ADAPTATION EVALUATION
– An Adaptive Cruise Control (ACC) System Used by Drivers with Lower Limb Disabilities –

Björn PETERS, M.Sc.

Graduate Student, Graduate School of Human Machine Interaction
The Linköping Technical Institute
Swedish National Road and Transport Research Institute - VTI, Linköping, Sweden

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Twenty subjects with lower limb disabilities participated in a simulator study. The purpose of the study was to investigate how an Adaptive Cruise Control (ACC) system together with two different hand controls for accelerator and brake influenced workload, comfort and driving behaviour and to further develop a method to evaluate vehicle adaptations for drivers with disabilities. The installed ACC system could maintain a constant speed selected and set by the driver and it also adapted speed in order to keep a safe distance to a leading vehicle. Furthermore, it included a stop-and-go function. Two common types of hand controls for accelerator and brake were used. The hand controls were different both with respect to function, single or dual levers, and position, on the steering column or between the front seats. The subjects were all experienced drivers of adapted cars equipped with hand controls. All subjects drove 100km at two occasions, with and without the ACC system available but with the same hand control. Subjective workload was found to be significantly lower and performance better for the ACC condition. The difference in speed variation between manual and ACC supported driving increased with the distance driven which seems to support the previous finding. The subjects thought they could control both speed and distance to leading vehicles better while the ACC was available. ACC driving did not influence reaction time, speed level, lateral position or variation in lateral position. Headway during car following situations was shorter for the ACC condition compared to manual driving. The ACC was well received, trusted and wanted. It was concluded that the ACC system substantially decreased workload, increased comfort and did not influence safety negatively. The only difference found between the two types of hand controls was that drivers using the dual lever system had less variation in lateral position. The applied evaluation method proved to be useful but needs to be further developed.

Key Words: Disabled drivers, Adaptation evaluation, Adaptive Cruise Control, Hand control, Driving simulator

1. INTRODUCTION

Mobility impairments are by far the most common type of impairment[1,2]. Many mobility-impaired people can achieve mobility and independence with access to a car they can drive on their own. Driving can also contribute to improvement of quality of life and health[3,4]. However, many people with mobility impairments cannot use a conventional car unless it is adapted. The objective of car adaptations is to fully compensate for the driver's disabilities. Routines and regulations for adapting passenger cars vary a lot between countries and there are no standardized requirements even within the European Community (EC)[4]. Furthermore, today there does not exist any adaptation evaluation aimed at investigating whether the adaptation objectives have been met. In case an evaluation is performed it is often done ad hoc and is neither comprehensive nor consistent and finally, it is usually not documented. The long-term goal, of which the current study was a part, is to develop a useful and user-centered evaluation method for adapted cars, which include aspects like function, safety, comfort and trust[5]. The current study focuses on the first three aspects and the users' opinion.

Driving is a complex and dynamic task, which can be modelled in many ways. An adaptation evaluation should be concerned with the various demands the driving task imposes on the driver. The driving task can be described as tasks on three different levels: strategical, tactical and operational[6], and the driver's behaviour as three corresponding levels (knowledge, rule and skill based)[7]. An adaptation evaluation for experienced drivers with lower limb impairments should, first of all, focus on the tactical and operational demand levels together with rule and skill based behaviour. This guided the design of the present evaluation.

An adaptation should provide the driver with the possibility to safely and efficiently control the vehicle. Safety is a prerequisite for independent mobility for the targeted group[8]. Only active safety, i.e., safe driving behaviour, was considered in this study. Passive safety was left out. Comparative methods were used for the evaluation, as there does not exist any well-defined and useful criteria for safe driving behaviour. The same driving behaviour requirements apply for drivers of adapted cars as for any other driver on the road[9]. Thus, comparisons should be made relative to able-bodied drivers of standard production cars[10]. Furthermore, a comparative method can be used to evaluate different adaptation solutions, as performed in this study.

Drivers of adapted cars do not seem to be involved in more accidents than other drivers. On the contrary, it seems like they are less involved[11,12,13]. However, underreporting due to, for example, the risk that drivers who feel unsafe give up driving can possibly be a problem. In that case, safety is maintained at the cost of reduced mobility. It seems likely that drivers of adapted cars drive more carefully and are well aware of their limitations and their dependence on the car. However, this cannot be taken as an excuse for accepting lower driving performance requirements compared to other drivers[5]. If the requirements are not met, this should be interpreted, as the adaptation was not sufficient. A suitable adaptation should make optimal use of the available resources of the driver in order to minimize the physical and mental load on the driver[14].

