Automation and the nature of driving - The effect of adaptive cruise control on drivers' tactical driving decisions

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Preface

My interest in the effects of advanced driving assistance systems started with incredulity at the blame assigned to the driver in every situation that goes awry, even if the driver is using a “smart” system to help them. The driver is responsible for the vehicle and its actions according to the Vienna convention (1968), but what are the opportunities for the driver to behave safely when aided by automation? Research sometimes seemed to indicate that driving with automation was more risky than driving without; at least in situations when automation failed to act and the driver had to respond (Nilsson, 1996; Stanton and Young, 1998). Thus, my curiosity was drawn to what the driver actually understood about a system’s capabilities, and how they were able to handle its possible shortcomings. System limitations, whether a conscious decision by designers or not, require the driver to revert to manual control fairly often.

At the beginning, the intention was to study the hand-over of control between automation and human. In essence, to investigate the ”bumpy transfer”-problem from aviation (e.g. Sarter et al., 1997), and see how it manifested in driving. Bumpy transfer is the term sometimes used for problems that occur when automation hands control back to the operator when it cannot handle a situation. The operator is then thrust back into control at a point where she not only needs to handle a hazard, but also understand how she ended up in the situation in order to resolve it safely. Thus, the operator has to spend some time diagnosing the situation.

After having started the project, it soon appeared that ”bumpy” transfer was difficult to identify in driving. A handover of control might not even be a good way of characterising what goes on between driving automation like ACC and the driver. As the ACC does not make any tactical decisions beyond keeping the set THW according to what its sensors can detect, there might not be a transfer of control the way there is in aviation.

A different angle was needed. Instead of viewing the driver’s use of ACC as a supervisory task, as is often done in automation research, I started using the concept of “delegation”. If using automation could not be seen as giving up control, maybe drivers were incorporating the system more into their actions? The term “delegation” also points to the necessities of informing the operator, and elucidates to what a human might (erroneously) expect from automation that is working toward the same goal as them. Drivers not only have the opportunity to delegate parts of driving, they should also be affected by that delegation. As the system takes over part of the longitudinal control, such shared control of driving may also alter the drivers’ motivation for looking at and responding to traffic and make them perceive the world differently.

The influence ACC exerts on tactical decisions made by the driver was unclear. In aviation, the auto-pilot can make strategic decisions, as well as the tactical ones, and does not communicate this to the pilot other than by the use of instruments and alerts. ACC on the other hand, while having a tactical component, still does not handle so much of driving that the driver is left outside of tactical considerations. Instead, the driver needs to handle the tactical side of driving regardless of being in manual control or not. The focus of the thesis therefore became the effects of delegating control to driving automation on tactical considerations. Mainly, how drivers work with ACC, instead of how driving may be made more complicated with the system.

Abbreviations

ADAS - Advanced Driving Assistance Systems

ACC - Adaptive Cruise Control

CCC - Conventional Cruise Control

THW - Time HeadWay

TTC - Time To Collision

List of papers

This thesis is mainly based on the following papers, herein referred to by their Roman numerals:

I - Larsson, A.F.L (2012). Driver usage and understanding of adaptive cruise control. *Applied Ergonomics*, 43, pp 501-506

II - Kircher, K., Larsson, A., Andersson Hultgren, J., Tactical driving behaviour with different levels of automation. Paper accepted into *IEEE Transactions on Intelligent Transportation Systems*.

III - Larsson, A.F.L., Kircher, K., Andersson Hultgren, J. Learning from experience: Familiarity with ACC and responding to sudden changes in time-headway in automated driving. Submitted to *Transportation Research Part F: Traffic Psychology and Behaviour*.

IV - Larsson, A.F.L., Lindgren, A., Exploiting FOT Data to Determine Driver Responses to Cut-In Situations With and Without Adaptive Cruise Control. Submitted to *Human Factors: The Journal of the Human Factors and Ergonomics Society*.

Contribution to the papers

I - Annika Larsson designed, performed and analysed the study and wrote the paper.

II - Annika Larsson designed and performed the study, and participated in the analysis and writing of the paper.

III - Annika Larsson designed and performed the study, did the analysis and was the main writer of the paper.

IV - Annika Larsson designed the database study and the script, analysed the results from the statistical study and wrote the paper.

Contents

The fact that we live at the bottom of a deep gravity well, on the surface of a gas covered planet going around a nuclear fireball 90 million miles away and think this to be normal is obviously some indication of how skewed our perspective tends to be.

- Douglas Adams (The Salmon of Doubt: Hitchhiking the Galaxy One Last Time)

1 Introduction

Human means for mobility have changed notably in the past two centuries; travel was primarily by horse or bicycle until the introduction of automobiles, the modes coexisting for a period of time until automobiles eventually took over. Development subsequently moved towards improving these automobiles, by increasing speed, comfort and safety. When automobiles were introduced in the 19th century, the public perception was that they were quite dangerous as they travelled significantly faster than other means of transport. To mitigate this, it was required that a man walk in front of the automobile waving a flag, in order to alert others. For horse car drivers, the arrival of the automobile also constituted a big change. From being alerted by the horse about certain dangers and learning to work with a specific horse, drivers of automobiles were now on their own, dealing with a machine (Norman, 2007).

Vehicle design has always been an area in rapid development, evident by the increase in speed, comfort and passive safety since the first automobiles were manufactured. From the invention of power steering, automatic gearboxes, and ABS brakes onward, drivers are no longer as involved in the mechanics of driving as they once were. In the past decade or two, development has focused increasingly upon facilitating the cognitive demands placed on the driver, by allowing automation to handle some tasks associated with driving. From having hands-on control of the steering wheel and pedals, drivers are now offered the opportunity to rely on the usage of various systems to handle the car.

With the invention of active safety systems and driver support systems that are able to handle a large portion of not only clutch control but also speed control, the act of driving is taking the next leap and is changing into something as yet unknown. Advanced driving assistance systems such as adaptive cruise control (ACC) are available in an increasing number of car models, and thus affect a growing number of drivers. The safety and robustness of the systems in various scenarios are of course tested thoroughly before market release, but the full effects on the driver and the transport system will not become apparent until systems are more extensively used. Long-term effects of system usage on the driver's actions, effects when using several systems in combination, and how or if experience with one system may transfer to another one cannot be fully predicted either, as drivers develop behaviours over time (e.g. Saad, 2004). The advent of systems that control central aspects of driving for prolonged periods of time therefore also necessitates further research into how drivers approach and make use of these systems in every-day traffic. The driver's understanding and opportunities to behave safely with the system are important, as the driver is responsible for all actions of the vehicle, including those that are the result of any automation present in the vehicle (Vienna convention, 1968).

The overall aim of this thesis is to improve the understanding of how drivers deal with the addition of continuous automation, more specifically adaptive cruise control, to their cars during a normal drive. Particularly, how drivers handle driving with ACC in common traffic situations that may require them to resume manual control. Examples will relate to ACC when possible, rather than to other systems. ACC is currently one of the more advanced systems available, and the only one capable of handling some actions of surrounding traffic without the need of driver interference. As such, it is also uniquely suited for a discussion of how the driver's role and actions may change with the addition of further automation.

1.1 General scope

The focus of this thesis lies on delegation of primarily longitudinal control while driving, mainly operationalised by the delegation of control to adaptive cruise control (ACC). ACC is a continuous driver support system that has been present on the market for over a decade. The results from this thesis will generalise to the use of continuous driving automation in cars, but not necessarily directly to the effects of using automation in other domains.

The thesis is written neither focusing on vehicle performance parameters nor merely studying automation from the human's perspective. Instead, an attempt is made to investigate driving itself; how the driving task changes for the driver, taking a qualitative stance. In conjunction with this, quantitative measures will be used to detail how drivers respond when working with the system. There will also be a review of how drivers adapt their utilisation of the system by using it and learning about its behaviours. Taking this perspective means other aspects fall outside the constraints, such as studying traffic dynamics, social aspects of using driver assistance systems, and effects on the transport system at large.

Further limitations include that only the actions directly associated with the system will be studied. Driver distraction and the use of ACC in combination with other systems are all beyond the scope of this thesis. The scope is also developed further in Chapter 2 on page 9.

1.2 Structure of the thesis

Next in the current chapter, ACC functionality and the definitions used throughout the thesis are detailed. In chapter 2, a conceptual framework focusing on cognition and control, mainly task delegation, is presented. Next, previous research on the use of automation in general and ACC in particular is discussed in Chapter 3, followed by the research questions in Chapter 4. Summaries of the empirical studies conducted in the course of this thesis are introduced and the results presented in Chapter 5, along with answers to the research questions (Section 5.5). The methodological considerations and the results are then discussed in a broader setting in Chapter 6, where recommendations for future research and an improved ACC are also suggested (Section 6.3.1). The thesis terminates with the conclusions in Chapter 7.

1.3 ACC functionality

Adaptive cruise control systems expand on the capabilities of conventional cruise control (CCC) systems by the addition of radar, allowing ACCs to respond to the position of the vehicle in front and adjust the ACC vehicle's speed to maintain a set minimum distance to it (see Figure 1.1). CCC systems maintain a constant set speed, therefore being of most use when there is no other traffic around. With ACC, the driver does not need to use the gas and brake pedals as much, thus providing relief during long drives. The time headway (THW) or time distance to the vehicle in front, can normally be set in five steps between about 1 and 2.5 seconds. If the vehicle in front speeds up or turns off, the ACC vehicle speeds up, but no more than to the set maximum speed. If a new vehicle enters between the ACC vehicle and the lead vehicle, ACC locks onto this new vehicle, making it the new lead vehicle. The ACC system thus switches automatically to any new vehicle in front. In cases with a very small time headway, it may take the ACC system a fraction of a second to identify that there is a new lead vehicle in front, making it accelerate until it identifies the new leader and locks onto it.

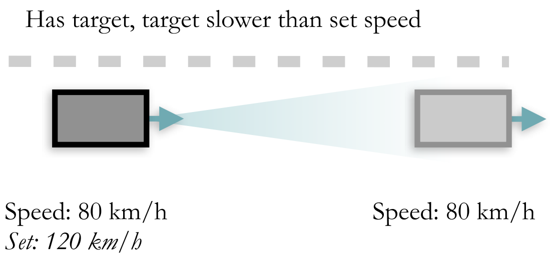


Figure 1.1: The ACC vehicle has a set speed of 120 km/h, but the lead vehicle is driving at 80 km/h. Thus, the ACC slows the vehicle down automatically to keep the set minimum distance, and drives at 80 km/h. If the lead vehicle were to disappear or speed up, the ACC would accelerate toward the set speed.

In the first versions of ACC, there was no forward collision warning (FCW) if there was a sudden low time to collision (TTC). FCW is a system that warns the driver about imminent collision by sound or visual signals, to allow the driver to respond by braking or by employing another avoidance manoeuvre. Current versions of ACC, to this author's knowledge, always come bundled with FCW. When ACC is off, FCW can still be active but it is not possible to activate ACC without FCW.

The ACC can interact with the driver in three modalities; visually, by haptics, and to a lesser degree, auditory. Icons on the dashboard show the set speed, set THW, if the system is active, and if the system is following the vehicle in front or not (see figure 1.2). An icon can also indicate whether the system has dirt on its sensors that needs to be cleaned off.

The ACC system has a maximum brake force as well as a maximum acceleration force, and the maximum brake force may or may not be enough to brake before collision given the characteristics of the specific driving situation. ACC is therefore not a collision avoidance system. Present ACC systems are generally able to brake the vehicle down to a standstill (known as full range ACC), but the systems studied for this thesis did not have this feature.

Figure 1.2: Adaptive Cruise Control

ACC systems are available under different names from a variety of different makers. They are primarily available in the premium vehicle segment.

1.3.1 Activation and deactivation

The driver activates the system by pressing buttons typically available on the steering wheel, either to resume a previously set speed, or to set the current speed as the maximum speed of the vehicle. The driver can also increase or decrease the vehicle speed as regulated by the system with the buttons on the steering wheel (Figure 1.3), as with CCC.

If the driver presses the brake, the ACC system no longer regulates speed and the driver resumes manual control. In order to allow the system to regulate speed again, the driver needs to activate the system by pressing the resume button. The throttle does not deactivate the system, but can always be used to drive faster than the set maximum speed. When the throttle is released, the ACC system once again automatically regulates speed.

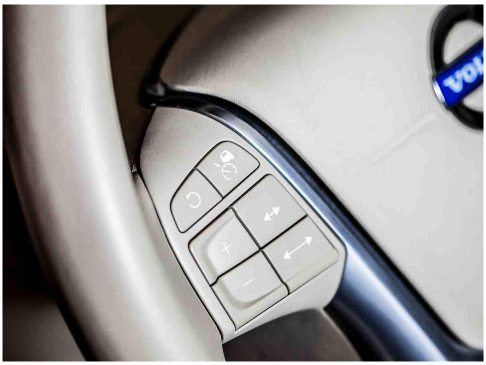


Figure 1.3: Control buttons for ACC, clockwise from top left: Resume, activate, distance and speed

1.3.2 Functional limitations

Being an automated system, ACC can only "see" what its sensors allow it to. Therefore, bad weather or dirt on the sensors can radically affect the system's opportunities to collect data. If the sensors are too dirty, the system cannot be engaged. In rain or snow, the effectiveness of the system's sensors is impeded and it may not respond to other vehicles as well as it normally does.

According to Winner (2012) the ISO standard ISO 15622, regulating the functional limits of ACC, states that priority is always given to driver interventions, and at steady speeds below 5 m/s, the driver is to be requested to resume manual control. Limitations for system settings are also regulated, and the minimum allowed time gap (THW) is 1 second. Acceleration is allowed within the limits of -3.5 m/s^2 to +2.5 m/s^2. Some limitations are also present with the ACC system. The ACC radar only detects vehicles straight ahead within a specific viewing angle by predicting their driving path, and at a specific maximum distance depending on the reach of the radar. It may also take a little while for the system to detect a vehicle, due to the movement or properties of that vehicle and the drive path predicted (Winner, 2012).

However, as Winner (2012) also notes, there are also situation-dependent constraints that complicate target identification. For comfortable braking when driving at high speeds, braking needs to commence before coming too close to a much slower vehicle in front. Still, with a large difference in speeds, it is likely that the slower moving vehicle will instead be overtaken. Early deceleration would in that case be disturbing to the ACC driver, hindering the overtaking process. Winner also mentions that the ACC system is slower at detecting a vehicle cut-in than the human driver is: The driver can identify a cut-in before that vehicle has crossed the lane marking. The system, due to its selection of targets and assigned driving paths, is slower by about two seconds (Winner, 2012, page 637). Furthermore, this slower response on the part of ACC could also only be rectified by the addition of situational knowledge, which according to Winner puts the transparency of ACC system behaviour at risk. If ACC had knowledge of the situations it acts in, it would be more difficult for the driver to understand when and why the system acts the way it does, if the system does not communicate this fully.

According to Winner (2012), ACC incorrectly identifies what should be seen as a lead vehicle about once every hour, something he notes as being difficult to improve upon. Thus, ACC will always continue to be an imperfect system. This imperfectness, however, could be an advantage. Winner suggests that it is more difficult to prepare drivers for something that they never experience, rather than having the current situation where drivers are used to having to get back into control occasionally. If an incorrect lead vehicle is identified at several occasions during a long drive, the driver will know that the system is fallible, and therefore be prepared to resume control if necessary. Had the system been too competent and almost never made these mistakes, mis-identification of a lead vehicle could have more hazardous consequences as the driver would struggle to identify something, to them, very improbable.

1.4 Definitions

The term *"ACC vehicle"* will be used to refer to the vehicle that is equipped with the ACC system. The *"lead vehicle"* is the vehicle that the ACC vehicle is currently following.

The systems included in the concept *"driver support system"* in this thesis are only those that rely on responding to events outside the vehicle, and relieve the driver of a continuous cognitive task (see Young et al., 2007). These are systems that also fall into the category of "driving automation" rather than "vehicle automation"; see Figure 1.4. Systems such as electronic stability control (ESC) and anti-lock braking system (ABS) are not included in this term, as they are more an enhancement of hardware functionality than systems that respond to events outside the vehicle. Automatic gearboxes are perhaps more closely related to advanced driving assistance systems (ADASs) such as ACC, being both continuous and attempting to respond to vehicle states. Typically, automatic gearboxes do not take the outside world into account, they are therefore not included in the current definition of "driver support system". Warning systems such as lane departure systems could also be seen as driver support systems or driving automation, though they only step in at discreet occasions, not continuously.

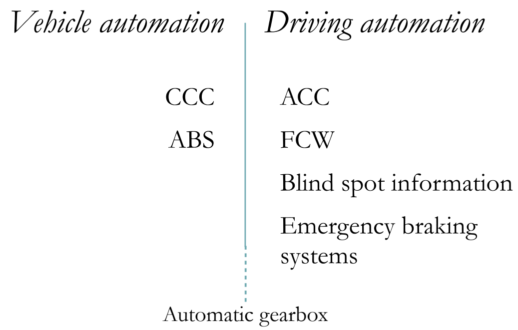


Figure 1.4: Systems as divided into driving automation or vehicle automation.

"Behavioural adaptation" has been defined by the OECD (1990) as "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". This thesis will extend behavioural adaptation to signify any behaviour by the driver that may follow changes to the road-vehicle-user system, intended or not by the initiators of the change.

"Control" will be mentioned several times in this thesis. What is normally meant by the term control is the physical, manual control employed, but the term also includes monitoring that the actions taken are having the intended effect on the manipulated object. An example of this would be the physical control needed when intending to follow a curve by turning the steering wheel, but also looking to see if the angle of the steering wheel is enough to take the curve appropriately or if it needs adjustment. Any other meanings will be specified in the text.

The driver constantly needs to attend to events outside his or her vehicle in order to avoid potential collisions and stay on course. Such potential collisions will henceforth be called *"traffic conflicts"*. Traffic conflicts are defined in transport engineering as an event where two (or more) vehicles approach each other such that a collision will occur if not at least one of the vehicles makes an avoidance manoeuvre (Hydén, 2008). The term is mainly used in urban traffic between two vehicles. For the purposes of this thesis, it will be applied to motorways and rural roads. Traffic conflict is not normally a term used in the area of human factors, but it is a useful definition in the descriptions of traffic events that are to follow.

In order to describe these traffic conflicts, the words *"event"*, *"situation"* and *"scenario"* will be used depending on context. "Event" is intended to be understood as the class of occurrence, say a cut-in event. When an event occurs and thus becomes a specific instance of that event, it is referred to as a "situation", in real life or when simulated. Lastly, a "scenario" is an event designed for use in for example a driving simulator, and so is a highly specified event where all variables except driver response are controlled.

"Borderline" traffic conflicts or events is a concept that will be used to describe traffic conflicts that may or may not be within the system's ability to respond to, a situation very similar to one where the system can respond. One example of this would be a vehicle cutting in front of the ACC vehicle, resulting in the system having to brake just above its maximum brake level in order to avoid a collision. In a very similar situation, the system's maximum brake level could be enough. To the driver, it will not be apparent until after the fact which of these hold true.

Having "experience" with a system is defined as having previously used and become familiar with system, on more than a single occasion.

Anything that happens, happens. Anything that, in happening, causes something else to happen, causes something else to happen. Anything that, in happening, causes itself to happen again, happens again. It doesn't necessarily do it in chronological order, though.

