Effecting the driver's awareness: Options, bounds, limits

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Kurzfassung

Die Automobiltechnik wurde über Jahrzehnte entwickelt. Während dieser Zeit war die Realisierung eines sicheren und effizienten Fahrens immer bedeutend. Die meisten Hybridelektrokraftfahrzeuge (hybrid electric vehicles, HEV) bieten einen "Eco"-Antriebsmodus, der zur Verbesserung der Kraftstoffeffizienz beiträgt, indem das Fahrzeugübertragungsverhalten, die Beschleunigungscharakteristik, die Nutzung der Klimaanlage usw. beeinflusst werden. Neben den gestaltbaren technischen Randbedingungen hat auch das Verhalten des Fahrers einen großen Einfluss, z. B. auf die Kraftstoffeffizienz. Der Fahrer/die Fahrerin handelt individuell und dynamisch. Es erscheint daher sinnvoll, auch den Fahrer/die Fahrerin in geeigneter Weise zu unterstützen, um sich effizient zu verhalten. Das vollautonome Fahrzeug ist eine der vielversprechenden Verbesserungen in der Kraftfahrzeugtechnik der Zukunft. Für eine Übergangsphase vom konventionellen manuellen Fahrzeug zum vollautonomen Fahrzeug werden Fahrzeuge mit mehrstufigem autonomen Fahrverhalten entwickelt. Diese Fahrzeuge beinhalten verschiedene Ebenen des autonomen Fahrens, was zu "mode error"/"mode confusion" Problemen führen könnte. Es ist wichtig, die Grenzen der Fahrer/Fahrerinnen zu kennen und ihnen zu helfen, die derzeitige Situation und die Fähigkeit des autonomen Systems zu erfassen. Zusätzlich muss eine sichere Übernahme gewährleistet werden.

In dieser Arbeit wird ein Konzept zur Schließung der Fahrer-Fahrzeug-Umgebungsschleife mit der Fahrer-Fahrzeug-Schnittstelle (driver-vehicle interface, DVI) vorgestellt. Der bidirektionale Informationsfluss auf das DVI hilft dem Fahrer/der Fahrerin, die Fahrsicherheit und Effizienz in verschiedenen autonomen Fahrstufen zu verbessern.

Um eine Zunahme der Kraftstoffeffizienz zu realisieren, werden auf dem vorgestellten Konzept basierende DVIs vorgeschlagen und untersucht. Das effizienzoptimale Verhalten wird auf unterschiedliche Weise als Head-Up-Display (HUD) und auf dem Instrumentencluster angezeigt. Es werden zwei Experimente durchgeführt, um die Wirksamkeit und Wirkung der DVIs auf das Verhalten von Fahrern/Fahrerinnen zu vergleichen. Die Ergebnisse zeigen, dass die Fahreffizienz verbessert werden kann, indem ein Verbesserungsvorschlag angezeigt wird. Die effizienteste Fahrt erfordert die höchste Beanspruchung (Workload). Durch die Berücksichtigung ablenkender Umgebungsfaktoren in das vorgeschlagene optimale Verhalten kann die kognitive Belastung reduziert werden.

Für Fahrzeuge mit mehreren Ebenen des autonomen Fahrens werden neuartige interaktive DVIs vorgeschlagen, um spezifische Probleme resultierend aus dem "mode error"/"mode confusion" zu reduzieren. Die aus den vorangehenden Experimenten gewonnenen Schlussfolgerungen werden hierbei für die untere autonome Ebene verwendet. Es wird ein drittes Experiment durchgeführt, um die Wirksamkeit und Akzeptanz der neuen DVIs zu evaluieren und das Übernahmeverhalten der Fahrer/-

Fahrerinnen in verschiedenen kritischen Situationen zu untersuchen. Die vorgeschlagenen DVIs wurden von den Teilnehmern positiv bewertet. Die Ergebnisse zeigen, dass die Übernahmezeit in der ersten Fahrt signifikant höher ist als bei den anderen. Das bedeutet, dass die Verwendung einer durchschnittlichen Übernahmezeit für das Design einer Übernahmeaufforderung (takeover-request, TOR) nicht geeignet ist. Aus den gewonnenen Ergebnisse lässt sich schlußfolgern, dass die Übernahmezeit auch vom individuellen Fahrer/Fahrerin, der Fahrgeschwindigkeit, der Schwierigkeit der kritischen Situation usw. abhängt. Die vorgeschlagenen interaktiven DVIs werden basierend auf den Schlussfolgerungen vorheriger Experimente angepasst. Sie zeigen die Informationen aus verschiedenen autonomen Fahrstufen systematisch auf dem HUD, dem Instrumentencluster, den Rückspiegeln und dem Touchdisplay. Die Funktionalitäten sind dynamisch und abhängig von dem aktiven Fahrmodus. Die Warnungen und Vorschläge für den Fahrer/die Fahrerin werden dynamisch an die aktuelle Blickposition angepasst. Es ergeben sich neue Forschungsfragen zur sicheren Übernahme, zu einem umfassenden Verständnis des TOR sowie qualitativen und quantitativen Zusammenhängen zwischen der Übernahme und der Beschäftigung bei den Nebentätigkeiten (non-driving-related task, NDRT). Designziele und -prinzipien sowie Anforderungen an adaptive DVIs für zuküünftige Entwicklungen werden in dieser Arbeit basierend auf den durchgeführten Experimenten und erzielten Ergebnissen abgeleitet. Zukünftige DVIs sollten in der Lage sein, situativ geeignete Information anzuzeigen, sich an das Verhalten des Fahrers/der Fahrerin anzupassen oder zu lernen sowie die Fahreffizienz, die zulässige Situation und die Intention des Fahrers/der Fahrerin zu verknüpfen.

Abstract

Automotive technology has been developed for decades. During this time the goal of realization of a safe driving stays always the same. Most hybrid electric vehicles (HEVs) provide the “eco” driving mode, which helps to increase the fuel efficiency by changing the vehicle transmission behavior, the acceleration characteristics, the air conditioning system, etc. Besides the alteration of the performance of the vehicle, the behavior of the driver also plays a crucial role in influencing the fuel efficiency. The human driver behaves individually and dynamically. It is necessary to assist the driver in an appropriate manner to behave efficiently. The fully automated vehicle is one of the promising improvements in the automotive technology in the future. As for a transition phase from conventional manual vehicle to fully automated one, vehicles with multi-levels of automated driving are derived. These vehicles consist of several levels of automated driving, which could lead to the problem of mode error/confusion. It is essential to study the limits of the drivers and to assist them to recognize the current situation and the ability of the automated system to ensure a safe takeover.

In this thesis, the concept of closing the driver-vehicle-environment loop with a driver-vehicle interface (DVI) is proposed. The bidirectional information flow displayed on the DVI could help the driver to improve the driving safety and efficiency in different automated driving levels.

To realize the increment of fuel efficiency, the DVIs based on the proposed concept displaying the suggested efficiency optimal behavior in different manners as Head-Up Display (HUD) and on instrument cluster are proposed and studied. Two experiments are conducted to compare the efficacy and effect of the DVIs on drivers’ behavior. Results show that the driving efficiency could be improved by showing the suggestion. The most efficient drive requires the most visual demand. By considering the distracting factors from the environment into the suggested optimal behavior, the cognitive workload could be reduced.

For the vehicles with multi-levels of automated driving, novel interactive DVIs are proposed to reduce the mode error/confusion. The results from previously performed two experiments are applied to the lower automated levels. A third experiment is executed to evaluate the efficacy and acceptance of such DVIs as well as to study the takeover behavior of the drivers in various critical situations. The proposed DVIs are positively confirmed by the participants. The obtained results show that the takeover time in the first drive is significantly higher than the following ones. This means that using only the average takeover time to design the integration of human as a fallback layer of automated vehicles is not suitable. It is concluded that the takeover time also depends on the individual driver, the driving velocity, the difficulty of the critical situation, etc. The proposed interactive DVIs are adapted based on the conclusions from the conducted experiments. They show the information from different automated driving levels systematically using the HUD, the instrument cluster, the rear view mirrors, and the touch display. The functionalities are dynamic to the active driving mode. The warnings and suggestions to the driver are displayed dynamically based on the tracked glance position. New research questions are posed regarding safe takeover, comprehensive understanding of the TOR as well as qualitative and quantitative relations between the takeover and the activity of driver in non-driving-related task (NDRT). Based on the performed experiments and obtained results, the discussion about the design goals and principles as well as requirements for adaptive DVIs for future development are concluded in this thesis. The future DVIs should be able to show the situation-dependent information appropriately, to learn, or to adapt to the individual behavior of the driver, as well as to combine the driving efficiency, the allowable situation, and the intention of the driver.

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Nomenclature

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
ANOVA	Analysis of Variance
AOI	Area of interest
AR	Augmented Reality
BLIS	Blind Spot Information
CbW	Conduct-by-Wire
CSW	Curve Speed Warning
DAS	Drvier Assistance System
DV	Dependent variable
DVI	Driver-Vehicle Interface
EID	Ecological Interface Design
En	The n-th experiment, $n = 1$, 2, 3, and 4
FCW	Forward Collision Warning
HEV	Hybrid electric vehicle
HiL	Hardware in the Loop
HMI	Human-Machine Interface
HUD	Head-Up Display
H-Metaphor	Horse-Metaphor
IV	Independent variable
IVC	Inter-Vehicle Communication
IVDS	In-Vehicle Display System
LCW	Lane Changing Warning
LDW	Lane Departure Warning
LKW	Lane Keeping Warning
MA	Mode Awareness
MANOVA	Multivariate analysis of variance
NDRT	Non-driving-related task
RCW	Rear-end Collision Warning
SAW	Situation Awareness
SD	Standard deviation
SL	Speed limit
SOC	State of Charge
ST	Secondary task
TOR	Take-over request
TSR	Traffic Sign Recognition
UID	User-centered Interface Design
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle

1 Introduction

The driver-vehicle interface (DVI) plays a crucial role to realize the communication between the driver and the vehicle, so that the drivers could be able to enter the operating commands (DVI as an input device) and to understand the status of the vehicle as well as the driving environment (DVI as an output device). The DVI is an essential part in different levels of automated driving. As long as the interaction between the driver and vehicle remains, the outputs from the system should be displayed to the driver. The advanced driver assistance systems (ADAS) are designed to assist the driver to achieve a safe driving. As a prompt solution to the issue lack of energy resources becomes imperative, ADASs should help human drivers also to realize efficient driving. Several solutions, such as optimizing the performance of powertrain, improving the performance of the vehicle, focus only on the vehicle. The other key variable in the driver-vehicle loop: the human driver also has to be considered, because the driver's behavior is dynamic and individual. The "eco" mode in most vehicle models helps to increase fuel efficiency by changing the transmission behavior, acceleration characteristics, the air conditioning system, etc. So far the driver is still in charge of the execution of the driving, the least fuel consumption will not be achieved with the inefficient driving style of the driver despite altering the performance of the vehicle. To help the human driver to drive efficiently or to make a right decision in time, the human drivers have to be assisted more specifically.

The trend of development of automotive technology denotes that the fully automated driving could be realizable, but till then, various problems should be overcome. The partially automated driving releases the driver from controlling the vehicle. However, the driver still needs to monitor the system and the driving situation steadily and take over the control in critical situations, where the automated system is not able to deal with. In such situation, DVI plays also an important role to show the driver the necessary information to take over the control of the vehicle in time. The questions how should the driver be informed and how to make sure the driver understands the situation and intent of the system correctly and in time should be answered. In the situation, in which the driver should take over the control of the vehicle from the system, mode error or confusion may occur because multi-levels automated driving is involved. This leads to another open point if it is possible to use the DVI to display several driving modes and their functionalities to avoid mode error and confusion.

In this chapter, the current open issues regarding the increment of fuel efficiency in hybrid electric vehicles (HEVs) and takeover behavior in multi-levels automated vehicles are discussed. Accordingly, the research issues are addressed in section 1.1. The scope and the objectives of this thesis are listed in section 1.2. The structure of this thesis is explained in section 1.3. Some of the aspects and ideas presented in this chapter are highlighted and introduced in [WMS15a] [WS16] [WS18].

1.1 Motivation and problem statement

The focus of vehicle development has changed from basic transporting tasks from point A to point B to additional requirements with regard to safety, efficiency, functionality, as well as further comfort and reliability. Whilst the automotive industry develops, the amount of fuel resource to support it decreases. As shown in Figure 1.1, the world oil consumption exceeds the production. The most of the world's liquid fuel is consumed by the transport sector, from which the trucks and cars contribute the most as shown in Figure 1.2. As the oil is non-renewable resource, to reduce the consumption is imminent.

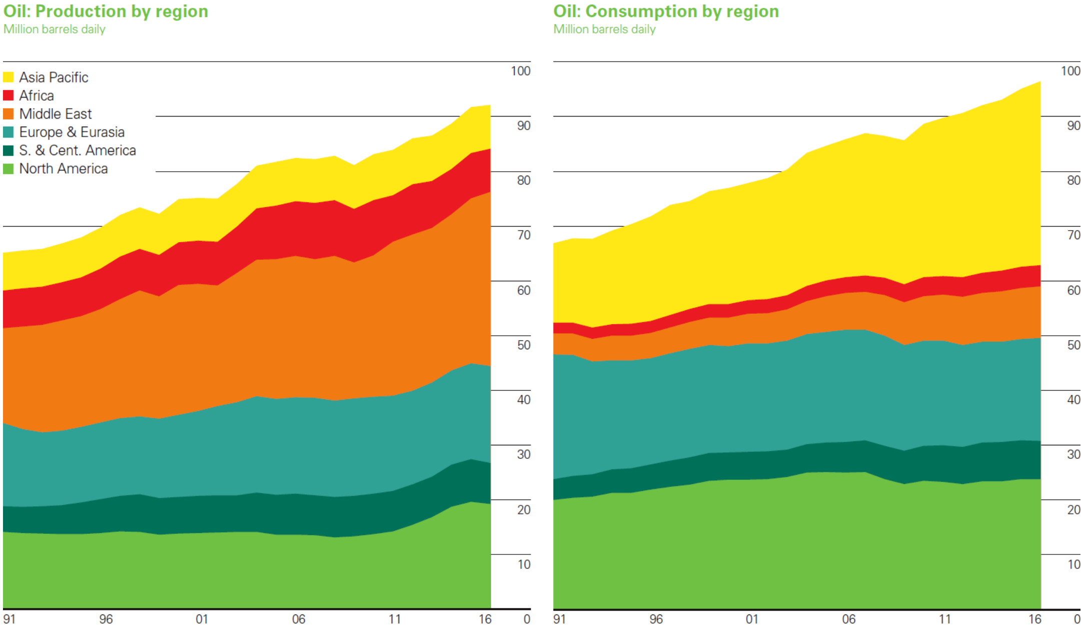


Figure 1.1: Trend of world oil production and consumption by region [BP17b]

In 2016, a total of 2,587,321 traffic accidents were recorded in Germany (2.8 % more than it in 2015), in which 3,214 people died [Sta17b]. Worldwide 1.25 million people die per year due to traffic crashes [Wor15]. According to [Sta17a], 66.6 % of the accidents with personal injuries were caused by the incorrect behavior of the drivers. As shown in Figure 1.3, the main reasons causing accidents are insufficient distance to the preceding vehicle, not suitable velocity, errors by turning, reversing, and approaching, etc. According to [Nat15], 94 % of the crashes are caused by drivers based on the study of 5,470 crashes weighted from about 2 million crashes in the USA. The main reasons are concluded as recognition errors, decision errors, performance errors, etc.

The number of registered vehicles in the world increases 16 % from 2010 to 2013 [Wor15]. This leads directly to global traffic congestion. According to [Tom17], the

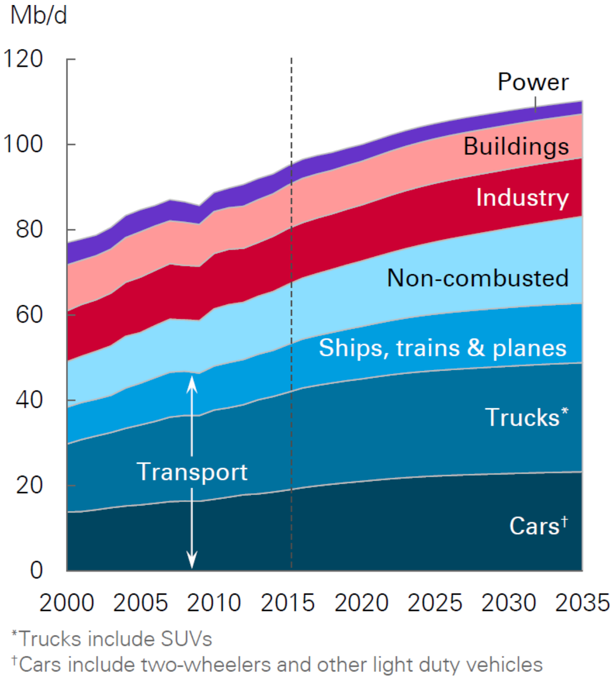


Figure 1.2: Distribution of liquid oil demand [BP17a]

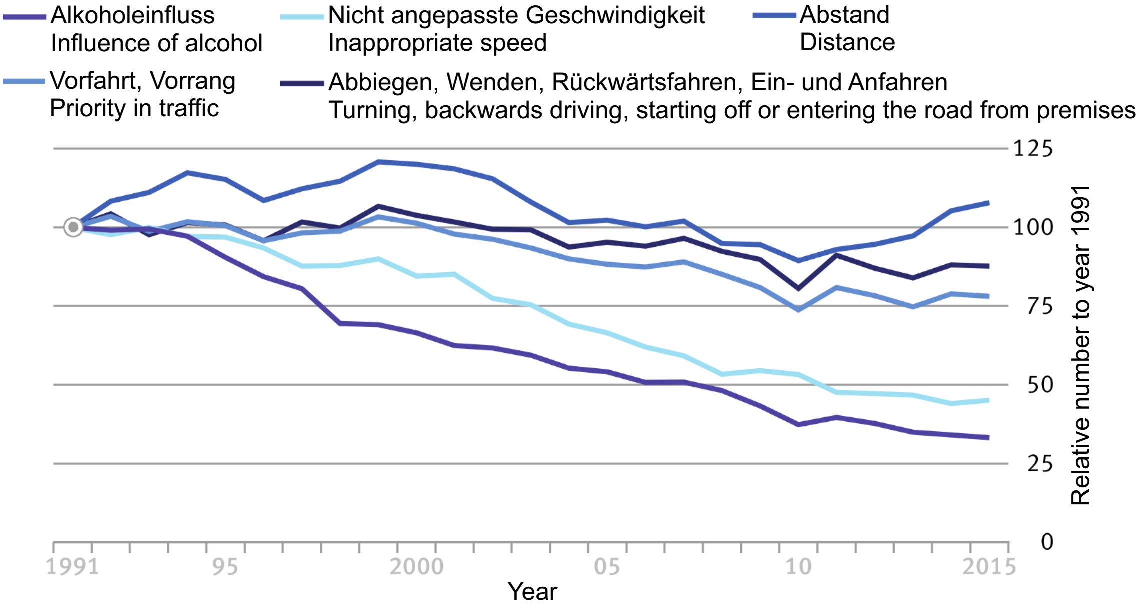


Figure 1.3: Development of driver-related causes of accidents involving personal injury in Germany (1991 = 100) (modified after [Sta16])

traffic congestion increased 23 % from 2008 to 2017 globally. In the city with worst traffic congestion, people spend 66 % extra time averagely suffering traffic jam on one day.

More and more elder people drive. The number of people with age 60 or more would grow by 56 % by 2030, which is 1.4 billion [Uni15]. To assist them to achieve safe driving and to familiarize themselves with the rapidly developing automotive technologies are challenging.

The issues from a sustainable point of view, such as: limited fuel resource [BP17a] [BP17b], air pollution [Wor16], etc., inspire people to develop green source vehicles. Manifold new energy vehicles have been developed, for example electric vehicle (EV), compressed natural gas (CNG) vehicle, liquid natural gas (LNG) vehicle, etc. Another widely used new energy vehicle to reduce fuel consumption is a hybrid electric vehicle (HEV). However, the way to achieve the most efficient driving within HEV is still under discussion [MGMk15] [ZZLF16] [SZS16]. The realization of more efficient driving does not only depend on the optimization of the powertrain, but also on the behavior of the human driver. During driving, it is difficult for the drivers to reach the maximum efficiency because the driving environment is dynamic. Besides the complex environment, the safety is another important factor to be considered. In this multi-variable environment, the drivers would need assistance from the system. The communication between the driver and the vehicle is realized with the Driver-Vehicle Interface (DVI). When the human driver is persuaded by the result from the optimization algorithm, the driver will possibly follow the instructions. The optimization algorithm needs to be proved to the human driver as useful, helpful, and realizable. Moreover, the calculated results should be displayed in a comfortable and acceptable way so that the driver does not need much time to understand the displayed information. This leads to the first set of research questions.

- *Is it possible to use DVI showing results from driving efficiency optimization algorithm to influence the driving behavior from efficiency perspective?*
- *In which way could the information be displayed to help the driver to increase the driving efficiency?*
- *How should the DVI influence the driving behavior in the way which the driver could accept?*

In 1951, the Fitts list was introduced to allocate the functions of humans and machines [Fit51]. The comparison of the strengths and weaknesses of human abilities with machine abilities [Fit51] [DW02] shows that the cognitive abilities of human are partially opposed to machine (routines). In other words, machines are significantly better in terms of known, accurate, and reproducible tasks and interactions. However, studies [SG83] on human reliability also reveal the other side of (one-time) ability of human: a high error rate, especially in cognitive-based activities, not only in situation recognition, target processing, planning, also in action control. Human and machine show strengths and weaknesses, which are only conditionally interchangeable. According to [WH90], the errors are hidden for a long time until the human trigger the accident at the end of events, which consist of several causal chains to achieve the goal. To avoid the potential serial of causes and effects, the decisions of human should be managed so that this kind of chains will not even accrue. The cause of the human error is manifold. One of them is the lack of situation awareness (SAW) [End95a]. The SAW came first into view within the aviation area and was first introduced in [BS83]. Study of the SAW helps to improve the understanding of the environment for the decision makers in complex and dynamic situations. Various definitions, models, and methods of measurement are proposed [Dom94] [End95b] [SH95] [BM99] [Fra91] [SW95] to study individual SAW. The most cited model of SAW [End95b] is debated in [Fla95] [BM99] [KMH06] [Fla15] [End15]. The team SAW [SPBS95], shared SAW [EJ97], and distributed SAW [Hut95] are more complex in collaborative systems, which are summarized in [SSW^{+}08]. In [Nat15], about 41 % of the driver-related critical reasons causing traffic accidents are due to recognition error, which includes the lack of SAW, distractions, etc. It is crucial to study SAW and to help the drivers to improve SAW in the automotive area.

Driver assistance systems (DAS) or advanced driver assistance systems (ADAS) are designed to assist the human driver to deal with emergency situations (Forward collision warning system), to generate a comprehensive understanding of the driving environment (Blind spot detection system), or to reduce the human error (Lane keeping assistance system), and thus help the driver to make the right decision reliably and to be aware of the available options. From the macro-perspective of traffic automation and traffic safety, the assistance systems include aspects of securing overall mobility, increasing traffic throughput, solving problems resulting from increased traffic density as well as reliability (the mobility function), at the same time solving society-related and demographic challenges and minimizing accident rates.

The degree of taking over the guidance from the driver can be highly critical [MAB12]. The ability, authority, control, and responsibility are noticed in [FHH^{+}12] to discuss the dynamic balance between humans and machines. It is mentioned in [FBB^{+}14], that the cooperative behavior should be a key aspect of future human-automation systems. The major challenge for designing ADAS is taking the driver's state into account [GTFC12]. Aiming to classify the features of driver assistance systems or automated features, levels of autonomy could be divided into five levels [Gas12] [Nat13] or six levels [SAE14b] based on different criteria. The most ADASs act on the second level so that the goal of safe driving could be achieved. Vehicles with fully automated driving functions have been researched for years, but various problems are still unsolved [BSR16] [BTAO16] [SC16] [TVS16]. Vehicles with more than one automated driving levels result from this transition phase. In this case, the takeover of the driving task from the automated system is required for the driver, who probably is engaged in a non-driving-related task (NDRT), when the automated system is not able to deal with the critical situation. The time for Takeover-Request (TOR) and the takeover time of the driver from the automated system are studied in plenty researches [LDS+16] [MRD+15] [MJMJ17] [HLK17]. In [HLK17], the participants are divided into four groups with average 27 participants in each group. According to [Pet97], the minimum sample size per group is suggested as 30. This deviation could lead to inaccurate or incorrect results by applying statistical analysis. Only one critical situation for takeover is studied in [HLK17], which is a sudden accident in the middle lane in front of the ego-vehicle with TOR time 7 s. Would the drivers behave differently when the critical situation is more complex? The driven speed by the two takeovers in [HLK17] is 120 km/h. According to [GDLB13], the takeover time depends on the TOR time. Would the takeover time of the drivers also be influenced by the driven speed? Another open point is whether a general conclusion for these two variables is suitable for every driver or not. The individualities of the driver and the driving situation are not considered. In systems with more than one mode and required information not available, mode error/confusion may occur [LN86] [BL05]. In such case, the communication between the driver and the vehicle is especially crucial to avoid the related mode error/confusion. To display the information from the automated system to the driver correctly and opportunely, an appropriate DVI is required. This leads to the second set of research questions.

- *What are the limits of the driver with respect to experiences and critical situations by taking over the driving task from the automated system?*
- *Is it possible for the drivers to take over the driving task when they are engaged in other activities?*
- *Is it suitable to use one standard TOR time for all individual drivers and situations?*
- *How to display the information about the multiple automated driving levels and the related functionalities?*

1.2 Objectives and contributions of the work

As discussed in section 1.1, it becomes more challenging in the field of automobiles regarding the trend of the world fuel consumption and development of automated vehicles. The human driver is nowadays still in charge of the driving. To influence the drivers to behave efficiently plays an important role in reducing the fuel consumption. The takeover behavior of the driver from the automated system directly influences the driving safety. To study the limits of the drivers in such situation and to assist them to realize a seamless takeover are crucial for the further development of automated vehicles. This limits the scope of this thesis to the interaction between the driver and the vehicle, especially the influence of the medium between the driver and the vehicle (DVI) on the behavior of the drivers.

The main objective of this research is to develop DVIs to increase driving efficiency in HEV and to improve mode awareness in vehicles with multi-levels of automated driving. Therefore the effect of DVI, as well as the automated system on the behavior of the human driver in varied situations, could be learned and analyzed based on simulator studies to achieve the design principles and requirements of DVI for the future developments. This could be achieved from the following specific objectives.

