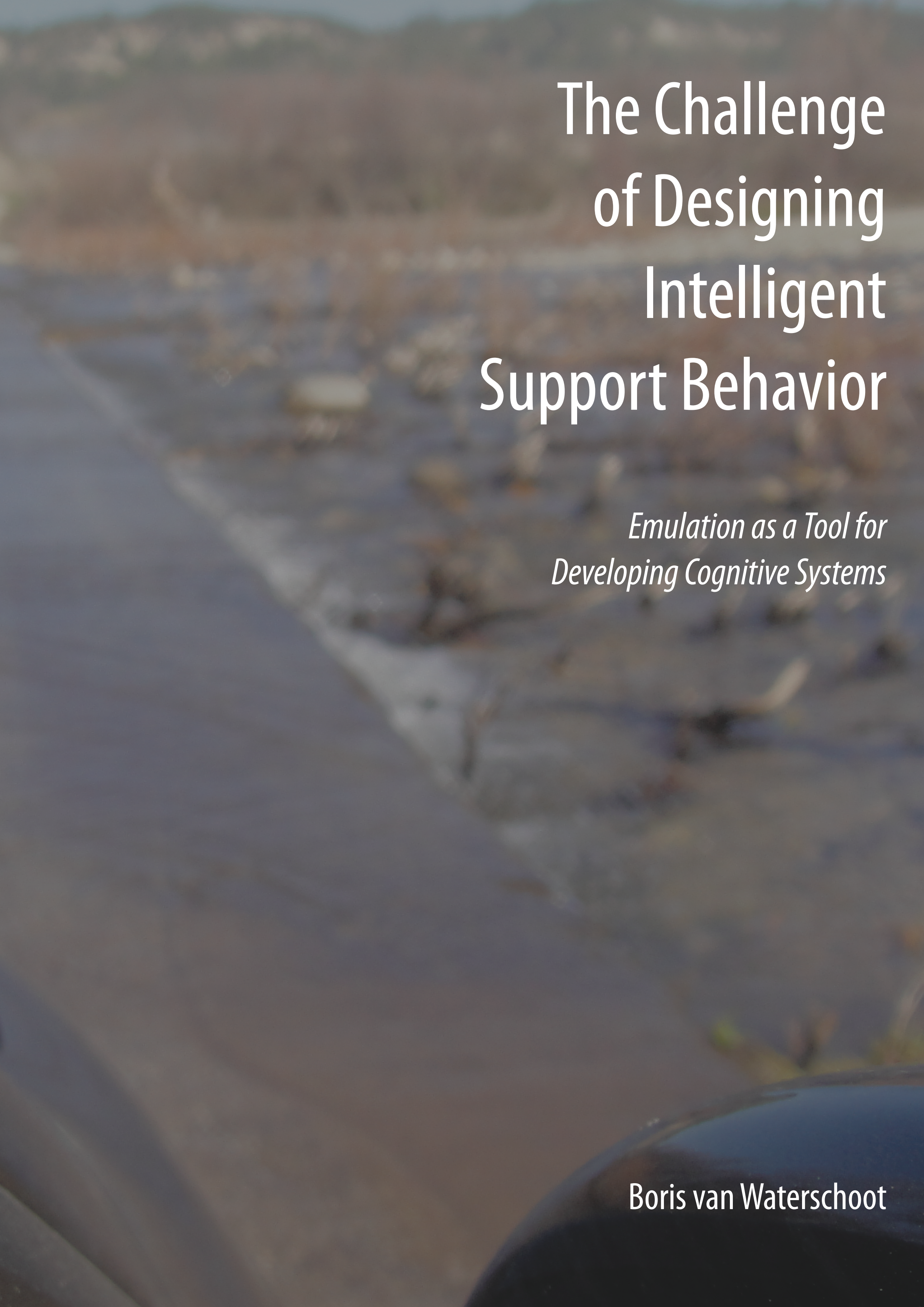

The Challenge of Designing Intelligent Support Behavior

Emulation as a Tool for Developing Cognitive Systems

Boris van Waterschoot

THE CHALLENGE OF DESIGNING INTELLIGENT SUPPORT BEHAVIOR

EMULATION AS A TOOL FOR DEVELOPING COGNITIVE SYSTEMS

Boris van Waterschoot

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THE CHALLENGE OF DESIGNING INTELLIGENT SUPPORT BEHAVIOR

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1

Introduction

While it is safe to say that modern day road transportation has proven its ability to benefit society by providing mobility and economic welfare, there are reasons for concern as well. Aside from reducing the environmental impact and energy consumption, two main challenges for future transportation are to increase both road safety and traffic flow throughput. In fact, although a general decreasing trend was observed for the number of fatalities in the Netherlands during the last decades, as compared to 2010 this number increased in 2011, especially among elderly and children (Statistics Netherlands, 2012). Besides traffic rules and regulations, a large amount of research is dedicated to address technological innovations that aim to increase the safety and efficiency on public roads. For example, in order to improve traffic safety and traffic flow, various technologies and solutions are currently available by means of driver support systems that assist the driver to cope with potential hazards. These advanced driver assistance systems (ADAS) warn and inform the driver or even take over part of the driving task. A vehicle equipped with such systems uses sensors and cameras to recognize potentially dangerous situations and typically intervenes by prompting the driver to make an appropriate action, for example when the vehicle departs from its lane, or actively controls the vehicle, for example by decreasing speed in a critical situation. While driver assistance systems come in many different flavors with different functionalities, their general purpose is to preserve safe, efficient and comfortable driving by supporting the driver.

However, whereas such systems represent dedicated support, relying on numerous sources of information, their effectiveness highly depends on the compliance of drivers when offered warnings and directions. Simply put, when the system evaluates a situation as being or becoming dangerous according to a set of predefined parameters, the system will only reveal its safety value when the driver acts in accordance with the support that is given. This means that the system's ability to communicate directions and intentions are as important as its ability to recognize hazardous situations. The development of driver support systems is therefore faced with the difficult task to equip vehicles with sophisticated sensing abilities, as well as to provide for driver assistance that is unambiguously understood by the drivers. In this view, developing driver support involves attuning or matching technical solutions with an understanding about humans interacting with such 'intelligent' vehicles. Since humans can be considered as unpredictable, at least when compared to systems that run on predefined protocols, providing safe and efficient 'teamwork' between humans and support systems is highly challenging.

Moreover, driver support systems can be described as cognitive since the vehicle needs to act on acquired knowledge, taking into account aspects about driver, vehicle and traffic state. The design of driver support systems is therefore confronted with the challenge of providing systems with a behavioral repertoire that acts in accordance with the demands of a given situation. That is, at design time it needs to be decided which information about driver, vehicle and traffic is required in order to evaluate a given situation and which system actions or 'behaviors' are needed in order to communicate the relevant directions and intentions to the driver. On the one hand, this means that those involved in the development process of cognitive driver support need to know how a cooperative setting between humans and automation is established in order to achieve optimal understanding between driver and support. On the other hand, the monitoring and inferring abilities of driver support systems should be of such a degree that they guarantee proper and anticipative support as envisioned by the system designers. Here, the support system's perceptual, cognitive and action capacities to provide proper support are seen as the behavioral repertoire of the system.

While the developments in the automotive domain show a demand for collaborative and reliable support systems, proper driver responses remain of prior importance when the system provides warnings and directions. For some even, the solution lies in the introduction of the driverless car as several attempts to provide for such an autonomous vehicle show (e.g. Thrun, 2010). In theory, combining the full potential of a vehicle's cognitive abilities with an infrastructure that enables communication between vehicles and the roadside would be quite feasible. Given this prospect, if one can imagine vehicles act according to an optimal traffic model with the ability to anticipate or adapt their actions through e.g. inter-vehicle communication, active human intervention becomes obsolete and autonomous driving is just a matter of time. Moreover, if car driving wasn't such a complex task that needs high adaptive power and flexibility, present day technologies would probably allow for such an implementation in the near future. However, while several initiatives already showed that vehicles can act autonomously by processing different types of sensory data (Campbell et al., 2010) limitations in terms of adaptation and flexibility will remain of major concern for introducing driverless cars on public roads. In the meantime, new advances in driver support are gradually introduced by different automakers, while the requirements and potential benefits of these 'co-driver' systems remain subject to a lively debate in the scientific community. Fortunately, there is a wide variety of disciplines, based on e.g. design, psychology and computer science, that have adopted the challenge to identify, address and solve the problems associated with humans and technology interacting.

In the recent past, it has been stated that ADAS design is highly technology-driven, which means that new functions are mainly added when they are technically feasible rather than because they are needed (Hollnagel, 2006; Schmidt et al., 2008). When this statement is typical for the current practice and ADAS design tends to focus on progress and availability of hardware, at least two main issues arise. Firstly, since the supporting technologies are often developed independently, their effects remain unknown until a given technology is evaluated within a cooperative setting between driver and support system. Secondly, mere feasibility of technology discards the view of driving as a cooperative act between drivers and support systems. Furthermore, such an approach doesn't consider the unified demands of the human and automated components of the system (i.e. a unified driver-vehicle system). Whereas single technologies (e.g. monitoring the vehicle's blind spot) can offer support for specific functions within the overall driving task, they are part of a larger system in which driver and vehicle share control in order to maneuver through traffic. While establishing a cooperative setting between driver and cognitive driver support can be appointed as a major challenge for ADAS design, the need for evaluating the effects of specific design considerations adds another level of complexity to the development process of driver support.

Although the specific consequences of adding automation remain speculative because of a lack of general consensus within the scientific community, it is generally agreed that driver assistance systems can lead to unintended changes in driver behavior, not anticipated by the system's designers (Rudin-Brown, 2010). In contrast with the purpose of increasing safety and efficiency on public roads, it is even argued that the potential influences on driver behavior can jeopardize safety (e.g. Hancock & Parasuraman, 1992; Lansdown et al., 2004; Michon, 1993). While the need for evaluating the impact of design choices seems apparent, a solution for translating such results into specific design alternatives or improvements is not readily available (van Waterschoot & van der Voort, 2009). Moreover, given the fact that modifications will only reveal their effect after re-evaluation, the view emerges that evaluation should be seen as an iterative process instead of a single and isolated event. To make things even more complicated, as discussed in chapter 3 of this thesis, among the available literature dealing with advanced driver assistance systems and ADAS evaluation, relatively little consensus exists about how to address and evaluate the cooperative setting of contemporary driving. A general and standardized approach for assessing driver support systems is therefore, to the author's knowledge, missing (cf. Aust, 2012). While little objections can be found to picture drivers and technology as cooperating within a unified system, relatively little is known about how to establish a qualitatively proper and sound cooperation or how to evaluate such cooperation. Anticipating or assessing design considerations solely based on a priori knowledge is therefore not a very likely approach.

Given these viewpoints, ADAS design could benefit from an approach in which those involved in the design process receive early feedback about the system's requirements and performance, and in which the nature of potential problems become apparent at an early phase of the design process. That is, if the influence of design choices cannot be predicted in advance and knowledge about design alternatives is missing, ADAS design could benefit from a design approach consisting of short and adaptive design iterations based on early evaluations. Potentially, such an approach takes into account the needs, competencies and limitations of the joint driver-vehicle system at an early phase of the development process.

The present research addresses the cooperative setting between drivers and support systems and attempts to serve as an aid for establishing and evaluating such a cooperative setting in order to improve the cognitive and cooperative abilities of driver support. In this way, the present research aims at supporting the design process of driver support systems. For this, it is proposed to anticipate the behavioral repertoire of driver support at an early stage of the design process using a simulation alternative called emulation that enables the exploration, execution and assessment of such driver support systems. Emulating driver support means that potential or envisioned system abilities are mimicked and represented by a human co-driver, allowing to produce support abilities even before such abilities are technically available. Through the execution of driver support by a human co-driver as a template for a fully automated version, it is suggested that the simulation environment has access to maximized cognitive abilities and therefore bypasses automation limitations that would otherwise constrain the potential behavioral repertoire of the driver support. Moreover, having access to human cognition, the social context of driver and support system coordinating their actions in order to fulfill the driving task safe and efficient, becomes readily available. Potentially, the proposed design and research environment therefore not only enables the exploration and evaluation of support behavior, but enables studying human support behavior as well. That is, by gaining knowledge about the cues and strategies used by human co-drivers, ADAS could be modeled after human support behavior when these cues and strategies are sufficiently understood. Within a general context of developing cognitive, cooperative and communicative technologies, the present research investigates the potential applications of emulation as a simulation alternative during the design process of advanced driver assistance systems.

Objectives

While the current research is embedded in a general aim to develop cognitive systems and to optimize their cooperation with humans, the focus lies on systems in which humans and automation share the driving task. The main objective of this research is twofold. On the one hand it aims to provide additional knowledge and insights about drivers cooperating with driver support systems. On the other hand, it tries to provide for a setting in which such cooperation can be established and used for research and design purposes. In this way, the current research intents to be of assistance for those involved in the design process of driver support and who are faced with the challenge to specify the behavioral repertoire and characteristics of future ADAS. For this, the following steps are taken:

1. Relevant theoretical background is addressed by associating the issues of cognitive systems design with car driving and the design of driver support.
2. As an attempt to contribute to the design practice of driver support an alternative approach is suggested that uses emulation during the design process. In the present thesis three potential applications of emulating driver support are suggested and their potential within the context of ADAS design is investigated by three driving simulator experiments that served the following goals:
    a. Providing a validation study in which the arguments for and against human emulation as a simulation alternative are addressed.

b. Exploration of the envisioned approach in terms of feasibility as a design and research tool.
c. Investigate the potential surplus value of having human co-drivers available during ADAS design.

Thesis outline

In Chapter 1 driver assistance systems were introduced and considered as part of the solution to increase safety and efficiency on public roads. By emphasizing the complexity of the driving task, it was shown how the design of cognitive support behavior is faced with several problems and challenges that need to be overcome in order to provide for safe, efficient and cooperative driver support. The present thesis aims to contribute to the design of such systems in two ways. First, by addressing the relevant theoretical issues concerned with the development of support behavior in the automotive domain. And secondly, by investigating whether mimicking or emulating support behavior is a useful tool during the design process of driver support systems.

In order to clarify the problems related to developing 'intelligent' support behavior, Chapter 2 addresses the theoretical background of cognitive systems. In order to set the stage for this thesis a context is provided from which the main setting, humans and automation cooperating, is exemplified. For this, relevant developments in cognitive science and their implications for cognitive systems are reviewed and the developments in human and machine interaction (HCI) research are discussed. In this chapter it is explained how a potential mismatch between the human and automated components sharing a task, constitutes a main challenge for those involved in the design of cognitive systems. Here, it is explained how dealing with unanticipated or even unwanted consequences of automation is difficult at design time and alternative approaches are discussed. Furthermore, it is addressed how an assumed automation paradox complicates increased automation.

In chapter 3, the scope is narrowed down further to the task of driving and those issues involved when driver and vehicle interact in order to share this task. The modalities of interaction with the driver will be discussed and ADAS will be classified after their behavioral repertoire. Furthermore, example scenarios of how a driver support system might complement the human driver in order to avoid a collision are provided.

Chapter 4 starts with the problem statements that led to the current research and three proposed applications of emulation as a design tool are specified.

The empirical part of this research consists of three experiments that are aimed at investigating the validity, practicability and potential surplus value of human agents emulating envisioned support behavior. In chapter 5 the research questions are provided and a brief description of the research environment is given.

Chapter 6 describes the first experiment which is set up as a validation study, investigating whether emulated support elicits similar driver responses as compared to implemented system functionalities. Serving as a review of emulation as simulation alternative, it aims at contributing to existing knowledge about the requirements for setting up and using an environment that allows for simulating driver and vehicle cooperation. Taking into account potential qualitative differences between emulated and implemented driver support, both support behavior and driver responses are determined objectively.

Chapter 7 describes the second experiment which is set up to investigate whether emulation allows for evaluating design choices at an early development phase. Such an approach would demonstrate its surplus value when design alternatives can be compared, evaluated and decided upon at the early phases of the design process.

Chapter 8 describes the third experiment which is set up as an exploratory study in order to address whether emulation could be used to establish a setting that reflects anticipative cognitive support. This experiment serves three purposes. First, it investigates whether the human co-driver is a valid simulation alternative for a support system that is able to predict driver intent, which is a quality difficult to automate when it comes to interpreting driver behavior. Secondly, it examines whether human cognition (i.e. the human factor or co-driver) has a surplus value as compared to pre-programmed algorithms when it comes to representing cognitive support systems. And thirdly, the experiment serves as an exploration for future research where the co-drivers' behavior is observed and potentially contributes to the understanding of the ability to predict the actions and intentions of others.

Chapter 9 and 10 provide the general discussion and conclusions, respectively.

2

Artificial Cognition and Cooperative Automation

While the challenges medieval man was facing are clearly not within the scope of the current work and the potential implications of humans and automation cooperating were not raised until recently, it is the work of a 13th century scholar that has re-emerged in contemporary science. Understanding the brain and how it creates intelligent behavior is a subject of long-standing interest for many, but whether one tries to unravel the mysteries of the brain, develop artificial intelligence or tries to find solutions for collaboration between human and artificial cognitive systems, the ongoing progress in different approaches and viewpoints is undoubtedly a driving force in all of these disciplines. Considering a time lag of more than seven hundred years, it is surely remarkable that one of those forces is Italian priest Thomas Aquinas (1225-1274), whose explanation of cognition is suggested to be the most compatible with recent findings in neuroscience (Freeman, 2008). However, before touching on the relevance of Aquinas' work, cognition and various positions on cognition are introduced.

Cognitive systems

According to Webster's dictionary, the etymology of cognition comes from the Latin *cognoscere*, which refers to *becoming acquainted with* and *come to know*. Furthermore, being cognitive involves conscious intellectual activity like thinking, reasoning and remembering (Merriam-Websters' dictionary, 2003). Within the present context, a cognitive system or agent is thought of having knowledge of itself and its surroundings by understanding how things are and how things might be in the future, taking into consideration the actions of different agents involved. When a system is able to respond thereupon, it is called cognitive. The aspect of anticipation is of particular interest in the current notion of cognition because when developing artificial cognition that needs to complement human behavior, the system is expected to have at least some amount of inferring and anticipative abilities. This stance on cognition is rather liberal because in order to anticipate future events a cognitive system could also be defined as one that reasons, learns from experience, improves its performance with time and is able to respond to situations it was never faced with before (Vernon et al., 2007). Moreover, for some being cognitive requires even a sense of self-reflection (e.g. Brachman, 2002; Hollnagel & Woods, 1999). Intuitively, imposing such robust requirements on a cognitive system that is expected to cooperate with a human agent seems fair. However, this is far from self-evident as will be discussed in the remainder of this thesis. Apart from the ongoing debate about what to expect from cognitive systems, different approaches can be observed in the cognitive sciences. As appears from Vernon et al. (2007) two main paradigms of cognition can be identified, which are presented in the next sections.

The cognitive approach

Cognitive science[1] has emerged from the late 1950's and since it gradually replaced behaviorism as one of the prominent philosophies in psychology, it is often referred to as the cognitive revolution (e.g. Baars, 1986; Greenwood, 1999; Miller, 2003). And while the developments and paradigm shifts are interesting for putting the study of brain and behavior in a historical perspective[2], it is the theoretical approach used by the cognitivist that is relevant in the present context. According to Freeman and Núñez (1999) the aim of the cognitivist-oriented study of the mind was to provide a paradigm and methodology for realizing and emulating the essential aspects of the mind in an objective and controlled fashion. The view of the mind as a rational calculating device served as a theoretical framework and the development of the digital computer influenced cognitivism in several ways. On the one hand the digital computer enabled the operation of an enormous variety of algorithms whose functions were believed to reflect emulations of the human brain and on the other hand the computer served as a metaphor for the human mind as a passive information processor that operates on logical manipulation of arbitrary symbols. It is this metaphor of the mind as a computer and the view of intelligent behavior as computation (using expressions like hardware and software) that influenced cognitive science to this day. However, the view asserting that cognition involves sequential processing of information which is subsequently (overtly or covertly) acted upon, is not only challenged by emerging views, which are discussed in the next section, but constrains the creation of artificial cognition in a profound and limiting way. Since this thesis is concerned with the design of artificial cognition that supports and even collaborates with humans, the potential limiting factors of such an approach should therefore be discussed. Before addressing the limitations of the cognitive approach, it should be noted that as specific acts and qualities of social behavior, terms like collaboration, coordination, joint action and cooperation have their own definitions and are often used in a specific context by different disciplines. Coordination, for example, is found difficult to characterize given its diversity in possible definitions (Malone & Crowston, 1994) and conditions for achieving and maintaining coordination might therefore differ. While this goes for each expression, in the present research they all refer to social interactions where (human or artificial) agents anticipate their behavior in order to complement each other on the task that is being shared. Different expressions are therefore used throughout this thesis, all referring to interdependency between agents.

To recap, the cognitivist' classical view of cognition is based on the idea that reasoning and planning are distinct functions or modules of the brain within a perception action cycle for

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[1] For the purpose of the current research, cognitive science is defined as the interdisciplinary approach for studying brain and (artificial) cognition, having its roots at least in psychology, artificial intelligence, neuroscience, anthropology, linguistics and philosophy (Miller, 2003). Since cognitivism became the predominant paradigm in the late 20th century and since humans and automation are studied in conjunction when they have to cooperate, in the remainder of this thesis both humans and automation will be referred to as cognitive systems or agents.

[2] It is therefore important to mention that different definitions and viewpoints concerning brain and behavior are subject to an ongoing debate in the scientific community.

which is decided what actions should be performed next. Simply put, this asserts a sequential process of perceiving stimuli who are processed and decided upon by specialized brain regions (i.e. cognition), resulting in proper responses. The computer metaphor of humans as information processors is therefore not far-fetched. The classical view of specialized brain functions and isolated perception and action planning, however, has been updated through the years by acknowledging a much tighter (e.g. Hommel et al., 2001; Hurley, 2008; Prinz, 1997), more flexible (e.g. Newman-Norlund et al., 2007; van Schie et al., 2008) and even reciprocal (e.g. Kadar & Shaw, 2000; Shaw et al., 1995) relationship between perception and action. Nevertheless, this approach seems very promising for developing cognitive support behavior since the cognitivist' view implies similar processes for cognition in humans and artifacts, meaning that they theoretically operate on a peer-to-peer basis. Furthermore, this could simplify things at both design and run time when tasks are to be shared or exchanged between human and artificial agents. Applying cognitivism to the design of artificial cognition, however, might be limiting in several ways. First, since the behaviors or cognitive features of the artificial cognitive system are the product of a human designer, the representations and abilities of the artificial 'brain' are dependent on the developers' own cognition and programming skills. It is this dependency on the human ability to represent causes and consequences of situations and how to provide for relevant modifications of the system that bias or even blind the system (cf. Winograd & Flores, 1986). By being dependent on a priori knowledge of its developers, the system is limited in its adaptability since the system depends on the assumptions designers have concerning the system's environment, its behavior and its space of interaction (Vernon & Furlong, 2007). This limitation portrays a serious paradox because in this view the human designer could be understood as the weakest or unreliable link in developing artificial cognitive behavior. If the system is constrained by its developers, the cognitive approach could fall short when aiming at proper cooperation between humans and automation. This means that the design of cognition not only faces the problem of providing inferring and anticipatory abilities, i.e. how to solve a task, it means that the designers could be regarded as part of the problem as well. Moreover, if the cognitive abilities of the system depend on an approach that predefines the steps to be taken for solving a task or how to overcome certain situations, it is not only biased or constrained by the knowledge or skills of the developers, its behavioral repertoire is fully subject to the amount of foreseen or potential situations it will come across. Those situations and abilities that were not anticipated or coded for by the developers, will fail in providing proper responses. This might seem obvious for those who rely on such systems when working with them, but at design time, i.e. anticipating all possible situations and responses, this is one of the core challenges. Some even claim that such comprehensive anticipation is theoretically impossible since it involves the reduction of all forms of tacit knowledge (i.e. knowledge that cannot be or is hard to express verbally, like riding a bike or driving a car) to explicit facts and rules (Winograd, 1990). This argues against the traditional approach of cognitivism since it might not reflect human cognitive abilities and puts apparent limitations on the abilities and characteristics of artificial cognition. However, emergent approaches have acknowledged these limitations and will therefore be discussed in the next section.

Alternative approaches

In a comprehensive survey of the various paradigms of cognition and their implications, Vernon and colleagues (Vernon et al., 2007) provide example architectures drawn from various approaches that show the advances made in building cognitive systems. One of the alternative approaches discussed by them is an approach that covers connectionist, dynamical and enactive systems and is referred to under the general term of emergent systems. In the present section the emergent systems approach is compared to the cognitive approach. Similar to the previous section, some potential limitations are discussed and will be complemented with an approach that serves as an additional alternative while acknowledging the limiting factors.

In the previous section it was explained how the cognitive approach is confronted with serious limitations for the design of artificial cognition. The emergent systems approach, however, might overcome these limitations. Its main view on cognition implies that the system, through self-organization, reorganizes itself continually in real-time. For this, interaction and co-determination with the environment are essential (Maturana & Varela, 1987). Co-determination refers to a view of cognition as a process where "the issues that are important for the continued existence of a cognitive entity are brought out or enacted: co-determined by the entity as it interacts with the environment in which it is embedded" (Vernon et al., 2007, p. 159). This view challenges the conventional view of a cognitive system since acquiring knowledge or becoming cognitive depends on the system's history of interaction with its environment. Therefore, nothing is pre-given and "the system builds its own understanding as it develops and cognitive understanding emerges by co-determined exploratory learning" (Vernon et al., 2007, p. 160). Again, intuitively this makes sense because such a stance on cognition implies that understanding and therefore the ability to respond properly, develops in time and emerges while the system learns by exploration. As humans regarding our own cognition, irrespective of any philosophical stance, such learning by experience seems obvious. However, for designing artificial cognitive systems that require proper coordination and interaction with humans in a vast amount of situations, this view, as compared to cognitivism, faces limitations as well. First of all, while cognitivist models are limited by the a priori definition of their behavioral repertoire, emergent approaches assuming a self-organizing nature, resulting in real time skill construction, are theoretically able to realize systems that develop relevant cognitive skills and knowledge. However, such co-determination is heavily constrained by the interactions the system has during its development. Moreover, such a developmental approach cannot be short-circuited or bootstrapped into an advanced state of learned behavior (Vernon & Furlong, 2007). While this means that the system has strong autonomy in its learning process and does not need to be told what steps to follow in order to solve a task, for commercial purposes like artificial cognition used for supporting drivers, this could have serious implications. Following the emergent systems approach this could mean that each system or each vehicle develops its own particular way of solving things. Without further elaboration on legal and reliability issues, applying such an approach in mass production can be problematic for apparent reasons.

For the remainder of this thesis, the fundamental differences between the cognitivist and emergent approaches are of particular interest since the theoretical issues and limitations have to be overcome in order to provide the design practice with pragmatic solutions that enables the development of cognitive support behavior. It is shown how the traditional cognitive approach faces difficulty in anticipating significant future situations. The emergent approaches on the other hand are able to provide systems that develop their own solutions without the necessity to predefine the entire cognitive architecture. However, considering the limitations of both, it can be argued whether the individual approaches are sufficient for the design practice to develop robust, reliable and unambiguous support behavior. It is therefore proposed to use additional hybrid and empirical solutions while the above-mentioned paradigms progress and improve in their own pace. One of the alternatives is to focus more on the understanding of the interactions between cognitive systems. Such a stance implies the understanding of the social context of collaborating agents, whether they are human or artificial. Since cooperation between agents implies sharing tasks and communicating intentions, comprehension of such a setting could be of assistance when choices concerning the behavioral repertoire of the artificial system are to be made. The social setting of cognitive systems interacting with each other is presented in the next section.

Collaborating cognitive systems

Although it seems odd to mention the work of a 13th century scholar when dealing with 21st century technology, since it reflects the view of those who emphasize the influence of the physical and social environment on the development of the human brain, it is worth noting that according to Freeman (2008) the philosophy of Thomas Aquinas (ca. 1225-1274) is the most compatible with recent findings about the neural mechanisms of the brain. In cognitive neuroscience the view has emerged that brain dynamics are accessible by the theory of nonlinear dynamical systems (e.g. Stam, 2005; for an introduction on nonlinear dynamics, see e.g. Faure & Korn, 2001). On the one hand, such a view applies chaos theory to the human brain, but in line with the context of the present work, the view of the brain as a dynamical system (e.g. Kelso, 1995) also shows the importance of context on human behavior and the coordination with others. Whereas the cognitivist' view asserts a computational realization of cognition, the cognitive development of emergent systems is heavily constrained by its ecological and social environment. Apparently, such co-determination and dependency of cognition on its environment was already acknowledged by Aquinas. This is expressed by Freeman paraphrasing Aquinas, who states that "the meanings of knowledge and information emerge through social interactions among intentional beings" (Freeman, 2008, p. 219). This view points to the problems faced in the present research, since humans who are supported by or cooperate with automation can be envisioned as socially engaged with artificial cognitive agents. The challenge for those who develop such collaborative systems is to understand the social interactions between the agents or co-actors involved and the requirements needed for safe and efficient collaboration. Such understanding is exemplified by the notion that automating coordination can be seen as trying to make automated systems "team players" (Malin et al., 1991; Roth et al., 1997; Christoffersen & Woods, 2002; Dekker & Woods, 2002; Klein et al., 2004; Dzindolet et al., 2006; Eccles & Groth, 2006) and that cognition is fundamentally social and interactive (Woods & Hollnagel, 2006). Humans operating within a social context need to interpret and understand a situation in order to act accordingly. In a similar vein, this requires at least some interpretive and anticipatory abilities of artificial cognitive systems in order to collaborate with others. Understanding and anticipating the social environment of collaborating cognitive systems is therefore a main challenge for those involved in the design of the cognitive abilities of automation. The importance of anticipating the interaction between human and automation is explicitly manifested in the presence of advanced driver assistance systems (ADAS) in vehicles. In the remainder of the current research the design of driver support will serve as the main example of humans and automation cooperating.