- Douglas Adams (Mostly Harmless)

2 Conceptual framework

Operator tasks and behaviour change with the addition of automation, and in order to analyse driver adaptation to ACC an short review of human cognition and a framework of control is needed. The text on cognition is chiefly intended as a background and introduction to how the author approaches the subject of driving automation. The framework on control is then explored from a mainly cognitive perspective, introducing theories and concepts that are useful for discussing some changes for the driver brought by the introduction of automation.

2.1 Cognition

Cognitive processes are those mental processes that describe how agents think about and know the world, including perception, attention, memory, learning, problem solving, and many more. Thinking and perceiving does not, however, take place in a vacuum independent of the world around it. Instead, all human action and cognition is mediated, filtered, through the artefacts and tools that surround us (Norman, 1993). It is therefore impossible to add or remove artefacts or systems, expecting to see the same behaviour or thinking in people as in the original setting. The addition of automation to the driving task will therefore modify driver behaviour, it does not merely remove responsibilities. As Bainbridge (1983) pointed out, the introduction of advanced automation into a task still leaves humans responsible for crucial monitoring and dealing with emergency situations.

2.1.1 Situated cognition

Generally, the concept of situated cognition is used to describe how the thinking of an individual is affected by their goals and experiences as modified by for example automation. With ACC, the driver and system are both observant for obstacles ahead, but the system can detect and do things that the driver cannot, as the driver can detect and do things the system cannot. This implies that the driver can both make use of the system to extend their cognition, and have their goals affected by the functionality of the ACC. Some things are better handled by the ACC, and others better handled by the driver.

The addition or removal of even just a small part of a task means that the task in its entirety will be changed (e.g. Hollnagel, 2001; Norman, 1993), as cognition is dependent on its surroundings. The reason is that the tools and artefacts we use affect our cognition, as it filters the world through the actions afforded by these artefacts, and guide our attention. Cognition thus cannot be taken out of context, as the experience of that context shapes our perception of the world and also constrains and shapes our perceived opportunity for action. Neisser's (1976) "perceptual cycle" provides a description of how perception, action and knowledge influence each other in the achievement of goals: An experienced driver may see a ball in the side of the road and immediately slow down and start looking for children, whereas the inexperienced driver only sees the ball, lacking knowledge of any implicit meaning. If the inexperienced driver then sees a child, they too may start to make a connection between a ball and children and thus adjust their attention in such circumstances. Having experience with a system or an event type therefore makes people more prepared to perceive some things than others. The three parts of action, perception and experience thus interact with each other, in a circular fashion, to provide a suitable interpretation of an event (Neisser, 1976). With the use of automation, the system also provides other means for exploration, perception and action than the human has alone (Norman, 1993).

Other researchers have also emphasised that as attention is to a large extent guided by experience and goals (e.g. Most et al., 2005), drivers can easily miss relevant information because it is unexpected or not relevant to the current goal (Hills, 1980 and Rumar, 1990 in Trick et al., 2004). Most and Astur (2007) have also shown that when sudden obstacles are unexpected in a given environment, collision rates in simulated driving are substantially greater. However, the goals guiding attention need not be constrained to being vigilant for hazards, but can be more fuzzy as well. The task of following another vehicle can capture driver attention, as the goal of driving along a road changes to that of following another vehicle manually (Crundall et al., 2004). The introduction of ACC will allow drivers to act differently than they would without the system, these new behaviours then modifying drivers' attention and interpretation of events.

2.1.2 Summary

Tools and artefacts, by their design, constrain actions and the construction of experience (Norman, 1993). Operators need to coordinate their actions with those of the automation, as well as intervene with the automation when necessary and respond to any disturbances. The addition of automation thereby causes humans to incorporate monitoring not only of the situation, but also of the system's actions and performance. The opportunity to partly rely on ACC functionality constrains and extends the opportunities for driver actions in ways that a car without ACC does not. Instead of having the continuous goal of keeping the distance to the vehicle in front manually, the driver allows the system to manage this task. With ACC, drivers have the opportunity to exploit system actions and to attend to things slightly differently, but also need to watch out for any traffic conflicts the system might have difficulties handling.

A driver is likely to act qualitatively different with ACC than without it, both by their behaviour and attention, as their experience of driving will be different with the system. Having access to a system that can handle some of the distance keeping to vehicles in front allows drivers to use ACC to accomplish goals of for example perception. The use of ACC to fulfil goals can also change how the driver attends to surrounding traffic.

One question that remains, however, is how the driver makes decisions of how to make use of and rely on ACC, and when not to. Another aspect is what the driver's chances are to continue driving well when delegating control to ACC, as the system affects their drive and their need to respond.

2.2 Control

To discuss what tasks can be managed with the help of ACC, it is useful to introduce framework of driving behaviour. The choice has fallen to Michon's well-known separation of control tasks in driving (Michon, 1979, 1985), for its usefulness to the perspective of actions and cognition taken in this thesis. The main reason for using Michon's model as a framework is to establish the boundaries of what will be observed, rather than as an explanatory model or to determine the demands placed on the driver. The model is not concerned with finding the reasons behind specific behaviours or responses, but rather aims at describing different aspects of driver behaviour when interacting with the vehicle, with traffic, and when planning the overall goal of the trip. Such a general framework can be more useful for describing possible changes in the driving task as a whole, on different levels, rather than in specific sub-tasks such as monitoring, regulating or operating the steering wheel.

For a comparison of different theories relevant to studying driver behaviour, see Table 2.1.

Table 2.1: A comparison of theories used to study and describe driver behaviour

	Starting point	*Time frame*	*Level of detail*	*Identified changes*
Three control levels (Michon, 1979, 1985)	Driver choices	Varied	Mainly lower	Vehicle behaviour
Field of safe travel (Gibson and Crooks, 1938)	Driver perception	Instances	Very low	Based on enironment
Joint cognitive system (e.g. Hollnagel et al., 2003)	Driver actions	Short	Mainly higher	In sub-tasks
Cognitive task analysis (e.g. Stanton, 2006)	Driver demands	Short	Very high	In sub-tasks/ demands

2.2.1 Three levels of driver behaviour

Michon (1979; 1985) categorises driver problem-solving and behaviour into three main levels of control: strategic, tactical and operational. The strategic level concerns the main planning stage of the trip including route choice, the goal of the trip, and even modal choice. At the tactical level, there is the negotiation of the more acute traffic situation. Thus, the tactical level applies for example to obstacle avoidance, gap acceptance, overtaking and turning. These tactical goals are adapted to the strategic goals, and may also adapt the strategic goals to fit more acute tactical ones for example by deciding on a detour to handle a build-up of traffic. Lastly, the operational level concerns the actual manual control, such as turning the wheel, pressing the brakes and so on - the basic motor skills of driving. ACC primarily affects motor actions and gap acceptance, or the operational level and parts of the tactical control level (see Figure 2.1).

By keeping a set speed and distance to the vehicle in front, ACC manages some of the operational parts of driving, mainly those of operating the accelerator and brake pedal. Due to its functional limitations, ACC cannot manage these parts completely independently and so more acute braking is still the main responsibility of the driver. Not only operational tasks are handled by ACC. The tactical task of gap acceptance is also delegated to the system during most car following. As the ACC system cannot detect more about the traffic situation than what is made possible by its sensors, the tactical decision of whether an action is appropriate or not given the circumstances still lies with the driver.

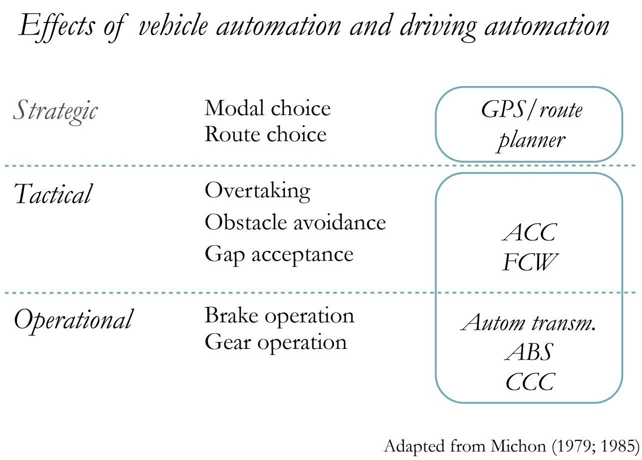


Figure 2.1: Michon's three levels of control when driving, where ACC primarily affects the operational and to some degree the tactical level of control

The operational tasks of driving are the easiest to automate, as has already been done with automatic gearboxes, ABS, and CCC (conventional cruise control). The automation of operational tasks, however, assigns the tactical task of determining if the system's response is adequate or appropriate to the driver (see Figure 2.2).

As the ACC system does not have sensors to perceive situations the same way an experienced driver does, the automation of operational (and to a certain degree tactical) tasks poses challenges for the driver. Comparing the event in Figure 2.3 to the event in Figure 2.4, it is clear that two situations can appear very similar if one only has access to a radar and no knowledge of the road or the traffic surroundings. The driver is therefore needed to determine if the system's

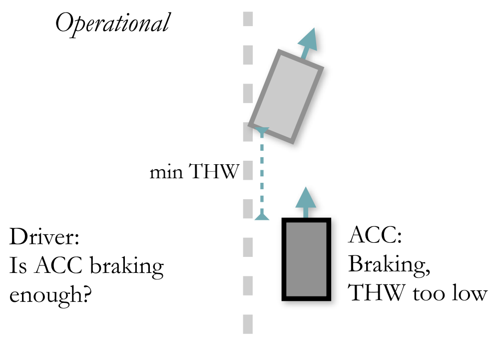


Figure 2.2: When the minimum THW is reached, the driver needs to determine if the ACC braking is adequate.

interpretation of the situation is correct or not. Situations such as these that are potentially difficult to respond to for the system will be called borderline traffic conflicts or borderline events. In these situations, drivers may be uncertain of system behaviour, and if manual control is necessary or not.

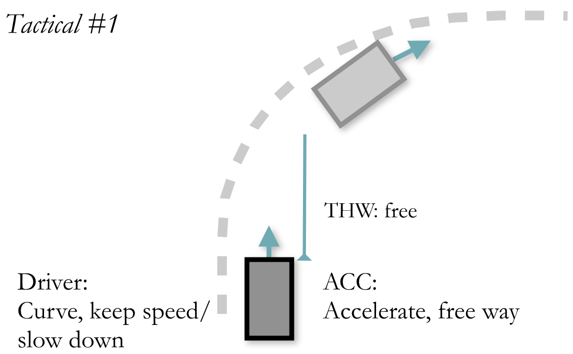


Figure 2.3: The ACC vehicle enters a sharp curve (or a roundabout), causing the system radar to lose contact with the lead vehicle. The ACC accelerates.

2.2.2 Delegating control

Whilst ACC can be conceived as being part of the driver's distributed cognition, it is also a separate system. As such, it needs to be designed as well as possible to correspond to the driver's

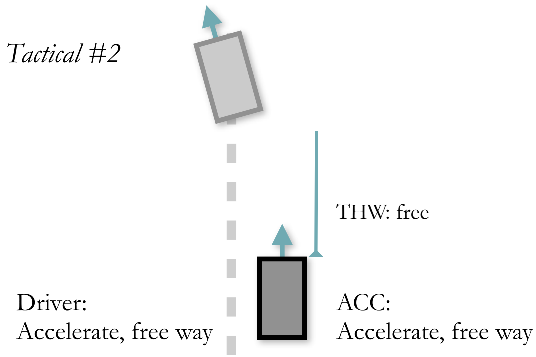


Figure 2.4: The lead vehicle switches lane, thus making the ACC vehicle lose radar contact with it. The ACC accelerates.

intentions and goals. As previously stated (see Section 1.3.2), ACC has and always will have certain functional limitations such as technical limitations of its sensors, and a lack of understanding of the traffic situation at large. When control is delegated to ACC, it may be unclear what the driver can do to identify, handle, and work with its shortcomings but also its strengths. Problems with the system's sensors for example, may not be apparent except in very bad weather, but ACC could also potentially be used in somewhat less adverse weather to maintain a safe distance in poor visibility.

To make full use of the automation, it needs to be allowed to accomplish its tasks without constant interference. Working with automation could thus be conceived as delegating certain tasks to it, and allowing it to control those tasks and regulate them itself. To understand task delegation from a more needs based perspective, instead of finding solutions to specific interaction design problems, the more general issues faced when delegating tasks need to be identified. Castelfranchi and Falcone (1998) propose a model of cooperative behaviour and task delegation between agents. This model specifically emphasises the more communicative and human aspects of delegation, and does not require a study of the transfer of information or the details in accomplishing one task alone. The advantage of using this theory, instead of others, is the focus on the relative independency of the two parties. Castelfranchi and Falcone specify types of communication and understanding that are necessary in order to achieve optimum cooperation, something not covered in other theories on cognitive systems.

Castelfranchi and Falcone describe delegation in broad terms as the action of trusting another agent to perform a task (Castelfranchi and Falcone, 1998; Castelfranchi, 1998; Falcone and Castelfranchi, 2002, 2001). Their model primarily describes task delegation as something possible between goal-directed agents, agents that regulate their actions based on feedback of the results. For vehicle automation, both the driver and the ACC system have a joint goal: Keeping a speed up to a set maximum without coming too close to the vehicle in front. ACC can therefore be concieved as not merely a tool, but more like an agent. It is capable of handling its tasks independently, without the driver's constant input.

The framework by Castelfranchi and Falcone assumes that both parties are not only goal-directed but also cognitive agents. That is, agents that have an internal representation of beliefs that can be manipulated generated and reasoned about. ACC is not an example of a cognitive agent, nor is this thesis arguing that ACC or similar systems will be cognisant in the coming years. People working in teams with automation do not make this distinction between cognitive and non-cognitive goal-directed agents, though. Instead, people behave towards automation the same way as to humans, in terms of coordination and similar social actions, if they are perceived to share the same goals (Nass et al., 1996). When working with complex systems, a heuristic approach like approaching the system as an intentional agent may also be more practical for the user in explaining and predicting its behaviour than an incomplete description of the system's workings (Wooldridge and Jennings, 1995). With complex systems such as ACC, a complete understanding and description of a system is not possible to achieve anyway, as the system's behaviour depends on too many factors and data sources for a full prediction of its behaviour in all circumstances.

Determining what can be delegated When allowing a system to regulate some aspects of driving, there needs to be an element of faith in the system's ability to accomplish its task in a particular situation. Falcone and Castelfranchi (2002) take the view that task delegation is the action of trusting another agent to do a specific task. This action of trusting is not necessarily only grounded in knowledge of what the other agent (or system) is capable of, or what it "understands". Rather, it is based on a combination of the safety and reliability of the environment and circumstances surrounding the action, the reliability of the other agent, as well as how convenient it is to trust the other agent in the current situation. To achieve delegation, trust is therefore necessary but not sufficient as preferences and conveniences are also taken into account.

Once deciding to make use of a system, the first step before task delegation is coordination according to Castelfranchi (1998). Coordinating actions can be accomplished in a range of different ways, from passively waiting for something to happen to actively negotiating the terms of the task delegation. With ACC, all these types of coordination are not possible. The driver can only adjust her own plan to accommodate the system's behaviour, or deactivate the system to make it abandon its goal. Changing the ACC system's goal outside that of the settings available to the driver is, however, not possible. Both positive and negative interference from the ACC system can be experienced at the tactical and the operational levels (see also "Monotoring delegated tasks", ahead). Adapting to the actions (or interference) by another agent does not involve active participation in the other, whereas the introduction of an action or the ceasing thereof is accomplished only by taking action towards the other. With ACC, adaption to the system could be exemplified by avoiding to use the brake at the exact time one would prefer to, as one knows that the system will respond shortly. The induction of action on the other hand is accomplished by switching on the system, regulating the set speed, or moving to the outer lane in order to go faster. In Castelfranchi's view, it is not delegation until one agent tries to induce a specific action (or avoidance of action) in another. Otherwise, there merely is coordination.

The driver delegates distance and speed keeping to ACC by pressing a button to start the ACC, not by asking for agreement. Complete delegation is not possible as the system is not aware that the driver intends to exploit its actions, it cannot fully adopt the driver's goals. Drivers also have several potentially conflicting goals, all in various ways directing their priorities when driving (see Figure 2.5). Such higher-level goals are natural to humans, but would need to be explicitly stated and programmed into a computer system. Any such implicit aspects of task delegation may be missed by the system, as the designer cannot think of all possible uses (or "mis"-uses, cf. Parasuraman, 1997) of the system.

Figure 2.5: Some of the goals directing driver priorities

With any system designed by a human, designers and engineers decide what is to be delegated and how (Hoc, 2001). System designers decide on cut-off levels and when to trust or not trust the sensors, and it will be up to the operator/driver to learn about these limitations. Thus, what the driver believes to be delegated may not necessarily be what the system designer envisions (Castelfranchi and Falcone, 1998). Consider this example: As the task of ACC is to keep the distance to a lead vehicle, it would not be unreasonable to assume that the system could handle the lead vehicle pressing the brake very hard. Such an event, however, depends on the specification of the system, as well as the current time headway and the speed both vehicles are travelling at. The ACC system cannot make a change in its braking power even if it often encounters such situations, and the driver can only determine system limits by trial and error. Some understanding of system limitations and behaviour in situations can be achieved by trial and error, but it is likely that the drivers' understanding is imprecise due to the many variables present.

Upon activation, ACC keeps a maximum set speed and minimum set distance to the vehicle in front, these being the main goals of the system. The ACC, however, has no way of knowing whether the driver is presently prioritising speed, safety or something completely different (see Figure 2.5). There is no communication between the driver and the ACC system about what the situation calls for, thereby making the driver's understanding of which tasks are delegated less clear. Drivers can therefore assume that more tasks have been delegated than is reality, as no confirmation can be had from the system. For instance, ACC systems have a maximum brake force, and cannot apply full braking force in the case of imminent collision. In order to adapt more to the driver's tacit goal of safety, ACC is generally bundled with forward collision warning (FCW). Through this bundle, the activation of ACC also entails being warned about possibly driving into other vehicles, such that the driver is made aware of the need to intervene. Through a solution like that, the system emulates a more complete delegation, behaving more in tune with driver goals. Other goals, like social factors or habit, can be more difficult to anticipate or respond to by system designers, and therefore the success of delegation relies on the driver knowing what to expect from the system.

As previously stated, it is likely that drivers construct heuristics to cope with system actions. The driver is the only one that can adapt, and needs to form strategies to enable using the system to her or his liking, despite perhaps not using the system to its full potential.

Coordinating and cooperating with ACC It may be tempting to characterise driver usage of automation as "cooperation" with automation, but in Falcone and Castelfranchi's (2001) view the possibility of doing so is limited by the capacities of the agents involved. For efficient coordination and actual cooperation, the agents need to be aware of each other's goals (Falcone and Castelfranchi, 2001). Then, and only then, can they coordinate proactively and mutually and achieve cooperation. Today's driver assistance systems have no mind of their own, and are merely reactive in their attempts to respond to changes in the outside environment. Systems with minds of their own are also unlikely if the systems are supposed to be used in traffic where vehicles operated by humans are driving. The sensors used by the ACC systems are only directed outwards, to the world outside the vehicle, so the system can only respond to the external world and not to the human operator other than the settings mentioned in Figure 2.6. ACC is therefore not able to coordinate with the driver, but is wholly dependent on the driver's understanding of the system's goals and the driver's ability to adapt to the system.

ACC controls	*Driver controls*
- Cut-off levels	- Minimum THW within range
- What vehicle to follow	- Maximum speed
- Deceleration and acceleration behaviour	- System active/inactive
- What can be delegated	- System override

Figure 2.6: The items controlled by ACC, and what the driver can control.

