Behavioural effects of Advanced Cruise Control Use – a meta-analytic approach

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In this study, a meta-analytic approach was used to analyse effects of Advanced Cruise Control (ACC) on driving behaviour reported in seven driving simulator studies. The effects of ACC on three consistent outcome measures, namely, driving speed, headway and driver workload have been analysed. The indicators of speed, headway and workload have been chosen because they are assumed to be directly affected by the ACC support, their relationship with road safety is reasonably established and they are the most frequently used outcome measures in the sample of analysed studies.

The results suggest that different operational settings of ACC that are important for the level of support provided by the system, are significant for the effects ACC have on various aspects of driving behaviour, i.e. on mean driving speed and mean time headway. The obtained effect sizes clustered in two groups, with more intervening ACCs having the effects of an increased driving speed and decreased mean time headway.

These results are further discussed in the context of road safety, especially in the context of behavioural adaptation.

Keywords: Advanced Cruise Control, Advanced Driver Assistance Systems, Behavioural Adaptation, Driving behaviour, Meta-analysis

1. Introduction

Advanced Driver Assistance Systems (ADAS) represent electronic systems that support the driver in his/her driving task. These systems are designed to support the driver, ranging from the simple provision of information (e.g. navigation, speed limit), through assisting (e.g. advanced cruise control, stop-and-go) or even taking over all of the driver's tasks (e.g. the automated highway system). One of the most important characteristics of ADA systems as compared to traditional road safety measures is that these systems directly intervene in the driving task.

By automating the driving task, it is expected that human drivers will actually perform only part of the driving tasks themselves while they will increasingly leave vehicle control to the electronic systems/ADAS that are now performing parts of the driving task. ADAS would replace some of the driver's functions (e.g. speed choice, distance keeping, detection of relevant traffic information, etc.) while at the same time the new function of the ADAS supervisor will be imposed on a driver. Although this general change in the role of the driver is expected to extend quickly, it is still unknown what actual effects ADAS are going to have on various aspects of driving behaviour.

One of the first ADA systems that were available on the market was Advanced Cruise Control (ACC). Although present on the market for ten years now, there are still a lot of questions about the effects that ACC have on the behaviour of drivers.

1.1 Advanced Cruise Control

Advanced Cruise Control is an extension of existing cruise control systems, providing assistance to drivers by automating parts of the longitudinal driving task: operational control of headway and speed. Using frontal radar, ACC automatically increases the following distance to a vehicle ahead by reducing fuel flow and/or actively braking the vehicle if it is set to a cruise speed that is faster than the speed of a vehicle ahead.

Ten years ago, the first ACC systems have been introduced into the market as a rather expensive option on the top-of–the line vehicle models. Today, ACC can be found on vehicles of various car manufacturers and on a wider range of vehicle models too (Bishop 2005). Most of the now available ACC systems are operational for speeds above 30 km/h, have a range of 120m to 150m, with a time gap, that can be set manually between 1.0 and 2 seconds. It is expected that in the near future the next generation of ACC, i.e. including "Stop and go" will also become available. Unlike common ACCs, this next generation of enhanced ACCs have to be able to slow down the vehicle to a complete standstill and to be operational for an extended speed range. To accomplish this, "Stop and go" ACC would also have to have the capability to detect other road users or obstacles in a much closer range than now.

ACC is marketed as a comfort and convenience rather than a safety system, mostly because of the limited braking and acceleration ranges and related liability issues (Van Wees, 2004). When driving with ACC, the driver remains fully responsible for the vehicle manoeuvring. However, although considered as comfort systems, it has been hypothesised that ACC systems could also affect traffic safety, efficiency and capacity. Basing their analysis on the ACC capability to effectively control the speed and longitudinal distances between vehicles ensuring that no rear-end collisions occur, Golias, Yannis and Antoniou (2002) categorise ACC as both road-safety and traffic-efficiency high impact systems. This article focuses on road safety effects of ACC.

