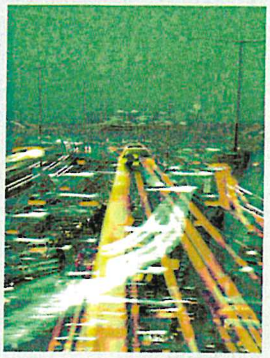
IEEE Intelligent Transportation Systems MAGAZINE

VOLUME 2 NUMBER 2
SUMMER 2010

FEATURES

DEPARTMENTS & COLUMNS

Digital Object Identifier 10.1109/MITS.2010.938162

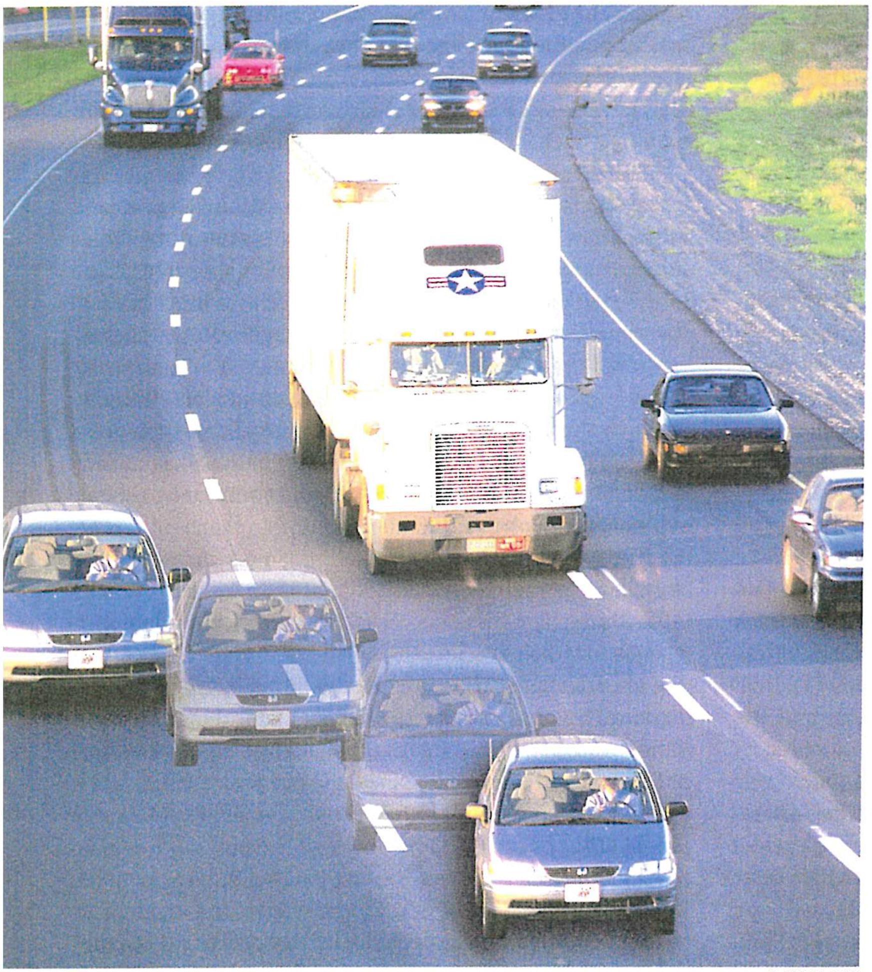


ON THE COVER:
© DIGITAL VISION

IEEE Intelligent Transportation Systems Magazine (ISSN 1939-1390) is published quarterly by The Institute of Electrical and Electronics Engineers, Inc. Headquarters: 3 Park Avenue, 17th Floor, New York, NY 10016-5997, USA +1 212 419 7900. Responsibility for the contents rests upon the authors and not upon the IEEE, the Society, or its members. The magazine is a membership benefit of the IEEE Intelligent Transportation Systems Society, and subscriptions are included in Society fee. Replacement copies for members are available for $20 (one copy only). Nonmembers can purchase individual copies for $88.00. Nonmember subscription prices are available on request. Periodicals postage pending. Postmaster: Send address changes to *IEEE Intelligent Transportation Systems Magazine*, IEEE, 445 Hoes Lane, Piscataway, NJ 08854 USA. Canadian GST #125634188 **Printed in USA**

SCOPE—*IEEE Intelligent Transportation Systems Magazines* publishes peer-reviewed articles that provide innovative research ideas and application results, report significant application case studies, and raise awareness of pressing research and application challenges in all areas of intelligent transportation systems and general information that is relevant to the IEEE Intelligent Transportation Systems Society, such as conference announcements, book reviews, and ITS-related standards.

Negative Behavioral Adaptation to Lane-Keeping Assistance Systems



© COMSTOCK

Abstract—In addition to the improvement of driving comfort, modern advanced driver assistance systems also aim to substantially increase traffic safety. Meanwhile, initial optimism with respect to potential safety gains has given way to a more critical view. There is, for example, a danger that continued use is associated with drivers systematically adapting their behavior to the new systems in a negative manner. According to theoretical considerations, excessive trust in such systems may lead to the development of a tendency for the driver to delegate safety-relevant aspects of the driving task to the system, which, in cases where system limits are reached, can result in the driver and other road users being endangered.

The present study examined this phenomenon in the context of lateral control assistance. In a field experiment, it was specifically investigated whether drivers who had become familiar with a heading control system developed excessive trust in the

(continued on page 22)

Felix Breyer, Christoph Blaschke, and Berthold Färber
Universitaet der Bundeswehr, Human Factors Institute, 85577 Neubiberg, Germany
E-mails: felix.breyer@unibw.de, christoph.blaschke@unibw.de, and berthold.faerber@unibw.de

Jörn Freyer and Reimund Limbacher
Audi AG, Driver Assistance Systems Department, 85045 Ingolstadt, Germany
E-mails: joern.freyer@audi.de and reimund.limbacher@audi.de

Digital Object Identifier 10.1109/MITS.2010.938533

1939-1390/10/$26.00©2010IEEE

(continued from page 21)

system and misjudged its limits. This question was addressed in a driving trial in which, unbeknown to the driver, the heading control system was repeatedly deactivated and the driver's behavior and lane control were observed. Analysis of subjective and objective data clearly demonstrated that drivers did not develop excessive trust in the system and accordingly regulated lateral control to a sufficient degree even after prolonged exposure to the system. Negative behavioral adaptation to the heading control system was thus not observed.

Keywords—advanced driver assistance system, lane departure warning, heading control, behavioral adaption, trust, lane keeping assistance.

1. Introduction

Adaptation to new conditions is one of the outstanding features of human intelligence. On a daily basis, we are confronted with problems which involve the selection and modification of acquired behaviors. In dealing with these problems, we continually search for solutions which are as simple and satisfying as possible. This adaptivity is also to be found among drivers in road traffic; a context in which it can have both positive and negative consequences.

The Organisation for Economic Co-operation and Development (OECD, 1990) defines behavioral adaptations within the total "driver-vehicle-environment" system as follows: "Behavioral adaptations are those behaviors which may occur following the introduction of changes in the road-vehicle-user system and which were not intended by the initiators of the change; behavioral adaptations occur as road users respond to changes in the road transport system such that their personal needs are achieved as a result they create a continuum of effects ranging from a positive increase in safety to a decrease in safety." (p. 23).