Automation paradox

In the previous sections it was shown how several approaches used different paradigms to study human cognition or to produce artificial cognitive behavior. While the cognitive abilities of an artificial system can be viewed as the automated component of a man-machine system, automation is a catch-all-term that needs some additional delineation since it might have different meanings in different areas of application. In order to provide for an unambiguous description of how automation is used in the current research, a definition in general terms will be followed by an illustration of automation in the automotive domain. In conclusion it will be shown how automation changed the nature of the driving task (cf. Hollnagel et al., 2003; Stanton & Marsden, 1996; Ward, 2000) and how an increase of automation can be viewed as one of the paradoxes that the design of cognitive systems is faced with.

In the current research, automation refers to the technique of making an apparatus, a process, or a system operate automatically and is derived from *automatic*, which has its origins in the Greek *automatos* (Merriam-Websters' dictionary, 2003). This self-acting of a man-made artifact or system is the most relevant quality of automation when seen as an individual entity that is able to perceive by means of sensors, which acquires knowledge by means of cognition and that is able to act upon this information accordingly. Within the present context, automation can be further specified as those behaviors that have a certain amount of autonomy in order to complement or replace human behavior. Since automation is assumed to act upon the information that is received, automated systems or devices resemble artificial cognitive agents and will therefore be addressed in this thesis as similar to (artificial) agents, computers or machines.

Given the description of automation as man-made behavior that supports or even replaces the tasks performed by a human agent, several descriptions of automation are available that use a hierarchical classification, considering the amount and types (or roles) of automated support behavior. For instance, Endsley and Kaber (1999) provide a ten-level taxonomy of level of automation (LOA) that specifies the degree to which a (human) task is automated. While such classifications are provided in order to address the degree to which automation should be implemented in a given system (Parasuraman, 2000; for alternative classifications see Endsley, 1987; Ntuen & Park, 1988; Sheridan & Verplank, 1978) the relevance in the present use of automation lies in the distinction and therefore potential interaction between humans and automation. The available taxonomies can be reduced and simplified to three kinds of interaction between human and machine. First of all, a human task can be performed manually, without any automated support. In this situation there is no human-computer interaction. Secondly, the interaction level refers to a task that is being shared between human and automation. Thirdly, automation can be of such degree and quality that it is able to replace the human actor and performs an entire task autonomously. When the automation performs fully autonomously and no human intervention is needed, again there is no interaction between human operator and the system. The situation of human and machine interacting within a single task is the main focus of the present research. The main task reflecting such man-machine interaction used in this thesis is contemporary car driving.

Although conventional car driving can be seen as mechanically automated and provides information about the vehicle's speed and operating status, it is used in the present context as an example of lacking automation. The vehicle is controlled manually and it is a task entirely performed by human agents. On the other hand, modern-day cars are equipped with sensors, acquire a certain amount of knowledge and are able to co-control several actuators of the vehicle. In general terms they have the ability to sense the environment and act upon this data by providing the driver with information or warnings and they can even take over part of the driving task. The abilities that make cars true cognitive systems will be addresses in a subsequent section, but for now it is the acknowledgement of driving as a task that is being shared between the human and automated components of the entire driving system that is relevant for mentioning an assumed automation paradox.

In general, providing driver support systems aims at reducing the cognitive requirements placed on the driver and therefore offers opportunities to increase traffic safety, efficiency and driver comfort (e.g. Parkes & Franzen, 1993). However, by adding interactive automation, the conventional manual task becomes a supervisory task as well (cf. Walker et al., 2001; Brookhuis et al., 2001) and this means that by increasing the amount of automation, the supervisory task increases as well. Instead of reducing, this could increase the cognitive efforts placed on the driver and it shows how the safety of the system is highly correlated with the quality of this supervision. This means that adding automation does not necessarily make things easier and could even be a problem when the behaviors of automation and drivers do not match. This emphasizes that the safety and efficiency of the entire system also heavily depend on the cooperation between the human and automated components of the system. Ironically, the more advanced and complex (i.e. automated) a system is, the more crucial becomes the contribution of the human operator (Bainbridge, 1983). A potential mismatch between the human and automated components sharing a task, associated with unanticipated or even unwanted consequences of automation are therefore significant challenges for all those involved in the design of cognitive systems.

Design and evaluation of man-machine interaction

Fundamental psychological research as a basis for applied research has evolved fast during the last decades due to increased computational power and other technological advances like progression in (brain) imaging techniques. The number of founding fathers in these disciplines grew exponentially during and after World War II, when practical issues arose from the requirements in (e.g. airborne) warfare. Research tried to answer questions like who to recruit as aviation pilots, why some airplane models elicited more errors than others or how a cockpit should be configured for optimal performance. As these issues prompted the use of controlled laboratory experiments, fundamental research and applied research grew apart because the experimental designs showed their ability to initiate new fundamental research questions which were not primarily dealing with the purpose of optimizing user and its environment. Instead, psychonomics and other sub-disciplines aimed at modeling brain and behavior, without the necessity of utilizing their results in the daily (human) practice. Their aim is to unravel the human brain and its behavior in order to complement scientific knowledge. In parallel to the growing body of fundamental knowledge, other sub-disciplines like human factors research and human computer interaction[3] (HCI) used the available experimental paradigms and methods to study and optimize the interaction between humans and their environment. The scope of the present research lies within this applied framework.

Historically, human mental and physical abilities or limitations guide much of the HCI research, as reflected by the search for the optimal distribution of functions shared by man and machine or by relating psychological constructs to various individual and environmental factors that limit the human operator. For example, the construct of situation awareness (SA), which is thought of to reflect the understanding of a situation and which tries to describe how humans develop and maintain such understanding, could be used to generate designs that enhance operator's situation awareness (Endsley, 1995). In contrast, within the notion of such a limitation-based approach, Flach and Hoffman (2003) pointed out that researchers adopting such a view can be viewed as being too selective in regarding certain human characteristics as limitations. Moreover, they argue that such an approach is prone to selecting the wrong capabilities and limitations for the wrong reasons. While it is not within the scope of the present thesis to participate in the discussion if and how automation should

[3] For simplicity reasons, all disciplines concerned with the interaction between humans and their environment, are referred to as HCI.

compensate for human limitations or to be judgmental about the strengths and weaknesses of HCI research, it should be noted that the present research is embedded within the recent developments in both automation and the shifting research approaches within the disciplines of HCI research. It is therefore important to mention that not only the amount of automation - that humans have to cooperate with - has evolved; it is the nature of the automation that has changed most drastically. Consequently, shifting strategies can be observed within the research communities dealing with such interactions. Rapid shifts in the control of human-machine systems (like automobiles) are responsible for emerging issues like safety and efficiency. Intuitively, this raises the question if present day designers are equipped well enough to tackle these issues and if they are fully aware of the changing nature of contemporary and future automation. Subsequently, one can ask if both traditional applied- and fundamental research provide the answers for dealing with the rapid shifts of control in HCI systems.

In the present research, it is therefore argued that recent developments in automated control, for which present and future generation support systems in cars are a good example, require adapting strategies to tackle the problems involved with these developments. When defining HCI within the context of the present research, the problems concerning the potential mismatch between technology and the human agent pose the main challenges for designing HCI systems and their evaluation. Differently stated, HCI research within the context of man and machine comprising a unified driving system is mainly concerned with anticipating and envisioning the complementary behaviors of humans and automation.

As already mentioned, HCI research is inherently related to human capabilities and disabilities (for a history of human factors research see Meister, 1999), the latter ones being prone to inefficient and faulty behavior. It is therefore important to realize that if a system (the interplay between operator and technology) shows failure, it hardly ever is a failure of a technical component or arrangement alone. Neither is it likely to be a sole error of the human component. Most of the time the (faulty) event is caused by a complex interaction of factors that may originate from any of the six system levels that Wilpert (2008) identifies as technical design features, individual hazardous actions, inadequate team performance, inappropriate management, ill-structured organization or even actors external to the facility. Although these levels refer to accidents in industrial settings, they can be applied in the present context of shared control in driving as well because both driver and vehicle, their interaction and external actors can be the (combined) source of incidents. Research, either problem or solution driven, could appreciate from this, that what we are dealing with is an interplay of factors and variables, that together make up an open, and for that matter, complex system. Depending on the system level and the level type, different competencies are therefore needed to perform this research in aiming at proper HCI. If different disciplines are needed to examine failures in a system, as HCI evaluation is commonly applied for, then the same disciplines are preferably involved in designing safe, functional and reliable applications or systems. Given this view, interdisciplinary collaboration in systems' design requires acknowledgement.

Within the context of the present study it is argued that an emphasis of human limitations on either faultfinding or systems design is not the most fruitful assumption. Instead, and this stance will return several times in this thesis, human performance and the design of human-technology interactions should be seen from within a systems viewpoint. That is, human actors, the interactive technology and their context, are part of a unified (open) complex system. In addition, it is argued that emphasizing limitations of human performance, in its turn, limits the scope of researchers and designers. Firstly, by anticipating the cognitive (dis)abilities of humans, one fails to recognize cognitive flexibility. Humans are an instance of dynamic systems and neural plasticity is reflected by their ability to learn according to the specific circumstances or demands. An example of this quality is the notion of working memory. The 7±2 chunks limitation to short term- or working memory is a concept that is mentioned in the curriculum of every freshman in psychology. While human factors practitioners and designers might adopt this knowledge in their research or design, they should be aware that observations like these are only facts when they are replicated in the original experimental context. Moreover, this observation can be seen as an ability instead of a limitation as well. In addition, it should be mentioned that practice can increase the amount of learned material and this amount of info (that can be integrated into chunks) is flexible and domain specific (Flach & Hoffman, 2003). Again, observations like these can be useful within controlled experiments, but are only trivia when adopted without the original context. A second limitation due to the emphasis on human disabilities arises when researchers adopt the machine centered bias (Norman, 1993), where automation is seen as being able to compensate for all human limitations. In this technology driven view, machines 'do it better' and often research assumes that design solutions involve adding more automation. Of course, automating specific functions within a given system can solve certain (safety) problems, however, they do not provide any guarantee in advance, nor should design problems be the argument for a competition between man and machine.

In the present thesis, it is therefore claimed that design and evaluation of man-machine interaction needs an approach that, first of all, shows no limiting scope due to wrong assumptions or undesirable emphasis on the performance of either human or machine. The systems viewpoint is chosen to account for the holistic and dynamic processes that design, performance and evaluation of ADAS are confronted with. It is believed that the design process of ADAS could benefit from the assumption that drivers and their environment are part of a single driving system, where human and machine are complementary resources of a complex semi-automated driving domain. In this view, capabilities and performance of the system are the result of the joint contribution of man and machine. Given the previous statement that the main challenges for designing and evaluating HCI are concerned with the potential mismatch between the technological and human elements of the system, anticipating the complementary behaviors of humans and automation becomes an important goal when developing ADAS. Consequently, this assumes two significant requirements for designing HCI and for the design process of driver support systems in particular. First, in order to define the cooperation between humans and automation, the behavioral repertoire of the support system should be determined early in the design process. Similarly, in order to consider and assess design alternatives, evaluation of performance and cooperation should be carried out early in the design process.

Given these considerations, a promising approach for designing, studying and evaluating the cooperation between technology and humans is rapid prototyping. Although rapid prototyping is commonly known as a method for generating physical prototypes from virtual and physical models in manufacturing, exploring and testing preliminary designs can be applied to other domains as well. The general idea of such an approach in the context of HCI can be described as generating, evaluating and adapting prototypes of interactive systems in an iterative fashion. In rapid prototyping, the intended system is implemented with its key features at an early phase of the design process. The main advantage of rapid prototyping is therefore that it allows for testing concepts at an early design phase when costs are small and changes are made more easily (e.g. Hardtke, 2001).

An instance of rapidly prototyping interactive systems is an approach called wizard of Oz (WOZ). The wizard of Oz approach is a method for rapidly prototyping systems costly to build or that require new technology (Wilson and Rosenberg, 1988; Landauer, 1987; cited by Maulsby et al., 1993). Applying such a method implies simulating the system's intelligence or abilities by a human operator through a real or mocked-up computer interface, while those interacting with the system are kept unaware that (some of) the expected functionalities are executed by (one or more) human operators. For example, when aiming to design a system that understands and acts on spoken language, WOZ could be considered when such system abilities are technically infeasible or difficult to implement. Because a human operator could serve as a simulation alternative (i.e. being the one that communicates with the system's user) requirements for and experiences with such a system could be investigated prematurely, without having to solve all technical details that are needed to implementation such abilities. In this way, simulating system abilities (i.e. the system's behavioral repertoire) allows for preliminary experiments and evaluations, e.g. involving expected users, potentially revealing different requirements as initially thought of by the developers. When requirements for optimal interaction between a system and its users are difficult to anticipate, efforts to realize system abilities technically, can be postponed until the necessary requirements are determined after thorough investigation. When system designers receive early feedback about system requirements, e.g. through user experiences and expectations, this would enable them to adapt the system accordingly, even before actual implementation. Conventional simulation, on the other hand, depends on the technical ability to implement the envisioned system abilities. Because WOZ allows for realizing and evaluating system abilities that are not or difficult to execute otherwise, this approach is of particular interest when having to anticipate and envision the complementary behaviors between drivers and support systems. In chapter 4, this approach will be further elaborated upon within the context of the challenges that ADAS design is confronted with. Since the implementation of automated driver support is the key example of human and machine interaction in this study, the next section will provide an overview concerning the developments of cooperation between humans and automation in the automotive domain.

3

The driving task and advanced driver assistance systems (ADAS)

In a previous section, it was argued how adding support behavior by means of advanced driver assistance systems changes the nature of the conventional driving task from a manual to a supervisory task. Moreover, it also changes from an individual task into a cooperative task where the support system can be viewed as an automated co-driver or team member (e.g. Davidsson & Alm, 2009; Young et al., 2007). However, the driving task as such has not yet been discussed in this thesis. The present section is meant to provide a general overview of the attempts to model the driving task and to address the available driver assistance systems that complement or cooperate with the human driver. Details concerning the functionalities of the available support systems and their potential effects on driver behavior are kept to a minimum since the focus of this thesis lies on the general view of driver and support behavior as analogous to human and automated cognitive systems sharing the driving task. Technical functionalities of ADAS and specifics concerning the possible behavioral effects associated with such systems are therefore not within the scope of the present thesis.

Driving task

In common terms, the driving task is little more than controlling a car by means of a steering wheel, some pedals and, in case of a manual transmission vehicle, a gear stick in order to travel from A to B. The vehicle can be directed laterally and longitudinally by steering, accelerating and decelerating. Despite an apparent simplicity of the driving task, attempts of modeling this skill are numerous and hardly any consensus exists about what exactly driving is and how it should be modeled in order to provide a valid and practical representation of the driving task. A generally accepted model of the complete driving task is therefore missing (Panou et al. 2007). However, efforts to model driving are an ongoing endeavor in the scientific community because much can be gained when the driving task is understood well enough to define all the components that together constitute the ability of controlling a vehicle through its environment. On the one hand, analytical models could provide insight about the underlying demands and mechanisms of the driving task. On the other hand, a general, flexible and cognitive representation of the driving task would be extremely valuable for research and development because of its ability to predict driver behavior. Such a comprehensive model could be helpful in providing relevant support behavior because it would reveal potential requirements of the driver and could help in assessing the effects of the design choices made to complement the driver with relevant support. Moreover, a comprehensive predictive model has the potential to monitor driver behavior in real time and to adjust and adapt support behavior according to the situation at hand, serving as an adaptive co-driver (cf. Cacciabue & Carsten, 2010; Carsten, 2007). In order to provide a general overview of the driving task some relevant contributions are discussed next by adopting the classification of the driving task models as given in Hollnagel (2006). This overview does not only try to demonstrate how modeling is subject to historical developments of the traffic system as a whole but also tries to show how the modeling highly depends on the purposes and intentions of its developers.

Driving as safe travel

One of the earliest attempts to shed light on the driving task comes from Gibson and Crooks (1938). They provided a psychological description of the driving task based on the conclusion that driving is predominantly a perceptual task and the motor reactions are relatively simple and easily learned. They therefore carried out their analysis on a perceptual level, where driving is a type of locomotion through a terrain or field of space. Gibson and Crooks claimed that driving is psychologically analogous to walking or running, with the addition that driving is locomotion by means of a tool (i.e. the car). According to them, driving is guided mainly by vision and this guidance is given in terms of a path within the visual field of the actor such that obstacles are avoided and the goal (reaching a destination) is being met. When Gibson and Crooks conceptualized the driving task as following a path in order to avoid obstacles by means of a field of safe travel, they appointed six limiting factors, among them natural boundaries and inflexibility at higher speeds. Although they recognized the kinesthetic, tactual, auditory and visual aspects of driving a car, relatively little attention was paid to the features and the behavior of the car itself, let alone to the human factor[4]. On the one hand this shows their appreciation of the driver-vehicle system as a unifying concept, "one in which the impression and the action are especially intimately merged" (p. 470). On the other hand it shows the rapid changes that drivers were confronted with during the past decades. Hollnagel (2006) notes that both the traffic environment and the vehicles of today are hardly comparable with the situation in the 1930's. Traffic densities have increased considerably and contemporary drivers have to deal with more road signs and signals. Furthermore, present day cars are more powerful and are equipped with all sorts of additional functions, including support and entertainment systems. However, while its shows that a change in the nature of driving is not only related to the introduction of driver support, these developments are not necessarily unambiguous about how the driving task changed in terms of task difficulty or about the cognitive requirements placed on the driver. To give an example, keeping a vehicle within the field of safe travel in the 1930's is considered by Hollnagel as a demanding task in itself since maneuvering the vehicle required more attention and effort as opposed to present day driving (Hollnagel, 2006). Given the general concern of the potential consequences of adding automation in present day vehicles, one could question whether the driving task has become more or less demanding as compared to conventional driving. This not only emphasizes the complexity of modeling and identifying the relevant elements of a seemingly simple task but also shows how each attempt to model the driving task becomes outdated exactly because of developments in car driving and systems design. This means that changing the driver-vehicle system has consequences for what driving tasks and traffic environments become, and therefore changes its own premises (Hollnagel, 2006). Moreover, because implementing driver support is aimed at changing the driver's task, the mental and psychomotor requirements of driving change as well (Fastenmeier & Gstalter, 2007) and should therefore be accounted for in any

[4] For the remainder of this thesis, the expression human factor refers to the social and cognitive properties as typical and innate characteristics of humans.

model that either represents the modified driving task or that is able to reveal the potential advantages or risks associated with the modifications of the system, for example when implementing a driver support system.

Driving as control

Following the rationale of Hollnagel (2006), modeling the driving task transforms with changes in vehicle and traffic characteristics. By the 1970s the number of functions and controls (e.g. radio) in cars had increased and driving became physically less demanding because of technologies like power steering and assisted braking. However, according to Hollnagel, due to more powerful engines, increased density of traffic and an increasing number of traffic signs and signals, the driving task changed and became more demanding as compared to the situation in the 1930's. Simply put, the change in the nature of driving is quite obvious since the task was added with technological features, and the increased density of traffic changed the 1930's task of keeping the vehicle within the field of safe travel into a more complex maneuvering task. In line with this change of task, models became available that put more emphasis on the controlling (laterally or longitudinally) aspect, where driving was seen as a number of control tasks being described in terms of inputs, outputs and feedback (e.g. McRuer et al., 1977). Within such a view, the control level of the driving task is characterized as following the desired path by using (i.e. controlling) the steering wheel, brakes and accelerator. Such an approach allows for describing specific traffic situations and the requirements needed (e.g. appropriate speed) to avoid a collision. However, the fundamental limitation of such functional models is that they do not consider psychological processes involved in driving. Given the changes in the nature of driving and an increased concern about the effects various factors (e.g. vehicle speed, traffic density, or adding automation) might have on the safety and efficiency of driving, a demand grew for more elaborate and predictive models. While the work of McRuer and colleagues is still influential, this type of modeling has a rather limiting scope, since operational performance has not proved to be indicative of accident involvement (Rothengatter, 1997).

Driving as situation management

According to Hollnagel (2006), due to changed vehicle and traffic characteristics in the 1970s, driving became physically less demanding, while it can be viewed as cognitively more demanding. Looking at the number of road fatalities in the Netherlands as a hypothetical constituent of task difficulty, it can be observed that an increase of fatalities between 1950 and 1970 decreases almost as strongly from 1972 onward (Stipdonk & Berends, 2008). While developments of vehicle characteristics and safety precautions (e.g. active and passive vehicle safety, alcohol and safety belt legislation, being introduced in the early 1970s) might be obvious explanations for this ongoing decreasing trend, it is believed that for single car accidents the decline can be explained by driver experience. However, as noted by the same authors, the risk of car-car accidents increases with traffic density and human factors like fatigue, impaired driving or other causes for a loss of control are therefore correlated with traffic volume. Although it is unclear whether there exists a robust relationship of potential safety issues with the demands of driving, it should be noted that in addition to active and passive safety systems, vehicle characteristics have evolved in terms of comfort and handling by introducing advances in active suspension techniques and vehicle noise reduction. Since this development could have serious implications for the driving task and safety, this trend is discussed before addressing the modeling of driving as a driver assessing the situation.

It appears that a modern trend in vehicle design is to reduce internal car noise (Horswill & Plooy, 2008). According to Trainham (2005) consumer expectations are anticipated by efforts to minimize noise by damping vibrations and blocking sound from the driver's compartment. However, reducing vehicle noise and vibration diminishes the level and type of feedback available to the driver (Walker et al., 2006) and because of potential implications for current and future vehicle design this trend should be pursued with some caution (Hellier et al., 2011). Walker and colleagues have noted that reducing the level of internal car noise comes with a cost since the level of noise correlates with vehicle motion and is therefore used as a relevant source of information by drivers. By reducing noise, one alters one of the cues that are used by drivers to make safety-related judgments (Walker et al., 2006). Consequently, this might be reflected by the task-related efforts to drive a car and can have an effect on the safety of driving. For example, because driving speed has been found to be an important predictor of crash risk (Horswill & McKenna, 1999; Wasielewski, 1984; West et al., 1993) reducing the level of noise could encourage drivers to drive faster and this would place them at greater risk of crashing (Horswill & Plooy, 2008).

Perhaps inspired by the cognitive revolution but certainly in line with the cognitivist view of humans as information processors, driving can be described as a number of tasks with different characteristics concerning time and demand. An influential contribution is the classification of driving as a hierarchical structured task with strategic, tactical and operational components demanding different levels of driver control (Allen et al., 1971; Donges, 1982; Janssen, 1979; McRuer et al., 1977; van der Molen & Botticher, 1987). In a similar vein, Michon (1985) subdivides driving as a problem-solving task into three hierarchical and coupled levels, being the strategic, maneuvering and control level. These levels are different in terms of the task requirements, the time needed to carry out the tasks and the cognitive processes involved (see figure 3.1).

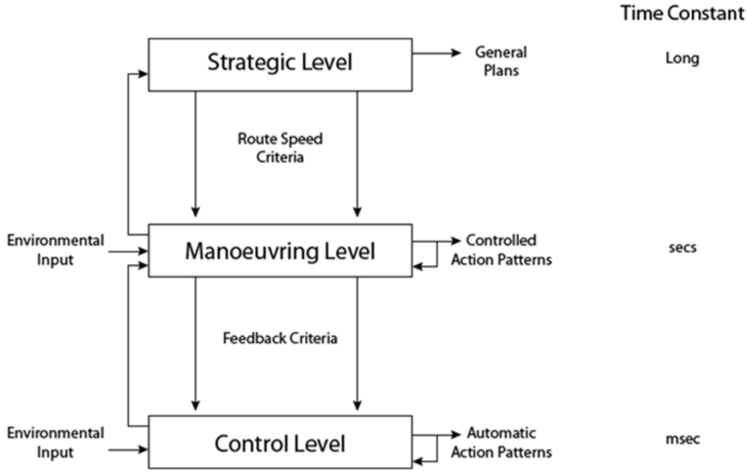

Figure 3.1: The hierarchical structure of the driving task (adapted from Michon, 1985; after Janssen, 1979).

At the strategic level the driving task is concerned with general issues of driving. At this level drivers prepare their journey, including the determination of available routes, mode of transportation and the determination of factors like time and speed. At this stage, driver's behavior is influenced by goals and attitudes. This means that decisions made by drivers depend on the amount and type of the available information, e.g. concerning traffic conditions and drivers state. The maneuvering level represents the actual driving stage and represents the interaction with the driving environment, i.e. other road users and the road system. At the maneuvering control level, driving is concerned with issues like overtaking, obstacle avoidance and obeying traffic rules. Finally, the control level of driving refers to the necessary control processes for navigating the vehicle through traffic. At this level the driver keeps the vehicle on the road by controlling speed and by steering. At the operational level drivers are therefore engaged with the elementary tasks or actions that control the vehicle laterally and longitudinally.

While it is assumed that the different levels of the driving task are coupled, different types of information are needed for the activities at each level. At the strategic level, information processing is mainly top-down. This means that decisions are cognitively controlled and knowledge is the main guidance for behavior. In addition, bottom-up processing with data from the environment is required at the maneuvering and control levels of driving. In short, goals and motives are defined at a higher (cognitive) level, while they are modified according to information gathered from a bottom-up process. Finally, Michon (1985) stated that a comprehensive model of driver behavior should not only identify the levels of control but should also explain how different tasks are concerned with different constraints in terms of available time to make decisions and to execute a task. As an example, planning a trip can be done in advance, while control decisions require only milliseconds to execute.

Roughly corresponding to Michon's hierarchical arrangement of driver behavior is Rasmussen's division of human behavior into three levels. First, skill-based behavior refers to behavior as more or less automatic procedures. Secondly, rule-based behavior refers to applying learned rules and thirdly, knowledge-based behavior refers to conscious problem solving (Rasmussen, 1983).

Both the models of Rasmussen (1986) and Michon (1985) can be combined as proposed by Donges (1999, cited from Weller et al., 2006), see figure 3.2. By combining these models, the driving task can be classified according to explicit examples of situations driving is confronted with and this allows to address driving in a more cognitive framework (e.g. Hale et al., 1990; Ranney, 1994; Weller et al., 2006; van den Beukel & van der Voort, 2010). Task examples classified according to a combination of the models developed by Rasmussen and Michon are given in figure 3.3 as proposed by Hale et al. (1990) and Ranney (1994), cited from Weller et al. (2006).

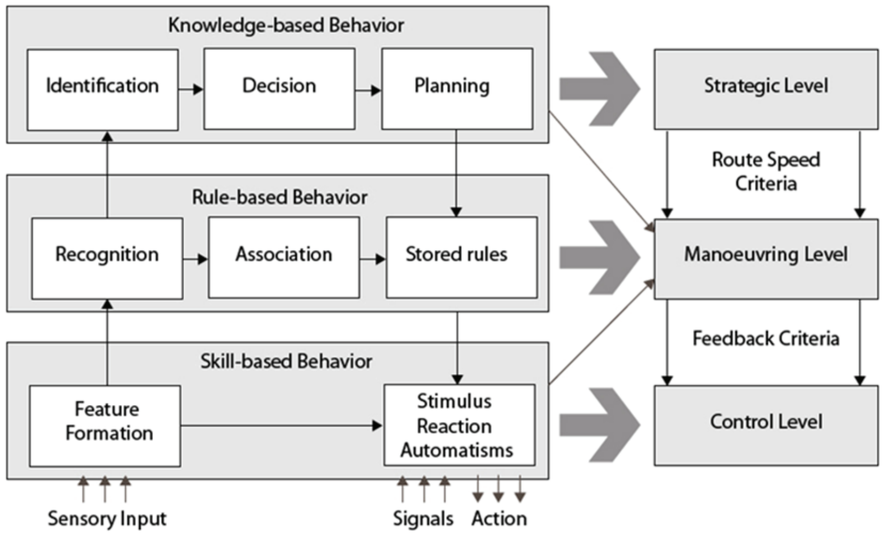

Figure 3.2: Combination of performance levels of Rasmussen (1986) and the hierarchical control model of Michon (1985). Adapted from Weller et al. (2006).

	Strategic / Planning	Tactical / Manoeuvring	Operational / Control
Knowledge	Navigating in unfamiliar area	Controlling skid	Novice on first lesson
Rule	Choosing between familiar routes	Passing other vehicle	Driving an unfamiliar vehicle
Skill	Route used for daily commute	Negotiating familiar intersection	Vehicle handling on curves

Figure 3.3: Examples of driving tasks when combining the models of Rasmussen (1986) and Michon (1985). Adapted from Weller et al. (2006).

Driving as driver and vehicle cooperation

In the previous section some examples were given of models representing the individual driving task as classified by Hollnagel (2006). Unfortunately, such an overview can hardly do justice to the numerous efforts made throughout the years to model this task. In addition, many attempts have been made to provide a structured classification and arrangement of the available types of modeling. In order to obtain a more elaborate notion of the available contributions, readers are referred to the existing literature in which these models are explained and grouped (e.g. Carsten, 2007; Cody & Gordon, 2007; Michon, 1985; Panou et al., 2007; Peters & Nilsson, 2007; Plöchl & Edelmann, 2007; Ranney, 1994; Vaa, 2001; Winter & Happee, 2012). Next, attempts to consider and to model the collaboration and interaction between driver and vehicle are discussed.

With the introduction of driver support systems, an increased appreciation for additional factors involved in driving was observed and gradually the focus changed towards an emphasis for the problems that might arise in the communication and relationship between the driver and the automated support behavior. Issues concerning human-machine interaction have therefore become of major interest due to rapid developments in systems engineering and in-vehicle technologies supporting the driver and the driving task. However, while the view of driver support as a virtual co-driver who collaborates with the driver within a joint cognitive system (JCS, see e.g. Woods & Hollnagel, 2006) has gained general consensus in the scientific community, relatively few attempts have been made to address this relationship by means of a model that represents the driver-vehicle system as a whole. Moreover, given the view that co-agency instead of interaction should be of main concern for designing a joint driver-vehicle system (JDVS, see Hollnagel et al., 2003), it can be observed that different approaches are suggested for achieving the envisioned collaborative driving system. Because of this, different views on this issue will be discussed while they have in common the view of driving as a cooperative or collaborative task.