The driving task designed for an adaptation evaluation has to be composed to include relevant, critical but still realistic subtasks. A distinction can be made between driving performance and driving behaviour[15]. Driving performance is the upper limit of what a driver can do while driving behaviour reflects what the driver actually does. Both performance and behaviour are of interest for an adaptation evaluation. A break reaction task can be used to measure performance but reaction times will depend very much on the driver's expectations[16] and also on the driving task context and complexity. As the driving task complexity increases the demands on the driver will rise and finally resource allocation becomes critical. This may prolong reaction times[17]. When demands are low, driving can be highly automated and observed reaction times can come closer to measure performance under the assumption that the driver is alert. Lateral and longitudinal control of the car is also critical to assess in an adaptation evaluation.

Hand controls systems for braking and accelerating can be implemented in many different ways. Two important aspects of hand controls are: position and whether the controls are combined or separate. A system where the controls are placed near the steering wheel so that both hands can be used for steering could facilitate the steering control but also interfere with it. A system where the controls are combined could facilitate the speed/brake control (no grip shift) but could also prolong brake reaction times (motion time). Finding the optimal solution with respect to both function and position can be difficult.

Drivers with lower limb impairments, which are so severe that the driver can only use the upper limbs in order to drive, often experience a high load on the upper limbs[18]. Both steering and speed maintenance require continuous control with the risk of static and uncomfortable postures that could have to be maintained over long periods. The possibilities to off-load their upper limbs are often limited and thus, strain and discomfort can become a serious problem. Thus, drivers of adapted cars often avoid long distance driving and restrict their mobility[19]. In summary, it seems like drivers of adapted cars drive just as safely as others but at a higher cost in workload and limited mobility. One way of reducing the load on the driver could be to install a Cruise Control (CC). A CC is a support system, which keeps a constant speed selected by the driver. One disadvantage of a conventional CC is that it only holds a constant speed independent of the traffic environment, which limits the usability. This problem is solved with an Adaptive Cruise Controller (ACC). An ACC can adjust speed so that slower preceding vehicles can be followed at a “safe” distance. The function is realized with a distance-measuring device at the front of the car. The ACC maintains a speed dependent distance to a leading vehicle by controlling both accelerator and brake. The system tested in this study had also a stop-and-go function implemented. An ACC should be able to reduce the load on the driver and thus enhance mobility. Apart from being a comfort system ACC driving can have both positive, reduced short headways[20] and negative effects, over-reliance[21].

The main purposes of this study were to investigate the influence ACC driving can have on comfort, behaviour, and workload for drivers who depend on hand operated controls and to further develop a method to evaluate vehicle adaptations for drivers disabilities. Two types of hand control systems for accelerator and brake, identified as single and dual lever system, were installed and used in this study.

2. METHOD

The experiment was performed as a two-by-two mixed factorial design. Within-subject design was used for the ACC condition and between-subject design with respect to hand control system was used (Table 1). The order of ACC condition was counterbalanced.

Table 1 Experimental design

	Single lever system	Dual lever system
With ACC	10 subjects	10 subjects
Without ACC	10 subjects	10 subjects

2.1 Subjects

Twenty subjects, seventeen men and three women, participated in the study. Their mean age was 39.8 years with a range of 19 to 60 years. All subjects had lower limb disorders, which made it impossible for them to drive conventional cars. Seventeen were paraplegics with complete paralysis in their lower limbs caused by a spinal cord lesion at the mid-trunk level. Two subjects were double leg amputees and one had spina bifida. All subjects had full strength and mobility in their upper limbs. All subjects were licensed drivers with a driving experience of adapted cars ranging from 2 to 17 years with a mean of 9.7 years. The inclusion criteria for subjects were that he or she had at least 40,000km experience of driving adapted cars. The youngest subject, 19 years, had driven 60,000km over a two-year period. The average annual driven distance was 22,200km. The subjects drove with the type of hand control with which they were most experienced.

2.2 Apparatus

A dynamic, high-fidelity driving simulator was used in this study[22,23]. The simulator consisted of six subsystems. The vehicle was modelled in the computer system and the moving base system simulated accelerations in three directions through roll, pitch and linear lateral motions. The visual system presented the external scenario in the form of computer-generated graphics on a 120° wide screen, 2.5 meters in front of the driver. The sound system generated noise and infrasounds that resembles the internal environment in a modern passenger car. The vibration system simulated the sensations the driver experiences from the contact between the road and the vehicle. A temperature system controlled the air temperature in the driver's cab. A number of validation studies have successfully been performed in this simulator[24]. These studies showed that the moving base system was important for the experienced reality and external validity (see Figure 1).