Behavioral adaptation has been investigated in numerous studies on advanced driver assistance systems. Sagberg et al. (1997), for instance, showed that drivers of vehicles with ABS (anti-lock braking system) chose smaller time lags between their vehicle and vehicles driving ahead as compared with drivers without ABS. Gains in safety due to improved braking performance were thus clearly lost through the selection of a smaller distance and a potentially earlier destination arrival. While the detailed accident analyses performed by Vaa et al. (2007) revealed that ABS generally reduces the number and severity of accidents, an examination of specific accident types showed partial increases for some types in comparison to vehicles without ABS. Such negative behavioral adaptations must be taken into account in the development of advanced driver assistance systems; there is otherwise a danger that, despite a theoretical gain in safety, assistance systems are actually of little or no use or even reduce traffic safety on a different level.

While ABS only intervenes in driving dynamics in critical situations, assistance systems in the domain of lateral control are now available which offer support on a far more frequent or even permanent basis. Lane departure warning systems (referred to in the following as LDW systems) alert the driver when the vehicle departs from the lane in which it has been moving. Upon approaching a boundary marking without prior manoeuvre indication, the driver's attention is attracted via either an audio warning or warning vibrations in the seat or steering wheel according to the specific system design.

Within a different approach in the field of lateral control systems, concrete instructions for action are provided rather than warning signals. Instead of generating direction-unspecific signals, the system applies steering torque to the steering wheel in order to lead the vehicle back to the centre of the lane. These "heading control systems" (referred to in the following as HC systems) are currently found in Lexus, Honda, and Volkswagen models. With respect to the form of support provided by such systems, a distinction is made between late intervention (i.e., shortly before lane markings are crossed) and continual guidance towards the centre of the lane.

Since the interventions of HC systems are considerably more perceivable and frequent than is the case with ABS, the probability that negative behavioral adaptation occurs may be even larger. For the analysis of this effect, the phenomenon of behavioral adaptation is first explained in detail before the positive effects of lateral control assistance and potential negative behavioral adaptations are discussed and the results of a study are presented.

2. Theory

2.1 Models of Behavioral Adaptation

Over the past 25 years, psychological theories have attempted to describe, explain, and predict driver behavior and, in particular, the phenomenon of behavioral adaptation (cf. Vaa, 2001). One of the most well-known theories is the risk homeostasis theory developed by Wilde (1982). This theory postulates that drivers constantly accept a certain degree of (accident) risk and strive to reach an individually optimal level of risk for the attainment of their goals. While driving, drivers compare the maximum level of accepted risk and the currently perceived level of risk and behavior adjustments are made in the case of discrepancies between the two. If the perceived level of risk exceeds the level of risk acceptance, then drivers attempt to reduce the perceived risk. If, for example, it begins to rain while a driver is on the road, perceived risk may be reduced by driving more slowly. If the level of risk is perceived to decrease, then the driver is prepared to modify his/her behavior in line with optimal goal attainment and in favour of greater objective risk.

It is important to ascertain that drivers do not excessively delegate safety-relevant aspects of the driving task to driver assistance systems.

Following Wilde's theory, further risk theories were developed which adopt different interpretations of risk assessment and perception and which also emphasize aspects of driver motivation (Fuller, 1984; Summala, 1988). In contrast, other theories not only focus on motivation but additionally include the driving task and aspects of performance, that is, drivers' skills and their self-evaluations (Summala, 1997; Fuller and Santos, 2002). The influence of personality attributes (Rudin-Brown and Noy, 2002; Brown, 2000) has also been discussed.

Despite extensive discussion, no model is currently available which is able to clearly predict behavioral adaptation. In addition to being partially too complex, existing models often possess a purely descriptive structure (Carsten, 2002; Rothengatter, 2002). However, all of these models feature one component which, while often taken for granted, has only been considered in more depth in Evans' human behavior feedback model (Evans, 1985): the perception and perceptibility of traffic-safety measures or, as the case may be, the effectiveness of driver assistance systems. According to Wilde's risk homeostasis theory (Wilde, 1982), introducing an assistance system causes drivers to experience a change in subjective risk and to subsequently adapt their behavior. The exact method used for subjective risk assessment remains unclear. It would, however, seem obvious that the perceived performance capacity of the system strongly influences the degree to which the system changes subjective risk levels and the extent to which the driver subsequently adapts his/her behavior. In contrast to Wilde (1982), Evans (1985) places particular emphasis on system feedback for the development of behavioral adaptations, proposing that clearly perceivable feedback is associated with a greater probability of adaptation.

Research from the area of automation expands upon these theoretical considerations. Studies by Muir (1994) and Muir and Moray (1996), for instance, showed that users' trust in the respective system primarily influenced the manner in which they monitored, intervened, and overrode an automated system. There are clear parallels between these findings and behavioral adaptation and the connection between system trust and driver behavior would seem obvious.

The development of trust in a system depends on various factors. Stanton and Young (2000), however, focus on the predictability and reliability of system behavior as a foundation for trust. If users have the feeling that they have understood the way in which the system operates and can anticipate individual system interventions, then they are able to rely more heavily on the system. If the system repeatedly shows the same behavior, then system trust increases further. It is on this basis that drivers begin to change their behavior and to delegate certain aspects of the driving task to the system.

However, this behavior does not always correspond with the objectively existing conditions. There is a danger that the user overestimates the capacity of the system and intervenes too late or not at all at the very point where the system reaches its limits (Parasuraman and Riley, 1997; Parasuraman, 2000). This problem can be applied to the use of lateral control assistance; the driver is in danger of paying less attention to driving due to excessive trust in the system. It is in those very situations where system limits are reached that a delayed driver reaction or a complete lack of reaction can represent a danger; such cases are a typical example of negative behavioral adaptation. The question thus arises as to how realistic drivers' "system trust" is in the case of lateral control assistance. Does the reliability and predictability of system behavior lead to excessive system trust, or are system users able to realistically assess the system's performance capacity?

2.2 Previous Studies on Lateral Control Assistance

In the following section, studies on lateral control assistance are reviewed. In addition to studies which have demonstrated the positive benefits of these systems, investigations on negative behavioral adaptation are addressed. Findings pertaining to LDW systems are presented first followed by studies on HC systems.

2.2.1 Objective Benefits and Subjective Assessments of Lateral Control Assistance

Evidence of objective benefits of lateral control assistance for car drivers has been provided by a number of simulation studies and field experiments.

Rimini-Döring et al. (2005), Kozak et al. (2006) and Navarro et al. (2007) investigated LDW systems in a driving simulator. In addition to a reduced number of lane departure events, they also found a lower standard deviation for the lateral position of the vehicle. The study conducted by Navarro et al. (2007) additionally employed haptic, direction-specific warning signals (similar to a heading control system) which proved to be superior to signals that were haptic and direction-unspecific as well as those which were acoustically delivered.

Portouli et al. (2006) examined LDW systems in a field experiment and also found a lower standard deviation for the lateral position as well as fewer lane departure events.

In two large-scale field studies performed by LeBlanc et al. (2006) and Alkim et al. (2007), the benefits of LDW systems were observed over a longer period of time and in naturalistic traffic settings. In the study by LeBlanc et al. (2006), 78 drivers each drove with vehicles equipped with an LDW system and a curve speed warning system for a period of three weeks. Participants' lateral control was considerably better when the system was active as compared to driving without assistance. Simultaneously, indicator use upon changing lanes strongly increased. Alkim et al. (2007) reported similar findings.

Similar studies employing HC systems have so far been rare. In a simulator experiment, Steele and Gillespie (2001) found improved lane keeping and reduced visual workload when using a HC system. Blaschke et al. (2009) conducted a field experiment in which drivers received varying support from a HC system during performance of a distraction task. It was shown that increasing support led to a reduction of the maximum lateral deviation of the vehicle from the middle of the lane.