According to Hoc et al. (2009) currently available driver support can hardly be called cooperative systems because the driver has to deal with both the driving task and an additional managing or monitoring task. Their stance on cooperation is that true driver support should act as a human co-driver. In practice, this means that advice and assistance should only be given when required and should remain in the background while under normal conditions. They claim that intervention should be on behalf of an optimized output of the human-automation team. Based on a framework introduced by Hoc (2001), which tries to identify, analyze, implement and support cooperation, Hoc and colleagues applied the concept of interference management to address potential problems in the cooperation between drivers and automation. As stated by these authors, supported driving can be seen as non-independent tasks being distributed among several agents. Because the goals of the agents are related and both agents can either facilitate or disrupt one another, interference can be positive or negative (cf. Castelfranchi, 1998). In order to manage potential interference, Hoc et al. (2009) provide a framework that decomposes the cooperative activities into three levels, roughly corresponding to the operational, tactical and strategic levels of driving as described in a previous section. At the action level, interference is managed for the short term and the agent's goals are only minimally anticipated for. As an example, at this level an auditory alarm can be presented as appropriate feedback given the environmental circumstances like a car entering the vehicle's blind spot area. At the plan level interference has a more anticipative character and depends on the common frame of reference (COFOR) between the driver and the automation. In order to facilitate activities at the action level, the automated and human agents need to have a shared understanding of the situation and should maintain similar goals. Only when intentions, status and activities are communicated between the human and automated components of the system COFOR can be gained and maintained. At this level the automation has knowledge of the driver's intentions and in this way support can be given only when required at the action level. At the meta level, the history of interaction and cooperation between the human and automated components are used to facilitate and update the activities at the lower levels. For example, at this level knowledge about the driver (e.g. an impaired sense of hearing) can be used to adapt the support behavior appropriate for that individual (e.g. giving haptic feedback instead of auditory feedback). While Hoc et al. (2009) fail to provide for an explicit explanation how to obtain and evaluate an optimal cooperation in terms of interference between human and machine; it can be seen as one of the first frameworks that try to incorporate the view of teamwork, resembling human-human cooperation into the context of driving. An example of their framework, which combines levels of cooperation with modes of cooperation, in their turn roughly comparable with the traditional LOA hierarchy, is given in figure 3.4. This outline is replicated from Hoc et al. (2009) and illustrates how automation complements the human driver, using a potential lane departure warning system as an example. The modes of cooperation (i.e. perception mode, mutual control mode, etc.), which are necessary to specify the cooperation at each level, are described in detail in the original article.

	Meta level	Plan level	Action level
Perception mode	Models of driver perceptual capabilities (e.g. limits of vision)	Compensation of drivers' limits of vision (e.g. blind spot warning)	Vision enhancement on head-up display (e.g. display of perceptual cues of road curvature)
Mutual control mode • Warning mode • Action suggestion mode • Limit mode	Efficiency of feedback modality to elicit appropriate driver responses, e.g. • Auditory • Tactile • Haptic	Knowledge of driver's intentions (e.g. overtaking instead of an erroneous lane departure) • Warning only if no turn signal used	Implementation of appropriate feedback for the circumstances, e.g. • Lateral auditory alarm • Motor priming on steering wheel • Steering wheel resistance
Function delegation mode • Mediatised mode • Control mode	Model of driver behaviour and mental models • Emphasising driver's action • Controlling function on request	Delegation of activities to machine • Feedback of system mode • Acceptance of instructions from the driver	Execution of driver's request • Lane-keeping assist • Active steering
Fully automatic mode	Model of driver workload and task demands	Agreement of criteria for dynamic allocation of function	Adaptive lateral collision avoidance system

Figure 3.4: Framework of cooperation between driver and automation. This example shows a theoretical design of a lane departure warning system from the machine's viewpoint. Replicated from Hoc et al. (2009).

While some claim that in order to be effective, driver support should produce human-like perception and action (e.g. Amditis et al., 2010a), the H-mode might be regarded as a less ambitious approach. Although not much experimental evaluation is available about the concept of the H-mode in the automotive domain (Abbink et al., 2012), as a metaphor and framework for driver-vehicle cooperation it is worthwhile mentioning because it was able to preserve research dedication (e.g. Damböck et al., 2011; Flemisch et al., 2012; Flemisch et al., 2008; Kienle et al., 2009) since its first introduction (Flemisch et al. 2003). H-mode was introduced by Flemisch and colleagues as a metaphor for driver and vehicle interacting similar to the relationship between a horse and its rider (cf. Norman, 2007). While it can be questioned whether the behavioral repertoire of a horse is sufficient for anticipating the human driver at a cognitive level, the interaction paradigm using haptic feedback provides a means for communicating intentions through a modality that has received increased interest in the last few years. As already stated, the notion of support behavior as a co-agent or team member in a joint cognitive system as coined by Hollnagel and Woods (2005) has been adopted in the context of cooperatively controlling the driving task, but as a premature conclusion, it seems that available cognitive systems still lack a level of sophistication for delivering the amount of intelligence and flexibility needed to anticipate the human factor in the driving task. This means that the contributions to model the complexity of the shared driving task have not yet provided the amount of cognition one might expect of an intelligent co-driver. However, as a concept of interaction and means of communication between human and automation, the H-mode is a promising contribution to explore the haptic modality as a way to support human-machine co-agency at an intuitive and potential efficient level. The haptic modality will be further addressed in the section dealing with driver support systems.

Not serving any metaphorical comparison, Hollnagel et al. (2003) provide a description of driving using several levels of control which is embedded in the notion of a joint driver-vehicle system (JDVS), emphasizing the aim to ensure the effective functioning of the JDVS (Hollnagel, 2006). The DiC (driver-in-control) model is based on the principles of cognitive systems engineering and distinguishes four layers of control. The tracking loop describes the low-level activities required for maintaining speed or distance from other vehicles. These are activities that typically require little attention and effort for skilled drivers. The regulating loop is mainly concerned with setting the goals and criteria for the activities at the tracking level. Here, aspects like target speed or position and movement relative to other traffic elements are regulated and driver attention is required because anticipatory control might occur. The state of the joint driver-car system is monitored at the monitoring loop. Monitoring implies generating the plans and objectives for the tracking and regulation. Traffic flow, potential hazards, available resources or vehicle's condition are examples of issues that this level is concerned with. And finally, goals concerning the destination and driving criteria are set at the targeting loop. The DiC model does not only acknowledge the nature of contemporary driving as being cooperative, it emphasizes how the performance of the JVDS depends on the ability to control or manage the driving task as well. In this way operational measures of loss of control could be used to evaluate the quality of driving (Hollnagel et al., 2003). The availability of such an operational tool would be valuable for the design practice, since it has the potential to evaluate the impact of new support functions.

Another application of Hollnagel's effort to describe the JDVS's task is the generation of a virtual co-driver. By revising the Extended Control Model (ECOM) by Hollnagel and Woods (1999; 2005) Da Lio and colleagues envision a joint driver-vehicle system constituted by a human driver and a virtual co-driver, who controls the car but who is able to adapt its behavior according to the goals of the human driver. They argue that the major prerequisite for a unified system is the ability of the automation to understand the driver by inferring the actions of the driver in order to predict meaningful goals (Da Lio et al., 2012). Moreover, and relevant in the present context of developing artificial intelligence is that they envision a virtual co-driver who emulates the human driver. In addition, their approach puts forward the ability of the system to evolve, potentially tackling the problems related to pre-engineered cognitive systems (as discussed in the introduction of this thesis). Although a general architecture (see figure 3.5) is provided and the main prerequisites are mentioned, specifics about the technologies to infer driver behavior and goals are unfortunately missing in their communication.

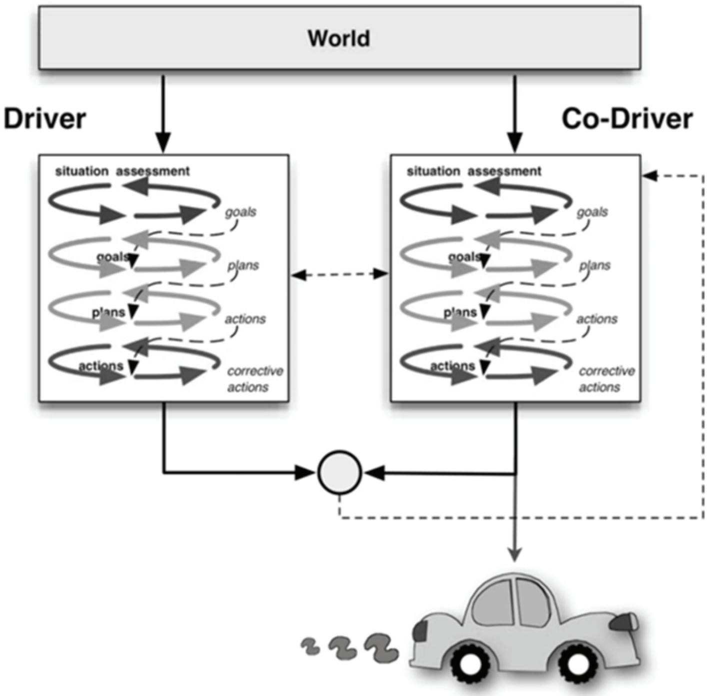

Figure 3.5: Extended Control Model (ECOM) revised by Da Lio and colleagues in order to reflect a unified driving system using a virtual co-driver. Replicated from Da Lio et al. (2012).

In line with Da Lio and colleagues, Vanderhaegen (2012) argues for the capacity of a driving system to learn and therefore to evolve. In his observation driver assistance systems are not able to solve any conflicts when a driver does not agree with or understands the solutions given by the system. His approach is embedded within the notion of systems' autonomy (Zieba, 2010; 2011) and its dependency on the competencies of the system. Competencies refer to what a system or an agent is able to do and limitations of these competencies might restrain the completion of a given goal. Vanderhaegen mentions two competencies that can make problem solving possible. The first capacity is cooperation or competition between agents and the second capacity is the ability to learn. Since the behavior of ADAS is predefined, such systems are rigid when it comes to the competencies described by Vanderhaegen. However, when a support system would have the ability to evolve by learning from prior conflicts it becomes flexible and adaptive, and potentially increases the cooperation between driver and support. While the benefits of such an ability are evident, Vanderhaegen does not specify the process of implementing such an auto-learning support system. Moreover, in line with the limitations of emergent systems, self-learning ADAS could not only result in vehicles that solve problems differently, such a process cannot be bootstrapped into an advanced state, possibly leading to a situation where each vehicle has different competencies.

The framework presented by Hoc et al. (2009) shows that cooperation at the meta level highly depends on the ability to infer driver behavior in order to facilitate the activities at the lower levels. More important, optimal human-machine interaction not only depends on the management of interference and a mutual understanding of the human and automated components of the system, but the ability to acquire knowledge about the state and intentions of the driver are the prerequisites for the ability to cooperate. In a similar vein, Cacciabue & Carsten (2010) argue that in order to be useful, a co-driver system should build up a picture of the individual driver rather than dealing with errors as isolated events or incidents. For this, anticipation and understanding of driver intention would be a vital property of a cognitive support system because driving deals with very short time frames in critical situations and intervention might be too late when the system lacks sufficient information in a predictive fashion. Indeed, the other approaches mentioned in this section which define driver and vehicle cooperation, stress the importance of inferring driver behavior as well. However, given a lack of explanation about the explicit technologies to implement such an ability, it appears that state of the art artificial intelligence does not yet allow for such an elaborate understanding and interpretation of human behavior. Nevertheless, as was shown in this section, for the time being, future scenarios, theoretical issues and potential properties of driver support are available to discuss an optimal cooperation within the notion of cognitive vehicles and an envisioned co-agency between driver and vehicle (see also Heide & Henning, 2006; Inagaki, 2010; Li et al., 2012; Wen et al., 2011).

Driver support

In the context of the present thesis, advanced driver assistance systems (ADAS) are instances of cognitive systems, or taking into account their ability to complement the human driver, joint cognitive systems (JCS). They are able to provide support for lateral and longitudinal control of the vehicle and they provide information and warnings. Figure 3.6 shows an overview of current support systems and how they might develop in the future. As with the description of the driving task, these support systems can be categorized in different ways because of their difference in function (see e.g. Bishop, 2005; Winner et al., 2009) or level of assistance (see e.g. Flemisch et al., 2008; Hiramitsu, 2005).

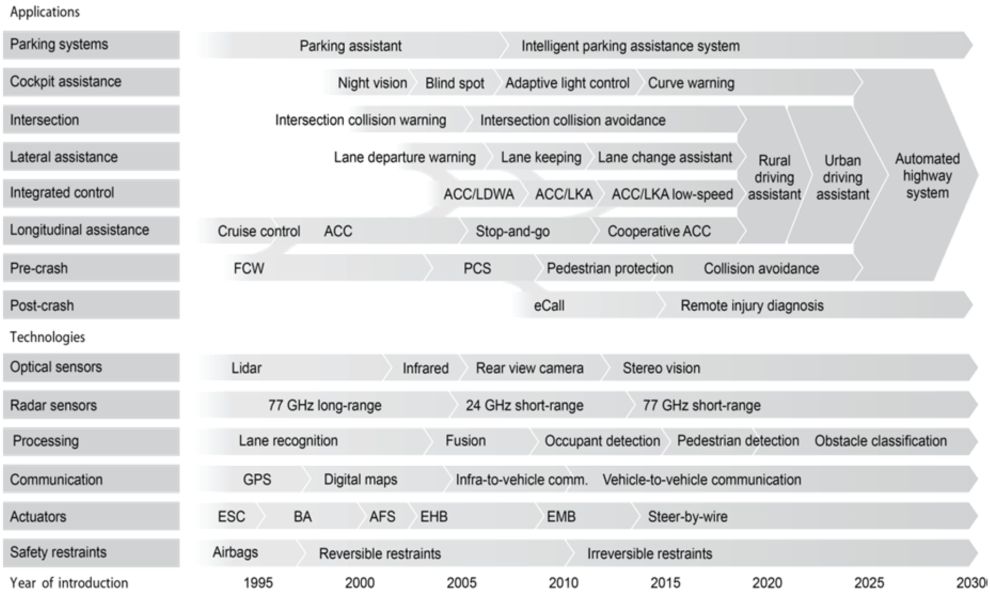

Figure 3.6: ADAS Roadmap. From Gietelink (2007), published with permission from the author.

ADAS use technologies like sensor and telecommunication devices to gather data about the vehicle's environment. Theoretically, the support system has access to an infinite amount of information going from vehicle dynamics and performance to traffic situation and environmental conditions. If technological advances would allow for it, this information could be added with all sorts of knowledge about the driver's behavior, intentions and needs. This knowledge, ranging from impaired driving, the intention to make a certain maneuver to interpreting the driver's state of mind, could be gathered in order to complement the driver with relevant support. A support system with such a comprehensive cognitive repertoire could potentially optimize the driving task in terms of safety, comfort and efficiency. However, due to the putative cognitive and behavioral abilities of driver support, the development of such systems is faced with difficult decisions. Because an infinite amount of information potentially elicits an infinite amount of warning and advice, at design time choices have to be made about which information needs to be gathered and how and when this information is communicated to the driver. Moreover, since fully autonomous vehicle behavior is not assumed in this thesis, required changes, e.g. in speed and direction of the vehicle, call for system characteristics that reflect intelligible and decisive support behavior in order to prompt the driver to execute the proper action.

Modalities

As a channel to communicate with a human driver, the support system might address five modalities, being the visual, auditory, somatosensory, olfactory and gustatory senses, although no studies have been found dealing with this latter modality in the driving domain.

Visual alerts can be given to warn drivers of approaching danger e.g. by presenting icons or visual indicators. An example of a visual alert would be the presentation of a visual cue presented in the spatially congruent outside mirror when a vehicle enters the blind spot area of the ego car. A potential disadvantage of using the visual modality might be the additional demand placed on the driver and the potential diversion of the driver's visual attention away from a focus on the actual hazard. Moreover, a claim in favor of using other modalities than the visual one is that in order to be effective non-visual warnings do not depend on the direction of a drivers gaze (Bristow et al., 2005; Stanton & Edworthy, 1999). A potential disadvantage is that visual warnings might not be noticed when drivers are distracted (Ho et al., 2005).

Auditory alerts can be used to warn drivers of approaching danger by generating sounds. An example of an auditory alert would be to present an acoustic signal when one of the safety belts is not fastened. Auditory alerts have the quality to grab the driver's attention and have the ability to convey urgency to the driver, although this is subject to sound intensity (e.g. Baldwin, 2011). When properly designed though, auditory warnings are able to reduce response times (e.g. Burt et al., 1995; Haas & Casali, 1995). However, auditory alerts must be presented loud, taking into consideration the presence of noise (Karwowski & Marras, 1999). This means that auditory warnings can be masked by ambient noise (Ryu et al., 2010). Moreover, a strong correlation can be found between perceived urgency and ratings of unpleasantness (McKeown & Isherwood, 2007).

Haptic alerts can be given to warn drivers of approaching danger e.g. by generating vibrations or by applying forces to the driver. An example of using this modality would be a vibrating seat to communicate a direction of a crash threat (Fitch et al., 2007). One of the advantages of this modality is that haptic cues have the ability to elicit faster response times as opposed to visually presented cues when communicating direction (van Erp & van Veen, 2004). As compared with auditory alerts, haptic seat alerts have been reported to be less annoying (Fitch, 2005) and might be more reliably perceived e.g. to alert drivers dealing with a hearing disability (Fitch, et al., 2007), although it is believed that haptic sensitivity decreases with age (Verrillo et al., 2002).

Another modality that might be used in the context of driver support is the use of olfactory signals. A potential application might be to make driving more pleasurable (for a review, see Spence, 2002) or to enhance some aspects of driving performance since certain fragrances might increase alertness (Baron & Kalsher, 1998). However, it should be noted that the effects of olfactory stimulation on performance are somewhat controversial since several studies showed inconsistent results (Ho & Spence, 2008).

Support behaviors

In the introductory pages of this thesis a cognitive system was described as one that is able to perceive and understand its environment and other agents, taking into account its own state or behavior, and one that is able to act upon the situation with proper action, anticipating the consequences of such action. In addition, a comparison was made with socially acting partners or team members when the cognitive system is required to coordinate its actions with a human. Within the present context, vehicles equipped with driver support systems are seen as an explicit example of such cognitive systems, since their ability to translate acquired knowledge into proper action is the main prerequisite to cooperate with the driver. However, given a minimal ability to acquire knowledge about the behavior of the driver (Hoch et al., 2007) it can be questioned whether currently available assistance systems satisfy the requirements needed for being a true cognitive system. That is, a cognitive vehicle that is able to understand and anticipate in order to complement the human driver intelligently. Considering the social context of cooperation and the qualities needed for such cooperation, the present section will provide an overview of driver assistance systems based on the behavioral repertoire of the system. For this, examples of driver support will be given according to their ability to acquire and act on available information.

Lateral and longitudinal support

The first example is blind spot assistance, which is able to provide lateral assistance by notifying the driver when an overtaking vehicle enters the blind spot region of the ego car and changing lanes would be inappropriate. Blind spot assistance systems monitor the areas directly alongside and behind the vehicle. When a vehicle enters the blind spot area, the driver is notified by a red warning signal presented in the corresponding outside mirror. When the driver would show the intention to change lanes by applying the indicator, the system gives an additional auditory warning. While lateral assistance could also imply notifying the driver when the vehicle is straying from its lane, blind spot assistance is meant as an aid for changing lanes safely.

Lateral support can be extended by longitudinal assistance in order to provide comprehensive collision avoidance support. When drivers are informed about potential dangers lying ahead on the road, drivers might adapt their speed in order to prevent forward collisions. When combined, the ability to influence the lateral and longitudinal position of the vehicle enables the support system to cover a timeframe from anticipation, warning and even actual interference by co-controlling the vehicle in case of time critical situations. For example, when vision is deprived at nighttime, because of rain or simply because the visual field is occluded by other traffic, the information gathered by the support system can be communicated to the driver. In order to anticipate a potential collision, the system might inform the driver of an upcoming event. In case of a more imminent situation, the system can become more intrusive by warning the driver and by presenting an advice e.g. to adjust speed or to leave the current lane. At pre-crash level, the system might become even more intrusive by co-controlling or even entirely taking over the control of the vehicle by applying forces to the control devices or by neglecting the driver's input. While present and future support systems can be described according to their explicit function as shown in figure 3.6 (for an extensive overview, see Winner et al., 2009), the behavioral repertoire of the system is basically defined by its ability to influence the lateral and longitudinal position of the vehicle by informing, warning or advising the driver or by co-controlling the vehicle itself. In order to do this safe and efficient, the behavioral repertoire of the vehicle needs to be expanded by an understanding of its environment. Relevant information to be gathered by the support system is provided in the next section.

Monitoring vehicle and environment

Cognitive systems, whether designed to operate in isolation or designed to coordinate their actions with others, need an understanding of their work area. For driver support systems this means that they at least have to monitor the vehicle and environmental status to be able to act according to a given situation. As a source of information, several parameters are available to reach such an understanding (cf. Amditis et al., 2010b). First of all, the vehicle signals and controls can be monitored in terms of status and position. Examples are the status of lights, alarms and indicators or the position of the steering wheel, brakes and clutch. Secondly, the system can monitor vehicle movement and dynamics like under- or oversteer by assessing properties like vehicle mass, aerodynamics, speed, acceleration and braking force. In addition, environmental information can be gathered in terms of road characteristics like road or bike lane width, the presence of roundabouts or crossing pedestrians. Traffic conditions like traffic density or mean headway on the other hand, can be used to provide a situational appraisal about the other vehicles on the road. Finally, information about weather conditions like rain or fog can be gathered to evaluate visibility or vehicle handling.

Monitoring driver status

An example of a system that monitors driver status is the ability to detect drivers' drowsiness or fatigue. In terms of safety such an ability might be very valuable (for a discussion, see Williamson et al., 2011). Such systems prompt drivers to take a break when they start to become drowsy and do so by observing driver behavior based on steering wheel movements and steering speed. However, while much can be gained from gathering data about the vehicle's control devices (i.e. speed and position of steering wheel, brake and gas pedal) or from drivers' psycho-physiological measures (e.g. heart rate, temperature or even brain activity, see e.g. Schrauf et al., 2011), in the example mentioned above, driver behavior is not monitored directly. As cognitive systems, this is what distinguishes humans from automation since humans have the innate ability to observe, interpret and act on the overt behavior of others, like eye and head movements or subtle movements of the trunk or hands. The significance of adding such an ability to the automated systems' repertoire has recently been acknowledged by attempts to mimic human road scene perception (Fletcher et al., 2001) and to determine drivers' visual behavior (e.g. Apostoloff & Zelinsky, 2004), eye movements, yawning and head rotation (Churiwala et al., 2012) or eye-blinking frequency (e.g. Flores et al., 2009) with the potential to analyze drivers fatigue. It should be mentioned though, that no single metric is thought of to be able to detect driver fatigue in an operational context (Kircher et al., 2002; Wright et al., 2007). However, if monitoring driver behavior could be optimized, this would allow the support system to expand its behavioral repertoire, beyond prompting the driver to take a short break. Theoretically, monitoring driver status in terms of covert behavior (psychophysiology) and overt behavior (movement) would increase the flexibility and adaptive qualities of the support behavior. This ability reflects the notion of adaptive automation (Byrne & Parasuraman, 1996; Kaber & Riley, 1999; Miller & Parasuraman, 2007; Parasuraman, 1987; Rouse, 1977; Scerbo, 1996, 2001) and such an implementation is suggested for the driving context as well (Dijksterhuis et al., 2012; Hancock & Verwey, 1997; Inagaki, 2008). Provided with monitoring and therefore adaptive abilities, this would allow for a type of driver support that adapts its behavior to the requirements of individual situations.

In order to exemplify the surplus value of a support system with increased monitoring abilities, the behavioral repertoire of the blind spot detection system as described above, is extended with a theoretical although potential ability to observe and interpret overt driver behavior. The next example scenario tries to exemplify how additional abilities could increase the cognition of a support system and how this could be used to add more flexibility to the system's behavior. In this scenario, the system perceives a vehicle approaching the ego-car. However, unlike the conventional blind spot detection system, this system has the ability to monitor and understand what the driver is actually doing in real time. In the present example this means that the system observes that the driver is using his mobile phone for text messaging and it therefore infers that it is very unlikely that providing a visual cue in the outside mirror will be perceived by the driver. Since the driver is switching his attention from the phone, faced down to the road ahead, slightly faced up, the driver's field of view is limited. Because the system has the ability to monitor head and eye movements, the situation can be validated by data implying a decreased amount of focus towards the outside mirrors. This is why the system chooses to present an auditory cue to notify the driver of a vehicle entering the blind spot area. In short, when the system understands that a warning signal is not or unlikely to be perceived by the driver, it can be given in another modality.

Inferring driver intent

The final ability to complement the behavioral repertoire of driver assistance systems is the capacity to infer driver's goals and intentions and would contribute to the social context of cooperation. This ability could potentially bridge the gap between present rigid and reactive support behaviors and future support systems that might be flexible and anticipative (van Waterschoot & van der Voort, 2012). Such systems are currently not available, since there is no general sensor or technique capable of measuring the intentions of drivers or to infer drivers' understanding of a given situation (Agamennoni et al., 2011; Inagaki, 2008). However, an increased interest from both academia and automotive manufacturers can be observed towards providing such systems by investigating the possibilities of using various sensory systems and algorithms (Beoldo et al., 2009). At least three approaches can be distinguished in order to infer driver intent.

First, vehicle cues can be gathered to predict the forthcoming trajectory of the vehicle. Data about the kinematics and dynamics of the vehicle can be gathered relatively easy since relevant data is already available through the vehicle's CAN-bus, which allows for gathering information in real time from several devices. Examples of data that can be gathered in this way are steering wheel angle and velocity or pedal and indicator positions. Since available support systems like lane keeping assistance are becoming more popular, additional information about the vehicle's lateral position becomes available as well (Berndt & Dietmayer, 2009; Berndt et al. 2008). Secondly, driver cues might provide insight about how drivers prepare for upcoming maneuvers. As an example, it has been argued that driver's gaze behavior is a valuable cue to predict the intention of changing lanes, since distinct gaze patterns precede such a maneuver (Lethaus & Rataj, 2007). When driver's eye gaze behavior could be combined with other sources of information provided by the vehicle's CAN-bus, laser or radar, this might improve the ability to predict driver intent (Lethaus et al., 2011). In addition to eye gaze, other driver cues such as head movements have shown to be relevant for the ability to infer the driver's intention to perform tactical maneuvers like braking, turning and changing lanes (e.g. Doshi & Trivedi, 2009; McCall et al. 2007). These studies are a strong argument to include the ability to infer overt or observable behavior into the behavioral repertoire of driver support. This would not only allow for anticipating dangerous driving situations, but it could also reduce the number of false alarm rates given by the support system (Doshi & Trivedi, 2011). Thirdly, environmental and contextual cues might provide the constraints that the driving task is confronted with. This means that topological and geometrical information gained by digital maps and GPS can be used along with vehicle state information to estimate an intended maneuver (Lefevre et al., 2011).

In order to show how an increased ability to infer driver intent could be beneficial to optimize the coordination between driver and support system, another example scenario is presented. In this scenario, the hypothetical monitoring ability as described above is extended with a potential ability to interpret driver behavior in order to draw conclusions about the intentions and therefore future actions of the driver. When the support system perceives an approaching vehicle it can notify the driver of the ego-car with an appropriate warning as soon as the vehicle enters the blind spot area. However, due to its extended cognitive features, the system understands that the driver has no intention to change lanes. Moreover, because of its ability to match all available data sources, the system infers that the driver has noticed the upcoming vehicle and that he keeps updating the changing position of this vehicle. For this, the system not only uses information about the vehicle and its controls, the driver status in terms of e.g. heart rate and head movements, but it also uses its additional ability to infer the future actions of the driver by means of indicators such as subtle movements from the hands or feet and eye gaze. Since the system understands that the driver is keeping up with the traffic condition and no dangerous situation is arising, warning signals at this stage are redundant and therefore not given. On the other hand, if the system could infer or predict the intention of the driver to change lanes in a situation where such a maneuver would be inappropriate or dangerous, it could anticipate its support behavior accordingly. Besides flexibility, this would give the support system the ability to foresee dangerous situations and to gain time in critical situations.

ADAS design

Roughly two types of approach for designing driver support can be identified in the human-automation literature. There is the conceptual one (e.g. socio-technological and human centered) proposing guidelines and principles and there is the experimental one assessing the consequences of system design on operator behavior (Wandke & Nachtwei, 2008). However, independent of an explicit approach, having man and machine collaborating in any given context involves the definition of the automation's behavioral repertoire in advance. As being stated several times in the present thesis, this problem can be characterized as one of the main issues in developing HCI since during the design of each system that consists of human and automated components some sort of allocation is needed. Within the context of driver support interacting and sharing the driving task with the driver, it should be established beforehand when and how the support system intervenes. Simply put, who does what, when and how? Which driving roles or functions are to be automated and how are they assigned to whom? As already mentioned, these design choices are inevitable since the design engineers have to provide the behavioral repertoire of the support system. This means that during the design process of ADAS as many as possible different driving situations (including factors like weather and traffic condition or driver state) need to be anticipated for. However, the allocation of functions between human and automation has not only raised a lot of discussion, at the same time it signifies once again the difficulties that HCI, and ADAS design in particular, is facing. Sheridan (2000) describes seven problems of function allocation. In order to highlight the potential difficulties that are involved in ADAS design, four of those aspects will be discussed next within the context of automation supporting the human driver.

Sheridan argues that an increase of automation and computing capabilities brings about increased system complexity. Technological advances bring along a situation in which a proper function allocation between man and machine is moving target. For ADAS design this can be expressed by advances in computing power and sensing improvement. If the ability for an automated system to sense the environment increases, the potential behavioral repertoire increases. That is, technological advances bring along new possibilities to share or take over a human task. Consequently, when the behavioral repertoire of the automation increases, the system becomes more complex with overlapping tasks that can be appointed to or shared between driver and driver support. This means that within a driving system the distinction between the human and machine function becomes less clear. Furthermore, when the opportunities to automate driving tasks are put into practice, the role of the human driver shifts from active participant to passive supervisor for those tasks being automated. In its turn, this brings along another level of complexity when taking into account that automated tasks need a transition phase when particular tasks are taken over by the human driver or vice versa. These possible transitions are to be anticipated as well. To put it briefly, in accordance with the automation paradox, technological advances do not only increase the possibilities to automate driving tasks and increase safety, they bring along advanced complexity as well. The challenges ADAS design is facing are therefore increasing as well. An approach that might be able to deal with such increased complexity is discussed by Vernon (2011) where multiple agents are engaged in a mutually shared learning process, similar to how learning evolves between human co-actors, who are theoretically able to communicate their knowledge and who are able to adapt their behavior according to the social context and requirements. However, since this approach is applied for the development of a humanoid robot, it is currently unknown whether such an architecture is suitable for developing cognitive support behavior in the context of driving.