The capability of ACC to automatically maintain the following distance and its potential to reduce the frequency of tailgating and high closing rates with vehicles ahead is not the only feature of ACC that could help to improve traffic safety. The ACC potential to help attentiveness and situation awareness by initiation of automatic braking that in certain circumstances could act as a wake-up warning to inattentive drivers and that at the same time could reduce harm in rear end crashes is also sometimes mentioned as significant for potentially positive effects of ACC on traffic safety (Scott, 1997).

But these effects are not really clear, because it is also possible that ACC could lead to a degradation of driver performance due to a lack of involvement in the primary driving task (Brookhuis and De Waard, 1999) or to negative behavioural changes in drivers' behaviour (Hoedemaeker and Brookhuis, 1998).

1.2 Behavioural Adaptation

"Behavioural adaptations are those behaviours which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change. Behavioural adaptations occur as road users respond to changes in the road transport system such that their personal needs are achieved as a result. They create a continuum of effects ranging from positive increase in safety to a decrease in safety" (OECD, 1990).

In line with the findings on behavioural adaptation effects with regard to a large variety of safety measures (OECD, 1990), it may be assumed that behavioural adaptation would also be present in response to ACC. Although behavioural adaptation is increasingly mentioned as a relevant issue with regard to ADAS implementation, studies particularly dedicated to behavioural adaptation in response to ADAS are still seldom found. Although it is evident that the driving task is significantly changed by the introduction of ACC, it is still not fully known how drivers adapt to this new technology. Because of the focus on safety aspects of ACC implementation, the changes of interest are particularly those changes in driving behaviour that can have a diminishing (or neutralising) influence on road safety. Therefore, we use the term behavioural adaptation to refer to ***unintended*** and ***unwanted*** changes in driver behaviour when driving with ACC.

A common way of determining the effects of a (safety) measure is to compare the number of accidents before and some time after its introduction. At the moment, it is not possible to assess the effects of ACC on traffic safety in this manner. Although ACC has been on the market for ten years, the ACC penetration rate is still low and data about ACC's accident involvement are still not available. However, even if applied, this method does not allow to determine which part of the overall effect is the result of behavioural adaptation.

An alternative way of analysing and possibly even predicting these effects before full ACC deployment is to use available data about the effects of ACC on various aspects of driving performance.

Without having to wait for accidents to happen, behavioural data could serve as surrogate measures demonstrating the process of behavioural change and providing an insight into mechanisms that provide the foundation of "safe" or "unsafe" driving behaviours. Using driving behaviour measurements as potential indicators of behavioural adaptation raises some difficulties because, unfortunately, there is no formal agreement about standards for the assessment of driving performance with ADAS. Different studies use different sets of variables/indicators as measurements of driving performance, while no harmonized procedures that allow comparison of obtained results exist yet (Nilsson et al., 2001). Regarding the indicators of driving performance, the question is which of them are the most suitable and relevant for measuring behavioural adaptation. The choice of particular driving performance indicators will be influenced by the choice of ADAS, which is in this case ACC, and the relationship between certain driving performance indicators and road safety.

In the past decade several studies of ACC effects on driving behaviour were reported but different studies show different results. Some studies showed that ACC could have a positive impact on traffic safety, while other studies showed the opposite with changes in driving performance such as an increased lane position variability (Hoedemaeker and Brookhuis, 1998), later braking (Hogema, van der Horst and Janssen, 1994) or colliding more often with a stationary queue (Nilsson, 1995). Therefore, a general conclusion as to what extent ACC will improve driving behaviour and traffic safety is difficult. The aim of this study, which is an extension of a previous study by Dragutinovic, Brookhuis, Hagenzieker and Marchau (2005), is to systematically analyse the outcomes of existing studies about the ACC effects on driving behaviour in order to come up with sound and general conclusions about these effects. To be able to integrate different, sometimes even contradictory findings, in this study a meta-analytic approach has been used.

2. Method

The meta-analytic approach is designed to accumulate experimental results of different studies that are considered to be comparable using the summary statistics from individual studies as the data points (Egger, Smith and Phillips, 1997). It is a method for reviewing quantitative research where data from several studies are being combined to produce a single estimate - the effect-size. Nowadays, meta-analysis has been used to help getting a better insight into the effectiveness of various interventions such as education, psychotherapy or road safety measures (Elvik and Vaa, 2004), to find out about the relative impact of certain independent variables or the strength of relationship between variables.