A series of studies have provided estimates regarding the reduction in accidents and accident severity which would result from the introduction of lateral control assistance systems (Abele et al. 2005; McKeever, 1998; De Ridder et al. 2003). However, these studies ignore aspects of negative behavioral adaptation and instead refer exclusively to the theoretical benefits of such systems with respect to various types of accident. Their results are therefore to be interpreted with caution.

These studies were often accompanied by an assessment of participants' subjective judgments. Overall, the objective benefits with respect to improved lane keeping were also subjectively perceived by drivers using LDW and HC systems. Partial acceptance problems occurred in the case of LDW systems in connection with the emission of too many false warnings. For a detailed description see LeBlanc et al. (2006).

2.2.2 Negative Behavioral Adaptation to Lateral Control Assistance

To date, there is only a limited amount of empirical work providing information on negative behavioral adaptation in the context of lateral control assistance. A frequently cited study is that conducted by Rudin-Brown and Noy (2002). Based on experiments in a driving simulator and on a closed test track, the authors showed that participants' trust in an auditory LDW system still did not seem to decrease when a prolonged period of driving under distraction with an efficient error-free system was followed by confrontation with a system variant which regularly failed to warn the driver in critical situations. Although this generally did not have a negative impact on driving performance within the investigation, the authors concluded that assistance systems of this kind harbour the danger of encouraging "blind trust" and thus represent a potential risk for traffic safety.

A field study by Portouli et al. (2006) also failed to provide any evidence of negative behavioral adaptation in prolonged use of a LDW system. Participants drove along a preselected section of the motorway on several days. One group drove a test vehicle with an active LDW system and a second group a vehicle without lane keeping assistance. Group comparisons revealed no differences with respect to the selected speed of travelling or distance from the vehicles ahead. Furthermore, no group differences were found in the number of performed lane changes. Overall, the study thus provided no indications of negative behavioral adaptation.

Further mention is to be given to the study conducted by LeBlanc et al. (2006). The authors examined whether an LDW system caused drivers to engage in more secondary activities while driving. They analyzed video recordings of participants who had been provided with a test vehicle equipped with a LDW system for a period of several weeks. A comparison of episodes in which the LDW system was activated and deactivated revealed no frequency differences with respect to previously defined behavior categories (e.g., conversing, eating, drinking, using mobile telephone). This finding is in line with the above-mentioned studies, suggesting that no negative behavioral adaptation occurred. Even the additional activation of a curve speed warning system did not cause greater distraction of participants from the driving task through increased engagement in secondary activities.

Popken et al. (2008) employed a driving simulator to investigate the extent to which different variants of assistance impacted both performance in a distraction task and the gaze aversions necessary for task performance. Results clearly showed that neither a LDW system with vibrotactile warning signals nor an active lane-keeping HC system caused participants to engage in more frequent or longer gaze aversion.

The literature review presented above clearly shows that the issue of negative behavioral adaptation in the area of lateral control assistance has seldom been subject to experimental investigation. Only a small number of studies of this kind are to be found and these have primarily focused on LDW systems. Investigations on negative behavioral adaptation to lateral control assistance systems with active steering control (HC systems) are limited to those conducted by Popken et al. (2008) in a driving simulator.

3. Research Question

Since research work on HC systems has so far relied exclusively on experiments in driving simulators, the present experiment was designed to provide data on test drives in a real traffic environment. It was investigated whether users develop excessive trust in a HC system and overestimate the limits of the system following prolonged system interaction. In line with the above-described theories (see Section 2), this should lead to misuse on the part of the user and, in turn, to neglect of lateral control.

In this context, situations of particular interest include those in which the assistance system suddenly fails and can no longer assist the driver in matters of lateral control. In cases where the driver has neglected lateral control of the vehicle and has delegated a disproportionately large share of the driving task to the assistance system, critical driving situations can occur during such system periods. If the driver is additionally distracted from driving events by a secondary activity during system unavailability, then the risk may increase even more.

Even in modern versions, the video sensor technology which is employed in LDW and HC systems (see Section 4.2.1) is so far not able to guarantee permanent system availability. Accordingly, the system employed in the present study also showed brief sporadic periods of system unavailability (referred to in the following as *"temporary system unavailability"*) during regular driving (see Section 4.2.2). Furthermore and unbeknownst to the participants, the investigator was able to induce longer periods of system unavailability during which no lateral control support was provided[1] (referred to in the following as *"prolonged system unavailability"*).

These episodes of system unavailability allow the investigation of negative behavioral adaptation in a number of different ways. First, the user's driving behavior during temporary system unavailability caused by the video sensor technology can be retrospectively analyzed and examined with regard to negative behavioral adaptation. In this context, however, a problem arises in connection with the fact that such episodes cannot be triggered by the investigator; there is thus no possibility for experimental variation. In the present study, it was possible to specifically disable system support for the employed test vehicle, so that experimental variation was nonetheless possible. This leads to two main research questions for the current study:

I) What driving behavior do system users show during episodes of ***temporary system unavailability*** whilst distracted by secondary tasks?

II) What effects do periods of ***prolonged system unavailability*** have on the quality of lateral control when system users are distracted?

The varying durations of the two types of system unavailability represent different degrees of criticality. While episodes of *temporary system unavailability* constitute a normal part of regular journeys and offer relatively little opportunity for critical consequences of negative behavioral adaptation due to their limited duration, periods of *prolonged system unavailability* expand the timeframe in which critical consequences may occur and are thus more likely to give rise to the phenomenon under investigation. However, the risk associated with both types of system unavailability is that users with excessive trust in the system will tend to misuse the assistance system (see Section 2) and to find themselves in unfavorable driving situations due to the neglect of lateral control. If there was negative behavioral adaptation, these situations should result in a decrease of lateral control and the maximum lateral deviance during the test drives would be expected to grow significantly in that case.

4. Methods

4.1 Participants

Presently, heading control is primarily available in middle-class, upper-middle-class, and luxury-class vehicles (e.g. Lexus LS, Honda Accord). To ensure that the attributes of the selected sample corresponded to those of a typical customer of such vehicles, only those participants who owned a vehicle in these classes were recruited. Furthermore, participants were required to have driven more than 10,000 kilometers in the last 12 months and to be above the age of 30 years. These additional criteria were employed with the aim of generating a random sample of experienced drivers. Based on these criteria, 30 participants (5 female) were selected.

4.2 Test Vehicle

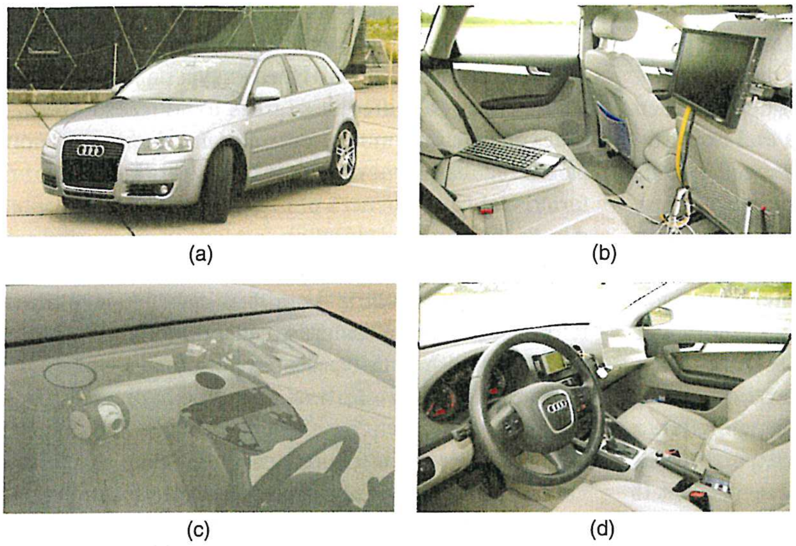
The test vehicle used in the experiment was an Audi A3 Sportback with an automatic gearbox. The car was equipped with low-profile sport tyres (225/40R16). While participants steered the vehicle, the investigator operated the measurement computer from the rear of the car and monitored the situation for safety issues (see Figure 1).