A second problem Sheridan addresses, is that a situation arises where "humans become supervisors and computers become mediators or intelligent agents" (p. 208). Given the situation delineated in figure 3.7, some tasks are simply not worth automating since the effort for implementing the automated behavior does not compensate for the effort put in the human task itself. In addition, other tasks might be simply too complex to automate. According to Sheridan, most social activities would be in this category. Elaborating on this line of thought, ADAS design is confronted with an almost impossible challenge since the characterization of driver and driver support as collaborating agents emphasizes the social context and interdependency. Following Sheridan's view, one should therefore be cautious with regard to the demands associated with increased vehicle automation.

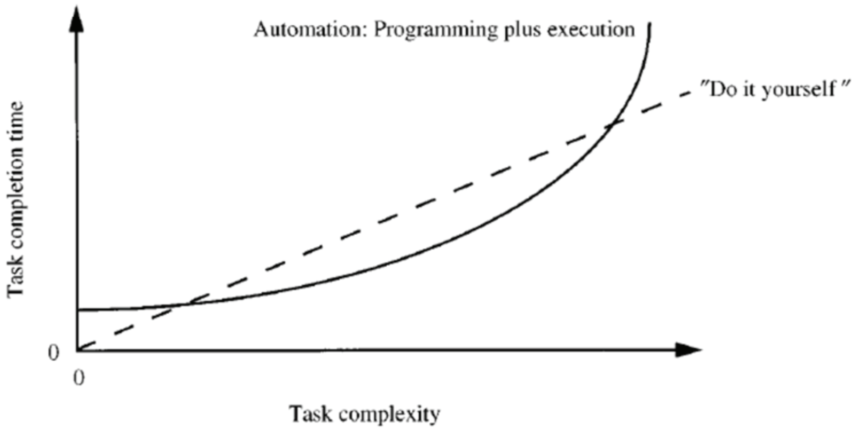

Figure 3.7: Advantages of automation for tasks of intermediate complexity. Replicated from Sheridan (2000).

A third issue that is addressed by Sheridan concerns the critique of Winograd and Flores (1986) that traditional rationality cannot be applied to cognition, computers and systems engineering. They argue that human beliefs and assumptions cannot be made explicit and that the traditional or cognitivist view of humans having mental representations (i.e. mental models) of their environment, does not hold. For Winograd and Flores, this means that humans do not understand their environment as a fixed relationship between the mental representations and the outside world. In other words, with each experience cognitive structures change and these changes are not explicitly known to a system designer. Within the context of ADAS design, the consequences are twofold. On the one hand fixed algorithms for a given support situation might fall short when the driver adapts its behavior after having experience with a given traffic situation. In addition, if no fixed relationship between driver behavior and environmental circumstance can be appointed, the support system should be extremely flexible and either the system should have learning abilities similar to the human driver or ADAS designers should anticipate and predict behavior under all given circumstances. This not only assumes cautiousness about the abilities to design such flexible and cognitive behavior, it confirms another main challenge for ADAS design, which is the ability to predict driver intent and driving situations in order to adjust driver support in a flexible manner. To put this into perspective, such flexibility might raise high hopes when referring to the view of Vernon et al. (2007) because according to them, a cognitive system should be able to show behavior that was not explicitly anticipated for at design time.

Another comment Sheridan raises is the position of design in (or even beyond) science. While normative approaches are available for design engineers to achieve a theoretical optimal allocation of function in their design, reality is often confronted with a subjective design stage because design alternatives are, especially in the initial phase of design, elusive and numerous. According to Sheridan (2000) "orderly methods of optimum function allocation exist in engineering, but they make so many assumptions and the application of these methods involves such complexity that in practice little real optimization is achieved" (p. 213). For ADAS design this means that implicit design choices are already made when a potential support behavior is proposed. While objective approaches can be used to evaluate system performance, functions allocated to both human and automated elements of the system are already subjectively assigned when new ADAS functionalities are considered. This comment is in line with an assumed shortcoming of assessing design choices after system functionalities are established. In short, this means that proposing new features for driver support (e.g. resulting from mere technological feasibility) already involves allocation of functions, at least implicitly. Moreover, and this issue will return in the next section and in the thesis' problem definition, it emphasizes the difficulty ADAS design is faced with when assessment is expected not only to evaluate but also to improve individual design choices.

ADAS evaluation

Besides the description of ADAS functionalities and applications, much emphasis in literature lies on the assessment of driver support. Although the conceptual approach provides guidelines and principles to establish proper coordination between driver and vehicle, these guidelines are often generally expressed and prone to discussion or interpretation. Nevertheless, despite a large amount of design guidelines for ADAS (e.g. Campbell et al., 2007; Green et al., 1995; Franzén et al., 1991; RESPONSE 3, 2009; Ross et al., 1995, 1996; Stevens et al., 1999) such an approach does not make subsequent assessment redundant. Moreover, since the guideline based approach of design can be characterized as static (Wiese & Lee, 2007) evaluation becomes even more significant because guidelines cannot be referred to when several support behaviors might interact or when contextual demands might alter due to changes in driving context.

While a commercially available and fully automated system for controlling a vehicle in traffic is not very likely for the near future - although testing autonomous vehicles is currently permitted in the US State of Nevada and a low-speed autonomous driving functionality is announced for the near future by several automakers (Newcomb, 2012) - the problems that might arise when the human driver needs to take over control from such a system were already addressed more than forty years ago by Sheridan (1970). Subsequently, many reservations have been raised since, concerning the behavioral effects related to the introduction of driver support systems (for an overview of these issues see Brookhuis et al., 2001; Lindgren & Chen, 2006). Although a primary goal for implementing automation into the driving context is aimed at improving safety, possible deleterious effects might undermine the envisioned contribution of such systems. Examples of unwanted effects are drivers' impaired responsiveness to critical events and behavioral adaptation (Ward, 2000). First of all, because the driving task becomes a monitoring task as well, this might lead to increased driver workload (e.g. Hancock & Parasuraman, 1992; Ward, 2000). However, several studies mention possible problems with a decrease in workload as well. For example, it is reported that driving with Adaptive Cruise Control (ACC), which controls both speed and longitudinal distance, might direct driver's attention away from the driving task, which could have a negative effect when the driver needs to retain control in an emergency situation (e.g. Rudin-Brown & Parker, 2004; Stanton & Young, 2005). Finally, behavioral adaptation refers to the unintended and unwanted changes in driver behavior when driving with driver support (Dragutinovic et al, 2005). Examples of such behaviors are increased lane position variability (Hoedemaeker & Brookhuis, 1998) later braking (Hogema et al., 1994) or colliding more often with a stationary queue (Nilsson, 1995) as cited by Dragutinovic et al. (2005). This assumes that drivers tend to use the safety margins provided by the support system to adapt their driving style in a negative way and this might eliminate the envisioned safety effect of driver support.

Because of the possible negative effects of driver support, and because design guidelines cannot anticipate or rule out potential negative consequences of providing support behavior, evaluating the support systems under development is an essential part of the design process. Although little is communicated in literature how and by which means the potential behavioral effects of ADAS are evaluated and anticipated by the suppliers of currently available support systems, an increased concern for developing structured approaches for ADAS evaluation can be observed (for an overview of projects dealing with this issue see Aust, 2012). In an effort to provide for an evaluation and impact assessment methodology for ADAS, in the project PReVAL the assessment of ADAS was organized into three aspects, being a technical evaluation, a human factors evaluation and an impact assessment (Scholliers et al., 2011, 2008). The technical evaluation refers to the technical performance of the system, its reliability and the ability of the system to detect dangerous situations. The technical evaluation process involves five steps. First, the expectations are defined about the system's ability to assess threats under different conditions (e.g. weather, road type and threat type). Secondly, test scenarios are described in detail in order to anticipate the most relevant situations. Thirdly, the evaluation method is selected, like simulator studies, hardware-in-the-loop tests or the use of a test track. Before the actual execution of the tests (step 5), a measurement plan is made containing the number of tests and the variables needed for answering the hypotheses under evaluation. The human factors evaluation refers to assessing the system's ability to provide the driver with information or warnings and therefore reflects the system's functional performance. Like the technical evaluation, this process involves five steps, including the description of test scenarios, defining and testing hypotheses and interpretation of results. It should be noted though, that the potential effects of the system's behavior are limited to evaluating the system in terms of usability and acceptance. These concepts are used to investigate whether the system is used by the driver as it was intended and how the system is received by the user in terms of usefulness and satisfaction, respectively. The third aspect of the evaluation process used in PReVAL is an impact assessment, which aims at revealing the preventive effects on relevant harm metrics, such as number of fatalities. This should give an estimate of the safety potential when a particular support system would be introduced. This assessment is based on a number of impact mechanisms, which are thought of to affect safety and makes use of information like accident statistics and fleet penetration rates.

Because it was acknowledged by Scholliers and colleagues that a technical verification of the system and its impact on driver performance and safety should be approached in a holistic fashion, they introduced the concept of situational control (Scholliers et al., 2011). They state that "situational control is defined as the degree of control that a joint driver-vehicle system exerts over a specific traffic situation. With this concept, the general purpose of a preventive safety system can be understood as an attempt to increase situational control. Consequently, the general goal of evaluation here becomes to assess the extent to which this goal is achieved" (p. 212). Unfortunately, it seems that this concept has not been defined in detail, since there is no mentioning of how situational control can be determined and whether there is a single metric available for evaluating the amount of control shared by the driver and vehicle. Nevertheless, their approach can be appointed as one of the first attempts that try to evaluate the performance of a joint driver-vehicle system within the context of ADAS design. Despite a large amount of design guidelines and the efforts to provide ADAS design with proper evaluation, there is relatively little consensus about whether a single and general approach can be adopted to evaluate the safety of ADAS (Aust, 2012; Carsten & Nilssen, 2001). Moreover, even if such an approach would be available, it can be argued whether the outcomes would be able to predict the explicit effects on traffic safety as a whole.

Although relatively little is known about the evaluation of ADAS in the current design practice, it seems that the potential impact of support behavior is often treated in isolation when it comes to the performance of drivers, vehicles and the impact on traffic safety. Although several attempts have been made to evaluate the system as a whole, at least in terms of a driver-vehicle system (Scholliers et al., 2011, 2008) or overall system performance (e.g. McCarthy & de Lange, 2008; Salmon et al., 2012) and while it is even claimed that the entire driver-car-traffic system needs to be evaluated (Fastrez & Haué, 2008) it can be concluded that none of the available approaches have reached a level of sophistication to provide for such a comprehensive evaluation.

4

Problem definition and suggested approach

In the previous sections of this thesis, it was addressed how the development of driver support systems is confronted with several issues that need to be solved in order to provide for support behavior that is able to complement the human driver safely and efficiently. Next, these issues are presented as the problem definition that led to the current research.

Problem definition

Developing driver support systems is not a straightforward engineering problem since adding automation increases the driver-vehicle system's complexity, which in turn might have counterproductive effects in terms of safety and efficiency. Given the fact that ADAS need to elicit proper responses from the human driver, both knowledge about the human factor and the cooperative setting between driver and support behavior are essential aspects that need to be incorporated in the design process of such systems. Furthermore, in order to be become truly cognitive support systems, and therefore flexible and adaptive, ADAS need to expand their behavioral repertoire with increased monitoring and inferring abilities. However, it seems that the current design practice lags behind the theoretical possibilities to provide for such cooperative cognitive support behavior.

First of all, it can be argued whether the cognitive and emergent approaches are sufficiently matured in order to provide for the behavioral repertoire that is thought of to complement the human driver. It is argued that pre-defining the entire behavioral repertoire at design time is not only unfeasible; it neither reflects the complexity and nature of humans and automation cooperating in the driving context. While these problems can be accounted for by adopting an approach in which the support system is given the ability to adapt and expand its own behavioral repertoire, for a complex and potential hazardous task such as driving, this might involve additional implications.

Secondly, while a comprehensive model of the cooperative driving task would be valuable to either evaluate the shared driving task at design time or even to serve as an actual cooperative driving system, due to the complexity of cooperative driving and a lack of consensus about how to reach a well-balanced co-agency between driver and support, such a model has not yet been provided.

During the last decades numerous efforts have been devoted to provide the development of ADAS with design support. This has resulted in a large body of research concerning design guidelines and evaluation methods. However, despite some large scale collaborations between automotive suppliers, research organizations and academia, it seems that a coherent and general approach for developing and evaluating ADAS has not been provided yet.

On the one hand, there is an explicit acknowledgement for a unified process in which design consequences are addressed early during development within the view of a driver-vehicle system. However, this acknowledgement does not comply with most available design and evaluation research, which usually deals with human and vehicle behaviour separately.

On the other hand, while several psychological constructs like situation awareness and workload have been adopted for evaluating ADAS, they do not reflect the potential impact on the performance of the entire driver-vehicle system. An objective methodology and associated metrics for assessing the cooperative driving task are therefore still missing. Moreover, and this reflects problems for both objective and subjective evaluation in general, post hoc evaluation typically does not entail an explicit design improvement or design alternative. While considerations about the relationship of design choices and their potential effects can be made iteratively, new configurations only show their envisioned potential after subsequent evaluation. This not only emphasizes the importance of an early evaluation during the design process, but it also suggests that anticipating the future behavior and impact of a modified driver-vehicle system cannot be covered entirely through the evaluation of such a system. While subjective and objective evaluations have proven to be valuable assessment tools, given this argument it has to be taken into consideration that their potential has limitations in terms of guiding the design process with unambiguous design solutions.

Because designing ADAS implies pre-defining the driver support's behavioral repertoire and therefore anticipating the interaction between the human and automated components of the system, assessing the cooperative system's potential in terms of safety and efficiency remains a major challenge for the development of ADAS.

To summarize, the main problems that ADAS design is currently faced with are:

- Providing flexible and adaptive support behavior by improving the system's behavioral repertoire in terms of monitoring and inferring abilities.
- Additional and comprehensive knowledge is needed to understand and to anticipate the social context in which humans and automation cooperate.
- Unknown impacts of design choices need to be anticipated for at an early phase of the development process, while a certain amount of unforeseen effects need to be accounted for.
- The inability of evaluation to provide for explicit design improvement and a lack of consensus about how to approach the development of ADAS, call for alternative approaches that are able to address the increased complexity of the driving task.

Current approach

In the previous sections, it was explained how ADAS design is confronted with the difficulty to envision and anticipate a cooperative setting between drivers and support systems in order to maintain or increase safe and efficient driving. Given the current practical and theoretical limitations of the available approaches to provide for cooperative cognitive systems, a more hybrid and adaptive approach is proposed. More explicitly, this means an aim to combine research and design activities within a single environment. In this way, the process of evaluating potential design choices is integrated and allows for objective and subjective assessment at design time.

As a promising tool during the design process of driver assistance systems, rapid prototyping was introduced because of its potential for early exploration and evaluation of design choices. As already addressed, one of the available techniques for rapid prototyping is an approach called Wizard of Oz (WOZ). Adopting the WOZ method implies an approach in which the users of the system are made to believe that they are interacting with a fully implemented system, though in fact they are not. While the purpose of this technique might differ for those adopting it, WOZ testing typically implies simulating sensor data, contextual information or system intelligence by one or more human operators, or wizards (Dow et al., 2005). One of the first appearances of WOZ was in Kelley (1983) in order to develop a natural language interface for a computerized calendar. Since then, the WOZ approach has been suggested for the development of all kinds of intelligent interfaces (Dahlbäck et al., 1993). The main quality of WOZ testing is that the method allows for early exploration and evaluation of an interactive application by simulating machine behavior with human operators, without being dependent on technical feasibility or availability of perceptual and cognitive system capacities. This flexibility might help designers to make reasonable technology decisions as the design iterates (Davis et al., 2007). In this way, sophisticated technologies such as speech recognition (Klemmer et al., 2000) or computer vision (Tran et al., 2005) can be simulated, even when such technologies are unavailable. In the automotive domain, WOZ testing might be a valuable tool for rapidly prototyping driver assistance systems. To this end, the WOZ approach has been suggested in order to investigate different degrees of control for highly automated vehicles (Schmidt et al., 2008) or to explore and test haptic-multimodal interactions between drivers and vehicles (Schieben et al., 2009). In a similar vein the WOZ technique has been successfully applied for mimicking a cooperative driving system (Biester, 2005) and for collecting domain-specific natural language speech data pertaining to in-vehicle speech interfaces (Lathrop et al., 2004).

Emulation

In the present research an approach is suggested where design and research activities are combined. Because of its potential in such a setting, it is proposed to adopt a simulation method similar to the wizard of Oz technique. However, because the WOZ paradigm has established its own particular meaning and significance during the past decades, this expression might evoke different connotations in different fields of application. In this thesis, mimicry of potential or envisioned support behavior by human operators will therefore be referred to as emulation. In the present context, emulation is regarded as a tool for establishing a setting in which humans interact with potential or envisioned driver support by simulating (part of) the system's behavioral repertoire by a human operator (or co-driver) through a real or mocked-up computer interface. Unless mentioned otherwise, those interacting with the support system are kept unaware that (some of) the functionalities are emulated. While (often time consuming) programming does not become completely redundant, it is believed that emulation as a tool for designing and studying the cooperation between drivers and support systems has several advantages:

Primarily, applying emulation allows for anticipating the system's behavior and the interaction with the driver in early phases of the development process. Envisioned support behavior can be explored and assessed without the need for programming the entire behavioral repertoire in advance. Because the human co-driver performs the supporting task by means of an instruction, at this stage of the design process, there is no need for having a protocol at detail level. This means that a co-driver can perform pre-formulated behavior, as well as exploring alternatives. By involving experts and future users in the design process, their knowledge and experience can become input for design considerations and provide relevant insight about the characteristics and requirements for appropriate support behavior. In this way, user preferences and support potential can be investigated at design-time. Emulation therefore allows for short iterations in the design and assessment cycle because the functional requirements can be formulated at an abstract level (e.g. defining support in terms of co-driver activities instead of a detailed protocol).

Secondly, by mimicking envisioned driver support, one can produce cognition that is not or difficult to simulate otherwise. Returning to the example of blind spot assistance, a human co-driver can observe the intentions of the driver by inferring subtle movements of the eyes, head or upper and lower extremities, while currently available systems infer the intention of the driver at the time he or she uses the indicator or by interpreting vehicle data. Simulating a system that uses sensors to infer e.g. eye and head movements is not only difficult and time consuming, research shows that predicting driver intent is improved when the system has the ability to observe drivers' preparatory scanning (Doshi et al., 2011). This intrinsic human ability can be employed during the design process of ADAS for implementing and evaluating such an ability as a substitution for sensors and algorithms that are not readily available. This allows for determining the need or added value of such technology before actual development effort has been exerted.

Thirdly, when a human co-driver emulates the envisioned support behavior, a cooperative setting is established that not only mimics supported driving but also renders human interaction and cooperation in order to co-control the driving task. Such a setting potentially provides insight about how human agents interact in a social setting and this knowledge could be used to improve cognitive support behavior and the cooperation between driver and support. When the human factor by means of a human co-driver is physically added to the design environment, one can study or even isolate requirements needed for optimized coordination and cooperation between driver and support system. Moreover, such a setting might allow for evaluating the quality of cooperation on a peer-to-peer basis. This approach, that potentially allows for design decisions based on how cooperation and coordination is established between human agents, represents an increased interest for social cognition and reflects recent developments in the study and development of social behavior. For example, as an emerging approach, social signal processing (SSP) tries to provide computers with social intelligence in an aim to bridge the 'social intelligence' gap between humans and machines (Vinciarelli et al., 2012).

In addition, given the inherent human ability to infer others' intentions by means of observation, such an ability potentially serves as a model for extending the behavioral repertoire of automated cognitive systems. In this way, the human co-driver supporting the driving task might become focus of research in order to gain fundamental knowledge about the means and cues that are used to predict drivers' intentions. By observing how the human co-driver infers the behavior of the driver and how he solves problems, ADAS design might gain additional knowledge to improve future driver support. Such research would be in line with recent findings that suggest a crucial role for kinematics in action prediction. For example, it has been demonstrated that humans have the ability to evaluate the actions of others as being social or non-social before the action becomes explicit (Sartori et al., 2012). Such findings not only emphasize the relevance of gaining knowledge about the subtle kinematic cues that are used to anticipate others' (action) intentions, but also argues for close collaboration between the applied and fundamental sciences. That is, practical issues such as increasing the anticipative abilities of driver support could be a valuable context for gaining increased (fundamental) understanding of the underlying mechanisms about how humans understand the intentions of others.

Applications of emulation

In the currently presented approach, implementing the ability to emulate support behavior constitutes an important prerequisite in order to establish an environment that allows for research and design of cooperative cognitive support behavior. It is believed that emulation might serve three potential applications during the design process of ADAS, which are specified next.

Emulation as exploration tool

Emulation of support behavior might be used during the exploring phases of the design process. At an abstract level, without considering details, functional requirements could be formulated during iterative design sessions involving those concerned with the development process, complemented with a variety of participants, ranging from future users to professional drivers and experts from relevant disciplines. While such sessions might provide for the functional requirements of an envisioned support system in an interactive fashion, it subsequently allows for evaluating the support system at this preliminary phase as well. For example, as user expectations can be translated directly into system characteristics that are performed by the emulator, it is made possible for the same participant to express his or her findings and successively evaluate the proposed support behavior. In this way a priori and theoretical considerations based on prior findings can be supplemented with expectations and experiences at the functional requirements phase of design.

Emulation as simulation alternative

Emulating support behavior as a simulation alternative implies the use of human participants providing the input behavior that is given as driver support. The requirements for setting up such an ability do not differ much from setting up a conventional simulation environment. Mockups, driving scenarios and interfaces, for example, are similar for both techniques. However, simulating driver support requires the implementation of the entire behavioral repertoire in terms of sensors covering the ability to perceive, algorithms covering the interpretation and decision process, and pre-defining in detail each step that has to be taken in order to solve a task. Emulation on the other hand, allows for running a simulation without having to specify and implement the entire behavioral repertoire in such detail.

Emulation as model for support behavior

Given that the ability to monitor driver state and to infer the intentions of drivers is a crucial but complex aspect of the behavioral repertoire of driver support, attempts to provide for such abilities will probably remain a core challenge for future research. Here, it is argued that an approach using emulation as a model for support behavior might be a valuable contribution since it allows for studying co-drivers' behavior in a context of driver and support collaborating in the driving task. For HCI research, this would mean a shift from observing drivers' behavior to observing human co-drivers' behavior as well. In this way, system functionalities might be derived from actual human behavior, while at the same time fundamental knowledge can be gained about the cues that are used to interpret the state and future actions of others within an applied setting such as providing driver support.

5

Introduction of experiments

Within the automotive domain, the use of emulation has been suggested for both exploration purposes and as a simulation alternative. For example, the theater-system technique has been used for designing longitudinal and combined longitudinal and lateral driver support (Flemisch et al. 2008, Schieben et al., 2009) emphasizing the need for early definition and testing of concepts in an iterative fashion. As opposed to the original WOZ method, the theater-system approach uses a setup in which users and emulators communicate directly. The theater-system technique is used to iteratively design and develop automated driver support by testing and selecting emulated alternatives which eventually result into software prototypes. The direct interaction between the confederate and users allows for moving "through scenarios and use cases together and discuss what the appropriate behaviour and interaction should be in a specific situation" (Flemisch et al., 2010). However, while the theater-system technique has been described for several projects and the philosophy behind this approach is well accounted for, experimental results, critical reviews of applying the theater-system technique and an objective validation of their approach have, to the author's knowledge, not been communicated so far.

Even though emulation as a design tool for establishing, exploring and evaluating interactions between drivers and support systems has been adopted several times (e.g. Biester, 2005; 2007; Lathrop et al., 2004) a critical review of the approach as such, is currently limited. This means that little is known about the requirements for setting up an environment where driver and support systems cooperate and whether the theoretical prospects of such an approach meet these requirements.

Furthermore, although emulation has been used in the past when a fully working prototype was difficult to realize or infeasible, the question whether emulation is an appropriate simulation alternative for mimicking driver support has been addressed only occasionally. To this end, Schmidt and colleagues (2008) validated the use of emulation in an instrumented vehicle. In order to investigate whether an emulator is able to represent and replicate system functionalities as accurately as an implemented prototype system, they executed two experiments in which the different setups of two driver support systems (traffic sign recognition and lane keeping assistance) were compared in terms of subjective evaluation ratings of the support systems. With these experiments, they showed that the subjective ratings of the different setups (emulation and working prototype) were evaluated similar for both support systems. While it was reported that emulation should not be used in order to identify system thresholds or any exact parameterization of driver support, Schmidt et al. underline the value of emulation as a tool for designing driver support because system functionalities can be generated, experienced and evaluated at a premature development phase. While their study acknowledges the need for validating emulation and provides arguments in favor of applying emulation as a tool for developing driver support system, research based on objective data collection is currently missing. That is, while support behavior was subjectively rated as similar between different setups, it remains unknown whether potential differences between the emulated and prototyped systems might have an influence on driver behavior that cannot be gathered subjectively, such as measurements concerning driver responses, efficiency or performance in general.

Since its original application in the early 1980's emulation has been adopted for representing a wide variety of human-machine interactions in different domains. In addition to acknowledging a need for rapid prototyping and addressing the prospects of emulation in iterative design, research experiences have provided several considerations about using and designing WOZ experiments. It has been argued, for example, that the emulator's role in the experimental design should be well defined and consistent (Dow et al., 2005). In addition, A WOZ test shouldn't overload the emulator and data should be logged for both user behaviors and environmental changes (Li et al. 2007). However, other than reflections on the requirements for emulation, little experimental validation of such an approach is provided in the academic literature.

In the present thesis, it has been argued that emulation can be a promising tool when designing or studying a cooperative setting between drivers and support systems. Within this view, three applications of emulation are suggested and their potential is being addressed both theoretically and empirically in the present research. However, as discussed above, a lack of critical examination can be observed when reviewing the existing research that applies or advocates emulation in the automotive domain. The present research therefore aims at providing additional validation of emulation as tool for developing and studying cooperative driver support, in particular within the scope of applying emulation as an exploration tool, as a simulation alternative and as a potential model for future ADAS support behavior. For this, three experiments are conducted.

Experiment 1

The first experiment concerns a validation study of emulation as a simulation alternative in order to find out if emulated (i.e. input given by a human co-driver) and simulated (i.e. algorithms run by a computer) driver support are perceived and acted upon differently by the subjects in a simulated driving task. If it is to be argued that emulated driver support can be used during a preliminary design phase as an exploration tool, it should be able to evoke similar driver responses as the simulated version. Differently stated, this means that if the behavioral characteristics of the support behavior are different for both versions (emulated and simulated), this should be expressed by drivers perceiving and acting differently on both support versions.

The experiment consists of a simulated driving task where drivers receive an early warning by means of a directional precue on the steering wheel (force feedback). If the driver is prompted to make a subsequent swerve maneuver, this cue is used to steer to the left or right, avoiding a decelerating vehicle. Time courses for both drivers' and support behavior are recorded and analyzed while subjective data is gathered by means of a questionnaire, for which participants are asked if both versions are perceived differently. In this experiment, the following question will be addressed:

- Since it is expected that an emulated and automated version of support might differ in their output behavior and thereby might evoke different behavior by the driver, both versions will be compared. For this, it is investigated whether an effect is found for support version (emulated vs. automated version).

Experiment 2

The second experiment is set up in order to investigate whether emulation as a simulation alternative is able to gather relevant information as a research tool. In order to verify and decide on design choices, research should be able to display the distinct properties and consequences of different design alternatives. For example, it is suggested that, when compared to visual warnings, auditory or haptic warning signals are able to improve driver's responses when receiving rear-end collision warnings (Scott & Gray, 2008). When emulation is regarded as a potential tool for assessing e.g. the influence of modality on driver responses, mimicking driver support at an early development phase should reveal similar distinguishing properties of design alternatives. If emulated support behavior would not have the ability to show such effects, this would be a claim against the use of emulated support behavior during the assessment of design alternatives. In order to reveal such a differentiating quality for emulation, this experiment compares driver responses for three different support configurations. For this, it is examined whether these alternatives have different effects in terms of drivers' response times. Drivers are given support by a system that provides the safe direction in case of a time critical traffic situation. When a leading vehicle brakes, the support system provides the safe direction for avoiding a collision. The different configurations or modalities (auditory, haptic and a combination of those) are compared by means of the elicited response times and are assessed subjectively by ratings gathered with a questionnaire. In the second experiment, the following questions are addressed:

- Design choices can only be evaluated when their distinct characteristics are related to their impact. A setup using emulation should therefore be able to reveal differences between design alternatives. For this, it is investigated whether emulated design alternatives are able to elicit observable effects in drivers' behavior and whether such an approach reveals similar results when compared to existing knowledge.

Experiment 3

The third experiment investigates the claim of emulation as a model for support behavior. When viewing support behavior as a "team player" or an artificial co-driver who complements the human driver in order to make the driving task more safe and efficient, the human emulator or co-driver might be relevant to investigate the social context of agents collaborating in a driving task. More explicitly, the human co-driver might serve as the human factor that potentially provides additional understanding of the interactions and behaviors of collaborating agents. In this experiment, the emulator's ability to perceive the intentions of the driver is used as an alternative (but unknown) algorithm to predict a lane change. The emulator's performance is compared with several other predefined algorithms for perceiving such a lane change by recording the time course of each indicated onset of the predicted maneuver. This experiment investigates whether the human co-driver is a valid simulation alternative for a support system that is able to predict driver intent, which is a quality difficult to automate. In addition, the experiment serves as an exploration for future research where the co-drivers' behavior is observed and potentially contributes to the understanding of the ability to predict the actions and intentions of others. This experiment explores the potential surplus value of having a human co-driver available during ADAS design. For this the following questions are addressed:

- Given the innate ability to infer others' intentions, a human co-driver might serve as a valuable model for automating such an ability. Since it is expected that the ability to infer others intentions is strongly associated with kinematic cues, several algorithms based on vehicle data are compared with the ability to infer overt human behavior. For this, a simulated and an emulated support system to predict a lane change are evaluated in terms of time and accuracy.