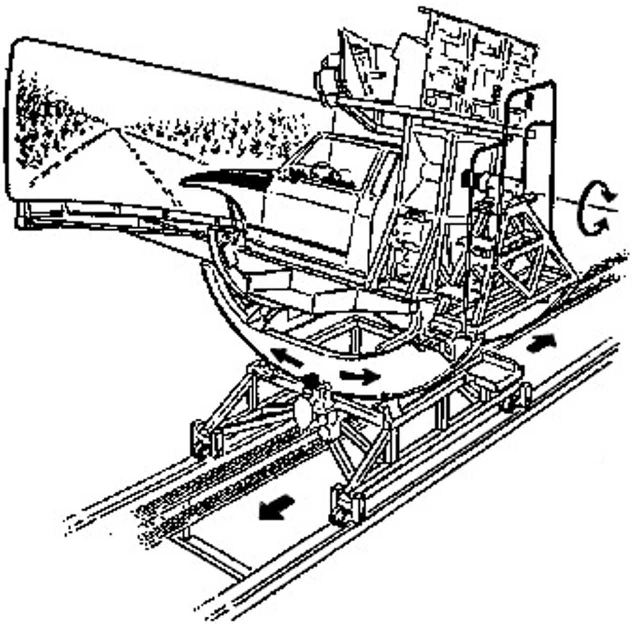


Fig. 1 The motion system of the driving simulator

The ACC used in the study could be described as an extended conventional CC. It controlled speed according to a target speed decided and set by the driver, but it could also adjust speed in order to keep a safe distance to a leading vehicle. The ACC controlled both the accelerator and the brakes. The driver could manually adjust the target speed up and down in increments of 10km/h. The ACC system was disengaged either by braking or manually turning it off. If the driver accelerated manually the ACC control would be overridden but the ACC resumed control automatically when the accelerator was released. When a leading car stopped at, for example, a traffic light during ACC driving, the ACC would automatically stop the subject's car and then start as the vehicle in front started to move – a stop-and-go function.

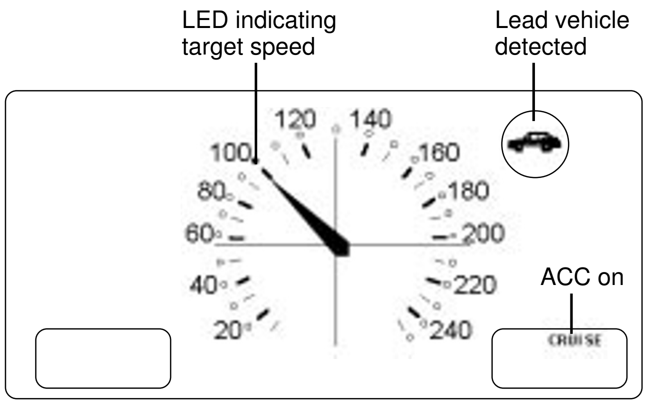


Fig. 2 ACC feedback presentation on the dashboard

ACC feedback was partly integrated in the existing instruments on the dashboard. For instance, the speedometer had a circle of amber LEDs, which were lit to display currently selected target speed. ACC status information was also provided (on/off, leading vehicle detected) (Figure 2). All ACC controls were placed on the direction indicator stalk to the left of the steering column (Figure 3).

The car body used in the simulator was an ordinary Saab 9000 with an automatic gearbox. The car body of the simulator was 2 meters above floor level. To make it

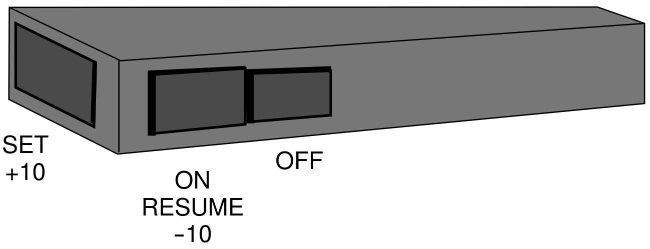
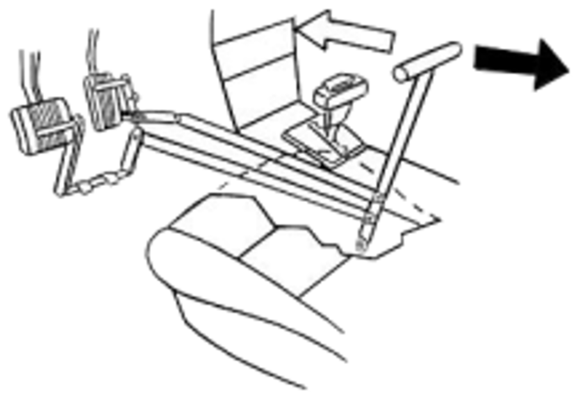


Fig. 3 ACC controls on the direction indicator stalk

accessible a wheelchair lift was used. If needed, subjects were supported when transferring from the wheelchair to the driver's seat. Two types of hand controlled accelerator and brakes were used (see Figure 4). The two systems were different both with respect to position and function. With the single lever system the driver braked by pushing and accelerated by pulling the lever (See Figure 4a). The other system had separate levers for braking and accelerating (see Figure 4b).