A non-cognisant system can only be proactive if it has complete knowledge of the world, as it cannot otherwise perceive visual signals such as turning indicators or brake lights of a vehicle far ahead. Such "understanding" is only possible if the world it occupies is artificial and fully defined (with plenty of infrastructure communication), and one where system control is the only control available. If artificial systems and humans are mixed, there will always be a case where humans behave in ways that automation cannot anticipate, or where automation behaves in a way humans dislike. As this highly specified world does not exist, the system is dependent on the drivers' ability to anticipate events and coordinate their actions to those of the system. Additionally, drivers can only adjust system behaviour within a small functional envelope, as there are limits to what system designers allow drivers control over. Drivers have no power over system logic or goals, but only over activating or deactivating the systems, and setting the time headway and maximum speed (see Figure 2.6).

Monitoring delegated tasks When a task is delegated, there is also the question of controlling that the actions are appropriate given the situation (Falcone and Castelfranchi, 2002). With ACC, the driver will need to delegate the continuous control of distance management to a certain degree in order to make use of the system. This leaves the driver having to focus on identifying disturbances and situations in which the system may not act in an ideal way.

Drivers can respond to borderline conflicts interfering with their goals on three levels (see Figure 2.7): the action level, planning level, and meta-cooperation level (Hoc, 2001; Hoc et al., 2009). These levels broadly correspond to Michon's operational, tactical and strategic levels. On the action (operational) level, interference management takes place with minimal anticipation, locally and in the short term, by reacting to sudden stimuli such as a FCW warning or uncomfortable acceleration. On the planning (tactical) level, coordination is managed in the medium term by the monitoring of actions and establishment of roles. With ACC, this can correspond to a determination to allow the system to handle situations where the ACC vehicle is overtaken, enabling it to regulate the speed and distance to the new lead vehicle. Lastly, on the meta-cooperation (strategic) level agents form and adapt their models about each other and about the communication. By agreeing on a meaning for a new code or signal, the outcomes on this level are used to facilitate the actions on previous levels. With ACC, this type of cooperative response is not possible as it requires that the system is able to learn and understand what the driver is doing.

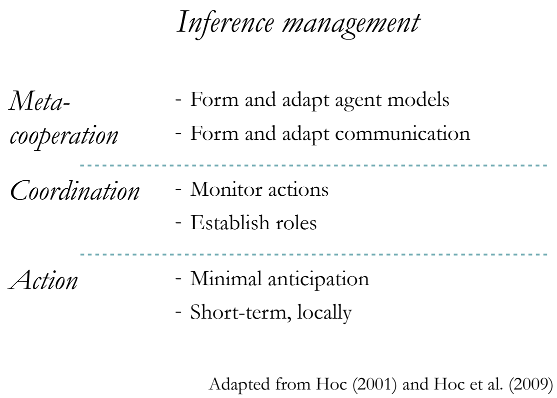


Figure 2.7: Three levels of interference management, broadly corresponding to Michon's three levels

Only the driver can form models or try to find a common frame of reference; a non-cognisant system such as ACC has no such capabilities. As a result, cooperating to deal with borderline conflicts on the planning level and the meta-cooperation level is more difficult to achieve with artificial systems (also see Figure 2.8). Instead, the driver has to adapt to system behaviour at the planning (tactical) level, rather than explicitly agreeing when ACC should handle an event, and when the driver should.

The effect of experience Previous experience directs what is seen as important and dangerous. Evaluating the outcome of an action, such as allowing the system to handle an event, in turn builds new experiences that direct attention as well as driver actions (see also Section 2.1.1 on page 9). If the ACC successfully handles a situation, the driver's monitoring in similar situations may be different than in new situations that the driver has not previously experienced with ACC. Which borderline conflicts relevant to ACC that drivers are able to anticipate, are therefore dependent on the experiences they have had with and without the system.

With today's systems, interference on the planning level extends to drivers forming an understanding of the ACC system's frame of reference, functional limitations, and of function delegation. Such understanding is not straightforward, but needs clarity in the communication of actions and status by the system, as well as extensive experience with the system in various circumstances to learn its behaviours and actions. Only then can a more usable model be formed

	Cognisant system	*Non-cognisant system*
Delegation	- Can agree explicitly - Adopts goal - Can renegotiate tasks	- Can emulate agreement - ”Unaware” of exploitation - Has a pre-programmed task
Control	- Interprets situations based on experience - Forms dynamic models about the world - Can form a common frame of reference	- Knows only what its sensors and algorithms tell it - Has a set image of the world dependent on its programming - Has its own frame of reference, can communicate it if well-made

Figure 2.8: The difference between delegating control to a cognitive and a non-cognitive agent.

about the system's abilities and reliability. Falcone and Castelfranchi (2001) also mention the importance of both explicit and implicit communications by the system, and attributions to the role or category the system belongs to. For example, previous experience of a CCC system may facilitate the use of an ACC system as they are both varieties of cruise control systems. The driver's previous experience of system acceleration/deceleration or FCW can also influence their ability to interfere in borderline situations.

2.3 Summary

With the addition of ACC, drivers no longer need to constantly regulate their distance to the vehicle in front. Still, the functional limitations of the system entails that ACC cannot predict events or understand the tactical side of driving even though it accomplishes some tactical actions (see Section 2.2.1 on page 11). Thus, the driver is required to monitor traffic to determine if ACC responses are appropriate. Meanwhile, only the ACC system is ”aware” of the set minimum THW as it relates to distance, and is more adept at keeping this distance constant than is the driver. The driver is therefore compelled to allow the system to handle most distance and speed control, if the system is active.

To determine how a borderline traffic conflict unfolds, however, the driver needs to monitor the situation more actively. In such situations, control is exercised when monitoring for inappropriate system behaviour or exceeded system limitations (see also figures 2.3 and 2.4 in Section 2.2.1). The addition of a system such as FCW can mitigate some of the difficulties with diagnosing risky situations, but most tactical decisions still rest with the driver.

When delegating control to a fellow human, the understanding of goals can be re-negotiated and there can be an understanding of how to communicate the goals so that both parties understand them in the same way. In the case of ACC, drivers can only respond and adapt their own behaviour to that of the system based on the actions of the ACC in specific situations, or by reading the manual. This also limits the opportunities for drivers to learn how the system works, as they may not read about or experience all types of situations they may encounter. Drivers are instead required to create their own ideas of system functionality and communication, in order to find strategies and heuristics that allows them to make use of the system as a tool.

Thus, learning how the system works is pivotal to coping with system behaviour. System capabilities in various situations as well as system communication are important aspects that the driver needs to identify. As the system is adept at handling its tasks, the driver mainly needs to learn when to allow the system to manage a situation, and when and how to intervene. This could be done either by proactively responding by identifying types of events that the system can or cannot handle, or by responding to system action or reactions.

Changes to driving brought on by using ACC When first learning to drive, drivers learn to recognise potential traffic conflicts and plan their actions accordingly. This separates human thinking from the functionality of automation. Drivers are able to handle occurrences like the build-up to traffic conflicts proactively, something that may transfer to their planning of when to use a system such as ACC. When driving with ACC, the driver also needs to make the tactical decision of either letting ACC handle a situation in its own fashion or stepping in herself, and in that case when.

The delegation of control to the system also means that the driver's perception and attention to the surrounding traffic may be affected, as some of the driver's actions are now coupled with those of the ACC system. The ACC system can therefore be seen by the drivers as a new intrinsic part of driving their vehicles, the system's actions and ability to control itself can also be taken into account when making tactical decisions.

Resuming manual control from ACC requires the driver to switch the system back on again if the manual control has been resumed by any other means than through the accelerator. Hence, the decision of when to resume control may be affected by the system's performance and how well it fits with the driving situation and the event in question. The drivers' goals when driving with ACC are probably similar to driving without ACC, but how they aim at accomplishing these driving goals and what sub-goals they have may be different with ACC than without (see Figure 2.9).

	Driving without ACC	*Driving with ACC*
Tactical	- Constant distance regulation to vehicle ahead - Determine response to all traffic conflicts	- Include ACC performance in tactical decisions - Respond to ACC actions - Determine if ACC response is appropriate - Determine if and when to reclaim manual control
Operational	- Handle throttle and brake continuously	- Handle throttle and brake occasionally - Brake now also shuts off ACC

Figure 2.9: Driving with ACC changes not only operational parts of driving, but also large aspects of the tactical element of the driving task.

With ACC, the driver's motivation for attending to the lead vehicle may decrease as distance keeping has largely been delegated. The driver's attention to traffic conflicts may also change depending on the attention strategies used to determine when to resume control. If the driver stays in automated mode, attention is also likely to be different from when choosing to resume manual control. In the next chapter, previous research on the use of ACC is presented and reviewed.

Everything starts somewhere,
although many physicists disagree.

- Terry Pratchett (Hogfather)

3 Previous research

The supervisory addition to the operator's tasks brought on by automation is one of the main issues studied in automation research (e.g. Stanton et al., 1997; Molloy and Parasuraman, 1996). Researchers have been sceptical about delegating headway control to automation, mainly pointing out the risks that may be involved if the system were to fail (Nilsson, 1996; Stanton and Young, 1998). Several studies have also been conducted on how driving behaviour may be affected when using ACC and similar systems, and also on how attention may be affected when using automation. These will be reported and discussed in the current chapter.

This chapter starts with a review of how drivers learn to use automation and ACC in particular, moving onto describing previous studies on behavioural adaptation when driving with ACC as well as field studies of ACC. Thereafter, research on how operator/driver attention changes with the use of automation is reviewed, and a recount of studies on driver responses to critical traffic conflicts is presented. Lastly, the previous research is summarised and some gaps in the research are identified before moving on to the next chapter and forming the research questions.

3.1 Learning to use ACC

As previously pointed out in Section 2.2.2, the driver is the only one who can coordinate with the ACC system. It is therefore important that the driver learns how to work well with the system, and knows its limitations.

Simon & Kopf (2001, in Simon, 2005) found several, not necessarily linear, learning phases in understanding ACC behaviour during a four-month field study with five participants. The drivers generally started out by testing the limits of the system and learning system reactions in different environments. After having done that, they learned the ACC's situation-specific limits, and lastly started integrating the system into their own driving style. Similar learning strategies were mirrored in a telephone survey of ACC owners by Llaneras (2007). Llaneras declares that drivers initially behave cautiously with the ACC system, but with time extend their usage of it and probably test its limits in doing so. After that initial testing period, Llaneras found that drivers seemed to go back to a more conservative way of using the system. Simon (2005) concludes, from the same field study as before, that there are four main difficulties in learning to work with the system: Handling the take-over in situations where system limits are exceeded, using the system in adverse conditions (e.g. bad weather or bad roads), operating the system's settings, and missing or faulty explicit knowledge about the system. Simon infers, from panic brake situations identified during the study, that after the four months of driving with the system some misconceptions about it were still at play. Some of these misconceptions were a lack of knowledge about the selectable distances, but also about the ability of the system to handle specific situations or not.

With increasing experience of the ACC system, more ACC limitations are known. According to a survey with 58 ACC users who had used ACC for up to five years, drivers who were more unaware of system limitations tend to use ACC in riskier environments, something that probably over time makes them more aware of limitations (Dickie and Boyle, 2009). Simon (2005) also points out that driver learning appears to be self-paced, so that drivers with risky behaviour push the system more in the beginning, thus learning about its limitations more rapidly. Drivers may also, depending on where and when they drive, take longer to experience events that reveal system limitations. Mainly, drivers do not appear to generalise limitations regarding sensor capacity, but link their knowledge of the system to specific situations that they apparently need to experience in order to know what the system may have difficulties with (Strand et al., 2011). Similar results can also be found in Jenssen (2010). Despite reading the manual where such information was available, 99% of 148 ACC owners in Llaneras' (2007) sample were unaware that the ACC system did not stop for stationary vehicles. Beggiato and Krems (2013) also found that drivers did not remember events they were merely told about, but did remember events they had personal experience of. So, it appears that drivers must experience events in order to learn from them.

Weinberger et al. (2001) found in a four-week field test that drivers claim that their learning period to learn to assess take-over situations properly with ACC is around 2-3 weeks. A further analysis of changes in TTC confirmed this self-reported learning period. It is important to note that the drivers in Weinberger's study drove about 1400 km/week, well over average, wherefore the learning period may be longer for other drivers who encounter fewer types traffic situations. Fancher et al. (1998) note that 95% of of those who tested ACC felt able to recognise situations where they need to reclaim control after one week with an ACC system. Sixty per cent felt comfortable doing so after just one day with the system.

3.1.1 Communication by the ACC

Learning how the system functions is made possible by how the driver understands what is going on with the system. How the automation interacts with the operator is therefore at least as important as the technical functionality of the system when learning to handle events safely. The system may use icons as its prime means of information, but the visual mode is not the only mode used by operators to learn about driving support system status. Dijksterhuis et al. (2012) found that drivers preferred using the actions by their driver support system as a warning signal rather than the information provided on a head-up display. A similar effect was found by Aust et al. (2013), who suggest that with experience, drivers learn to respond to system warnings rather than to the event causing the warning.

The system's actions therefore communicate what it has been able to detect about the world around it. When the system's logic indicates that it has no vehicle in front or that the vehicle in front is very far away, it accelerates. When it determines it does have a vehicle in front, and that the vehicle in front is slower than the current set speed, it decelerates (also see Figure 1.1 on page 3). These actions can both be felt and, in the case of acceleration, heard by the driver. The decelerations by the ACC system have also been suggested to draw the driver's attention to potential conflicts (Ervin et al., 2000).

Donald Norman (1990) has suggested that inappropriate and inadequate feedback and interaction is the main problem when working with automation. Systems are also very rarely designed to communicate how certain they are of a particular diagnosis. This lack of communication by automation means the operator cannot proactively learn if something is wrong or not, Norman argues, and the lack of information thus keeps the operator "out of the loop". It could, as done by Ervin et al. (2000), be argued that the behaviour of ACC constitutes continuous information in itself. The semi-continuous nature of ACC acceleration as a cue to system status is coherent with research pointing to the importance of indirect information building a shared context between operator and automation (Wiese and Lee, 2007; Norman, 2007). Providing context-relevant information about system reliability can also lead drivers to allocate attention more appropriately and thus improve driver-automation performance (Bagheri and Jamieson, 2004). The ACC's behaviour, however, misses out on also communicating the system's view of what is going on between accelerations and decelerations, thus leaving out one key factor in understanding why it responds the way it does. A human co-driver might not communicate such considerations either, but can always be asked to divulge them. Thus, drivers are required to respond to system actions rather than be able to predict them.

3.2 Behavioural adaptation to ACC

Studies of behavioural adaptation to driving with ACC generally focus on changes in speed behaviour, adopted safety margins, lateral control of the vehicle, and lane occupancy/lane change behaviour (Saad, 2004). Of these, lane occupancy and lane change behaviour are the only more complicated tactical behaviours by the driver that are being measured. As Saad and Elslande (2012) point out, such a focus does not provide a deeper understanding of the underlying principles of behavioural adaptation.

The results from the studies on behavioural adaptation are not always in agreement with each other either. With regard to safety margins and driving speeds, results point in different directions according to two meta studies (Saad, 2004; Dragutinovic and Brookhuis, 2005). Dragutinovic and Brookhuis propose that the diverging results may, at least to some extent, be due to the design of the ACC systems used in the various studies. The methods used, such as simulator study or closed-track field studies, could also according to Saad et al. (2004) have had some influence on the findings. The level of support provided by the ACC system may also affect behaviour, as full-range ACC appears to lead to an increase in speed and decrease in time headway whereas ACC active only over 30 km/h does not (Dragutinovic and Brookhuis, 2005). Tactical driving decisions may lie behind these changes, but as more composite behaviours by the drivers were not studied, it is difficult to say.

Those who have studied tactical behaviour with ACC have indeed found changes in driver strategies with the system active. Drivers' overtaking strategies appear to change when driving with ACC, as drivers initiate the manoeuvre earlier in order to avoid being slowed down by the system detecting the vehicle in front and braking (Rajaonah et al., 2008). The tactical decisions made by the driver therefore appear to change, as drivers are affected by what actions are afforded by the ACC system. Reports also consistently point out that drivers are more prone to stay in the fast lane with ACC active (Saad, 2004; Hoedemaeker and Brookhuis, 1998). Saad and Villame (1996) speculate that the preference for the fast lane may be the result of drivers not wanting to intervene with the vehicle too often, and instead opting to change their strategies to allow for driving where they need to reclaim control as little as possible. In a field operational test from the 1990's, Fancher et al. (1998) also found that drivers adopt strategies in order to explicitly prolong the period of ACC engagement. Such strategies were for example not overriding the system by pressing the accelerator when the system was accelerating, even though drivers felt the ACC acceleration was insufficient. Further evidence of this type of strategy was found by Jamson et al. (2013), reporting that drivers using automation while driving in a simulator study were less prone to change lanes and overtake. Through aspects such as these, ACC-type systems appear to make the driving behaviour of the users more uniform (Saad and Villame, 1996).

3.2.1 Experience with ACC

When gathering experience with ACC, certain patterns emerge. Kopf and Nirschl (1997) found that both workload and intervention frequencies decreased with driver experience of ACC, indicating that drivers take system behaviour into account in their tactical decisions. These results were mirrored by Simon (2005), who also determined that drivers intervene less with ACC over time as they improve their ability to integrate ACC into their driving. Despite these effects, little research has thus far explicitly compared the behaviours of experienced and inexperienced ACC users. In a simulator study by Rajaonah et al. (2008), six of the forty-two participating drivers had experience with ACC from a previous trial. These six drivers were more likely to use ACC on motorways than the novices, though not on other major roads. The participants with previous experience also exhibited a more homogenous behaviour with ACC than the other participants did. Drivers with more experience of ACC also demonstrated a more conservative driving pattern than did other users, and so challenged the system less. This is similar to the results found by Llaneras (2007), that after the initial learning period drivers return to a more conservative driving pattern with ACC.

3.3 Field operational test studies of ACC

Analysis of data from real-world usage and real-world effects are important to understand the effects ACC can have on traffic safety, as the number of cars with the option of adding an ACC system increases. While some older vehicle automation systems such as ABS brakes are part of the car registry in Sweden and other countries, there are no public records of vehicles equipped with advanced driver assistance systems. Accident statistics are therefore difficult to come by. To gain knowledge of the effects and usage of ACC in real traffic, another option is to use data from a field operational test (FOT) study, where instrumented vehicles are driven for a longer time period. FOTs are large-scale testing programmes, designed to evaluate functions and vehicles under normal operating conditions, using a quasi-experimental method (FESTA, 2008). FOT data also provide an opportunity to study ACC with real drivers using ACC as and when they wish. The fact that the drivers select if and when to use the available systems fundamentally differentiates FOT studies from controlled studies. As participants are normally allowed to drive as they ordinarily would during FOT studies, comparisons between different vehicles and situations are wholly dependent on finding them in the data. The quasi-experimental manner of the method also means that results may be biased due to factors such as where drivers choose to activate their systems.