Brief description simulator setup

Several methodological approaches are available in order to anticipate the potential safety and usability issues associated with driving automation. Among these approaches, the use of virtual reality (VR) in driving simulator studies enables the controlled presentation of different driving scenarios and support behaviors. Moreover, driving simulators potentially serve as both design and research environment, combining the design and evaluation of driver support. The notion of humans and automation being collaborating agents, combined with the availability of VR, is of special interest for the current study because it provides the possibility to establish a setting for human-agent teamwork within the context of anticipating and evaluating their collaboration.

The basic setup consists of a fixed-base, medium-fidelity driving simulator, having a car mock-up placed in front of a visual screen with 180 degrees field of view. The mockup is being equipped with an automatic gearbox, steering wheel with force feedback, gas pedal and brake. The virtual driving environment is generated using Lumo Drive version 1.4 by Re-lion. Driving data is recorded with a frequency of 30 Hz and contains trial number, time, vehicle position, steering wheel angle, and codes for the events presented in the driving scenario and events executed by drivers. Traffic dynamics and vehicle characteristics ensure a basic resemblance to actual driving.

The current research and design environment makes use of human drivers and co-drivers who have co-agency between the different tasks that are involved in driving. While a human driver performs his task in a driving simulator, driver support is provided by means of visual, auditory or haptic stimuli. Driver support behavior in any of these modalities is executed by a human co-driver based on predefined instructions. In theory, the human co-driver has access to all necessary devices (i.e. clutch, steering wheel, brakes and throttle) to control the driving task by his own and these devices can be coupled with the ones in the simulator mock-up in order to provide haptic feedback. In figure 5.1 it is shown how the human co-driver, physically separated from the main driver, is able to provide visual, auditory or haptic support. Within the current research and design environment, the co-driver's output behavior can be received by the driver as haptic feedback on the steering wheel and as auditory support. In the basic setup the co-driver controls an additional steering wheel which is coupled to the driver's steering wheel. In this way, forces can be applied to the driver's steering wheel in order to resemble haptic feedback or in order to present auditory cues, as soon as the co-driver initiates a steering wheel movement.

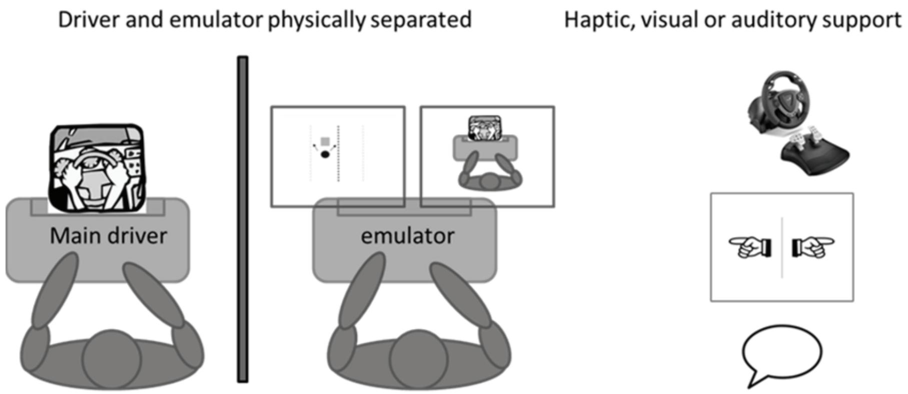

Figure 5.1: Setup for supporting driver with haptic, visual or auditory stimuli.

6

Experiment 1

Validation study

Introduction

While the use of human emulation (cf. Wizard of Oz studies) is well covered in literature and its application is already acknowledged, implemented and reported useful in the context of designing and evaluating driver support (e.g. Schieben et al., 2009), validation of such an approach in the automotive domain is currently limited. In order to address the accuracy of human emulators, Schmidt et al. (2008) compared emulated driver support with automated system functionalities. They applied the emulation approach in an instrumented vehicle and found minimal differences in drivers' subjective evaluation of two support systems (Traffic Sign Recognition and Lane Keeping Assistance). However, while the study of Schmidt and colleagues recognizes the use of human emulation as a valuable exploration and evaluation tool during the development of driver support, two questions remained unanswered. First, to what extent does the co-driver's support behavior vary between replications? And secondly, are potential variations in co-driver's behavior responsible for different objective driver responses? Research based on objective data collection is therefore currently missing. The aim of the current experiment is to provide for such an objective validation.

Two qualities that - at least intuitively - distinguish humans from pre-programmed algorithms (i.e. an automated version) are timing and accuracy. On both variables humans are known for their inconsistency and as a result this might constitute one of the potential drawbacks of the current approach because it potentially influences the support's behavioral characteristics. However, while such inconsistency is inherent to human behavior, the variation of this characteristic might be of such a (small) degree that it complies with our claim of appropriately simulating automation by means of human emulators. An important prerequisite for using human co-driver behavior as a simulation alternative for driver support is that it should elicit driving behavior similar to that of an automated version. Because, when the assumed inconsistencies of the co-driver have a different effect on the driver's behavior this would prove the inability of humans to emulate specific driver support.

In order to address whether a human co-driver and an automated version have a different effect on drivers' behavior, a driving simulator experiment was performed in which both versions of a single support system were compared. While drivers received directional support by means of a haptic precue on the steering wheel, fifty percent of the trials were given by an automated version and fifty percent of the haptic feedback drivers received was provided by a human co-driver.

Method

In this experiment it is hypothesized that, while variations in timing and accuracy are specific qualities of human behavior, this should not be an objection to use humans as emulators of automation. More specifically, given the assumed differences between an emulated and automated version, the onset of the precue is expected to be different for both conditions. That is, assuming variation in co-drivers' behavior in terms of timing, while keeping this variable constant for the automated version. Since this could result in different time courses, and therefore different support behavior for both versions, the drivers' responses on the imperative stimulus are expected to be different for both conditions as well.

In order to investigate potential differences between an automated and emulated support system and the potential effects on driver responses, the behavior of both drivers and their support were observed objectively in terms of timing during a simulated driving task. Since the support behavior (emulated and automated version) served as input behavior for the drivers' task, timing was used as both dependent (i.e. driver response) and independent variable (i.e. moment of presenting support).

Although the driver support can theoretically be given by means of three modalities (visual, auditory and force feedback, implying shared control of the steering wheel), this experiment uses only the haptic modality in order to reduce the amount of factors and therefore the total amount of driving time. To prevent bias, drivers were kept unaware of the presence of any human support.

Participants

Twenty-eight participants (23 male and 5 female, aged between 18 and 44) attended an experimental session of 45 minutes. Participants were divided into Drivers and Co-drivers. Three participants attended the experiment as both Driver and Co-driver, in this order and in different sessions. All participants had normal or corrected-to-normal vision and were naïve about the purpose of the study. 44 percent of the Drivers had a driving license for 10 years or more and 56 percent had their driving license for 10 years or less.

Driving task, driver support and apparatus

Participants drove, with a short headway, behind an ambulance in the center of a three-lane highway in ACC mode. This means that they remained a fixed speed (approximately 84 km/h), not using accelerator, brakes and clutch. Because of the short headway, participants were deprived of upcoming traffic and this forced them to make a swerve manoeuver when the ambulance would press brakes due to upcoming stationary vehicles. During each run of approximately 1.7 km, drivers received driver support by means of a directional precue on the steering wheel, which indicated the safe direction in case of an inevitable lane change. As soon as the ambulance pressed brakes, drivers acted according to the earlier received cue and reaction times for initiating a lane change to the right or left were measured. The imperative stimulus consisted of the ambulance' brake lights turning red.

Driver support was either generated by a predefined automatic version or by a Co-driver, who was seated behind a curtain. Drivers were unaware of the Co-driver's presence and task. Co-drivers controlled a secondary steering wheel that was connected to the Driver's steering wheel. An additional monitor showed an animated representation of the traffic situation and indicated the appropriate direction by means of a green arrow. Co-drivers were asked to respond as soon as a visually presented cue (purple vehicle) appeared on the screen by turning the steering wheel in the pre-cued direction.

The setup used for the present experiment consisted of a fixed-base, medium-fidelity driving simulator as described in chapter 5. Figure 6.1 (left and right) show the Co-driver's interface and an animated impression of the current setup, respectively.

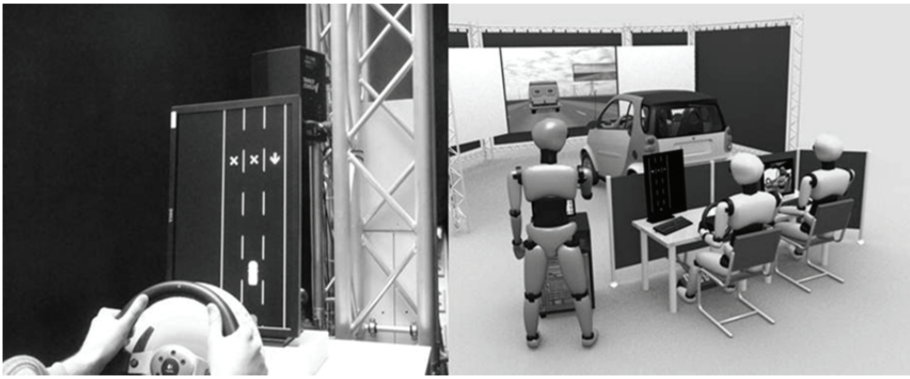

Figure 6.1: (left) Co-drivers' task was to respond to a visually presented stimulus. Their manual responses served as input behavior for the haptic feedback on the steering wheel, received by the Drivers. An animated impression of the current setup is shown on the right. Note that in the actual situation, Co-drivers were seated behind a curtain, visually separated from the Drivers.

Procedure

Participants could be either Driver (n = 25) or Co-driver (n = 7) and were welcomed separately in order to keep Drivers unaware of the Co-drivers' presence.

Co-drivers received information about their role as driver support system and it was explained how their actions would serve as input for the support behavior. In addition, it was explained how the directional information could be used by the Drivers in order to avoid a collision. Co-drivers were instructed to prepare for a steering movement to the left or right, as soon as a visual cue was presented (i.e. green arrow, see figure 6.1). As soon as a second cue was presented (i.e. represented by a purple vehicle at the top of their screen) Co-drivers executed a steering wheel movement corresponding to the pre-cued direction. Co-drivers were instructed to respond as fast and as accurate as possible. Co-drivers were expected to make a steering wheel movement of 45 degrees. Both the starting position (0 degrees) and end position (45 degrees) were visually marked on the steering wheel. Through their instruction, Co-drivers were under the impression that their input served as driver support during the entire experimental session.

After being informed about the general procedure of the experiment and after being familiarized with the driving task, Drivers performed 18 runs with a short break in between. The entire experimental session lasted about 25 minutes. During the experimental trials

(67%) Drivers received a directional precue on the steering wheel, which indicated the safe direction for a future swerve manoeuver. After receiving the haptic cue, Drivers had to respond accordingly as soon as the ambulance would hit brakes due to upcoming stationary vehicles. Precues were induced either by the human Co-drivers or by an automated version in a 50/50 ratio and were presented randomly. Since Co-drivers provided input during all experimental trials, neither they, nor the experimenter knew which version induced the driver support (i.e. double blind design). During the remaining trials (33%) Drivers received no directional precue and they performed a two-choice reaction time task after the imperative stimulus appeared. Since Co-drivers were assumed to show variable responses, the time courses for both versions were expected to be different. After cue onset (i.e. the Emulator's imperative stimulus) a fixed interval of 3.3 seconds followed before the Driver's imperative stimulus was presented. However, while the Driver's precue (target) was set within a fixed interval in the pre-programmed version, the onset of the Driver's precue depended on the (early or late) responses of the Emulator. This means that the time course for the automated condition was the same for all trials, while the time course for the emulated condition might differ for trials. In figure 6.2, the time course for the emulated condition is given.

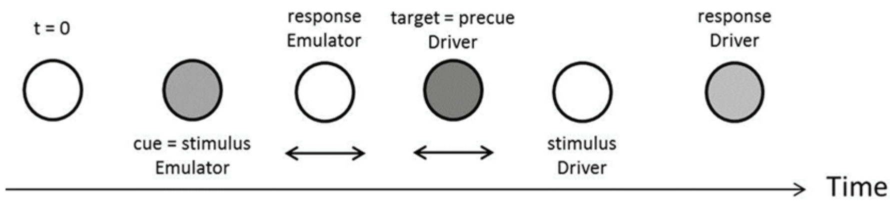

Figure 6.2: Time course for experimental trials in the emulated condition. While the time interval between cue and target is fixed in the automated support version, here the onset of the target depends on the speed of the Emulator's response.

Experimental design and data analysis

This study used a 2 x 3 repeated measures design. The first within-subject factor was Support Type (emulated vs. automated version), the second factor Support determined whether support was given and in which direction (no support and left vs. right). Dependent variable was reaction time (RT) and was recorded for both Drivers and Co-drivers responses. RT for both groups was defined as the time from their respective imperative stimulus onset to the moment in time at which the steering wheel angle was 10 degrees. In order to determine whether Drivers received the directional precue at the same time for each Support Type, RT Support compared the timing of emulated support and automated support. Trials in which participants responded before or at stimulus onset (anticipated responses) and trials with RT > 2 seconds (missed responses) were discarded from data analysis. The number of trials submitted to analysis was 388 (86%) and the probability level for statistical significance was set at $p < 0.05$. In the next section all relevant variables are explained.

Independent variables and manipulations

Support Type. Emulated version vs. automated version. Ratio was 50/50. It was investigated whether the onset for both versions (i.e. the moment at which the drivers received a directional cue on the steering wheel) was different. In addition, it was investigated whether an assumed difference in timing between both versions led to different drivers responses in terms of reaction time.

Support. Drivers received a directional precue in 67 percent of the trials. Support was given to the right or to the left in a 50/50 ratio, randomly presented. During the remaining trials, randomly presented as well, no support was given.

Ability to anticipate. In order to generate a functional driver support system, the driving task is being performed with a short headway. In combination with using a larger vehicle (ambulance) that the driver's car is following, visibility of the upcoming traffic situation, and therefore the ability to anticipate, is minimal.

Accuracy. In this experiment, accuracy (as characterized by the force and amplitude that were perceived by the drivers' on the steering wheel) is expected to be equal for both versions of support. Although the present setup did not allow us to measure accuracy in terms of force, amplitude and duration in real time, this characterization was made comparable for both versions. For this, when asked to execute a steering motion, the human co-drivers were instructed to keep the steering wheel angle, for each trial, at 45 degrees, which was visually indicated on the steering wheel.

Dependent variables

Reaction Time (RT). In the present study, reaction times represent two different behaviors and are measured for the supports' input behavior (RT Support) and during the Drivers' responses (RT Driver).

RT Support reflects the moment directly preceding the support given to the Drivers and the timing of the support might differ for both support versions. Since the emulated version uses human Co-Drivers who are instructed to act on a visually presented cue, their responses (i.e. RT Support), who serve as the input given to the Driver's steering wheel, might differ from the automated version. The moment at which the support is received in the emulated version depends on the responses (i.e. reaction times) given by the Co-Drivers. This might differ for each trial (within subject variability) and for each Co-Driver (between subject variability). The automated version on the other hand, uses a pre-set algorithm which is expected to provide minimal variability in the support's timing. However, both the Co-Drivers' imperative stimulus and the moment at which the automated version is prompted to activate the directional cue for the Driver, are related to a single event in the simulated driving scenario being $t = 0$ in the time course of each trial. Since the present driving scenario does not allow for full control over this event at design time, variability in timing of the automated support version cannot be ruled out. Possible variations in the event prompting the driver support should therefore be revealed by the amount of variability in RT support during the automated support version. The relevance of the assumed differences between both support versions, for which RT Support and its variability are observed, lies in the possibility that emulated and automated support versions might elicit different responses in drivers' behavior (as reflected by their reaction times). As already mentioned, if both versions show different driver responses, this would mean that emulating support behavior would not be a valid approach for representing and simulating an envisioned support system.

RT Driver reflects the moment at which the Driver responds to the imperative stimulus, being the preceding vehicle's brake lights. Reaction time is being calculated as the difference between the appearance of the brake lights (i.e. stimulus Driver) and the time at which the Drivers' initiate their maneuver, being calculated as the moment at which the steering wheel angle reaches a fixed threshold of 10 degrees (i.e. response Driver). The Drivers' task reflects a spatial precueing paradigm, for which it is assumed that providing relevant information by means of a directional cue prior to the imperative stimulus, might have an effect on the speed of Driver responses (cf. Rosenbaum, 1980). Since the time course of the Drivers' task might differ not only for both support versions (emulated and automated) but between trials in the emulated condition as well, it is investigated whether such an assumed difference leads to differences in Drivers' response times. In conclusion it should be noted that the use of steering wheel position for determining the initiation of a lane change differs from an approach used in similar paradigms, where reaction time might be derived from the velocity profiles of the steering wheel angle (e.g. Hofmann et al., 2010). While this approach might result in different reaction times as opposed to studies that used other definitions for reaction time, given the objective to compare results between two different support versions within a single experimental paradigm, in the current study defining this dependent variable is arbitrary.

Questionnaire. In order to provide for a subjective assessment, participants were presented with a questionnaire evaluating whether both versions were experienced as similar. By using two different phrases expressing a single question, it was addressed whether the support induced by a human co-driver was experienced differently from the fully automated version. Participants rated their level of agreement using 6 point Likert scale (from "definitely not true" to "definitely true"). The first item explicitly asked whether the offered support was initiated by a human instead of a computer. A second item asked whether human behavior was used as a model for the support system, A third item asked whether the offered support was induced by a computer instead of a human. A fourth item asked whether support induced by a human would be presented with better timing. The final item asked whether automated support would be as accurate as human induced support. These written questions were presented after each experimental session. It should be noted that these items only verify whether the support versions are experienced as similar. Because both the emulated and automated versions were presented in a 50/50 ratio, the current paradigm does not allow for asking whether emulation is seen as an equal substitute for a fully implemented system, as could be investigated when emulation is used exclusively.

Results

RT Support

A 2 Version (emulated vs. automated support) x 2 Direction (left vs. right) repeated measures ANOVA revealed a main effect for Version, $F(1,24) = 297.55$, $p < 0.01$, partial $\eta^2 = 0.93$. This means that the emulated support (M = 1.02 sec, SD = 0.26 sec) was presented faster than the support given in the automated version (M = 1,77 sec, SD =0.07 sec). In the current paradigm it is assumed that the time courses for both support versions differ and this is reflected by the observed differences in timing of the presented support behavior for both versions. In addition, a substantial difference in reaction time variability between both support versions can be observed. This means that the moment at which the emulated support was given shows more variation between trials as compared to the timing of the automated support version. The differences in timing variations are expressed by the standard deviations presented above (SD emulated support vs. SD automated support). Analysis showed no significant (n.s.) interaction effect for Version and Direction ($F(1,24) = 3.28$, n.s.) as was reflected by an absent effect for Direction ($F(1,24) = 1.29$, n.s.). This means that in both versions support is assumed to be presented equally for both directions. While support was given earlier during the emulated condition, support to the left (M = 1.41 sec) and to the right (M = 1.38 sec) is given according to a similar timing. Results for the differences in timing of the support between both support versions are shown in figure 6.3. In terms of support characteristic, Mean RT Support reflects the moment at which a directional precue was presented to the Drivers, directly preceding the Drivers' target stimulus, as denoted in figure 6.2.

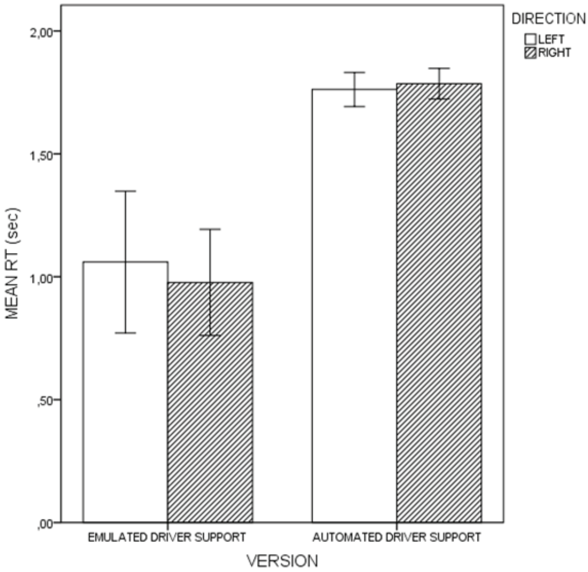

Figure 6.3: Mean reaction time (RT) for Support, reflecting the timing of presenting a directional cue to the drivers. Emulated support is presented earlier that than the automated version. Error bars represent interval SD (1), showing a larger variation of timing when presenting emulated support.

RT Drivers

A 2 Version (emulated vs. automated) x 3 Support (no support and left vs. right) repeated measures ANOVA revealed a main effect for Support, $F(2,23) = 29.7$, $p < 0.001$, partial $\eta^2 = 0.72$. This implies faster responses for precued trials to left (M = 1.18 sec, SD = 0.12 sec) and right (M = 1.20 sec, SD = 0.12 sec) as opposed to driver responses that were not preceded by directional support (M = 1.38 sec, SD = 0.15 sec). Pairwise comparisons between the levels of Support showed that the effect was due to the presentation of advance information to the driver, since direction of support did not show different mean reaction times for left and right responses ($p < 0.5$, n.s.). Given an absent interaction effect ($F(2,23) = 0.6$, n.s.) a similar advantage for precued trials, with no effect for cued direction, was observed for both support versions. In line with the assumption that different timings for both support versions (as reflected by differences in RT Support) are not reflected by different driver responses, an effect for Version was not found ($F(1,24) = 2.3$, n.s.). This means that emulated and automated support behavior elicited similar driver responses (M = 1.19 sec). These results are summarized in figure 6.4.

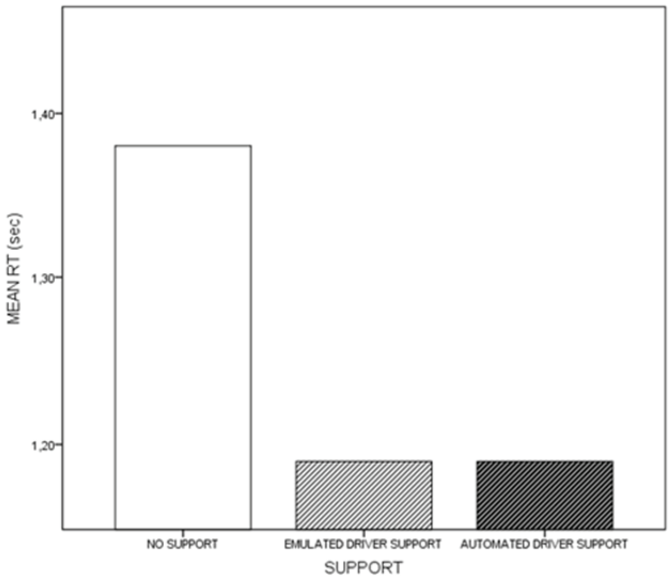

Figure 6.4: Reaction time (RT) as a function of support version. Given an absent effect for cueing direction, reaction times are collapsed for this variable. It is shown how precueing elicits faster response times, while this advantage is similar for the emulated and automated support versions.

Questionnaire

Analysis of the questionnaire revealed that the support given in the current setup was perceived as being an automated support system by an average of 74 percent of the respondents (as reflected by items 1 and 3). Since the participants were kept unaware of the co-drivers' presence, this suggests that for a majority of the drivers, support behavior was not perceived as different in both support conditions. This complies with the objective measurement of drivers' reaction times, where no difference was found between emulated and automated support behavior. Interestingly, subsequent analysis of variance revealed an effect for subjects' driving experience, when asked if the driver support was initiated by a human ($p < 0.05$). This reflects a difference between drivers with a driving experience of 10 years or less ($n = 14$) and those who had a 10 years of driving experience or more ($n = 11$). This means that the first group was more confident that the support system was fully automated, while the second group showed some uncertainty.

Discussion

The aim of this study was to investigate whether emulating driver assistance is a valid simulation alternative during the design process of ADAS. Given an assumed difference between an emulated and an automated version in terms of moment of presenting and variation in timing, it was investigated whether both versions induced similar reaction times when a time critical lane change is provided with advance directional information. Since an emulated version is subject to the co-driver's responses as generated by a written instruction, support behavior initiated by human emulators might be different from a pre-programmed algorithm or automated version. Because similarity partly depends on synchronizing the support behavior's time course at design time, the co-driver's task needs to run parallel to the events constituting the automated version's behavior. And this synchronization not only depends on the conducted procedure (e.g. defining events or markers that prompt co-driver's input) but on the compliance and performance of the co-drivers as well. If both versions have different time courses, the moment of presenting the support might differ for both versions. Moreover, given an assumed variation in human behavior, time courses within the emulated condition might be different as well. Emulating driver support might therefore be disadvantageous when the support behavior is qualitatively different to such an extent that driver responses show different effects for a fully automated version or even between repeated presentations of an emulated version. On the one hand, emulated support should resemble the envisioned support behavior in terms of various characteristics like timing, force and frequency (e.g. in similar situations) because of its potential predictive value for future support behavior. On the other hand, its characteristics need to be distinct and unequivocal in order to be reproducible and in order to serve as a model for design alternatives.

Given these assertions, the validation of emulation as a simulation alternative is implemented by investigating the potential differences between an emulated and automated support system in terms of characteristics and how they might influence driver behavior differently. In this way, assumed differences between an emulated and automated driver support system were studied in order to examine the feasibility of emulation as a simulation alternative during ADAS design. For this a driving task was employed in which drivers were supported by means of a directional precue on the steering wheel, which indicated the safe direction in case of a required lane change. In the present experiment two different versions of support were compared. Because the emulated support version was induced by a human co-driver, the onset of the support in this condition depended on the task description, the speed of the co-driver's response to a visual cue and a potential variation between responses. The automated version, on the other hand, was executed by a computer program and therefore minimally prone to variable timings of the support behavior.

The results show that, although both versions differed in terms of timing of the support behavior, this was not reflected by different driver responses. This not only implies a relatively high tolerance for the moment of presenting a directional precue when used as driver support, but also serves as a claim in favor of human emulation as a simulation alternative since both versions were acted upon similarly in terms of drivers' reaction times. Furthermore, by applying the precueing paradigm in order to elicit driver responses, these results confirm the suggestion that drivers might benefit from response preparation as reflected by decreased reaction times (e.g. Hofmann et al., 2010).

While the basic assumption of the current paradigm concerned a potential difference in timing and its variability between the emulated and automated support versions, differences in terms of accuracy might have contributed to a qualitative difference between both versions. Given the emulator's task to execute a steering wheel movement towards an angle of 45 degrees, the steering wheel angle velocity (degrees/second), the duration of the entire movement and the accuracy of the response (i.e. variance around target angle of 45 degrees), might have been responsible for an additional difference between both support versions. If potential variations of these kinematic variables are experienced differently by the drivers since it might alter the quality of the support in terms of force, amplitude and duration (defined as accuracy), the current setup should be adjusted in order to allow for controlling and measuring these variables. Although these differences remain speculative because the current setup did not allow for logging the emulator's kinematic characteristics, it is not assumed that their influence is underestimated, since both versions were not acted on differently. Given similar response times for both support versions, it is not assumed that they might have been responsible for a qualitatively different nature of both versions. Moreover, according to the results obtained from the questionnaire, support behavior was not subjectively perceived as different in both support conditions. However, it should be noted that the use of subjective measurements needs to be interpreted with some reservations. First of all, given that the subject pool primarily consisted of students and colleagues at the institute where the experiments were carried out, it remains unknown whether and to what extent participants had prior knowledge about the experiment's setup and purpose. Secondly, while this information was not collected for each participant, the presence of the experimenter during the driving sessions might have biased the participants' view on who initiated the driver support. That is, several participants indicated that they were under the impression that the experimenter was responsible for the presentation of driver support. Such uncertainty was ruled out for collecting the participants' response times, since driver support was presented randomly within a double blind experimental design.

The present experiment showed how the assumed differences between two simulation alternatives of a single support system did not result in different driver responses. This led to the conclusion that the observed variations in the time course of the emulated support version in this experiment, are not a constraint for applying emulation as a simulation alternative. However, in addition, the present results could be interpreted as simply due to an absent effect of the moment of presenting directional information as a precue. While the effect of precueing is typically reflected by faster and more accurate responses to an imperative stimulus, this effect is assumed to occur only for short intervals between cue and target (Busse et al., 2006). This means that providing advance information reduces the uncertainty of the drivers and therefore speeds up their responses, given that the information is not provided too soon before the driver is expected to respond (i.e. late cueing). The time between a precue (i.e. the advance information) and an imperative stimulus (i.e. the stimulus that elicits a response) might therefore have an effect on the speed of drivers' responses. Such a precueing effect has been observed in several studies (e.g. Busse et al., 2006; Lukas et al., 2010) and indicates a difference between early and late precueing. However, whether or under which conditions such an effect might occur for precueing drivers with directional information, is currently unknown since no known studies are available that address this issue within the context of driving. As mentioned previously, a high tolerance for the moment of presenting a directional precue might be the explanation for observing similar driver responses during both support versions. Simply put, whether directional information is presented early (emulated version) or late (automated version) such differences in timing do not affect drivers' reaction times in the present experimental paradigm. While this interpretation might serve as an additional argument in favor of applying emulation as a simulation alternative, the question arises to what extent differences in timing canceled out other potential differences between the characteristics of both versions. For example, early precues in the emulated version might have outweighed potential differences in e.g. force and duration of the haptic feedback, provided in the automated version. Unfortunately, the present setup did not allow for such an analysis and although a comparable precueing paradigm was applied by Hofmann et al. (2010), since they used a fixed interval between precue and imperative stimulus, this issue remains unsolved. It is therefore recommended for future research to control and record those variables that might constitute the qualitative differences between human induced and automated support behavior, thoroughly.