4.2.1 Video Sensor Technology

For lane detection, a video camera (CMOS) which was fitted with automatic exposure control and an aperture angle of 31° was mounted behind the interior rear-view mirror. Lane features were extracted and registered using an image processing procedure based on dark-light transitions of the lane surface; these features were subsequently used to determine the position of the vehicle. The camera had a

---

[1] Epsiodes of this kind during normal use are highly unlikely and served the sole purpose of allowing an examination of misuse on the part of the user during the experiment.



(a) (b)

(c) (d)

FIG 1 Test vehicle, Audi A3. (a) External view of the vehicle; (b) Investigator's operating environment; (c) Vehicle's video sensor technology; (d) Driver's cockpit.

maximum detection range of 60 meters. For the purpose of a retrospective classification of situations, a standard scene camera which targeted the area in front of the vehicle was also installed in the car.

4.2.2 Heading Control System

If the driver got too close to lane markings the vehicle's HC system generated corrective steering movements towards the centre of the lane[2] which could be clearly noticed by the driver. Corrective actions of the system depend on different factors such as speed, curve radius, lane width and steering angle. Steering torque is generated at a distance of approx. 40 cm to the lane boundaries. The driver was able to activate and deactivate the system using a button attached to the indicator. The system switched between an active and inactive mode according to the quality of the lane markings and other environmental factors, for instance narrow lanes or small curve radius. Moreover, the system temporarily deactivated itself when the driver steered against its steering torque and also during episodes, in which the driving speed was lower than 65 km/h. The system generated reliable steering torque when in an active mode and did not intervene in the driving activity when in an inactive mode. Since inactive episodes are not necessarily related to missing lane markings, video-based variables, such as lateral deviation and distance to the lane markings, could still be measured during these periods.

The driver was informed via yellow LED lights in the instrument panel *("temporary system unavailability")* as soon as the system became inactive. Otherwise, green LED lights were illuminated indicating system availability as long as the system was activated. This system interface is identical to that currently found in the Volkswagen Passat CC (Rohlfs et al. 2008) and was mounted in the test vehicle used here solely for investigative purposes. In the present study, the investigator was also able to suppress the steering torque generated by the system *("prolonged system unavailability")* so that no supportive steering movements occurred despite an allegedly activated system and illuminated green LED lights.

4.3 Experimental Design

4.3.1 Training

At the beginning of each trial, participants were provided with a brochure and supplemental verbal instructions in order to familiarize them with the operating principles of heading control. To ensure a basic level of routine in handling the test vehicle, participants subsequently took part in a special training course on a closed test track. The training included slalom manoeuvres and full brake application. Finally, participants were introduced to the telephone system component of the Audi Multimedia Interface (referred to in the following as HMI) for the purpose of practicing the subsequent experimental secondary task (see Figure 2).

4.3.2 Procedure

The test phase began immediately after completion of the training phase on a pre-selected route in normal road traffic. The route comprised 30 percent country roads and 70 percent motorway. Each participant covered a distance of 350 kilometers. The motorway sections of the route, which were straight for the most part, were comprised of two to three lanes. The country road sections consisted of narrow, winding episodes (approx. 20 kilometers) as well as of straight, broad sections (approx. 80 kilometers). On a pre-defined section of the motorway and country roads, participants were prompted to commence performance of a secondary task (see Section 4.3.3). This task was intended to distract the driver from the driving activity and to create a situation which, in the case of excessive trust in the HC system, should result in neglect

---

[2] The system implemented in the test vehicle thus operated on the basis of the late-warning system described in Section 1 and did not provide continual support.

of lateral control. The route was designed as a circuit so that the secondary tasks could always be performed on the same road sections. After completion of the last test drive, the investigator explained the actual objectives of the test to the participants.

(a) (b)

FIG 2 Secondary task and HMI of the test vehicle. (a) Position of the 25-digit number. (b) Rotate-and-press controller for operation of the speller function.

4.3.3 Secondary Task

The distraction task involved participants reading a 25-digit number series and entering it into the HMI using a rotate-and-press controller (see Figure 2). This type of distraction task was selected based on previous experimental studies (e.g. Blaschke et al. 2009) in which entering telephone numbers into a similar HMI was accompanied by a clear deterioration in the performance of lateral vehicle control. These studies have thus demonstrated the usefulness of such tasks for driver distraction.

To avoid practice effects, participants were given a new number series for each task. Number series were selected in such a way that numerical intervals between the digits were the same in each task. This ensured that each number series had the same level of difficulty. Each secondary task lasted 60 seconds.

Upon performing the first secondary task, all participants were familiar with the HMI to a comparable degree as a result of the previously conducted training (see Section 4.3.1). Each participant was reminded that traffic safety was of utmost priority during performance of the secondary task.

4.3.4 Test Drives Under Distraction in a Motorway Context

On the motorway section of the experimental route, participants were confronted with one secondary task during which the HC system was activated. During task performance, participants were required to stay in the right-hand lane (designated as the slow lane on German motorways) to refrain from overtaking and to predominantly focus on safely controlling the vehicle despite distraction. The right-hand lane of the motorway section used for this task was 3.60 metres wide and lane markings were, at the time of the experiment, optimally detectable by the HC system.

4.3.5 Test Drives Under Distraction in a Country-Road Context

On a section of the country road which was carefully selected according to various safety criteria (e.g., no potential collision objects at the side of the road, low traffic density, no oncoming traffic), participants performed three secondary tasks. This country road section of the route was winding, the participants had to pass through four stretched curves, of which two headed to the left whilst the others were right-hand turns. One of the secondary tasks was performed with the heading control system activated, as in the motorway context, and a further task with the system deactivated. Prior to a third distraction task, the investigator instructed the driver to activate the heading control in order to perform the final task with system assistance[5]. During this task, however, and unbeknownst to the participant, the investigator suppressed all steering movements generated by the system. Despite suppression of steering torque, the green heading control warning light continued to signalize normal system availability to the driver (see Section 4.2.2). The country road section was also in a very good condition with respect to lane markings at the time of the experiment. The width of the lane was approximately 2.95 metres.

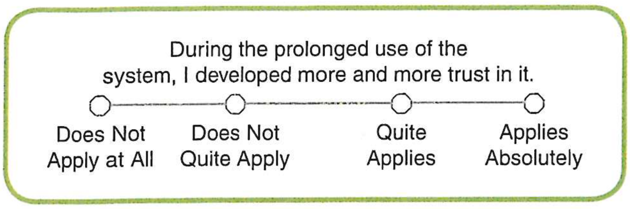
The processed data consists of 29 test drives with active heading control in the motorway context. Furthermore, the test drives in the country road context consisted of 29 test drives with prior deactivation of the system by the participant, 29 test drives with suppression of the steering torque by the investigator ("allegedly with hc") and 29 test drives with active HC system.

