) may be due to the dissimilarities of the experimental setups. In conclusion, it can be argued that the results from the two types of experiments should not be seen as competing, but rather complementary. Indeed, while this comparative analysis focused in the "intersection" of the two types of experiments, a wealth of information specific to each of them can be used to shed light to other aspects of ACC impacts.

One important finding that can be supported by the presented results and analysis is that there does not appear to be a critical penetration level, above which the benefits of ACC may be reversed. To the contrary, it is suggested that the benefits increase as penetration of the system increases. An interesting research question would be whether these findings apply to other ADA systems. The presented methodology could be used to conduct and analyze further studies focusing on other ADA systems.

One of the outputs of this synthesis should be the identification of directions for future research. One obvious direction is the investigation of more ADA systems and situations in identical situations in both the traffic simulations and the driving simulators. Thus, the results that were presented above would be enriched and would cover a more complete spectrum of available technologies. The output of such an effort would then be used to evaluate the projected impact of each system and would become a valuable decision-support tool for decision makers at multiple levels: academic/research, industry/funding, or even political decisions. In order to be accurate, however, these experiments will have to be designed in close cooperation between the involved parties. Making sure that the parameters and characteristics that will be used are realistic/appropriate, as well as common among all experiments, is key to obtaining a set of meaningful and consistent results.

Additionally, the detailed behavioural information that can be extracted from the driving simulator experiments would provide useful intuition into the change the drivers' behaviour due to the existence of the various ADA systems. These detailed driving simulator data could be very helpful in calibrating the behavioural and driving models within the microscopic traffic simulations after the introduction of the ADA systems; obviously no real field data exist for these situations.

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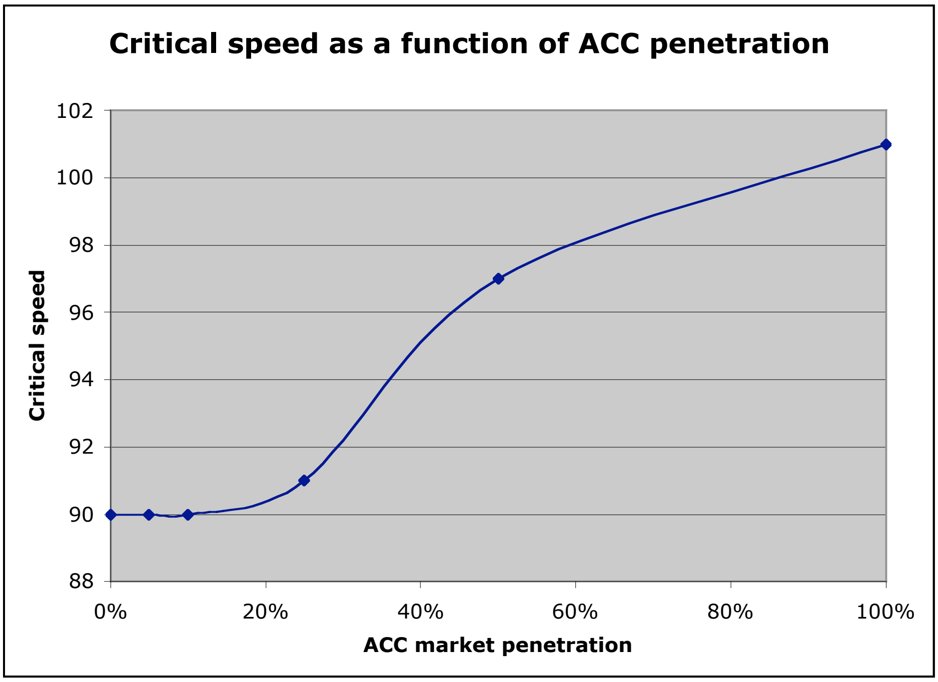
Figure 2. Headway distribution by lane (no ACC, SIMONE microscopic simulator)

Figure 3. Headway distribution by lane (25% vehicles equipped with ACC, SIMONE microscopic simulator)



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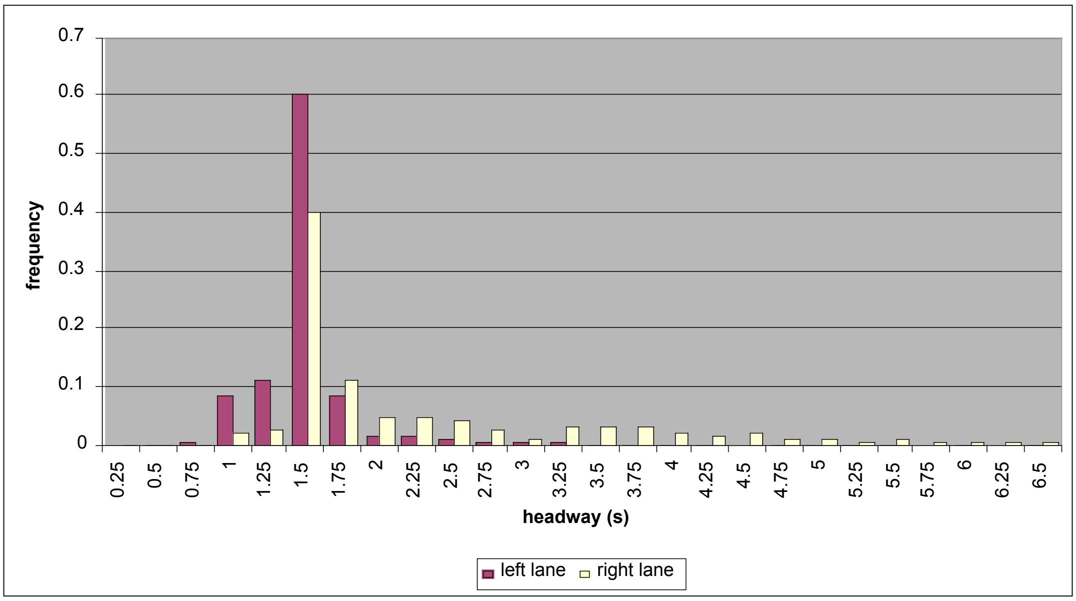