The analyses in FOT projects have generally focused on describing when and how systems are used, but some have attempted to study effects on safety as well. Driver behaviours have been analysed in situations where ACC initiates braking, using the data from a three-week FOT study (Xiong and Boyle, 2012). The authors attempted to predict driver behaviour by constructing a model through logistic regression, and found that several situational factors seem to affect driver responses to system-initiated braking. The propensity for drivers to brake after ACC has initiated braking appears to depend on factors such as road type, speed, gap setting and driver age. In the data, drivers were more likely to intervene in near-crash closing situations (drivers intervened in about 50% of the cases) than in low-risk situations (drivers intervened in about 7% of cases), and more likely to intervene if they were not on a motorway, or middle-aged (40-50) rather than youger (20-30). The model has not been tested on other FOT data, or on data from a longer measurement period. Viti et al. (2008) suggest that deactivation of ACC often occurs because the ACC does not act the way the driver would prefer, not necessarily because of a need to brake because of a dangerous situation. The situations where ACC acts in an unwanted manner would, according to Viti et al., account for 65% - 70% of the total number of cases where drivers deactivate the ACC system, as identified by very soft braking. In 5% - 10% of the total number of deactivations, the situations were judged to be more acutely risky, as drivers braked hard straight away.

In the results from the EuroFOT trials, where the behaviours of 100 vehicles were recorded for 18 months, video analysis indicated neither a significant increase nor decrease in critical traffic conflicts with ACC (Malta et al., 2012). The lack of significance is probably due to the rarity of such more severe conflicts; only 68 were found in the data. More general safety indicators may, however, be affected by the use of ACC. Researchers (e.g. Ervin et al., 2005; Alkim et al., 2007) have found that the number of very short following distances is smaller with ACC active than without. Results from EuroFOT (Malta et al., 2012) also suggest that ACC is connected to an increase in average THW and a decrease in the number of critical THWs below 0.5 seconds, when using ACC on both motorways, urban and rural roads. The increase in general THW was about 15%, and the frequency of critical THWs decreased by over 60%. The authors suggest that the reason for this was the limitations in possible THW with ACC: The system does not allow for THW to be as low as 0.5 seconds, whereas drivers are completely free to choose THW when driving without the system. After deactivating ACC by pressing the brake pedal, THW decreases again (Pauwelussen and Feenstra, 2010). Nevertheless, results pointing to larger THW with ACC may be biased by the conditions in which the system is typically used. Viti et al. (2008) found that drivers do not use ACC in congested traffic, suggesting this might be due to the system not allowing such short headways as are needed in queues.

Alkim et al. (2007) as well as Rudin-Brown and Parker (2004) and Fancher et al. (1998) found that drivers engage more in secondary tasks with ACC, the number of those tasks also increasing with time according to Alkim et al. However, ACC is seldom used in traffic where it may be more likely that attention is needed outside the vehicle, such as congestion or in urban areas (Alkim et al., 2007). Instead, drivers predominantly use ACC during free flow on motorways, something also reflected in the driver statements collected by Strand et al. (2011).

To summarise, ACC does not appear to affect driving safety in a negative way. Instead, the use of ACC increases the THW to the vehicles in front. In combination with drivers using ACC in less congested traffic, this may be the reason behind a lack of adverse effects. Drivers do however still appear to deactivate the system in circumstances where it does not respond in a manner preferred by the driver.

3.4 Attention when working with automation

Visual attention is one of the most important aspects of car driving, as most information while driving comes from a visual source. Driver attention is often operationalized and then studied by eye-tracking, as what the driver attends to can then be studied by doing a comparison of gaze distributions or the number of gazes to specific areas.

Victor et al. (2009) found that active ACC was correlated with more focused driver gazes, much as in the study on manual car following by Crundall et al. (2004) reported in Section 2.1.1. Victor et al. do not speculate as to why, and it was unclear whether they compared gazes with ACC to car following without ACC or driving without following another vehicle. Contrary to this, Carsten et al. (2012) suggest that with increasing automation, the amount of gazes into the middle of the road ahead decreases. With the addition of lateral control to ACC (assisted steering), drivers tended to be less attentive to the roadway than when driving with longitudinal support alone.

3.4.1 Monitoring automation

Parasuraman and Wickens (2008) argue that with active automation, operators tend to allocate attention away from monitoring and controlling automation by decreased attention to “raw data”, the information operators normally use to achieve a task. One reason given for this effect is the lower workload, or even ”underload,” afforded by automation. Young and Stanton (2002a) have suggested that a decrease in workload could affect the amount of attentional resources available. The authors argue that if task demands are too low, the available pool of attention decreases, thus making it less likely that drivers notice potentially important things.

Over-reliance, depending on the system outside its functional limits, has also been pointed out as a risk when using systems that have proven themselves over a longer period of time. With ACC, this would be the case if the system suddenly malfunctioned and did not brake in a situation it normally would. Over-reliance may even cause the operator not to intervene, or intervene too late upon realising the system cannot, in fact, cope (Stanton and Marsden, 1996). This brings the concept very close to that of trust in automation.

Factors that may influence monitoring behaviour It has been suggested that ”complacency”, not monitoring the system ”enough”, is the effect of automation competing with manual tasks for the operator’s attention when using reliable automation (Parasuraman and Manzey, 2010). With reliable automation, operators (or drivers) are thought to stop monitoring automation, believing that the automation does well anyway. The operator’s level of trust in automation is mainly measured by operators’ subjective ratings on several dimensions, such as predictability, dependability, responsibility and confidence (Muir, 1994). Other factors that come into play are desirable and consistent system behaviour (Muir and Moray, 1996), and the trust the operator has in cooperating with the automation (Rajaonah et al., 2008). In a study by Rajaonah et al. (2008), drivers who trusted ACC more waited until it was clear that a system response was insufficient before they responded themselves. Drivers with less trust intervened before the ACC did so. Increased trust in automation has thus been suggested to lead to decreased monitoring of automation performance, especially with higher levels of system reliance (e.g. Muir and Moray, 1996; Bailey and Scerbo, 2007). Xiong et al. (2012) however, did not find that the group with the highest trust in ACC was behaving in the most risky manner. Instead, risky behaviour was rather connected to participants having less knowledge of system limitations. A slightly different result was found by Dickie and Boyle (2009), who state that drivers with higher levels of trust in ACC were more likely to be unaware of its functional limitations. Lee and See (2004) in their review found no conclusive evidence that higher levels of trust in a system were associated with less monitoring, but still concluded that what is important is not high trust, but appropriate trust.

Trust is thus seen by some researchers as something to be influenced and ”corrected” so that operators exhibit the ”right amount” of trust and thereby behave ”correctly” (e.g. Dickie and Boyle, 2009; Lee and See, 2004). These are normative statements, and tend to be dependent on hindsight in determining ”correct” behaviour. The perspective also ignores whether drivers' behaviours may be making sense to them, and in that case why. Studying ”trust” alone misses out on a wider perspective that could offer more insight into how operators handle and understand working with automation. Whether measuring trust in the system or in one's cooperation with the system, ”trust” appears to be more a proxy of the understanding the operators have of system capabilities.

Measuring monitoring behaviour Farrell and Lewandowsky (2000) suggest that the reason for a possible decline in monitoring reliable systems is mainly that automation makes the operators learn to avoid responding to cues when automation is active, which is why the effect can be mitigated by the operator periodically going back to manual control. The delegation of control to automation has for example been seen with intelligent speed adaptation, ISA (Hjälmdahl and Várhelyi, 2004). Hjälmdahl and Várhelyi found that outside the ISA test area, where the system no longer provided indication of the current legal speed, drivers neglected to adapt their speed when entering a new speed zone.

However, successful monitoring might not be the best measure of attention. Moray (2003) and Moray and Inagaki (2000) state that monitoring may be a bad way to determine over-reliance or over-trust in a system as it is impossible to determine a ”correct” monitoring strategy except with hindsight. Monitoring also depends on when a signal appears and what the operator's priorities are at that moment. The attention strategies employed by the operator are therefore be a better item of study (Moray et al., 2000).

3.4.2 Attention in traffic conflict situations

The results reported above largely imply that driving with automation decreases driver attention to both automation and roadway regardless of the situation. However, several studies compare gaze or workload over a longer period of time that is not situation-specific (e.g. Victor et al., 2009; Carsten et al., 2012), thus only forming general ideas of how attention may be affected. Some exceptions can also be found. Studying driving in more detail, Brookhuis et al. (2009) found that driving with a congestion assistant (a congestion warning system with integrated ACC stop and go) led to a decrease in workload, except just as the driver approached the congestion the system warned about. Garrison (2011) found there was no difference in gaze frequency to hazards for distracted drivers compared to non-distracted drivers. For traffic signs, which were not connected to hazards in any way, there was a decrease in the amount of gazes in that direction of distracted drivers compared to non-distracted drivers. Similarly, though driver attention is directed away from the roadway in light traffic, in heavy traffic driver gazes to the road centre increase again (Jamson et al., 2013). Video analysis in the EuroFOT project (Malta et al., 2012) also found that while drivers were more prone to do secondary tasks when using ACC with FCW while driving, no such difference could be found in crash-relevant events. So, drivers appear to adjust their attention strategies according to situational demands.

3.5 Responding to traffic conflicts with automation

The term ”traffic conflict” has previously been defined in Section 1.4 on page 6. It is important to keep in mind that traffic conflicts need not be very serious. The traffic conflict only entails that at least one of the vehicles involved needs to do an avoidance manoeuvre to avoid collision. The avoidance manoeuvre, however, does not need to be abrupt, but can involve just a minor decrease of speed.

de Waard et al. (1999) surmise that system functionality needs to be communicated very clearly in a highly automated situation. They also suggest that drivers should not have a completely passive role in the system if a sudden system failure requires the driver to reclaim control (see also Young and Stanton, 2007). Farrell and Lewandowsky (2000) argue that a decline in monitoring performance reflects that operators are suppressing their natural responses to driving with regard to e.g. the longitudinal control. Using automation therefore means that operators need to actively stop themselves from intervening in order to allow automation to handle a situation. One way to counteract this effect is to make the operator intermittently reclaim control, as this diminishes the effects of learning not to react (Mouloua et al., 1993; Farrell and Lewandowsky, 2000). Though intermittently reclaiming control may be a good approach, drivers seem to be reluctant to perform actions that cause them to actively disengage or engage the system, at least with regard to tactical decisions such as overtaking, as explained in Section 3.2 on page 25 (Jamson et al., 2008; Fancher et al., 1998; Rajaonah et al., 2008). Such strategies might therefore be difficult to implement.

Drivers of fully autonomous vehicles have, in simulator studies, found to respond more slowly to alarms signalling imminent collision than manual control drivers (Merat and Jamson, 2009). Vollrath et al. (2011) also found that drivers were several seconds slower when driving with automation to reduce their speed when cued by a sign or when driving into a fog bank, compared to driving manually. In simulated traffic conflicts where there is a need to brake for stationary vehicles, drivers have been shown to not necessarily respond when ACC systems fail to react. Instead, around 30% collide with the stationary vehicle (Stanton et al., 1997; de Waard et al., 1999; Nilsson, 1995). Researchers have sought to explain this in a number of different ways, ranging from driver expectations of system capabilities to bad communication by the system, or that the driver is no longer an integral part of the control loop. Going back to the previous discussions on delegating control (see Chapter 2.3), it is important to point out that a slower driver response is not in itself faulty behaviour. It is suitable when using ACC to allow it a chance to respond before deciding to step in. Ervin et al. (2000) also speculate that the rarity of traffic conflicts exceeding system braking capacity makes it difficult for drivers to assess the situation correctly straight away.

Despite the fairly concurrent research pointing to drivers' slower response times with automation, problems with slower response times or a neglect to respond have so far not been apparent with commercially available systems in real traffic. One reason may be the addition of forward collision warning (FCW), alerting drivers to the risk of imminent collision. FCW was not present in the studies by Nilsson or Stanton et al.; drivers had to diagnose the situation by themselves. A signal like FCW could have led to results being more similar to that of Merat et al. (2012), who found that the response time when drivers performed a lane change to avoid collision as advised by a sign was similar to that in manual driving. There are other studies that indicate a lack of difference in response times between manual and automated modes as well, but only in certain situations. In Nilsson (1995), another scenario required drivers to respond to a sudden cut-in situation after the vehicle cutting in had activated its indicators. Here, no difference between supported and unsupported modes was found. Why the drivers responded differently in Nilsson's cut-in situation compared to imminent collision in other studies is not clear. Malta et al. (2012) also report from the EuroFOT trials that when real driving situations exceeded the braking capabilities of ACC, the warnings presented by ACC+FCW were enough and drivers responded in timely fashion. Proactive responses are not mentioned, but drivers had no worse or better response times with ACC than without when responding to FCW warnings.

The next step in continuous vehicle automation is likely to be automated steering, which could further "disconnect" drivers from the immediate driving task. However, the addition of automated steering to an ACC function does not necessarily affect brake response times more than ACC does (Stanton et al., 2001; Young and Stanton, 2007), even though automated steering may decrease workload (Stanton et al., 2001; Flemisch et al., 2008; Carsten et al., 2012). Even so, steering responses may be affected. Flemisch et al. (2008) suggest that when drivers were allowed to use their hands for other things than steering and not told to always keep their hands on the wheel, they failed to keep the vehicle on the road when the automated steering stopped working. Shared control with automation by always insisting on physical driver contact with vehicle controls may be preferred, as it would allow the driver to experience more aspects of vehicle control as the system communicates its actions with the driver to a larger extent (e.g. Kienle et al., 2009; Norman, 2007). In a study of a shared control lane keeping assistance system, assisted and non-assisted drivers both were equally successful in avoiding an obstacle by steering (Mas et al., 2011).

3.6 Summary and empirical gaps

Drivers largely appear to learn ACC limitations on the go, and do not remember limitations they have merely read about (Llaneras, 2007; Beggiato and Krems, 2013). This also means that with time, more of the system's limitations are known to the drivers (Dickie and Boyle, 2009). Researchers (e.g. de Waard et al., 1999) also suggest that improving the driver's understanding of the system's limits ought to function as a mitigating factor to make the driver respond quicker in critical situations. However, knowing system limitations and the criticality of a traffic conflict may not necessarily be the cause of driver responses: drivers may instead learn to respond to the system's response to events (Aust et al., 2013; Ervin et al., 2000). The speed and perhaps manner in which experienced users and novice users respond to ACC behaviour may therefore be different.

The use of ACC does not affect THW or speed in a distinct way: results point both to increases and decreases (Saad, 2004; Dragutinovic and Brookhuis, 2005). However, drivers' tactical driving decisions are affected: Drivers are reluctant to intervene with the ACC and prefer to stay in the fast lane with the system (Hoedemaeker and Brookhuis, 1998; Fancher et al., 1998; Saad and Villame, 1996). There are some indications that drivers change their overtaking behaviour with ACC, in order to avoid the system's distance adjustment interfering (Rajaonah et al., 2008). Tactical behaviour has not been studied in FOTs, but the research so far indicates that drivers keep fewer very short time headways with ACC (Ervin et al., 2005; Alkim et al., 2007; Malta et al., 2012) which may serve as indicative of changed driver behaviour. Saad and Villame (1999) in Saad (2006) also stress the importance of taking context into account when studying the effects of driving automation. Semi-automated vehicles add to the drivers' sources of information and provide novel ways to interact with the vehicle. These changes affect the conditions in which the driving task is performed, influencing it by its design. Driving with ACC or similar systems may entail that some environments change importance, as what was before a simple curve requiring the driver to ease off the accelerator may require a different response or behaviour with the system. However, few studies have aimed specifically at investigating driver interaction with ACC (Saad et al., 2004). Therefore, the question of how drivers take ACC system behaviour into account when driving is still not quite clear.

Researchers are also interested in the ability of drivers to reclaim control in traffic conflicts if the system fails (Stanton et al., 1997; de Waard et al., 1999; Nilsson, 1995). Results indicate that drivers are slower to respond in situations with automation failure than in a manual control situation. System failures have so far not been reported from FOT studies, wherefore such occurrences are likely to be highly uncommon. Responses to critical traffic conflicts in the EuroFOT study do not point to any significant changes in response times (Malta et al., 2012). Systems are unlikely to fail, having been tested extensively before release. However, their functional and operational limitations will force the driver to reclaim control at some point while driving with the system, prompted by the system or not. It would therefore be of great interest to study situations that arise more often, where the driver still feels compelled to reclaim control.

The appearance and handling of more commonly appearing traffic conflict situations also constitute the learning set for drivers learning system limitations (Simon, 2005; Dickie and Boyle, 2009; Strand et al., 2011). The studies reviewed above, bar very few, study novice users and their responses to driving with ACC. There is a lack of studies looking at experienced users' responses, and knowledge of how they may be different from those of novices. Having learned how ACC works should lead to a difference between experienced users and novice users in their response to system actions and tactical considerations in various circumstances. When drivers become accustomed to driving with ACC, they do appear to change their usage of the system (e.g. Dickie and Boyle, 2009). It is likely that drivers' plans and tactical behaviours for accomplishing the task of driving change as they become used to the system handling some of the car following itself. The events requiring driver attention are likely to be different when driving on their own compared to when delegating control to a continuous support system of some sort. Having previous experience with ACC may therefore also affect drivers' use of future automation, such as ACC with the addition of active steering (ACC+AS). With the addition of lateral control, some of the drivers' habitual behaviours with ACC may transfer. As it is likely that those who own ACC today will be among the first to use ACC+AS, it is interesting to study if and how those used to ACC respond when driving with ACC+AS.

Perhaps it would be simpler if you just did what you're told and didn't try to understand things.

- Terry Pratchett (Sourcery)

4 Research questions

The main setting for this thesis is driver delegation of control to ACC in commonly occurring borderline traffic conflicts where drivers may or may not wish or need to reclaim manual control. The focus lies on how drivers incorporate longitudinal automation into their tactical driving decisions, by studying both experienced and inexperienced ACC users. The aim and how the research questions connect to the four papers can be seen in Figure 4.1. There are three studies, reported in the four papers appended to the thesis. One questionnaire study (Paper I), one simulator study (Paper II and Paper III) and a FOT database study (Paper IV). The results in Paper II reported in Chapter 5 also include some further analysis of the data only reported in the thesis.

First, the effects of experience with ACC on responding to common traffic conflict situations is studied to provide an answer to how experience may matter when studying the effects of longitudinal automation. Then, a broader description of changes to mainly tactical driving behaviour brought on by ACC is studied, to expand on any findings in the previous question. Lastly, a comparison between ACC and ACC+AS is made in order to see if experience with ACC may affect how drivers behave with an even more advanced type of continuous automation.

4.1 Research question 1 - Experience

- How do experienced ACC users understand and respond to the ACC system in common traffic conflict situations, compared to novice users? (Paper I, III and II)

With more knowledge of system functionality and actions, experienced drivers could delegate control to ACC in a different way than novices, having adapted to the system's limitations. Studying the behaviour and understanding of experienced ACC users compared to new users can also reveal whether there is a difference in how drivers resolve which traffic conflicts the system can handle, and which borderline conflicts that require a manual response. A combination of

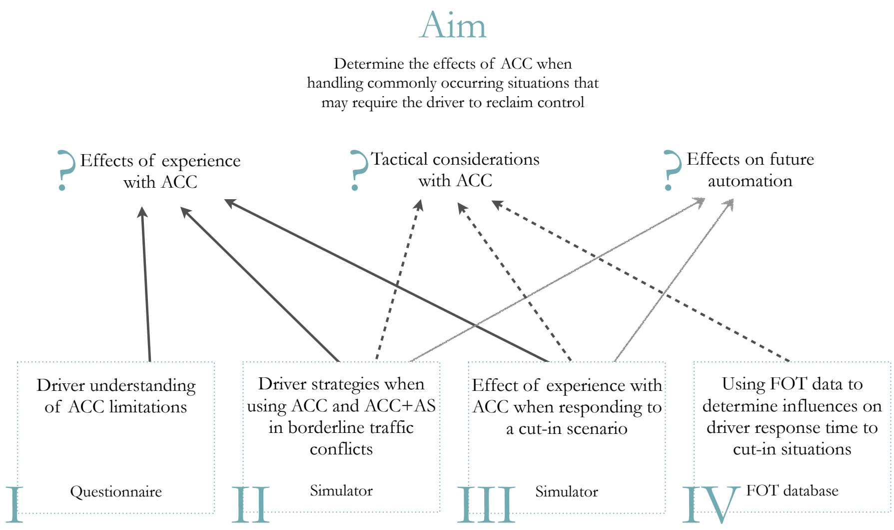


Figure 4.1: How the empirical studies in the papers connect to the research questions

approaches can therefore provide a more extensive understanding of how response times, strategies, and knowledge of system limitations interact.