4.3.6 Measurement Variables and Experimental Factors

The computer installed in the test vehicle recorded various signals of the experimental car's Controller Area Network (CAN-Bus) during the experimental test drives, including current *lateral deviation* of the vehicle from the middle of the lane. This signal allowed subsequent computation of further variables. The *maximum lateral deviation* during a distraction task, for example, provides information regarding the greatest deviation of the test vehicle from the middle of the lane. This thus represents the moment at which lateral control has reached its most unfavourable point. Furthermore, the distance of the vehicle from lane markings can be calculated based on lateral deviation and *lane width.* For the purpose of addressing the research questions of the present study, analyses particularly focused on the *distance from lane boundary markings*, since the crossing of these boundaries at the very latest can be considered critical. In such cases, the driver has left the area intended for his/her vehicle and

---

[5] The order of the different types of system status had been randomized.



During the prolonged use of the system, I developed more and more trust in it.

○ Does Not Apply at All ○ Does Not Quite Apply ○ Quite Applies ○ Applies Absolutely

FIG 3 Example of item and scale design used in the experiment.

thus runs the risk of running off the road or into oncoming traffic. Another approach would be to define a critical area near the lane edges. The percentage of time that participants are driving in this area could theoretically serve as a measure for the quality of the lateral control. However, this approach does not account for individual differences in driving style. Some drivers prefer to stay on the right-hand area of the lane, whilst other drivers keep to the middle of the lane. Hence, there will always be some participants driving through the predefined area near the lane edges without actually showing a worse lateral control of the vehicle. The comparison of the maximal lateral deviation during test drives without heading control system and test drives with an allegedly active system control for these individual differences.

In addition to this essential measurement variable, other CAN variables were included into the measurement data in order to validate the results given by the maximum lateral deviation during the test runs. The *average speed* and the *maximum lateral acceleration* serve as additional indicators for a potential negative behavioral adaptation to the HC system. A faster and more dynamic driving style results in an increase of these variables and is interpreted as negative behavioral adaptation.

In addition to these objective measures, subjective measures were also assessed by means of questionnaires which were administered following the driving trials. These comprised questions on various system assessment dimensions, using a four-point scale for each item (see Figure 3). With regard to the present research objectives, one question on perceived system trust (i.e. "During the prolonged use of the system, I developed more and more trust in it") and two questions concerning user acceptance of the system (i.e. "In my opinion, the system increases roadworthiness"; "How did you perceive the system's corrective actions") were most relevant. Furthermore, participants were asked after the last test drive on the country road ("allegedly with hc"), if they had noticed anything remarkable during the last drive.

Table 1. Overview of measurement variables and experimental design for the country road context.

Independent Variables (System status)	Dependent Variables (CAN data)
Heading Control activated	Maximum lateral deviation (distance to lane boundary)
Heading Control deactivated	Average driving speed
Allegedly with Heading Control	Maximum lateral acceleration

Due to the fact that episodes of temporary system unavailability were system dependent and not triggered by the investigator (see section 3), no experimental design or ANOVA-relevant factors could be realized for the test drives in the motorway context. The systematic variation of the system status was performed on the country road and resulted in the experimental factors illustrated in Table 1.

5. Results

The data of the present study can be divided into two areas allowing an investigation of negative behavioral adaptation. These are data from brief episodes in which heading control was not available ("temporary system unavailability", see Section 4.2.2) and data from prolonged periods of system unavailability during which, unbeknown to the participant, the investigator suppressed all steering movements generated by the heading control system. Analyses of participants' subjective evaluations are based on the questionnaires administered following the driving trials.

5.1. Subjective Participant Evaluations

An analysis of the item measuring the *trust* which participants had developed in the heading control system failed to reveal a clear picture. While 42 percent[4] of participants reported a lack of complete system reliance even after prolonged driving, the remaining 58 percent reported positive system trust. A clear tendency was thus not apparent within the present sample.

Nonetheless, a large majority of the participants (approx. 77 percent) considered the system to represent an increase in safety and found the steering movements generated by the system to be useful (approx. 85 percent). This clearly reflects a high degree of *user acceptance.* Furthermore, the analysis showed that only one of the 30 participants noticed the prolonged episode of system unavailability during the last test drive on the country road. Consequently, the experimental simulation of an unrecognized interruption of the system activity can be considered successful.

5.2 Temporary System Unavailability

The analysis of periods of temporary system unavailability was based on data from a total of 58 test drives under distraction in a motorway and country-road context. Test drives were examined with respect to the occurrence

---

[4] With the purpose of giving a better overview to the reader, participants' answers on the four-point scales were classified as either positive or negative answers.

and duration of episodes of system unavailability as well as with respect to the maximum lateral deviation of the vehicle from the middle of the lane and the distance from the lane boundary markings. These features allow individual test drives under distraction to be classified into the following categories:

I) Test drives under distraction without temporary system unavailability

II) Test drives under distraction with temporary system unavailability

  II.1) Test drives under distraction with maximum lateral deviation during temporary system unavailability

  II.2) Test drives under distraction with maximum lateral deviation outside of temporary system unavailability

While the only difference between Categories I and II is the occurrence of temporary system unavailability, Category II.1. is distinct with respect to the fact that the point of maximum lateral deviation of the vehicle from the middle of the lane occurs in a period of temporary system unavailability. In these cases, lateral deviation is thus most unfavourable (i.e., largest) at a moment in which the assistance system is temporarily not available to the driver. As outlined in Section 3, these very cases represent the basis for investigation of the phenomenon of negative behavioral adaptation in the present study.

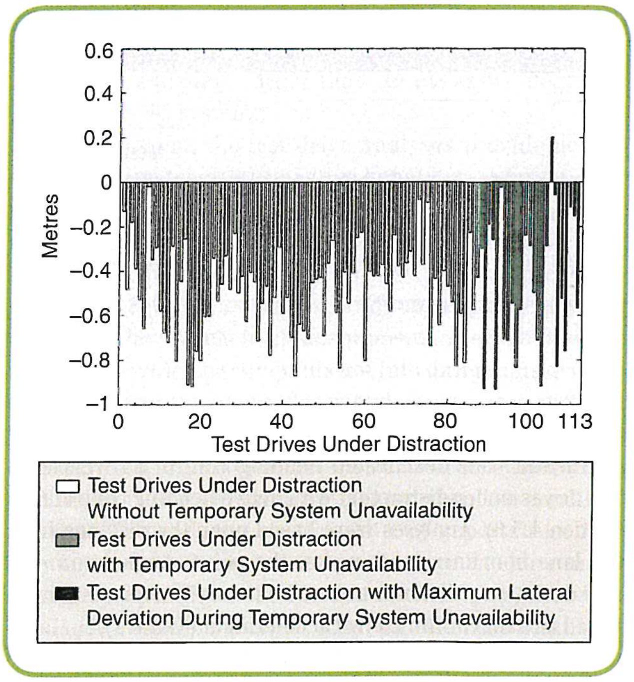


FIG 4 Distance from lane boundary markings in the case of maximum lateral deviation for all test drives under distraction.

Figure 4 provides an overview of those test drives under distraction in which heading control was activated. Each bar represents a single test drive and the shading of the bars signifies classification of the test drive to one of the above-mentioned categories. The diagram illustrates the maximum lateral deviation registered during each individual test drive. Distances crossing over from negative to positive values (zero baseline in diagram) represent cases in which participants had crossed the lane boundary markings. Accordingly, negative values reflect distances from the lane boundary markings to the middle of the lane and positive values distances by which the driver had crossed the lane boundary markings.