2.1 Literature search

One of the first steps in the meta-analysis that would assure that all relevant studies are included in the analysis was to perform a thorough literature search in which various scientific literature sources were consulted. The search for relevant studies was conducted by using the International Transport Research Documentation (ITRD), the ISI web of knowledge databases, the library of the Dutch Institute for Road Safety Research SWOV, tables of contents of relevant journals, the reference lists from relevant studies and comprehensive science-specific internet search engines (e.g. www. Scirus.com). After a preliminary search, in order to enhance comparability between selected studies, it was decided to restrict the survey to driving simulator studies. Using a suitable set of search key words seven relevant publications comprising nine separate studies were found. Included studies had to use a driving simulator methodology and they had to assess the effects of ACC on driver behaviour indicators such as driving speed and headway. However, some studies could not be included in the analysis because of a lack of adequate statistical information although they fulfilled the inclusion criteria in general.

An overview of the set-ups of selected studies is given in table 1.

Table 1. Overview of the analysed studies

Study	Simulator	Participants			
		N	Age	Driving licence (year)	Driv. exp. Km/year
Hogema, van der Horst, Janssen 1994	Fixed-base	60♂	37.1* (21-54)	>3	>10 000
Hogema and Janssen 1996	Fixed-base	12♂	<60	>3	
Nilsson and Nabo 1996	Moving-base	30[1]	35.7* (23-57)	>5	>10000
Stanton, Young and McCaulder 1997	Fixed-base	6♂ 6♀	21*	3.4*	
Hoedemaeker 1999a	Fixed-base	25♂ 13♀	25-60	>3	>2500
Hoedemaeker 1999b	Fixed-base	24♂ 6♀	25-60	>3	>2500
Brook-Carter et al. 2002	Moving-base	16♂ 16♀	16>60 16<25		
Tornros et al. 2002	Moving-base	12♂ 12♀	40* (23-55)	19* (5-37)	15 100* (2000-55 000)

[1] In the Nilsson and Nabo (1996) study, there were originally 60 participants. The other 30 participants were engaged in an experiment where beside ACC, the influence of a mobile phone on driving behaviour was also investigated. The effects on driving behaviour of ACC only, were included in this analysis.

* Mean value

(..-..) Range

2.2 The dependent variables

The number and the type of measured driving behaviour variables varied considerably between studies. The meta-analysis did not allow all these variables to be included and therefore the effect of ACC on driving speed and headway have been chosen as dependent variables to be coded and further analysed. The choice of these dependent variables was based on the following grounds:

1. ACC directly and foremost supports drivers in the control of speed and headway
2. Speed and headway are considered significant driver performance indicators regarding traffic safety
3. Meta-analysis requires a sufficient amount of measurements and speed and headway turned out to be the most consistently used driving behaviour indicators in the present selection of studies

Additionally, "driver workload" was also included, since it was one of the most frequently reported variables in the included studies and considered relevant for safe driving behaviour as well.

2.3 The selection and computation of effect size

The choice of the indicator for the effect size is one of the most important choices in meta-analysis. The type of the analysed research plays an important role in the choice of this effect size measure but this choice is also influenced by the statistical data that are available in the analysed studies (McGaw andGlass, 1980).

The "unstandardized" mean difference (ES_{um}) was chosen as the effect size to be used in this analysis. In order to be able to use this effect size, the following conditions had to be fulfilled:

1. The same operationalisation of the variable of interest was used in all research findings.
2. The variable of interest was continuous.

Both of these two conditions were satisfied for the dependent variable "speed" because all studies included did measure speed on the same scale (km/h) and used the same measurement procedures. The unstandardized mean differences were calculated according the following formula:

$$ES_{um} = \overline{X}_{G1} - \overline{X}_{G2} \text{ (Lipsey and Wilson, 2001), i.e. } ES_{um} = \overline{X}_{ACC} - \overline{X}_{noACC} \quad (1)$$

It was not possible to use the unstandardized mean difference as an effect size for the variable "driver workload". Although the analysed studies in generally use the same kind of scales (i.e. NASA-TLX or RSME), the reported workload data are not precise enough to enable testing the differences and to compute effect sizes. Therefore, for the analysis of effects of ACC on driver workload, the "vote-counting" procedure was applied. In this procedure only information about the direction of findings is used: "workload lower" or "workload higher" in ACC condition.