Whereas the present experiment argues in favor of applying a simulation alternative, referring to the potential advantages of such an approach, it should be noted that the current study did not fully address the potential drawbacks of applying human emulation during ADAS design. While the assumed differences in timing and accuracy between the emulated and automated versions of the present support system did not influence driver behavior in terms of reaction time, these qualities might not be representative when developing and evaluating other types of driver support. In addition, differences in performance envelope between human and automation should be recognized as they might limit the number of support behaviors suitable for emulation. Challenges for future research therefore lie in revealing the full potential of human co-drivers as relevant contributors in the design of ADAS, while defining and acknowledging their limitations.

Moreover, in order to serve as input behavior during the design and assessment of driver support, emulation should be able to reveal the consequences of different design alternatives. Typically, this implies studying the relationship between the properties of the support system and the effect these properties might have on the driver's behavior and their compliance with the offered support. In the present experiment, an absent effect of support version on driver's behavior served as an argument in favor of applying emulation as a simulation alternative. However, such a paradigm is not able to investigate design alternatives, since support characteristics can only be decided on when they reveal an impact of the features that were manipulated during research. Given this limitation, the ability to apply emulation in order to investigate distinct design alternatives will therefore be addressed in the next experiment.

7

Experiment 2

Comparative study

Introduction

While the first experiment served as a validation study for the question whether a human co-driver and an automated version have a different effect on drivers' behavior, it was argued how the adopted paradigm might be inappropriate for evaluating design alternatives. When emulation is used as a tool for comparing different support characteristics, the variations in co-driver behavior in terms of e.g. timing and kinematics might result in support behavior that varies qualitatively between presented trials. Since the present research is based on the assumption that emulation could be a valuable tool within a setting of exploring and investigating cognitive support behavior, a significant prerequisite for such an application is the ability to provide consistent and unambiguous input behavior. The reason for this is twofold. First, variations in the behavior that constitutes the driver support might obscure the evaluation of those support characteristics that are under investigation. For example, when variations in co-driver behavior potentially contribute to the results concerning a comparison between support modality, such variation might be a confounding factor and therefore a considerable limitation for design choices based on such an evaluation. Secondly, consistency in presenting driver support would allow for an approach where the qualifying parameters, such as timing and frequency of signals that are used as the support's input behavior, might serve as a model for the support under development. In this way, specific characteristics of the co-driver's behavioral repertoire might generate a template for future driver support during the exploration phase of ADAS design.

In the present experiment it is assumed that emulation has the ability to reveal the influence or quality of different design choices. For this, it is investigated whether emulation can be used to demonstrate distinguishing properties of design alternatives at an early development phase. Previous studies showed that collision warnings have the ability to reduce the number and severity of rear-end collisions (e.g. Lee et al., 2002) and this ability is, among other characteristics, associated with the modality in which the support is given. For instance, Scott & Gray (2008) compared driver responses in rear-end collision situations between auditory, visual and tactile warning conditions. Their study showed an effect for warning modality, indicating that tactile warnings elicited faster responses than visual warnings. While comparisons between the other modalities did not reveal any differences, their results are in line with the suggestion that auditory or haptic warning signals are able to improve driver's responses (e.g. see Chun et al., 2012; Fitch et al., 2007; Ho et al., 2006). By comparing three different versions of a single support system, it is examined whether this suggestion holds when emulation is applied instead of conventional simulation techniques. Within the present context of investigating the ability of emulation to compare different design solutions, it is assumed that emulation reveals similar effects of support modality on driver behavior in terms of reaction times when drivers respond to a directional cue. If similar results are found, this would imply that the advantages associated with emulation, such as representing support behavior prematurely, can be attributed to the evaluation purposes of emulation as well.

Driver support used in the present study can be described as a forward collision warning system and is typically used to speed up driver responses in a general aim to reduce the amount of rear-end collisions. While such warnings are often used to prompt drivers to increase the distance between a lead vehicle or to direct their attention towards a hazardous situation (Muhrer et al., 2012), the present support system provides directional information in order to guide driver responses for initiating a lane change in a time-critical situation. Given the limitations and objections as discussed above, the paradigm used in experiment one was slightly modified. In order to cancel out different driver responses due to different moments of presenting directional information (i.e. due to variations in co-driver behavior), the precueing paradigm was replaced by a paradigm that elicited driver responses as soon as they received this information. This means that the precue used in experiment 1, served as the imperative stimulus during the present experiment. In this way, the moment of presenting directional information should not have an effect on the speed of driver responses, since driver responses were not coupled to an event after presenting driver support (i.e. in experiment 1 drivers responded to the ambulance' brake lights, after receiving a directional cue). Instead, in the present paradigm drivers were instructed to react immediately and responses are therefore coupled to the presentation of the support itself.

Method

In the current experiment three different modalities of a single support system are compared. Given that an influence of support timing is kept to a minimum, all support behavior is initiated by a single human co-driver. Driver support was presented as a collision warning system and was provided by means of a directional cue on the steering wheel (haptic modality), an auditory cue (auditory modality) and a combination of these modalities (crossmodal modality). Drivers were expected to make a lane change in accordance with the directional cue, as soon as they received this information. In order to investigate whether emulation has the ability to reveal the influence of different design choices, it is hypothesized that drivers' reaction times are improved when provided with collision warnings and that drivers show varying responses for different modalities.

Participants

Forty-one participants (36 male and 5 female, aged between 21 and 47) attended an experimental session of 15 minutes. All participants had normal or corrected to normal vision and were naïve about the purpose of the study. 10 percent of the participants had their driving license for 5 years or less, 42 percent of them had driving experience between 5 and 10 years and 34 percent of the participants were licensed to drive for 10 years or more.

Driving task, driver support and apparatus

The driving task was kept the same as for experiment one. However, instead of using the directional information as a precue, participants were instructed to initiate a lane change as soon as they received the driver support. In this way, drivers were directed to the safe lane. Each lane change was immediately followed by an emergency stop by the preceding ambulance in the middle lane. In addition, adjacent to each lane change two stationary vehicles were visible, one closely in front of the ambulance and one stationary vehicle in the lane opposite from the one the driver's vehicle was directed to. In this way, drivers received feedback about the cause of the ambulance' sudden deceleration and the effectiveness of the driver support. Co-drivers' task and setup were kept the same as described for the first experiment one (see figure 6.1). Instead of having several co-drivers, the co-driver's task in the present experiment was executed for all trials by the same experimenter. For the auditory and mixed modality, a female voice was recorded who instructed drivers to change lanes by using the expressions "links" (left) or "rechts" (right). Loudness level of these verbal warnings was 69 dB(A) as measured at the position of the driver's head. Both had a duration of 0.5 seconds. The loudness of the auditory stimuli exceeded the loudness of the simulated engine sound, which had an average peak of 64.8 dB(A). Stimuli were presented with a stereo speaker-set, located at ear-level with an approximate distance of 40 cm from both ears.

Procedure

Being kept unaware of the emulation paradigm, participants were briefly instructed about the general procedure, after which they performed a test run in one of the support conditions (i.e. modalities). These modalities were presented in 3 separate blocks of 4 trials each. Modalities were presented in random order for each participant. Each condition (modality x direction) was presented 2 times in random order and its direction was counterbalanced for all runs. Within each block, drivers performed 4 experimental trials and one default trial, in which no support was given. Default runs were randomly presented and were added to prevent biased and anticipated responses and to keep participants alert during each run. Each participant was offered 12 experimental runs (3 modalities, 2 directions and 2 replications) and three default runs. After each session, which lasted about 15 minutes, participants completed a questionnaire that served as the subjective assessment of each support version. The time course for the current experiment is shown in figure 7.1.

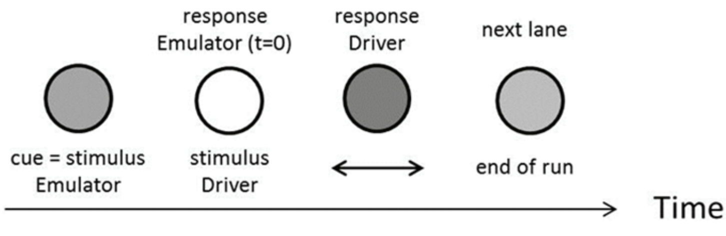

Figure 7.1: Time course for experimental trials in experiment 2. Emulator's response to a visually presented cue serves as the imperative stimulus for the Driver. Emulators response is defined as t=0, meaning that the speed of this response is independent from the Driver's response.

Experimental design and data analysis

For this study a 3 x 2 repeated measures design was used. The first factor Modality had three levels and was used to investigate whether auditory, haptic and mixed modality support elicited different driver responses. The second factor Direction determined whether the support was given for a lane change to the left or right. Dependent variable was reaction time (RT) and was defined as the difference between the Emulator's response, which subsequently served as the Driver's imperative stimulus, and the moment at which the Driver initiated a lane change. Trials in which participants responded before or at stimulus onset (anticipated responses) and trials with RT > 2 seconds or where no response was given (missed responses) were discarded from data analysis. The number of trials submitted to analysis was 564 (91,7%) and the probability level for statistical significance was set at $p < 0.05$. Relevant variables are explained in the next section.

Independent variables and manipulations

Modality. At interface level, drivers received support in three different modalities. In the auditory modality, directions were provided verbally with the expressions "links" (links) and "right" (rechts). The haptic modality support, as introduced in experiment 1, consisted of a steering wheel movement presented to the driver, which was felt as a slight jerk in the cued direction. During the crossmodal support condition the auditory and haptic stimuli were presented simultaneously. It was investigated whether emulating three different modalities was able to reveal different driver responses in terms of reaction time.

Support. Drivers received a directional cue, which had to be responded to as soon as it was received. Responses were congruent with the cued direction of the support. While direction of support is inherently associated with a lane change, directions are manipulated (presented randomly) in order to anticipate Drivers' expectations.

Ability to anticipate. In addition to the randomly presented directional cues, participants' expectations are further anticipated by a short headway between ego-car and the preceding ambulance. In this way, the driver support system shows it value, since relevant information about the upcoming traffic situation is unknown for the Drivers.

Dependent variables

Reaction Time (RT). Reflects the moment at which the Driver responds to the imperative stimulus, being the auditory and/or haptic warnings. RT is calculated as the difference between stimulus onset (i.e. moment of presenting directional cue) and the time at which drivers initiate a lane change (i.e. as soon as a driver responds to the imperative stimulus) which is calculated as the moment at which the Driver's steering wheel reached a threshold of a 10 degrees angle.

Questionnaire. As a subjective assessment of the support versions, an acceptance scale was used, as provided by van der Laan et al. (1997), which is thought of measuring usefulness and satisfaction after experiencing an in-vehicle support system. This questionnaire has nine items, which are rated on a 5 level scale between -2 and 2. In order to evaluate driver support in terms of usefulness and satisfaction, these scores are averaged over subjects.

Results

RT driver

A 3 Modality (auditory, haptic and crossmodal version) x 2 Direction (left vs. right) repeated measures ANOVA revealed a main effect for Modality, $F(2,39) = 281.8$, $p < 0.001$, partial $\eta^2 = 0.94$. However, this effect was not shown for each level of modality (haptic vs. crossmodal, n.s.). This means that both haptic and crossmodal support elicited faster responses as compared to responses within the auditory support condition. In addition, a main effect was found for Direction ($F(1,40) = 16.6$, $p < 0.001$, partial $\eta^2 = 0.29$) indicating faster responses to the left than to the right. This effect was observed for all levels, indicating faster responses to the left for each modality, as reflected by an absent interaction effect for Modality and Direction ($F(2,39) = 0.7$, n.s.). Furthermore, Analysis of variance was submitted to the mean reaction times of both supported (cued trials, three modalities) and unsupported trials (default trials), in order to investigate whether an effect for cueing was present. Repeated measures for Version (no support, auditory support, haptic support and crossmodal support) showed an effect for providing directional support, $F(3,38) = 230.2$, $p < 0.001$, partial $\eta^2 = 0.95$. This means that each modality elicited faster responses as opposed to those lane changes that were not provided with driver support. On average, drivers not receiving any support, responded 1.19 seconds after the appearance of the ambulance' brake lights, which served as the imperative stimulus in the no-support condition. As observed, providing relevant directional information as driver support caused for significant decreasing reaction times when such information was immediately acted upon (auditory support, M = 0.75 sec; haptic and crossmodal support, M = 0.40 sec). However, these results should be put into perspective since the number of trials where no support was given was 25 percent as compared to the amount of trials in which drivers received directional support. Moreover, while drivers receiving driver support responded to cues that were perceived auditory and/or haptic, drivers not receiving driver support acted on visual information (i.e. the brake lights of the preceding vehicle). In figure 7.2, the results are summarized.

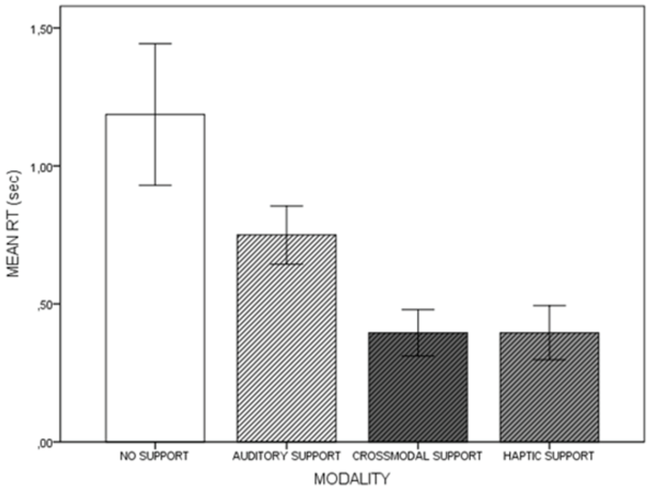

Figure 7.2: Reaction time (RT) as a function of cueing modality. Here, it is shown how providing directional support elicits faster responses (i.e. initiate lane change) as compared to manoeuvres that are not supported with relevant information. Furthermore, it is observed that both haptic and crossmodal support elicit faster responses than auditory cued responses.

Given an effect for Direction during the experimental trials, it was investigated whether such an effect was present for the default trials as well. Although average reaction times for lane changes to the left (M = 1.18) were dissimilar from those to the right (M = 1.20), such an effect was statistically not significant ($p = 0.66$). This means that Direction as a factor for decreased responses, is only observed for those manoeuvres that are supported with directional information. Results furthermore showed a slight tendency for lane changes to the left, given the observation that 61.7 percent of non-cued lane changes were made to the left.

Questionnaire

An analysis of variance was executed for Modality (auditory, haptic and mixed modality) x Assessment (usefulness and satisfaction) x Driving Experience (less than 5 years, between 5 - 10 years and 10 years or more), in order to reveal effects for Driving Experience (between subject factor) or Modality (within subject factor) on the average ratings of both subscales. A main effect was found for Assessment ($F(1,38) = 96.9$, $p < 0.001$), which indicated that providing directional support was rated as more useful than satisfactory, and this effect was revealed for each modality ($p < 0.001$). Given an interaction effect for Assessment and Modality ($F(2,37) = 5.5$, $p < 0.01$) mean scores for each assessment were compared among all three modalities in order to reveal how rating scores were distributed among each support condition. Analysis of variance for Modality showed no main effect for the average ratings for both usefulness and satisfaction between the auditory, haptic and mixed modality. This means that, on average, each modality was rated similar, while each support version was experienced as more useful than satisfactory. Ratings on both subscales, which together are thought of to reflect acceptance of driver support (van der Laan et al., 1997) are summarized in figure 7.3. In order to assess the overall acceptance ratings, post-hoc analysis showed no main effect for modality, $F(2,39)= 0.6$, n.s., again indicating that auditory ($M = 0.53$), haptic ($M = 0.49$) and crossmodal ($M = 0.57$) driver support were rated similar.

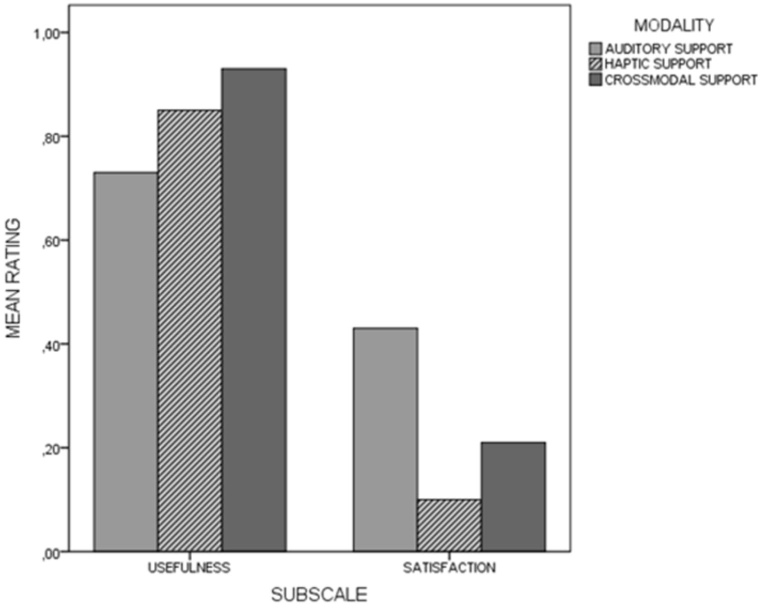

Figure 7.3: Averaged ratings (original values between -2 and 2) of subscales usefulness and satisfaction. While directional support was rated as more useful than satisfactory, no different assessment scores were revealed between all three support modalities.

Interestingly, a second interaction effect was found for Assessment and Driving Experience ($F(2,38) = 3.7$, $p < 0.05$), which revealed different mean scores on the satisfaction scale for drivers with driving experience of 5 years or less ($n= 10$; $M = 0.5$) and drivers with driving experience of 10 years or more ($n= 14$; $M = 0.04$), reflecting decreasing satisfaction ratings for experienced drivers when receiving directional driver support as compared to those with relatively little driving experience. Scale reliability tests for each support version were executed for both scales (usefulness and satisfaction) and revealed a Cronbach's α (alpha) of 0.80 or more for each support modality.

Discussion

The present experiment was conducted in order to reveal whether emulating driver support enables the evaluation of different support behaviors. For this, three different versions of a forward collision warning system were compared. Each version was presented by a human co-driver and different support modalities were evaluated in terms of drivers' reaction times and a questionnaire for assessing acceptance ratings. Since emulated support showed an effect for modality (i.e. different driver responses in terms of timing and acceptance), in line with previous research findings, it is concluded that emulation as a simulation alternative can be considered when evaluating different design alternatives.

Prior research showed how providing directional alerts might be beneficial as driver support, particularly when such information is spatially compatible with the driver's response (Liu & Jhuang, 2012; Wang et al., 2003). This means that faster responses can be elicited when the direction of the response corresponds to the direction of the warning signal (for an alternative view, see Müsseler et al., 2009; Beruscha et al., 2010). In accordance with the suggestion that collision avoidance systems should signal the escape direction (Wang et al., 2003; for a discussion, see Wang et al., 2007), the support system used in the present experiment provided directional information corresponding to the driver's response. In addition, several studies have shown how different warning modalities for a single support system elicited different driver reaction times, suggesting the use of nonvisual warning signals to speed up driver responses and potentially reduce the number of rear-end collisions (Ho et al., 2007). In line with previous observations, the present study revealed facilitated driver responses when directional information was presented by an emulated support system. Results showed that such information speeds up driver responses in each of the cueing conditions as compared to the non-cueing condition. Furthermore, haptic and crossmodal cues elicited faster responses than auditory cues, while an assumed advantage for multisensory warning signals (e.g. Ho et al., 2007) was absent. Subjective evaluation showed that directional cueing was rated as more useful than satisfactory, while ratings on the subscale for satisfaction were lower for experienced drivers (10 years or more) when compared to drivers with relatively little driving experience (5 years or less). Given an observed effect for modality for driver response times and an absence of such effect for the subjective rating scales, it can be concluded that the efficiency of the support versions (in terms of response facilitation) and the subjective assessment of the support versions are dissociated. It should be noted though, that these results are being interpreted in light of the evaluation of a design approach that applies emulation as a design alternative. Design recommendations based on these results are therefore not the primary goal in this study. Instead, consistencies with other research are addressed in order to reveal the potential for applying emulation as a support tool for designing ADAS.

Because the present study showed that emulated driver support was able to reveal an effect for modality, the goal of investigating whether emulation allows for evaluating different support configurations has been met. In this way, the present experiment can be seen as a contribution to existing attempts to implement emulation as an approach that supports the design of HCI and driver support systems in particular. However, while emulation has been addressed as a valid and appropriate alternative for conventional simulation, the present use of emulation raises the question whether there is an advantage of this approach as opposed to conventional simulation techniques. Because the presentation of the emulators' cue to initiate a steering wheel movement was coupled to a predefined event in the driving scenario and a potential effect of inter-stimulus variation (i.e. time between precue driver and stimulus driver) was kept to a minimum by removing the drivers' precue (see figure 6.2) establishing an emulated support setting highly resembles simulating driver support. While this might be seen as an argument in favor of emulation, those adopting conventional simulation techniques might lack an incentive for applying emulation as a tool for evaluating design choices, when assuming that conventional simulation and emulation are able to elicit similar results (e.g. revealing effects of design alternatives). In the present context, flexibility might be one of those incentives. With this it is meant that emulating driver support allows for altering the support behavior while running an experiment. While implementing support behavior in a conventional simulation setting implies running a pre-programmed protocol, emulation allows for deviating from the procedure at any given moment. For example, in the present experiment both timing and direction of the support are established and guaranteed by providing the emulator with a predefined instruction, similar to the process of running a computer program's executable files. However, the emulation approach allows for deviating from the protocol at runtime, for any given reason, while driver data is still being collected. In this way, emulation allows for exploring different support behaviors, for example by de-coupling the presentation of support from a predefined event and instead presenting support at an alternative, freely chosen, event. Such flexibility during an evaluation might therefore provide for the ability to implement expectations, preferences and requirements during iterative sessions, without having to edit the computer program's source code. Furthermore, flexibility is reflected by the ability to change the mode of presentation since emulation can be established through direct observation of driver behavior and traffic conditions as well. That is, while relevant information in the present experiments was presented by means of a dedicated interface, an emulator might gather such information in different, and therefore varying ways, as well. For example, by using real-time video recordings or one-way glass, the emulator remains out of the driver's sight, while being able to act on overt driver behavior or events in the driving scenario.

As already expressed, given the ability to reveal different driver responses, it is suggested that emulation is a valid approach for simulating driver support behavior. For example, when assuming that haptic or crossmodal support might elicit faster driver responses when compared to auditory support, emulation allows for setting up such a comparative study. Moreover, since present results are in agreement with previous findings that auditory or haptic warnings elicit faster driver responses when compared to no-warning conditions (e.g. Chun et al., 2012; Scott & Gray, 2008) and due to an observed dissociation between efficiency and acceptance (e.g. Navarro et al, 2010), it is argued that emulation is not only a valuable approach for the evaluation of design alternatives, but might serve the exploration of potential support behaviors as well when assuming similar results for emulated and simulated driver support. In this way, exploring the possibilities of driver support behavior might be combined with the evaluation of its effects on the driver-vehicle system at an early or even premature phase of the design process.

Within the present context of developing cognitive support behavior that is expected to cooperate with the human driver, a limitation of the present study might be the argument that the currently used support behavior and its interactions with the driver does not reflect cognitive support as described in this thesis. Since co-drivers did not act upon drivers' behavior, the support behavior can be characterized as rigid instead of adaptive and flexible. While it was already discussed how the cognitive support's behavioral repertoire can be improved by an increased ability to monitor driver behavior and by inferring driver intent, it can be questioned whether the support used in the present experiment satisfies with the requirements needed for being a true cognitive system.

Considering the above and given the developments towards a cognitive car (e.g. Heide & Henning, 2006), a third experiment was set up to further explore the ability to apply an approach that uses human co-drivers during the design of driver support. Since humans have the innate ability to infer others' intentions, such an ability might be of surplus value when monitoring and adaptive abilities are technically infeasible or unavailable in a research and development setting for intelligent vehicles.

8

Experiment 3

Exploratory study

Introduction

Given an increased amount of possible support behaviors, it can be argued that a demand for efficient and adaptive implementation of driver support has increased as well. By this, it is meant that the ability to provide drivers with assistance should reflect their demands and intentions. Simply put, while future driver support might be able to provide assistance for a large amount of traffic situations and potential dangers, their impact could be counterproductive when provided in a reactive fashion, not taking into account the necessity of such support. For example, a vehicle equipped with a lane departure warning system (LDWS) monitors the vehicle's position on the road and is designed to issue a warning when the vehicle is about to leave its lane, provided that the vehicle's indicators are switched off (Navarro et al., 2011). This means that, in order to infer the driver's intention not to change lanes, such a system relies on the proper use of the vehicle's indicators. However, following the rationale of such a system, when a driver initiates a lane change without applying the indicators, a redundant warning is evoked. This means that driver assistance systems could provide warnings or interventions that are incompatible with the intentions of the driver. While redundant warnings might cause nuisance, improper assistance might even become dangerous when the support system and the driver physically share the vehicle's control. This demonstrates how the safety and efficiency of driver support depends on proper intervention and emphasizes the need for systems that take into account the driver's intentions in order to show adaptive support strategies.

The ability to understand and to infer driver behavior might therefore be a valuable characteristic for future driver support. By extending the support behaviors' repertoire with the quality to understand and to anticipate human behavior, driver assistance might provide flexible and anticipative ways to assist drivers and therefore potentially prevents dangerous situations. The potential of such an ability can be shown by the possibility to predict drivers' intentions to initiate specific manoeuvres like lane changing or turning. Such intentions can be inferred by analyzing vehicle data (e.g. Berndt & Dietmayer, 2009), information from the environment (e.g. Lefèvre et al., 2011) and information based on the actions of the driver (e.g. Doshi & Trivedi, 2011). While it is stated that all three sources of information should be taken into account in order to predict the future actions of the vehicle and to provide relevant support (Toma & Datcu, 2012; Tran et al., 2011), it can be observed that overt - and therefore observable - driver behavior has gained increased interest to serve as an additional cue for inferring the intentions of the driver to initiate specific manoeuvres. One reason for this trend is that it is believed that prediction improves when measures of driver behavior are included (Doshi et al., 2011; Doshi & Trivedi, 2011).

For existing research, a typical approach can be identified where drivers' behavior is being tracked for multiple sources of information such as hand, foot or head movements, gaze direction and body postures. Analysis of such data subsequently allows for revealing specific patterns or features that precede the driving actions of interest. That is, by observing the way how drivers prepare for initiating driving actions or manoeuvres, relevant cues might be extracted from the drivers' behavioral repertoire in order to predict their future actions and therefore the vehicle's future trajectory. For example, previous research proposed drivers' head motion as one of those relevant cues (Cheng & Trivedi, 2006; McCall & Trivedi, 2007) and it was shown how such information, together with lane detection and the vehicle's CAN data, allows for establishing a lane change intent prediction system (Doshi et al., 2011; Doshi & Trivedi, 2009; McCall et al., 2007). However, despite the large amount of research efforts, developing reliable systems that monitor and understand human activity still remains an open question (Tran & Trivedi, 2011).

Given the human ability to predict the actions and intentions of others (e.g. Blakemore & Decety, 2001) social cognition has been subject to investigation for many years and might be of particular interest when developing systems that are equipped with the necessary features to understand and anticipate the actions of drivers. In line with the approaches to infer driver intent by monitoring overt behavior, kinematic information is thought of to express the action intentions of others. This means that by observing the movements of others, we might know their intentions and how we should respond in a social setting (Becchio et al., 2012). Although it is argued that kinematics alone cannot fully specify others' intentions (Obhi, 2012), in a recent study it has been shown that social interaction and understanding can be established without explicit communication between individuals (Patel et al., 2012). Given an assumed sensitivity to subtle changes in the kinematic properties of an observed action (e.g. Becchio et al., 2012; Stadler et al., 2012; Stapel et al., 2012) comprehensive knowledge about the movement cues that potentially reveal the intentions of drivers, could be valuable for developing the artificial counterpart of this inherent human ability.

In the current research it is believed that, in addition to driver behavior, human co-driver or emulator behavior could contribute to the development of cognitive support as well.

First of all, a human co-driver allows for a setting in which the human ability to infer others' intentions is applied to simulate an assistance system with such a characteristic. Although several algorithms and sensors are available for inferring driver intent, a human co-driver could be an uncomplicated and accessible alternative, potentially outperforming the currently available techniques. Not only could such a setting be used for simulating an envisioned system that monitors and infers drivers' behavior, its theoretical abilities might allow for premature investigations concerning its potential and efficiency for support characteristics that are not yet available. In this way, feasibility of specific system abilities and requirements for proper cooperation between driver and support system could be investigated without the need for fully implemented system functionalities. In addition, when assuming assisted driving as a cooperative act between driver and support system, such cooperation could be established in a simulated driving environment while representing the social setting by means of human drivers and co-drivers.

Secondly, within the context of finding the relevant cues that could reveal the intentions and future actions of drivers, a human co-driver becomes the subject of interest for understanding those cues. Given a setting in which a human co-driver would emulate the ability to predict drivers' actions, observing the co-driver and investigating the strategies used (e.g. by tracking eye movements) contributes to our understanding of this innate ability. That is, acquiring knowledge about how and by which means a human co-driver infers the intentions of a driver might help to improve the cognitive abilities of driver support. Ultimately, such information could serve as a template feature for driver support when assuming that the human ability to predict others' intentions reveals the (subtle) cues that are required. For now, it is hypothesized that a co-driver setting might allow for addressing these issues in a driving context.

Method

In order to explore the potential applications of a human co-driver during the design process of driver support, a driving simulator experiment was set up in which a co-driver emulated the ability to predict drivers' intention to change lanes and to which direction. While the present study was primarily aimed at revealing the feasibility of establishing a setting in which a human co-driver serves as a simulation alternative for detecting a lane change, alternative algorithms that represent lane change detection were used to evaluate its performance in terms of detection speed. The main hypothesis is therefore that the detection performances are similar for each detection algorithm.

Participants

This experiment directly followed the driving sessions of experiment two, with the same participants (36 male and 5 female, aged between 21 and 47). They participated in an experimental session of approximately 10 minutes. Participants were kept naïve about the purpose of this study.

Driving task and apparatus

Similar to the previous experiments, a simulated driving task was used. Participants drove in the center of a three-lane road. Their task was to initiate a lane change to the left or right as soon as a green arrow was presented on the dashboard, indicating the required direction. While they had full control over the accelerator, they were instructed to press down the accelerator pedal fully in order to reach and maintain a speed of approximately 90 km/hr. When desired, drivers could decelerate by temporarily releasing the accelerator pedal.