The majority of test drives were classified as belonging to Category I (light grey bars) and thus did not show episodes of system unavailability (n = 87). System unavailability[5] was, in contrast, registered at least once during 25 test drives (Category II.1., dark grey bars; and II.2., black bars).

A total of 8 test drives were classified as Category II.1. (black bars). As can be seen from the diagram, across all test drives, there was only one case in which the lane boundary markings were crossed (approx. 20 cm). During that incident the driver was gradually drifting towards the left side of the road and corrected the course shortly after crossing the markings for the first time. This clearly remarkable case belongs to Category II.1., which means that the situation arose while the heading control system was not available.

The analysis of temporary system unavailability thus reveals that temporary unavailability during test drives under distraction was not necessarily accompanied by critical driving situations. Only 1 of the 25 test drives in which heading control was unavailable for a short period of time led to the lane boundary markings being crossed.

The data on temporary system unavailability does not include a reference condition which allows an experimental comparison between distraction tasks with and without activated heading control. It is therefore, for example, not possible to determine whether a crossing of the lane boundary markings may also have occurred if the HC system had previously been deactivated. Accordingly, an experimental comparison would allow the question regarding potential negative behavioral adaptation to be more precisely addressed and would in turn lead to a higher generalisability of the findings. Such a comparison will be made in the following section on prolonged episodes of system unavailability.

5.3 Prolonged System Unavailability

For the analysis of negative behavioral adaptation, those test drives under distraction in which, unbeknownst to the participant, the investigator triggered selective periods of

---

[5] The mean duration of these episodes was 2.3 seconds.

Table 2. Means and standard deviations for CAN variables separated by system status.

	HC on		HC off		Allegedly with HC	
	Mean	SD	Mean	SD	Mean	SD
Distance to lane boundary (metres)	0.401	0.192	0.262	0.225	0.261	0.176
Average driving speed (km/h)	79.3	12.4	77.6	5.1	78.2	6.8
Maximum lateral acceleration (g)	0.13	0.05	0.14	0.02	0.14	0.04

system unavailability, were compared to test drives under distraction with deactivated heading control as well as to test drives under distraction with active heading control (see Section 4.3.6). Analyses were based upon the distance from the lane boundary markings at the point of maximum lateral deviation ("distance to lane boundary"), average driving speed and maximum lateral acceleration (Table 2).

Prior to statistical analyses the authors checked if the data met the assumptions for parametric tests. In order to examine potential interactions between the system status and CAN data, three one-way repeated measures ANOVAs were conducted. Mauchly tests indicated that the assumption of sphericity can be met for the variable "distance to lane boundary" ($\chi^2(2) = 1.39$, $p > 0.05$), whereas "maximum lateral acceleration" ($\chi^2(2) = 0.65$, $p > 0.05$) and "average driving speed" ($\chi^2(2) = 22.71$, $p < 0.05$) show a significance value lower than the critical value of 0.05. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.81$ and $\varepsilon = 0.62$, respectively).

The results of the ANOVAs show that neither the average driving speed ($F(1.25, 31.17) = 0.7$, $p > 0.05$), nor the maximum lateral acceleration ($F(1.62, 40.41) = 0.62$, $p > 0.05$) were significantly affected by the system status. Only the maximum lateral deviation differed significantly ($F(2, 50) = 8.56$, $p < 0.01$). Bonferroni post-hoc tests revealed that the test drives with active heading control ("HC on") resulted in a significant larger distance to the lane boundaries than did test drives without heading control ("HC off") and test drives with allegedly active HC. Both tests show significance values of $p < 0.01$. However, the distance to the lane boundaries did not differ significantly during test drives without heading control ("HC off") and test drives with allegedly active HC ($p > 0.05$).

6. Discussion

The present experiment was designed to determine whether and to what extent drivers develop excessive system trust accompanied by system misuse following prolonged interaction with a HC system. It was assumed that such negative behavioral adaptation may, in particular under conditions of distraction, lead to poorer lateral control.

To examine this assumption, 30 participants were invited to take part in test drives in regular road traffic. The test drives were carried out on a pre-selected test route, which consisted of motorway sections (245 km) and country road sections (105 km). The test vehicle employed was equipped with a HC system which supported the driver in lateral control of the vehicle by exerting active steering movements in the case of excessive lane deviation. On certain sections of the test route, participants were required to perform secondary tasks, each of which distracted the driver from the driving task for approximately 60 seconds. During these distraction tasks, various measures, including lateral deviation from the middle of the lane, were registered by the vehicle CAN bus.

If system users indeed delegate too great a share of the driving task to the system following a prolonged phase of becoming familiar with heading control, then this may lead to critically large deviations from the middle of the lane during episodes of system unavailability. To test this hypothesis, brief periods of system unavailability due to the operating principles of the sensor technology ("*temporary system* unavailability") as well as more extended episodes initiated by the investigator ("*prolonged system* unavailability") were analyzed with respect to their effect on the participants' driving behavior.

Neither temporary nor prolonged system unavailability led to critical driving situations in the test drives of the present study, with one exception. One participant briefly crossed the lane boundary markings during an episode of temporary system unavailability. All other participants correctly kept their vehicle in the respective lane. Even prolonged periods of system unavailability which, unbeknownst to the participants, were triggered by the investigator did not provide evidence of negative behavioral adaptation. Neither lateral control nor the average driving speed or the maximum lateral acceleration was impaired under these conditions. All variables of interest showed similar values to those during test drives that were conducted with a deactivated HC system of which participants had been informed. Nonetheless, appropriate to the general focus of HC systems, the lateral control has been improved during test drives with active heading control. During that condition, the test vehicle's position was more centred, which resulted in a lower maximum lateral deviation. This fact also demonstrates that the participants "made use" of the system and accepted its corrective actions. Moreover, they used the system as it was intended, which means that they interpreted its steering action as corrective interventions and did not misjudge the system as an "autopilot" for lateral control.

In interpreting these results, it is decisive that participants were not informed about the current system status during episodes of prolonged system unavailability. During these episodes, the green LED lights (see Section 4.2.2) continued to be illuminated and signalised to the driver that the system was active and ready for operation despite an actual absence of HC-system activity. On account of their previous experience with the system, participants thus found themselves in a situation in which they expected the system to intervene with steering movements if they deviated too far from the middle of the lane. If they had handed over lateral control of the vehicle to the HC system during this situation, then lateral-control deficits would certainly have arisen due to the fact that the system was not able to provide any form of support. Since lateral control in these situations did not differ from that measured during test drives with knowingly deactivated systems, it would seem that the users of the HC system did not develop an excessive and therefore a false sense of trust in the system and did not neglect the regulation of lateral control. Furthermore, system activity did not lead to a more dynamic or aggressive driving behavior, which could have been interpreted as negative behavioral adaptation, too. Maximum lateral acceleration and average driving speed did not show different values during test drives with active HC compared to test drives without HC. This fact indicates that the system did not provoke a change in driving style.

The analysis of temporary system unavailability reveals a similar picture. While drivers were informed about the lack of system activity provided that they glanced towards the yellow LED lamps (see Section 4.2.2) which were lit up during these periods, they were also distracted by the secondary task and were thus forced to alternate their glances between the HMI display of the vehicle and the traffic around them. Moreover, periods of temporary system unavailability had a mean duration of 2.3 seconds, so that the probability of glancing towards the LED lamps in the very moment of system unavailability can be considered to be very low. With respect to episodes of temporary system unavailability, it can thus be assumed that participants were actually also not informed about the lack of system activity. Nonetheless, these episodes did not necessarily lead to unfavourable lateral control or critical driving situations, which again implies an adequate rather than an excessive degree of trust in the HC system.