One of the biggest problems when coding for meta-analysis is that very often, researchers do not (always) report results such as the mean, standard deviation, and sample size per condition. The consequence of not reporting basic statistical data is that effect sizes must be estimated from incomplete information. The problem of incomplete data was also encountered in the present meta-analysis. A few studies did not report some of the basic statistical data or included two- or multi-factorial designs, so that effects of ACC on the selected dependent variables have been reported by levels of some other factor (e.g. type of the road, driving style of participants, traffic density, etc.). Occasionally, researchers did not report actual data but merely indicated that results were found to be non-significant. This fact led to a choice between two (bad) options:

1. To set the effect size in this case at zero
2. To exclude these findings from meta-analysis

The first option seemed preferable, although the drawback of this conservative approach is that it generally underestimates the true effect size because, most likely, effect sizes for these results are not exactly zero. The problem of missing data has been solved in some cases by estimating additional results based on graphics (although this is not a very precise way to obtain the required information) or by consulting additional sources about the same experiment.

In the present meta-analysis, all experiments have been given equal weight for which there are several reasons:

1. Most of the studies did not report any statistics that would allow correcting obtained individual effect sizes for unreliability (e.g. measurement error).
2. All studies used the same methodological approach (i.e. all were performed in a driving simulator) and similar sample sizes that ranged from 12 to 38, which are all rather usual sample sizes for driving simulator studies. Furthermore, the study with the biggest sample size (Hoedemaeker, 1999) is at the same time the 'outlier', so any weighting based on sample size would be only in further favour of the maximal differences in mean speed and headway found in Hoedemaeker's experiment.
3. The effect sizes are grouped in negative and positive effect sizes (i.e. decreased and increased speed or headway), mirroring the grouping of less and more intervening ACC. So in this analysis, the sign and not the absolute effect size was crucial for revealing the underlying relationship between the type of ACC and its effect on speed and headway. Therefore, even if weighted, the sign of effect sizes would remain the same and the weighting would not change the established connection between the 'intervening level' of ACC and its effects on speed and headway.

3. Results

3.1 Speed

The magnitude of the effect size represents the difference in average speed between the driving-with-ACC and driving-without-ACC condition. The computed effects show both positive and negative signs. Effects with a positive sign refer to an increase in average speed when driving with ACC, as compared to driving without ACC. A negative sign refers to a decrease in average speed when driving with ACC.

The mean effect size is ES_{um}= 0.0956. Because the computed effect sizes per study represent actual differences in speed, the mean effect size of 0.0956 actually means that overall ACC increased the mean driving speed with 0.0956 km/h. From a road safety point of view, an increase in average driving speed of 0.1 km/h is considered negligible. Hence, it could be concluded that ACC has no effect on average driving speed. However, given the sensitivity of a mean to the sample size and the presence of outliers (both characteristics highly challenging for this analysis), a detailed analysis of this mean effect size was required.

Looking in detail at the distribution of the nine individual effect sizes, it becomes apparent that studies cluster in two groups: a group with negative and a group with positive effect sizes. The mean effect sizes for each of these groups are $ES_{um\ positive}$= 2.5 and $ES_{um\ negative}$= -2.3. Not surprisingly, the two means differ mainly in direction.

In all three experiments that resulted in relatively high positive effect sizes (Hoedemaeker, 1999; Nilsson and Nabo, 1996 and Brook-Carter et al., 2002) a more assisting application than just common ACC had been used. The ACC used in the first Hoedemaeker's experiment was ACC and Stop-and-go, capable of stopping in every possible situation; Brook-Carter et al. also used "stop and go ACC". The Nilsson and Nabo (1996) study compared automatic with only informative ICC. It seems that those ACCs which take over more tasks from the driver and/or support drivers in a wider range than common ACC, show an increase in the mean driving speed. The 'bare' types of speed control systems, common ACC and ICC, were accompanied by no or positive effects on mean speed.