Drivers were instructed to initiate a lane change by applying the proper rules for such a maneuver. This means that they were instructed to look into the rear-view mirror and side mirror before looking over the shoulder in order to check the blind spot. When a safe lane change could be made, drivers were asked to apply the indicator before executing the actual maneuver. In order to emphasize the relevance of such preparation, the driving scenario consisted of occasional upcoming traffic. These vehicles could overtake the ego vehicle at either the left or right side.

While drivers were instructed to prepare and execute several lane changes, a human co-driver observed their overt behavior by monitoring video images that were recorded by a webcam located centrally and diagonally across from the driver. An example image of these recordings is provided in figure 8.1. The co-driver was located in such a way that he could only infer the intentions from the driver by observing this video footage. Note that the image was mirrored in order to provide for spatially congruent images. The co-driver's task was to indicate an assumed lane change by the driver. As soon as the co-driver inferred a forthcoming lane change, a custom-made response box was used to log the timestamp and direction. Similar to experiment 2, the co-driver's task was executed by a single experimenter.

The setup was similar to the one used in the prior experiments. The Smart car mock-up was replaced by a custom-made mock-up, while traffic dynamics and vehicle characteristics had a similar resemblance to actual driving.

Figure 8.1: Camera view of drivers in experiment 3. Based on this information, the co-driver indicated when drivers initiated a lane change.

Procedure

After being seated in the mockup vehicle, drivers received a pre-recorded auditory instruction as described in the previous section. In order to become accustomed to the task, a test drive was provided after which a second instruction was played that preceded the actual experimental trials. Each participant had twelve runs in which the vehicle started in the middle lane. The first part of each run was a free ride, for which drivers' only task was to stay in that lane. After a visual cue was presented that indicated the required lane change direction, drivers executed the necessary actions to ensure a safe lane change. When a lane change was accomplished, an auditory message prompted them to return to the middle lane. The time course for the present experiment is shown in figure 8.2. Each participant executed ten lane changes, while two default trials were added (in which no lane change was executed) in order to prevent bias. The conditions (lane change left or right and default conditions) were presented randomly for each participant. For each lane change, the co-driver's responses were logged. In order to compare its performance, three additional algorithms were used to infer the intention of a lane change based on the vehicle's position and steering wheel movement. These algorithms are explained in the next section.

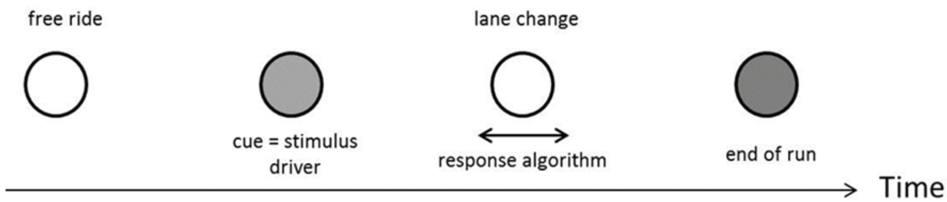

Figure 8.2: Time course for experiment 3. After a free ride, keeping the vehicle in the middle lane, drivers were prompted by a visual cue to initiate a lane change. Drivers were instructed to execute the appropriate actions that are required (i.e. looking into the mirrors and checking the blind spot) before applying the indicator and setting in the steering maneuver. Four lane change detection algorithms were used to infer driver intent, one being a human co-driver who observed overt driver behavior by means of video images presented on a monitor.

Experimental design and data analysis

For this study, no factors were varied in order to investigate potential effects on driver behavior. Instead, driver behavior served as the input for the evaluation of four lane change detection algorithms. The main independent variable is therefore the direction of each executed lane change. Depending on the performance of each detection algorithm, lane changes could be correctly or incorrectly inferred in terms of direction (left or right) and moment in time. The main dependent variable is the detection speed of lane changes by each of the four algorithms. Results were analyzed by applying a repeated measures design that included four algorithms (human co-driver, response trigger, lane change logged and lane change counter), their responses (reaction time, seconds) and lane change direction. This means that no driver data was analyzed. Trials in which responses were given after the vehicle had entered the next lane, or trials in which the detection algorithm responded faster than one second after the presentation of a driver's cue, were regarded as missed or anticipated responses, respectively. Trials in which the cueing direction did not correspond to the actual lane change direction were rated as incorrect responses. Together with the default trials (82 in total) and negative or missing values, these trials were discarded from data analysis. In addition, four incorrect co-driver responses were found and these runs were deleted from the data set. The total number of trials collected was 492 (41 subjects x 12) and the number of trials submitted to analysis was 397 (92.5%). The probability level for statistical significance was set at $p < 0.05$.

Lane change detection algorithms

WizardCounter. The human co-driver served as an alternative detection algorithm that inferred drivers' intent to change lanes by means of observing the driver's overt behavior. Available information was presented by a video camera placed above the driver (see figure 8.1 for an example). Given this camera angle, cues included body posture, head and eye movements, position of the hands and indicator use.

ResponseTrigger. The detection of a lane change by this algorithm was based on two conditions. First, similar to describing the start of a lane change in experiment two, a threshold value of 10 degrees steering wheel angle should be reached. Second, the difference between two preceding values of steering wheel angle (Δ angle) should be smaller than Δ angle at the moment of reaching the threshold (tx). This means that (Δ angle) between (tx) and (tx-1) should be larger than (Δ angle) between (tx-1) and (tx-2). For this, the algorithm traces back in time, searching for the moment at which (Δ angle) starts to increase, indicating the initiation of a lane change. When both conditions are met, a lane change detection is recorded.

LaneChangeLogged. During the free ride section of each run, the vehicle's lateral position on the road was recorded. The LaneChangeLogged algorithm was based on 1.3 x the maximum deviation from the mean value of this position. This means that as soon as the vehicle's position during the phase of lane changing exceeded this value, a lane change detection was logged.

LaneChangeCounter. This algorithm is based on the actual lane change. That is, as soon as the center of the vehicle crosses the lane boundary, a lane change is logged.

Dependent and independent variables

The main dependent variable detection speed (reaction time, seconds) reflected the time between the presentation of the driver's cue to initiate a lane change and the moment at which an algorithm detected a lane change. In addition, analyses were run to compare the differences between the moments of detection for three algorithms and the moment of an actual lane change. Main independent variable was the lane change direction (left and right).

Results

The first analysis compared the reaction times for all four algorithms. For this a 4 Detection Algorithm (WizardCounter, ResponseTrigger, LaneChangeLogged and LaneChangeCounter) x 2 Direction (Left vs. Right) repeated measures ANOVA was used. A main effect for Detection Algorithm ($F(3,38) = 1143$, $p < 0.001$, partial $\eta^2 = 0.99$) reflected differences in detection time between all levels. Pairwise comparisons for average reaction times showed that the co-driver (WizardCounter) detected a lane change 2.5 seconds after the driver was prompted to start a lane change. For ResponseTrigger, LaneChangeLogged and LaneChangeCounter these reaction times were 3.8 seconds, 4.4 seconds and 5.9 seconds, respectively. No differences were found between left and right lane changes (F(1,40) = 2.35, n.s.), although an interaction effect for Detection Algorithm and Direction reflected a change of tendency for detection based on LaneChangeLogged. This means that lane changes to the right were detected slightly faster (i.e. non-significant) for each algorithm, except for the algorithm based on the vehicle's position on the road, where this tendency was reversed. An overview of the detection performances is given in figure 8.3.

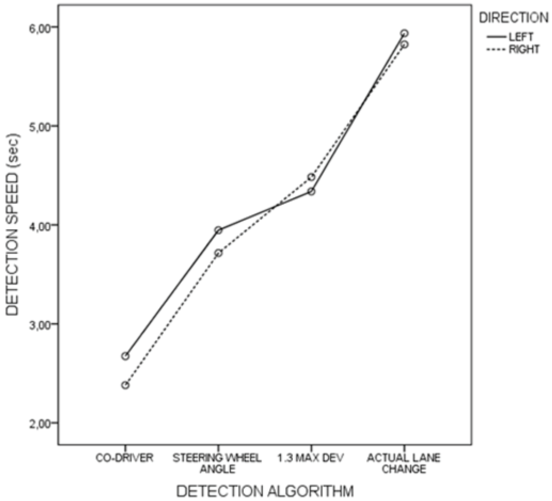

Figure 8.3: Performance of each lane change detection algorithm in terms of detection speed. These values represent the time it takes to infer a lane change after presenting a cue that prompts the driver to initiate the maneuver. From left to right, the levels of Detection Algorithm correspond to WizardCounter, ResponseTrigger, LaneChangeLogged and LaneChangeCounter, respectively.

The speed of detecting a lane change was calculated as the difference between the moment at which a driver receives a cue for initiating a lane change and the moment at which the algorithm detects such an initiation of a lane change. Since such a paradigm does not allow for specifying the exact moment of task execution by the driver (i.e. drivers need to process the information before starting a lane change), variations between drivers responding fast and drivers responding slow might obscure the algorithms' detection speed. In order to show whether potential variations in time between driver cue and driver response (initiating lane change) influenced these results, the time between a lane change detection and an actual lane change was compared for each algorithm. When a similar tendency is found, it can be concluded that possible variations in driver response are not the primary cause for the present results. Therefore, a second analysis tried to reveal whether the differences between the moment of detection and the moment of an actual lane change (LaneChangeCounter) showed a similar tendency as the difference between presentation of a driver's cue and the moment of lane change detection. For this, three additional variables were constructed. The first variable was the difference between co-driver's detection (A) and the actual lane change (D), represented by AtoD, the second variable was BtoD (ResponseTrigger, B to actual lane change) and the third variable was CtoD, representing the difference between LaneChangeLogged (C) and the actual lane change. Repeated measures ANOVA with three levels of the constructed variable (AtoD, BtoD and CtoD) showed a main effect ($F(2,39) = 210$, $p < 0.001$, partial $\eta^2 = 0.92$) which was reflected by differences for each level of comparison ($p < 0.05$). That is, pairwise comparisons showed decreasing values when comparing differences between a given detection algorithm and an actual lane change. The mean values for AtoD, BtoD and CtoD were 3.35 seconds, 2.0 seconds and 1.7 seconds, respectively. The length of time between each detected lane change and the occurrence of an actual lane change is shown in figure 8.4.

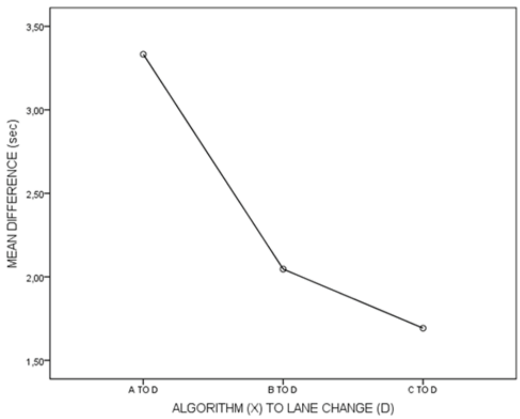

Figure 8.4: The time between each detection algorithm and an actual lane change was determined and showed a decreasing trend. The time between a co-driver detecting a lane change (A) and a vehicle's actual lane crossing (D) was, on average, 3.35 seconds. For the algorithms based on steering wheel position (B) and the vehicle's position on the road (C), these differences were smaller.

To put these results into perspective, pairwise comparisons between co-driver responses and the other levels of Detection Algorithm showed that for 397 trials the co-driver (WizardCounter) had 22 responses (5.5 %) that were slower than the algorithm based on the steering wheel position (ResponseTrigger). For these responses, the mean difference was 0.58 seconds. On average, the mean difference between both detection speeds was -1.3 seconds (WizardCounter minus Response-Trigger). When comparing the co-driver's performance with the algorithm based on the vehicle's position on the road (LaneChangeLogged), the co-driver responded 68 times (17.1 %) slower with a mean difference of 2.0 seconds for these trials. On average, the mean difference between WizardCounter and LaneChangeLogged was -1.9 seconds. For each trial, the co-driver was able to infer driver intent before an actual lane change (LaneChangeCounter) occurred. In the current setup, the mean advantage of using emulation as an alternative for simulating a lane change detection system is 3.35 seconds. This means that, on average, the human co-driver shows the ability to detect an upcoming lane change, 3.35 seconds before an actual lane change occurs.

Discussion

The aim of the present experiment was to establish a simulated setting that resembles the ability to predict a lane change maneuver. Here, a human co-driver served as a simulation alternative for such an ability. Results showed that such a feature can be established with relatively little effort, while its prospects and relevance might be valuable for investigating the feasibility of such a feature for future driver assistance systems. As was argued in the experiment's introduction, the surplus value of such a co-driver becomes apparent when the co-driver's strategies to infer driver intent are well understood. The experimental setting presented here is therefore considered as an initial impetus to initiate such research.

Regarding the choice of using one of the alternative algorithms based on steering wheel position (ResponseTrigger), it should be noted that Lee et al. (2004) reported that steering angle is not a sensitive measure for indicating a lane change. However, in the present study this information appeared to be a reliable and fairly predictive source for inferring a lane change. This observation might have been caused by two reasons. First, the steering data recorded in the study by Lee and colleagues showed a fair amount of noise and they reported that this was probably, among other things, due to road curvature, road irregularities and wind. Given an absence of such conditions in the simulated driving environment, this might have been the reason for less noisy data recorded in the present experiment. While this emphasizes the different nature of driving in a controlled environment, it also shows how detecting lane changes based on vehicle data becomes more complicated when driving in a naturalistic setting. Secondly, the algorithm used in the present study was not merely based on a threshold value of the steering wheel angle, because it was able to subsequently trace back the distinguishing characteristic of a lane change initiation. However, this calculation was performed at the end of each experimental run. This implies that such an approach is difficult to implement in a system that needs to infer potential lane changes in real time. For apparent reasons, this means that making calculations on real-time data is one of the difficulties that systems with inferring abilities are faced with.

While the co-driver was able to reveal the drivers' intentions to change lanes prior to an actual lane change, some comments should be made concerning its performance when compared to existing (automated) alternatives. First of all, given the instruction for drivers to perform preparatory actions (i.e. using mirrors and checking the vehicle's blind spot), it can be questioned whether the lane changes executed in the present experiment resemble drivers' behavior in a natural driving setting. While it can be concluded that driver behavior is an important cue for lane change prediction, in naturalistic driving it can be observed that drivers do not use their indicators for each lane change, nor do they show appropriate mirror glances before initiating such a maneuver (Lee et al., 2004). This means that the success rate reported in the present experiment might not be representative for inferring driver intent by a human co-driver when such study would be replicated in a naturalistic setting. Secondly, although the emulated version of a lane change prediction system was compared with several algorithms in order to reveal its potential, this approach does not allow for drawing any conclusions about the alternatives used in this study. While it was shown that, on average, a human emulator has the ability to infer driver intent 3.35 seconds before an actual lane change, since the alternative methods did not have access to overt driver behavior, comparing their performance in order to determine an optimum solution is therefore inappropriate.

Instead, given the difficulties of predicting lane changes solely based on vehicle characteristics, the currently presented approach revealed emulation as a valid and practical alternative when taking into account an overestimated success rate for detecting lane changes. By applying such an approach, it was shown how a human co-driver can be used to represent the perceptual and cognitive abilities of driver support with relatively little effort. Moreover, by integrating overt human behavior as a source of information, the present study argues for increasing the behavioral repertoire of driver support with the ability to infer driver intent based on overt driver behavior. Since currently available lane change detection systems, based on both vehicle and driver data, are faced with the difficulty to optimize their performance in terms of reliability and consistency (including success rate), it is concluded that applying a human co-driver might be valuable for improving the existing approaches. As already mentioned, increased knowledge about the cues that are used by human observers to infer the actions of others could be relevant for improving a system's cognitive abilities based on driver's overt behavior. That is, if such investigation shows how and by which means a human co-driver infers the (future) actions of drivers, the information could be used to implement co-drivers' strategies as a feature of driver support. However, despite the prospects of such knowledge, it should be recognized that the present study does not provide this information and that it remains unknown whether predictive cues can be specified by applying such an approach. Moreover, whether a human co-driver is able to infer driver intent reliably and consistently in a naturalistic driving setting, remains an open question. Therefore, additional research is required since little is known about how humans infer the actions of others, based on observing their movements. For example, while research concerned with the human ability to predict the behavior of others has found that intentions can be inferred from (subtle) body movements (Becchio et al., 2012; Stapel et al., 2012) and emphasizes the notion that actions of others are understood and predicted by observing kinematics (Gowen, 2012), explicit knowledge about those cues and strategies is currently lacking.

Nevertheless, while finding the information that is used by co-drivers to predict upcoming driving events has not been addressed empirically, the present experiment allows for posing some assumptions. For example, given the camera angle used in the present experiment (see figure 8.1), potential cues that reveal an upcoming lane change include eye gaze, head rotation, position of the hands and movements of the trunk, arms, hands and fingers. Following the protocol of the present experiment, kinematics that could reveal an upcoming lane change are related to the observer's basic assumption that each lane change is associated with applying the proper rules for initiating such a maneuver. This means that checking the mirrors, looking over the shoulder, applying the indicator and turning the steering wheel were all indications for which kinematics were observed by the co-driver. Given that the present study did not elaborate further on revealing co-drivers' strategies and cues for inferring driver intent, the question whether and how human co-drivers could contribute to the development and improvement of cognitive systems, requires further investigation. It is therefore suggested for future research to aim at gathering valuable information about which cues and strategies are used by humans to infer the intentions of others and their upcoming actions.

For example, such research could entail an experimental setup similar to experiment 3, in which co-drivers' eye movements are tracked in order to learn where observers are looking in order to infer the actions of others. When assuming that observers show strategies that are typical of predicting upcoming driving manoeuvres or actions, perceptual cues that are attended to by the co-driver could reveal the kinematics that correspond with a driver's intention to initiate a specific action. In this way, typical patterns of eye movements could emerge when specific driving tasks such as overtaking or changing lanes are related to distinguishing strategies as used by an observer for predicting upcoming actions. Moreover, data about the moment at which co-drivers report an upcoming action can be used to compare spatial information (eye movement data) and temporal information (moment of detection), which in its turn allows for investigating whether specific cues can be found that correspond to action intentions. When assuming that action prediction results from observing kinematic cues, such information can be gathered in a controlled and structured fashion, since the methodological approach allows for using pre-recorded video images. This means that the experimental setup is simplified substantially because video images can be reused and physical drivers are not required during the experimental sessions.

Moreover, since prior research proposed that the actions of others activate corresponding neuronal activation in the observer, such research could be expanded with collecting data about observers' brain activity. Because it is suggested that the human brain's parieto-frontal mechanism allows observers "to understand the action of others 'from the inside' and gives the observer a first-person grasp of the motor goals and intentions of other individuals" (Rizzolatti & Sinigaglia, 2010), brain imaging techniques could complement our knowledge about how and by which means action prediction is established. For example, when assuming corresponding neuronal activity in drivers and observing co-drivers, the kinematic information used by the observers could be extracted by recording neural activity in the relevant brain areas. This means that approaches as used for acquiring fundamental knowledge about the human brain, can be applied in a more practical domain such as the development of cognitive systems.

Within the context of finding the relevant cues for predicting upcoming driver's actions, it is therefore argued that co-drivers could be of surplus value when they become the subject of study. That is, if specific kinematic cues (such as eye-, hand- or head movements) are found that reveal drivers' intentions, specialized sensors could be developed to monitor these cues. Following the rationale of such an approach, a driver support system could be implemented with an ability to act on driver's overt behavior and human behavior could become a model for the potential features of future driver support systems.

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General discussion

As stated in the introductory pages of this thesis, the purpose of the present research is twofold. On the one hand, this thesis provides additional knowledge and insights about drivers cooperating with driver support systems. On the other hand, it provides a setting in which such cooperation can be established and used for research and design purposes. In this way, the current research aims to be of assistance for those involved in the design process of driver support systems and who are faced with the challenge to specify the behavioral repertoire and characteristics of future ADAS.

The theoretical sections of this thesis introduced the challenges of developing 'intelligent' driver support systems within a more general context of developing artificial cognition. By addressing the developments in the cognitive sciences, by reviewing the attempts to model the driving task and by introducing an overview of driver assistance systems most commonly available, it was shown how the current design practice lags behind the theoretical possibilities to provide for cooperative and cognitive support behavior that represents highly flexible and adaptive driver support.

In order to overcome the practical and theoretical limitations for providing cooperative driver support, an alternative approach is proposed. As a main characteristic of this approach, human co-drivers are used to rapidly prototype an envisioned support system. While such an approach has been described for simulating several interactive systems in several different domains, it can be concluded that knowledge about applying emulation in the automotive domain currently lacks experimental results and a critical review. The experiments described in this thesis are therefore set up in order to provide for additional insights and knowledge about the requirements for such an approach. The general framework of emulation as a tool for studying and designing cooperative driver support systems has been addressed for three potential applications, which are discussed next.

Emulation as exploration tool

Following the ability to rapidly prototype human-machine interactions, in the automotive domain emulation has previously been adopted as a technique for establishing, exploring and evaluating interactions between drivers and support systems (e.g. Biester, 2005; 2007; Lathrop et al., 2004; Schieben et al., 2009). In this way, mimicking driver support systems allows for representing support behavior without having to implement the entire system in detail. Although emulation has been recommended as a valuable tool during the development of driver support, few experimental results are available about the requirements and limitations of such an approach. For example, the theater-system technique (Schieben et al., 2009) has been applied in several projects dealing with vehicle automation and might therefore be regarded as a validation of emulation by itself. However, a critical review and an objective evaluation of emulation as a valid alternative for conventional simulation techniques, is currently missing. Given that emulated driver support tries to mimic a fully implemented setup, human co-drivers are required to provide driver support similar to an automated version. In order to validate emulation, Schmidt and colleagues (2008) showed how emulated driver support is experienced the same as an actual implemented system in terms of subjective system evaluations. While Schmidt et al. (2008) provided for a validation study with subjective ratings, two questions remained unanswered. First, to what extent does the co-drivers' support behavior vary between replications? And secondly, are potential variations in co-drivers' behavior responsible for different objective driver responses?

In the present research, experiment 1 was set up in order to provide for a validation with objective measurements, assuming variation in terms of co-drivers' timing and accuracy, while measuring the potential effect on drivers' response times. For this a driving task was employed in which drivers received a directional precue on the steering wheel, which indicated the safe direction in case of a required lane change. The results show that, although the emulated and automated support versions differed in terms of timing, this was not reflected by different driver responses. Since drivers responded to both versions in a similar manner in terms of response times, it can be concluded that emulating a support system as applied in the current experiment is a valid simulation approach when exploring driver-vehicle interactions at an early phase of development. However, while this experiment provided an additional validation of emulation as an exploratory tool for designing driver support systems, several limitations can be appointed.

First of all, since the current setup does not allow for logging the force, amplitude and duration of the steering wheel movements, it remains unknown whether and to what extent these variables (defined as accuracy) showed variation within and between support versions. Moreover, due to this lack of information, it remains unknown whether potential variations in terms of accuracy relate to the aspect of timing. For example, early precues in the emulated version might have outweighed potential differences in e.g. force and duration of the haptic feedback, provided in the automated version. While potential differences in accuracy did not have an effect on drivers' response times, they become increasingly relevant when an explored emulated support version needs to be specified in more detail in order to be converted into an automated version. It is therefore recommended for future applications of emulation to control and record both input (emulator) and output behavior (driver) with those variables that are associated with the devices controlled by the drivers and co-drivers. For example, when using a steering wheel, important information in order to replicate and characterize the behavior of drivers and co-drivers is gathered by logging the events that are responded to, together with the characteristics of the steering wheel movements such as timing, duration, speed, acceleration, force and rotation angle.

Secondly, although speculative since this question was not explicitly addressed in the current experiment, the presence of an experimenter might influence results when gathering subjective information. For example, several respondents were under the impression that driver support was triggered or brought about by the experimenter since the simulators' operating station was prominently present in the experimental setting. The reaction time paradigm was not related to such an assumption because driver responses were triggered by an event occurring in the driving scenario. Biased responses due to the mere presence of an experimenter are therefore highly unlikely. That is, when ensuring that the conditions in the test setting remain the same throughout the entire experiment, for each subject. Subjective ratings on the other hand, might be influenced by the experimenter's presence. More specifically, while drivers were kept unaware of the presence of co-drivers, questions referring to the nature of driver support (i.e. initiated by human or automated) might have been answered with the assumption that driver support was initiated by the experimenter, which in its turn might have biased the results of the questionnaire. In order to prevent biased responses when gathering subjective ratings and preferences, it is therefore recommended to separate the simulator's operator from the participants as well, similar to the separation of co-drivers and drivers. Moreover, and this concerns data gathering for behavioral experiments in general and collecting opinions and preferences in particular, researchers should be aware that participants might adapt to the task at hand by showing increased motivation to perform well in a given task or to provide for answers that are 'socially acceptable'. However, given that these considerations apply to each study or evaluation of driver support systems, a demand for careful interpretation of results is not only applicable to the use of emulation.

Thirdly, it is argued that the current study did not fully address the potential drawbacks of applying human emulation during ADAS design, since only a single type of driver support was used. While the differences between the emulated and automated versions of the present support system did not influence driver behavior in terms of reaction time, it remains an open question whether emulation can be considered as a valid approach for the entire range of available and conceivable types of driver support. For example, differences in performance envelope (e.g. speed and accuracy) between human co-drivers and automation should be recognized as they might limit the number of support behaviors suitable for emulation. That is, human limitations in terms of responding to a stimulus or limitations in terms of task precision could restrain the amount and types of support behavior that are suitable for emulation. It is therefore recommended to consider and determine the limitations of emulation in advance when exploring the feasibility and functioning of driver support systems under development.

Emulation as simulation alternative

For the validation study in the first experiment, a precueing paradigm was used in order to explicitly address the consequences of assumed variations in co-drivers' timing. Since this allowed for studying an assumed effect of varying co-drivers' responses (i.e. timing of emulated support) on driver responses, the experimental paradigm and the corresponding support system revealed their ability to validate the use of emulation as a tool for exploring such warning systems. However, the precueing paradigm might not allow for the investigation of design alternatives since support characteristics can only be decided upon when they reveal an impact of the features that are manipulated during research. Since the setup used for the present research does not allow for determining the quality of the support behavior in full detail because data about force, amplitude and duration of the steering wheel movements are missing, the experimental paradigm was slightly changed in order to overcome these research limitations.

The second experiment showed how emulation can be used to evaluate design alternatives at an early stage of the development process without the need for fully implementing the system's abilities. In line with existing research, it was demonstrated how emulation was able to reveal the impact of specific design choices, such as mode of communication between humans and automation. However, in line with the application of emulation as an exploration tool, it remains unknown whether emulation is appropriate for evaluating the entire range of available and conceivable types of driver support.

Since it cannot be claimed that conventional simulation techniques do not allow for a similar evaluation of system functionalities, the distinguishing aspect of the current approach lies mainly in the prospects associated with the availability of the human factor, which are primarily the flexibility of the approach and the ability to mimic driver support that is not or difficult to simulate otherwise. More specifically, because prompting the co-driver to initiate a steering wheel movement was coupled to a predefined event in the driving scenario and potential variation in the timing of the support was kept to a minimum, establishing an emulated support setting in the present study highly resembles conventional simulation of driver support. Consequently, assuming that setting up such an evaluation with conventional simulation techniques asks for similar effort, the surplus value of emulation becomes opportune when a setting is needed where the innate characteristics and abilities of human co-drivers exceed the abilities of conventional simulation techniques. The demands and opportunities for applying such an approach are summarized in the concluding section.

Within the context of applying emulation as a research tool, it should be noted that the present research did not use an objective evaluation method that addresses the driver-vehicle system as a whole. To the author's knowledge, such a proven and validated methodology is not yet available and the present research was unable to provide for such a method. Given the claim that human-technology interactions should be seen from within a systems' viewpoint, currently used data collection, merely based on drivers' behavior, does not conform with the approach that is proposed in the current thesis, namely to evaluate the performance of the entire driver-vehicle system. It is therefore recommended for future research, when adopting a stance where human and machine are complementary resources within the driving task, to elaborate on the possibility to evaluate ADAS in terms of a unified driver-vehicle system, e.g. by assessing the quality of cooperation (cf. Skjerve & Skraaning, 2004) between the human and automated components of the system or by evaluating the impact of design choices on the entire system's performance, as proposed by Schollier et al. (2011). Due to a limited understanding of the underlying mechanisms of crash causation (Aust & Engström, 2011) relating design choices with safety might be problematic. Providing a method for objective evaluation of driver and vehicle cooperation (i.e. Quality of Cooperation) could therefore be a valuable tool when adopting a systems' stance.

Emulation as model for support behavior

While having a more exploratory nature, the final experiment showed that human co-drivers can be regarded as a flexible and efficient alternative for producing cognitive support behavior. In this experiment a setting was established in which a human co-driver served as a simulation alternative for a system that infers the intentions of the driver. Although it was argued that it is inappropriate to compare the performance of this emulated system with available alternatives, results showed how driver support could benefit from increased cognitive abilities such as inferring drivers' intentions. In this way, the present emulation approach allowed for the observation that driver support becomes more adaptive and proper support can be given sooner.

Assuming the potential value of a human co-driver to serve as a template for systems' increased cognitive abilities, the present approach contributes to the development of systems that resemble the inherent human ability to infer others' actions and intentions. Such an approach allows for expanding the behavioral repertoire of driver support with skills like monitoring and inferring driver behavior. Theoretically, the ability to infer driver status and intent would allow for flexible and adaptive systems, partly overcoming the problems that are faced when support behavior is fully determined at design time and which is rigid by nature. However, in order to apply human co-drivers as a design feature, one should take into account that such an approach requires a great deal of knowledge about the specific characteristics of the human behavioral repertoire (e.g. kinematics, timing and accuracy). That is, in order to fully characterize the automated support behavior, one needs to monitor an extensive amount of factors that might contribute to the human ability of action understanding. It is therefore argued that the application of emulation as a model for future support behavior is only feasible when the relevant parameters for monitoring and inferring driver behavior, such as hand, foot or eye movements, are delimited in advance. The development of dedicated and easy to use software and hardware for behavioural monitoring are therefore important conditions in order to fully exploit the benefits of emulation as a tool for exploring and prototyping human-computer interactions. More specifically, for emulation to be effective, those designers applying it must be able to bridge the gap between the emulator's role and actual system implementation (Dow et al., 2005). This means that when emulation is used as a tool for prototyping HCI applications in progress, the setup should allow for easy and complete translation of emulator behavior into system properties.