This question is first addressed with a questionnaire study looking at how drivers with various amounts of experience with ACC understand the system (Paper I). Then, experienced and novice users of ACC are compared in a simulator study, contrasting their response times (Paper III) and strategies (Paper II) when using automation.

4.2 Research question 2 - Tactical considerations

- Which tactical driving consideration can be found in common traffic conflict situations when delegating control to ACC? (mainly Paper II and IV, also Paper III)

Previous studies of changes in the tactical aspects of driving with automation have largely been described quantitatively, such as time spent in a specific lane or if the driver overtakes other vehicles at all. A more qualitative approach should be of benefit to describing broader patterns of how driver strategies change when using automation, helping to elucidate on the reasons behind the changes in overtaking or lane positioning. By comparing response times in a simulated scenario to the corresponding real-world events as in EuroFOT, further considerations made by drivers in the real world may be ascertained.

This research question is mainly investigated by determining driver responses to common borderline traffic conflict scenarios set up in a simulator. Driver behaviour with automation will be studied in and during the approach to these traffic conflicts, where drivers may wish to reclaim manual control. The EuroFOT database will also be used to contrast response times in a real-world event to the similar cut-in event in Paper III (Paper IV).

4.3 Research question 3 - Effects on future automation

- Do drivers behave and respond the same way with ACC that also includes a lateral component as they do with ordinary ACC in common traffic conflict situations? (Papers II and III)

There is little understanding of why drivers' attention strategies are different with lateral automation than longitudinal automation (Carsten et al., 2012), and also what may be the mechanisms behind behavioural adaptation. Uncovering the workings behind any changes in tactical driver behaviour would enable a prediction of the effects of future systems, and allow the design of systems better suited to human cognition. Comparing both tactical driver responses and pure response time measures in different scenarios with ACC and ACC+AS enables a discussion of some of the behavioural effects and considerations that drivers make with these systems.

This research question is addressed by designing borderline traffic conflict scenarios and testing them in a simulator. Here, comparisons are made between driver responses when driving with ACC and ACC with active steering (ACC+AS). Comparisons are also made to intentional car following, a "manual" way to delegate decisions of where to drive, in order to determine whether cognitive and automation based delegation are similar.

There isn't a way things should be.
There's just what happens, and what we do.

- Terry Pratchett (A Hat Full of Sky)

5 Empirical studies

This chapter summarises the methods and results from the empirical studies performed for this thesis. For a more detailed description of the methods chosen and the data, see the papers attached. The studies were conducted from 2009 to 2012, using three main methods: a survey by questionnaire (Study I), a simulator study (Study II) and a database study (Study III).

5.1 Study I
Driver understanding of ACC limitations

This study is reported in Paper I. The purpose of the study was to investigate to what extent owners of ACC equipped vehicles know the limitations of the ACC system, and how they use the systems in real-life situations. A questionnaire was employed in order to reach as many users as possible.

5.1.1 Method

A questionnaire, comprising 16 questions (translated version in appendix), was sent by post to owners of Volvo XC60 identified with the help of the Swedish car register. Volvo XC60 was chosen due to the high rate of ACC systems bought by owners, around 30% according to Volvo Cars Sweden (personal communication, 2009). The XC60's were registered in Sweden between 2008 and 2009, as this was then a new model. Currently, no records of the addition of ADAS to vehicles exist in the Swedish car register. Through the car register, 632 addresses of Volvo XC60 owners were identified, providing a maximum of roughly 200 respondents with ACC. To assist drivers in determining if they should answer the questionnaire or not, a thorough explanation of the differences between conventional cruise control and ACC was enclosed. Only drivers with ACC were encouraged to answer the questionnaire.

The aim of the questionnaire was for the respondents to provide their understanding of ACC and its limitations, and to generate hypotheses for future studies. The questionnaire comprised 16 questions, and took about 20 minutes to complete. As this was an explorative and predominantly qualitative study, no statistical analysis of the answers was undertaken. Instead, answers should be seen as an indication of what types of limitations owners are aware of. Questions were primarily in free form, and respondents were required to write down their answer manually. Free form questions were used to avoid influencing the respondents unnecessarily. As knowledge of system limitations was sparse at the time of this study on behalf of the author, including a list of the known limitations may have caused the respondents to focus on them unduly, thus not listing or referring to other limitations they knew about. The disadvantage of free form questions is that this design relies on the respondents' memory and understanding to a higher degree, as well as being more time consuming and effortful to complete. Therefore, the results are probably on the conservative side compared to giving participants a list of possible system limitations to select from.

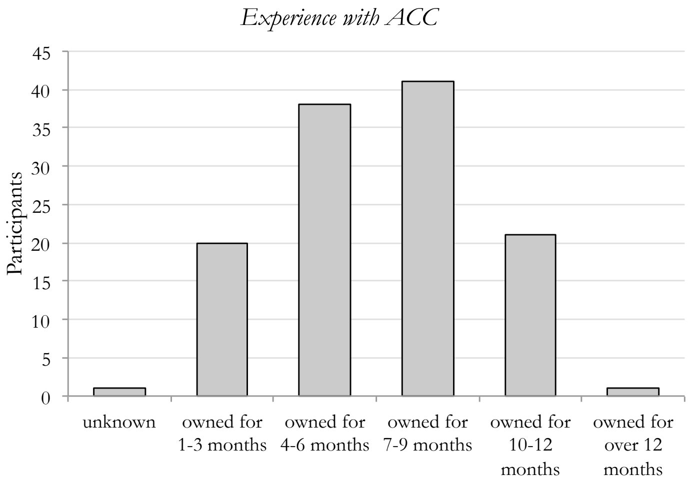


Figure 5.1: Driver's experience of using their ACC-equipped vehicle

5.1.2 Participants

Of the 632 questionnaires, 131 were returned. Questionnaire responses were examined to eliminate drivers who did not have ACC, and one answer was discarded as a result. This left 130 respondents with ACC in their vehicles, at a response rate of 65% compared to the theoretical maximum of 200 respondents (30% of the total number of XC60 owners). Of these, 106 were men and 23 were women. One respondent did not provide information on gender. Nine of the respondents, four women and five men, claimed to never use the system (several mentioning that it did not suit their driving style) and were excluded from the analysis, leaving a total of 121 respondents.

5.1.3 Results

The participants had used the system for up to approximately 12 months; half of them less than 6 months and the other half more than 6 months (see Figure 5.1). Respondents drove a median of 23 750 km/year, to be compared to the Swedish national average of 13 360 km/year (in 2009, see SIKA, 2010). Ages ranged through all age brackets provided, from below 25 to over 66, with half of the respondents in the age bracket 45-55 years. Drivers reported primarily using ACC on motorways and other larger roads. Half of the respondents disengaged the system when entering cities.

Drivers mention the physical sensation of acceleration as a cue to the system having lost radar contact with the lead vehicle in sharp curves (see Table 5.1). 31 of the 121 respondents (26%) also reported having experienced insecurity of whether the system was on or off until action/lack thereof alerted them to the fact.

Most respondents reported being aware of limitations in the system, but 36 did not. The most commonly reported limitation was car following in sharp curves, where the radar can lose contact and the system subsequently speeds up. Other known limitations can be seen in Table 5.1.

Limitation	*Quote*
Sharp bends	*"The car 'loses' contact in relatively sharp bends, and speeds up as a consequence."*
Vehicle in front braking sharply	*"When the vehicle in front brakes sharply, I sometimes have to revert to manual control."*
Overtaking on the fly	*"The speed goes down just as I am about to overtake [the car that I have just reached]."*
Vehicle cutting in	*"When someone squeezes into my lane in front of me. Sharp braking!"*

Translation from Swedish by the author

Table 5.1: Sample of the limitations reported by the participants, with quotes.

Depending on how long the driver had used the system, the number of drivers who state knowledge of at least one system limitation increased (see Figure 5.2). For the more experienced users, "simple" limitations such as problems in sharp curves were mentioned less, with more specific examples such as system performance in snowfall surfacing.

Brief discussion The key finding from this study was that the knowledge of system limitations increased with the amount of time spent with the system. The complexity of the limitations mentioned also increased when drivers had more experience with the system. Drivers also mention the physical sensation of acceleration as an important cue to system state. It was also evident that some drivers chose not to use the system as they claimed it did not suit their driving style.

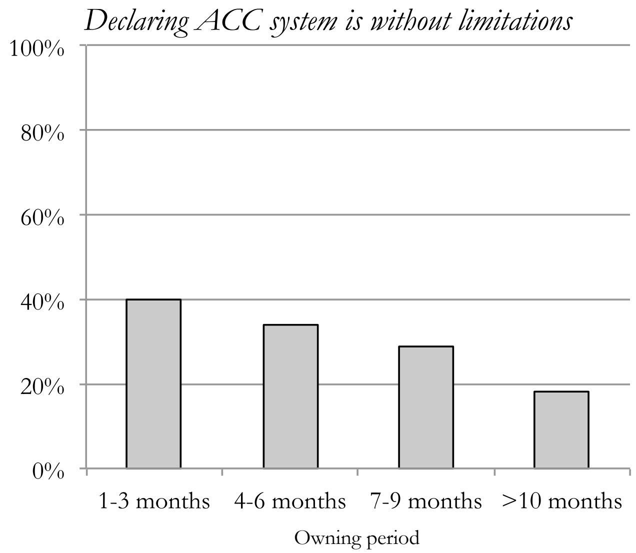


Figure 5.2: Percentage of respondents in the respective groups who claim that the ACC system has no limitations, each adds up to 100%.

5.2 Study II
Responding in tactically important driving situations

The results of this study are reported in Paper II and Paper III.

A simulator study was designed to allow the investigation of driver responses in different traffic scenarios requiring a tactical evaluation of the situation. The intention was also to compare novice users of ACC to those with previous experience of the system, thus limiting the relevant sample. Four different driving conditions were tested in the study to examine the effects of mentally or physically delegating longitudinal and lateral control.

The automation included the use of two ACC-type systems; one was a typical ACC system, the other was based on the same ACC system but with the addition of active steering (ACC+AS). Both systems lacked FCW due to limitations in the simulator. Two types of manual driving were also tested; manual driving with the instruction to follow the road, and manual driving with the instruction to follow a specific vehicle in front (intentional car following, ICF). Intentional car following has previously been shown to focus drivers' gaze on the vehicle in front, and affect their attention to the forward roadway (see Section 2.1.1 on page 9). Delegating lateral physical control as well as longitudinal control to a system has been hypothesised to affect driver attention, as it removes the driver further from the manual aspects of driving (eg. Carsten et al., 2012).

All scenarios were designed so that the driver would feel the need to intervene if driving in manual mode. If driving in automated mode, the system would respond at the last second to avoid a collision if the driver neglected to act.

5.2.1 Participants

Participants were recruited in two steps. Participants new to ACC were recruited by means of the Swedish National Road and Transport Research Institute (VTI) database of interested members of the public. Participants with previous experience of ACC were recruited with the help of Volvo Cars Sweden. Both sets of participants were first sent an e-mail describing the basics of the study and asking if they were interested. If responding in a positive manner, they were booked for the study and sent the background questionnaire. As those driving cars with ACC generally drive more than the national average (see Paper I), an effort was made to recruit novices to ACC who also drove more than average. More information on the participants can be seen in Table 5.2.

Due to technical difficulties, not all participants completed all conditions. Details follow in the results of the specific studies.

	Experienced with ACC, n = 21 (sd)	*Novices to ACC, n = 10 (sd)*	*Total, n = 31 (sd)*
Age	55 (sd 10)	38 (sd 9)	50 (sd 12)
Years with driving license	36 (sd 10)	19 (sd 8)	31 (sd 12)
Annual mileage (km)	29 000 (sd 13 000) median: 25 000	30 400 (sd 33 000) median: 22 500	30 000 (sd 21 000) median: 25 000
Years with ACC	1.6 (sd 2)	-	-
Annual mileage with ACC (km)	18 000 (sd 11 000) median: 15 000	-	-

Table 5.2: Background information on the participants in Study II, means (standard deviation in brackets)

5.2.2 Equipment and materials

The simulator used was the VTI Driving Simulator III, a moving-base simulator with linear motion in the lateral direction, roll and pitch movement of the whole simulator, as well as a vibration table for simulating bumps and road roughness. The simulator is equipped with six HD projectors, and has a field of view of 115 degrees. Three LCD screens were used as mirrors. For further information about the simulator, see Papers II and III.

Participants were asked to complete a questionnaire on their demographic background and experience with ACC before coming to drive the simulator. Participants were later issued with questionnaires on their trust in the systems, their attitudes towards the automated systems, and how they experienced the scenarios.

The ACC and ACC+AS systems both had a maximum brake and acceleration force, and took a second to lock on to a vehicle entering in front of it. Drivers were requested to always keep at least one hand in contact with the steering wheel, when driving with ACC+AS. The assisted steering could follow most turns, but when the yaw rate exceeded 45°/second the system was simulated to stop functioning and issued a warning signal. At the warning signal, the driver must immediately resume control as the steering system no longer is active. The drivers could not adjust system speed or chosen THW. These were pre-set at 75 km/h and 1.6 seconds respectively, to allow for some acceleration. The choice of 1.6 seconds was made as informal interviews with users (not reported) had indicated that a mid-level THW was the most commonly used.

Gaze behaviour was measured with the Smart Eye Pro remote eye-tracking system with four cameras. Gaze tracking availability lay at over 95%. The time during which the gaze cases were sampled varies both with event and individual, but encompassed about 3-8 seconds. As an indicator of attention to the roadway, per cent road centre (PRC) was computed for the moments of a scenario during which an action was required. PRC is defined as the percentage of valid gaze cases located within a circle of eight degrees radius around the centre of the gaze distribution of the whole trip (Kircher et al., 2009). The percentage of glances to the mirrors were also registered as an indicator for monitoring behaviour.

5.2.3 Procedure

Drivers first completed a training scenario of 10 minutes, allowing them to get used to the ACC and ACC+AS systems. Before the training scenario, all drivers were informed about the systems' functionality and functional limitations. The scenarios were driven in a within-subjects repeated measures design in four different conditions; manual driving, intentional car following, ACC and ACC+AS. Driving conditions as well as event order were counterbalanced. For each condition, driving took 15 minutes over a course of approximately 18 km. The drive consisted of five events (four of which are reported in this chapter) as well as single carriageways connecting them. The fifth event is the subject of a forthcoming paper.

Further information can be found in Papers II and III (appended).

5.2.4 Paper II: Driver strategies when using ACC and ACC+AS in borderline traffic conflicts

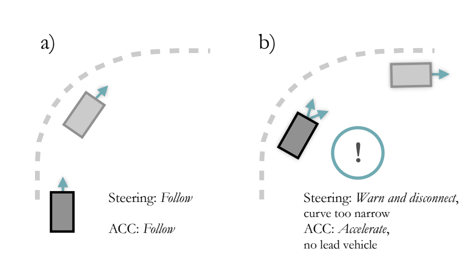
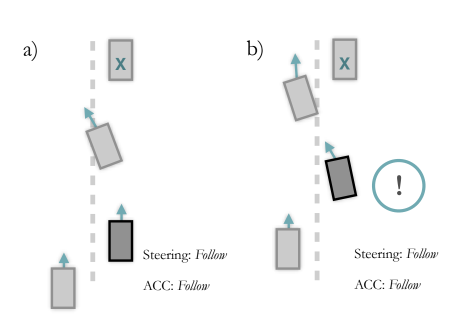
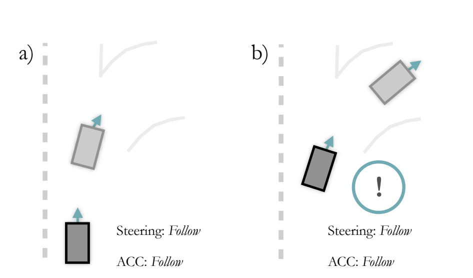
The changes in tactical driving behaviour in borderline traffic conflicts with automation were investigated for this paper. There was also an attempt to connect trust in automation to driver behaviour with the systems, to determine if trust affected driver responses (see Rajaonah et al., 2008). Three scenarios were examined, in which either environmental constraints or the actions of other vehicles forced the participant to respond (Table 5.3). One participant was excluded due to technical difficulties.

For the analysis, whether and where the driver had braked or steered was determined, as well as if and how the driver deactivated the system. How far and for how long the driver crossed the lane markings was also determined.

Results Trust in automation was high for both systems amongst the participants, and no connection between trust levels and behaviour with automation could be found. High trust in one system was not correlated to high trust in the other. Drivers exhibited different gaze patterns depending on the situations, but no differences with regard to the four driving conditions was found. For the broken car scenario, drivers tended to react earlier in the fully manual condition by easing off the accelerator than they did in the ICF condition (one-sided $X^2(2) = 3.6$, $p < .10$).

Drivers also seemed to make informed choices on how and when to use automation, and when to switch the system off either via vehicle controls or manually. In cases where the system was not expected to be able to handle the situation, the system was normally switched off before it reached its limits, such as in the exit scenario for ACC+AS. If, on the other hand, the system was expected to be able to handle the situation, manual control was generally not resumed as illustrated by the curve scenario and the broken car scenario: In the broken car scenario, some

Table 5.3: Illustrations and descriptions of the three events studied for Paper II. The ACC vehicle is in dark gray. The left (first) part of the image depicts the start of the event, the right (second) part depicts the middle of the event, when a response is needed.

Event illustration	*Event description*
	*Sharp curve scenario.* When entering the curve (a), ACC and ACC+AS have radar contact with the lead vehicle, but as the car drives further into the curve (b), ACC loses contact and accelerates the vehicle as ACC+AS cannot steer as hard as needed and warns the driver to reclaim steering, as the curve is too steep.
	*Broken car scenario.* In image 1 the lead car switches lanes on a 2+1 road to avoid the broken car, the participant needs to follow (image 2). The ACC+AS system follows the lead car around the broken car (image 2), despite the approaching vehicle in the outer lane. The ACC system requires the driver to steer.
	*Exit scenario.* The lead vehicle exits the main road (image 1), and the ACC+AS vehicle will follow the lead car off the road if allowed (image 2). ACC will accelerate the ACC vehicle until it locks onto a new lead car.

drivers even accelerated while still allowing the ACC+AS system to follow the lead vehicle. When driving with ACC in the curve scenario, 11 drivers reduced their speed below that of the lead vehicle, while six did so when driving with ACC+AS. When driving without automation, only six (manual) and four (ICF) drivers took no action, neither lifting their foot off the accelerator nor pressing the gas pedal (see Table 5.4).

Driver gaze patterns varied according to the scenarios ($F(2, 330) = 54.5$, $p < .05$), but generally not by the different conditions. The exception is the exit scenario, where the actions of the ACC+AS system caused drivers to look less at the road centre than in the other conditions. In the broken car scenario, drivers looked less at the road centre and more into the mirrors than during the curve or exit scenarios.