(a)

(b)

Fig. 4 The two hand controls used in the study: (a) single lever and (b) dual lever system. White arrows indicate braking, and black arrows acceleration. (from Betjeningshjelpmidler i bil ©with permission of RTF, OSLO)

2.3 Driving task

The subjects drove on a two-lane, 9m wide and 100km long asphalt road under high friction conditions. Driving was done under daylight conditions with a sight distance of approximately 500 meters. The route included also crossroads with traffic lights. The signed speed limit was in general 90km/h but 70km/h at traffic lights. Drivers were instructed to drive, as they would normally do under the same conditions in their own car. The same route was used for all subjects and under both conditions, with and without ACC. The subjects were told that they could turn on and off the ACC system according to their preferences in the ACC condition. Different traffic situations appeared in a randomised, but equal to all subjects, sequence during the driving session. There was oncoming traffic with varying density. Six crossroads with traffic lights where the drivers had to stop appeared along the route. Red squares appearing four times at the left side of the road were used to simulate critical traffic events to which the drivers were instructed to react by pushing the brake control. Four similar but yellow squares were also displayed along the route. The drivers were told not to react to these. The squares were 4×4 cm in size and at a distance of 2.5m from the driver's eyes, representing an approximate sight angle of 1°. The described task was used to measure the drivers' choice reaction time. Sixteen car-following situations, where the subjects caught up with slower moving vehicles, were included. As the subjects approached the leading vehicles, oncoming traffic flow was increased to prevent the subjects from overtaking directly. Catching up was randomly followed by five different types of car-following situations: four lead vehicles braked and then drove off, four drove with varying speed, four drove aside to the right shoulder, and another two cars just drove off after catching up. The fifth situation appeared just before traffic lights. At two occasions the lead cars would stop at the traffic lights, which gave the subjects a chance to use the stop-and-go function during ACC driving conditions.

2.4 Measures

A number of dependent variables like speed, lateral position on the road, time headway, and reaction time were used to analyse performance and behaviour. Other measures like subjective workload and questionnaire responses were used to investigate workload and subjective opinions. The driving simulator's main computer controlled the simulator system at a frequency of 50Hz while data were recorded at a frequency of 2Hz. Means were calculated for individual subjects and standard deviation (S.D.) was used as a measure of variation.

The lateral position on the road was measured in relation to a zero position, which was defined as the position where the centre line of the road coincides with the centre line through the driver's body or rather the centre of the steering wheel. Brake reaction time was calculated as the time elapsed from the appearance of a visual stimulus, red square, until the brake lever was depressed with a force of 0.2N. The resolution was 20msec. If there was no response from the driver after five seconds it was regarded as a miss and the stimulus disappeared. Time headway was calculated as the distance between the front of subject's car and the rear of a leading vehicle divided by the speed of the subject's car. ACC status was also monitored and recorded. Subjective workload was measured with the NASA-RTLX (Raw Task Load Index) rating scale[25,26]. The subjects had to rate the six workload factors: mental demand, physical demand, time pressure, performance, effort and frustration level on a continuous scale ranging from very low to very high (0 – 100). The raw scale version RTLX without pair wise comparison of the six factors was used. Directly after the test all subjects filled in the NASA-RTLX scales for the complete task and the specific car following situations and car following at traffic lights. Questionnaires were used to collect the subject's opinion of driving simulator realism, simulator sickness, speed and distance control, and ACC usage.

3. RESULTS

3.1 Driving behaviour

Group means were calculated and two-way ANOVAs (Analysis of variance)[27], with repeated measure on the second factor, were used to evaluate the results and the level of significance was set to $p < 0.05$. General driving behaviour was analysed in terms of mean speed and lateral position on the road and the variations (i.e., standard deviation - S.D.) of these measures. Analysis of driving behaviour for the total driving task, 100km, including car following situations, overtaking and stops at traffic lights did not reveal any significant differences among groups or conditions. Free flow driving, 60% of the route, was defined as those parts of the route where the subjects did not have to deal with catching up, overtaking, or traffic lights but occasionally met oncoming traffic. Free flow driving behaviour was analysed with respect to mean speed, lateral position, and variations in speed and lateral position (Tables 2, 3).

Table 2 Mean speed and speed variation (S.D.) (km/h) for free flow driving (approx. 60km) for the different experimental conditions

	Single lever system	Dual lever system	Both
With ACC	95.4 / 3.25	94.1 / 3.27	94.7 / 3.26
Without ACC	95.0 / 5.33	97.6 / 4.06	96.3 / 4.69
Both	95.2 / 4.29	95.8 / 3.66	

Variation in speed was significantly lower for the ACC condition (Table 4). Other differences were not significant.

Table 3 Mean and variation (S.D.) of lateral position (m) for the free flow driving (approx. 60km) for the different experimental conditions

	Single lever system	Dual lever system	Both
With ACC	1.52 / 0.29	1.64 / 0.21	1.58 / 0.25
Without ACC	1.48 / 0.24	1.63 / 0.21	1.55 / 0.23
Both	1.50 / 0.27	1.64 / 0.21	

Drivers using the single lever system drove 14cm more to the right compared to those using the dual lever system (Table 3) but the difference was not significant (Table 4). The single lever users had a significantly greater variation in lateral position than the other group and the variation for this group was greater with ACC compared to without (Tables 3, 4). The drivers using the dual levers were not influenced by the ACC with respect to variation in lateral position, which caused an interaction between ACC and hand control (Table 4).