In conclusion, the test drive analyses provide no evidence of a tendency for negative behavioral adaptation to the HC system among the study participants. Even after prolonged episodes of driving in regular road traffic with the system, participants did not develop inappropriate, excessive trust in the system, and they regulated lateral control of the vehicle in an adequate manner. There were no cases in which participants got into dangerous driving situations and the above-described, single-case incident in which a participant crossed the lane boundary markings during a test drive under distraction also did not, according to reports of the investigator, result in a critical situation. Instead, the participant was reported to have duly noticed the deviation of the vehicle and to have made appropriate position adjustments. Summing up, concerns of misuse and over-reliance on automation as formulated by Parasuraman and Riley (1997) cannot be verified on the basis of the analysed experimental data.

Relating the clear absence of negative behavioral adaptation to a complete lack of trust in the HC system would not seem justified. More than half of the participants reported system reliance in the survey following the driving trials. This demonstrates that while many of the participants placed their trust in the HC system, they were able to judge its strengths and weaknesses correctly and thus did not succumb to the temptation of delegating too great a share of the driving task to the assistance system.

These conclusions concur with the findings of Popken et al. (2008) and expand upon this previous study by providing field-experimental data from a natural traffic environment. Based on the results of the study presented here, there is a necessity for future investigations to examine long-term effects of interaction with HC systems. Field studies with longer test drives are therefore required and may help to provide further insight into negative behavioral adaptation in the context of lateral control assistance systems.

About the Authors

Felix Breyer Dipl.-Psych. Felix Breyer studied Psychology at the Philipps-Universitaet of Marburg, where he graduated in 2007. Since the beginning of 2008 he is working as a researcher at the Human Factors Institute, Faculty for Aerospace Technology, Universitaet der Bundeswehr, Munich. His main research interests lie in the fields of human factors within advanced driver assistant systems and driver state recognition.

Christoph Blaschke Dipl.-Psych. Christoph Blaschke is working in the lane keeping assistance team at AUDI AG.

Berthold Färber Prof. Dr. Berthold Färber studied Psychology at the University of Regensburg, where he received his doctoral degree in 1980. Since 1989 he is professor of human factors studies at the Universitaet der Bundeswehr, Munich. Research topics: traffic safety, human factors for advanced driver assistance systems and robotics.

Jörn Freyer Dr.-Ing. Jörn Freyer is head of the development of lane keeping assistance systems at AUDI AG.

Reimund Limbacher Dipl.-Ing.(FH). Reimund Limbacher works for Audi as development engineer since 1990. He was responsible for the development of several driver assistance systems like adaptive cruise control and lane keeping assistance.

References

[1] J. Abele, C. Kerlen, S. Krueger, H. Baum, T. Geißler, S. Grawenhoff, J. Schneider, and W. H. Schulz. (2005). *Exploratory study on the potential socio-economic impact of the introduction of intelligent safety systems in road vehicles. Final report SEiSS* [Online]. Available: http://ec.europa.eu/information_society/activities/esafety/doc/call_4/final_seiss.pdf

[2] T. P. Alkim, G. Bootsma, and S. P. Hoogendoorn, "Field operational test 'The Assisted Driver'," in *Proc. Intelligent Vehicles Symp.*, Istanbul, pp. 1198–1203.

[3] C. Blaschke, F. Breyer, B. Färber, J. Freyer, and R. Limbacher, "Driver distraction based lane-keeping assistance," *Transport. Res. Board F: Traffic Psychol. Behav.*, vol. 12, no. 4, pp. 288–299, 2009.

[4] C. M. Brown, "The concept of behavioural adaptation: Does it occur in response to lane departure warnings," in *Proc. Int. Conf. Traffic and Transport Psychology*, 2000, pp. 4–7.

[5] O. Carsten, "Multiple perspectives," in *Human Factors for Highway Engineers*, R. Fuller and J. A. Santos, Eds. Oxford: Pergamon, 2002.

[6] S. N. de Ridder, J. Hogema, and M. Hoedenaeker. (2003). *The Dutch experience with lane departure warning assistant systems: A field operational test. TNO document TM-03C048* [Online]. Available: http://www.psychology.nottingham.ac.uk/IAAPdiv13/ICTTP2004papers2/ITS/deRidder.pdf

[7] L. Evans, "Human behaviour feedback and traffic safety," *Hum. Factors*, vol. 27, no. 5, pp. 555–576, 1985.

[8] R. Fuller, "A conceptualization of driving behaviour as threat avoidance," *Ergonomics*, vol. 27, no. 11, pp. 1139–1155, 1984.

[9] R. Fuller and J. A. Santos, "Psychology and the highway engineer," in *Human Factors for Highway Engineers*, R. Fuller and J. A. Santos, Eds. Oxford: Pergamon, 2002.

[10] K. Kozak, J. Pohl, W. Birk, J. Greenberg, B. Artz, M. Blommer, L. Cathey, and R. Curry, "Evaluation of lane departure warnings for drowsy drivers," in *Proc. 50th Annu. Meeting Human Factors and Ergonomics Society*, San Francisco, 2006, pp. 2400–2404.

[11] D. LeBlanc, J. Sayer, C. Winkler, R. Ervin, S. Bogard, J. Devonshire, M. Mefford, M. Hagan, Z. Bareket, R. Goodsell, and T. Gordon. (2006). *Road departure crash warning system field operational test: Methodology and results. Transportation Res. Inst.*, Univ. Michigan [Online]. Available: http://www.nhtsa.dot.gov/portal/nhtsa_static_file_downloader.jsp?file=/staticfiles/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2006/RDCW-Final-Report-Vol-1_JUNE.pdf

[12] B. B. McKeever, "Working paper: Estimating the potential safety benefits of intelligent transportation systems," FHWA, Rep. DOT F 1700.7, 1998.

[13] B. M. Muir, "Trust in automation—Part I: Theoretical issues in the study of trust and human intervention in automated system," *Ergonomics*, vol. 37, no. 11, pp. 1905–1922, 1994.

[14] B. M. Muir and N. Moray, "Trust in automation—Part II: Experimental studies of trust and human intervention in a process control simulation," *Ergonomics*, vol. 39, no. 3, pp. 429–460, 1996.

[15] J. Navarro, F. Mars, and J. M. Hoc, "Lateral control assistance for car drivers: A comparison of motor priming and warning systems," *Hum. Factors*, vol. 49, no. 5, pp. 950–960, 2007.

[16] OECD, Behavioural Adaptations to Changes in the Road Transport System. Paris: OECD Expert Group, 1990.

[17] R. Parasuraman, "Designing automation for human use: Empirical studies and quantitative models," *Ergonomics*, vol. 43, no. 7, pp. 931–951, 2000.

[18] R. Parasuraman and V. Riley, "Humans and automation: Use, misuse, disuse, abuse," *Hum. Factors*, vol. 39, no. 2, pp. 230–253, 1997.

[19] A. Popken, L. Nilsson, and J. F. Krems, "Drivers' reliance on lane keeping assistance systems. Effects of different levels of assistance," in *Proc. European Conf. Human Interface Design for Intelligent Transport Systems*, Lyon, 2008, pp. 301–310.