- To develop DVI to assist the driver to realize an efficient driving
- To study the influence of DVI on driving behavior from driving efficiency perspective
- To develop DVI to assist the driver within vehicles with multi-levels automated driving
- To study the takeover behavior of the driver from automated system for safe takeover and increment of situation awareness
- To investigate the design principles and requirements of DVI for future developments

These objectives are mainly studied through three conducted experiments. The focus of experiment 1 (E1) and experiment 2 (E2) is to study the driver's behavior from efficiency's point of view within an HEV context. With one of the proposed DVI, the most efficient driving could be realized, but with the largest workload, which is improved in E2 by considering the environmental influencing factor. This is applied in experiment 3 (E3), which focuses on multi-levels automated vehicles. The conclusions regarding the effects of different DVIs on driving efficiency from first two experiments could be integrated into the lower automated driving levels in E3. The other focal point of E3 is to analyze the takeover behavior of the driver. The contributions of this work could be summarized as following points.

- The driving efficiency could be influenced by appropriately designed DVI in a positive way, but the most efficient driving behavior requires the most workload.
- The workload could be reduced by considering the environmental restrictions into the suggested optimal behavior.

- It is not suitable to use one general TOR time for all drivers in all critical situations, because it does not only depend on TOR time but also on the driven speed as well as the complexity of the critical situation.
- New research questions are posed regarding a safe takeover, understanding the TOR, and the risk awareness based on the relation between the activity of the driver with the NDRT and takeover.
- Requirements and design goals are concluded based on the performed experiments for the future development of DVI.

1.3 Outline of the thesis

In this thesis, the usage of DVI and influence of DVI on drivers within HEVs and vehicles with multi-levels of automated driving are discussed. First, the influence of DVI on efficient driving behavior is studied. Second, the takeover time and the behavior of the driver from the automated driving system are investigated. Lastly, the DVIs displaying information and functionalities of multi-levels automated driving are proposed.

The thesis consists of 8 chapters. Some parts of this thesis are prepared for journal papers [WS] [WS18] or have been published in proceedings of conferences [SWS$^+$13] [WS14] [SMW14] [WMS15a] [WS16].

In chapter 2, a discussion of levels of automated driving and related problems are addressed. A detailed review of the state-of-the-market of DVI and the related problems are introduced. A comprehensive insight in reviewing the solution concepts and the evaluation methods in combination with levels of automated driving is presented. The contributions of these concepts are compared from various perspectives. The trend of interaction mode due to digitization is analyzed.

The chapter 3 introduces the proposed concept of closing the human-vehicle-environment interaction loop with the interface. To achieve a safe and efficient driving within different levels of automated driving, an appropriate interaction between the driver and the vehicle is crucial. The driver-vehicle loop closed by the DVI realizing the aforementioned goals is represented.

An overview of the simulation environment and measuring technique used for the development of DVIs and in the experiments are introduced in chapter 4.1. The proposed ideas and executed experiments in this thesis are realized with the driving simulator. An eye tracker is used for capturing the information of the eyes of the participants as part of the evaluation data.

In chapter 4, the research question about the possibilities to influence the driver's behavior in an appropriate manner from an efficiency perspective is answered. Three ways (numerical, verbal, and iconic) of displaying the suggested optimal driving velocity are suggested. The efficacies of them are evaluated and compared with a baseline test in experiments with 32 participants. The results are discussed and concluded from both objective and subjective aspects.

Based on the results and conclusions obtained from the chapter 4, two DVIs suggested to be used for the increment of driving efficiency and in the meanwhile reducing the cognitive workload of the driver are introduced in chapter 5. Experiments with 34 participants are conducted to validate the proposed ideas. The corresponding objective and subjective results are discussed in this chapter.

Whilst the improvement of fuel efficiency using DVI is studied, higher levels of automated driving are discussed in chapter 6. The takeover behavior and time of the drivers from Level 3 are investigated with experiments. Two DVIs are suggested to be used for vehicles with multi-levels automated driving. Experiments with 38 participants are carried out to investigate the limit of the driver by taking over the driving task and to compare the two proposed DVIs. The results of the experiments are explained and discussed accordingly. Based on the results and comments from the participants in the previous studies, two DVIs are adapted displaying basic information, safety-related warning, efficiency-related suggestion, automated driving modes, and corresponding functions.

Finally, the summary of the thesis, conclusions, and future work are outlined in chapter 7. In addition, the requirements and principles in designing in-vehicle information system are concluded and discussed based on the experiments conducted in this thesis.

2 Literature Review

After fulfilling the basic requirement of automobiles: transportation of human and goods, the goal of automobile is transformed to increase also driving safety, efficiency, and comfort. Various driver assistance systems (DAS) have been developed to achieve these goals on the one side, on the other side different degrees of automation in driving are playing a more and more important role. To realize a suitable, task-related, and reliable communication and cooperation between the driver and the system, the driver-vehicle interaction/interface (DVI) is essential.

In this chapter, a discussion of levels of automated driving and related problems are addressed in section 2.1. In section 2.2, a detailed review of the state-of-the-market of DVI and the related problems are introduced. A comprehensive insight in reviewing the solution concepts and the evaluation methods in combination with levels of automated driving is presented. The contributions of these concepts are compared from various perspectives. The trend of interaction mode due to digitalization is analyzed in section 2.3. The open issues are concluded in section 2.4.

The contents, figures, and tables in this chapter are based on publication of [WS18] and prepared for publication of [WS]. Part of the contents, figures, and tables in this chapter are modified after previous publication [WMS15b].

2.1 Automated driving levels and related issues

The common goal of vehicle development is to provide a safe and comfortable driving to the driver. In this section, the driving modes and degree of automated driving are introduced in section 2.1.1. A short introduction of driver assistance system will be given in section 2.1.2. The different driving modes caused problems are summarized in section 2.1.3.

2.1.1 Degree of automated driving

The development of driver assistance system can be understood as both driver assistance in combination with autonomous functionalities. In [WMPM98] [PSW00], the automation of decision and action selection are divided into 10 stages. On the lowest stage no influence from the system is realized: “The computer offers no assistance: human must take all decisions and action”. To decouple the user and system in the highest stage “The computer decides everything, acts autonomously, ignoring the human”. The degree of automation is differentiated in [LKF08] as a continuous spectrum between “manual”, “assisted”, “semi automated”, “highly automated”, and “autonomous fully automated”.

The automation in the automotive field is divided into 5 levels following the criteria of roles from human (Decide, act, concur, or veto) and system (Suggest, decide, and act) according to [EK95], which are

- "Level 1: None",
- "Level 2: Decision Support",
- "Level 3: Consensual AI (Artificial Intelligence)",
- "Level 4: Monitored AI", and
- "Level 5: Full Automation".

To provide a common terminology for automated driving, 5 levels of automated driving are delivered by the Germany Federal Highway Research Institute (Bundesanstalt für Straßenwesen (BASt)) [Gas12] in 2012. One year later, the US National Highway Traffic Safety Administration (NHTSA) also published the levels of vehicle automation [Nat13]. Similar to the above described levels, 6 levels of driving automation are summarized according to Society of Automotive Engineers (SAE) [SAE14b] and updated in 2016 [SAE16b]. The levels are divided following the criteria [SAE14b] to distinguish the human driver and the system:

- "Execution of steering and acceleration/deceleration",
- "Monitoring of driving environment",
- "Fallback performance of dynamic driving task", and
- "System capability (driving modes)".

Using the same criteria, the listed levels are compared with the ones of BASt and NHTSA. The last level in [SAE14b] describes that the system is able to execute all driving modes, which is different from the ones from BASt and NHTSA. One year later, the German Association of the Automotive Industry (Verband der Automobilindustrie (VDA)) suggested 6 levels of automated driving [Ver15]. The table in [SAE14b] is modified summarizing the levels of automated driving as shown in Table 2.1.

Research related to automated vehicle is realized in numerous research groups and projects, for instance: DARVIN (Driver Assistance using Realtime Vision for INntercity areas) [HFN00], VIAC (the VisLab Intercontinental Autonomous Challenge) [BBB$^+$10], DARPA (Defense Advanced Research Projects Agency) [CEHM11], Stadtpilot [NHF$^+$11], HAVEit (Highly automated vehicles for intelligent transport) [Hoe11], Google Driverless Car [DSB16], etc. The full application of automated vehicles on

Table 2.1: Summary of levels of automated driving (modified after [SAE14b])

SAE level [SAE16b]	BASt level [Gas12]	NHTSA level [Nat13]	VDA level [Ver15]
Level 0 No driving automation	Driver only	0	Driver only
Level 1 Driver assistance	Assisted	1	Assisted
Level 2 Partial driving automation	Partially automated	2	Partially automated
Level 3 Conditional driving automation	Highly automated	3	Highly automated
Level 4 High driving automation	Fully automated	3/4	Fully automated
Level 5 Full driving automation	-		Driverless

road is still in testing phase. Several challenges like safety, legalization, user acceptance, interaction, etc. are still in discussion.

Besides the first and the last levels in each standard, the driving task is executed by both driver and assistance system defined as cooperative driving. Mainly two types of cooperation in driver-vehicle-systems can be distinguished: namely "in-vehicle" cooperation and "between-vehicles" cooperation. The "in-vehicle" cooperation is understood as the collaboration between the driver and the assistance system in one vehicle. To increase the safety, the efficiency, and the comfort of the total traffic system, the "between-vehicles" cooperation is used to build a communication connection between the vehicles on the road or between the vehicles and the infrastructure.

2.1.2 Advanced driver assistance system (ADAS)

Driver assistance systems (DASs) present in vehicles from SAE level 1. They are developed to aid the driver to improve traffic safety, to reduce workload, and to increase recognition of the driving situation, etc. In [KNB$^+$09], the DAS is defined as a way, in which the driver is informed, warned, and provided with feedback on driver actions to increase the comfort and to reduce the workload of the driver. Advanced driver assistance system (ADAS) is defined as a subset of the driver assistance systems [KNB$^+$09]. In [Eur16], the ADAS is defined as "vehicle-based intelligent safety systems which could improve road safety in terms of crash avoidance, crash severity mitigation and protection, and automatic post-crash notification of collision; or indeed integrated in-vehicle or infrastructure based systems which contribute to some or all of these crash phases".

According to [Don78], [Don82], the driving task can be divided into three levels:

Navigation level Route planning based on road network and time schedule

Guidance level Trajectory decision, such as: left lane or right lane

Stabilization level Chosen trajectory transformed into physical inputs, such as: steering wheel, gas, or brake pedal on a local and situational scale

The introduced three task-oriented levels are compared to the three behavior-oriented categories [Ras83] (knowledge-based, rule-based, and skill-based behavior) [Don95]. The driving task is also divided into three levels and compared to the three behavioral levels in [KNB$^+$09]. The "Manoeuvring level" is defined instead of "Guidance level" to describe the rule-based behavior in driving task, such as decision making. The ADAS is mainly realized in this level, as well as part of the "Stabilization level". One of the first DASs is the Anti-lock Braking System (ABS) [Rei03]. In 1903, a braking force controller was introduced for railway vehicles [Rei03]. A braking force controller for vehicles was developed in 1928 [Rei03]. Afterwards, a similar system was also developed in aircraft. The serial production started from the 1970s [Rei03]. Later in 1995, the Electronic Stability Control (ESC), which helps to improve a vehicle's stability, was introduced and implemented in serial production [Vol09]. The cruise control system was first designed to control the velocity automatically. It was later improved to ACC (Adaptive Cruise Control) to keep the velocity set by the driver and in the meanwhile to maintain a safe distance to the preceding vehicle. These embedded systems in automobiles achieve a recognized development in last decades. A detailed overview of the design of embedded systems is given in [SCA11]. The following ADASs are discussed in [SCA11] as

- Cruise control,
- ACC,
- Precrash system,
- Blind spot information system,
- Lane departure warning system,
- Autonomous parking assistance system, and
- Drowsiness detection system.

The mentioned ADASs from several selected manufacturers are compared based on sensor type, system response, and model year. The development trend of these systems is expounded.

In [BBF$^+$14], the development and future focus of assistance systems are summarized. It is stated that individualized assistance system as well as cooperative driving would be the trend, which will finally point to automated driving.

It can be stated that the use of ADAS helps to increase the driving safety, the human situation awareness, and comfort. Therefore it is advantageous. In addition to the increase in driving safety, accidents caused by elementary operating errors or, for example, by driver's fatigue can be reduced. Furthermore, the working load of the driver is also reduced by the used of ACC [SY05].

However, it is well known that any type of automated system generates new problems with increasing complexity [Bai83]. According to [BWJ01] automated system may also cause problems, such as

"Behavioral changes" Increment of reaction time because of continuous monitoring of more than one function,

"Human supervision" Requirement of supervision and adjustment from human,

"Complacency" (Over)reliance on automated systems [WC80], and

"Acceptance/attitude towards ADAS" Handing out control of vehicle.

In [LWZS12] research directions of ADAS are studied and discussed. According to [LWZS12], one of the research directions is based on driver's side, which is to recognize the driver's position (head/arm/body and movement), physiological state, decision, behavior, and action. Another direction focuses on the assistance system with the goal of enhancing the driver's perception, providing suggestion, and delegating the vehicle motion control. One of the suggestions for further research is to combine both sides to achieve a cognitive assistance system.

2.1.3 Situation/mode awareness

Another issue caused by the automated system is mode confusion or mode error. Before going into details about the two terms, the related information needs to be explained. "Situation awareness" (SAW) became apparent first in aviation area and was first introduced in [BS83]. In [BS83], a touch-sensitive control/display unit was integrated into an aircraft. One of the benefits of the prototype is the improvement of the situational awareness of the aircraft pilot. Not only in the aviation area, SAW is required in areas of air traffic control [Mog97], large-scale operations [RHI$^+$12], decision making process [CCH08], vehicle driving [MK07], etc. Later SAW is studied in [Woo86] [WK88], [RRB88] from different aspects.

In general, SAW could be understood from technological perspective and human perspective. From a technological perspective SAW can be used for automated decision making of machines, which is "the ability of machines to collect and fuse large amounts of data to find "interesting" objects, situations or threats" [Nik07] [SB04]. In the aviation area, this ability could be judged by required navigation performance (RNP) or area navigation (RNAV) [Kra03].

The human-oriented perspective of SAW, which is the focus of this paper, will be discussed in detail. In [Dom94], 15 different definitions of SAW are summarized. Based on this, Dominquez [Dom94] defined SAW as "continuous extraction of environmental information, integration of this information with previous knowledge to form a coherent mental picture, and the use of that picture in directing further perception and anticipating future events". According to [SH95], SAW is defined as "adaptive, externally-directed consciousness". The authors in [SH95] state that SAW is a dynamic concept staying between the agent and its environment. They combine the perceptual cycle from [Nei76] to understand SAW. In [BM99], the activity theory is used to describe SAW as a reflective-orientated activity. It provides an individual conscious dynamic reflection on the situation. In [End95b], a three-level model of the SAW is developed, composed of the three levels

- "Level 1: Perception of the elements in the environment",
- "Level 2: Comprehension of current situation", and
- "Level 3: Projection of future status".

Even the SAW approach [End95b] is widely cited, it is criticized in several papers. In [Fla95], the perception and action are coupled in a dynamic environment, which is inconsistent with the position defined in [End94]. Bedny and Meister [BM99] claim that the three-level model from [End95b] focuses on the functions of memory and attention, not thinking processes. They also mention that without the thinking process, the comprehension of the situation is not meaningful and dynamic anymore. The model to describe the dynamic nature of SAW is criticized in [SSW$^+$08]. It is claimed that Endsley's model does not distinguish the process from product [KMH06]. Endsley [End15] summarizes and replies these claims or misunderstandings. In the same time, Flach [Fla15] concerns that using block diagram to describe the three-level SAW model would cause deviation with the original intention, because this kind of representation leads to a dyadic interpretation. This view considers the situation and awareness as two distinctive systems. However, Flach [Fla15] supports for the triadic paradigm, which provides a monist ontology for the interaction between situation and awareness as one system.

In [Fra91], reliability and validity are defined as two principle criteria for SAW measurement, which cannot be considered separately. The SAW can be measured by mainly three different methods [Fra91] [SW95] as

- Subjective ratings,
- Explicit performance measures, and
- Implicit performance measures.

Other SAW measurement techniques are summarized in [SSWG06].

In collaborative and complex systems, the development of models and measures for team SAW [SPBS95], shared SAW [EJ97], and distributed SAW [Hut95] are challenging, which are summarized in [SSW$^+$08].

According to [Nor81], the “mode error” is defined as “erroneous classification of the situation”. It is potentially caused in devices, which have multiple modes [LN86]. “Mode awareness” (MA) is first mentioned in the field of aerospace during the research of SAW [SW94]. Mode awareness is considered in [SW95] as “the ability of a supervisor to track and to anticipate the behavior of automated systems”. The “mode error”, which occurs when the existing information provided by the system is understood erroneously [Dek06]. It is different from “mode confusion”, which happens when the required information is not available [BL05]. Mode error is modeled using the Georgia Tech Crew Activity Tracking System (GT-CATS) methodology able to track the activities of operators using modes to control complex dynamic systems [CM94]. In [MP99], two complementary strategies are used to detect mode confusion.

Similar work is done in [NLH14] to validate user interfaces. According to [NLH14], the user interface in the aircraft operation system can be validated by using mode confusion detection. In [NLH14], the automation system’s intention as well as those of the pilots are inferred and compared. Both of them are modeled as discrete-event systems. Once a mismatch between both inferred intentions is confirmed, a mode confusion is detected. Based on locating the mismatch, the user interface can be improved to increase SAW and MA. With increasing automation in automobile field, these concepts are also considered [LAY14] [Kom08] [Mar13] [FSIW03].

Along with automation benefits, unexpected problems arise, which are summarized in [SWB97] and listed by keywords below:

- “Workload - Unevenly Distributed, Not Reduced”
- “New Attentional and Knowledge Demands”
- “Breakdowns in Mode Awareness and “Automation Surprises””

- “New Coordination Demands”
- “The Need for New Approaches to Training”
- “New Opportunities for New Kinds of Error”
- “Complacency and Trust in Automation”

As pointed out in [BMRW75], also automation systems remain a human-machine systems, which require to be monitored by the human. It is mentioned in [Bai83], that “one is not by automating necessarily removing the difficulties, and also the possibility that resolving them will require even greater technological ingenuity than does classic automation”.

The “out-of-the-loop” problem also mentioned in [EK95] is much similar as the second problem discussed in [Bai83]. It is proved in [EK95] that humans perform the task slower when they take over the task after the breakdown of the automation than if they do it manually from the beginning. The reasons are a possible loss of skills and SAW, the change of information processing from active to passive, and the change of feedback to the human. It is studied in [GDLB13], at which moment in time for the assistance system direct the driver’s attention to take over the driving task in the situations, which cannot be handled by the automation. The authors designed a takeover scenario that the actual driving lane of ego-vehicle is occupied by an accident. The driver has to either stop on the current lane or the change lane to the left to avoid the accident. The takeover request (TOR) of the automation is displayed to the driver 5s and 7s before the accident location respectively. The two moments in time are compared with the ones without automation. The study is done with the help of 32 participants. Results show that the participants react faster with less TOR time, but with worse quality, such as decrement of gazes in mirrors and shoulder checks as well as excessive usage of the brake. The participants use fewer brakes to react when they have more time for the decision. In both 5s and 7s groups, the blind spot check is insufficient, which could lead to an accident if a vehicle is in the blind spot. It is concluded that the increment of 2s cannot completely compensate for the effects of transition and situational orientation due to out of the loop.

Based on the referred literature, it can be concluded that the implemented aims of driver assistance systems are the same regardless automated level. However, the boundary conditions and the focus of them vary based on the automated level as well as the problems occurred. To increase the functionality of automation systems as well as the resulting acceptance from user side, the modality to interact with drivers and the moment to warn/suggest them are still up for final discussion. It should be noted that only these two aspects (How to show? When to show? When to intervene?) seem to be the only remaining options to improve the functionality of the driver-vehicle interaction as well as the reliability of the driver-vehicle-environment system.

2.2 Review: Graphical, haptic, and acoustic interfaces

2.2.1 Driver-Vehicle Interface (DVI)

The interface between the human and a technical device is called Human-Machine-Interface (HMI). According to [Var98], an HMI can be basically described by interactions, such as information, warning, advice, and control. The HMI related technologies, practices, and implementation in the current and upcoming industry trends are discussed in [Vas14]. Actual HMI technology is based on multi-touch and multi-modal technologies [Vas14]. This includes touch recognition, proximity and gesture recognition, face/eye recognition, voice recognition, handwriting recognition, haptic feedback, etc.

At present, the interaction between driver and vehicle is mainly realized by input devices (steering wheel, pedals, etc.) and output devices (displays) as Driver-Vehicle Interface (DVI). The information about the vehicle states and related surroundings of the observed (ego-)vehicle can be represented with the help of DVI so that the driver may perceive the current situation correctly and will be enabled to make the correct decision at the right moment. A wrong decision in a critical situation may be based on an incomplete understanding of the situation, inattentiveness, negligence, etc. A further reason for the occurrence of wrong decisions could result from misunderstanding of the displayed information or, for example, unclear and therefore interpretable information displayed on the graphical interface. The driver-specific interpretation of incorrect or unclear information may lead to a wrong (unintended) understanding or even to delay time due to cognitive work needed for interpretation and reasoning. Finally both aspects affect the probability for the occurrence of critical and dangerous situations even during regular driving situations. For this reason, the DVI and here especially the interaction design for information representation plays a crucial role in assistance systems.

The main components with respect to driver-related HMI are summarized in [WBRK97] as

- Primary controls of vehicle,
- Instrument cluster,
- Displays supporting the primary driving task such as navigation, and
- Supplementary displays such as HUD (Head-up display).

The common options of presenting information are visual, acoustic, and haptic. Visual displays are used for both showing general driving information and warnings. A graphical representation according to [Tul97] is suitable for the representation of real and complex facts. For this reason, graphic elements are generally used for the representation of complex information about driving efficiency. In [OMLT$^+$13], the proper location for the driving information is studied. The information can mainly be grouped as [OMLT$^+$13]:

- “Mandatory signals”,
- “Vehicle data”,
- “Entertainment”,
- “Communication”,
- “Navigation”,
- “Settings”,
- “DAS”, and
- “Apps”.

The impact of the location of such information on the driver’s performance and gaze is studied in [OMH14]. The results show that the layouts used in the experiment are not essentially different from the ones existed on the market, but the interface for connecting smartphones with the vehicle as well as their interaction should be considered in future systems. The text size for displaying information in the vehicle and the touch-key size for entering commands are investigated in [VM13] [KKHL14]. The results from [VM13] confirm the recommended cap height of 4.0mm in [RMC12]. In [KKHL14], the results show that with increased touch-key size the usability of IVDSs (in-vehicle display systems) as well as driving safety increase. The validation is based on statistical tests of the variables error rate and driving safety (lane position, speed, and glance). Beyond a specific size, the usability and safety do not increase anymore.

In contrast, acoustic and haptic displays are used for safety violation warnings. Common types of sounds used in vehicles are: pure tones, musical tones, auditory icons, earcons, speech, etc. [NW11]. It is mentioned in [Cat04], that three forms of information may be identified in any auditory warning: “what (semantic)”, “where (location)”, and “when (perceived urgency)”. In [Gra99], two auditory icons, which are the sound of a car horn and the one of skidding tires, are compared with two traditional auditory warnings, a pure tone and a verbal tone used as collision warning in three scenarios. As result, auditory icons could help drivers to realize a faster reaction. However, more inappropriate responses are also caused by auditory icon. A similar experiment is done in [BRC99] to compare pure tonal sound and auditory icon as forward collision warning. The results also show the improvement of driver performance using auditory icons. In [Baz16], whether lane keeping can be realized only by auditory feedback or not, is tested. Experiments with 2 participants were done, during which the visual projection of the used driving simulator was turned off. Based on the results, it is suggested that the feedback should be provided using the predicted error rather than the current error. It is mentioned in [LWZS12] that the acoustic warnings cause relatively less distracting, but they deliver less information than visual warnings in certain situations.

Haptic interface is mostly used for lane keeping warning n steering wheel. In [Cao10], the earcon and vibration forms are designed for 4 different priority levels and compared in 5 conditions. The results show that the vibration form is identified more accurately and interfered less. The haptic interface is applied to realize a shared control between human and automation [GG05]. In [GG05], the automated action to the lane-following behavior is provided to the driver through the steering wheel. Experimental results from 11 participants show that both the primary task (lane-following behavior) and the secondary task (localization of sound emission from three speakers) are improved using the haptic assistance.

The implementation of the assistance system is either realized by the displayed warning or by the input of the desired value from the driver, such as ACC. However, the response of the driver to the instructions of ADAS is not checked, for instance, if the driver responses, how does the driver response. As the way of interaction between driver and vehicle becomes manifold, it is necessary for the system to provide enough useful possibilities to realize the same function but also not superfluous to avoid overload of the driver.

2.2.2 Realized DVIs of selected hybrid electric vehicles (HEVs)

Based on [OMLT$^+$13], possible areas to display information/warnings are restructured shown in Figure 2.1. The five main display areas denoted with numbers 1 to 5 in Figure 2.1 are:

1 Instrument cluster,

2 HUD (embedded [WBY$^+$09] [CPCP13] or add-on [OMGSF12] [HY17]),

3 Central console, and

4 and 5 Outside rear-view mirrors.