Table 4 Results from a two-way ANOVA performed on mean speed, variation (S.D.) in speed, lateral position, and variation (S.D.) in lateral position for free flow driving conditions (approx. 60km) for the different experimental conditions (df = degree of freedom)

Factor	Source	df	F	p
Speed variation	ACC	1,18	19.79	< 0.001
Variation in lateral position	ACC	1,18	8.266	0.010
	Hand control	1,18	6.765	0.018
	ACC* Hand control	1,18	8.266	0.010

Variation in speed (km/h) during free flow driving was analysed to detect possible degradation in manual speed keeping performance compared to ACC driving. The difference in speed variation between no ACC and ACC condition increased with distance driven (Figure 5).

There was a significant [F(1,18) = 5.093, p = .037] linear trend but the apparent difference between hand controls was not significant.

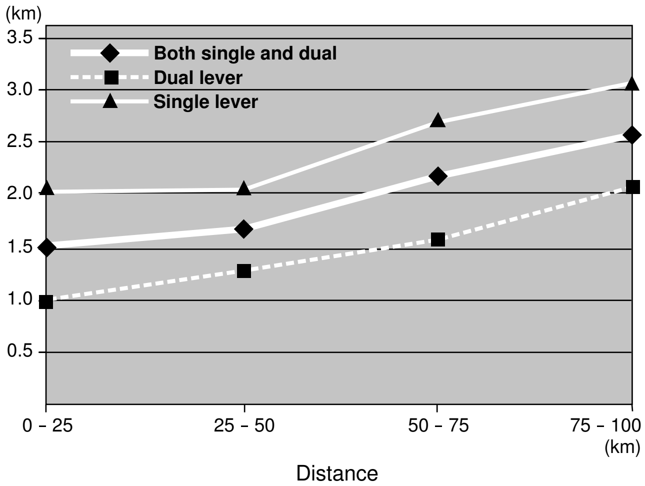


Fig. 5 Differences in speed variation (km) between ACC and no ACC conditions per distance driven

3.2 Choice reaction time

Mean reaction times were calculated for the two conditions with ACC and without ACC for all subjects (Figure 6). The average reaction times were shorter for the ACC condition and for the dual lever drivers but these differences were not significant. The reaction times were also analysed for both groups with respect to order of presentation, but no statistically significant effects were revealed either due to order of presentation or ACC mode.

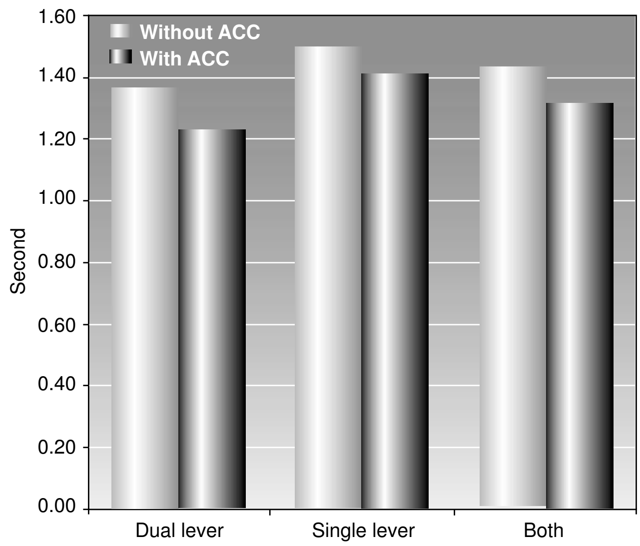


Fig. 6 Mean reaction time (s) for the different experimental conditions

3.3 Car following

The car following situations were analysed with respect to mean headway, variation in headway and shortest headway. Time headway was calculated as the distance between the front of the subject's car and the rear of the car in front divided by the subject's speed. The catching up procedure was the same for all situations but they ended differently as previously described. Fourteen car following situations were included in the analysis. The two car following situations at traffic lights were disregarded as they were considered to be different in character. Mean headway was significantly longer, [F(1,18) = 9.234, p = .007] for the unsupported condition compared to ACC driving (Table 5). Furthermore, variation in headway was significantly reduced when the ACC system was available [F(1,18) = 16.273, p = .001]. There were no significant main effects with respect to hand control and no interactions.