[20] E. Portouli, V. Papakostopoulos, F. Lai, K. Chorlton, M. Hjälmdahl, M. Wiklund, E. Chin, R. de Goede, D. M. Hoedemaeker, R. F. T. Brouwer, F. Lheureux, F. Saad, C. Pianelli, J.-C. Abric, and J. Roland. (2006). Behavioral effects and driver-vehicle-environment modelling: Assessment of variables: Integration (long-term phase test and results). AIDE—Adaptive Integrated Driver-vehicle Interface, Fraunhofer IAO, Sub-Project 1, Deliverable 1.2.4 [Online]. Available: http://www.aide-eu.org/res_sp1.html

[21] M. Rimini-Döring, T. Altmüller, U. Ladstätter, and M. Rossmeier, "Effects of lane departure warning on drowsy drivers' performance and state in a simulator," in *Proc. 3rd Int. Driving Symp. Human Factors in Driver Assessment, Training and Vehicle Design*, Rockport (Maine), 2005, pp. 88–95.

[22] M. Rohlfs, S. Schiebe, A. Kirchner, J. Müller, T. Kayser, M. Walter, R. Adomat, R. Woller, and C. Eberhard, "Gemeinschaftliche Entwicklung des Volkswagen 'Lane Assist'," in *Proc. der 24. VDI/VW-Gemeinschaftstagung - Integrierte Sicherheit und Fahrerassistenzsysteme*, Wolfsburg, 2008.

[23] T. Rothengatter, "Drivers' illusions-no more risk," *Transport. Res. Board F: Traffic Psychol. Behav.*, vol. 5, no. 4, pp. 249–258, 2002.

[24] C. M. Rudin-Brown and Y. I. Noy, "Investigation of behavioral adaptation to lane departure warnings," *Transport. Res. Rec.*, vol. 1803, pp. 30–37, 2002.

[25] F. Sagberg, S. Fosser, and I. A. Saetermo, "An investigation of behavioural adaptation to airbags and antilock brakes among taxi drivers," *Accid. Anal. Prev.*, vol. 29, no. 2, pp. 293–302, 1997.

[26] N. A. Stanton and M. S. Young, "A proposed psychological model of driving automation," *Theor. Issues Ergonom. Sci.*, vol. 1, no. 4, pp. 315–331, 2000.

[27] M. Steele and R. B. Gillespie. (2001). *Shared control between human and machine: Using a haptic steering wheel to aid in land vehicle guidance. Proc. Human Factors and Ergonomics Society 45th Annu. Meeting* [Online]. Available: http://www-personal.umich.edu/~brentg/Web/Conference/hfes01.pdf

[28] H. Summala, "Hierarchical model of behavioural adaptation and traffic accidents," in *Traffic and Transport Psychology: Theory and Application*, J. A. Rothengatter and E. Carbonell Vaya, Eds. Oxford: Pergamon, 1997.

[29] H. Summala, "Risk control is not risk adjustment: The zero-risk theory of driver behaviour and its implications," *Ergonomics*, vol. 31, no. 4, pp. 491–506, 1988.

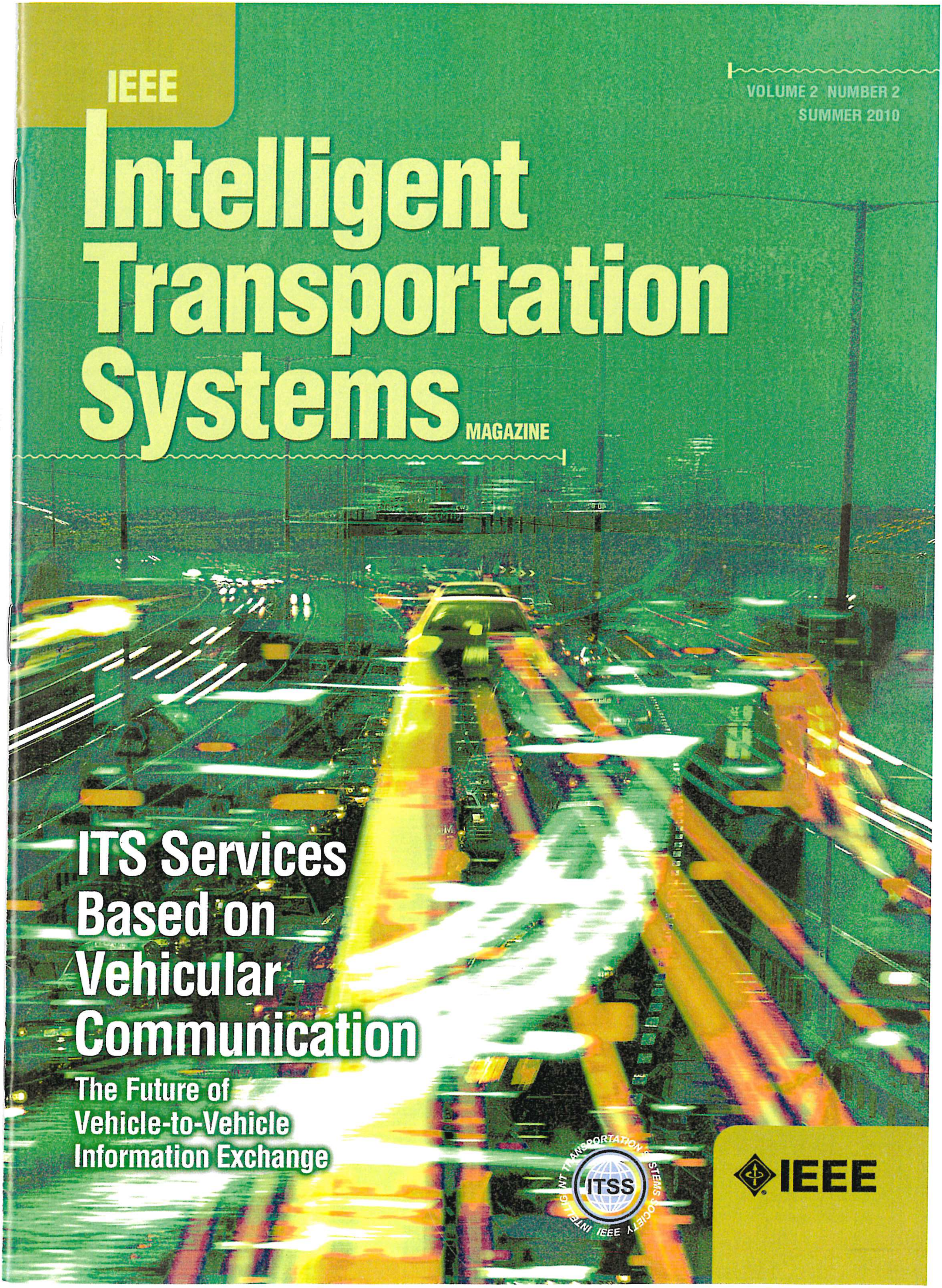
[30] T. Vaa, M. Penttinen, and I. Spyropoulou, "Intelligent transport systems and effects on road traffic accidents: State of the art," *Intell. Transport Syst.*, vol. 1, no. 2, pp. 81–88, 2007.

[31] T. Vaa. (2001). *Cognition and emotion in driver behaviour models—Some critical viewpoints. Proc. 14th ICTCT Workshop* [Online]. Available: http://www.ictct.org/dlObject.php?document_nr=225&/Vaa.pdf

[32] G. J. Wilde, "The theory of risk homeostasis: Implications for safety and health," *Risk Anal.*, vol. 2, no. 4, pp. 209–225, 1982.

VOLUME 2 NUMBER 2
SUMMER 2010

IEEE Intelligent Transportation Systems MAGAZINE



ITS Services Based on Vehicular Communication

The Future of Vehicle-to-Vehicle Information Exchange

ITSS
INTELLIGENT TRANSPORTATION SYSTEMS SOCIETY IEEE

IEEE