The influence of Cruise Control and Adaptive Cruise Control on driving behaviour – A driving simulator study

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Abstract

Although Cruise Control (CC) is available for most cars, no studies have been found which examine how this automation system influences driving behaviour. However, a relatively large number of studies have examined Adaptive Cruise Control (ACC) which compared to CC includes also a distance control. Besides positive effects with regard to a better compliance to speed limits, there are also indications of smaller distances to lead vehicles and slower responses in situations that require immediate braking. Similar effects can be expected for CC as this system takes over longitudinal control as well. To test this hypothesis, a simulator study was conducted at the German Aerospace Center (DLR). Twenty-two participants drove different routes (highway and motorway) under three different conditions (assisted by ACC, CC and manual driving without any system). Different driving scenarios were examined including a secondary task condition. On the one hand, both systems lead to lower maximum velocities and less speed limit violations. There was no indication that drivers shift more of their attention towards secondary tasks when driving with CC or ACC. However, there were delayed driver reactions in critical situations, e.g., in a narrow curve or a fog bank. These results give rise to some caution regarding the safety effects of these systems, especially if in the future their range of functionality (e.g., ACC Stop-and-Go) is further increased.

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1. Introduction

During the last years an increasing number of Advanced Driver Assistance Systems (ADAS) has been developed to support the driver. A very prominent example is Adaptive Cruise Control (ACC) which is a longitudinal support system that can not only maintain a chosen velocity (like Cruise Control, CC) but also keep a safe distance to a lead vehicle. ACC is commercially available since 1998. Using this system on a highway the driver only has to steer while the system manages vehicle speed and distance. This system was introduced in order to support the driver by making it easier to comply with speed limits and to keep safe distances especially on long trips on the highways. However, from a theoretical point of view, this support may not only be beneficial but also lead to new problems while driving. Young and Stanton (2002) describe some of these in their malleable attentional resources theory. They suggest that as the mental workload while driving decreases, because automation systems take over some part of the driving task, the attentional resources available to the driver are also reduced. Thus, there is less capacity to observe relevant cues in the environment which might be detrimental to driving.

Similar concern arises from the compensatory control model of Hockey (1997) but from somewhat different reasons. According to this model, humans monitor their level of performance in any given task including car driving using two different loops. The first loop is concerned with keeping one's performance at a level conforming to one's goals. The second loop monitors the workload involved in achieving this level of performance. If the workload exceeds a certain level, goals will be adapted, e.g., accepting a lower level of performance. However, this second loop reacts also, if workload undergoes a certain minimum level. Thus, if drivers' workload decreases too much because ACC takes over the speed and distance control, drivers may try to increase their workload again. To this aim they could engage in other, secondary tasks. But they could also achieve this by making driving more difficult which could be done by driving at higher speeds and selecting small distances towards preceding cars.

Thus, both theories predict negative effects of an automation system which reduces the workload of the driver. In fact, both positive and negative ACC effects have been shown in several stud-
ies. For example, Abendroth (2001) found in a field study that when driving on highways with ACC drivers chose a mean speed of 119 km/h as compared to 129 km/h when driving without the system. Additionally, speed limits were less frequently violated by more than 20 km/h when using ACC. Similar effects were found in field operational tests (Sayer et al., 2005; NHTSA, 2005) and driving simulator studies (e.g., Törnros et al., 2002).

Besides these positive effects, several studies have also found contradictory or negative effects of ACC. For example, Hoedemaeker et al. (1998) reported a driving simulator study with 38 drivers who drove on a motorway with and without ACC. All of them chose smaller headways with ACC than in manual driving and all drivers went faster with ACC (Hoedemaeker and Brookhuis, 1998). In the study of Törnros et al. (2002), subjects drove longer in the left lane with ACC and the minimum time-to-collision with ACC was reduced. Buld and Krüger (2002) found that when a lead car went through a narrow curve much too fast drivers following that car with ACC used the same inadequate speed. Furthermore, drivers' lane keeping performance deteriorated with ACC. Stanton and Young (Stanton et al., 1997; Stanton and Young, 2000, 2005; Young and Stanton, 2002a,b, 2004) found in a series of simulator studies a reduction of workload when driving with ACC which at first glance might be described as a positive effect. However, situation awareness when driving with ACC was also reduced. Situation awareness is a concept widely used in human factors research. It was introduced by Endsley who defined it as “…the perception of the elements in the environment within a span of time and space, the comprehension of their meaning and the projection of their status in the near future” (Endsley, 1995, p. 36). As drivers rely on the ACC system they do not monitor the surrounding as carefully and might thus lose some of their situation awareness. Additionally, the reduced situation awareness could also be due to reduced attentional resources as Young and Stanton (2002b) describe in their theory of malleable attentional resources (see above).