The information from driver assistance systems and hybrid driving systems from models of 9 selected manufacturers are analyzed. The displayed information can be categorized into two types: information related to driver assistance systems and

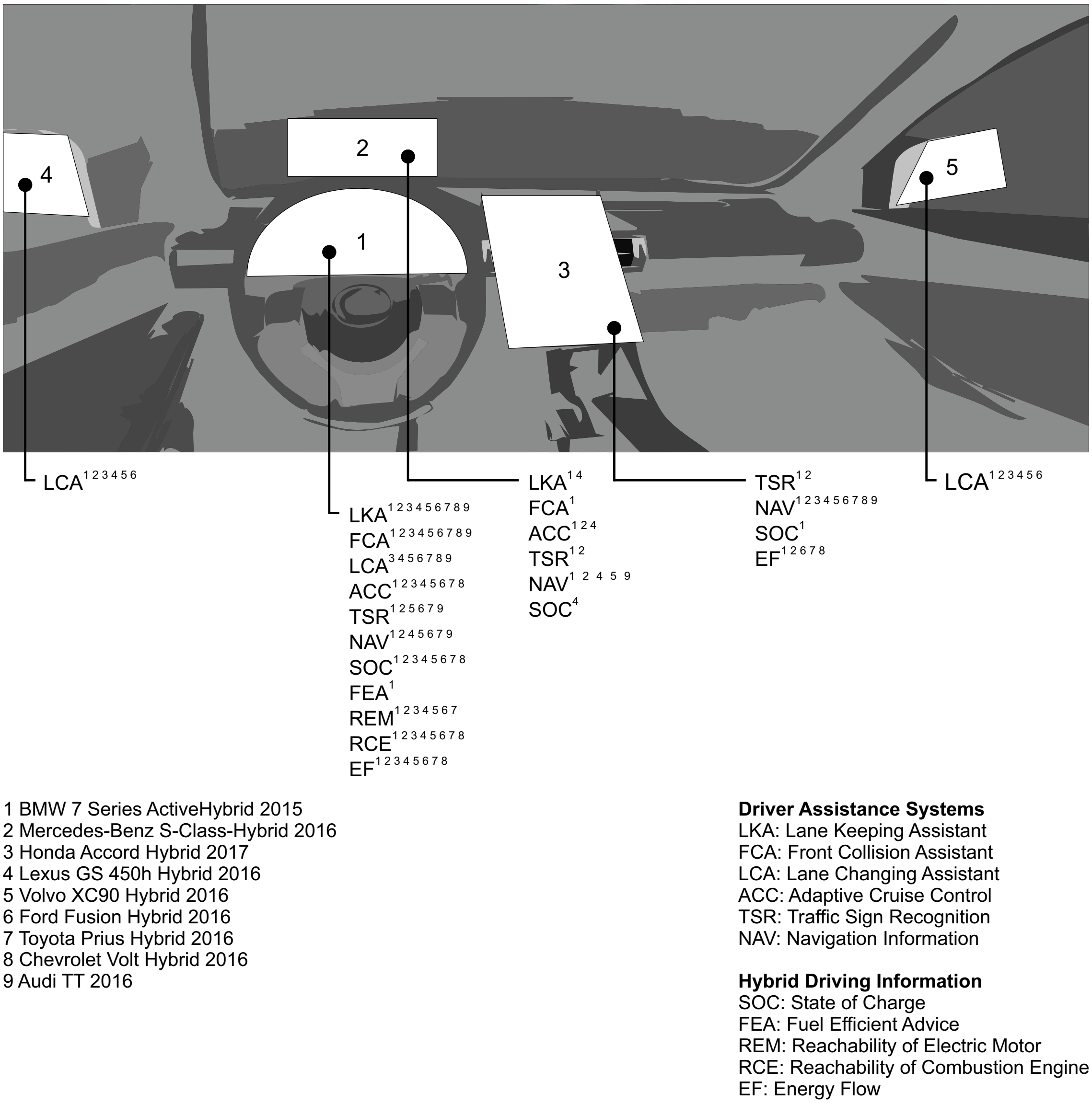


Figure 2.1: Summarization of IVDS in selected HEVs [WS]

information related to hybrid driving systems. As depicted in Figure 2.1, the instrument cluster is the main area displaying all information. The warnings from LKW (Lane Keeping Warning), FCW (Foward Collision Warning), TSR (Traffic Sign Recognition), and LCW (Lane Changing Warning), the status of ACC, the navigation information about next short range, and information of SOC are chosen to be displayed on HUD. The long-term and complex information, such as complete navigation information and energy flow of the hybrid system, is displayed on the central console. The LCW is also displayed on outside rear-view mirrors, because during the lane changing process or overtaking process, the focus of the driver is on the rear-view mirrors to perceive the situation. Redundancy is also applied to display warnings. The safety relevant warnings, such as: LKW, FCW, LCW, etc. are displayed in more than one area.

Hybrid system state information is mainly displayed on the instrument cluster and the central console. To increase the driving efficiency, several realizations use metaphors in the DVI to help the driver better to understand the actual current energy flow [Bru60]. The number of leaves and butterflies in Ford, trees in Toyota an Nissan etc., give the driver a direct impact with respect to his/her actual driving status with respect to efficiency. “The more the better”-metaphor shows the driver to achieve the most efficient driving. This kind of information should obviously guide the driver to achieve an efficient driving. It represents however only the actual current efficiency status of the vehicle. It is not clear, which behaviors in detail to achieve more efficiency should be realized by the driver.

2.2.3 Concepts of DVI

Two methods to design a DVI, namely user-centered interface design (UCD) [ND86] and ecological interface design (EID) [VR88] are commonly used. As interpreted from definitions, the UCD focuses on the end users while the EID pays more attention to the related working environment. The UCD is based on interviews and questionnaire methods on the objectives, while the EID relies on the abstraction hierarchy and the skills, rules, knowledge framework [WLLL16]. The UCD considers the preferences, needs, and limitations of the user. It focuses on simple and static systems [WLLL16]. However, in a complex system, such as a nuclear plant, it is not possible or even not necessary for the user to understand every relation, constraint, realized step by the system, etc. The EID could improve the users’ perception in the working environment, highlight the conflicts, and support the user in decision making.

Several concepts/ideas about the use of DVI can be found in the literature. These concepts are used to display the information of the vehicle and the assistance system to improve driving safety and efficiency from different aspects (FCW, LCW, LKW, etc.), which are summarized in Table 2.2 and detailed in the following discussions.

The actual ADAS are designed to help drivers solving conflicts within time-critical and short-term situations. The anticipation tasks for long-term situations are left to the driver, for example, the traffic intersection or traffic light lying further to the current position of the ego-vehicle. As proposed in [NDP$^+$09], future traffic condition can be anticipated and visualized to the driver. It is realized with the help of a virtual bird-eye perspective (VBEP) based on the incorporation of Augmented Reality (AR) displayed in the digital instrument cluster between speedometer and tachometer. In addition, a DVI named “smart deceleration” is shown to the driver to perform an efficient drive by decelerating when an obstacle occurs in the near future. Situations with permanent obstacles, temporarily stopped vehicles, and

Table 2.2: Summarization and comparison of DVIs [WS]

	Goal		Method								
Function	Safety relevant	Efficiency relevant	Position of display	Modality	Judgment of driving behavior	Variables used for warning or suggestion	Comparison between actual and optimal behavior	Suggested behavior	Individualization	Adaption	Reference
Deceleration suggestion	-	√	Between speedometer and tachometer	Visual	-	Safety distance	-	Begin of deceleration	-	-	[NDP^{+}09]
Avoidance of forward collision	√	-	HUD	Visual and/or acoustic	-	Safety distance	-	-	-	-	[AGR^{+}13]
Avoidance of forward collision and lane keeping	√	-	HUD	Visual, acoustic, or haptic	-	Risk level	-	-	-	√	[CLC12]
Lane changing assistance	√	-	No indication	Visual	-	Recommended maneuver	-	Lateral and longitudinal behavior by	-	-	[HWB^{+}11]
Suggestion about velocity and acceleration	√	-	No indication	Visual	√	Suggested velocity and acceleration	√	Velocity and acceleration	-	-	[ST12]
Improvement of car- following performance	√	-	HUD	Visual	-	Time headway to leading vehicle and acceleration of it	-	-	-	-	[Saf13]
FCW, LDW, CSW, BLIS, and RCW	√	-	No indication	Visual and acoustic	-	TTC for FCW; distance between wheel and lane marking for LDW; threshold velocity in curve for CSW; no indications of BLIS and RCW	-	-	-	-	[MAL11]
Suggestion of gas pedal usage	-	√	In the tachometer	Visual and acoustic	-	Reduction of fuel consumption based on [GES11]	√	Pedal usage	-	-	[HJJ15]
Obstacle detection	√	-	HUD	Visual	-	Position of obstacle, velocity, road markings, head and eye's position and orientation	-	-	√	-	[GTFC12]
Lane changing assistance	√	-	Left side of driver	Visual	-	TTC	√	-	-	-	[LMHB15]
Avoidance of forward collision	√	-	Under windshield	Visual	-	Distance between ego-vehicle and critical object	-	-	-	-	[PCB13]
Avoidance of forward collision	√	-	Driver seat	Haptic and acoustic	-	Threshold distance	-	-	-	-	[HR10]

slower driving vehicles are categorized to detail the displayed information shown with corresponding signs to represent different traffic situations to help the driver realizing an anticipate driving.

Alves et al. [AGR^{+}13] proposed two visualization metaphors based on traffic signals to warn the driver of violating the safety distance to avoid a possible forward collision. The authors incorporate the AR with the windshield using Head-Up Display (HUD). One of the visualized warnings is based on a traffic sign to keep a certain minimum distance to the preceding vehicle. Instead of the concrete limited distance, Alves et al. replace it with an exclamation mark. The second proposed visualized warning is based on road safety marks, which suggests keeping safety distance to the preceding vehicle. The designed warning is composed of three arrows showing the driving direction displayed to the driver. Two color schemes are used: yellow indicates violating the safety distance and red showing the imminence of a collision to reduce times of blink on instrument panel using AR displayed on HUD. The proposed approaches are validated by experiment with 22 participants. The preferences regarding age groups, average distance, percentage of safety distance violation, and reaction time are mainly compared. The results are not evaluated on a statistical case.

A coordinated multi-level cognitive assistance is proposed in [CLC12] to improve the cognitive adaptability of drivers presenting dynamic confidence information on an interactive interface. The relation between human and machine is divided into three types: soft aid, soft intervention, and hard intervention [KWPC05] [MKC05]. According to Cai et al. [CLC12] the driver is more adaptable to soft aid because in this case the driver remains in the decision-making loop. The confidence information of a system is transmitted to the driver through an appropriate interface between human and machine. Therefore, a coordinated assistance using multimodal interface consisting of visual, auditory, and tactile interfaces is developed by Cai et al. to realize the warnings of headway maintaining and lane keeping. Twenty participants were recruited in the experiment to validate the approaches. The evaluation is mainly conducted from primary driving performance (number of collisions, number of dangerous approaches, average lateral deviation, and its standard deviation), secondary-task performance, and subjective impression by one-way ANOVA (Analysis of variance). The results show that the performance in both the primary and the secondary tasks is improved. This approach increases the driver's trust in system by displaying dynamic confidence level of the system using multimodal interface. The open issue of the work [CLC12] is how to guide the driver to make concrete right decision.

Habenicht et al. [HWB^{+}11] proposed a maneuver-based lane change assistance system, which assists the driver from the intention of the driver about lane changing to the complete implementation of the lane changing without automation of the vehicle guidance. In [HWB^{+}11], the proposed concept is based on four pre-defined open loop control programs: no lane change, lane change with acceleration, lane change with deceleration, and lane change without acceleration. It combines the pre-defined open loop control programs and their information about timing, direction, and longitudinal dynamics. One of the proposed assistance systems was evaluated with the help of 37 test drivers [RHW$^+$12]. In [RHW$^+$12], the proposed assistance system is evaluated using the variables: available reaction time of leading vehicle on target lane, following vehicle on target lane, and leading vehicle on start lane. Results show that the approach is better than a normal lane change assistance system. This approach improves lane change behavior based on situation perception. As disadvantage is should be noted that the interface is not driver-individualized.

In [ST12], the velocity and acceleration advice is provided to the driver to realize distance keeping, more efficient gas pedal changes, and more effective traffic flow. Shahab et al. [ST12] calculate the optimal distance between the ego vehicle and the preceding vehicle based on the current velocity of the ego vehicle and transfer the distance to optimal velocity and optimal acceleration, so that the comparison between the actual values and optimal values are shown to the driver as well as the suggestions using different color schemes. The evaluation is done with help of 29 participants from subjective (interview and RSME (Rating Scale Mental Effort)) and objective aspects (speed, time headway, and accelerator pedal analysis). The results are analyzed based on one-way ANOVA and MANOVA tests. The validation experiments mainly focus on the variables (velocity, time headway, and accelerator pedal throttle), which should be improved with the proposed approaches, in combination with subjective variables (rating interface with 5-Likert scale of useful, effective, assisting, desirable, unpleasant, annoying, and good). These interfaces show the current situation and also provide suggested optimal velocity or acceleration to the driver. However, the designed interfaces are not adaptive.

An assistance system enhancing car-following performance of driver is proposed in [Saf13]. The information about acceleration of preceding vehicle as well as the time headway are displayed as HUD onto the rear window of the preceding vehicle. The idea is to show the driver the acceleration of preceding vehicle with color green to right side in horizontal bar and deceleration with red to left. The time headway is illustrated with vertical arrow. An experiment based on 22 drivers is realized to validate the assistance system. The minimum, maximum, and mean distance between two vehicles, mean relative velocity, acceleration, and jerk, and the percentage of variate ranges of time headway were measured. The measured values, driver model parameters, and the subjective evaluation were used for statistical analysis using independent-sample t Test and paired t Test. The proposed interface helps the driver to obtain an advanced view of the preceding vehicle, but it still stays on the situation perception level. The concrete suggestion about how to avoid forward collision is not integrated.

In [MAL11], an ADAS was developed based on EID. The proposed approach combines FCW, lane departure warning (LDW), curve speed warning (CSW), blind spot information (BLIS), and rear-end collision warning (RCW) as one group of icons to reconstruct the driving environment around the ego-vehicle. An auditory warning is played when the driving situation is critical and the driver is needed to react to avoid a collision. After heuristic evaluation by 5 experts in the areas of automobile, the idea is improved. The improved assistance system was evaluated based on driving simulator studies with 30 participants. Due to limitation of simulator, only three of the functions (FCW, LDW, and CSW) were implemented in the simulator evaluation. The standard deviation of lane position and the minimum time to collision were measured and analyzed with one-way repeated measures ANOVA. This approach displays the driving situation and shows the warning in a compact form, but the driving efficiency is not considered.

An eco-driving assistance is proposed in [HJJ15]. Three approaches, one visual and two haptic interfaces, are developed to help the driver achieving the most efficient driving. The visual interface is displayed in the tachometer. The suggested efficient behavior is shown to the driver as gas pedal pressure illustrated with a foot icon. Three color schemes (blue, green, and red) indicate the insufficient, appropriate, and excessive gas pedal pressure. The actual and desired gas pedal positions are also displayed to make the suggestion more understandable. The two haptic approaches integrate the force feedback and stiffness of the gas pedal to the driver, respectively. These three assistance systems are validated by experiment with 22 test drivers. The test scenario consists of six hill sections so that the variation of gas pedal position on the ascent, flat, and descent sections can be easily realized. The objective data (root mean squared gas pedal error and percent road center) are compared with two-way ANOVA with repeated measures. The subjective data (workload and system acceptability) are compared with non-parametric Friedman's ANOVA. The proposed approach simplifies the suggested optimal behavior into gas pedal pressure. The suggested efficient behavior considers the road condition but consideration about safety is not clear. The driver might wonder why the suggested optimal behavior is the real optimal one because of the lack of information about the environment.

In [GTFC12], a driver assistance system considering the drivers' state to improve driving safety is proposed. The approach combines position of obstacles as well as their level of danger and the driver's eye movement to assist the driver only when the help is needed. The driver is assisted with an augmented reality interface, which is displayed on the HUD. The interface is designed based on:

- The type of danger,
- The level of danger, and
- The criticality.

The proposed system is implemented in a real road test with the experimental vehicle, but no quantitative evaluation is done. This approach realizes an individualized assistance based on observing the driver's behavior using an eye tracker. Efficient driving was not considered in the concept.

Löcken et al. [LMHB15] proposed a lane change assistance system using an ambient in-vehicle light display. The light display is positioned to the left side of the driver with LED. Two concepts, namely discrete and continuous light patterns, are suggested to provide the driver with the information about the driving environment. The proposed idea is validated with an experiment, which consists of three conditions: baseline, with discrete light pattern, and using continuous pattern. Totally 19 drivers were recruited in the experiment. Hypotheses are formed to compare the number of good maneuvers and cognitive workload among three conditions. The good maneuver is defined by using two variables: the distance as well as TTC (time to collision) between the ego-vehicle and vehicles in front and behind. The measurements are compared with the help of one-way ANOVA with repeated measures and Quade's test for those not normally distributed data. This approach realizes an assistance system for lane changing decision and reduces the missing opportunities to overtake the preceding vehicle. However, the idea of using ambient light assistance may not be suitable for driving in the daylight because the contrast might be not suitable.

In [PCB13], the driver's attention about hazard objects is influenced by using a LED strip, which is affixed 360 degree around the interior of the vehicle under the windshield. The indicated area of the LED is marked by intersection points between the LED strip and the lines, which connect the driver's center point and the left-/rightmost points of the hazard object. The width of the displayed area is inversely proportional to the distance between the ego-vehicle and the hazard object. The proposed assistance system is evaluated by 13 participants in a driving simulator study. The test scenarios consist of 4 situations. The gaze attention time is measured, which is the elapsed time from the appearance of the object to the visual fixation on the object. The acceptance, the understandability of the system, and the mental effort are collected by questionnaires and interviews. No statistical tests are conducted in the evaluation. In other contributions [LCR11], [LMHB14], the light display is also used to help drivers keeping informed from current situation and making decision. Ambient lighting assistance system is a novel approach in recent 5 years to help drivers to recognize the driving environment and critical situations. However, the confusion of colors of the light and the environment could occur and therefore the warning could be easily overlooked especially while driving in the daylight.

A seat vibrotactile warning interface is introduced for FCW in [HR10]. Six transducers, which are controlled by a PC, are built up in the driver seat. The frequency of the vibration warning is chosen as 50Hz by test drivers. A micro scale electric vehicle is used to evaluated the proposed system. Three different warnings (auditory, seat vibrotactile, and both of them) are compared by 8 drivers. Braking reaction time is used to compare the three warning types. Furthermore, the headway distance, the minimum time headway, and the warning reaction time are used to compare the effectiveness between auditory and multimodal warning system. Haptic feedback in driver seat is also studied in [Das13] for lane departure warning. The haptic feedback in driver seat reduces driver's visual workload and distraction, but the functionality is limited and the effect would be changed under different road surface conditions.

Different aspects of the introduced novel approaches are summarized in Table 2.2. The comparison follows the design goal, applied method, and realized function. There is no approach considering both safety and efficiency perspectives. Only one approach displays the suggested behavior based on a comparison of actual and optimal behaviors. This is important because the user may wonder why the suggestion is the real optimal one. This combination may be more persuasive. The two criteria "Individualization" and "Adaption" are only fulfilled by one approach respectively. These two criteria are taken into consideration because every driver behaves differently and individually by facing problems. The preferences of drivers are also various. It can be concluded that the acceptance of the DVI is increased if it considers the driver's intention and adjusts to it.

2.2.4 Evaluation methods and discussion

The proposed concepts have to be evaluated to prove the feasibility and the acceptance of the users which requires the researchers to design an experiment. The evaluation methods of introduced DVI concepts in part 2.2.3 are listed and compared in Table 2.3. These summarized DVI concepts focus on lower automated driving levels. Therefore the variables considered for evaluation are different from these for higher automated driving levels, such as: takeover request time, hands-on time, takeover time [ES17]. As listed in Table 2.3, the variables used to evaluate the DVIs can be distinguished to objective and subjective ones. The objective measurements could be various depending on the specific function of the DVI. The most subjective measurements are acquired from questionnaires regarding annoyance, acceptance, trust, disturbance, etc. Besides these properties, the perceived workload of the driver is also an important variable. The perceived workload could be obtained using psychophysiological measurements and subjective reports [MHRD95] [VG96] [Bro10] [Mat15]. From Table 2.3 it can be concluded that most simulator-oriented evaluation methods are combined with statistical methods. This leads to another problem, whether the conclusion drawn from the experiment is strong enough or not. The minimum sample size by applying parametric statistical analyses varies from 20 to 30 [Pet97] [War08]. However, only considering the sample size can not ensure strong outcomes. Therefore it is helpful to estimate the sample size using the power analysis or to measure the strength of outcome by calculating the effect size [McD09]. The distribution of age and gender of the participants may influence the outcomes as well. These two factors are barely considered in listed studies. In [MAL11], the design and

Table 2.3: Summarization and comparison of evaluation methods [WS]

Reference	Function	Evaluation method	Secondary task	Number of participants	Dependent variables for statistical test	Applied hypothesis testing method(s)	Evaluation after	
							Gender	Age
[NDP$^+$09]	Suggestion for deceleration	-	-	-	-	-	-	-
[AGR$^+$13]	Avoidance of forward collision	Simulator	No	22	No	No	No	- $\geq$ 27 - 28-41 - $\geq$ 41
[CLC12]	Avoidance of forward collision and lane keeping assistance	Simulator	Search for six given street names on GPS navigator	20	• Headway maintaining performance • Lane-keeping performance • Secondary task performance • Subjective impression	One-way ANOVA	No	No
[HWB$^+$11]	Lane changing assistance	-	-	-	-	-	-	-
[ST12]	Suggestion about velocity and acceleration	Simulator	No	29	• Velocity • Time Headway • Accelerator pedal usage • Subjective rating • Workload based on RSME	No	No	No
[Saf13]	Improvement of car-following performance	Simulator	No	22	• Min., max., and mean distance • Mean relative speed • Mean acceleration • Mean jerk • Percentage of THW in three ranges • Parameters from driver-model • Subjective rating	• Independent-sample t-test • Paired t-test	No	No
[MAL11]	FCW, LDW, CSW, BLIS, and RCW	• Usability testing • Heuristic • Workshop • Simulator	No	• 6 • 5 • 3 • 30	• Lateral position • Minimum time to collision	One-way repeated measure ANOVA	No	No
[HJJ15]	Suggstion of gas pedal usage	Simulator	No	22	• Root mean squared pedal error • Percent road center • Minimum headway • Workload based on NASA-TLX	• Two-way repeated measures ANOVA • Friedman's ANOVA	No	No
[GTFC12]	Obstacle detection	Experimental vehicle	No	-	No	No	No	No
[LMHB15]	Lane changing assistance	Simulator	No	19	• Number of "good" maneuvers and corresponding requirements • Workload based on RTLX • Subjective rating	• One-way repeated measures ANOVA • Quade's test	No	No
[PCB13]	Avoidance of forward collision	Simulator	No	13	No	No	No	No
[HR10]	Avoidance of forward collision	Experimental vehicle	No	8	No	No	No	No

evaluation are executed actually parallel by applying “usability testing”, “heuristic evaluation”, and “workshop”. However, due to limitations of driving simulators, the realized functions BLIS and RCW can not be evaluated. This could be improved with real vehicle evaluation or redesign of the experiment.

Depending on various functions of designed assistance systems or interfaces, the experimental setups are also diverse. The commonly used device is driving simulator. The advantages and disadvantages of driving simulators are summarized in [de 12]. It is stated that compared to real vehicles, the driving simulator is easy to control and to collect data. The experiment using driving simulator is reproducible and possible to confront hazard situation without being injured. The simulation scenario is flexible to design, record, and analyze after the experiment. In [de 12], one of the essential disadvantages of using driving simulator to evaluate concepts is the limited belief in the driving simulator, which will directly lead to invalid outcomes due to unreal driving behavior. Furthermore, the experience of the driving simulator influences the operation of driving simulator as well. The behavior and reaction time could be influenced by the experience of using driving simulator. A participant with more experiences in driving simulator needs less time to deal with emergent situation or collision because of the familiar operating environment. During collecting the participants, the experience with driving simulator of them should be considered and variance should be avoided. In addition, the configuration of driving simulator varies as well among researchers. Some could be with 3D movement and force feedback, but some could be base-fixed without force feedback. The embedded model of vehicle is also different as well as the performance. These factors influence the driving behavior, recognition of the driving speed, reaction type, etc. It is difficult to achieve comparable results among different research groups, such as the study of takeover time.

To complete the process of proposing a DVI, experiments have to be performed, with which the feasibility of the concept could be proved and therefore the acceptance of the users could be assured. Depending on various functions of designed assistance systems or interfaces, experimental setups are diverse. Driving simulators are commonly used for experiments. According to the degree of freedom, fidelity, usability, complexity, and cost [MGMk15] [Slo08], driving simulators in general can be distinguished into three levels (high-level, mid-level, and low-level). By considering general characteristics, such as motion, visual, and sound systems, a method to classify driving simulators is proposed in [ETC$^+$14] based on existing classification standards of helicopter flight simulators. Virtual reality (VR) could also be used in driving simulators [BFP96] [Kem14]. As an application, head-mounted displays can be used to replace fixed screens with higher image resolution and wider field-of-view [MS01] [CEH$^+$02]. The effect of different levels of driving simulators is studied [APCF07] [PARF05] [de 07] [RA14]. In [RA14], a desktop driving simulator and a fixed-base full cab driving simulator are compared with proband tests. The results show that participants behave less smoothly using a desktop simulator than these using a full cab simulator. The accident rate with a single monitor fixed-base simulator with narrow field of view is larger than the one with a three-monitor simulator, which has wider field of view [APCF07]. The advantages and disadvantages of driving simulators are summarized in [de 12]. It is stated that compared to real vehicles, driving simulators are easy to control. Furthermore it is stated that the collection of data is easy to realize. Experiments using driving simulators are reproducible, so it is possible to confront hazard situation without being injured. Simulation scenarios are flexible to design, record, and analyze after the experiment. In [de 12], one of the essential disadvantages of using driving simulators is denoted as the limited believe of participants in driving simulator, which will directly lead to invalid outcomes due to unreal driving behaviors. Furthermore, driving simulator experiences influence the operation of driving simulator as well. The behavior and reaction time could be influenced by the experience of using driving simulators. A participant with more experiences needs less time to handle emergent situations or collisions. As a consequence during recruiting participants, the experience with driving simulator of them should be considered and variances should be avoided. In addition, the configuration of driving simulators vary. Some could be with 3D movement and force feedback, but some could be fixed-base without force feedback. The embedded model of vehicle is also different as well as the implemented performance. These factors influence the driving behaviors, recognition of the driving speed, reaction type, etc. It is difficult to achieve comparable results among different research groups.

Field studies using a real vehicle are the alternative option. Using real vehicle the behaviors of drivers are more natural. The components of the vehicle are fixed and thus the behavior of the vehicle is reproducible allowing other researchers to compare results. The differences of driving behaviors and results caused by different driving simulator types could be minimized using a real vehicle. On the other side studying hazardous situations using real vehicle becomes difficult.

Driving simulators are commonly used to evaluate proposed assistance systems. Regardless applied experiment device (driving simulator or real vehicle), also age, gender, and experience should be considered. Extra attention should be paid during the experimental design. It is critical to use repeated events in experiment to evaluate active safety systems [AEV13]. The FCW is evaluated using simulator study with repeated braking events of preceding vehicle in [AEV13]. It is concluded in [AEV13] that the repeated exposure and initial time headway play a significant role in evaluating the assistance system. Participants behave more proactively and anticipatively [AEV13]. Actions to response to the braking of the preceding vehicle are planned as, for instance, earlier release of accelerator pedal and earlier start of avoidance response [AEV13]. The experimental design to evaluate the proposed approach is essential to prove the efficacy of the system. It is suggested in [AEV13] that evaluation method using experimental studies should consider the scenario exposure and criticality.

Regardless of the automated driving level or the complexity of the system, the DVI should be always easy and quick to understand. The essential function of the DVI is to ensure that the driver is aware of the system status and environment as well as able to communicate with the system. The DVI should be simple and straight. One of the introduced DVI concepts [ST12] displays the comparison of the actual and optimal accelerations. As reported this can not be directly understood by the participants and leads to not applicable in dynamic driving environments. Using metaphors is commonly helpful for the driver to understand the abstract information. Various modalities have own properties. Among these various options, the maximum effect should be exploited and shortcomings should be avoided.

2.3 Change of interaction due to digitalization

Automation is primarily designed to simplify the tasks of human, to release the human's workload, to make human's life much easier, furthermore to realize stable processes and to ensure quality. As concluded in [Bai83] "ironies of automation" are: "... one is not by automating necessarily removing the difficulties, and also the possibility that resolving them will require even greater technological ingenuity than does classic automation." With respect to human-driver interaction different strategies of cooperative driving are developed to avoid the problems. Two types of cooperation in traffic system: in-vehicle cooperation and between-vehicles cooperation [ZBL$^+$14]. The first cooperation strategy mainly focuses on the human and the system considered as single operator and cooperating with each other in a complex situation [ZBL$^+$14]. The between-vehicles cooperation, as implied by the name, considers the cooperation between vehicles, which namely is a collective of the human and the system [BTD06]. The traffic problem such as congestion could be improved using this kind of cooperation. Between-vehicles cooperation can also be extended to among-vehicles cooperation, when more than two vehicles are involved in a complex situation. The combination of these two strategies provide also the opportunity to improve the driving safety as well as the driving efficiency, such as Truck Platooning, which consists of a number of trucks driving one closely after the other to reduce extra fuel consumption and tailbacks [YR17]. The following sections will describe these three strategies separately.