Requirements and limitations of emulation

Theoretically, driver support systems have the ability to act on an infinite amount of information, ranging from vehicle dynamics to contextual information about the car, the driver and the driving environment. Evidently, human emulators are confronted with limitations regarding the nature and amount of such information for which proper responses are called for. While these limitations are difficult to specify in advance and depend on specific situations and individual differences, they cannot be disregarded when emulation is considered for design and evaluation purposes. Since the current research did not address the full potential of emulation empirically, the 'boundaries' of such an approach are discussed next by considering the requirements and limitations of applying emulation as a tool for developing ADAS.

Concerning the requirements for emulation, it can be said that they are subject to the purpose of applying such an approach. However, while different purposes might require a dedicated setup, as a general requirement it is recommended to record the input behaviors of both drivers and co-drivers as accurately as possible for the entire range of driving actions that are associated with the driving task under investigation. When assuming that vehicle data is available through the program that runs the driving simulation, acquiring additional data about the participants' actions increases the possibilities of both describing the characteristics of emulated support as well as evaluating the simulated support system at hand.

On the one hand, it is proposed to gather the typical features of specific driving actions, such as steering wheel movements, in order to capture co-drivers' behavior. When such information is recorded, replicating the input of co-drivers is simplified and increases to do so with the amount of characteristics that are known. In this way, early explorations and iterations of co-drivers' behavior can be converted with relative ease into a preprogrammed protocol that runs an algorithm based on this information. The value of such information becomes apparent when considering that the functionalities of simulated driver support can be expanded progressively. In line with the previous statement that human co-drivers are limited in terms of perceiving and acting on relevant information, an emulated setup could progress into a more hybrid form in order to release co-drivers from certain tasks, while presenting them with others. This enables controlling the task difficulty for emulators while the simulated support system can be added with additional properties. For instance, when simulating a driver support system that uses information about vehicle status, such as position on the road, as well as contextual information, such as traffic situation, the simulated system could be configured as partly human and partly automated. Such a hybrid system or *bionic wizard* (as coined by Fraser & Gilbert, 1991) could use pre-programmed algorithms for monitoring and acting on vehicle status while emulation is applied for the ability to monitor and assess the situation inside and outside the vehicle. For example, such an approach could represent a support system in which a lane departure warning (LDW) or a lane keeping system (LKS) is automated, which subsequently enables the human co-driver to focus entirely on monitoring contextual information. This not only limits the cognitive efforts placed on the co-driver, such a configuration covers adaptive support behavior as well, since the system can be fed with relevant information gathered by the co-driver about whether and which support is appropriate. Accordingly, given different potential configurations between humans and automation, driver support systems can be represented in a progressive and adaptive fashion and allows to combine fixed (and perhaps well established) algorithms with the less well understood abilities of human co-drivers. It is therefore argued that future research could benefit from dedicated software packages that allow for logging both the presented support and the recipients' behavioral characteristics in detail in order to serve as valuable information when hybrid forms of simulation are required.

On the other hand, evaluating design choices benefits from the ability to expand the range of variables that are expected to reveal or reflect the effects of specific support characteristics. Simply put, evaluating design choices is subject to the amount and quality of information gathered about the effects of those choices. While subjective evaluations and drivers' reaction times are able to reveal driver preferences and allow for a basic comparison between different support configurations, subtle and detailed information is needed when a support system needs to reveal its effects on detailed level. For instance, presenting drivers with haptic feedback on the steering wheel poses the question which effect those forces have on the driver's behavior. Although the vehicle's position on the road contains relevant information, having access to detailed information about the steering wheel movements might answer specific questions such as whether and to which degree counterforces are applied by the driver. Having the ability to address such issues at an early stage of the design process could be valuable since such information might lead to conclusions about the safety and efficiency of specific design choices. As an example, evaluation based on such information could lead to optimizing the characteristics of force feedback at an early stage of development, but it might lead to radical choices such as changing the support modality as well. The possibilities for describing and evaluating or fine tuning support characteristics therefore increase when the range of relevant variables is sufficiently available.

Apart from the argument that data about participants' input behavior is required in accordance with the purpose of applying emulation, it is recommended to consider the degree of simulation fidelity that is needed. That is, one might consider questions such as to what degree simulated driving should correspond to actual driving or whether a naturalistic driving setting is required. In this context, at least two applications of emulation can be distinguished.

First, for an approach in which emulation is used for comparing drivers' behavior, a basic resemblance with real driving (low to medium fidelity) should be sufficient, given that the experimental conditions remain the same for each participant. In contrast, a naturalistic driving setting (e.g. emulating driver support in an actual vehicle, as used by Schmidt et al., 2008) or a high fidelity simulation could be required when such comparisons are strongly related to vehicle dynamics or to subtle environmental details and changes. However, while increasing such details improves the simulator's fidelity, it should be taken into account that setting up a simulated environment takes a lot of effort to resemble actual driving situations. Whether such effort is required therefore depends on the driving conditions under investigation. Nonetheless, within the context of comparing the influence of specific design choices at an early stage of development, it should be sufficient that the support characteristics represent the envisioned driver support correctly and that the driver support is representative for its intended use. Unless detailed vehicle dynamics or contextual characteristics are specifically demanded, it is argued that, in general, low to medium simulations allow for evaluating design choices based on comparing alternatives.

Second, when aiming to improve the cognitive abilities of driver support by investigating the cues and strategies as used by human emulators, potential differences in simulated and actual driving should be taken into account as well. Following the suggestion that emulation could reveal such valuable information, it should be acknowledged that a naturalistic driving setting might evoke a different pattern of overt behaviors in drivers. That is, while a controlled experiment could yield a specific sequence of driver actions for a specific driving task, given a lack of controlled variables and specific instructions, drivers in a naturalistic setting might behave quite differently from those engaged in an experimental setting. Moreover, since the safety and efficiency of cognitive support is related to the amount of false alarms, information gathered by investigating co-drivers' observations should be conceived with reservation. That is, while studying the means and strategies as uses by co-drivers could generate important knowledge about how to increase the cognitive abilities of driver support systems, whether such knowledge is immediately suitable for equipping vehicles with such abilities, highly depends on whether driver intentions are predicted sufficiently reliable and accurate. Depending on the purpose of investigation, it is therefore suggested to consider in advance whether and to which degree a simulated driving environment should resemble actual driving or whether an actual driving setting is needed.

In the present research, emulation is proposed for both design and research purposes. However, in terms of the limitations of applying emulation, it should be considered that the efficiency and performance of specific tasks might differ for both humans and automation. While it is beyond the scope of the present discussion to present a detailed comparison between the perceptual, cognitive and action abilities of humans and automation, some general comments can be made.

First of all, humans have their limitations in terms of dividing their attention between different tasks. Monitoring, assessing and acting on different aspects of the driving task increase in difficulty with the amount of tasks that need to be dealt with. For example, when one needs to act on a predefined stimulus, responses are made with relative ease because humans are able to confine their attention to a single feature in the environment. However in multiple task conditions, performance and efficiency degrade because it becomes difficult to divide attention since the human brain has its own, albeit individual boundaries in terms of processing resources. Furthermore, when providing a human emulator with multiple tasks, it becomes harder to remember the specific instructions of these tasks. In addition, co-drivers might get distracted and tired during sessions. Given that healthy humans have no control over their perceptual abilities unless the role of individual senses is isolated, for example by intentionally occluding vision or hearing, emulation is prone to distractive or unexpected events. Unfortunately, knowing whether a co-driver was distracted or logging such events is difficult and therefore argues for controlling and observing the emulated environment as careful as possible. Furthermore, since emulators are susceptible to fatigue, their performance and efficiency could degrade over time, for example as reflected by increased reaction times or by carrying out a task less accurately. Automated support on the other hand, is able to process different dedicated algorithms at the same time, without being distracted by conditions for which they are not meant to act on. Importantly, computers do not get tired and it's safe to say that they are dedicated followers of directions. Moreover, when additional sensors or processing power is needed for an increased amount of functions, such an extension can be realized in accordance with the demand. Evidently, humans do not have such an ability.

Secondly, emulation is confronted with the notion that humans are confined in their ability to monitor and assess situations. While humans can achieve beliefs and assumptions based on direct observations, without being provided with the aid of dedicated instruments they are unable to verify such assumptions. For example, while noise, vibration and contextual cues are relevant sources of information for inferring a vehicle's speed, without any aid or reference, such metrics cannot be obtained directly. This means that human co-drivers can only rely on basic assumptions, while they are unable to specify their observations on a detailed level of measurement. That is, unless they are provided with the proper means to do so, for example by using dedicated measurement instruments such as speedometers.

Such confinements have several implications for the use of emulation during ADAS design and evaluation. First of all, it constraints the range of support functionalities that can be adequately emulated. Following the classification of ADAS based on their behavioral repertoire, as presented in chapter 3, representing lateral and longitudinal support should be conceivable for the entire range of behaviors, being informing, warning, advising and co-controlling the vehicle. However, given that human co-drivers might lack a sufficient level of performance and accuracy when compared to automation, interventions that are time critical could pose a problem for emulation when required reaction times are not within the performance envelope of humans. For example, in case of unexpected events, time critical situations might occur in which an emulator cannot provide a proper and timely response. Due to a speed-accuracy tradeoff, co-drivers might become less accurate when fast responses are required. For example, while haptic feedback on the steering wheel might be given fast enough in a time critical driving situation, responses (e.g. defined as co-drivers' steering wheel movements with a given angle or position) could become less accurate resulting in varying or improper feedback characteristics. Conversely, accurate response might be given at the expense of decreased response times. In terms of representing the ability to monitor vehicle and environment, emulation might pose some restraints as well. That is, while it is assumed that emulators can detect specific conditions such as status of vehicle signals and controls (e.g. indicators or steering wheel direction) or the presence of a pedestrian, they cannot specify information about vehicle movement and dynamics, such as yaw rate or braking force.

Furthermore, in line with the statement that humans are confined in their ability to monitor and assess situations, some general comments can be given regarding the application of emulation for research purposes. While the innate ability of humans to act on the behaviors of others is used in the present thesis as an argument in favor of emulation, such an ability is primarily based on the ability to monitor and infer overt behaviors such as movements of the head, trunk or hands. Despite the value and potential of such information, for example to infer driver intent, it is very unlikely that overt behavior alone reveals the conditions concerning a driver's mental state. This means that ADAS evaluation, for example by detecting the degree of cognitive load a driver is experiencing, might not be possible since humans do not have the ability to carry out psycho-physiological measurements without the aid of devices such as those recording EEG or heart rate. It is therefore assumed that an emulation setup, merely providing the ability to observe overt driver behavior, does not allow for relating design choices with their impact on driver's mental state.

However, hybrid systems, in which the functionalities of a driver support system are shared between humans and automation, could overcome these limitations. That is, known or potential limitations of human co-drivers could be compensated by automating part of the simulated support system. Stemming from the present discussion, such an approach could be valuable in at least two important ways. First, hybrid configurations between humans and automation allow for expanding the support functionalities progressively while being able to control the co-driver's task difficulty. Secondly, such an approach allows for presenting co-drivers with relevant information, which they cannot perceive or derive themselves directly. That is, provided that monitoring the relevant specifics about vehicle, environment or driver is technically feasible, such information could be passed on to the co-driver. Consequently, this allows for representing driver support systems in such a way that the human and automated components complement each other, while taking into account the strengths and weaknesses of both.

10

Conclusions and future prospects

When addressing system functionalities and evaluating the use of driver support at an early phase of the development process, the innate ability of humans to infer and act on others' behavior can be applied to overcome technical restraints or difficulties to generate perceptual and cognitive abilities. Assuming that technical infeasibility and potential difficulties typically become known while already establishing the system's functionalities in hardware and software, emulating (part of) the system's abilities allows for experiencing and evaluating the performance of a given system before spending time and effort in realizing the actual system abilities. Moreover, applying such a procedure can be beneficial and efficient when preliminary evaluation reveals system properties that are unsuitable and therefore calls for suspending or discontinuing further development. In this way, time and effort are spent on the optimal cooperation between humans and their support, instead of overcoming potential technical constraints associated with system properties that might eventually be evaluated as redundant or unsuited for further development.

In addition, emulation can be considered when a flexible procedure is needed for simulating a setting of drivers being supported by cooperative driver assistance. Such a demand is not only associated with the ability to represent system functionalities that are not or difficult to simulate otherwise, but is expressed by a general need for rapidly establishing and altering a cooperative support setting as well. In the present thesis flexibility refers to the ability for system designers to make technology decisions as the design iterates or while running an experiment. On the one hand, flexibility is expressed by evaluating driver support at an early development phase which allows for implementing expectations, preferences and requirements during iterative sessions by merely altering the co-drivers' protocol. On the other hand, system designers and researchers gain flexibility by having the opportunity to alter the systems' behavioral repertoire, for example in terms of timing, duration and intensity of driver support, without having to edit the software code.

Thirdly, when adopting the view of humans and technology interacting in a cooperative fashion, similar to socially acting partners, a setting is required that resembles driving as a cooperative and social act. By introducing a human co-driver who serves as a model for increased cognitive support behavior, such a social setting becomes available when one needs to investigate the interactions between drivers and support systems. In this way, such a setting can be used as a support tool for studying the problems and requirements associated with driver and vehicle cooperation and communication. For example, given the recent developments of introducing fully automated driving systems for low speeds, issues such as handing over control between driver and vehicle might be addressed in a simulated environment consisting of human drivers and co-drivers.

In the current thesis an appreciation has been expressed for the numerous efforts that are being made to develop intelligent vehicles. In order to contribute to these efforts, the present research addressed the significance and potential of applying emulation during the development of driver assistance systems. However, it is believed that the expectations about the potential safety impact of such systems should be addressed with some reservation. This is not because of any doubt concerning the progress that can be made in developing intelligent support behavior, but instead refers to the inherent flexible nature of the human factor, which means that anticipating and predicting how humans behave when interacting with (human or artificial) others is subject to inherent uncertainty. While the present research suggests emulation as a tool for rapidly prototyping driver support systems during design and research activities and therefore helps to reveal potential problems associated with driver-vehicle cooperation at an early phase of development, a certain amount of unforeseen implications of driver support systems will probably persist and should therefore be accounted for. That is, due to aspects like behavioral adaptation and the inherent flexible nature of humans, which manifest themselves only after hands-on experiences with driver support, predicting the specific impact of design choices is difficult. The problem of anticipating the interaction between the human and automated components of the driving task therefore remains an important challenge for future research.

A valuable contribution to the challenge of developing true cooperative driver support systems would be to increase the behavioral repertoire of driver support systems. In the present research it has been argued that a human co-driver contributes to improved cognitive and social abilities of future driver support. It was suggested how, for example, the ability to monitor driver status and to infer driver intent might increase the safety, efficiency and flexibility of driver support. By establishing a setting such as introduced in the current research, one could observe the social and inferring behavior of a human co-driver. Adopting such an approach could allow for a research setting where the co-driver becomes subject of study in order to find the relevant cues that reveal driver status and intent. In addition, this could increase our knowledge of how a relevant complementary action could be executed. Such insight and knowledge would empower OEMs or service providers to equip vehicles with the best possible support for drivers.

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Summary

Advanced driver assistance systems (ADAS) are systems that provide drivers with information and warnings or that even take over part of the driving task. In general, their aim is to contribute to the safety of driving. Given their ability to acquire relevant knowledge about the driving situation at hand and the subsequent responsibility to communicate or act on this information, they are instances of cognitive systems. However, finding ways to develop such systems is not an easy and straightforward problem since the safety and efficiency of the system, comprised of driver and vehicle, heavily depends on the cooperation between the human and automated components of the system. Moreover, while the driver support systems are intended to reduce the cognitive efforts placed on the driver, their impact could be counterproductive when the actions of the support system are not in agreement with the intentions of the driver.

The current research is embedded in a general aim to improve the safety of the driving task. For this, an ongoing endeavor in both the automotive and scientific community is to provide for cognitive support behavior that is able to anticipate potential hazardous situations through intervention strategies that take into account the vehicle's status, the traffic situation and the driver's behavior. However, when reviewing the attempts to provide for artificial cognition and for developing 'intelligent' driver support in particular, several problems can be appointed.

On the one hand, it can be concluded that the paradigms of cognition as discussed in this thesis are limited in providing the current design practice with straightforward design solutions and their potential implications. The cognitivist approach is a conventional method that defines the system's behavioral repertoire at design time. Since the behaviors or cognitive features of the system, which should be determined a priori, are the product of a human designer, system competences highly depend on the skills and knowledge of the developers involved. This means that the system's abilities are fully subject to the amount of foreseen or potential situations it will come across. The possibility to by-pass the difficulty of anticipating the entire system's behavioral repertoire is provided by an approach that enables the support system to adapt its behavior by learning from experience. In this way, the system learns by itself without the need for its developers to anticipate all possible situations and response solutions. However, such a system cannot be short-circuited into an advanced state of learned behavior and needs a unique developmental process to mature. Moreover, the self-organizing nature of such systems could lead to a situation where each individual vehicle develops its own particular way of problem solving.

On the other hand, it can be questioned whether the cooperative driving task and the requirements for establishing driver and vehicle cooperation are sufficiently understood for guiding the design process of driver assistance systems. For example, despite a general

acknowledgement for a unified driver-vehicle system for which the human and automated components might act in a peer-to-peer fashion, little consensus exists about how to establish and evaluate driver support that cooperates safe and efficient with the human driver. Moreover, it can be observed that developing artificial cognitive abilities and studying the requirements for optimal interaction with the driver are conducted in relative isolation and might call for interdisciplinary efforts to establish proper intervention at interface level. That is, while the efforts to develop cognitive systems that monitor and infer driver behavior have provided promising approaches to this end, evaluation of such abilities are typically limited to the performance and predictive power of the system, without addressing how and when the system should communicate or intervene. A general and ready to use approach for implementing or improving design choices according to ADAS evaluation is therefore lacking.

Given these limitations, an alternative approach is proposed that uses human co-drivers as a tool for developing advanced driver assistance systems. This approach of emulating the system functionalities of driver support by a human co-driver is characterized by rapidly prototyping or establishing a cooperative setting between drivers and the support system. By mimicking driver support, it is argued that design solutions can be explored and evaluated prematurely, while design alternatives can be compared without the need for fully implemented system functionalities. Furthermore, such an approach would allow for addressing issues concerning the potential of increased cognitive abilities for driver support even if such abilities are not yet technically feasible. Given the innate cognitive abilities of humans, it is believed that such an approach would contribute to the development of 'intelligent' driver support when the cues and strategies of a human co-driver are sufficiently understood.

In the automotive domain, the use of emulation has previously been adopted to explore and evaluate interactive driver support. However, little experimental results are available about the validity and requirements of such an approach. In order to contribute to the existing knowledge about applying emulation for the purpose of developing driver assistance systems, a validation study was set up in which an emulated and fully implemented support system were compared. By determining the moment at which driver support was given for both versions, it was investigated whether the potential differences between emulated and automated support had an effect on driver responses. Although it remains an open question whether emulation is a valid approach for each possible type of driver support, results revealed that an assumed variability in the emulated support behavior in terms of timing and accuracy should not be considered as a limitation for applying emulation, since driver responses were similar for both versions.

Given the potential for applying emulation as a simulation alternative, a second experiment was set up in order to investigate whether the use of emulation can be extended with the purpose of studying design alternatives. For this, driver responses in terms of subjective ratings and response times were compared between several support versions that differed in mode of communication between driver and support. While it cannot be concluded that the current setup allows for studying the entire range of available and conceivable types of driver support, research results showed that emulation was able to reveal the impact of specific design choices in line with existing research.

In an attempt to increase the cognitive or cooperative abilities of driver support and to provide for 'intelligent' vehicles, several initiatives have been set up to develop anticipative driver support that infers the intentions of drivers. In this way, driver support can be given in a fast and adaptive fashion. In order to explore the possibility of emulating driver support that predicts and infers driver intentions, a third experiment was set up in which human co-drivers served as a simulation alternative representing such ability. It was demonstrated how emulation allows for addressing issues concerning the potential of increased cognitive abilities for driver support, even if such abilities are not available or when they are difficult to simulate otherwise. In addition, it was suggested how human co-driver behavior could serve as a template for future assistance systems when knowledge and insights become available about the requirements of establishing cooperation between humans. Moreover, knowledge about how humans anticipate and understand the actions of others could be valuable for developing advanced driver assistance systems. That is, when the human co-driver becomes subject of investigation, emulation can be applied for studying their innate abilities in order to increase the anticipative and cooperative skills of future driver support systems.

Samenvatting

Bestuurdersondersteunende systemen (ADAS) zijn systemen die bestuurders voorzien van informatie en waarschuwingen en die zelfs een deel van de autorijtaak kunnen overnemen. In het algemeen zijn ze bedoeld om bij te dragen aan de verkeersveiligheid. Gezien hun vermogen om relevante informatie te verzamelen omtrent een bepaalde verkeerssituatie en gezien hun verantwoordelijkheid om die informatie vervolgens over te brengen op de bestuurder of te handelen in overeenstemming met de omstandigheden, zijn het voorbeelden van cognitieve systemen. Echter, het vinden van manieren om dit soort systemen te ontwikkelen is geen eenvoudige opgave omdat de veiligheid en de efficiëntie van het systeem, dat bestaat uit de bestuurder en het voertuig, sterk afhankelijk is van de samenwerking tussen de menselijke en geautomatiseerde componenten van het systeem. Daar komt bij dat, hoewel de ondersteunende systemen bedoeld zijn om de mentale belasting van bestuurders te reduceren, zij een averechts effect kunnen sorteren wanneer het systeem niet handelt conform de intenties van de bestuurder.

Het huidige onderzoek is te plaatsen binnen het algemene doel om de veiligheid van autorijden te verbeteren. Hiervoor worden in zowel de auto-industrie als de wetenschap

pogingen ondernomen om intelligente ondersteuning te ontwikkelen die in staat is om te anticiperen op potentieel gevaarlijke situaties. Dit doen zij door strategieën te bedenken waarbij rekening gehouden wordt met de toestand van het voertuig, de verkeerssituatie en het gedrag van de bestuurder. Echter, omtrent het ontwikkelen van kunstmatige cognitie en intelligente bestuurdersondersteuning in het bijzonder, zijn een aantal problemen aan te wijzen.

Ten eerste kan geconcludeerd worden dat de modellen van cognitie, zoals die in het huidige proefschrift behandeld worden, beperkt zijn in hun vermogen om de ontwerppraktijk te voorzien van duidelijke ontwerpoplossingen en hun mogelijke gevolgen. De conventionele of cognitieve aanpak definieert het gedrag van het systeem tijdens de ontwerpfase. Echter, omdat de gedragingen of cognitieve functies van het systeem, die op voorhand dienen te worden bepaald, het product zijn van een menselijke ontwerper, zijn de vaardigheden van het systeem op hun beurt sterk afhankelijk van de deskundigheid en kennis van de ontwikkelaars. Dit betekent dat de competenties van het systeem onderhevig zijn aan het voorzien van alle situaties die zich mogelijkerwijs kunnen voordoen. Het probleem van het op voorhand vastleggen van het gehele gedragsrepertoire van het systeem kan omzeild worden door een aanpak waarbij het systeem zichzelf gedragingen aanleert door het opdoen van ervaringen. Op deze manier leert het systeem uit zichzelf, zonder dat ontwikkelaars op alle mogelijke situaties en al het mogelijke gedrag moeten anticiperen. Een dergelijk systeem kan echter niet in een vergevorderde staat van aangeleerd gedrag komen, zonder zijn eigen unieke ontwikkelproces te doorlopen. Daar komt bij dat de zelforganiserende aard van zo'n systeem kan leiden tot een situatie waar ieder afzonderlijk voertuig zijn eigen specifieke manier ontwikkelt om met problemen om te gaan.

Ten tweede kan men zich afvragen of de coöperatieve rijtaak en de vereisten om een dergelijke samenwerking tussen bestuurder en voertuig tot stand te brengen, voldoende begrepen zijn om het ontwerpproces van bestuurdersondersteunende systemen van goede richtlijnen te voorzien. Bijvoorbeeld, hoewel het beeld van een bestuurder-voertuig systeem - waarbij de menselijke en geautomatiseerde componenten op een gelijkwaardig niveau opereren - algemeen erkend wordt, bestaat er weinig overeenstemming over hoe een veilige en efficiënte samenwerking met de bestuurder tot stand moet komen en hoe deze samenwerking geëvalueerd moet worden. Tevens kan opgemerkt worden dat de ontwikkeling van kunstmatige intelligentie of -cognitie en het onderzoek naar de benodigdheden om een optimale samenwerking te realiseren, in relatieve afzondering van elkaar plaatsvinden. Die situatie kan daarom aanleiding zijn voor een behoefte aan een meer interdisciplinaire aanpak om veilige en efficiënte bestuurdersondersteuning te ontwikkelen. Hoewel de pogingen om cognitieve systemen te ontwikkelen, die menselijk gedrag monitoren en interpreteren, veelbelovende methoden hebben opgeleverd, beperkt de evaluatie van zulke systemen zich in het algemeen tot hun prestaties en voorspellende vermogens, zonder aan bod te laten komen hoe en wanneer het systeem zou moeten communiceren en interveniëren. In een algemene kant en klare aanpak om ontwerpkeuzes door te voeren of te verbeteren aan de hand van ADAS evaluatie is daarom nog niet voorzien.

Gezien de genoemde beperkingen wordt er in het huidige proefschrift een alternatieve aanpak voorgesteld waarbij menselijke *co-drivers* of bijrijders worden gebruikt als middel om bestuurdersondersteunende systemen te ontwikkelen. Deze methode, waarbij systeem-functionaliteiten van bestuurdersondersteuning worden geëmuleerd, kenmerkt zich door een snelle realisatie van prototypes of een coöperatieve setting tussen bestuurder en het ondersteunende systeem. Door het systeemgedrag na te bootsen, wordt bepleit dat ontwerpoplossingen vroegtijdig kunnen worden verkend en geëvalueerd, terwijl het vergelijken van ontwerpalternatieven mogelijk is zonder dat daarvoor volledig technisch werkende systeemfunctionaliteiten nodig zijn. Daarnaast kan een dergelijke aanpak het mogelijk maken om kwesties omtrent een toename van cognitieve vermogens aan de orde te stellen, zelfs wanneer zulke eigenschappen technisch niet of moeilijk realiseerbaar zijn. Gezien de aangeboren cognitieve vermogens van mensen, kan deze aanpak bijdragen aan de ontwikkeling van intelligente systemen, mits de informatie en strategieën die een *co-driver* gebruikt, voldoende onderzocht zijn.

Op het gebied van autorijden is het gebruik van emulatie al toegepast om interactieve bestuurdersondersteuning te verkennen en te evalueren. Er zijn echter weinig experimentele resultaten beschikbaar betreffende de validiteit en vereisten van deze werkwijze. Om bij te dragen aan de bestaande kennis over het toepassen van emulatie in het kader van de ontwikkeling van bestuurdersondersteunende systemen is er een validatiestudie opgezet, waarin een nagebootst en een daadwerkelijk geïmplementeerd systeem met elkaar zijn vergeleken. Door vast te stellen op welke momenten de bestuurdersondersteuning in beide versies werd aangeboden, is onderzocht of de potentiele verschillen tussen nagebootst en geautomatiseerde support effect hebben op de reacties van de bestuurders. Hoewel het onduidelijk blijft of emulatie geschikt is voor iedere soort van bestuurdersondersteuning, tonen de resultaten aan dat een op voorhand veronderstelde variabiliteit in timing en nauwkeurigheid binnen het geëmuleerde gedrag geen belemmering is om emulatie toe te passen zoals dat is gedaan in het huidige onderzoek. De reacties van bestuurders voor beide versies waren immers gelijk.

Gezien de mogelijkheden die emulatie als simulatiealternatief biedt, is een tweede experiment opgezet om te onderzoeken of het gebruik van emulatie ook kan dienen om ontwerpalternatieven te bestuderen. Hiervoor zijn de reacties van bestuurders in termen van subjectieve beoordelingen en reactietijden vergeleken voor verschillende versies van ondersteuning die zich onderscheiden door de wijze van communicatie met de bestuurder. Hoewel niet geconcludeerd kan worden dat de huidige opstelling in staat is om alle denkbare soorten van bestuurdersondersteuning te bestuderen, tonen de resultaten aan dat emulatie in staat is om de impact van specifieke ontwerpkeuzes te openbaren, in overeenstemming met bestaand onderzoek. Verscheidenen pogingen zijn ondertussen ondernomen om intelligente bestuurdersondersteuning te realiseren die handelen op basis van aannames betreffende de intenties van bestuurders. Zo kan ondersteuning snel gegeven worden en kan de ondersteuning zich aanpassen aan de situatie. Om te onderzoeken of emulatie daarvoor gebruikt kan worden, is er een derde experiment opgezet waarbij een menselijke *co-driver* dienst deed als een simulatiealternatief waarbij zo'n eigenschap werd nagebootst. Dit experiment liet zien dat het gebruik van emulatie het mogelijk maakt om kwesties aan de orde te stellen omtrent een toename van cognitieve functionaliteiten, zelfs wanneer die functionaliteiten technisch niet voorhanden zijn of wanneer het moeilijk is om die cognitieve eigenschappen op andere wijze te simuleren. Daarnaast is voorgesteld, indien er kennis en inzicht beschikbaar komt over hoe zo'n samenwerking werkt bij mensen, hoe een menselijke *co-driver* kan dienen als een model voor toekomstige assistent systemen. Bovendien kan kennis omtrent de wijze waarop mensen de acties van anderen anticiperen en interpreteren waardevol zijn voor de ontwikkeling van bestuurders-ondersteunende systemen. Dat wil zeggen, wanneer de menselijke *co-driver* het onderwerp van onderzoek wordt, kan emulatie gebruikt worden om hun aangeboren eigenschappen te bestuderen met als doel de anticiperende en coöperatieve vaardigheden van toekomstige ondersteunende systemen uit te breiden.

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