Rudin-Brown and Parker (2004) found that while driving with ACC drivers performed better in a secondary task, but the response time to break increased when a safety hazard was introduced. Cho et al. (2006) also found that drivers tended to shift their attention away from driving when they used ACC. Finally, when ACC fails and does not adapt speed correctly, drivers have significantly longer reactions times than in similar situations when driving without ACC (Young and Stanton, 2007).

In summary, although ACC was shown in field tests to lead to increased distances towards leading cars and to following speed limits better, there is also strong evidence that drivers have difficulties to keep an adequate level of situation awareness which leads to prolonged response times in some situations. They may also shift their attention away from driving and engage in secondary tasks. Furthermore, their attentional resources may be diminished by the reduced workload caused by ACC.

It is interesting to note that these kinds of studies are missing for Cruise Control (CC). CC is already on the market since the 1960s. When there is hardly any other traffic and driving at a constant speed is possible, the support of CC is quite similar to that of ACC. In this situation, one would expect similar effects of CC, namely that the drivers tend to shift their attention away from driving, that they might focus on secondary tasks, and that they take more time to react in situations that cannot be controlled by CC. However, we are not aware of any research dealing with this issue.

In order to close this gap, a simulator experiment with CC was conducted. In this study, ACC was also included in order to be able to compare the effects of CC and ACC. Both systems were compared to manual driving. Highway driving and driving on a motorway (a German Autobahn) was used in this study, as this is the typical situation where ACC and CC is engaged. In order to provide drivers the opportunity to use CC, there was hardly any traffic in some situations. As it should also be examined whether drivers really tend to direct their attention away from driving, scenarios were implemented which required the drivers to manually adapt speed (e.g., because the speed limit changed or because fog came up). Additionally, driving scenarios were used where the drivers were instructed to engage in secondary tasks.

2. Materials and methods

The study was done in the driving simulator of the German Aerospace Center (DLR, DeutschesZentrum für Luft- und Raumfahrt e.V.). The simulator is a motion based system that provides a realistic driving feeling due to the efficient motion system, a high quality projection system with visualisation and the integration of a complete vehicle. Environment and surrounding traffic are visualised by the projection system and a frontal and lateral field of view (270° × 40°) with a high resolution of 9200 × 1280 pixel to allow a detailed image. Driving data are transferred to the simulation computer via CAN-bus. Vehicle and environmental sound are rendered by integrated loudspeakers.

The experiment was conducted as a within-subjects design, where each driver drove once with CC, with ACC and manually without any system. The order of the conditions was balanced over the subjects. Twenty-two test subjects participated in the study. Eleven of them were experienced CC drivers which were included to examine whether long-term use of CC changed their driving behaviour in the simulator. However, as this was not the case, the analyses were conducted for the whole group. The sample consisted of 10 women and 12 men with a mean age of 38 years (sd = 10.5). Nine participants drove less than 12,000 km per year, the others drove more than that.

As CC is used mainly on motorways and highways, the test route was constructed to include these road types (see Table 1 for an overview). It was divided into three parts and took an overall of about 3 h to complete. The first and third parts were a motorway route (German Autobahn) consisting of different segments with varying speed limits (100 km/h, 120 km/h, no speed limit) of different length. Overall, the length of each of the two parts was about 90 km. One of the segments was a two-lane road. The others consisted of three lanes. Furthermore, the traffic density was varied between a moderate and low level. A high traffic density level was not included in order to ensure that both systems could be used over longer time periods. A critical situation was introduced at the end of the first motorway segment where a traffic jam occurred. The last motorway part was comparable to the first part with respect to speed limits, duration, number of lanes and traffic density. There was no critical event in this part, but instead it included two secondary task sections of about 10 min duration, one with low and one with medium traffic density. These were included to examine if the drivers would engage more in secondary tasks when they were

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supported by either CC or ACC. To this aim drivers were instructed to do as many secondary tasks as safely possible. However, driving was to remain their first priority and they were requested to still drive safely. As a secondary task, the Surrogate Reference Task (Mates and Hallen, 2009) was used which is a visual search task where subjects have to identify a circle with a greater radius within a large amount of smaller circles. The task was presented on a touch-screen on the center console. The subjects answered by touching the display. Because this secondary task took a substantial part of the driving time, a critical event was not included as this would have been too much within the relatively short driving time.