2.3.1 In-vehicle cooperation and related examples

According to [FHH$^+$12] the relation between humans and automated systems is dynamic and fragile . As mentioned in [FHH$^+$12], "A sufficient consistency of the mental models of human and machines, not only in the system use but also in the design and evaluation, can be a key enabler for a successful dynamic balance between humans and machines." Four cornerstone concepts: ability, authority, control, and responsibility are developed in [FHH+12] for the design of a human-machine system, which are coupled to the concept of level of automation. The consistency between the four cornerstones is the “key enabler for a successful dynamic balance between humans and machines”. In more details, the relation between the four cornerstones are: “Ability should not be smaller than authority”; “authority should not be smaller than responsibility”. An operator with no appropriate ability would not be suitable to get the authority. It would be not adequate that the operator has to take whole responsibility even though the operator does not have sufficient authority and ability. The basic relations between the four cornerstones combined with the level of automation are illustrated to help design and analyze the human machine system.

To represent a concept of cooperative driving, Flemisch et al. introduced the H-Metaphor (Horse-Metaphor) in [FAC+03]. Similar to the desktop metaphor managing digital elements in the computer, the H-Metaphor describes the human vehicle interaction based on a man riding a horse. Comparing to a bicycle, a horse can bypass the obstacles instinctively and give physical feedback such as reins. It then releases the human, who can focus on the work needed to be done in parallel. Furthermore, the notions of “Tight Rein” and “Loose Rein” are used to represent the two modes “Person controls” and “H-vehicle controls”, respectively. The concept is improved in a later publication [DKBB11], the driver and the automation system work parallel and simultaneously to achieve a common goal by communicating with each other via haptic, acoustic, and/or visual way. The notion of “Rein” is extended in [FBB+14] into “Tight Rein”, “Loose Rein”, and “Secured Rein” to represent “Assisted/Lowly automated”, “Highly automated/driver in the loop”, and “Highly automated/driver (temporarily) out of loop”, respectively. As explained in [FBB+14], the H-Mode mainly focuses on the guidance and control layers and can be realized as a trajectory-based or maneuver-based assistance system with the combination of a haptically active interface.

To realize the concept of H-Mode, active control elements for haptic feedback are developed and used [KDK+09]. The essential feature of the active control element is a bi-diretional communication between driver and automation. Instead of steering wheel, gas pedal, and brake pedal in conventional vehicle driving, a side stick is used to manipulate the vehicle driving with the force feedback or position feedback to represent the current state of the vehicle. This haptic feedback can be designed either from the control of the driver self or from the combination of the driver and the automation [DKB10]. In this way, the drivers can sense the suggestions of the automation and are not be out of the loop in the “Loose Rein” mode or “Fully automated” mode. According to [FBB+14], the current prototype of H-Mode HMI consists of either an active side stick or a combination of active steering wheel and pedals, a HUD used to display the current and alternative trajectories, and an extra display to show the automation levels.

Another concept of cooperative driving named Conduct-by-Wire (CbW) is proposed by Winner and Heuss in [WH05]. The idea is then improved in [WH06]. The main idea of CbW is to assign the automation system to accomplish the maneuver-based driving commands using predefined specialized maneuver interface. As described in 2.1, the driving task can be divided into three levels: navigation, guidance, and stabilization level. In conventional vehicle driving, drivers have to go through all the three levels to achieve the goal. But in the concept of Conduct-by-Wire, the driving task is simplified from "Guidance level" to "Stabilization level" into maneuvers, so that the translation from guidance level to stabilization level is not necessary any more, which releases the driver from stabilization tasks on the one hand. On the other hand, the necessity of vehicle managing skills decreases because the automation system controls the actuator elements instead of human drivers.

The concept of CbW is originally realized by integrating a tactile touch interface, which is fixed in the middle of the steering wheel, to display basic driving maneuvers and parameters, such as: lane change right/left, follow lane, desired velocity, etc. [KSB10]. The disadvantage of using tactile interface is that the percentage of gazes on the road is low. To solve this problem, gesture recognition device [FKB$^+$12] is integrated as input device instead of the tactile touch interface. A static HUD gives the visual feedback of the gesture recognition. These aforementioned approaches and the conventional steering wheel and pedals are compared in [FKB$^+$12]. To eliminate the disadvantages, an input concept named pieDrive is introduced in [FKBG12]. The improvement in pieDrive is to separate input and output device. As input device, a touchpad is used for the driver to perform the wished driving maneuver as well as related parameters. Using the HUD as output device, the driver can be enabled to see the executed driving commands. It also displays the preview of the trajectory of the vehicle. As concluded in [FKBG12], compared to the two previous concepts, the pieDrive enhances the eye gaze on road and reduces the interaction time. However, the disadvantages cannot be eliminated. The visual inputs may be overloaded and difficult for older drivers to input precise maneuver and parameters. Furthermore, the vibration and movement of the vehicle may cause dangerous input errors and result to negative impact on kinesthetic learning process and acceptance.

Besides the aforementioned two concepts, other options to realize the interaction between driver and vehicle for automated driving are known: gesture input [TLW$^+$] [BMB16] [GMY$^+$16] [JAK$^+$17], speech input [JBL$^+$16] [HRJ$^+$17] [KAF17] [SCS17], combination of them [NK16], brain computer interface [HBLS16], etc. Furthermore, helping the driver to intervene from automated driving mode in an appropriate manner is studied in [Van16]. Two approaches to support the driver of role changing from automation are proposed: i) sound in combination with visual warning behind the steering wheel; ii) sound and illumination in windscreen in combination with vibro-tactile stimulus in seat cushion. Results [Van16] show that the proposed approaches perform similarly in supporting the driver by intervention compared to the baseline test, which is only with sound feedback. In [MJG$^+$16], the driver's intervention during automated driving is studied. Two kinds of intervention are provided to the drivers: takeover (disable the automation and drive as operator) and takeover and influence (influence the vehicle without disabling the automation). Results show that drivers prefer behaving as supervisors than as operators in case of intervention.

2.3.2 Between-vehicle cooperation and related examples

Between-vehicle cooperation is referred to vehicular communication or inter-vehicle communication (IVC) which is used to increase the driving safety and efficiency [YR17]. The field of view of driver is limited physically. It is not possible for the driver to perceive the situation in the next crossing, the traffic along the trajectory to the goal, the coming vehicle behind an obstacle, etc. The IVC is designed with the goal to coordinate the vehicles or to collaborate with each other considering pedestrians, bicyclists, etc. from bird's eye perspective to assist the driver behaving anticipatively. The driver could be assisted by provided warning/information from IVC (Level 0 after SAE) or even higher levels, but the DVI is not the focus in the area of vehicular communication [HPY$^+$14]. However, DVIs for warnings obtained from sensor or camera techniques such as FCW, LCW, BLIS, etc. could also be used for IVC.

The IVC is mainly realized by using vehicular ad hoc network (VANET), which is a subclass of mobile ad hoc network [SAI14] [ASADABZ14] [SBP17]. Over 25 projects in European Union, the USA, and Japan have been conducted implementing VANET to develop intelligent transportation system [BK14]. The VANET provides a wireless platform for the moving vehicles to communicate. The VANET consists of three architectures [SAI14]

- Pure cellular (Vehicle-to-infrastructure (V2I)),
- Pure ad hoc (Vehicle-to-vehicle (V2V)), and
- Hybrid (V2I and V2V).

The routing protocols of the two basic architectures (V2I and V2V) are detailed, summarized, and compared in [SAI14] [BK14]. Practical applications to increase driving comfort and safety are detailed in [ASADABZ14] [HPY$^+$14], such as

- “Intersection collision avoidance, e. g.: Warning about blind merge detection”,
- “Public safety, e. g.: Approaching emergency vehicle warning”,
- “Sign extension, e. g.: Curve speed warning”,
- etc.

Three HMI concepts indicating the status of the traffic light signal are proposed in [KHTS16]. The test driving is based on V2I to deliver the status of the traffic light signal to the vehicle with the automated longitudinal guidance. The concepts are compared based on simulator experiment of 12 participants. The results show that a correct situation representation should be provided to the driver.

The challenges in VANET from technical point of view are discussed in [ASADABZ14]. One of them is how to maintain the communication quality. In the reality, obstacles, such as other vehicles or buildings, between two communicating vehicles, could cause signal weakening. Also the security and privacy are discussed in [ASADABZ14]. How to balance the reliability of the information sent to the receiver and the privacy on the sender's side is a challenging issue. The challenges of IVC applications are summarized in [JHH13].

2.3.3 Combination of in-vehicle cooperation and between-vehicle cooperation and related examples

In [ZB13], Zimmermann and Bengler summarized several definitions of cooperative systems, in particular related to cooperative driving. Five layers of cooperation between user and machine are proposed

- "User and machine intention",
- "Mode of cooperation",
- "Allocation",
- "Interface", and
- "Contact".

A lane-change scenario with two participants/vehicles consists of four units, namely two human and two machine partners is used, which involves both the in-vehicle cooperation and the traffic cooperation. During cooperation, mode error is observed [Nor98]. The goal of the designed cooperation is to achieve a "mutual understanding of the user mode and system mode" via a sequence of modes: "Intention Mode", "Cooperation Mode", "Allocation Mode", "Interaction Mode", and "Interface Mode". In the "Intention Mode", the common goal is defined. Afterwards, the suggestion about how to achieve the goal is provided in "Cooperation Mode". The "Allocation Mode" means the analysis of useful resource of the current situation to realize the discussed common goal. After that, in the "Interaction Mode", the action is executed in five phases: "request", "suggest preparation", "prepare", "suggest action", and "action". Finally in the "Interface Mode", a multi-modal interface is established to realize a continuous communication. Using AR the proposed prototype for the visual interface [ZB13] is improved in [ZBL+14]. In Table 2.4, the three above mentioned concepts are compared related to previous statements.

The "five layers of cooperation" introduced in [ZB13] is only suitable if there are no time requirements for the interaction. The proposed system is not capable of assisting in short-term driving maneuvers, such as a lane change maneuver during heavy traffic. In the Conduct-by-Wire [WH05] a "mode confusion" by a long-term execution of driving tasks exists, because the status of the assistance system might not be perceived by the driver. A satisfactory solution for this point is found in the H-mode [FHH+12]. Here only the lowest level of driving task execution can be intervened, which is also implemented on exactly the same channel. This is advantageous (the same channel, in which the influence can be directly perceived and carried along or rolled over) and disadvantageous because no complex automated solutions are or can be realized.

Concluding from the previous analysis it can be stated that the role of the interface and related additional functionalities are restricted. More complex systems will lead to a more complex system state representation to be displayed to the driver. In the best case the DVI and the related system (vehicle) behind ensure a successful interaction between driver, vehicle, and environment. Advanced approaches (CbW, H-mode) compress the information available so that the interaction between the driver and the system is less complex. Furthermore it can be stated that existing DVIs do not provide guidance advices to overcome detected critical solutions (as example: for taking over driving after TOR).

2.3.4 Interaction in higher automated driving levels and related examples

Defined as level 3 in [SAE16b], the automated driving system issues a "request to intervene" (RTI) to the "DDT (dynamic driving task) fallback-ready driver", when "ODD (operational design domain) limits are about to be exceeded" or "there is a DDT (dynamic driving task) performance-relevant system failure of the automated driving system". However, in most publications [Pet17] [ES17] [LDS+16] [MRD+15] [MJMJ17], the term takeover request (TOR) is applied. In [Pet17], it is defined as "when a highly automated car reaches its operational limits, it needs to provide a takeover request (TOR) in order for the driver to resume control". The term TOR is used in this work as the more general case.

The TOR time and takeover time of the driver are often studied. The used TOR time ranges from 0 to 30 s and the takeover time needed by drivers ranges from 1.14 to 15 s [ES17]. The range of takeover time is obtained based on various simulation environments, takeover scenarios, non-driving-related tasks (NDRTs), etc. In [GDLB13], the takeover scenario takes place on a motorway with three lanes.

Table 2.4: Comparison of three interaction concepts [WS]

Reference	Name	Number of interaction channels to be coordinated	Coupling/decoupling of geometrical and problem -oriented input channels	Robustness of input	Modality and method how can the automation intervene the interaction
[FHH$^+$12]	Horse-Mode (H-Mode))	3	The input realizes only stabilization task or rather restrict execution task.	Strong	The automation intervenes in the same channel and can be overdriven.
[WH05]	Conduct-by-Wire (CbW)	2	The input realizes execution task; the stabilization task is realized automatically (both are decoupled).	Middle; partially weak	The automation is integrated (stabilization level is automated; further intervention is not planned).
[ZB13]	-	5	The input realizes execution task; stabilization task is realized automatically.	Weak	The automation cannot intervene.

Because of an accident on the right lane, the driver should take over the vehicle control and could either stop on the current lane or veer to the middle lane. The NDRT is visually demanding Surrogate Reference Task (SuRT; ISO/TS 14198). The driver should find and mark a pre-defined target from various similar forms. The experimental results show that the drivers respond faster with shorter TOR time. A three-lane motorway is used in [LDS$^+$16] to study the effect of additionally displayed TOR on nomadic devices. The driver should take over and change to the middle one because the right lane ends due to roadwork. Similarly, SuRT is used as NDRT. Results show that a better takeover performance could be obtained with additional TOR on nomadic devices. A two-lane motorway with road construction site at the end is used in [MRD$^+$15] to study the effect of additional brake jerk after TOR besides the TOR displayed on mobile phone. The driver should take over and perform lane change maneuver. Up to the TOR the driver should solve a mobile quiz game as NDRT. Results show that both the additional brake jerk and the TOR displayed on mobile phone could increase the users' acceptance. However, no effect on the takeover time could be obtained. In [GKLB16], the driver should takeover because of a stopped vehicle on the current lane. The effect of traffic density on takeover is studied. A conversational "20-Questions" task is used as NDRT [MJLC12]. The participants have to guess predefined animals by asking the experimenter questions answered with only yes or no. The results show a longer takeover time with presence of traffic. The "20-Questions" task as NDRT has no influence on takeover time. In [MJMJ17], the drivers should take over the vehicle control by a curve with failed lane markings because of road construction. The drivers are asked to play a popular iPad game. The takeover time is studied with different TOR time (2, 5, and 8 s). All 10 participants with 8 s TOR time complete the takeover successfully. The prior familiarization with the TOR could increase the takeover time of the driver [HLK17]. A modified SuRT is used as NDRT. However, only one takeover situation is studied in [HLK17], which is a sudden accident in the middle lane in front of the ego-vehicle with TOR time 7 s. Results show a positive effect of prior familiarization on takeover performance in the first drive than the second one.

To summarize the critical scenarios used in the mentioned studies [GDLB13] [LDS$^+$16] [MRD$^+$15] [GKLB16] [MJLC12] [MJMJ17] [HLK17], the often used takeover scenarios are based on emergency brake or lane change maneuvers. In some cases [GDLB13] [LDS$^+$16], the situation is simplified by removing the traffic near to the ego-vehicle. In reality, the influencing factors in the surrounding could not be neglected. The applied tasks for NDRT are various, with which various cognitive activities are used. In [HLK17] it is observed that the sequence of experiencing the TOR and the takeover maneuver influences the takeover time. As reason it is stated that the human needs more effort and time to manage the task by the first experience. The question arises if the results are comparable based on the variation of those variables. In the analyzed studies [GDLB13] [LDS$^+$16] [MRD$^+$15] [GKLB16] [MJLC12] [MJMJ17] [HLK17], the TOR time is previously defined and fixed using mean or median value. The individuality of the takeover situation as well as its experience are not considered. Is it suitable to do so? Would drivers behave differently when these variables are various? Is one general TOR time suitable regardless the individual abilities of drivers, specific features of takeover situations, and also the combination of individual experiences of the drivers with specific situations? These questions will be answered in this work.

As increment of level of automated driving, the kind of communication between the driver and the vehicle changes from previous one-directional (system displays information to driver) to bi-directional (additional driver input commands to system) [BMB16] [SCS17]. In this context, higher level of automated driving is involved as well as the transition between two automated driving levels.

Augmented reality (AR) is used in [LS16] to smooth the takeover reaction with respect to the steering rate, depression speed of gas and brake pedals, and the resulting acceleration in longitudinal and lateral directions. The surrounding vehicles and the route to follow are displayed with AR. Results from experiments with 26 participants show that the lane change maneuver is more anticipated and the brake behavior is smoother using AR, but the takeover process and takeover time are not improved by using AR. In [KJY$^+$17], two visual windshield concepts are proposed to enhance the surveillance of the driver before the takeover. The idea of the two approaches is to highlight a dangerous vehicle with a rectangle with AR on the windshield based on useful field of view and object view respectively. This idea focuses only on the preparation of the driver for the takeover. In [FNN16], a visual DVI is proposed for conditionally automated driving to depict the driving state, the action executed by the system and the reason, and TOR. After driven by 6 human factors experts, improvements about symbols for specific situation are realized. The whole TOR is displayed to the driver 20 s before the real breakdown, which includes 5 s for description of the critical situation, 12 s for soft TOR with amber color (symbol with hands on wheel), and 3 s for hard with red color. The TOR does not include auditory warning. The description of the critical situation is not shown with the soft and hard TOR. If the drivers miss the 5 s, they might not be able to understand the situation with help of the DVI. This approach is similar to the one in [KJY$^+$17], which prepares the driver for a successful takeover. In combination with the proposed DVI in [FNN16], an auditory feedback is used in [NFWN17]. The upcoming actions of the automated system are provided to the driver with either generic auditory feedback or additional speech output to increase the understanding of current driving situations and in the meanwhile not to interrupt the driver during the NDRTs. Based on the results with 17 participants the authors concluded that informing the driver about the upcoming automated actions with additional speech could decrease the ratio between the time spent on monitoring the visual DVI and the time of the automated driving maneuver. In the meanwhile, the NDRT was not affected. This approach focuses on better understanding of the automated system in only one automated level. A cooperative interface is developed in [WSH$^+$16] to avoid full handover when the system can not deal with critical situations. Several options including the TOR are displayed on the central console and with speech. The driver could choose one of the provided options either by pressing it with a touch or saying relevant number of the option. The system then executes the selected option if the driver does not want to take over. This idea provides the driver options alternative to takeover, but the mode confusion/error problem could still occur. Multimodal and directional TORs are investigated in [Pet17]. In [Pet17], auditory (single pair of beeps), vibrotactile (same pattern as the auditory ones but stimulated on driver seat), and both of them are provided as TOR. All three different realizations of TOR are provided with directions: left, right, and both. The results show that the multimodal TORs help the driver having faster steer-touch times, but no directional response is caused because of the directional stimuli. For higher automated driving levels, two DVI concepts for highly and fully automated driving (SAE level 4 and 5) in [MDT16] are proposed to realize a balance between trust and comfort using HUD (Head-up display) to display information about system uncertainty level, timer for automated mode, activities of assistance systems, current velocity, and trip related information, etc. The information about why and how the system is performing an action is shown in one concept with HUD and another based on central console. This concept does not consider, how the drivers should be announced in critical situations the system not able to handle. Even on SAE level 4, on which the system as fallback in performance of dynamic driving task, the system is still not capable for all driving modes. In such situations, the driver should also respond although they are not expected to do it appropriately.

The DVI design goals are summarized in Table 2.5 based on [SAE16b]. The requirements on designing DVIs for levels 1 to 4 are the highest, such as increasing SAW [BS83] and MA [SW94]. The introduced DVIs [LS16] [KJY$^+$17] [FNN16] [KJY$^+$17] [NFWN17] [WSH$^+$16] [Pet17] [MDT16] focus only on one or two automated levels, especially on how to help the driver to take over the control of the vehicle. However, in this process multiple driving modes and the corresponding functionalities are involved. This could cause mode error/confusion [Nor81] [BL05]. Is it possible to use one DVI to show the different status of automated driving levels and its corresponding limitations to avoid mode error/confusion and in the meanwhile to increase the situation awareness of the driver? This will be answered in this contribution.

2.4 Summary and conclusions

In this chapter, the state-of-the-art of the driver assistance system in combination with levels of automated driving, as well as the potential problems caused by automation are discussed. The states of the market and the art of the IVDS are

Table 2.5: DVIs in different automated driving levels: Summary [WS18]

SAE level	Goals of DVI	Goals of design DVI	Interaction mode	
			Input	Output
0	- Displaying information from ADAS - Warning of potential danger	- Information shown in time - Less distraction - Ergonomics	-	- Visual - Acoustic - Haptic
1 - 4	- Description of driving situation - Warning of potential danger - Pointing out focus in critical situation - Providing suggestions and options - Assisting driver to take over control from higher mode	- Information shown in time - Less distraction - Increasing SAW and MA - Filtering essential information - Ergonomics	- Touch - Speech - Motion	- Visual - Acoustic - Haptic
5	- Description of driving situation - Description of vehicle status	- Ergonomics	-	- Visual - Acoustic

summarized. The change and challenges of the interaction between the driver and the vehicle due to digitalization are investigated.

Concerning the discussion in this chapter, the existing challenges and potentials in ADAS and DVI can be identified. For lower automated driving level, guiding drivers to realize a safe and efficient driving using DVI is possible. For higher automated driving level, the same purpose for lower automated level as well as to hand over the drive to the driver using DVI should be considered. For the vehicle with multiple driving modes, the system status and related capabilities should be also provided to the driver. Furthermore, the limits and boundaries of the driver should be investigated.

These lead to the goals of this thesis, which are:

- to develop DVI displaying suggestion to realize an efficient driving,
- to study the effect of different ways of displaying information in driver's behavior,
- to develop DVI to realize different levels of automated driving,
- to study the takeover behavior of drivers, and
- to investigate the design principles and requirements of DVI for vehicles with multiple automated driving levels.

3 Concept of closing driver-vehicle-environment loop with DVI

This chapter introduces a concept of driver-vehicle-environment-interface interaction loop. To achieve a safe and efficient driving within different levels of automated driving, an appropriate interaction between the driver and the vehicle is crucial. The driver-vehicle-environment loop closed by the DVI realizing the aforementioned goals is represented. The concept and figure are modified after previous publications [SWS+13] [WS14].

The way of interaction between the driver and the vehicle changes when different automated driving modes are introduced. In manual driving without any assistance system, the driver's command is realized through the steering wheel, pedals, buttons, etc. The area of displaying the state of the vehicle is limited to the instrument panel and central console. As increasing level of automated driving, the area of displaying information is extended to the windshield and rearview mirrors. The way of entering driving commands is expanded to using touch display [FKBG12], gesture [JAK+17], and speech [SCS17]. The communication between the driver and the vehicle tends to a real interactive dialog. All the ways for the communication could be summarized as a driver-vehicle interface (DVI). This interface realizes the bidirectional information flow and closes the driver-vehicle-environment interaction loop.

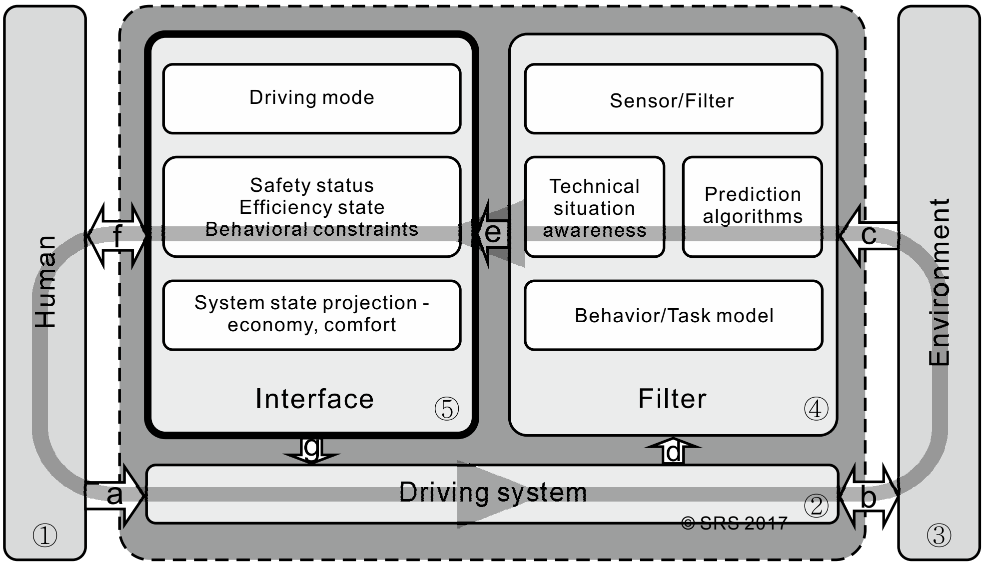


Figure 3.1: Concept of human-vehicle-environment-interface interaction loop (modified after [SWS+13] [WS14])

As shown in Figure 3.1, the named modules (① to ⑤) and interconnections (a to g) of the concept introduced are explained in Table 3.1.

Table 3.1: Description of modules

①	The human driver affected by the information displayed on the interface. According to the suggested next operator, he/she can follow the suggestion.
②	The driving system or related hardware realizes the vehicle propulsion.
③	The environment (including other vehicles) affects the driving interaction and is affected by the human driver. The environment includes traffic scenarios, driving scenarios, rules, technical systems, and humans.
④	The models regarding the technical situation awareness, intention prediction, fuel efficiency optimization, etc. are built from the filtered or compressed sensor data. Within this module, the warning or suggestion for next action of the human driver can be obtained based on the combination of the results from the built models.
⑤	The interface is used to display information to the human driver. Beside the status information, the conflict between the current driver behavior and allowed one is represented as warning shown to the driver. In non-critical situations, the optimal behavior can be illustrated. The levels of automated driving are highlighted to the driver to maintain mode awareness.
a	The realized action of the human driver affects the status of the vehicle directly through pressing pedals, steering, etc. The desired command could be indirectly transferred to the module ② through the interface.
b	Due to the affected behavior of the ego-vehicle, the environment including the surrounding vehicles is also affected. In the meanwhile, the situation of the ego-vehicle can also be influenced by the environment.
c	Technical sensors are used to measure available parameters from the environment.

d	Technical sensors are not only used for measuring the parameters from the environment, but also from the ego-vehicle. Based on these two parts, the algorithm inside the module ④ builds a technically realized situation recognition and therefore realizes a technical situation awareness. The intention of the driver could also be predicted and compared with the results from the technical situation recognition part. The efficiency optimization algorithm needs the information from the driving environment and the status of the vehicle to calculate the next efficiency optimal behavior.
e	The combined results from the technical situation recognition, intention prediction, and driving efficiency optimization algorithms will be displayed to the human driver on the interface with a well-performed form as a suggestion or a warning.
f	The drivers could obtain the displayed information in an appropriate manner to realize a safe and efficient drive. Using an interactive device, the driver could input desired parameters or driving command to control the driving and switch among different driving modes.
g	The desired parameters and driving mode from the human driver are transferred to the driving system and realized.