The relationship between the speed level and accidents has been shown in several studies. The often mentioned study of Finch et al. (1994) showed that an increase in speed of 1km/h leads to a 3% increase in the number of accidents. In this sense, the average increase of the mean speed of 2.5km/h in the case of the group of more assisting types of ACC, could have significant negative consequences for traffic safety. However, one should be cautious when trying to directly "translate" this increase of 2.5km/h in the mean speed in a possible increase in the number of accidents without considering other factors. The relationship between speed and accidents is a complex one and among others dependent on the type of road and the driving speed taken as starting point (see Aarts and Van Schagen, 2005).

3.2 Headway

Regarding the ACC effect on headway, unfortunately not all studies used an equivalent indicator: five used mean time headway, one mean distance headway, one preferred headway and for the remaining two studies headway results were not obtained at all. Therefore, only the available differences in mean time headway between *driving-with-ACC* and *driving-without-ACC* are reported and no mean effect size was calculated and only differences in mean time headway between two ACC conditions are given. Because of the missing data and because of some peculiarities in calculating differences in the mean time headway between driving-with-ACC and driving-without-ACC, the obtained results should be considered only as suggestive. Regarding the sign of the difference in the mean time headway, again the same grouping of studies was found. The same studies that found an increase in mean speed, also found a decrease in the mean time headway. It was again ACC with an enhanced level of driving support that showed riskier changes in driving behaviour.

Maintaining a safe headway between their own vehicle and the vehicle ahead is a critical safety task for drivers. It is not far from common sense that driving at short following distances increases the risk of an accident because of the limited time to react to sudden changes in speeds of the vehicle ahead. What would be a safe time headway? Recommended values for safe headways slightly vary in different countries. In the USA, there is a 2-second rule (Michael, Lemming and Dwyer, 2000). In Germany, there is a rule of "half of speedometer" that could be translated to a recommended time headway of 1.8s, while in Sweden the National Road Administration recommends a 3s time headway in rural areas (Vogel, 2003).

However, although the mean time headways found in ACC conditions were smaller than in no-ACC conditions, it has to be noted that most of these ACC headways were experimentally predefined.

Table 2. Unstandardized mean differences in mean speed, difference in the mean time headway and comparison of level of driver workload between driving-with-ACC and driving-without-ACC conditions

Study		**Sample size**	**Type of Acc**	**Difference in *mean speed* between ACC and no-ACC condition ($ES_{um\ Speed}$)**	**Difference in *mean time headway* between ACC and no-ACC condition**	**Comparison of *workload* level between ACC and no-ACC condition**
Hogema, van der Horst, Janssen, 1994.		12	ICC	-3.85	-	-
Hogema andJanssen, 1996.		12	ICC	-3. 68	0.2	-
Nilsson and Nabo, 1996.	Exp_1	20	Info ICC	-1.50	0.29	Lower
Nilsson and Nabo, 1996.	Exp_2	20	Automatic ICC	0.90	-0.11	Lower
Stanton, Young, McCaulder, 1997.		12		0.00	0	Better secondary task performance
Hoedemaeker, 1999.	Exp_1	38	ACC complete stop	8.00	-1.1;-3;-1.3; -1.7[1]	Lower
Hoedemaeker, 1999.	Exp_2	30	ACC	-0.11	-	Lower
Brook-Carter, Parkes, Burns, Kersloot, 2002.		32	ACC stop and go	1.00	Used distance mean headway	Lower
Tornros, Nilsson, Ostlund, Kircher, 2002.		24	ACC	0.10	Used preferred, not mean headway	Lower
		Total: 200		average : ES_{um}= 0.0956		

[1] Hoedemaeker presented the results of the mean time headway for each of the four participant's groups (i.e. high speed – high focus, low speed- high focus, high speed- low focus, low speed – low focus) and therefore,

having no overall mean headway, we calculated the effects size for each of these groups. From three ACC headway conditions, i.e. preferred headway 1 s and 1.5 s, we chose 1.5 s headway as $\overline{X}_{ACC.}$ Therefore, the differences in the mean time headway could be considered even greater than calculated here.