The second part of the test route was a highway route of about 80 km with oncoming traffic. It had also different sections concerning traffic (no lead vehicle, following a slow lead vehicle, being able to overtake) and road characteristics (narrow curves with speed limits of 70 km/h and 80 km/h). One critical scenario was also generated. At the end of the highway a fogbank arose and the subjects had to adjust their speed.

The system was activated and deactivated using a key at the left side of the steering wheel. Subjects could change their speed with two keys at the right side of the wheel. The system could also be deactivated by braking or accelerating. Following a deactivation, drivers could resume their last speed by use of a resume key. The controls were identical for both systems. Usually, an ACC system also provides the means to change the desired distance. In order to keep the two systems (ACC and CC) comparable, this function was not implemented in the study. Instead, a fixed headway of 1.5 s was selected.

After the test subjects arrived, they filled in a questionnaire and read a general instruction as well as the instruction manual of the systems. They were instructed that the study was concerned with examining driving behaviour with different ADAS like Cruise Control and Adaptive Cruise Control. Then a test run was performed to check data recording and to familiarise the test subjects with the driving simulator. Next, subjects were trained giving them the possibility to explore the systems and become accustomed to them. Their understanding of the system was checked by giving them different tasks like “accelerate manually to 120 km/h”. If the subjects successfully managed all tasks the investigator stopped the training and started the presentation and test trial of the secondary task, which was also conducted until the subjects reported that they were familiar with the task. This was confirmed by the investigator who ensured that the subjects reacted in the correct way.

Next, the subjects were given the instructions for the first test drive. They were instructed to use the system as often as possible during the trip. This was additionally supported by a verbal instruction given repeatedly during driving. Otherwise, the subjects were instructed to drive as usual and in compliance to the legal restrictions. The two secondary task trials in the third part of the route were started and stopped using a verbal instruction. After each part of the route (motorway 1, highway, motorway 2) subjects had to evaluate their own driving performance using a short questionnaire followed by a short break of about ten minutes. At the end of the experiment, acceptance and usability of CC and ACC were examined. Finally, subjects were given their financial compensation for participation.

Driving data were examined including velocity, headway, time to collision, steering wheel angle and lateral position. Furthermore, the response times after the occurrence of the critical events (traffic jam, fog bank) were recorded as well as the response times to changes in speed limits. Regarding the secondary task, the number of completed tasks as well as performance errors was registered. Due to technical errors, there was no data from one of the subjects. Thus, only the data of 21 subjects can be reported.

3. Results

First of all, it was checked if the drivers really used the systems. On average, both systems were used in about 90% of the complete driving time. For CC, the percentages ranged from 87% on rural roads with fog to 99% on rural roads during car following sections. For ACC, the percentages ranged from 95% on rural roads with fog to 99% on the motorways with secondary tasks. Thus, ACC was used somewhat more often which can be explained by the extended functionality including the ability to keep distances. Systems were frequently switched off in the traffic jam scenario (CC 26%, ACC 31% system use) and the narrow curves on the highway (CC 28%, ACC 44% system use) which also makes sense as the systems are not able to handle these situations. Thus, the results really represent changes in driving behaviour when driving with the two different systems as compared to manual driving.

For each of the 13 scenarios described in Table 1 a MANOVA was calculated using system (ACC, CC, manual driving) as an independent variable. If a significant result was found, univariate tests were used for the single parameters and in case of significance post hoc tests were calculated to find out which condition differed from the others (ACC vs. CC, ACC vs. manual driving and CC vs. manual driving).

In the first part, possible positive effects of CC and ACC were examined. For this purpose, maximum speed and the time spent above the different speed limits were analysed. Regarding maximum speed significant effects were found on the first motorway with a speed limit of 120 km/h ($F_{(2,40)} = 6.5, p = 0.004$). On the highway, a significant effect was found in the scenario with 100 km/h ($F_{(2,40)} = 13.2, p < 0.001$), in the scenario with overtaking ($F_{(2,40)} = 3.9, p = 0.027$) and the car following scenario ($F_{(2,40)} = 5.3, p = 0.009$). The effect is comparable in these situations as is shown in Fig. 1. Maximum speed is lower with both CC and ACC as compared to manual driving. The magnitude of the reduction is between 5 and 10 km/h.