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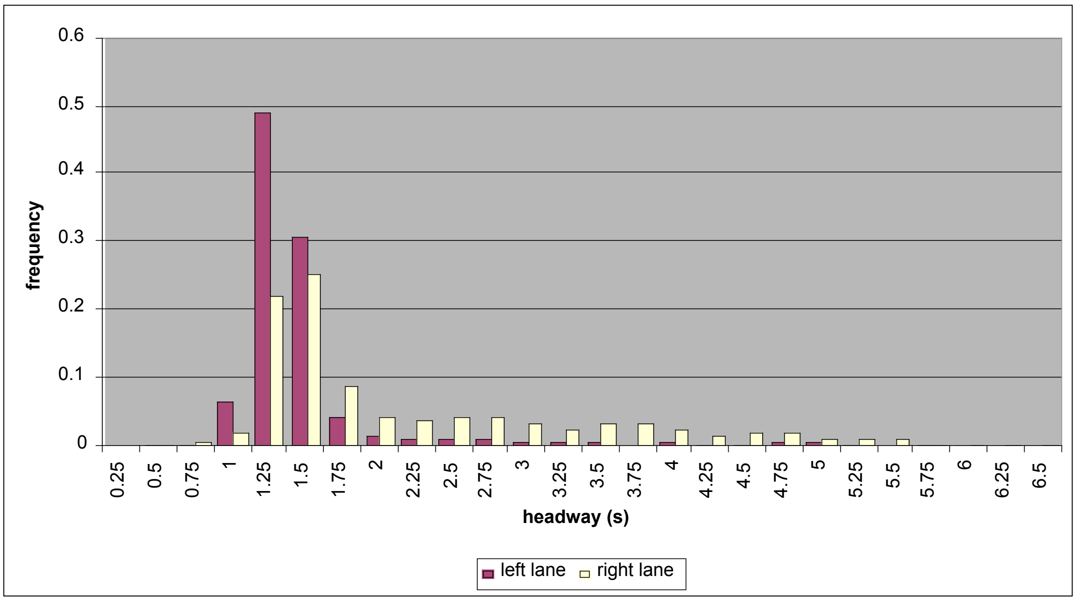

Figure 3. Headway distribution by lane (25% vehicles equipped with ACC, SIMONE microscopic simulator)

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TABLE 1. Advanced Cruise Control (ACC) Functional Characteristics

Characteristic	***Microscopic traffic simulation models***	***Microscopic traffic simulation models***	***Driving simulator***
	SIMONE	***SISTM***	***VTI***
Speed range (km/h)	30 to 170	0 to 142	50 to 140
Acceleration range (m/s^2)	0 to 4	0 to 0.28	0 to 1
Deceleration range (m/s^2)	0 to 2.5	0 to 1.25	0 to 2.5
Minimum time headway (s)	1 to 2.5 (based on control settings)	1.5 2.0	0.8 1.0 1.5
Penetration rates	0% 5% 10% 25% 50% 100%	0% 10% 50% 90%	(indirect assessment)

TABLE 2. Summary of Results (Quantitative)

Measure	***Microscopic traffic simulations***	***Microscopic traffic simulations***	***Driving simulator***
	SIMONE	***SISTM***	***VTI***
Average speed	Up to 10% increase in *critical* speed	Up to 7% increase	No change
Headway distribution	ACC leads in a narrower distribution (around the system-dictated headway)	Small increase (1% - 2%) for low flows, 2%-5% decrease otherwise.	Significant decrease in average distance headway from 51m to 31 m. Average preferred headway: 1.4s-2.8s (without ACC) and 1.5s-2.5s (with ACC)
Time-to-collision	50% decrease in "dangerous" values, i.e. less than 1.5s 15-20% increase in "uncomfortable" values, i.e. below 3s	Up to 35% decrease in proportion of TTC less than 10s Up to 15% decrease in proportion of TTC less than 1s	Decreases in large values (e.g. from 17s to 10s), and increases in other cases (e.g. from 2.35s to 2.52s)

TABLE 3. Summary of Results (Qualitative)

Measure	***Microscopic traffic simulations***	***Microscopic traffic simulations***	***Driving simulator***
	SIMONE	***SISTM***	***VTI***
Average speed	0, (+)	0, +	0
Headway distribution	+	+	+
Time-to-collision	+	+	+