Table 5 Mean and variation (S.D.) in time headway (s) over 14 car following situations for the different experimental conditions

	Single lever system	Dual lever system	Both
With ACC	2.56 / 1.03	2.61 / 1.05	2.59 / 1.04
Without ACC	3.19 / 1.40	3.42 / 1.30	3.31 / 1.18
Both	3.02 / 1.22	2.88 / 1.18	

The shortest time headways were considered to be critical for the car following situations. Mean of shortest headways for both groups of subjects was prolonged when the ACC was used, 1.26s as compared to 1.08s. However, the individual differences were great and differences between conditions were not significant. Analysis of speed and lateral position for the car following situations showed that variation in speed decreased with 10% and variation lateral position increased by 12% when the ACC was available (Table 6). Single lever drivers drove on average more to the right with the ACC available while the other group showed a reversed pattern, which resulted in a significant interaction [F(1,18) = 6.428, p = .021]. Other differences were not significant.

Table 6 Results from a two-way ANOVA performed on speed and lateral position measures for the car following situations (df = degree of freedom)

Factor	Source	df	F	p
Speed variation	ACC	1,18	22.025	< 0.001
Lateral position	ACC* Hand control	1,18	6.428	0.021
Variation in lateral position	ACC	1,18	8.094	0.011

3.4 Workload

The subjects rated their workload for the total driving task, car following situations, and car following at traffic lights using the NASA-RTLX scale. The loading factors were in general rated lower and performance higher when driving with ACC (Figure 7) for both groups. The ACC system was engaged over 97% of the driving time for both groups.

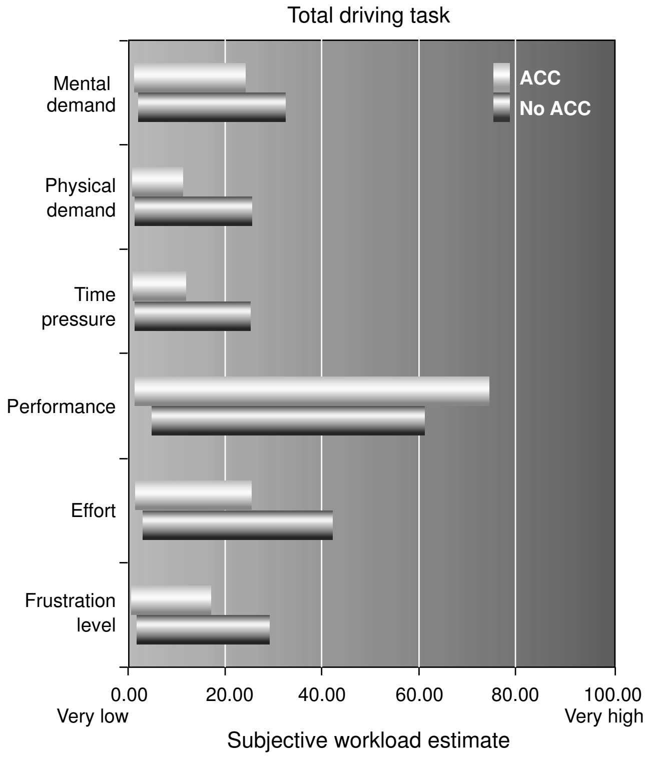


Fig. 7 Mean workload ratings for both groups (n=20) of the total driving task with and without ACC

Five of the differences shown in Figure 7 were significant: mental demand [F(1,18) = 7.618, p = .018], physical demand [F(1,18) = 11.759, p = .003], time pressure [F(1,18) = 7.044, p = .016], performance [F(1,18) = 8.455, p = .009], and effort [F(1,18) = 4.584, p = .046]. There were no significant differences between hand control used and no interactions were found.

The 16 car following situations were also considered to be substantially less loading under ACC driving conditions, e.g., 70% decrease in physical demand. The differences between ACC conditions were significant for all of the workload factors (Table 7). There was also a significant difference between the two experimental groups for mental demand, i.e., 21 (single) vs. 37 (dual). Apart from this, there were no significant differences between single and dual lever drivers. No interactions were found.

Table 7 Results from a two-way ANOVA performed on the six workload factors of NASA- RTLX for the car following situations (df = degree of freedom)

Factor	Source	df	F	p
Mental demand	ACC	1,18	14.510	0.001
Physical demand	ACC	1,18	24.636	< 0.001
Performance	ACC	1,18	12.895	0.002
Effort	ACC	1,18	7.556	0.013
Frustration	ACC	1,18	9.466	0.007

Workload was also assessed for the two car following situations at traffic lights. ACC driving condition for these situations meant that the subjects used the stop-and-go function of the ACC. Only one driver disengaged the ACC, and this was done by mistake. Workload was rated significantly lower for the ACC condition, i.e., all loading factors were significantly lower and performance was higher (Table 8). Also it was found that drivers using the dual lever system found the situation more mentally loading.