A similar effect is found when analysing the percentage of time drivers spent above the mandatory speed limit. Significant differences were found for the two parts of the two motorways with speed limits, but not on the highway (first motorway 120 km/h: $F_{(2,40)} = 4.1, p = 0.025$, and 100 km/h: $F_{(2,40)} = 7.1, p = 0.002$; second motorway 120 km/h: $F_{(2,40)} = 6.9, p = 0.003$, and 100 km/h: $F_{(2,40)} = 9.9, p < 0.001$). As can be seen in Fig. 2, the time spent above the speed limit was substantially reduced when driving with either CC or ACC. The difference amounts to 20–30% of the driving time.

The second part of the analyses addressed possible negative effects of the systems. To this aim we examined response times to speed limits and to the fog occurring on the highway. Significant effects were found at the highway in the curves and when fog occurred (curves with 70 km/h: $F_{(2,40)} = 7.1, p = 0.002$; curves with 80 km/h: $F_{(2,40)} = 6.1, p = 0.003$; fog: $F_{(2,40)} = 3.3, p = 0.046$). In
all these scenarios, an adaptation of speed is more time-critical than on the motorway. The effects are shown in Fig. 3. Negative values indicate that drivers reduced their speed well in advance of the signs, while positive values correspond to late reactions. Again, the effect is similar for both systems showing a later response with CC and ACC as compared to manual driving. Drivers started to adapt their speed about 5 s later when driving with ACC or CC active as compared to manual driving.

In the fog scenario, a significant main effect of the systems on the average speed ($F_{(2, 40)} = 6.2, p = 0.004$) was found. Whereas drivers reduced their speed to 59.2 km/h without systems and to 60.0 km/h with CC, they kept a faster speed of 65.7 km/h with ACC. Obviously drivers seemed to rely on ACC to adapt speed if any other vehicle appeared.

Secondary task performance was examined to find out whether drivers concentrated more on these when they were supported by one of the two systems. A repeated measurement two-way ANOVA was calculated with system (ACC, CC, manual driving) as the first factor and condition (no secondary task, secondary task during low vs. medium traffic density) as the second factor using the number of completed tasks and of errors as the dependent variables.

There was no effect for the number of errors (all $p > 0.05$). For the number of tasks there was no significant effect of the system ($F_{(2, 40)} = 1.4, p = 0.249$), no significant interaction ($F_{(4, 80)} = 2.0, p = 0.153$), but a significant effect of traffic density ($F_{(2, 40)} = 31.3, p < 0.000$). Regardless of the system, the number of tasks completed was larger in medium traffic density than in low traffic density (see Fig. 4). As medium traffic density was always second, this might be a learning effect showing that drivers were better able to perform the secondary tasks in the second phase than in the first phase. Thus, it could not be shown that drivers engage more in secondary tasks when using either CC or ACC.

Finally, in the subjective ratings after each condition there was a significant main effect of the systems for both workload ($F_{(2, 40)} = 4.0, p = 0.027$) and the perceived safety during the trip ($F_{(2, 40)} = 4.8, p = 0.013$). As Fig. 5 shows, both CC and ACC reduced the workload during the trip and drivers felt safer with either of the systems.

4. Discussion

Although CC is a widespread driver assistance system, there is hardly any research on the effects of this system on driving behaviour. In Germany, about 50% of the larger cars are equipped with CC. ACC is less frequently used but was already the object of several studies beginning in the late 90s when the system was developed. As described above, there are several studies which have shown that when driving with ACC there was a better compliance with speed limits and driving was slower at large (Abendroth, 2001; Sayer et al., 2005; NHTSA, 2005; Törnros et al., 2002). This was confirmed in our study and could also be demonstrated for driving with CC. On the highway and the motorway, drivers had an about 5 to 10 km/h lower maximum speed with these systems as compared to manual driving. Additionally, the percentage of time spent above the speed limit was substantially reduced by CC and ACC. It seems that the conscious selection of speed by having to set it at discrete time-points leads to a better compliance with regulations than when controlling speed continuously by means of the accelerator pedal.

However, there was also some indication of negative effects for both systems. When drivers had to reduce their speed manually at curves and when they entered fog, this was done about 5 s later than under conditions of manual driving. This is similar to results...
of ACC studies which found reduced minimum time-to-collisions (Törnros et al., 2002), the failure to adapt speed in curves when following a faster car (Buld and Krüger, 2002) and the prolonged response time for safety hazards (Rudin-Brown and Parker, 2004). It seems that it takes some time for drivers to notice that a situation has arisen that the system is not able to handle and to intervene and override the system. The current study shows that this is not only the case for ACC but also for CC as well.