The interface in the concept is not only limited to a visual display option. It should be multi-modal and adaptive depending on which kind of information should be provided.

At lower automated levels, the drivers are still in charge of driving. “How to drive” in context with safety could be assisted with DVI by showing warnings. The suggestions or options could be provided to the drivers for the realization of an efficient driving. They do not only denote as a rule-based action or a complex set of rule-based actions but include a situational sequence adapted to higher goals. These warnings, suggestions, or options are realized in the module ④ combining the results from technical situation recognition, intention prediction, and fuel efficiency optimization algorithms [WS14] [SMW14] [WMS15a]. The interface is placed between the environment and the human, interacting with the vehicle in combination with the environments’ reaction. Using the internal prediction algorithms, the system state, safety status, etc. are visualized to affect the human acting and decision behavior. The human perceives the information and can change the current behavior. The effect of the behavior can be directly observed. Here a loop between human, environment, and driving system is realized including the visualizing interface.

At higher automated levels, but not fully automated driving, the interface is not only used to guide the driver “how to drive”, but also to display the limitation of the vehicle and the requirement of intervening in special cases. The focus of the interface in this case is to ensure a safe takeover.

The development of automated vehicles is in a transition phase. It could be the case that more than one automated levels are included in one vehicle. In such case, the current automated level, as well as their functionalities, should also be displayed on the interface to avoid the mode error/confusion.

4 Using Head-Up Display (HUD) to increase driving efficiency

As concluded in chapter 2, the DVIs have the potential to assist the drivers to increase driving efficiency. This leads to the following two questions.

- *In which way could the information be displayed to help the driver to increase the driving efficiency?*
- *How should the DVI influence the driving behavior in the way which the driver would accept?*

The fuel efficiency mentioned in this chapter is indicated as fuel economy, which is defined as a ratio between the distance and the amount of fuel consumption. In this chapter, three ways (numerical, text, and iconic) of displaying the suggested optimal driving velocity are suggested (section 4.2). The efficacies of them are compared with a baseline test without any suggestion through an experiment (E1). The objective and subjective results are explained in section 4.3. In section 4.4, the results are discussed and concluded. The hypotheses for next experiment are derived.

The contents, figures, and tables presented in this chapter are modified from publication [WS16].

4.1 Simulation environment and measuring technique

First of all, an overview of the development and simulation environment, as well as the measuring technique used in the experiments, are introduced. The concrete application of each device and corresponding setup are explained in each experiment respectively.

4.1.1 Driving simulator

As introduced in 2.2.4, a driving simulator is advantageous because it is easy to control and to collect data. Using driving simulator, a hazard driving situation could be analyzed without any injury. Therefore a base-fixed driving simulator is used to develop the proposed DVIs and to realize the experiments.

The overview of the driving simulator is shown in Figure 4.1. It consists of 5 monitors with a total angle of view of 180° projecting the driving environment. The instrument panel, also named as the dashboard, is displayed on a 10-inch monitor

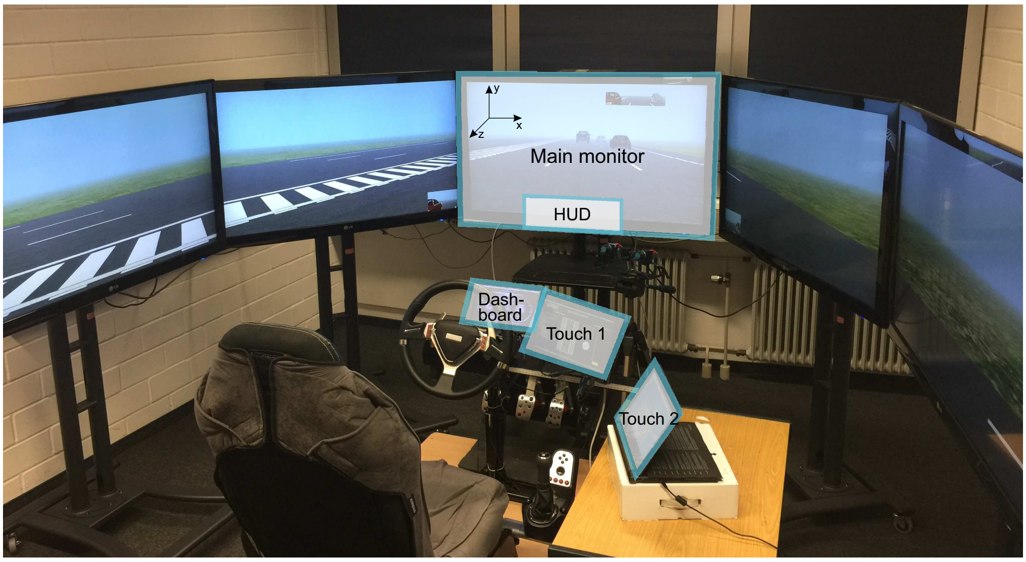


Figure 4.1: Driving simulator of the Chair of Dynamics and Control, University of Duisburg-Essen

behind the steering wheel. The head-up display (HUD) is realized on the main monitor. The bidirectional interaction between the driver and simulator is realized by a touchpad with the size of 11.6 inches (touch 1). The touch 1 and another touchpad (touch 2) sized with 11.6 inches could be used for the secondary task. The position of the dashboard along the y- and z-axes, as well as the rotation along the x-axis, can be adjusted. The positions and rotations of both touchpads can be adjusted as well as set for both right- and left-hand users. The inside rearview mirror is displayed on the top of the main monitor. The two outside rearview mirrors are shown in the corresponding bottom corners of both monitors beside the main one. The experiments are realized in a darkened environment to ensure a realistic driving scene.

The software SCANeR^{TM}studio is used to build the simulation environment. It can be used for vehicle ergonomics and advanced engineering studies as well as for road traffic research and development. The driving simulator can be coupled with a HiL hybrid drive test rig so that the powertrain model of the driving simulator could be replaced by the hybrid electric vehicle model. The driving simulator and the HiL (Hardware-in-the-Loop) are connected via Matlab and SIMULINK so that the information about the status of the HEV model could be transferred to the driving simulator. The DVIs proposed in this thesis are developed based on the driving simulator. The driving scenarios can be constructed and the information about the driving tests can be recorded using the driving simulator. The simulation could be recorded as video to confirm the correctness of the exported data. The data could be exported with frequency ranged from 20 to 1000 Hz.

4.1.2 Eye tracker

Figure 4.2: Eye tracker of the Chair of Dynamics and Control, University of Duisburg-Essen

During the experiment, an eye tracker (faceLAB 5) as shown in Figure 4.2 is used to measure and record the gaze, head, and facial features of the participants. A set of cameras as a passive measuring device is used to export the characteristics of a participant's gaze, face, and head, which include the current position and orientation in 3D space, the gaze direction, and other measurements. The eye tracker provides two tracking methods: pupil tracking and iris tracking. The default one is the pupil tracking, which is more robust if the pupil could be tracked correctly. However, it may be more effective using iris tracking when the iris is very dark or the subject is far away from the cameras. With this method, the pupillometry is not available [fac12].

The data from the eye tracker can be recorded with a sampling rate of 60 Hz. The eye tracker can also be connected to the driving simulator through SIMULINK so that the data from the eye tracker can be transferred to the driving simulator in real time. The head movement, as well as the gaze direction on predefined planes, can be recorded as video to ensure the quality of the recorded data. The position of the eye tracker varies depending on different areas of interest.

4.2 Experimental design

4.2.1 Development of DVI on HUD

To increase fuel efficiency, optimizing the power management of the powertrain in an HEV is one solution. In most HEVs, the driver is accepted as being passive and informed with the results, such as: how much energy was returned to the system by the last braking. The fuel efficiency could also potentially be increased based on the change of driving behavior of the driver. The optimal behavior calculated from the system is based on the environment, which is influenced by the driver and vice versa. The connection between the driver and system is the interface, which closes the driver-vehicle loop. Showing the corresponding consequences let the user know the reason, why the so-called optimal behavior is the real optimal one, and therefore, should be displayed to the user as the recommended one.

As written in chapter 3, one of the goals of designing the human-vehicle interface is to realize an efficient driving. As an example, when the desired goal is to realize an efficient driving, the optimization model will be used to calculate the optimal velocity for next few seconds. The resulting State of Charge (SOC) of current velocity, as well as SOC, resulted from optimal velocity are calculated within the hybrid electric vehicle model. The calculated results are displayed on the interface. The algorithm to calculate the optimal SOC considers the actual SOC, the actual driving style, and assumptions about the upcoming driving cycle/load. This integrates the human using the interface into this specific control loop.

Figure 4.3: Interface “Number” [WS16]

In [WB92], several suggestions about displaying exact value are given. Considering the dynamic driving environment, three possible forms: digital, analog, and text, are chosen to display the suggested optimal velocity. According to [WB92], the digital form is “optimum” to display an exact value, whilst the analog and text forms are “workable but suboptimum”. To compensate this unbalancing, the comparison of consequences using SOCs in analog form is coupled to the latter two forms in the design. In this way, the drivers might understand the suggested behavior and follow it, so that an efficient driving could be achieved. However, the visual workload could be increased by adding more information.

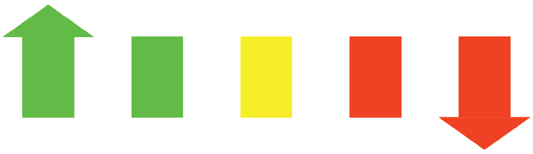


Figure 4.4: Five suggested driving behaviors of interface “Image” [WS16]

As mentioned, three approaches displaying the calculated information from optimization algorithm [MWS15] are introduced. One interface named as “Number” displays only the text “Optimal Velocity” and the corresponding value in digital

Accelerate
Decelerate
Keep

Figure 4.5: Three suggested driving behaviors of interface “Text” [WS16]

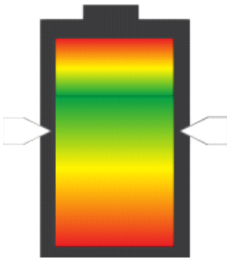


Figure 4.6: Comparison of current and optimal SOCs [WS16]

form as shown in Figure 4.3. This informs the driver to follow the displayed velocity. The second interface named “Image” (Figure 4.4) shows the elements developed to illustrate the effect of the current velocity on the current SOC, which is indicated by the icons. Five classes are illustrated. The arrows and bars represent accelerate hard (green), accelerate gently (green), constantly drive (blue), brake gently (red), and brake hard (red), respectively. The effect of the future optimal velocity on the future SOC is shown to the driver in comparison to the current one (Figure 4.6). The optimal SOC is shown with a movable progress bar. The dark black line in the battery indicates the SOC when the suggested optimal velocity is followed. As explained in last paragraph, the comparison of SOCs are displayed to the driver near to the suggestion. Considering it might be difficult for the driver to remember the meanings of the arrows and bars in combination with different color schemes, the last interface named as “Text” is proposed as shown in Figure 4.5. Interface “Text” shares the same logic behind of the interface “Image”. The difference here is the categories of suggested actions are reduced from former 5 classes into 3 classes, namely accelerate, keep the actual velocity, and decelerate. Furthermore, the suggestions become also more directly compared with the interface “Image”. It uses a text description with different colors (green, red, and blue) to show the suggested actions to the driver (Figure 4.5). The comparison between SOCs is displayed near to the suggestion. The differences and effects of these three approaches on driving efficiency and behavior are studied by experiments, which are introduced in the following sections.

4.2.2 Independent and dependent variables

In this experiment (E1), only the main monitor as shown in Figure 4.1 is used to display the related information. The speedometer and the tachometer as HUD are displayed on the main monitor. The fuel efficiency optimization algorithm uses the current velocity of the ego-vehicle as the input to calculate the current SOC, the optimal future velocity, and the resulting SOC [MWS15].

The goal of the experiment is to test if the fuel consumption could be reduced by using the DVIs. The efficacy of the DVIs should be compared. Furthermore, the relation between the achieved increment of fuel efficiency and the perceived workload should be studied.

Figure 4.7: Simulated scenario for E1

The driving scenario as shown in Figure 4.7 consists of a curved country road with two lanes. Totally 20 speed limits with 70 *km/h* and the corresponding end of speed limit based on fixed distances were set along the road. The total driving distance was ca. 22 *km*. These speed limits provided different situations for the test driver to accelerate and decelerate. The goal of the test driver was to realize an efficient drive within an HEV. Considering to eliminate the disturbance of the environment, no traffic was designed in the scenario. The idea was to consider the effects only from different interfaces on driving efficiency. A real traffic environment will be integrated into next experiment with improved interfaces.

Four driving tasks based on the same scenario, but with three different interfaces and one without interface were performed by each participant. Herein a repeated measured experiment is used. As the goal of the experiment was to analyze the influences of different interfaces on the behavior of the driver, the interface (I) is one independent variable (IV). Another ID results from the design of the scenario. The driving behaviors would also be influenced due to the speed limits. Therefore speed limit (SL) is considered as the second IV.

The difference among the proposed interfaces are analyzed from these perspectives: usability of the interface, situation awareness, and workload of the driver. They are evaluated using the dependent variables (DV) listed in Table 4.1.

4.2.3 Hypotheses

Several hypotheses are established based on the introduced IV interface and DVs. They are summarized in Table 4.2. The hypotheses focus mainly on testing the usability of the proposed interfaces, visual impact of them on the drivers, and consequent workload on drivers.

4.2.4 Participants

Thirty-two participants (29 male, 3 female, mean age = 24 years, min. = 19, max. = 28, SD = 3) were recruited. They all held valid driving licenses. The driving experience ranged between 2 and 12 years (mean = 6, SD = 3). They drove min. 500 *km* a year and max. 30,000 *km* a year (mean = 11,244, SD = 8,378), of which, 47 % drove everyday and 47 % several times per week. As reward, the participant could take part in the time management course. Before participating a consent declaration was signed. They were told that they are free to stop the experiment. The study has been approved by the ethics committee of the Faculty of Engineering at the University of Duisburg-Essen.

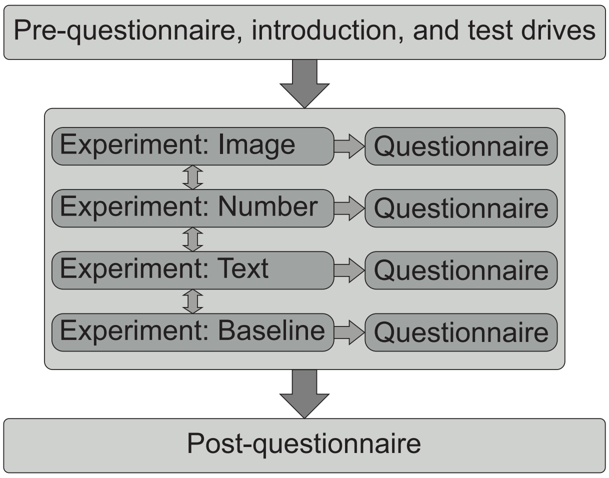


Figure 4.8: Procedure of E1 comparing HUD DVIs

Table 4.1: Description of dependent variables in E1

Purpose	Dependent variable	Description
Usability of interface	Average fuel consumption	The average fuel consumption during the experiment was measured to prove the efficacy of the interfaces as well as the effect of interfaces on driving behavior.
	Proportion of matched velocity	The actual velocity of the ego-vehicle was compared to the suggested optimal velocity to prove if the fuel efficiency was improved by following the suggested velocity or by chance. The matched velocity was calculated based on the output values from the driving simulator. If the difference between the actual velocity and suggested optimal velocity was smaller than its mean value, it was denoted as a match. Otherwise, it would be denoted as a not match.
Visual impact of interface on driver	Proportion of matched gaze area	The eye gaze position was recorded to calculate the percentage of times the participants looked at the displayed information to compare the visual distraction of the interface from the view of the road.
	Blink frequency	The blink frequency is usually used as an indicator for attention, workload, and fatigue [BPM$^+$11]. During driving, this variable can also be affected by the required visual attention, for example: looking at the traffic signs or intending to execute lane changing maneuver.
	Blink duration	The blink duration is mostly used to obtain the impact of visual task demand and attention. According to [IAP$^+$06] [AFB06], shorter blink duration indicates sustained attention paid on. In other words, the visual task demand increases when the blink duration decreases [AFB06] [VG96]. The longer blink duration is also an indicator for drowsiness [IAP$^+$06] [AFB06], which is not considered here, because of the short time of each driving task.
	Pupil diameter	The pupil diameter is proved as a direct measure of mental activity [HP64]. The size of diameter increases when the required mental workload is high [IZB04] [Van00] [Van01] but also reflects ambient luminance [Bea82] [Hol11].
Workload of driver	NASA-TLX score	The NASA-TLX scores represent the participant's perceived workload from six aspects: mental demand, physical demand, temporal demand, effort, frustration, and performance [HS88].

Table 4.2: Hypotheses to be tested in E1

Focuses	Hypotheses	Variables
Usability of interface	H0: The interface does not influence the average fuel consumption. H1: The interface influences the average fuel consumption.	Average fuel consumption
	H0: The interface does not influence the proportion of matched velocity. H1: The interface influences the proportion of matched velocity.	Proportion of matched velocity
Visual impact of interface on driver	H0: The interface does not influence the proportion of matched gaze area. H1: The interface influences the proportion of matched gaze area.	Proportion of matched gaze area
	H0: The interface does not influence the blink frequency. H1: The interface influences the blink frequency.	Blink frequency
	H0: The interface does not influence the blink duration. H1: The interface influences the blink duration.	Blink duration
	H0: The interface does not influence the pupil diameter. H1: The interface influences the pupil diameter.	Pupil diameter
Workload of driver	H0: The workload rating dose not depend on interface. H1: The workload rating depends on interface.	NASA-TLX score

4.2.5 Procedure

The purpose of the experiment was emphasized to the participants, which was to realize an efficient driving within an HEV. As shown in Figure 4.8, the participants were informed about the right to give up without any consequences at any time if they did not feel comfortable during the experiment. As next, they were asked to sign a written consent. The study has been approved by the ethics committee of the faculty of Engineering in the university Duisburg-Essen. A demographical questionnaire was filled out by the participants. The procedure of the experiment, operation of the driving simulator, the meaning of the interfaces, etc. were then explained. Afterwards, the participants were allowed to perform a training drive for minimum 2 min. After confirmation from the participant, the driving tasks were started in a randomized order. After each driving task, the participants were asked to assess their workload using NASA-Task Load Index (NASA-TLX) [HS88]. At the end of the experiment, a post-questionnaire about the effects of interfaces on participants' behavior and acceptance of interfaces was executed after the experiment.

4.2.6 Data collection and analysis

The data collected from the driving simulator, the eye tracker, and questionnaires are divided into two groups: objective and subjective. Statistical analysis methods with the significance level 0.05 are used to analyze the data. Two-way MANOVA (multivariate analysis of variance) is used to evaluate the interaction effects between the two IVs on the selected DVs. Two-way ANOVA (analysis of variace) and Scheirer-Ray-Hare (SRH) are used to analyze the DVs.

4.3 Results

Descriptive statistics are given in Table 4.3 (SL: speed limit).

Two-way MANOVA was conducted to evaluate the interaction effects between the two independent variables I and SL on the selected DVs. The proportion of matched gaze area was not considered because it is used to evaluate the visual distraction of the displayed suggestion. The pupil diameter was not selected because of the different sample size. The NASA-TLX score is based on the whole drive, therefore it was not taken into account in the two-way MANOVA analysis. The blink frequency and duration were not considered because they are not normally distributed, which does not fulfill the assumption of the applied method. Results from the two-way MANOVA analysis show no significant interaction effect between interface and speed limit on the combined DVs (average fuel consumption and proportion of matched velocity). The results indicate a significant main effect for the interface on the combined DVs ($F(6,\ 494) = 2.3$, $p < .05$; Wilks' $\Lambda = .95$; partial $\eta^2 = .03$) as well as for speed limit on the combined DVs ($F(2,\ 247) = 110.1$, $p < .001$; Wilks' $\Lambda = .53$; partial $\eta^2 = .47$). The effect for the interface on the average fuel consumption can be obtained ($F(3,\ 248) = 3.8$, $p < .05$, partial $\eta^2 = .04$). The effect for the speed limit on the matched velocity is also detected ($F(1,\ 256) = 220.7$, $p < .001$, partial $\eta^2 = .47$).

The separate analysis of the results is detailed in sections 4.3.1 and 4.3.2.

Table 4.3: Descriptive statistics (Means and SD (*italic*) of different variables) in E1 [WS16]

Dependent variables	Baseline		Number		Image		Text	
	W/o SL	With SL	W/o SL	With SL	W/o SL	With SL	W/o SL	With SL
Average fuel consumption [mL/km]	55(*13*)	48(*14*)	32(*10*)	34(*16*)	22(*11*)	28(*13*)	27(*17*)	36(*17*)
Matched velocity [%]	61(*12*)	33(*23*)	70(*13*)	25(*25*)	70(*13*)	30(*28*)	73(*11*)	31(*31*)
Matched gaze area [%]	-	-	4.5(*4.0*)	3.3(*3.1*)	5.1(*7.0*)	4.2(*6.9*)	5.6(*8.0*)	3.4(*6.6*)
Blink frequency [1/min]	16(*9*)	16(*10*)	16(*8*)	16(*8*)	16(*10*)	16(*10*)	16(*9*)	15(*9*)
Blink duration [ms]	153(*31*)	153(*32*)	155(*27*)	155(*28*)	151(*24*)	151(*24*)	157(*24*)	158(*23*)
Pupil diameter [mm]	3.67 (*0.63*)	3.71 (*0.65*)	3.72 (*0.64*)	3.72 (*0.66*)	3.71 (*0.62*)	3.75 (*0.57*)	3.74 (*0.63*)	3.78 (*0.62*)
NASA-TLX score [0-100]	29(*15*)		36(*16*)		38(*19*)		35(*17*)	

4.3.1 Objective results

Average fuel consumption

The results show significant interaction effect ($F_{I*SL}(3{,}29) = 44.938$, $p < .001$, partial $\eta^2 = .82$). Furthermore, the main effects for the interface and speed limit on the fuel consumption are also significant ($F_I(3{,}29) = 52.987$, $p < .001$, partial $\eta^2 = .85$ and $F_{SL}(1{,}31) = 140.878$, $p < .001$, partial $\eta^2 = .82$). The results are depicted in Figure 4.9. Post hoc comparisons between paired interfaces were realized using Bonferroni corrections. The fuel consumption without interface was significantly larger than the ones using interfaces ("Image": $p < .001$, "Number": $p = .003$, "Text": $p = .042$). The paired-wise comparison among three interfaces showed no significant differences.

Proportion of matched velocity

A significant interaction effect ($F_{I*SL}(3{,}29) = 6.362$, $p = .002$, partial $\eta^2 = .40$) is observed. The main effect for the interface on the proportion of matched velocity is significant ($F_I(3{,}29) = 24.413$, $p < .001$, partial $\eta^2 = .72$). The results are shown

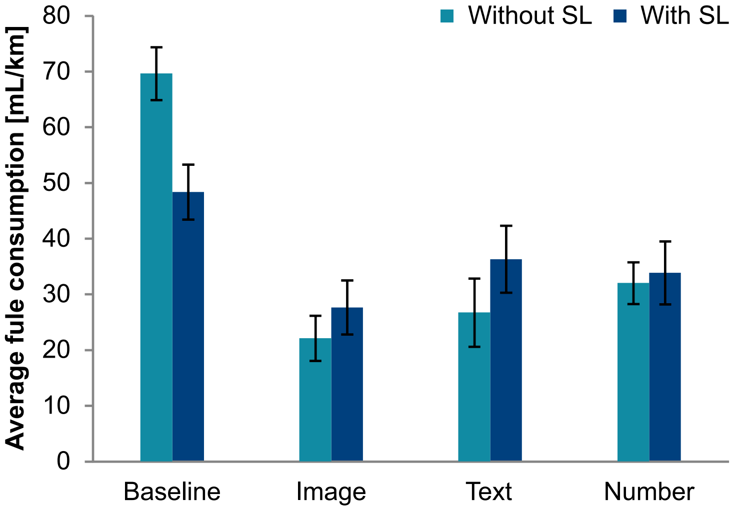


Figure 4.9: Comparison of average fuel consumption in four drives

in Figure 4.10. No difference between the sections with speed limits and the ones without was obtained. Bonferroni corrections were conducted to analyze matches among the interfaces. The matched velocities with interfaces were more than the baseline test ("Image": $p < .001$, "Number": $p < .001$, "Text": $p < .001$). No difference among three interfaces was detected.

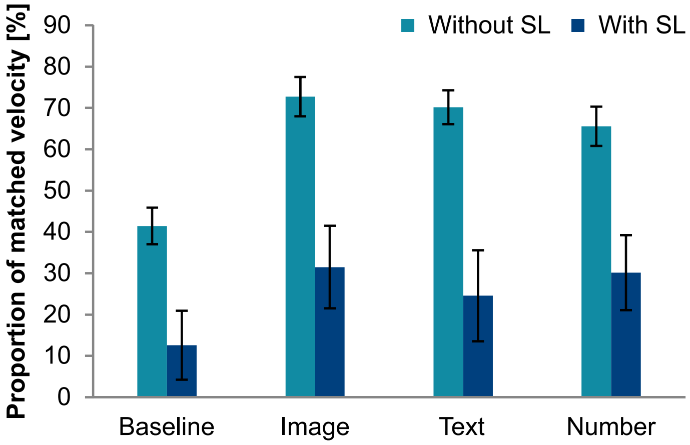


Figure 4.10: Comparison of matched velocity in four drives

Proportion of matched gaze area

Significant main effect for the SL on the proportion of matched gaze area is obtained with $p = .02$ (Figure 4.11). No significant interaction effect and main effect for the interface are detected.

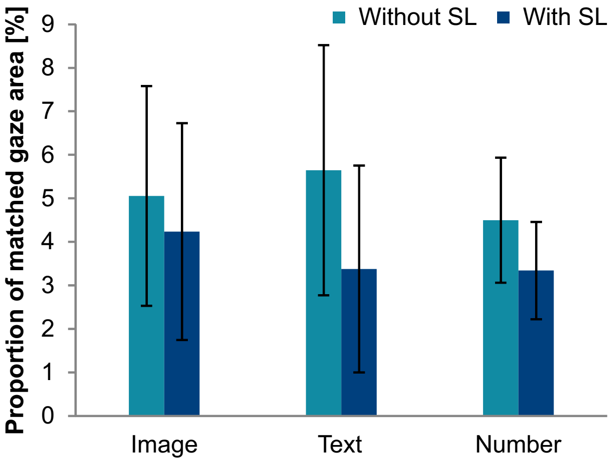


Figure 4.11: Comparison of matched gaze area in four drives

Blink frequency

No significant results are obtained in this analysis.

Blink duration

It results in no significant interaction effect. However, the ratings for paired samples were tested for differences using Wilcoxon signed-rank test. The results show the blink duration with interface “Image” was shorter than the ones with interfaces “Text” (Z = 1,432, p = .009, r = .23) and “Number” (Z = 1,409, p = .014, r = .22). The results can be seen in Figure 4.12.