When taking experience with ACC into account, those previously acquainted with ACC reveal significantly higher levels of trust in ACC ($t(27)=2.96$, $p<0.05$). No effect of experience was

Table 5.4: Count of driver cases in the curve scenario of drivers did not respond with their foot, those who eased off the accelerator, and those who pressed the brake. All depending on driving condition.

Condition	*No action with foot*	*Off accelerator*	*Braking*
Manual (30)	6	24	8
ICF (29)	4	25	7
ACC (30)	19	N/A	11
ACC+AS (30)	24	N/A	6

found for trust in ACC+AS. The responses and gaze patterns of experienced and inexperienced users of ACC were largely similar. Still, some differences could be found. In the curve scenario, only those previously experienced with ACC crossed the lane markings in the ACC condition, whereas there was no such difference when driving with ACC+AS. Those experienced with ACC also looked less into the mirrors with ACC+AS in the curve scenario than did the novice users, $t(28)=-2.14$, $p<0.05$. In the broken car scenario, no behavioural differences were found, but there was a tendency in the ACC condition for those experienced with ACC to look less at road centre, $t(27)=-2.01$, $p<0.10$. Lastly, in the exit scenario, none of the drivers experienced with ACC deactivated the system by using the button in the ACC condition but novice users did. In the ACC+AS condition, similar rates of deactivation by using the buttons were exhibited by both those new to ACC and previously experienced with ACC.

Brief discussion Drivers appear to take system behaviour and limitations into account, whether the system is ACC or ACC+AS, and plan their actions accordingly. Drivers also appeared willing to drive according to the speed provided by ACC or ACC+AS in the curve scenario. Few disconnected the systems in the curve, despite decreasing their speed when driving with manual control, either by refraining from accelerating or by pressing the brake pedal. Experience with ACC appeared not only to be linked to higher trust in the ACC system, but also to driver behaviour. Drivers with experience of ACC did not feel a need to deactivate ACC when the current lead car left the lane, but allowed a transfer of lead car to the next in front. This is one of the events the system was designed for, wherefore experience causing a different behaviour is not surprising. Similar transfer effects were not found with ACC+AS, where those used to ACC and those inexperienced with it behaved in largely similar ways with regard to deactivations. It also seemed that ICF could affect driver strategies, so that drivers were slower to take their foot off the accelerator when following than when driving in fully manual and independent mode.

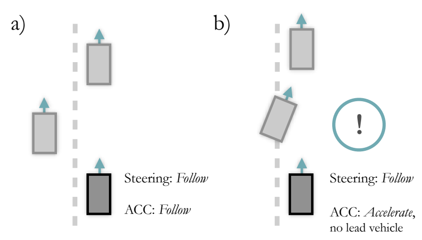
Gaze patterns were affected by driver experience in both the curve and broken car scenarios, though for different conditions. The reasons for these differences warrant further study. However, driver experience with ACC appears to play a role in how drivers work with ACC, and to a lesser degree also ACC+AS, and also to a certain extent how drivers allocate attention when driving with the systems.

5.2.5 Paper III: Effects of experience with ACC when responding to a cut-in scenario

This part of the study focused on the effect of experience with ACC on responding to system limitations in a cut-in situation for both ACC and ACC+AS (see Table 5.5). Understanding of system limitations has been suggested to improve driver responses in critical situations (de Waard et al., 1999). The cut-in situation consisted of slow-moving traffic where a vehicle from the left lane in a 2+1 road suddenly used its indicator and cut in front of the participant's vehicle. Such an event caused the ACC and ACC+AS systems to accelerate, the way the system were designed for this study, as they take a second to latch onto the new vehicle. As before, there was no possibility of a collision, but the drivers were meant to be uncomfortable and want to respond.

For the analysis, response time was calculated as the difference between the vehicle indicating and the participant pressing the brake.

Table 5.5: Illustration and description of the event in Study III. The ACC vehicle is in dark gray with a black frame. The left (first) part of the image depicts the start of the event, the right (second) part depicts the middle of the event, when a response is needed.

Event illustration	*Event description*
	*Cut in scenario.* A vehicle from the outer lane suddenly indicates (image 1) and enters the right lane in between the ACC vehicle and the lead vehicle (image 2), becoming the new lead vehicle. The ACC accelerates the ACC vehicle upon losing contact before again recovering contact.

Results Only cases where the participants reduced their speed by braking or deactivating the system were included in the analysis. As not all participants responded to the cut-in event by reducing their speed in all conditions, the sample sizes in the conditions vary. For this reason Kruskall-Wallis tests were employed to examine differences in response time between the conditions, followed by post-hoc analyses with Mann-Whitney.

Both the new users of ACC ($Z=-3.05$, $p<0.05$) and the experienced ACC users (Mann-Whitney $U=71.5$, $p<0.05$) were slower to respond in the automated control conditions than in the manual control conditions, by about two seconds. Comparing new and experienced ACC users, the experienced ACC users were significantly faster (about 0.5 seconds) to respond in automated control modes than the new users were, $U=202$, $p<0.05$. No such difference was found in the manual control modes. There was no difference in response times when driving with ACC compared to when driving with ACC+AS.

Brief discussion The quicker response by the experienced ACC users may be due to them having learned to respond to the system's acceleration rather than to the situation itself (Aust et al., 2013). Both groups respond slower with automation than without, but as the system is designed to handle less abrupt cut-in situations these results were not unexpected.

5.3 Study III
Using FOT data to determine the influence of ACC on response times

The results of this study are presented in Paper IV: The purpose of the study was to determine the effect of ACC on driver response times in real-world situations. Previous research has indicated that response times increase with the use of automation (e.g. Merat and Jamson, 2009). Research from field operational tests (FOTs) have, however, primarily indicated that there are fewer very short following distances with ACC than without (e.g. Ervin et al., 2005; Alkim et al., 2007). Even with a longer response time, it may therefore not be as risky to drive with ACC active. First, however, there is a need to determine any differences in response time with and without ACC in real traffic. The proposed method was to find comparable cut-in situations in the EuroFOT database, and statistically determine the influence of ACC. FOTs allow for the study of user behaviour with systems in the real world, instead of in artificial settings where users are asked to activate the systems in situations that may be unnatural to them. For a discussion of studying driver behaviour in FOT data compared to simulator data, see Section 6.1.3.

5.3.1 Overview of EuroFOT

The data set used in this study belonged to Volvo Car Company, comprising their part of the 18-month EuroFOT project. The database contains 18 months of data from 100 vehicles, collected between 2010 and 2011. A total of 284 drivers participated in the study, about 2.8 drivers per car. The vehicles involved were the Volvo XC70 and V70; an SUV and a station wagon. The upload of data was not complete at the time of this study, but at least three months of baseline driving (without access to systems) and three months of treatment driving (with access to systems) were uploaded per vehicle. The time periods did not necessarily connect. The total distance driven in the available data was 984 000 km, by 184 drivers. For more information on the EuroFOT trials, see the EuroFOT website: http://www.eurofot-ip.eu

The cars were equipped with ACC and FCW. During baseline driving none of these systems were available, but conventional cruise control (CCC) was, and during treatment ACC and FCW were available whereas CCC was disabled. Other systems available in treatment were blind spot information and a drowsiness warning. Participants chose freely where to drive and when to activate and use the available systems.

5.3.2 Procedure

An attempt was made at detecting cut-in situations that caused the driver to respond by braking. This was first accomplished by a script that extracted events from the database that corresponded to a specific set of criteria, leading to 1450 cases being found. The criteria used was a sharp decrease in THW, no lane change in the last three seconds, at least a momentary TTC of less than one second, and that the FOT vehicle's driver pressed the brake. The majority of events detected were however mergings where it could not be said another vehicle cut in front. Only cases where the driver had set a THW of 1.8 seconds or less were included in the analysis, for the results to be comparable to those in Paper III.

The videos taken from the cars of these potential events were inspected, and 674 cut-in events where the vehicle came from the lane to the right were identified. Too few events where the vehicle cutting in came from the left were identified to warrant statistical analysis. The distribution of ACC and CCC usage in the true cut-in events from the right can be seen in Table 5.3.

The situations were then analysed with a stepwise linear regression to determine what factors affected driver response times to the cut-in events. Variables were included and excluded based on p. P in was 0.05 and p out was 0.10. The dependent variable was brake response time to the cut-in event as detected by the script. Independent variables were ACC or CC usage, traffic density, and if the system had been deactivated by braking before the cut-in event. The control variables trip month, driver gender, driver age, distance driven before the event, and driving

ACC/CCC use during all cut-in events

	Cruise system inactive	*Cruise system active*	*Total*
CCC available	*109*	163	272
ACC available	195	*207*	402
Total	304	370	

Figure 5.3: The number of events in each category, with CCC or ACC available

experience were also used in order to avoid any interference with the results. The aim of the analysis was not to come up with a model to explain the variance in response times, but to determine if any of the independent variables had an effect, and in that case how large.

5.3.3 Results

Data were first analysed for all cut-in events identified ($n = 674$), regardless of whether the indicators were used or not before cutting in. Here, there was a tendency (p in < 0.10) that drivers using ACC were marginally (0.09 seconds) faster to respond compared to driving without any system active.

Events where the vehicle cutting in did not use its indicator prior to cutting in were then excluded from the analysis, in order to compare with the simulator study. In the simulator study, the vehicle cutting in used its indicator, thus providing an extra cue for the ACC driver. In the current FOT study, the use of ACC in events where the vehicle cutting in used its indicators ($n=547$) resulted in drivers being 0.24 seconds faster to respond, $t(530)=-1.97$, $p<0.05$.

Brief discussion The results from the FOT data indicate that drivers can be faster to respond to comparable cut-in situations with ACC active than driving in the same vehicle with CCC inactive and ACC unavailable. These results warrant further investigation of the conditions in which ACC is activated. Further investigations are also needed to determine any differences in driver responses, such as braking or releasing the accelerator in manual mode, and braking or decreasing speed by using the speed buttons for the ACC system in ACC mode. Perhaps, braking in manual mode does not fully correspond to braking when using ACC, but this needs to be studied further.

5.4 Summary of results

A first basis of driver understanding of ACC limitations was provided by the questionnaire results from Study I (Paper I). The questionnaire revealed that drivers are mostly aware of limitations to following in curves, but also cut-in situations and overtaking. Drivers can also be unaware of the system mode, and are cued to its state primarily by acceleration and deceleration. The scenarios in Study II were partly based on the limitations reported in Study I, but other fairly frequently occurring events where system limitations could become apparent were also included. The use of a simulator provided the means to study not only an ACC system, but also the addition of active steering. The decision was also made to include intentional car following (ICF) to see if such more abstract delegation of control may have an effect on driver attention similar to automation. Attention was operationalized as gaze patterns and response times to the events.

In the scenarios for Paper II (Study II), strategies of when to deactivate the system varied according to experience, as did trust in ACC. Those previously acquainted with ACC exhibited higher trust in that system, but there was no transfer effect to their trust in ACC+AS. It was evident that drivers appeared to have strategies of when to allow the ACC and ACC+AS systems to deal with an event. These strategies appeared to be connected to the limitations of the system; if the system could be conceived to be able to handle a situation is was generally allowed to do so.In the curve scenario, few drivers disconnected the systems, despite having decreasing their speed when driving without the systems. If, on the other hand, the situation was out of the system's capabilities, drivers deactivated the system before entering into the situation. In the exit scenario, where the current lead car leaves the lane, drivers generally deactivated the ACC+AS system. An effect of experience could also be found. Drivers with previous experience of ACC did not feel a need to deactivate ACC, but allowed a transfer of lead car to the next in front. Those inexperienced with ACC instead deactivated the system by pressing the button, reactivating it only after the lead car had left the lane, the same strategy as with ACC+AS.

The results reported in Paper III (Study II) indicated that differences in response times were not significant when comparing the different types of automation for both experienced and inexperienced users, but distinct between the manual and automation assisted conditions. Drivers were about 2 seconds slower to respond with automation than without. There were also differences between the response times of experienced and inexperienced users of ACC, as experienced users were faster to respond with automation active by about 0.5 seconds, $U=202$, $p<0.05$. In the FOT data for Study III (Paper IV), opposing results to the simulator study were found. The FOT data indicated that an activated ACC was connected to a faster response time (up to 0.24 seconds) to a cut-in situation, $t(530)=-1.97$, $p<0.05$.

When talking to and interviewing the participants for the studies, it became apparent that they did not view working with ACC as handing over control. Instead, drivers believe themselves to be in control at all times, and as such they are correct; the driver can always resume hands-on physical control of the vehicle from the ACC. Drivers also divulged that they use the set speed to manipulate the acceleration and deceleration behaviour of the car.

5.5 Answering the research questions

The results from the empirical studies are here put into the context of the research questions. The next chapter puts the results into a wider setting for a general discussion.

5.5.1 Research question 1 - experience

- How do experienced ACC users understand and respond to the ACC system in common traffic conflict situations, compared to novice users? (Paper I, III and II)

In line with other research (Dickie and Boyle, 2009), Paper I indicated that drivers learn ACC limitations while driving. Drivers understand more over time about the system's limitations with regard to handling traffic conflicts and environmental constraints, and are less inclined to state that ACC is without limitations. Drivers also mentioned that they used the system's acceleration as an indicator, to whether the system was active or not, in cases where they did not remember what state the system was in.

In Paper III, unexpected ACC acceleration also proved to be a cue affected by experience. Drivers with previous experience of ACC responded quicker to the unexpected ACC acceleration, as demonstrated by their faster response in a cut-in situation where the system accelerated when it ”should” have been decelerating. Knowledge of system limitations has also been suggested to make drivers respond faster in risky situations (de Waard et al., 1999) Paper II also revealed some differences between experienced and inexperienced users with regard to their gaze patterns with ACC. Those with previous experience of ACC tended to look less at the road centre during the broken car scenario than the novice users did, and in the curve scenario those with experience looked less into the mirrors. Thus, driver experience with ACC affects attentional strategies, as demonstrated both by the difference in response time in the cut-in scenario in Paper III and the gaze patterns in the curve and broken car scenarios in Paper II. In order to know more about these changes, interviews and further studies are needed to understand why drivers look less to the road centre or mirrors.

The results of the empirical studies indicate that not only do drivers learn more about the system's functionality over time, they also adjust their behaviour to the system's actions both by actions relating to handling the vehicle and attentional strategies. Deciding how and when to use the system seems, at least in the scenarios studied, to be affected by the known limitations of the system. If the system is able to handle an event well enough, it is mostly allowed to do so until the driver deems it necessary to reclaim control. If an event instead is immediately deemed to be outside system capabilities, the system is often deactivated (Paper II). Differences in strategies can be found between novice and experienced users as they have different levels of knowledge of system behaviour. Novice users appeared to be more conservative, as several deactivated the ACC system in the exit scenario of Paper II whereas no experienced users did so. It remains to be seen how long it takes for a novice user to be classified as an experienced user, and if that measure is time or distance driven.

5.5.2 Research question 2 - tactical considerations

- Which tactical driving consideration can be found in common traffic conflict situations when delegating control to ACC? (Paper II, IV and III)

Drivers appear to use the system differently in different circumstances according to the results from Paper II, and seem adept at deciding when to allow the system to handle traffic conflicts. Drivers are also seemingly able to incorporate system functionality into their decisions, sometimes reclaiming control before the system has responded, at other times waiting for a system response before deciding to reclaim control. It also appears that drivers allow the system to keep controlling the vehicle even in situations where the system's behaviour might be less comfortable than their own manual behaviour would be. So, these situations appear to make drivers reluctant to resume control, as indicated by previous research (Paper II, Saad and Villame, 1996; Fancher et al., 1998; Jamson et al., 2013). In the curve scenario, the system keeps a higher speed than drivers did in manual mode (see Paper II). Here, drivers appear to resolve that reclaiming control is more onerous than driving at a higher speed with the system active.

Even though drivers were slower to respond to traffic conflicts in the simulator with ACC active (Paper III), such behaviour was not mirrored in the study of FOT data (Paper IV). The results from Paper IV further suggest that drivers may, depending on the situation, even be faster to respond to cut-in situations with ACC than without. These results contradict previous research in simulators (Vollrath et al., 2011; Merat and Jamson, 2009), where drivers exhibit a slower response with active systems. The results from Paper IV indicate a difference between responding when being asked to use ACC in a simulator study and responding when drivers themselves had decided to activate ACC. It is likely that in real-world use, drivers' attention or choices of when to activate ACC is different from how they are told to use the system in the simulator, and their braking behaviour thus affected. One possible reason for the difference in response times is also that drivers press the brake to deactivate the system rather than to reduce their speed, thus responding more in order to reclaim control than anything else. The actions in the FOT data are thus proactive in a different way than in the simulator data. Such a response is likely if the drivers recognise that the ACC might not be able to handle the situation the way they would prefer, similar to the behaviours identified in Paper II.

5.5.3 Research question 3 - effects on future automation

- Do drivers behave and respond the same way with ACC that also includes a lateral component as they do with ordinary ACC in common traffic conflict situations? (Paper III and II)

The results from Paper II indicate that drivers' strategies of choosing to deactivate ACC+AS is not affected by their experience or lack thereof with ACC. Instead, ACC+AS appears to be seen as a completely different system. In the trust measures, experience with and trust in ACC did not lead to trust in ACC+AS. In the scenarios used, the addition of active steering mainly caused vehicle behaviour to be affected when the lead car changes lanes or exits, causing a different vehicle behaviour than with mere ACC. Drivers do need to learn these additional events as well, which perhaps reflects their lower trust in ACC+AS. It is therefore still unclear to what extent behaviour with future automation can be predicted from behaviour with current automation. With experience of ACC, driver trust in ACC was affected positively but no such effect was found for ACC+AS. So, it seems that experience with a system causes trust in that specific to increase. Perhaps, the trust measured may therefore be more akin to trust in cooperation with the system (Rajaonah et al., 2008).

The addition of assisted steering to ACC did not cause any further changes in driver response times in the longitudinal scenarios studied, compared to driving with ACC alone. These results are in line with previous research (Stanton et al., 2001; Young and Stanton, 2007). Thus, ACC specific behaviour in a longitudinal scenario with lateral assistance added does transfer for experienced drivers, who were faster both with ACC and ACC+AS (Paper III). However, for the scenarios studied, the use of ACC+AS did not appear to cause any changes in either driver attention or driver strategies compared to ACC except when the event targeted ACC+AS functionality only.

The impact of lateral automation may be independent of previous experience with longitudinal automation, possibly because the limitations and opportunities while using the systems are different. In mere response time situation with a longitudinal component on the other hand, experience with ACC leads drivers to recognise the behaviour of the system thus making them quicker to respond.

If you try and take a cat apart to see how it works, the first thing you have on your hands is a non-working cat.

- Douglas Adams (The Salmon of Doubt: Hitchhiking the Galaxy One Last Time)

6 General discussion

First, the methods chosen are described and discussed with regard to how they contribute to the results of the thesis. Then, the results are discussed using the theories outlined at the beginning of the thesis. Thereafter, the research questions are answered, and suggestions for further research are made.

A suggestion for a structure to describe how drivers work with automation in traffic conflict situations as well as the conclusions are reported in the next and final chapter.

6.1 Methodological considerations

The methods chosen were picked due to their ability to complement each other in the endeavour of studying driver responses with longitudinal automation in common conflict situations. In order to reach as many participants as possible at the beginning of the project, as well as collect more information on the use of ACC, a qualitative questionnaire was used. Using some of the information from the questionnaire data, the simulator and FOT studies were designed to observe and measure the use of ACC. The simulator study was employed for the control provided over the situations drivers end up in, and for repeatability. The FOT study, to determine driver behaviour in the real-world data to complement the simulator results.