It is hard to say how this effect comes about. In accordance with the studies of Stanton and Young (Stanton et al., 1997; Stanton and Young, 2000, 2005; Young and Stanton, 2002a,b, 2004) drivers reported a reduced workload when driving with ACC and with CC. According to the malleable attentional resources theory, this would result in reduced attentional resources which could be the reason why drivers took longer time to react to traffic signs and fog. However, there was no effect of either of the two systems on the number of secondary tasks conducted. Young and Stanton (2002b) had inferred a lower mental workload from an increased number of correct responses and found that only when ACC was combined with an active steering driver assistance system. Thus, from the objective data about secondary task involvement, drivers do not show a reduced workload with either ACC or CC. As we did not record gaze behaviour, it is not possible to directly test how much gaze time was required for the secondary tasks. However, from our point of view, the constant level of secondary task performance with ACC and CC and the subjectively reduced workload is not explained well by the malleable attentional resources theory. Additionally, as drivers do not engage more in secondary tasks when their subjective workload is reduced, the compensatory control model of Hockey (1997) gets into difficulties to explain the effects observed in our study. It seems that the reduction in workload caused by ACC and CC does not encourage drivers to increase their own workload either by driving faster or by engaging in other activities.

Thus, from our point of view it could be possible that the observed effects of ACC and CC are simply due to the fact that the chain of action of the drivers changes. Drivers do not have to continuously watch and adjust the speed of the car since ACC or CC takes over the task of adjusting or maintaining speed. Drivers still have to watch the surrounding for traffic signs or road conditions that require the driver to adjust speed. However, it takes longer to intervene than when they drive manually. This may either be due to a reduced attention for signs or cues which require an adaptation of speed because this is taken over by ACC and CC. Or it may be due because of having to shift from automatic to manual control. Probably, both aspects are involved. The present study is not able to distinguish between these two explanations, as attention and situation awareness were not separated from action planning and execution. Future research should try to elaborate on this point.

There was one additional, new problem with ACC. Drivers went faster in the fog when they were supported by ACC. It seems that they rely on this system to detect other cars or obstacles better than they themselves could. It would be very interesting to see if this effect can also be found in real traffic.

If these effects found in the driving simulator can be transferred to real driving, there are implications for the design and development of such systems. On the one hand, as drivers have difficulties to notice that they should adapt their speed, it could be advisable to expand these systems. Thus, they would be required to detect speed limits and to change speed accordingly, to detect adverse weather conditions etc. However, on the other hand this might lead to a further disengagement of the driver from the driving task. For this reason, it would be more difficult for drivers to intervene if this is necessary. Perfect systems would be required which do not need any intervention by drivers anymore. From this point of view, as drivers still have to intervene and to be able to understand the traffic situation, these driver assistance systems which take over only parts of the driving task may improve the well-being of the driver, but not traffic safety. Disengaging the driver from the driving task may not be the best way to prevent driver errors, at least as long as the driver assistance systems are not able to perform better than the average driver. From a traffic safety point of view it would make more sense to develop warning and intervention systems which support the driver to detect dangers and which may correct errors of the driver.

But, there are still some aspects to be mentioned. Our experiment was conducted in a motion based driving simulator. This included the simulation of the kinaesthetic cues of acceleration and deceleration so that the drivers could well perceive the systems working. From this point the driving situation was highly realistic and comparable to real driving. However, the drivers knew of course that they were in a driving simulator and that nothing could happen to them even if there was a virtual accident. So it might be that they did not take the scenarios as seriously as they would do in real driving. However, there is some indication that this was not the case. For example, the speeds chosen were comparable to real driving and drivers complied well with the traffic rules. Thus, it seems reasonable to assume that the results are comparable to real driving with regard to this point.

What is more critical is the relatively short duration of the experiment. While it was made sure that drivers were well able to handle both systems and were familiarised with them, they were also instructed to use them as often as possible. Moreover, they did not have time to really get used to them over the course of multiple trips, over days and weeks. It may well be that system use and the manner when and how it is used changes with long-term experience. This may especially be true for effects like the loss of situation awareness and the shifting of attention away from the driving tasks. If drivers experience in many situations that ACC and CC work well and are able to cope with the different situations, they will rely more on these systems and feel less obliged to monitor them. It might be that in this case even stronger negative effects of CC or ACC would be found. To that aim, it would be highly important to conduct studies with really experienced users of CC and ACC examining their natural driving behaviour.

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