Table 8 Results from a two-way ANOVA performed on the six workload factors of NASA- RTLX for the car following situations at traffic lights (df = degree of freedom)

Factor	Source	df	F	p
Mental demand	ACC	1,18	21.758	< 0.001
Mental demand	Hand control	1,18	6.225	0.023
Physical demand	ACC	1,18	22.844	< 0.001
Time pressure	ACC	1,18	12.412	0.002
Performance	ACC	1,18	9.133	0.007
Effort	ACC	1,18	9.292	0.007
Frustration	ACC	1,18	6.604	0.019

3.5 Driver opinions

The subjects were asked how well they thought they could control speed and distance to lead vehicles during following situations and how much effort they allocated. Answers were given on 7-point discrete scales. Speed and distance performance were rated higher under ACC conditions and the allocated effort as lower (Table 9).

All differences were found to be significant: speed control [F(1,18) = 27.140, p<.001], speed effort [F(1,18) = 19.776, p<.001], distance control [F(1,18) = 5.959, p = .025], and distance effort [F(1,18) = 17.744, p = .001]. There were no significant effects due to type of hand control used. After driving with the ACC the subjects were asked to rate some aspects, which were considered to be

Table 9 Mean subjective estimations of speed and distance keeping performance and effort for the different experimental conditions

Aspect	Hand control	ACC	No ACC
Speed keeping very bad (1) to very well (7)	Single	6.2	3.5
	Dual	6.2	4.5
	Both	6.2	4.0
Speed effort none (1) to very high (7)	Single	1.5	3.9
	Dual	1.6	3.3
	Both	1.6	3.6
Distance keeping very bad (1) to very well (7)	Single	5.7	4.6
	Dual	5.9	4.6
	Both	5.8	4.6
Distance effort none (1) to very high (7)	Single	1.9	3.1
	Dual	1.5	2.8
	Both	1.7	3.0

important for ACC usage and acceptance (Table 10). The results showed that they rated the ACC system very high, all means were over 6 on a 7-point scale.

Table 10 Mean subjective ratings for some aspects of the ACC system for all subjects (n = 20)

Aspect	Mean	S.D.	Rating scales
General opinion of the ACC?	6.7	0.75	very negative (1) very positive (7)
ACC contribution to comfort?	6.5	0.95	very negative (1) very positive (7)
Learning to use ACC?	6.7	0.59	very difficult (1) very easy (7)
Trusting ACC?	6.5	0.69	not at all (1) completely (7)
Wishing to have ACC?	6.9	0.45	not at all (1) very much (7)
ACC better than own CC?	6.5	0.77	much worse (1) much better (7)

The subjects were asked to estimate where they placed their right hand when the ACC was engaged. The driver's right hand is normally used for the accelerator and brake control. Single lever users drove with both hands on the steering wheel only 28% of the time compared to 48% for the other group. Almost all subjects, 95%, had a CC in their own car. They used it frequently and rated the usefulness as very high. Finally, the subjects were asked to rate the experienced realism in the simulator on a seven-point scale ranging from 1 (not at all realistic) to 7 (very realistic). The mean rating for the ACC condition was 5.3 and for the no ACC condition 5.0. The difference was not significant.

4. DISCUSSION

The purpose of this study was twofold. The first purpose was to evaluate specific adaptations, the ACC and the two types of hand controls, and the second was to contribute to the development of general method to evaluate vehicle adaptations. The current evaluation included aspects like usability, safety, workload, and acceptance.

4.1 Usability and safety

Driver behaviour was analysed in order to evaluate the usability aspects. The driver should be able to use the adaptation, as intended, and it should have a positive or, at least, not a negative effect on driving behaviour. The evaluation has to consider safety in order to reveal possible negative effects. Safety in this context is limited to active safety, i.e., the driver's ability to control the vehicle in a way that crashes and incidents are avoided. Passive safety, i.e., possible consequences of a crash was not considered here.

Driving behaviour was analysed with respect to speed and, lateral and longitudinal control. There were no significant effects of ACC or type of hand control on the average speed for free flow driving but the speed was approximately 5km/h above signed speed (Table 2). This corresponds rather well to how Swedish drivers actually drive. The variation in speed during free flow driving was significantly reduced when the ACC was in use (Table 2, 4). This implies a softer and thus a safer driving behaviour with possible positive environmental effects for both hand controls.

Steering control was analysed by investigating the lateral position of the vehicle. It was found that the variation in lateral position was less when the ACC was not available (Table 3). However, this difference was only found for the group using the single lever system. The other group was not influenced by ACC usage and had a consistently lower level of variation. Approximately the same was found for the car following situations: ACC usage increased the variation in lateral position and the single lever drivers varied more than the other group (Table 6).