3.3 Workload

Available data show that regarding ACC and workload, results across studies are in every case in the same direction, i.e. driving with ACC was associated with lower workload than driving without ACC.

The enhanced support level of the ACC group that show higher average speeds and shorter time headways, raises the question whether a difference in workload effects was reported between this and the other group of ACCs. The hypothesis could well be that sophisticated ACCs would be associated with lower levels of workload when compared to common types of ACC. Unfortunately, this hypothesis about the lower workload for the special group of ACC could not be tested because of the lack of clarity in the available data. In general, driving with ACC is experienced as less demanding.

4. Conclusions

Speed and time headway have been selected as main variables in this analysis of the ACC effects on driving behaviour because of their significance for the kind of support that ACC provide to drivers, as well as because of their relevance for traffic safety. Regarding traffic safety, the potential increase in speed and decrease in time headway are considered negative effects that are not the intended or wanted kind of changes in driving behaviour. That makes them perfect candidates for indicators of behavioural adaptation.

The results of the analysis indicate that it is not possible to provide a unanimous conclusion about the effects of ACC on speed and headway. These effects seem to be dependent on the type of ACC used. When driving with the ACC types that take over more of the driving task and offer more support to drivers in more critical situations than others (e.g. stop and go function, capabilities of complete stop in every situation), drivers seem to adapt their behaviour in those cases by increasing their speed and at the same time decreasing their time headway. Therefore, it is difficult, if not impossible to speak about the general effects of ACC because it appears that certain differences in operational characteristics of various ACCs could result in contradictory effects on driving behaviour.

The different operational characteristics that seem to be important for determining the type of effects of ACC on speed and headway could actually be “translated” into a variation on the “information-warning-control” dimension of the ACC support. ACCs that are offering support mostly on the “control” end of this dimension seem to be those who provoke more negative i.e. more behavioural adaptation changes in behaviour of drivers regarding their speed and headway. The question is what the thresholds are on this “information-warning-control” dimension for certain operational characteristics that would warrant that negative behavioural adaptation changes be as small as possible. At this moment, it is difficult to give an answer to this question and more experimental research is needed in order to come up with a fine and calibrated "information-warning-control" scale for ACCs. Once this "calibration" is clear, defined thresholds could be used as a base for standardization of ACC characteristics so that negative effects of ACC on driving behaviour would be as small as possible. In that sense, it is possible to think about a redefinition of values of ACC time headways that could be currently set by the drivers (e.g. no headways smaller than 2s).

Besides the "calibration" of ACC that would be based on the behavioural adaptation potential of certain types and characteristics of ACC, the solution for decreasing the ACC behavioural adaptation potential could be found in the integration of ACC with some other ADA systems. So, with regard to the finding that more enhanced ACCs lead to an increased driving speed, it is a plausible assumption that the integration of ACC with some form of Intelligent Speed Adaptation system could, for example, prevent this ACC effect from occurring.

Finally some limitations of this study should be mentioned. The results of the meta-analysis as performed have to be taken as suggestive because they are based on statistical data which quality differed across the analysed studies and because only studies that used driving simulator methodology were included. Therefore, it is necessary to further experimentally test this "moderating variable" status that the "information-warning-control" dimension seems to have for ACC's behavioural adaptation potential:

1. It should be tested whether the relationship between the "information-warning-control" dimension and the behavioural adaptation potential of ACC is still valid for other indicators of driving behaviour than speed and headway. For example, increased deviation in lane position, increased time to collision, more driving on the left lane or increased frequency and riskier overtaking, could also be useful indicators of behavioural adaptation.
2. It should be tested whether the relationship between the "information-warning-control" dimension and behavioural adaptation potential is present for other ADA systems than ACC.

If these experiments would suggest a more 'universal' significance of the "information-warning-control" dimension for behavioural adaptation potential of ADA systems, than this could be even used as the basis for a "yardstick" or guideline for designing the future ADA system with minimal behavioural adaptation potential.

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