Pupil diameter

To achieve high tracking quality, the gaze of 11 participants was tracked using the iris contour and the rest with pupil contour. Therefore the data of pupil diameter from 21 participants are used. However, no significant effect is obtained.

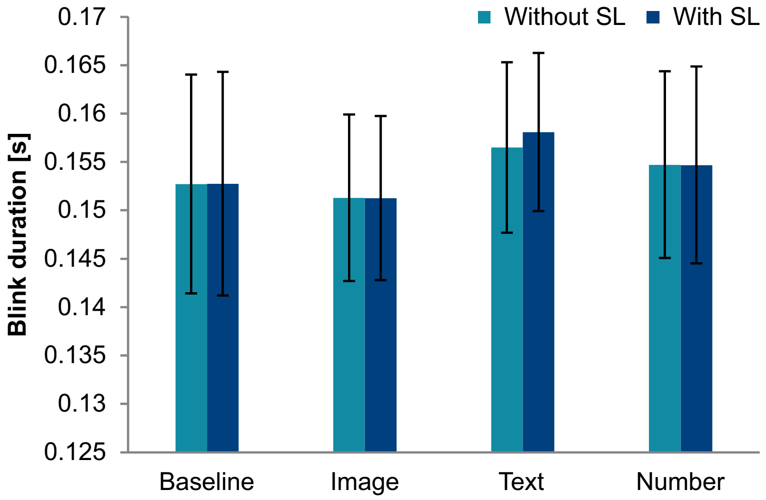


Figure 4.12: Comparison of blink duration in four drives

Workload

The NASA-TLX score was tested to be reliable using Cronbach's alpha in four test drives (Baseline: .799; Image: .873; Text: .803; Number: .789). The results show significant effects for interface on workload ($F(3,29) = 4.079$, $p = .016$, partial $\eta^2 = .30$). The post hoc comparisons between paired samples were realized using Bonferroni corrections. Comparing to the workload in baseline test, the ones in "Image" and "Number" tests were significantly higher ($p = .01$ and $p = .049$) as shown in Figure 4.13. No significant difference between the test with interface "Text" and the baseline test ($p > .05$) was obtained.

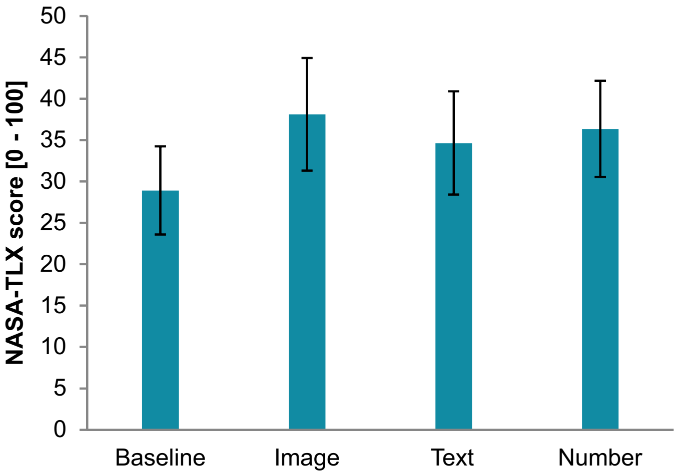


Figure 4.13: Comparison of workload in four drives

4.3.2 Subjective results

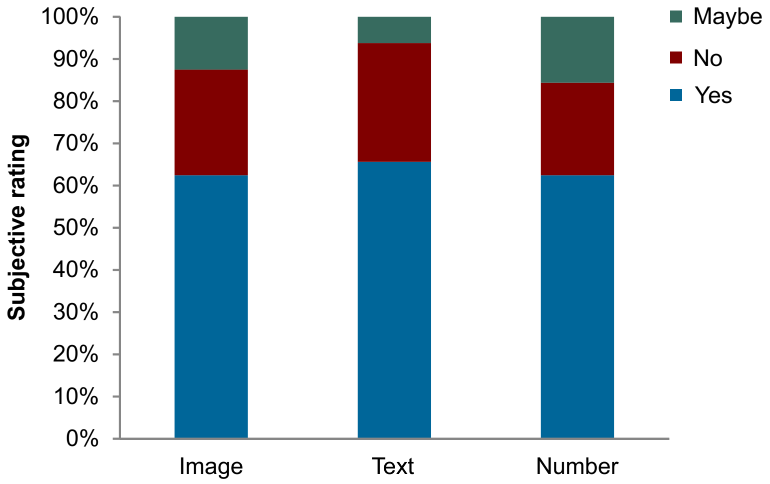


Figure 4.14: Subjective rating about influence of three HUDs on driving behavior

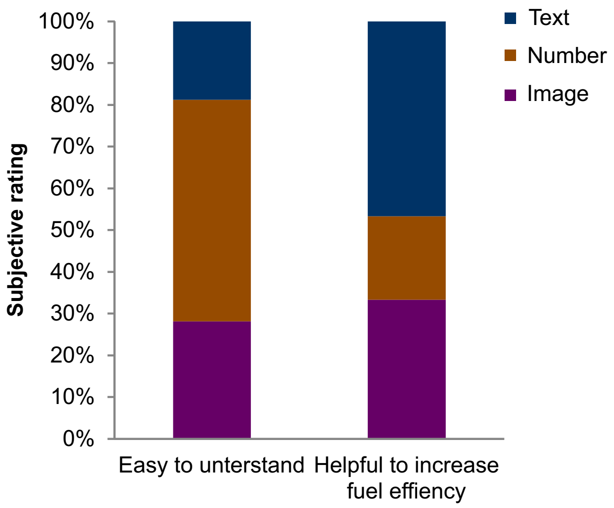


Figure 4.15: Subjective rating about usability of three HUDs

More than 60 % of the participants declared their driving behaviors are affected by the displayed interface (Figure 4.14). As for the preference, 53.1 % of the participants chose the interface “Text”. Interface “Text” as shown in Figure 4.15 was chosen by 43.8 % of the participants as the most helpful one to increase fuel efficiency. Almost 70 % of the participants would like to integrate such interface to increase the fuel efficiency, of which the interfaces “Text” and “Image” were confirmed by 36.4 % and 27.3 %, respectively. It can be concluded that the participants accept the integration of such an interface to increase fuel efficiency.

Table 4.4: Hypotheses verification in E1

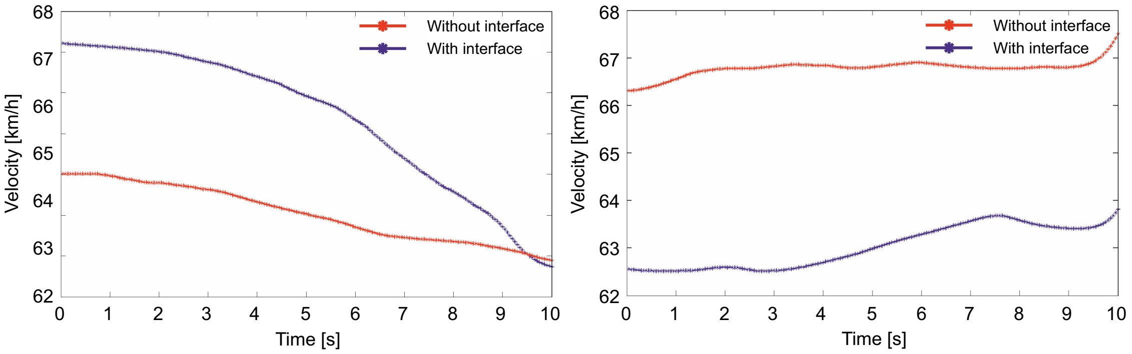
Focuses	Hypotheses	
Usability of interface	H0: The interface does not influence the average fuel consumption.	×
	H1: The interface influences the average fuel consumption.	√
	H0: The interface does not influence the proportion of matched velocity.	×
	H1: The interface influences the proportion of matched velocity.	√
Visual impact of interface on driver	H0: The interface does not influence the proportion of matched gaze area.	√
	H1: The interface influences the proportion of matched gaze area.	×
	H0: The interface does not influence the blink frequency.	√
	H1: The interface influences the blink frequency.	×
	H0: The interface does not influence the blink duration.	×
	H1: The interface influences the blink duration.	√
	H0: The interface does not influence the pupil diameter.	√
	H1: The interface influences the pupil diameter.	×
Workload of driver	H0: The workload rating dose not depend on interface.	×
	H1: The workload rating depends on interface.	√

4.4 Verification of hypotheses and discussion

The detailed description of results from section 4.3.1 shows, that the three arts of showing suggested optimal velocity are partially different. These support the alternative hypotheses, which are summarized in Table 4.4.

The goal of this experiment is to compare the efficacy of the three realized DVIs in reducing fuel consumption within an HEV. Besides, the relation between the reduced fuel consumption and perceived workload should be investigated. It was expected that the fuel consumption could be reduced using proposed interfaces. The results comparing it among four driving tasks show that the fuel consumption using all three interfaces was reduced in relation to the baseline setting, which proves the efficacy of the proposed approaches. No difference between each pair of interfaces was observed. Displaying the comparison of consequences of actual and optimal behaviors did not have the expected effect. One reason could be that despite the consequences, the driver did not get benefits. In a simulation, it is hard to realize a live experience under the pressure of low fuel status or SOC.

The proportion of matched gaze area was used to prove how often the participants looked at the interface. It was expected that it is influenced by both interface and speed limit. The results show this variable is only influenced by speed limits, which means the three different ways of displaying the suggestion had the same effect on the drivers perceiving the information. The designed interfaces were placed at the left bottom corner. The distributions of eye gaze position of baseline test and with interface “Image” are shown in Figure 4.17(a) and Figure 4.17(b). Based on the eye

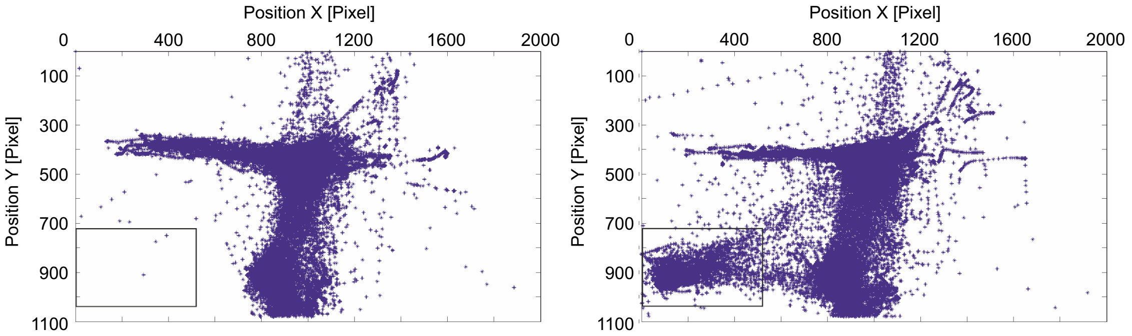


(a) Before speed limit

(b) After speed limit

Figure 4.16: Comparison of average velocities in baseline test and with interface "Image" for 10 seconds before and after speed limits [WS16]

movements within the area of the interface, about 13 % of the glances are realized during the 10 seconds before the speed limit. The suggested driving behavior is based on the optimization of the powertrain in the hybrid vehicle, in which the traffic signs are not considered. It leads to cognitive conflicts between the displayed optimal behavior and the limitation of the road sign. This can be concluded from the fact of a high density of eye movements in the area of the interface during the 10 seconds before speed limits. The drivers could not be able to concern both limited velocity and displayed optimal velocity simultaneously. This could be overcome by displaying the driver the optimized velocity considering the traffic signs, which will be improved in the next experiment.



(a) Baseline test

(b) With interface "Image"

Figure 4.17: Comparison of distribution of eye movement between baseline test and with interface "Image" [WS16]

The blink frequency was used to test attention and workload. It was expected that it was influenced by both factors. The results of blink frequency show no significant difference among tests. As shown in Table 4.3, no high variability among means and SDs can be obtained. But the min. and max. values of each participant vary between 1.80 - 31.83 and 6.42 - 47.06. This may indicate that the blink frequency could be influenced by inter-subjects and other factors, which were not observed in the experiment.

The blink duration was used to test visual workload. It was expected that the interface “Image” requires more visual workload. The results show the blink duration of task “Image” is shorter than the ones of “Text” and “Number”. It means that more visual workload is required by interface “Image”. The reason could be that the meaning of the instructions is difficult to be remembered in a short time. The participants needed time to get used to the description. It is a challenge in a short time to keep the relations between the displayed symbols and the suggested driving behavior in mind. In contrast, text-visual descriptions are easier to be understood.

The perceived workload of the participants was assessed using NASA-TLX score. As expected, the results show that the score of the test drive with “Image” requires most workload. This supports the conclusion drawn from the measured parameters of eye movement. The task using “Text” has no significant difference in the baseline test, which means the interface “Text” is more accepted and easier to handle. An “optimum” effect (digital form) [WB92] could be achieved through the combination of a “workable but suboptimum” display (text form) and consequences in the dynamic driving environment.

Most of the HEVs in the market show only the judgment for fuel economy from the drivers without guiding them to realize it. In this chapter, the concrete economic driving behavior in three different manners is displayed to the driver. As summarized in Table 4.3, a more cognitive workload is required to achieve more economic driving. The reason could be the adjustment of the actual driving behavior to the optimal one due to the cognitive perception of the difference between the suggested driving behavior and the actual one. It requires more workload and attention to adjust the actual behavior closer to the suggested one especially in the situation, in which the suggested optimal velocity is in contrast to the limited velocity. Would it be more helpful to show the suggestion considering the speed limit?

In this chapter, different manners of showing driving efficiency optimal velocity using HUD are compared. The other very often used area to display such kind of information would be the dashboard behind the steering whee. Usually the dashboard shows the speedometer and tachometer with circular scale. Would it be possible to show them in other form, like linear scale? Would this be different as the circular form?

These questions are summarized as hypotheses in Table 4.5 and Table 4.6 for the next study, which will be detailed in chapter 5.

Table 4.5: Hypotheses to be tested in E2 with regard to interface

Focuses	Hypotheses	Variables
Usability of interface	H0: The interface does not influence the average fuel consumption. H1: The interface influences the average fuel consumption.	Average fuel consumption
	H0: The interface does not influence the proportion of matched velocity. H1: The interface influences the proportion of matched velocity.	Proportion of matched velocity
	H0: The interface does not influence the proportion of matched gear. H1: The interface influences the proportion of matched gear.	Proportion of matched gear
Visual impact of interface on driver	H0: The interface does not influence the proportion of matched gaze area. H1: The interface influences the proportion of matched gaze area.	Proportion of matched gaze area
	H0: The interface does not influence the performance of secondary task. H1: The interface influences the performance of secondary task.	Performance of secondary task
Workload of driver	H0: The workload rating dose not depend on interface. H1: The workload rating depends on interface.	NASA-TLX score

Table 4.6: Hypotheses to be tested in E2 with regard to suggestion

Focuses	Hypotheses	Variables
Influence of suggestion on driving behavior	H0: The art of showing suggestion does not influence the total fuel consumption. H1: The art of showing suggestion influences the total fuel consumption.	Average fuel consumption
	H0: The interface does not influence the proportion of matched velocity. H1: The art of showing suggestion influences the proportion of matched velocity.	Proportion of matched velocity
	H0: The art of showing suggestion does not influence the proportion of matched gear. H1: The art of showing suggestion influences the proportion of matched gear.	Proportion of matched gear
Visual impact of suggestion on driver	H0: The art of showing suggestion does not influence the proportion of matched gaze area. H1: The art of showing suggestion influences the proportion of matched gaze area.	Proportion of matched gaze area
	H0: The art of showing suggestion does not influence the performance of secondary task. H1: The art of showing suggestion influences the performance of secondary task.	Performance of secondary task
Workload of driver	H0: The workload rating dose not depend on the art of showing suggestion. H1: The workload rating depends on the art of showing suggestion.	NASA-TLX score

5 Using dashboard to increase driving efficiency

As concluded from chapter 4, the fuel efficiency could be increased by integrating the DVI to influence the driving behavior. However, the cognitive conflict occurred due to different displayed velocities, which leads to the higher workload. To overcome that, the information about the environment, such as traffic signs, should also be taken into consideration. This leads to the following questions.

- *Is there another option to display the suggested behavior?*
- *Is there another option to display the comparison of actual and suggested optimal behaviors?*
- *Does it help to display the suggestion with consideration of traffic signs?*

The fuel efficiency mentioned in this chapter is indicated as fuel economy, which is defined as the total amount of fuel consumption. In this chapter, two DVIs are suggested to be used for the increment of driving efficiency (section 5.1). Experiment (E2) to compare the two DVIs with baseline interface is introduced. The corresponding objective and subjective results are explained in section 5.2. The discussion of the results is concluded in section 5.3. The hypotheses for next experiment are derived.

5.1 Experimental design

5.1.1 Development of DVI on dashboard

The optimal velocity within an HEV for the near future can be calculated using the fuel consumption optimization algorithm [MWS15]. To reduce the cognitive conflict, the combination of optimal behavior and allowed one as a suggestion is displayed to the driver. The resulting State of Charge (SOC) of current velocity, as well as the one of the optimal velocity, is calculated. This comparison is shown to the driver as consequences of the own behavior and the possible optimal behavior. By recognizing the difference, the driver could be convinced to follow the suggested optimal behavior. The displayed information is then updated upon the new behavior of the driver. In this way, the driver is integrated into the control loop, which is closed with the DVI.

The information can be coded either in digital or analog form [BSD96]. The digital display is suitable for quick and precise readings of quantitative values [BSD96], which is proper to display the actual and suggested optimal gear numbers. The analog display is suitable for ranges, zones, or trend information [BSD96]. Therefore the actual and suggested optimal velocities are chosen to be displayed in this form. The scale indicators are represented either by using moving-pointer with fixed-scale (good for qualitative information and tracking) or fixed-pointer with moving-scale (good for saving panel space) [BSD96] [WB92]. The former one is chosen to display both velocities because showing the moving direction of both velocities is helpful for the driver to follow. The comparison between the actual and the suggested velocity is shown by a moving pointer with either circular or horizontal scale. The comparison of resulting actual and optimal SOCs is displayed by the moving pointer either with vertical scale or the trend diagram with two curves [WB92].

Based on aforementioned design principles, two approaches (D1 and D2) are suggested as illustrated in Figure 5.1 and Figure 5.2 respectively. In Figure 5.1, the speedometer is shown with a horizontal line. The actual velocity is displayed with the green arrow labeled with “CURRENT” while the suggested optimal velocity uses a bar with “Suggested”. The color of the bar showing the optimal velocity changes dependent on the difference between the actual velocity and the suggested optimal one, which is listed in Table 5.1. To simplify the process of achieving the suggested optimal velocity, the corresponding optimal gear is also shown to the driver in comparison with the current gear. It is illustrated over the speedometer. The arrow is green when the current gear is lower than the optimal one; it is red, when the current gear is higher than the optimal one. When they are equal, only one number is shown. This approach does not show tachometer. The comparison between the resulting SOCs in the past few seconds from the driver’s behavior (indicated as “Current SOC” in green) and the optimal behavior (indicated as “Optimal” in red) is shown with two curves under the speedometer. In this way, the driver could get an overview of the own driving behavior compared to the possible optimal behavior. After getting this difference, the driver might follow the displayed optimal gear and velocity.

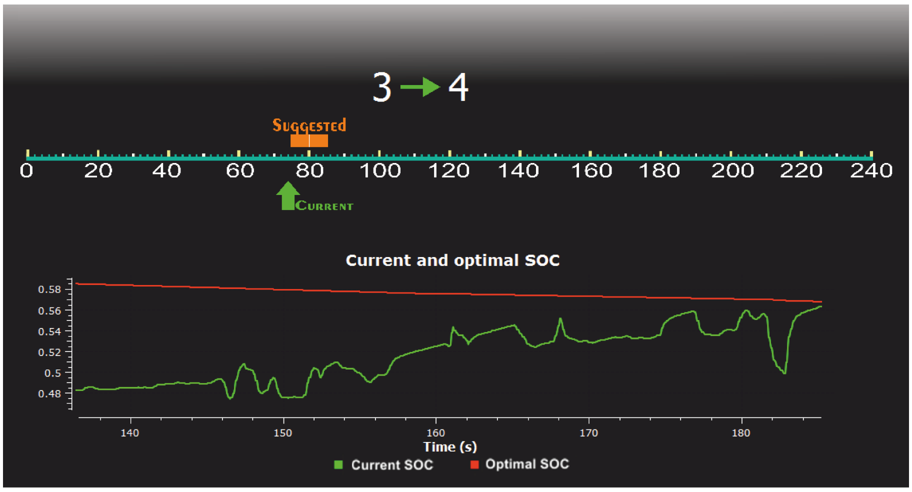


Figure 5.1: D1 on dashboard

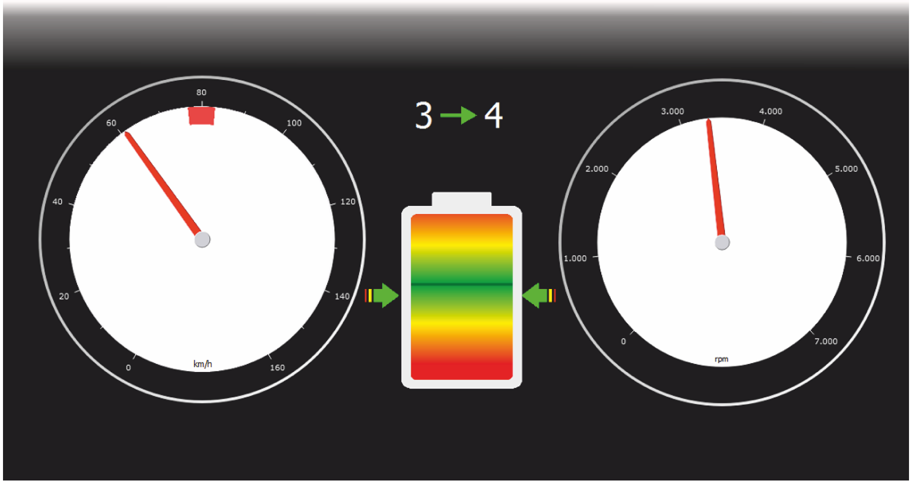


Figure 5.2: D2 on dashboard

The second approach follows the design of the conventional dashboard. The suggested optimal velocity is placed on the outer ring of the speedometer also using a bar. The color scheme displaying the optimal velocity is the same as the first approach as well as the suggested gear. The SOCs are represented as a battery between the speedometer and the tachometer. The black line in the battery indicates the resulting SOC of the optimal velocity while the arrows on both sides of the battery show the one of the current driving behavior of the driver. The green areas over and below the optimal SOC denote current behavior as efficient and red as not efficient.

Table 5.1: Color scheme of suggested optimal velocity

Absolute value of difference between actual and optimal velocities |d| [km/h]	Color of suggested optimal velocity
$0 \leq \lvert d \rvert \leq 5$	Green
$5 \leq \lvert d \rvert \leq 10$	Orange
$\lvert d \rvert > 10$	Red

The suggested optimal velocity results from the fusion of the allowed maximum velocity on the driving road and optimal velocity, which is calculated using a driving efficiency optimization algorithm. It is displayed in combination with the current velocity so that the driver could directly obtain the difference. Displaying the comparison of resulting SOC as consequences of current and optimal behaviors could persuade the driver to adjust the current behavior to realize an efficient driving.

5.1.2 Independent and dependent variables

The proposed two DVIs are developed and evaluated using the driving simulator. In the experiment (E2), the dashboard shown in Figure 4.1 is used to display the two DVIs. The touch 1 is used for the secondary task, which is detailed in the following sections. Same as by the proposed HUDs in chapter 4, the current velocity of the ego-vehicle is used as the input to calculate the resulting current SOC, the optimal future velocity and, the resulting SOC.

The experiment should be done to evaluate the two proposed DVIs in increasing fuel efficiency without impairing consideration of traffic signs. The efficacy of the two DVIs should be compared. The effect of considering traffic signs should be validated through the perceived workload and performance of the secondary task.

The two introduced DVIs on the dashboard were compared with a baseline DVI as shown in Figure 5.3 to evaluate the effect of them on driving behavior. As for the driving scenario, a motorway scenario as shown in Figure 5.4 was chosen with the total length about 15 *km*, which consisted of six lanes with two directions and the simulated traffic environment. Several traffic signs such as speed limits were set up to simulate the real motorway driving environment. During driving, the participant should also accomplish an arithmetic secondary task [NN:17] using the touch 1, which was positioned on the right side of the steering wheel as shown in Figure 4.1. Each participant performed five test drives, of which two test drives used the proposed two paradigms considering the traffic signs respectively, two did not consider the traffic signs, and one used default DVI of the driving simulator representing the baseline test. The DVIs were displayed on the dashboard behind the steering wheel as shown in Figure 4.1.

Figure 5.3: Baseline DVI on dashboard

Figure 5.4: Simulated scenario for E2

The goals for the participants were to drive safely, to minimize the fuel consumption of the HEV, and to realize the secondary task as many and as correctly as possible. These goals are difficult to realize in parallel. The driver should make own decision to only focus on driving efficiently after own opinion or to follow the displayed optimal suggestion so that the fuel consumption could be reduced relatively easier, or to compromise the number of completed secondary tasks to gain more fuel consumption back.

Each driver performed five drives. Herein a repeated measured experiment is used with two independent variables:

Interface (I) D1, D2, and baseline

Suggestion (SU) Suggestion with considering speed limit (w/), suggestion without considering speed limit (w/o), and no suggestion (baseline)

The dependent variables are listed in Table 5.2.

5.1.3 Participants

Thirty-four participants (26 male, 8 female, mean age = 25 years, min. = 18, max. = 33, SD = 4) were recruited. They all held valid driving licenses. The driving experience was from 0.2 to 12 years (mean = 6.7, SD = 5.5). They drove min. 500 *km* and max. 30,000 *km* per year (mean = 9,743 *km*, SD = 8,143 *km*), of which, 38 % drove everyday and 38 % several times per week. As reward, the participant could take part in the time management course. Before participating a consent declaration was signed. They were told that they are free to stop the experiment. The study has been approved by the ethics committee of the Faculty of Engineering at the University of Duisburg-Essen.

Table 5.2: Description of dependent variables in E2

Purpose	Dependent variable	Description
Usability of interface	Total fuel consumption	It is measured as the total fuel consumption of each test drive.
	Proportion of matched velocity	The difference between the actual velocity and the suggested optimal velocity was compared to its mean value. It was denoted as a match if the former one is smaller than the later one and vice versa.
	Proportion of matched gear	It is the proportion of actual gear compared to the suggested optimal gear, which is similar to the proportion of matched velocity.
Visual impact of interface on driver	Proportion of atched gaze area	The eye movement on the dashboard and the main monitor could be observed and recorded using the eye tracker. The times of gaze position on the dashboard and the main monitor was conducted and used to calculate the proportion. It is the proportion of eye gaze positions on both the dashboard and the main monitor.
	Performance of secondary task	It is denoted as the number of the completed arithmetic task and the one of correctly calculated tasks.
Workload of driver	NASA-TLX score	It is the perceived workload with respect to six aspects: mental demand, physical demand, temporal demand, effort, frustration, and performance [HS88].