The methodology discussion is divided into three parts, one for each study.

6.1.1 Study I - questionnaire

As driver assistance systems are not registered in any way, researchers are reliant on the goodwill of car manufacturers to get in touch with users if no large scale newspaper campaigns are used. A questionnaire study thus provides contact with drivers that otherwise had been difficult to reach, as Sweden is a large country with a small population. Questionnaires are generally used to provide a quantitative measure of the prevalence of behaviours or opinions. As the study was conducted at the beginning of the project, qualitative background knowledge had not yet been collected to any large extent. Free form questions were therefore used to gather new details about driver understanding of ACC limitations. Thus, trends could be identified as well as appraised due to the number of respondents. A structured list of previously known ACC limitations was considered, but such a list may have guided participants away from other limitations they were aware about, and thus not served as well to gather new knowledge.

The results of the questionnaire were in line with other research using phone interviews or focus groups of people driving different car models (Strand et al., 2011; Llaneras, 2007), despite targeting only XC60 owners in Sweden. Thus, it was demonstrated that a limited sample is still useful. The high response rate of over 60% also indicate that a substantial number of opinions have been gathered, though some measure of bias toward those with strong opinions of the system is to be expected.

The free form questions used provided knowledge of the types of situations where hand-overs between system control and human control occurred, as well as what knowledge drivers had of them. Mainly, the results pointed to it being fairly common to reclaim control from ACC. As a questionnaire study can only capture what respondents are aware of and able to articulate, studies of actual driver behaviour were used in the next step.

6.1.2 Study II - simulator

Simulator studies provide the control necessary to design traffic conflicts where drivers would feel a need to get back into manual control. They also provide knowledge of the position and behaviour of all other vehicles in the simulated world, and the opportunity to repeat scenarios. Therefore, what is being studied is more distinct, and drivers can also be asked to use the system in order to elicit behaviours with ACC in the specific scenarios constructed.

However, the high level of control can make it difficult to introduce the complexity necessary to mimic real traffic. In the real world, drivers will have the end target to focus on as well as be in charge of monitoring and physical control even if this has been delegated to automation. In a lab setting, the implicit goal to keep monitoring the traffic situation is probably weaker as there are no real dangers if drivers neglect to do so. Therefore, effects on gaze distribution may be different if similar situations were possible to design in a field test. Due to the safety of the participants, safety critical scenarios are also less suited for real-life studies.

The simulator studies focused on experience with ACC as a factor when responding to events when the driver is required to get back into manual control. No secondary task was used, as the focus lay more in the process of the driver delegating control and how that was done. The lack of secondary tasks may have caused drivers to be more attentive than with a secondary task, but results were still comparable to those in previous research. The introduction of a secondary task may therefore not be indispensable when studying driver responses during automated driving. As Garrison (2011) notes, even with the addition of secondary tasks drivers tend to direct their attention to the road again in hazardous situations.

There were differences, mainly based on age, between the two groups of experienced and inexperienced ACC users (see Figure 5.2 on page 41). Those experienced with ACC were on average 55 years old, whereas those inexperienced with the system were 38 years old. Owners of ACC tend to be somewhat older (half of the respondents in Study I were 45-55 years old), thus affecting the possible sample. Results, among others, indicated that those experienced with ACC were faster to respond to its behaviour than those inexperienced (Paper III). As it has previously been known that older drivers have slower response times than younger drivers (e.g. Broen and Chiang, 1996), this effect may be even larger than indicated. The effect is therefore most probably due to experience with the system. Driver strategies should not have been affected by any age differences, as it is not possible to exhibit the behaviours found in Paper II without ACC or ACC+AS.

It is clear that the choice of scenarios in the simulator study affected what responses and strategies can be discerned, and the broad range of scenarios used therefore were an advantage. The use of simulators still does not necessarily provide an accurate description of how drivers respond in actual traffic when using driving automation, as their driving strategies are seldom observed. Therefore, the ability to compare simulator data to data from a field test would be necessary to discern any similarities or differences.

6.1.3 Study III - FOT database

One event from Study I that might cause drivers to reclaim control was a cut-in situation, and these became the focus of the FOT study. The identification of a sharp curve was also attempted, but proved too difficult to identify in the available data. A cut-in situation was also implemented as a scenario in the simulator study, allowing a comparison to be made. One major difference between the FOT study and the other studies was that access to data was granted only post-data collection. Therefore, it was neither possible to influence the selection of participants, nor to include any other questions or controls not already present in the data.

As the same selection criteria have been used, the cut-in situations identified in the FOT data are comparable to each other with regard to vehicle dynamics and vehicle controls. The simulator study was also designed so that a mid-level THW of 1.6 seconds would be used, though the simulator included a slow-moving queue and the cut-ins originating from the left. In the FOT data, situations occurred in higher speeds, and cut-ins originated from the right. These differences may have had an influence on driver responses as the simulator scenario could be conceived as more critical. More research is needed into the choices of scenarios for both FOT studies and simulator studies. Cut-in situations not identified with the same criteria will have been missed, at least in part due to that situations entered with ACC and without can be different. Reducing speed with ACC may also be seen as a more effortful action than allowing ACC itself to act, and more severe events may therefore have been captured in the ACC condition than the manual conditions.

The advantages of studying the cut-in event in FOT data is that the drivers have been free to choose when to use ACC, whereas in simulator studies they are told when to use it making the comparison of situations more straightforward. The difficulty therefore lies in comparing the situations in FOT data, as there is an infinite amount of external factors that may influence driver responses and choices. Defining what to use as baseline is also problematic, as drivers may end up in qualitatively different situations with and without the system, depending on how they incorporate it into their driving and how ACC influences the strategies that may lead to certain situations or not. Such dissimilarities are difficult to know without additional understanding of when drivers choose to activate or deactivate the system. The construction of a ”complete” model of a cut-in event is therefore practically impossible. The resulting focus thus was to find the contribution of ACC on driver response time, not all contributing factors.

The possibility to use video for event validation can provide more information when identifying events and driver strategies, as non-relevant events can be discarded before data analysis. Yet, to increase comparability of baseline and treatment situations as well as comparisons with simulator results, a mixture between a FOT study and a field test would probably be advantageous. Asking drivers to drive certain roads during specific times or days would offer a wider perspective of system usage and effects. Changes in the tactical aspects of driving with systems in the real world can only be found this way; by observing driving choices during a specific time, at a specific road, on several different occasions and by looking for changes over time. Such results would then complement research on response times, providing a broader description of the effects of automation on driving.

6.2 Results discussion

This thesis originated in a desire to understand how the automation of parts of the longitudinal driving task, operationalised by ACC, is incorporated into driving by those using the system. A representative of a form of driving automation that will probably be even more prevalent in the future, ACC relieves the driver from some cognitive effort (see Young et al., 2007). To expound on the differences of driving with and without automation, specific effort was placed on studying driver behaviour on the tactical level.

Driving with automation has not in this thesis been intrinsically valued as being better or worse than driving without automation, only different. Also, the preferences of the users have been taken into consideration to indicate how and when they deem automation to be useful or not.

Key findings from the studies concern

- Different ways drivers choose to make use of ACC
- The effects of driver experience with ACC on their responses with the system
- The implication of studying tactical behaviour with the system

6.2.1 Delegating control to ACC

As previously discussed in Section 2.2.2, control is defined partly as performing an action, partly as controlling that the action has the intended effect. Delegation is defined as the act of trusting another agent to do a specific task (Falcone and Castelfranchi, 2002). With ACC, the delegation of control can be studied in the choices drivers make of when to delegate, and when not to. The primary focus for this thesis is borderline traffic conflicts, i.e. studying situations where drivers often choose to resume manual control from automation.

Drivers appear to keep in mind that ACC is not a cognisant system with the disadvantages mentioned by Falcone and Castelfranchi (2001) and in Figure 2.8 on page 19. Inexperienced ACC users also appear to assume a more cautious behaviour and and do not delegate either manual or monitoring control to ACC (Paper II). They reclaim manual control before ACC has a chance to respond instead of expecting a response. This was apparent in the exit scenario in Paper II, where the novice users reclaimed control from ACC whereas none of the experienced users did so. The success of working with ACC is thus dependent on the driver's understanding of the system's role, or as Hoc et al. (2009) describe it, management at the coordination level (see also Section 2.2.2). In the simulator study, the drivers took the system's behaviour into account and appeared to be aware that it was active. In real traffic, drivers may be aware that ACC is present, but do not always realise if it is active or not until it does/should perform actions (Paper I). Action or inaction on the part of the system serves as a cue to the driver of system perception at a given time. Inference management at the action level (see Hoc, 2001; Hoc et al.,

2009) is therefore also dependent on the coordination level for the driver to monitor the most suitable cues (Paper III). To facilitate a fast response at the action level, experience with and the possibility to know the system's role is important.

Delegating THW control to ACC might be conceived as the delegation of two separate tasks. One is the continuous speed keeping and small adjustments in THW needed in most traffic. The other is the interference management of (more noticeable) borderline traffic conflicts, where drivers may need to reclaim manual control themselves. For the speed keeping, ACC is a very useful system. Drivers are not able to perceive THW limits to the same level of detail or as continuously as ACC does, there the system is much superior. For the borderline traffic conflicts on the other hand, drivers are forced to control that the actions of ACC have an appropriate effect, either visually or to a certain extent via the haptic feedback of acceleration. Therefore, drivers may choose ahead of time not to delegate control to the system if they do not think that system control will be appropriate. In designing for suitable task delegation, the actual interference management needed must be taken into account in order to describe what kinds of delegation are occurring and where.

6.2.2 The importance of experience with ACC

With today's driving automation, cooperation is not possible. Drivers are instead forced to exploit action tasks by ACC (see Section 2.2.2 and Falcone and Castelfranchi, 2001), and determine what can be delegated and when themselves. This usage of automation needs to be learned for the driver to know when different strategies will be successful. As the experienced users have worked with ACC and learned how the system responds and acts in various situations, these system behaviours appear to be established in the driver's understanding of the system, demonstrated in the results from Paper III and II.

Traffic conflicts or environmental constraints that, in the mind of the driver, are beyond the scope of ACC seem to be incorporated in the driver's plan also at an earlier point (see Paper II). As Kopf and Nirschl (1997) point out, experienced ACC users intervene less often with ACC as they incorporate system behaviour into their plans. In Study II, both experienced and inexperienced ACC users took ACC behaviour into account. However, having been informed about system limits, novice ACC users appeared to overextend the knowledge that ACC would accelerate some in the exit condition in Paper II before connecting to a new lead vehicle. Instead of allowing the ACC system to lose contact, accelerate and reconnect with a new lead vehicle, the novice users switched off ACC. This even though the system would be able to cope with the situation and is, indeed, meant to do so. A similar but different conservative response, in a different situation, was also evident in the behaviour of the more experienced users who respond earlier to inappropriate acceleration of the ACC and ACC+AS than did novice users. This mirrors the results found by Llaneras (2007), in that drivers are more cautious initially with the system, but extend their usage over time. The earlier response of the more experienced users to acceleration (Paper III) may be due to their larger awareness of system limitations (Dickie and Boyle, 2009). That experienced users are indeed faster to respond when using ACC is, however, new knowledge.

As continuous control has been delegated both with regard to monitoring and manual handling, the main choice drivers have of monitoring system performance in borderline conflicts is to wait and see. The other is to be so proactive that the system is not allowed to respond. Waiting for a system response can also be used to remind the driver if the system is on or off, something drivers can become confused about (see Paper I). Previous research has shown that drivers start out by testing system limitations (Simon, 2005), thus experiencing system haptics and system behaviour in borderline situations, later settling for a more stable way of using the system in their drive. With experience, drivers also appear to depend at least partly on system actions to diagnose such borderline conflict situations; drivers who were used to ACC were faster to respond to system action than novice users (Paper III). So, in some circumstances, drivers appear to respond to system behaviour connected to the situation at hand. As the more experienced users know of system behaviour and its consequences to a larger extent than novice users, they were able to respond to system action rather than the decreasing gap to the next vehicle. This is somewhat similar to previous research (Aust et al., 2013; Ervin et al., 2000; Dijksterhuis et al., 2012), indicating that drivers learn to respond to system actions rather than to a situation. In the specific case reported in Paper III, drivers had to perceive the system response and diagnose it as being incorrect.

With regard to assisted steering, it did not appear that experience with ACC could transfer to all aspects of using ACC+AS. Brake response times were similar (Paper III), indicating that in a longitudinal scenario, system behaviour can be generalised to include cases of active steering as well. When handling ACC+AS-specific behaviours it was clear that knowing of ACC limitations did not affect driver behaviour. Instead, drivers appeared to behave similarly regardless of their experience with ACC. These results add to previous knowledge that drivers need to experience system behaviours in a specific situation in order to learn it (Strand et al., 2011).

When studying driver responses in borderline traffic conflicts, the behaviours of experienced users clearly need to be taken into account. The importance of including drivers with experience of system behaviours mainly lies in their knowledge of what systems may or may not be able to handle, and thus what may or may not require a response (Paper II). The question remains how long is required for drivers to get accustomed to the system sufficiently to respond faster to system actions, and if the learning process needs to be or could be speeded up.

6.2.3 The effects on driver attention

Gaze was studied in order to examine the effects of experience on attentional strategies when dealing with borderline traffic conflicts. Previous research has shown that experience modifies driver attention (e.g. Most and Astur, 2007). Thus, experience with ACC could entail drivers being more alert to some ACC-relevant behaviours in traffic, and therefore also having a different gaze pattern. In the current study, an attempt was made to find effects on less obviously expected or unexpected events. That is, to see whether gaze differs in borderline traffic conflicts that demand more from the driver than just following a road, but still occur fairly frequently. Previous studies have indicated that drivers are as attentive to the road in complicated scenarios with and without automation (Garrison, 2011; Jamson et al., 2013), and so studying visual strategies may be more appropriate than on-road glances only.

Experienced drivers did exhibit different gaze patterns than did novices to some extent (Paper II), but only in certain situations. In the broken car scenario in Paper II, the experienced ACC users looked less at the road centre than did the novice ACC users. This change in attentional strategies by experienced ACC users can serve to indicate that their targets when driving with ACC are somewhat different than the targets attracting novice user attention due to experienced users having a more clear goal with automation (e.g. Most et al., 2005). The differences were not large and the question is clearly in need of more investigation. The results from Paper II do not support those from Carsten et al. (2012), who expect driver gaze to the roadway to decrease with ACC+AS. As previously mentioned, this may be due to Carsten et al. not only studying specific scenarios, which were the focus of this thesis. Driving with automation does in some ways appear to affect the visual strategies involved in driving.

The intention when measuring driver trust in ACC was to replicate the results found by Rajaonah et al. (2008); high trust in the system leading to overly reliant behaviour toward the system and decreased monitoring. Some of the participants in Study II did indeed delegate the scenarios to automation and did not reclaim control, but this was not a repeating tendency found in specific drivers, and not connected to trust or experience with ACC. It might also be necessary to pose the question if trust offers much of an explanation with regard to driver cooperation with automation.

Experienced ACC users had higher levels of trust in ACC than did novice users. It is therefore likely that "trust" in this respect was related to drivers' confidence in working with the system, like the trust mentioned by Rajaonah et al. (2008). The experienced users are more likely to know more about system limitations (Paper I), and the higher levels of trust exhibited by these drivers therefore contradict the results of Dickie and Boyle (2009). Dickie and Boyle had found that higher levels of trust in a system was associated with less knowledge of system limitations. The results from Rajaonah et al. (2008) could not be replicated either, as high trust was associated with experience of ACC and faster driver responses rather than slower (Paper III). As the same questionnaire for trust ratings was not used, it may well be that the trust measured was different. "Trust" may therefore also be the wrong term to use, as it apparently depends to a very large extent on the survey used to gauge it. Perhaps it is more important to decide why trust is measured and why it should be influenced. If the aim is to improve driver collaboration with the system, finding the factors that actually make drivers able to do so is needed, such as their experience with system limitations.

6.2.4 Delegating control in borderline traffic conflicts

The use of a system such as ACC has an effect on how drivers make tactical decisions such as the manner in which they overtake or what lane they drive in, as previously demonstrated (e.g. Vollrath et al., 2011; Saad and Villame, 1996). In the studies undertaken for this thesis, it is demonstrated that drivers also incorporate system actions into their plans for responding to traffic conflicts, allowing the system to respond if possible (Papers II and III). Drivers also use the system differently depending on their understanding of system limitations, sometimes not allowing the system to control the situation (Paper II). With experience of using ACC, drivers learn to collaborate with the system by understanding its actions and creating strategies for responding to it in borderline conflicts (Paper III). Drivers learn what tasks the system can and cannot act on, and what may be used as a signal to resume control. With this knowledge, they become more adept at handling and detecting borderline situations that may be better handled manually, thus responding faster (Paper III).

When driving with automation, drivers in the simulator study reported in Paper III were slower to respond to a cut-in situation than without automation (similar to previous research, e.g. Merat and Jamson, 2009; Vollrath et al., 2011). As driving automation requires a delegation of manual control, this could be seen as a natural tactical strategy from the driver. System action or inaction is an important cue to drivers, and will take time to identify after having chosen to delegate a task or sub-task to the system. As demonstrated in Paper II, drivers can also exhibit a more proactive and conservative behaviour, disengaging the system before it acts, but such a response may be depending on the type of event. A study of response times to borderline traffic conflicts, whether caused by the system or surrounding traffic, are therefore not the ideal way to study the effects of driving automation.

Simulator studies do not provide a comprehensive understanding of how ACC is used in borderline traffic situations. When comparing driver responses to cut-ins in the simulator data (Paper III) to cut-in events identified in the FOT data (Paper IV), it appears that there is no detrimental effect of ACC usage in the FOT data. Rather, there was even a tendency towards a faster response in the FOT data, contradicting the results of Paper III as well as other studies where the use of automation leads to a slower response by drivers (e.g. Merat and Jamson, 2009; Vollrath et al., 2011; Stanton et al., 1997). The results of the EuroFOT study similarly indicate that when responding to FCW warnings, drivers responded as fast with ACC active as they did without (Malta et al., 2012). Though the situations with and without ACC active are similar in the FOT study, drivers may have developed a strategy to work with ACC and therefore responded faster. The reasons behind may, for example, be that they wish to avoid a potentially uncomfortable decrease in speed if the system is allowed to respond alone.

In simulator studies, drivers are typically told to use a system the entire drive, and cannot exhibit the same behaviours in activating or deactivating the system as they would in the real world. Conversely, in FOT studies drivers choose when to activate the systems, based on their previous experience and preferences. Therefore drivers may in simulator studies end up in situations with ACC active where they themselves would not have kept the system on. Drivers might choose to deactivate the system in certain situations due to not knowing how the system responds, not be keen on the system's response in that specific situation, or just out of habit. It may also be the case that the frequent activations and deactivations in real traffic serve as a reminder on a subconscious level for the driver to attend to longitudinal events, and this affects general response times. More research is clearly needed on when and how drivers choose to use ACC, and how this differs from the constructed scenarios in simulator studies.

The results the simulator studies provide answers from one perspective on how ACC can affect driving in the real world. This perspective is, however, limited to cases where the system is used the way it was in the simulator study. If instead driver strategies in real traffic are affected to the point that drivers do not end up in the situations tested in the simulator, the potential problem (such as an increase in response time) decreases. It is therefore important to study both sides of the issue; how drivers may respond in situations that can be studied in simulators, as well as where and how the system is used in traffic. Of course, it may also be that drivers are more watchful and aware of the system in real traffic, so that they are faster to respond even to perhaps less risky situations. This faster response may also be due to them pressing the brake more to reclaim control than to reduce speed as such, thus the situation being different from driving without ACC. Further studies are needed.