It was expected to find differences among the four conditions. First of all, a cruise controller could improve lateral control for driver using hand controls as both hands could be used for steering. Furthermore, in an earlier simulator study[18] with quadriplegic drivers it was found that the variation in lateral position was greater for these drivers who used the dual lever system compared to single lever users. It was suggested that this could have been a result of an interaction between the steering and speed keeping control. The current findings do not correspond to the expectations but there are several possible explanations. First of all, subjects participating in this study had full function in their upper limbs while the quadriplegic drivers in the previous study were impaired in their upper limbs. Furthermore, the current driving task was less demanding with respect to steering control compared to the other. The single lever users steered with one hand more than 70% of the time even when the ACC was available and they could have used both hands. This supports the assumption that the driving task was not demanding enough to reveal the potential effects of ACC on steering control. One possible explanation for the increase in variation for the ACC condition could be that driving became more relaxed, less loading. Nilsson[20] found a tendency that variation in lateral position decreased as task load increased, telephoning while driving. The observed differences, even though significant, were small (2–3cm for ACC and 4–6cm for hand control condition) and even if the single lever drivers had a greater variation in lateral position, they were still well within the lane. In summary, the results do not suggest that there were any relevant differences in safety between the conditions.

Car following situations require the driver to control both speed and distance to leading vehicles. These are situations where the ACC can provide support but not a conventional CC. The analysis of time headway showed that both variations in headway and mean headway decreased by 0.7 seconds when the ACC was available. This means that on average the subjects were driving 17m closer at a speed of 90km/h to the vehicle in front. The decrease in variation is probably a clear positive effect of ACC usage. However, the shorter distance was accepted but it does not seem to conform to the distances found under the unsupported condition. Comments were also made that the ACC used a too short headway. Nilsson & Nåbo[20] found that the shortest headways were reduced under ACC supported condition. Even if some of the shortest headways were eliminated also in this study the average of the shortest headways was not significantly different with respect to ACC condition. The results indicate that it is important that headway can be individually adjustable according to driver's characteristics and preferences within a certain range. The need for adjustable headway is likely to be even more pronounced in bad weather conditions, nighttime driving etc.

When the ACC system was engaged the driver could place his/her right hand on the steering wheel or on the brake lever or somewhere else irrelevant to the primary driving task. If the driver chose to place it on the brake lever this could influence the brake reaction time. Single lever drivers estimated that they on average had the right hand half of the time on the brake and the dual lever drivers one third of the time. However, there was no influence of ACC mode or type of hand control on brake reaction times. The same result was found for able-bodied drivers[20].

In summary it was found that the ACC in combination with both hand controls was usable and had no negative effect on traffic safety and there were no substantial differences between the hand controls. However, it seems like the ACC used too short time headway criterion compared to what they use when free to choose. This was a reversed result compared to what Nilsson and Nåbo[20] found for able-bodied drivers.

4.2 Workload

Driving with hand controls often imposes a high load on the driver's upper limbs. Both hands are continuously occupied with the primary driving task. This often causes strain and discomfort and could reduce active safety but most frequently it will result in reduced mobility and independence, for example, driving less frequently and shorter distances. The ACC system was evaluated to find out if it could reduce the load on the driver. Workload was measured with NASA-RTLX rating scales. It was found that ACC supported driving was experienced to be substantially less loading, especially physical demand and effort, and performance was better (Figure 7). This result was even more pronounced for the car following situations including the situations at traffic lights (Table 7 & 8). The levels found for the unsupported condition were in good correspondence to what was found in the earlier cited study with quadriplegic drivers[18], while the workload level for the ACC condition was approximately equal to what was found for able-bodied drivers using ACC[20]. However, the ACC support did not influence the workload level for able-bodied drivers. Specific questions on speed and distance control showed that the subjects found it easier and required less effort to control both speed and distance to leading vehicles with the ACC system available (Table 9). Difference in speed variation increased with driven distance (see Figure 5), which also supports the conclusion that ACC reduced workload. In summary it was found that experienced workload decreased substantially when the ACC support was available for both driver groups.

4.3 Driver opinion

The drivers participating in this study had extensive experience of conventional cruise controllers as 95% had a CC in their own car. This percentage is high even among drivers of adapted cars. A recent survey among drivers of adapted cars showed that about 40% of their cars had a CC installed[13]. The ACC system, including the stop-and-go function, was very well accepted, considered easy to learn, wanted and trusted by the subjects (Table 10). The ACC was also very much preferred over conventional CCs. Thus it seems very likely that the ACC application will be very well received by drivers who drive with hand controlled accelerator and brakes.

5. CONCLUSIONS

In conclusion it was found that the ACC application served its purpose well independent of what hand control system the driver used. The applied evaluation method seems to be useful, however, not comprehensive. There is a need to further develop, e.g., principles of how to design the driving task in relation to the evaluation objectives. Maybe the current driving task was not demanding enough to reveal potential risks. Furthermore, there is a need to elaborate the evaluation parameters and criteria. Steering, speed and distance control are critical parameters but the way to measure and interpret the results needs to be refined. Finally, the ACC application can, from the users point of view, be seen as consisting of three parts; the function provided by the ACC, the input or control of the ACC and the output or feedback from the ACC. The current evaluation method does not explicitly include the in- and output aspects of the ACC device. A comprehensive evaluation should also include these aspects.

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