5.1.4 Procedure

As shown in Figure 5.5, the purpose and procedure of the experiment, the meanings of interfaces, and operation of the driving simulator were emphasized to the participants. Before participating they signed the consent declaration. They were told that they are free to stop the experiment if they do not feel well. The study has been approved by the ethics committee of the faculty of Engineering in the university Duisburg-Essen. Afterward a trial drive of about 5 min. was performed to help the test driver to get familiar with the driving simulator, the interfaces, and the secondary task. After confirmation of the participant, the five driving tasks were performed with a randomly chosen order. The five driving tasks were followed by a workload assessment using NASA-Task Load Index (NASA-TLX) [HS88] and a questionnaire about acceptance of the interface. A post-questionnaire about preference and suggestions was filled out by the participant at the end of the experiment. During the post-questionnaire, the participants were asked about the acceptance and understandability of the interfaces, the distraction of the difference between the speed limit and the suggested optimal velocity, etc. Furthermore, questions about the personal preference and the recommendation for integration were given.

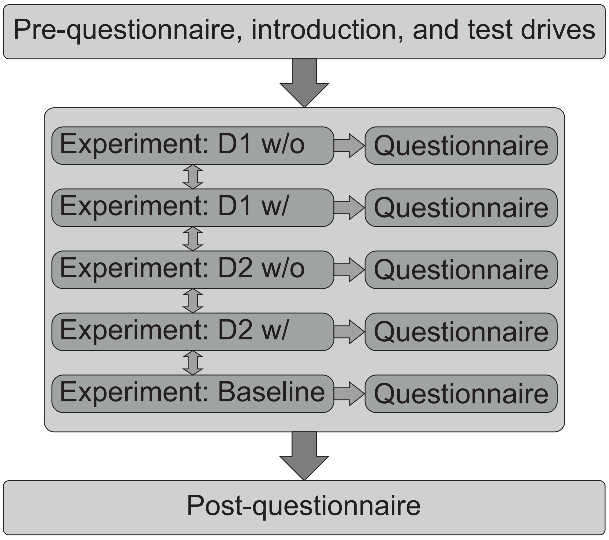


Figure 5.5: Procedure of E2 comparing dashboard DVIs

5.1.5 Data collection and analysis

The data used to validate the proposed DVIs were collected from the driving simulator, the eye tracker, and the questionnaires, which were divided into two groups: objective and subjective. The pupil diameter could not be analyzed because the required data was only available from 7 participants, which matched the gaze tracking requirement explained in section 4.2.2. The data were analyzed using statistical analysis methods with the significance level 0.05. Two-way MANOVA is used to evaluate the interaction effects between the two IVs on the selected DVs. Two-way ANOVA (analysis of variace) is used to analyze the DVs.

5.2 Results

Descriptive statistics of dependent variables are given in Table 5.3.

Two-way MANOVA was conducted to evaluate the interaction effects between the two independent variables SU and I on all DVs. The non-normally distributed DVs are transformed to meet the assumptions of the parametric analysis techniques. Results from two-way MANOVA show no significant interaction effect between driving scenario and interface on the combined DVs. The results indicate a significant main effect for the SU on the combined DVs ($F(6, 140) = 16.5$, $p < .001$; Wilks' $\Lambda = .59$; partial $\eta^2 = .41$) but no effect for the interface. Significant differences can be obtained in total fuel consumption ($F(1, 145) = 14.1$, $p < .001$, partial $\eta^2 = .09$), proportion of matched velocity ($F(1, 145) = 63.0$, $p < .001$, partial $\eta^2 = .30$), and

Table 5.3: Descriptive statistics (Means and SD (*italic*) of dependent variables) in E2

	Baseline	D1 w/o	D1 w/	D2 w/o	D2 w/
Total fuel consumption [L]	0.991 (*0.118*)	0.913 (*0.091*)	0.856 (*0.077*)	0.884 (*0.082*)	0.824 (*0.069*)
Proportion of matched velocity [%]	17.17 (*17.09*)	20.85 (*14.08*)	39.20 (*17.15*)	19.63 (*12.24*)	38.03 (*18.26*)
Proportion of matched gear [%]	36.54 (*27.63*)	70.27 (*15.29*)	70.76 (*11.87*)	66.38 (*16.53*)	70.59 (*10.25*)
Proportion of gaze on dashboard and main monitor [%]	19.80 (*17.32*)	31.65 (*25.31*)	20.53 (*14.06*)	23.10 (*16.14*)	16.43 (*11.86*)
NASA-TLX total score [0-100]	44.86 (*15.42*)	54.62 (*13.82*)	52.61 (*14.77*)	56.35 (*13.93*)	50.55 (*16.28*)
Number of total completed secondary task	48 (*38*)	37 (*28*)	38 (*29*)	43 (*37*)	43 (*31*)
Number of correctly completed secondary task	45 (*37*)	35 (*27*)	36 (*28*)	40 (*35*)	41 (*29*)

proportion of gaze on the dashboard and on the main monitor ($F(1,\ 145) = 7.2$, $p < .001$, partial $\eta^2 = .01$).

The concrete description and comparison are detailed in sections 5.2.1 and 5.2.2.

5.2.1 Objective results

Total fuel consumption

No significant interaction effect is obtained. However, the main effect for the SU on the total fuel consumption is significant ($F(1,\ 160) = 14.3$, $p < .001$, partial $\eta^2 = .08$), while no main effect for the interface is detected. Post hoc paired comparisons were realized. Results show significant differences among baseline, w/o, and w/ (all three pairs: $p < .001$). The results are shown in Figure 5.6 .

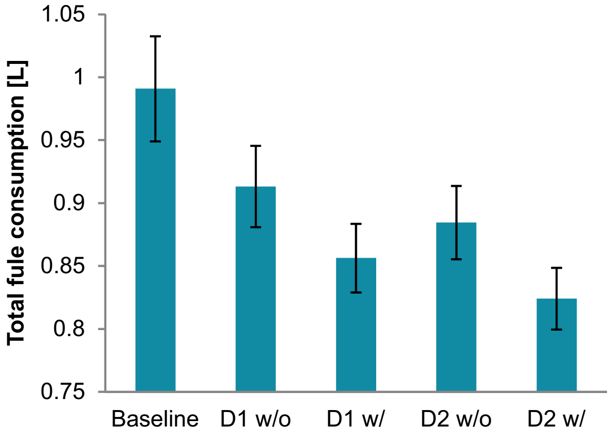


Figure 5.6: Comparison of total fuel consumption in five drives

Proportion of matched velocity

No significant interaction effect for both IVs on the proportion of matched velocity is obtained. However, a significant main effect for the SU on the DV is obtained ($F(1, 160) = 43.9$, $p < .001$, partial $\eta^2 = .22$), while no main effect for the interface is detected. Results from post hoc tests show difference between w/ and both no suggestion and w/o (both pairs: $p < .001$). The results regarding the proportion of matched velocity are shown in Figure 5.7.

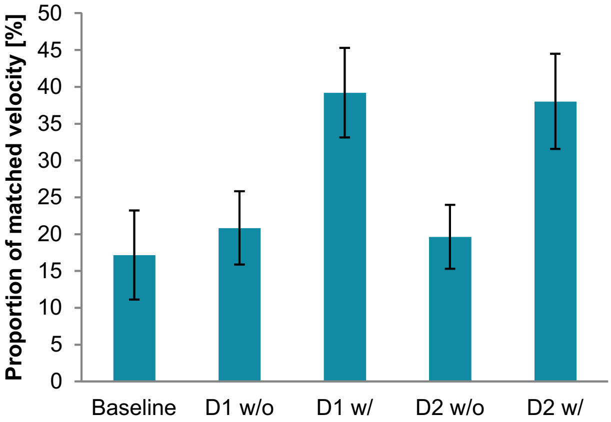


Figure 5.7: Comparison of proportion of matched velocity in five drives

Proportion of matched gear

Neither significant interaction effect nor main effects for both IVs on the proportion of matched gear is obtained.

Proportion of gaze on the dashboard and on the main monitor

No significant interaction effect for both IVs on the DV is obtained. However, significant main effects for the I and SU on the DV are obtained (I: $F(1, 165) = 4.27$, $p = .04$, partial $\eta^2 = .03$; SU: $F(1, 165) = 8.45$, $p < .005$, partial $\eta^2 = .05$). Results from post hoc tests show that D1 is different from D2 ($p = .04$). The DV with no suggestion is different from the one with suggestion not considering SL ($p = .045$). The proportion with suggestion considering SL is different from the one not considering SL ($p < .005$). This means to display suggestion considering SL has similar visual distraction as the one not showing any suggestion. The results are depicted in Figure 5.8.

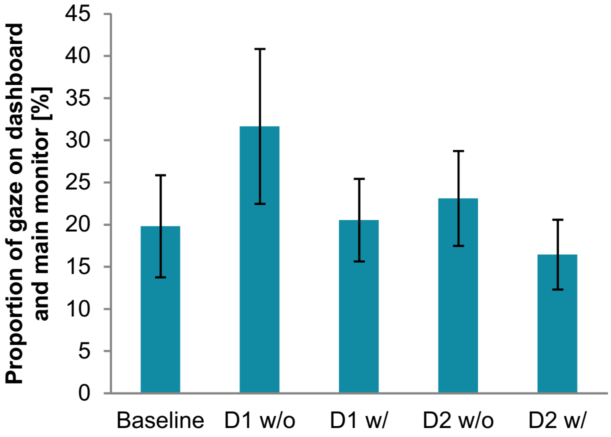


Figure 5.8: Comparison of proportion of gaze on dashboard and main monitor in five drives

Performance of secondary task

The results show neither significant interaction effect nor main effects for both I and SU.

Workload

The results show neither significant interaction effect nor main effects for both I and SU. Almost every assessment of workload had a high internal consistency with Cronbach's alpha being .828, .799, .825, .816, and .884 for baseline, D1 w/o, D1 w/, D2 w/o, and D2 w/.

5.2.2 Subjective results

The results from the post-questionnaire are shown in Figure 5.9 to Figure 5.13. The DVIs considering speed limit were more comprehensible than the ones without considering speed limit. The similar results were also proved by asking about annoying in Figure 5.10. More distraction was caused by the variation between the speed limit and suggested optimal velocity using the interfaces without considering traffic signs than the one considering the traffic signs (Figure 5.12). The DVIs with consideration of speed limit influenced the driving behavior in a positive manner more than the one without (Figure 5.11). Almost 60 % participants mentioned that the D2 is better than the D1. About 80 % participants would like to integrate such system in a vehicle to reduce the fuel consumption, which means the proposed approaches are acceptable.

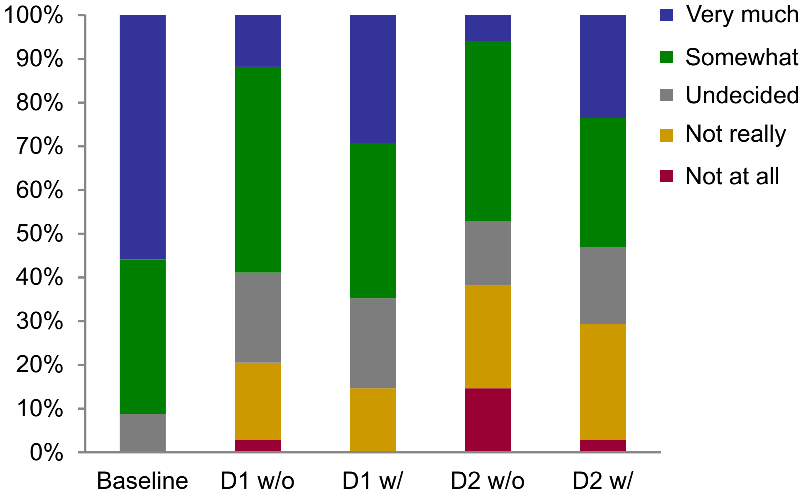


Figure 5.9: Subjective rating about comprehensibility of five DVIs

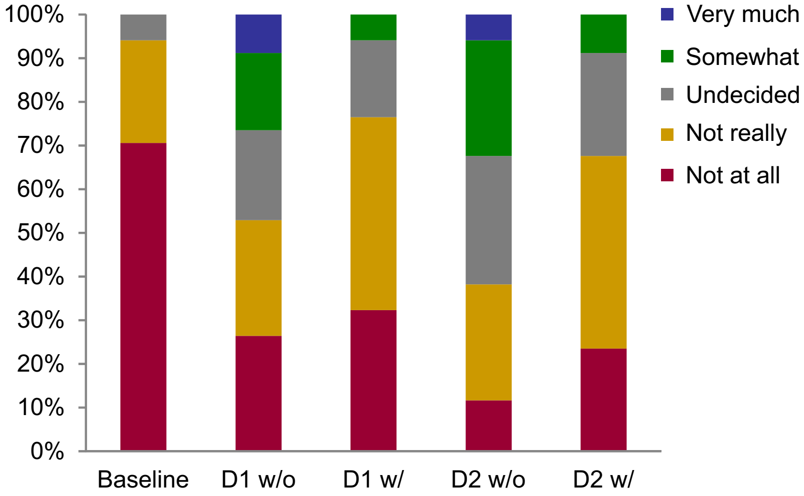


Figure 5.10: Subjective rating about annoying of five DVIs

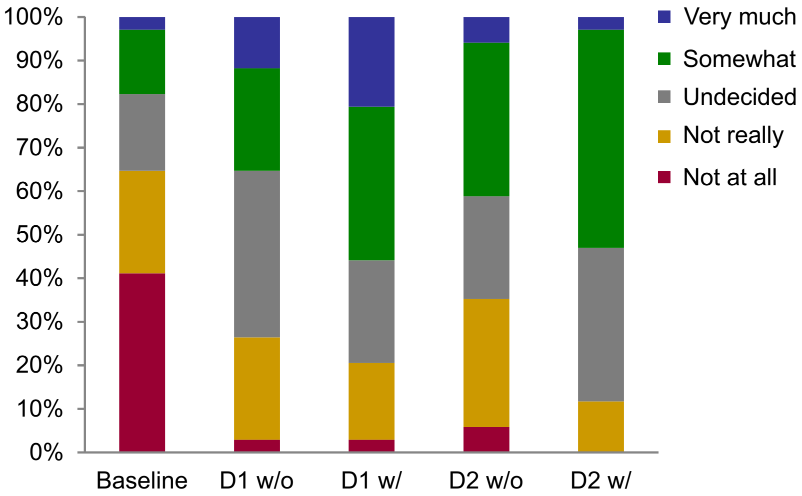


Figure 5.11: Subjective rating about influence of five DVIs on driving behavior

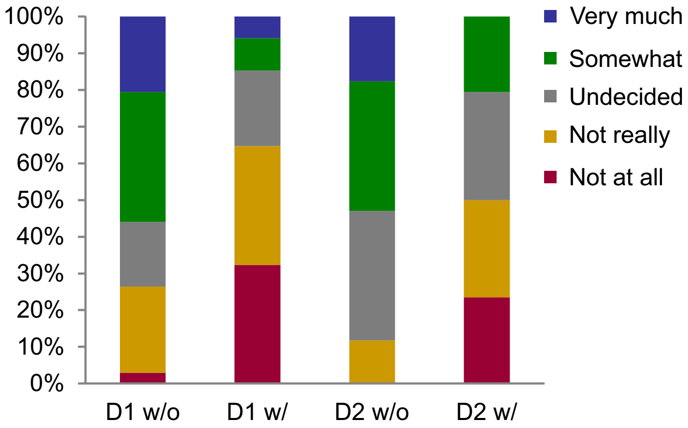


Figure 5.12: Subjective rating about distraction of four DVIs due to difference between suggested and allowed velocities

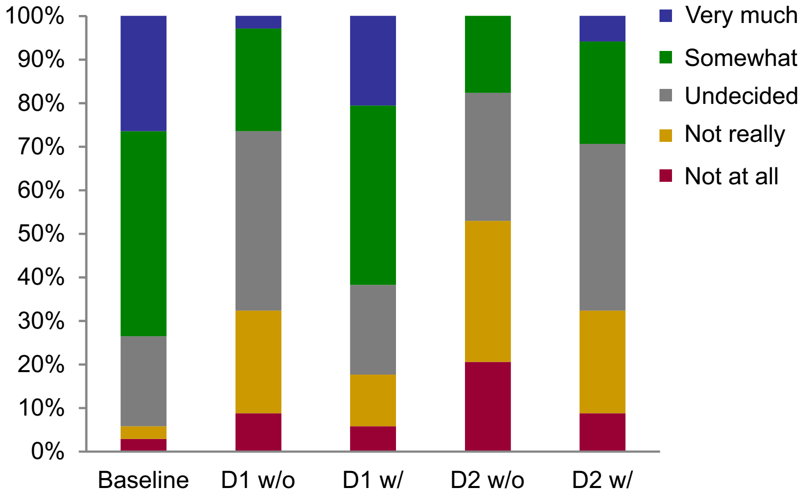


Figure 5.13: Subjective rating about preference of five DVIs

5.3 Verification of hypotheses and discussion

The detailed description of results from section 5.2.1 shows, that the two different layouts of dashboard have similar effects. These support most of the null hypotheses, which are summarized in Table 5.4. Considering speed limit into the suggestion helps people to adjust the velocity to the optimal one without struggling with facing three different velocities (actual, suggested, and limited). The verification of hypotheses regarding the suggestion is summarized in Table 5.5.

The aim of this experiment is to realize fuel reduction of HEV by displaying a suitably designed feedback to the driver. Therefore, the total fuel consumption of the whole test run was chosen as one of the dependent variables to analyze the effect of different interfaces on the drivers. The results show that the fuel consumption was reduced significantly by displaying the suggestion considering the SL. However, no difference is shown between two interfaces. The proposed two interfaces displaying the suggestion for next action in combination with powertrain optimization and traffic signs help the drivers to decrease the fuel consumption. The proportions of matched velocity and matched gear were used to find out if the reduced fuel consumption was realized by the participants following the instructions or by chance. It was expected that these two variables of the tests with suggestions are higher than the ones of the baseline test. The results show that the proportion of matched velocity using two interfaces considering the speed limits are significantly higher than the ones of baseline test as well as the ones without considering speed limit. Based on these results, it can be concluded that the proposed two DVIs could realize an efficient driving from the perspective of fuel consumption.

As no difference between the two DVIs could be concluded from the three variables described in last paragraph, the visual distraction was further analyzed, which could

Table 5.4: Hypotheses verification in E2 with regard to interface

Focuses	Hypotheses	Variables
Usability of interface	H0: The interface does not influence the average fuel consumption.	√
	H1: The interface influences the average fuel consumption.	×
	H0: The interface does not influence the proportion of matched velocity.	√
	H1: The interface influences the proportion of matched velocity.	×
	H0: The interface does not influence the proportion of matched gear.	√
	H1: The interface influences the proportion of matched gear.	×
Visual impact of interface on driver	H0: The interface does not influence the proportion of matched gaze area.	×
	H1: The interface influences the proportion of matched gaze area.	√
	H0: The interface does not influence the performance of secondary task.	√
	H1: The interface influences the performance of secondary task.	×
Workload of driver	H0: The workload rating dose not depend on interface.	√
	H1: The workload rating depends on interface.	×

Table 5.5: Hypotheses verification in E2 with regard to suggestion

Focuses	Hypotheses	Variables
Influence of suggestion on driving behavior	H0: The art of showing suggestion does not influence the total fuel consumption.	×
	H1: The art of showing suggestion influences the total fuel consumption.	√
	H0: The interface does not influence the proportion of matched velocity.	×
	H1: The art of showing suggestion influences the proportion of matched velocity.	√
	H0: The art of showing suggestion does not influence the proportion of matched gear.	√
	H1: The art of showing suggestion influences the proportion of matched gear.	×
Visual impact of suggestion on driver	H0: The art of showing suggestion does not influence the proportion of matched gaze area.	×
	H1: The art of showing suggestion influences the proportion of matched gaze area.	√
	H0: The art of showing suggestion does not influence the performance of secondary task.	√
	H1: The art of showing suggestion influences the performance of secondary task.	×
Workload of driver	H0: The workload rating dose not depend on the art of showing suggestion.	√
	H1: The workload rating depends on the art of showing suggestion.	×

be evaluated using the dependent variable proportion of gaze position on the dashboard and the main monitor. Results show that the D2 distracts the participants less than the D1. The reason could be that the SOCs are represented with two dynamic curves. This attracts the driver's attention easily. Showing the optimal velocity with consideration of the traffic signs reduces the time to compare the actual velocity, the suggested optimal velocity, and the allowed maximum velocity.

Analyzing the performance of the secondary task helps to better understand if the participants were overloaded by the displayed suggestion. In other words, the driver would follow the suggestion if the system gains the trust from the driver. In this case, the driver would be able to complete more secondary tasks in parallel. Although no significant effect for both I and SU on the performance of secondary task is obtained, the tendency shows that the total completed secondary task using D1 is the smallest. This means that the D2 could better help the drivers to achieve the goal of efficient driving.

The interaction effect and main effects for the two IVs for the perceived workload using NASA-TLX show barely significance. However, the tendency shows that the workload using DVI with suggestion considering SL is lower than the one without considering SL.

From the post-questionnaire, it can be concluded that the D2 is more acceptable than the D1 and most participants prefer to integrate this DVI into the real vehicle to reduce the fuel consumption. Summarizing the comments from participants from post-questionnaire, to display the velocity in conventional form is more acceptable because of usualness. It requires less time to perceive the information displayed by D2. It was also stated by several participants, that displaying the consequences realized with D1 is not helpful due to distraction. It cost time and attention to get such complex information during driving.

These two performed experiments are based on lower automated driving levels. What will be changed when the automated driving level is higher? As introduced in chapter 2, the driver should take over the control of the vehicle when the system is not able to deal with specific critical situations in SAE level 3 vehicle. What will be the factors influencing the takeover time and behavior of the drivers as well as their SAW, MA, and workload by takeover? These questions are summarized as hypotheses in Table 5.6, Table 5.7, Table 5.8, and Table 5.9 for the next study, which will be introduced in chapter 6.

Table 5.6: Hypotheses to be tested in E3 with regard to takeover time and behavior

Focuses	Hypotheses	Variables
Experiencing sequence	H0: The takeover time does not depend on the sequence of experiencing the critical situation. H1: The takeover time depends on the sequence of experiencing the critical situation.	Takeover time
Critical situation	H0: The takeover time does not depend on the critical situation. H1: The takeover time depends on the critical situation.	
	H0: The takeover behavior does not depend on the critical situation. H1: The takeover behavior depends on the critical situation.	Number of takeover type
Interface	H0: The takeover time does not depend on the interface. H1: The takeover time depends on the interface.	Takeover time
	H0: The takeover behavior does not depend on the interface. H1: The takeover behavior depends on the interface.	Number of takeover type

Table 5.7: Hypotheses to be tested in E3 with regard to performance of NDRT

Focuses	Hypotheses	Variable
Automated driving level	H0: The automated driving level does not influence the performance of NDRT. H1: The automated driving level influences the performance of NDRT.	Performance of NDRT
Complexity of scenario	H0: The complexity of scenario does not influence the performance of NDRT. H1: The complexity of scenario influences the performance of NDRT.	
Interface	H0: The interface does not influence the performance of NDRT. H1: The interface influences the performance of NDRT.	

Table 5.8: Hypotheses to be tested in E3 with regard to SAW and MA of driver

Focuses	Hypotheses	Variable
Complexity of critical situation	H0: The complexity of critical situation does not influence the SAW of the driver. H1: The complexity of critical situation influences the SAW of the driver. H0: The complexity of critical situation does not influence the MA of the driver. H1: The complexity of critical situation influences the MA of the driver.	Correctly answered questions in mid-questionnaire regarding SAW and MA
Interface	H0: The interface does not influence the SAW of the driver. H1: The interface influences the SAW of the driver. H0: The interface does not influence the MA of the driver. H1: The interface influences the MA of the driver.	

Table 5.9: Hypotheses to be tested in E3 with regard to workload of driver

Focuses	Hypotheses	Variables
Complexity of scenario	H0: The pupil diameter dose not depend on the complexity of scenario. H1: The pupil diameter depends on the complexity of scenario.	Pupil diameter
	H0: The workload rating dose not depend on the complexity of scenario. H1: The workload rating depends on the complexity of scenario.	NASA-TLX score
Interface	H0: The pupil diameter dose not depend on the interface. H1: The pupil diameter depends on the interface.	Pupil diameter
	H0: The workload rating dose not depend on the interface. H1: The workload rating depends on the interface.	NASA-TLX score

6 Using touch interface to increase mode awareness

Whilst the improvement of fuel efficiency is studied, the automated vehicle has also become the focus. However, the technology is not ready for mass production due to manifold reasons. In this transition phase, vehicles with more than one driving mode are introduced. Such vehicles could perform the automated driving in specific situations. In critical situations, in which the automated system could not be able to handle, the drivers should take over the driving task. This leads to the following questions.

- *What are the limits of the driver with respect to time by taking over the driving task from the automated system in specific situations?*
- *Is one general takeover request time suitable for all individual drivers and driving situations?*
- *How can the information about multiple automated driving levels and related functionalities be displayed to increase the driver's situation awareness and in the meanwhile to avoid mode error/confusion?*

In this chapter, two DVIs are suggested to be used for vehicles with multiple automated driving modes (section 6.1). In this section, experiment (E3) to test the limit of the driver by taking over the driving task is introduced. With the experiment, the two DVIs are also compared. The corresponding results are explained in section 6.2. The discussion of the results is concluded in section 6.3. In section 6.4, subsequent improvement of DVIs is provided.

The contents, figures, and tables presented in this chapter are prepared for the publication [WS18].