For the active steering, it was clear that drivers incorporate this system functionality as well into their driving decisions. Drivers utilise system actions even when the system is new to them, and were also to a large degree able to predict what the active steering may do and exploited this behaviour; some drivers worked with the ACC+AS system without disengaging it, allowing the system to continue steering while accelerating themselves (Paper II). Problems have previously been found with automation that allows the operator to focus on planning and longer-term tactical decisions rather than manual responses and short-term tactical decisions (Endsley and Kaber, 1999). With ACC, such removal from manual responses does not occur, as the driver is still responsible for steering. Most tactical planning is still the responsibility of the driver in both the short term and the long term. With the addition of active steering, additional short-term decisions of how to position the vehicle in the lane are delegated to automation. Since drivers appear to be reluctant to reclaim control when automation handles things well enough (Saad and Villame, 1996; Fancher et al., 1998), supported by Paper II, there may be consequences also affecting other tactical behaviour such as overtaking. As there was no effect of automated steering in the longitudinal scenarios compared to ACC only, perhaps the monitoring of the system's actions by itself acted as a buffer in the scenarios studied. The results on response times were also in line with previous research (Stanton et al., 2001; Young and Stanton, 2007), as driving with ACC+AS did not differ from driving with ACC. Perhaps the response to a longitudinal scenario is equally quick both with and without lateral control, and delegation of the lateral aspects will be apparent in tactical and strategic behaviours only. Another explanation might be that there were enough conflicts and traffic to attend to for the driver to stay "connected" to driving, thus not delegating more monitoring control.

6.2.5 A tactical or operational perspective on automation

Driving is a time-critical, somewhat risky, and highly visual undertaking. As long as the driver drives instead of being allowed to act as a passenger, fear that the driver does not respond to events may be largely unsubstantiated. If the current trend of delegating continuous control to automation continues, demanding that the driver drives actively they way she would without automation, the whole time, is somewhat unreasonable. As demonstrated in Paper II, drivers make use of automation functionality and incorporate it into their driving decisions. Even if the driver is provided with information about borderline traffic conflicts and is helped in diagnosing them, reliable systems will (and have, see Paper II) change drivers' attentional strategies. These changed strategies should not be seen as being intrinsically "bad", but rather as an adaptation to working efficiently with for example ACC.

Behavioural adaptation has previously been defined by an OECD expert group (OECD, 1990) as "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". This definition is quite broad and requires further delimitations if operationalised in scientific studies. Previous research (e.g. de Waard et al., 1999; Seppelt and Lee, 2007; Fancher et al., 1998) have often focused upon fairly isolated effects on driver behaviours, like improving increased response times with automation and pointing out risks with the driver engaging in more secondary tasks with automation than without. Studies have also measured but not gone into the reasons behind spill-over effects into sub-tasks like using direction indicators; a task that has not yet been automated (Hjälmdahl and Várhelyi, 2004). These observations of phenomena do not by themselves hold any explanatory value. In order to make sense of the measures made, a connection to theory is needed. So far, the explanations offered (such as changes in workload suggested by Young and Stanton, 2002b) do not provide insight into how (or why) drivers work differently with automation than without. Neither have they been able to explain why certain behaviours and factors, but not others, change with the use of automation (Saad and Elslande, 2012).

Continuing with a normative view of how cars and drivers "should" behave with regard to lane positioning or response times without knowledge of the surrounding circumstances does not move theory or practice forward. We need to ask if it is practical to rely on the driver to control system actions in all borderline traffic conflicts, or if this is beyond what is sensible to do with a competent system. If a system is designed to allow the driver to attend to other things, perhaps the driver should not also be required to attend to all possible traffic conflicts? Using manual driving as something to strive for could almost be compared to counting errors - only revealing differences that are "wrong", not just different (for further discussions on the pointlessness of counting errors, see e.g. Dekker, 2003, 2007).

Focusing on performance through operational measures such as response times (Merat and Jamson, 2009), time headway (Dragutinovic and Brookhuis, 2005), gaze (Victor et al., 2009), or any number of things, means not approaching driving with automation as the situated task it is (see Chapter 2). A strategy focused on operational tasks has lead to a focus on improving quite a limited range of behaviours instead of gaining an understanding of how drivers work with new systems, what changes are brought by automation, and what support might be needed to improve that. Of course, everything cannot be studied, and a start must be made somewhere. However, if an attempt is made to understand why behavioural changes transpire, the underlying processes are not necessarily possible to obtain by taking an operational level standpoint. Indeed, measures like response time have not been used for comparing car driving to horse riding (to this author's knowledge), despite suggestions of modelling system cooperation on interaction with horses (Norman, 2007; Kienle et al., 2009). That driver response times with ACC in FOT data (Paper IV) are different than in simulator studies (Paper III) for the same type of event, also demonstrate that a wider perspective is needed.

By first taking a more qualitative approach and describing changes in tactical behaviour (as demonstrated in Paper II) before deciding on operational (or tactical) measures, a more accurate description of the changes brought on by automation can be formulated. It will not be clear what situations drivers end up with while using driving automation until an analysis of tactical driving behaviour is employed. Changes in the driver's tactical behaviours may thereby also provide insight into why operational level actions are changed, as indicated by the disparity in the results between Paper IV and Paper III.

Few studies before the current simulator study (Study II) have focused on changes in tactical driver behaviour (Vollrath et al., 2011; Hjälmdahl and Várhelyi, 2004; Saad and Villame, 1996, have, but only to a small extent). Yet, characterising the qualitative differences for the driver between manual and automation-supported drives is of importance to understand more about the effects of automation on driving. There is a lack of knowledge of how systems are actually being used and experienced, and what thereby may be the most interesting operational behaviours to measure in simulator studies. As research has, to a large extent, focused upon driver responses to system failure or acute hazards that occur very rarely (e.g. Stanton and Young, 2005; Flemisch et al., 2008), driver responses and behaviours in more common situations have also been largely unknown. It could even be the case that automation has an adverse effect on the driver's ability to respond to highly unusual and very serious traffic conflicts, but a positive effect on more common traffic conflicts. This is, largely, undetermined. Making an effort to study the changes in tactical behaviours, a more informed conclusion can be made about the safety of systems such as ACC.

6.3 Further research

Adaptive cruise control is one of the more advanced systems available on the market today, but here are of course also autonomous and driverless cars, where there driver is intended to be redundant. Despite this, drivers can still resume control over driverless cars, possibly to comply with the Vienna convention (1968) which states that drivers should always be in control. Thus, the questions raised in this thesis of transferring control is important also in "autonomous" vehicles. As the driving automation available today operates in a human's world, it needs to allow its user to identify and manage situations it cannot handle. Some suggestions for further research have already been mentioned in the discussion, but two main research tracks are here explored further; driver attention and responses with automation, and learning processes.

Studying the the differences found between novice and experienced users of ACC from the angle of driver attention with automation would be interesting. Farrell and Lewandowsky (2000) proposed that operators learn not to respond when using automation, which does not match the quicker response by experienced ACC users found in Paper III. However, Farrell and Lewandowsky also describe that, in a short trial, intermittently reclaiming control improves recovery speed. Drivers with more experience of ACC have reclaimed control more often from the system, but over a long time period. If a shorter trial of frequently reclaiming control from automation would elicit the same improvement in response time for new users, not completely letting go of control by practicing to return to control may be an appropriate way of describing how drivers learn to use ACC and other systems. It could, however, also be conceived that drivers are being overly cautious, thus responding more quickly, but this difference may be possible to discern by interviews. Another potential explanation requiring further study would be that drivers only learn to avoid responding in situations they know the system should be able to handle. Therefore, if something truly unexpected happens, such as system failure in a situation the system normally always handles, drivers are slower as they are waiting for a response that should come. If instead the situation is a borderline traffic conflict or clearly out of bounds, drivers may be faster to respond as they are aware that they may need to reclaim control. It would therefore also be useful to determine how drivers judge events to be within or outside ACC capabilities, if they do, so that these aspects are not missed in simulator studies.

From the results found in this thesis, understanding the system's behaviours and responses appear to be of high importance. Therefore, a follow-up study investigating drivers' learning processes and their effects on tactical driving decisions when collaborating with the system would be of use. Such a follow-up would best be conducted as a combination of interviews, diaries and observation of complete novices with the system. If participants are grouped by how much they drive per month, it could be revealed whether the distance driven is more important than other factors, such as range of events encountered, when learning to use the system. It would be of great interest to know how much of the strategies are dependent on learning to respond to system actions (reactive), and how much depend on learning what situations the system can and cannot handle (proactive). The combination of methods would also allow for an understanding of the learning process and decisions made by both what is deemed important enough for drivers to write down and how drivers believe they learn system behaviour. How much experience is necessary to learn useful strategies to benefit maximally from the systems and avoid situations exceeding system limitations is also important issue, as well as what may cause drivers to become overly conservative. An observation of driver strategies to validate driver statements would require some method development, but fitting their vehicles with sensors and cameras like in a FOT would be preferable. Such an instrumented car study would require a larger element of control, to ascertain for example where and when drivers decide to activate or not activate ACC. Drivers could be requested to drive a specific stretch of road with some regularity, and a combination of infrastructure and in-vehicle sensors and cameras could be used to study driver behaviour. The propensity for drivers to behave in potentially risky ways with or without automation could also be studied this way, as actual involvement in more serious traffic conflicts are rare.

6.3.1 Improving ACC and other driving automation

As previously mentioned (see Section 2.2.2 on page 13), one limitation of ACC and similar systems is that they cannot learn about the driver's preferences. Communication is not only needed to understand what the system is doing, but it is the natural way for humans to know what is being delegated and if it might need adjustment (Falcone and Castelfranchi, 2001). In the case of driver assistance systems, such communication is only made from system to driver, never the other way around. The effects of this lack of reciprocity should be taken into account when designing new ADAS. If the driver would prefer the system to avoid doing something, this attitude cannot be learned by the system. Instead, the driver is always forced to deactivate and reclaim manual control. Drivers, however, become reluctant to do so when using automation, often preferring to keep automation in control until the situation develops so that this strategy is proven to be unsuccessful (Paper II).

Some drivers avoid using ACC as they claim it does not suit their driving style (Paper I). Acceleration behaviour (as well as deceleration behaviour) is a comfort factor with ACC, and may be possible for the system to learn at least concerning environmental factors such as road pitch (going up or down hills). Learning how to respond to the driver's preferences in situations more dependent on the behaviour of others may be more difficult, but perhaps some general trends can be identified and imitated.

The driver may also use the system less than to its full potential by acting more conservatively than necessary (Paper II). Improving the driver's ability to understand what the system is doing would be one way to provide a more accurate understanding of system capabilities (Norman, 1990), for example by communicating if the system may be approaching its maximum braking force. More understanding of the situations where not only novice users but also experienced users may act overly cautious is therefore necessary.

And then the world is your mollusc!

- Terry Pratchett (Men at Arms)

7 Conclusions

The aim of this thesis was to study the effects of longitudinal automation when handling commonly occurring situations that may require the driver to reclaim manual control. During the course of the project, it became apparent that drivers consider system behaviour in a number of different ways when driving (see Paper I and Paper II)[1]. However, in the majority of studies where the focus has been on the driver reclaiming control, system failures have provided the context. Yet, system failures constitute but one reason for transfer of manual control to the driver (Paper I, Section 6.2.4). In this thesis, there have been several mentions of borderline traffic conflicts (studied for Paper II and Paper III, mainly), situations where it is not quite clear if the driver needs to reclaim control or not. Some of the reasons behind these situations are listed in the "Reaction" module of Figure 7.1. Reactions are not the only ways in which drivers work with ACC, though. As could be seen in the results from Paper II, the driver can also proactively decide use the system for their benefit, or reclaim control before the system acts. Drivers not only respond to system behaviour in a limited time frame, but also exploit the system and may fall into a habit of using it a certain way (again, see Figure 7.1). Focusing on system breakdowns therefore misses much more common situations where system behaviour influenced driving, situations where the driver's response and also proactive behaviour is perhaps of higher importance. These other situations being just that, commonly occurring, suggests that they potentially have a larger impact on driver behaviour than the rare system breakdowns.

The proactive factors probably contribute to driver behaviour in ways that in turn can affect factors such as THW or lane positioning, thus explaining the behavioural modifications found in previous studies (Saad, 2006). Therefore, proactive behaviour also needs to be studied so that a generalisation is not made from a sample of variables that do not fully reflect system usage.

[1] This does not include situations where the driver might struggle to reclaim control due to conflicting actions between the automation and the operator, as the operator so far always has a veto over driving automation.

Figure 7.1: A categorisation of driver actions with automation

To improve the driver's prospects of managing the limitations of driving automation, studies need to be performed on a wider range of hand-over situations than merely system breakdowns or highly critical traffic conflicts. Not only do drivers resume control from the ACC, but they also delegate control to the system. From the simulator study (Paper II), it is apparent how the choice of scenarios affects what responses and strategies can be discerned. I therefore encourage using a broad spectrum of scenarios, so that a wider range of driver behaviours can be studied. What constitutes a broader spectrum is not yet clear, but as a beginning, the scenarios should presumably not all fall into the same category in Figure 7.1.

7.1 Final remarks

The perspective taken in this thesis, that automation is to some degree used as an independent actor to delegate tasks to, has hopefully inspired a new way of thinking about driving with automation.

Studying the effects of change in a complex system such as the advent of partly automated vehicles in traffic is by no means an easy feat. It can be done from a variety of different perspectives, at different levels, all describing part of the change. Automation is designed to facilitate driving, and driver exploitation of system actions should not be unduly complicated or criticised. Rather, automation needs to be studied with an open mind to learn how drivers make use of these systems, and where problems in doing so may arise. What is seen as the nature of driving needs to be reconceptualised when studying the safety of continuous driving assistance systems such as ACC, along with what is used as baseline. The priority given to measures of operational driver behaviour, without sufficient knowledge of how driving with automation is qualitatively different from driving without it, means the measures taken might be interpreted incorrectly. A change in TTC or THW may be less significant than a change in more composite behaviours, as drivers use the car differently on a tactical level with the system than without.

Driving with automation can be something new, something allowing drivers to achieve and attend to other things than today - much as driving a car allows the driver to achieve and attend to other things than a horse and cart does. Purely quantitative measures of behaviours such as lane positioning or response time do not illuminate how or how well a driver and a system (or horse) work together. Therefore, they do not provide examples of how the collaboration between driver and automation could improve either. Once having established the importance of studying tactical behaviours, new research questions can be posed, and the future of driving can evolve in more human-friendly ways.

To summarise, the main results and conclusions of this thesis are as follows:

- In FOT data, ACC leads to a faster driver response times to cut-in situations compared to driving without ACC availability, opposing previous research in simulators. Possibly, this is due to drivers using ACC differently when allowed to choose for themselves. (Paper IV, Section 6.2.4)

- Experienced ACC users are 0.5 seconds faster to respond to inappropriate ACC/ACC+AS actions in a cut-in situation in simulated driving than are inexperienced ACC users. Both experienced and inexperienced users were slower to respond with ACC active than without. It is therefore important to not only study novice responses to systems. (Section 6.2.2, Paper III, Paper II)

- Response times studied in simulators only answer the question of whether driver behaviour in that specific scenario is affected with an activated system. Drivers may change their driving with the system so that the scenario does not occur in real traffic, but others may occur instead. (Section 6.2.4)
- Studies need to be made on a wider range of hand-over situations between system and driver than system breakdowns, as this is only one aspect of many involving drivers working with automation. (Paper I, Paper II and Figure 7.1 on page 64)

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"There is an art, [the Guide] says, or rather, a knack to flying. The knack lies in learning how to throw yourself at the ground and miss. … Clearly, it is this second part, the missing, which presents the difficulties."

- Douglas Adams (The Hitchhiker's Guide to the Galaxy)

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Linköping, 9 September 2013

Appendix - Questionnaire for Study I

Questionnaire for car owners with adaptive cruise control

Our research group at Lund University is conducting a research project on driver support systems in cars. The reason you have received this letter is that many people who have the same car model as you have chosen adaptive cruise control, ACC for your vehicle. Adaptive cruise control keeps both the set speed and the distance to the vehicle in front. The study is about adaptive cruise control, so only car owners with this system need to answer the questions. If you do not have this system in your car, we would like to thank you for your time!

The aim of the study is to determine how **adaptive cruise control (ACC)** is being used today, and in what ways the system can be improved to create a safer traffic environment for all. We would be grateful if you could spare a few minutes of your time to answer this questionnaire. Active driver support systems are still quite rare, making *your* views especially important. All the data collected will be treated anonymously, and will not be possible to connect to you personally.

The questionnaire is only intended for car owners with adaptive cruise control in their vehicles. If you do not have this system in your car, we thank you for having read this; you do not need to send us the questionnaire.

If you have any questions or anything to add, please call or email:

xxxxx.xxxxxxxx@xxx.xxx.xx

TRANSLATION TO ENGLISH FROM THE SWEDISH ORIGINAL

Questionnaire for car owners with ACC, adaptive cruise control

Our research group at Lund University is conducting a research project on active support systems in cars. These systems are still rare, making *your* opinions especially important.

The aim is to determine how **adaptive cruise control (ACC)** is being used today, and in what ways the system could be improved to create a safer traffic environment for all.

1. Do you have adaptive cruise contro, ACC, in your car? The system keeps both the set speed and distance to the vehicle in front.

❑ Yes ▷ *If yes, go to the next question!*

❑ No

❑ Don't know } ▷ *If no/don't know, thank you for your time; you do not need to send us the questionnaire!*

2. How often do you use ACC, adaptive cruise control?

❑ Every week

❑ At least once a month

❑ Less often } ▷ *Proceed to question 4!*

❑ Never ▷ *Proceed to the next question!*

If you *never* use ACC:

3. Why do you not use ACC, adaptive cruise control?

....

....

▷ *Please proceed to question 11.*

If you use ACC :

4. What do you feel is the most positive and most negative part of using adaptive cruise control?

....

....

....

....

5. Mention a situation in which you know that the ACC system may have difficulties functioning:

....

....

....

....

6. In what situations do you activate and deactivate the system?

Activate when...

....

Deactivate when...

....

7. Have you ever been unaware that the system is on or off? If yes, what happened?

……

……

……

……

8. Have situations occurred where you have thought that the system does not live up to your expectations? Please describe.

……

……

……

……

……

9. Is there anything about the system's functionality you would like to change? If so, what?

……

……

10. Do you believe that the ACC system, in general...

Is useful…

❑ Practically always ❑ Most of the time ❑ In certain situations ❑ Not very

Demands attention …

❑ Complete attention ❑ Regular attention ❑ In certain situations ❑ Seldom

Any comments:

……

……

11. For how long have you had your current vehicle?

❑ 1-3 months ❑ 4-6 months ❑ 6-9 months ❑ 10-12 months ❑ over 12 months

12. Are you...

❑ Female ❑ Male

13. Your age group

❑ -25 ❑ 26-35 ❑ 36-45 ❑ 46-55 ❑ 56-65 ❑ 66-

14. How many Swedish miles [tens of kilometres] do you drive per year (approximately)?

………………………………………..

15. How much of that drive (in percent) do you drive in the following traffic environments

Motorway ………….% Rural roads ………….% City traffic ………….%

16. Do you have any further comments? (please use the back to write on as well)