6.1 Experimental design to find out the limits for takeover

6.1.1 Development of DVI on interactive interface

As analyzed in chapter 2, the driver's intervention is required in the first 5 levels, which means the change of automated driving level could appear in these 5 levels. The automated driving level could fall from any higher level back to level 0. A clear separation of different automated driving levels and related functionalities could help to reduce mode error/confusion. This idea stimulated the authors to design the DVI. The gap from higher level to lower level could be bridged using DVI by

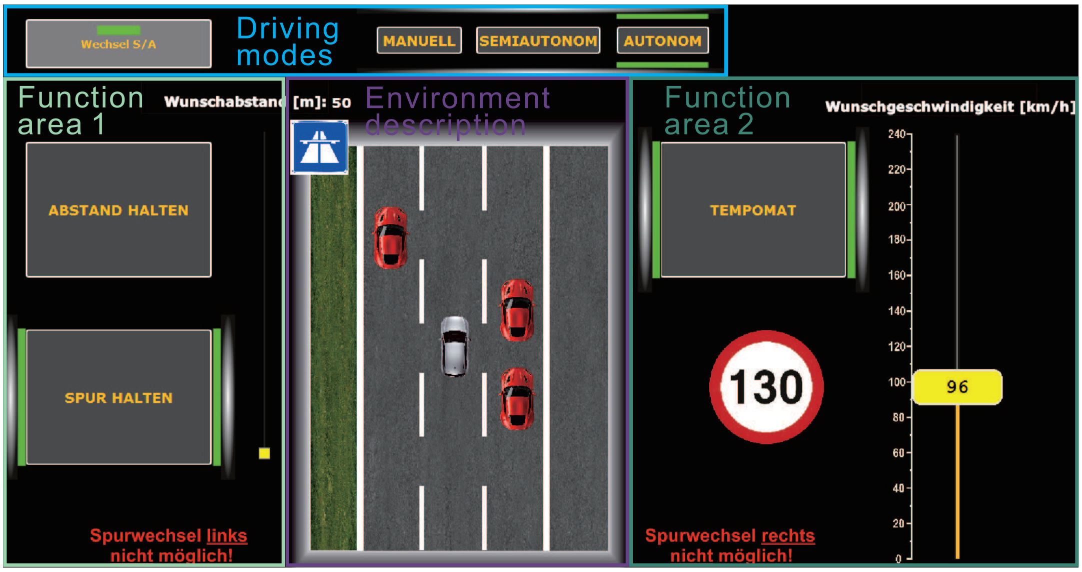


Figure 6.1: Interactive DVI concept 1 (I1)

Wechsel S/A: Switch S/A
MANUELL: Manual
SEMIAUTONOM: Semi-automated
AUTONOM: Automated
ABSTAND HALTEN: Distance keeping
SPUR HALTEN: Lane keeping
TEMPOMAT: ACC
Wunschabstand: Desired distance
Wunschgeschwindigkeit: Desired velocity
Spurwechsel links nicht möglich: Changing lane to left not possible
Spurwechsel rechts nicht möglich: Changing lane to right not possible

describing the critical situation and showing the driver what the system intents to do and how the driver could take over the control. In this way a seamless transition should be realized.

Three areas are needed in the DVI: driving mode area to avoid mode error/confusion, function area to interact with the driver and to increase mode awareness, and environment description area to increase situation awareness (SAW) of the driver. Based on this idea, two DVI concepts based on the requirements [Wag96] are proposed as illustrated in Fig. 6.1 and Fig. 6.2. Both interfaces realize the same automation strategy (same automation level related function in spite of different layouts). The activity status of buttons in I1 is denoted with green and silver stripes on both sides of the buttons, while in I2 they are denoted with green symbols according to functions on the left side of the buttons. The mapping of the described environment (the driving scene) maps the ego-vehicle (silver in I1, white in I2), other vehicles

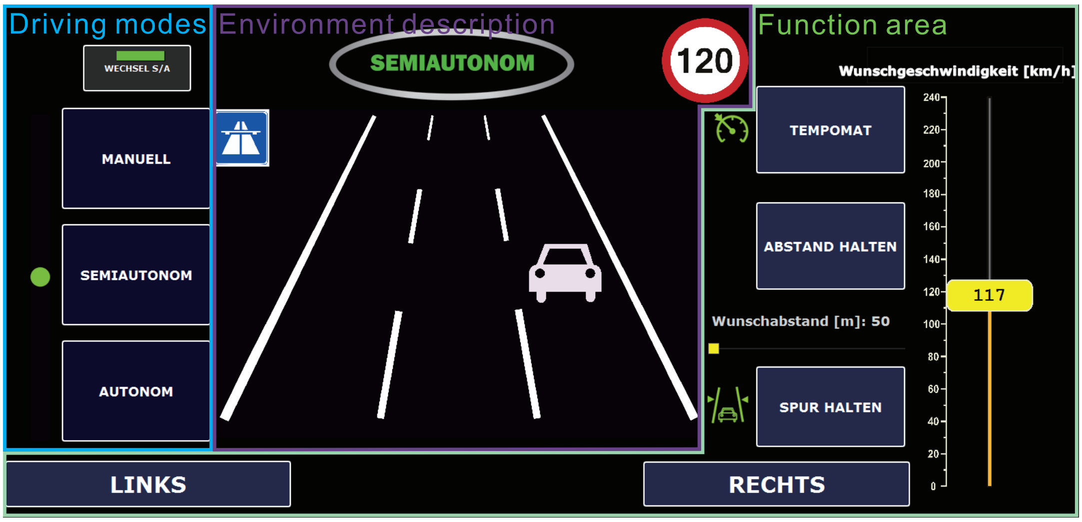


Figure 6.2: Interactive DVI concept 2 (I2)

Wechsel S/A: Switch S/A
MANUELL: Manual
SEMIAUTONOM: Semi-automated
AUTONOM: Automated
TEMPOMAT: ACC
ABSTAND HALTEN: Distance keeping
SPUR HALTEN: Lane keeping
Wunschabstand: Desired distance
Wunschgeschwindigkeit: Desired velocity
LINKS: Left
RECHTS: Right

(in red), and detected traffic signs. The displayed traffic sign, driving lanes, and position of ego-vehicle change adaptively with the real driving scene. The other difference between these two DVIs is the way of displaying the driving environment: bird-view perspective is applied in I1 whilst driver-view is used in I2. The acceptance of the two DVIs regarding different layouts and perspectives of describing the driving environment is to be compared with experiment.

Based on the analysis of ADASs, driving maneuvers, and design requirements [SAE03] [SAE10] [SAE16a] [SAE14a], the functions described in Table 6.1 are realized in the proposed DVI concepts and will be used in the experiments.

Three automation levels are defined in the proposed DVI concepts based on SAE levels (Table 6.2). The switch from MANU mode to SEMI mode or to FULL mode is realized by clicking on the mode buttons and vice versa, the driver could take over the vehicle control by either steering or pressing the brake pedal. By activating the button “Wechsel S/A” (Switch S/A), the SEMI mode would be switched to FULL

Table 6.1: Description of functions of assistance systems

Forward collision warning (FCW)	warns the driver about potential frontal danger. It is provided to the driver visually on HUD and acoustically. The size of visual display and frequency of sound vary based on time to collision (TTC).
Blind spot warning (BSW)	warns the driver about obstacles within the blind spot areas. It is displayed on two outside rear-view mirrors.
Distance keeping (Abstand halten)	realizes vehicle-following maneuver. It allows to follow the frontal vehicle with the predefined distance. It can be activated related to a preceding vehicle, otherwise an acoustic announcement would be played in both German and English languages: No frontal vehicle. Once it is activated, the driver can set the desired distance to follow the frontal vehicle by adjusting the position of the vertical slider near to the button. The numerical distance varies whilst the adjustment of the slider. The traffic signs have higher priority, so that the overspeed can be avoided.
Lane keeping (Spur halten)	realizes keeping the vehicle driving in the middle of the current lane.
ACC (Tempomat)	realizes driving with desired velocity, which can be adjusted by moving the slider near to the button. The selected velocity is displayed in the middle of the slider.
Lane changing	realizes lane changing maneuver to left or to right. In I1, the function is realized by clicking on the desired lane in the environment description. In I2, the maneuvers changing lane to left and right are realized by clicking on the buttons “LINKS” and “RECHTS” respectively. This function is not deactivated when a vehicle is on the desired lane within given dangerous area and TTC. In the meanwhile, a visual explanation about “lane change not possible” is displayed near to the environment description in I1 and the buttons in I2.

Table 6.2: Description of driving modes

Manually (MANU)	mode is related to SAE level 0. The driver self should execute the complete driving tasks longitudinally and laterally. Both of the driver assistance systems FCW and BSW are activated in this mode.
Semi-automated (SEMI)	mode is related to SAE level 1 and 2. The driving tasks are simplified into assistance system functions and maneuvers, such as: giving desired velocity, keeping and setting distance to the frontal vehicle, keeping in the current lane, changing lane to left or right, etc. Drivers are released from steering and pressing pedals, instead of which they can enter the driving command using the touchpad. If the speed limit is exceeded, an acoustic warning is played in both languages: Within speed limit.
Automated (FULL)	mode is related to SAE level 3. The driver only needs to give the desired maximal velocity. The system could execute overtaking maneuvers when the maximal velocity is allowed (due to traffic sign and surrounding vehicles) and brake if not. According to the given goal, the route could be planned and the system could drive accordingly.

mode automatically when the situation has potential to be hazardous but the driver does not response in time. In this case, the system would take over the vehicle control automatically. When it is not activated by the driver, the mode would not be automatically switched from SEMI to FULL mode. A visual and acoustic TOR is given a predefined time (here: 8 s) before the critical situation based on [MJMJ17]. The visual TOR is displayed as HUD on the main monitor. The acoustic TOR is given related to the failure of the system so the driver should take over the drive. The content of the acoustic TOR in English is: Attention! Automated driving failed.

6.1.2 Independent and dependent variables

The two interactive DVIs are developed and evaluated using the driving simulator. They are displayed on the touch 1 as shown in Figure 4.1. The dashboard is used in this experiment (E3) to display the speedometer, the tachometer, and information about assistance systems as shown in Figure 6.3. The HUD on the main monitor

Figure 6.3: Dashboard used in the E3

and the outside rearview mirrors are used to display FCW and BSW during manual driving. The touch 2 is used for the non-driving-related task (NDRT), which is detailed in following sections.

In this experiment, the takeover time and behavior from the automated driving mode to the manual mode in different driving scenarios are studied. The situation awareness by taking over and perceived workload in different scenarios are compared. The performance of the NDRT in different driving modes is evaluated.

Three driving scenarios depicted in Table 6.3 were designed to test the driver-vehicle interaction in three different driving modes with two different DVI concepts.

Table 6.3: Description of driving scenarios

Scenario 1 (S1)	comprises a straight country road with the total length about 8 km and driving lane width 3.5 m, which consists of two lanes with two directions and low traffic density (Figure 6.4). Several speed limits (70, 80, and 90 km/h) and end of speed limits are used to simulate the real driving environment. The allowed maximal velocity on country road is 100 km/h. After experiencing all three driving modes, the FULL driving mode fails because of appearing heavy fog. A preceding vehicle stops at the position with 8 s time to collision (TTC) on the same lane as the ego-vehicle is driving when the TOR is shown to the driver. This happens in a section with speed limit with 70 km/h and no surrounding traffic. The driver could either brake and stop after the preceding vehicle or overtake it.

Scenario 2 (S2)	includes a motorway with the total length about 11 km and driving lane width 3.5 m, which contains six lanes with two directions and high traffic density (Figure 6.5). Speed limits (70, 100, and 130 km/h) and end of speed limits are designed to realize a dynamic driving environment. Within the section without any speed limitation, the driver can drive so fast as wanted. After driving with three modes, the FULL driving mode fails because of sudden heavy fog. While the TOR is shown to the driver, a preceding vehicle stops in front of the ego-vehicle with the TTC 8 s on the same lane. This happens in a section with speed limit of 80 km/h and no surrounding traffic. The driver could brake and stop after the preceding vehicle or overtake it.
Scenario 3 (S3)	consists of a motorway with seven exits and seven entries as well as low traffic density (Figure 6.6). The total length is about 15 km. The width of the driving lane on the motorway is 3.5 m and the one of the ramp is 8.5 m. The driver should realize two times leaving and entering the motorway manually, three times with SEMI mode, and two times with FULL mode. The driver was informed about the exits 1 km in advance. In FULL mode, the exits are defined previously, so that the driver only needs to set the desired maximal velocity. At the 8th exit, the FULL driving mode fails because of sudden heavy fog, but the indicator is activated with acoustic feedback. This happens in a section with speed limit with 80 km/h and no surrounding traffic. The driver should take over the vehicle control and leave the motorway.

Each scenario can be considered as a combination of experiencing the DVI and taking over, which are performed by the driver subsequently. In the phase of experiencing the DVI, the number of lanes in one direction (one, three, and mixed of sections with three lanes and ramp), the traffic density (one vehicle per kilometer and ten vehicles per kilometer), and the driving terrain (country road, motorway, and motorway including several entries and exits) are considered to realize various driving environment. Three scenarios can be combined: one lane & one vehicle per kilometer & country road; three lanes & ten vehicles per kilometer & motorway; mixed sections & one vehicle per kilometer & motorway with entries and exits. The complexity of first two combinations for experiencing the DVI is roughly comparable because of increasing number of lanes, traffic density, and driving terrain. The third scenario can not be compared because of degraded traffic density and low driven speed in ramps. However, the driver has the opportunity to interact with various

Figure 6.4: Simulated scenario 1 for E3

Figure 6.5: Simulated scenario 2 for E3

Figure 6.6: Simulated scenario 3 for E3

driving environments through the DVI, so that the usability of the DVI could be evaluated.

In the takeover phase, the driven speed (70 and 80 km/h) is considered, which are assigned to the three scenarios (70 km/h in the first one; 80 km/h in the second and the third ones). No surrounding traffic is added excepts the vehicle parked in front of the ego-vehicle. Furthermore, the required awareness of the driver is distinguished. In the first two scenarios, the driver should be aware of the driving environment. The options left for the driver is to brake, to steer, or both. The difference between them is the number of lanes and the driven speed. In the third scenario, the driver should be aware of the driving environment and understand the intended goal, which is to leave the motorway. The option left for the driver is to brake and to steer. The complexity of the three takeover situations increases because of the driving environment (driven speed and number of lanes), the required awareness, and the options left for the driver.

Each driver performed six drives. Herein a repeated measured experiment is used with following independent variables:

- Experiencing sequence (ES),
- Scenario (S),
- Driving mode (DM), and
- Interface (I).

The six drives result from the combination of driving scenario and interface. During each drive, the driver experiences three driving modes continuously. They are informed about switching driving modes at previously defined specific points, which divide the whole driving route into three equivalent parts. The ES is considered as one of the IVs to study the difference of the takeover time in the first drive and the other drives.

The participants were encouraged to do the NDRTs as many and as correctly as possible with guaranteed driving safety during the complete drive regardless in which driving mode they are. The NDRT is based on arithmetic tasks including addition, subtraction, multiplication, and division of two-digit numbers. They were programmed for each drive to ensure that all the participants calculate the same set of arithmetic tasks with the same sequence. It can be assumed that all participants are very familiar with this kind of tasks.

The dependent variables are described in Table 6.4.

Table 6.4: Description of dependent variables in E3

Perspective	Dependent variable	Description
• Study of takeover time • Study of takeover behavior	Takeover time	The takeover time is defined from the time point, when the TOR is provided to the driver. It ends when either the movement of the steering wheel is larger than 2°, the brake pedal is pressed (5 %), or the accelerator pedal is pressed (5 %) as also suggest in [WGR17].
	Number of takeover type	The number of takeover represents the times of the driver taking the control of vehicle from the automated driving by steering, braking, or accident.
• Effects of automated driving levels and complexity of driving scenarios on performance of NDRTs • Comparison of interfaces	Performance of NDRTs	The performance of NDRT was evaluated using the number of the completed arithmetic tasks per minute in corresponding driving mode.
• Effects of complexity of critical situation on SAW and MA • Comparison of interfaces	Number of total correctly answered questions in mid-questionnaire	The mid-questionnaire, which consists of two parts, is given to the participants after each drive. This variable is the number of total correctly answered questions.
	Number of correctly answered mid-questionnaire regarding SAW	Five questions are asked in mid-questionnaire regarding the SAW. They focus on the position surrounding vehicles and driving lane of ego-vehicle.
	Number of correctly answered mid-questionnaire regarding MA	Six questions are asked in mid-questionnaire regarding the MA. They focus on the driving mode, the activities of assistance systems, the actual driven velocity, and the set one on the touch 1.
Workload of driver	Pupil diameter	The pupil diameter is proved as a direct measure of mental activity [HP64]. The size of diameter increases when the required mental workload is high [IZB04] [Van00] [Van01] but also reflects ambientluminance [Bea82] [Hol11].
	NASA-TLX score	The perceived workload with respect to six aspects: mental demand, physical demand, temporal demand, effort, frustration, and performance [HS88].

6.1.3 Participants

Thirty-eight people (31 male, mean age = 25 years, min. = 19, max. = 40, SD = 4) were recruited for the study using advertisements during lectures, online, and on billboards in the university. All the participants held valid driving licenses and had an average driving experience of 6 years (min. = 1, max. = 17, SD = 4) with mean annual mileage of 14 396 *km* (min. = 60, max. = 100 000, SD = 21 069). As reward, the participant could choose either 10 EUR or take part in a time management course.

6.1.4 Procedure

As depicted in Figure 6.7, participants were given a general introduction of the experiment and consent to read and sign for data collection. They were told that they are free to stop the experiment. The study has been approved by the ethics committee of the faculty of Engineering in the university Duisburg-Essen. The pre-questionnaire was asked regarding the driving experience. Then they were asked to sit in the simulator and adjust the positions of the seat, the instrument panel, and the two touchpads. Afterwards, the participants were introduced to the operation of the driving simulator, the procedure of the experiment, the scenarios, and the functions of three driving modes. They were told that if the FULL driving mode does not work, they will be previously informed by acoustic and visual warning and should take over the control. Afterwards the drivers were asked to execute test drives to get used to the driving simulator, the NDRT, and ensure about no simulator sickness symptoms. In the test drives, the drivers experienced all the three scenarios, two interfaces, and three driving modes. After the test drives, the questionnaires about the situation awareness were explained to the drivers to avoid the inequivalent results, because otherwise the participants know already the questions in the second to the sixth drives but in the first one not. After confirmation of the participants, the six experimental drives were performed with a randomized sequence to avoid learning effects and confounds. Each experimental drive was followed by the situation awareness questionnaire and a workload assessment using NASA-Task Load Index (NASA-TLX) [HS88]. After the complete drives, a post-questionnaire was given to the participants to fill out.

6.1.5 Data collection and analysis

The data collected from the driving simulator, the eye tracker, and the questionnaires are divided into two groups: objective and subjective. The takeover time and behavior are used to analyze the interaction between driver and vehicle. Statistical analysis methods with the significance level 0.05 are used to analyze the data.

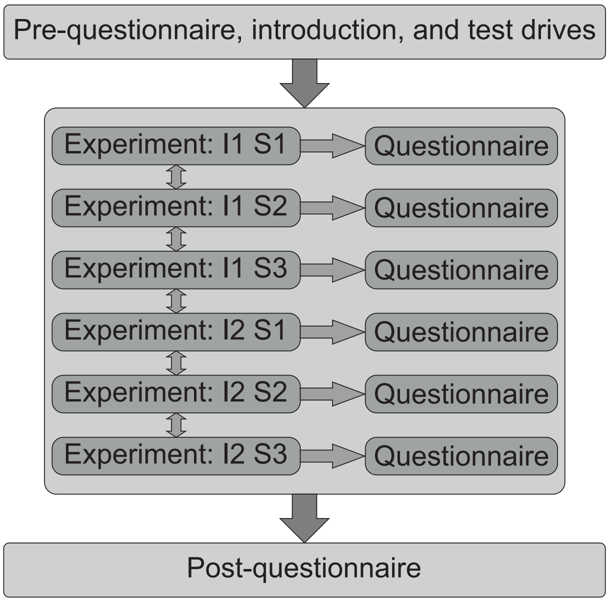


Figure 6.7: Procedure of E3 comparing interactive DVIs

Two-way MANOVA is used to evaluate the interaction effects between the two IVs on the selected DVs. One-way ANOVA, two-way ANOVA, and Chi-square test are used to analyze the DVs.

6.2 Results

Descriptive statistics of dependent variables (DVs) are given in Table 6.5. The non-normally distributed DVs are transformed to meet the assumptions of the parametric analysis techniques.

Two-way MANOVA was conducted to evaluate the interaction effects between the two independent variables S and I on the selected DVs. The takeover behavior was not considered because it is not continuous variable. The pupil diameter was not selected because of the different sample size. Results from two-way MANOVA show no significant interaction effect between driving scenario and interface on the combined DVs. The results indicate a significant main effect for the driving scenario on the combined DVs ($F(8, 420) = 18.6$, $p < .05$; Wilks' $\Lambda = .55$; partial $\eta^2 = .26$) but no effect for the interface. Significant differences can be obtained in all DVs: takeover time ($F(2, 213) = 48.9$, $p < .001$, partial $\eta^2 = .32$), performance of NDRT ($F(2, 213) = 11.7$, $p < .001$, partial $\eta^2 = .10$), number of total correctly answered questions in mid-questionnaire ($F(2, 213) = 11.4$, $p < .001$, partial $\eta^2 = .10$), and total NASA-TLX score ($F(2, 213) = 8.0$, $p < .001$, partial $\eta^2 = .10$).

The separate analysis of the results is detailed in sections 6.2.1 and 6.2.2.

Table 6.5: Descriptive statistics (Means and SD (*italic*) of dependent variables) in E3

		1st	**2nd**	**3rd**	**4th**	**5th**	**6th**
Takeover time [s]		9.04	4.80	5.69	5.42	5.72	5.20
		(3.44)	*(2.63)*	*(2.94)*	*(3.81)*	*(3.33)*	*(3.22)*
		S1I1	**S2I1**	**S3I1**	**S1I2**	**S2I2**	**S3I2**
		8.79	5.11	4.50	8.50	4.41	4.00
		(2.93)	*(3.67)*	*(1.94)*	*(2.75)*	*(3.26)*	*(2.51)*
Number of takeover type [-]	Steering	21	24	32	25	22	29
	Braking	15	13	4	13	15	6
	Accident	2	1	2	0	1	3
Number of total completed NDRTs [-]	MANU	0.62	0.30	0.67	0.58	0.27	0.83
		(0.54)	*(0.36)*	*(0.82)*	*(0.51)*	*(0.26)*	*(1.27)*
	SEMI	4.70	3.15	3.86	4.58	3.36	3.89
		(2.81)	*(1.71)*	*(2.08)*	*(2.93)*	*(2.93)*	*(2.18)*
	FULL	4.65	3.62	5.58	4.70	3.24	6.09
		(2.81)	*(1.61)*	*(2.27)*	*(3.37)*	*(2.93)*	*(3.27)*
Number of total correctly answered questions in mid-questionnaire [-]		9.34	8.34	9.55	9.29	8.76	9.53
		(1.36)	*(1.72)*	*(1.27)*	*(1.35)*	*(1.33)*	*(1.39)*
Number of correctly answered questions in mid-questionnaire regarding SAW [-]		4.63	4.11	4.74	4.74	4.50	4.89
		(0.81)	*(0.37)*	*(0.55)*	*(0.50)*	*(0.79)*	*(0.38)*
Number of correctly answered questions in mid-questionnaire regarding MA [-]		4.71	4.26	4.82	4.55	4.29	4.63
		(1.07)	*(1.21)*	*(1.07)*	*(1.16)*	*(1.17)*	*(1.37)*
Pupil diameter [mm]		4.55	4.22	4.23	4.61	4.19	4.22
		(0.56)	*(0.65)*	*(0.65)*	*(0.71)*	*(0.67)*	*(0.66)*
NASA-TLX total score [0-100]		27.85	38.06	29.96	28.23	34.31	28.50
		(13.34)	*(12.82)*	*(14.71)*	*(15.06)*	*(15.19)*	*(16.68)*

6.2.1 Objective results

Takeover time

A statistically significant difference can be detected at the $p < .05$ level in takeover time for experiencing sequence: $F(5, 213) = 7.2$, $p < .001$. The effect size is .14 calculated by η^2. Post-hoc comparisons using the Bonferroni correction indicate that the mean takeover time for first drive is significantly different from other drives. No significant difference can be detected among the other 5 drives. With the focus on the first and second drives, the takeover time and the ES are significantly associated $r =$ -.572, $p < .001$. The results are depicted in Figure 6.8.

No significant interaction between the effects of driving scenario and interface on takeover time can be obtained. The results indicate a significant main effect for the critical situation ($F(2, 227) = 30.7$, $p < .001$, $\eta^2 = .22$) but no effect for the interface. Tukey's HSD post hoc tests were performed. For both interfaces, S1 is significantly different to S2 ($p < .001$) as well as to S3 ($p < .001$). No significant difference between S2 and S3 can be obtained. The results are shown in Figure 6.9.

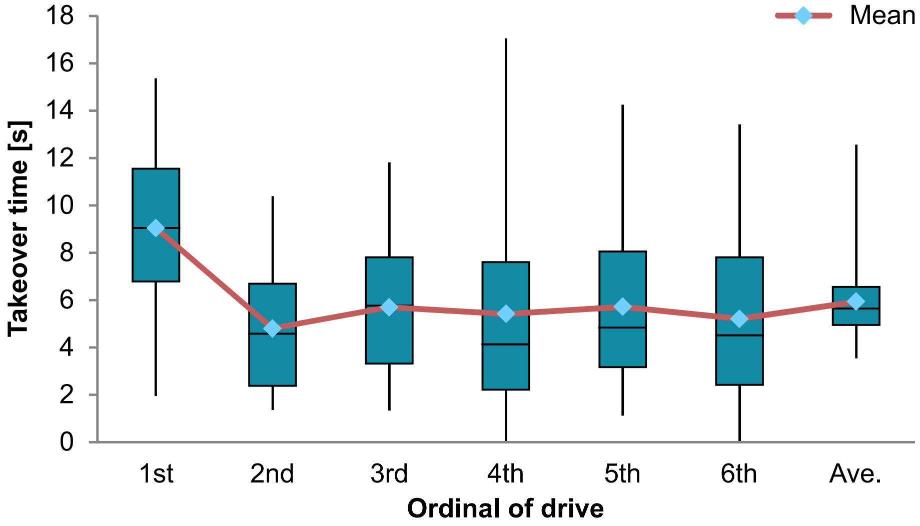


Figure 6.8: Takeover time according to driving sequence

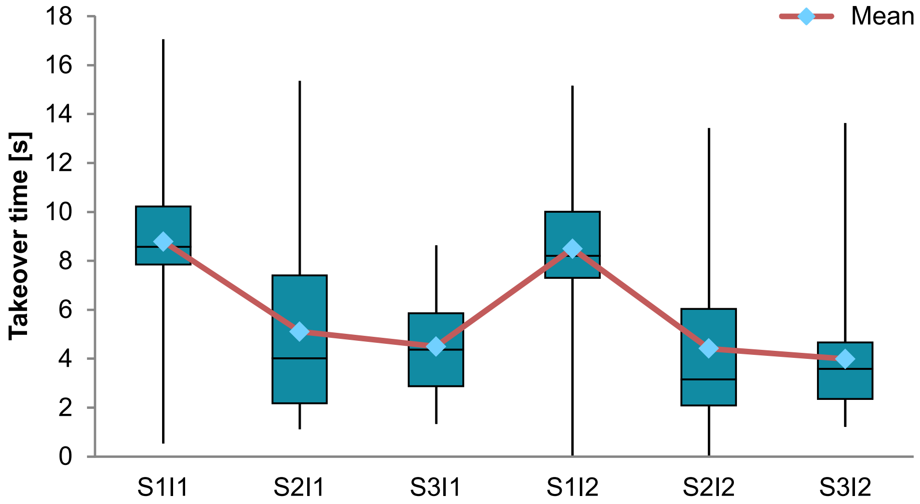


Figure 6.9: Takeover time according to combination of scenario and interface

Takeover behavior

A Chi-square test for independence indicates a significant association between type of takeover behavior and driving scenario ($\chi^2(4) = 14.759$. $p < .05$), but the measured effect size presents a small level of association ($V = .180$). Based on the results, a tendency for steering to S3 and braking to S1 and S2 can be stated. The

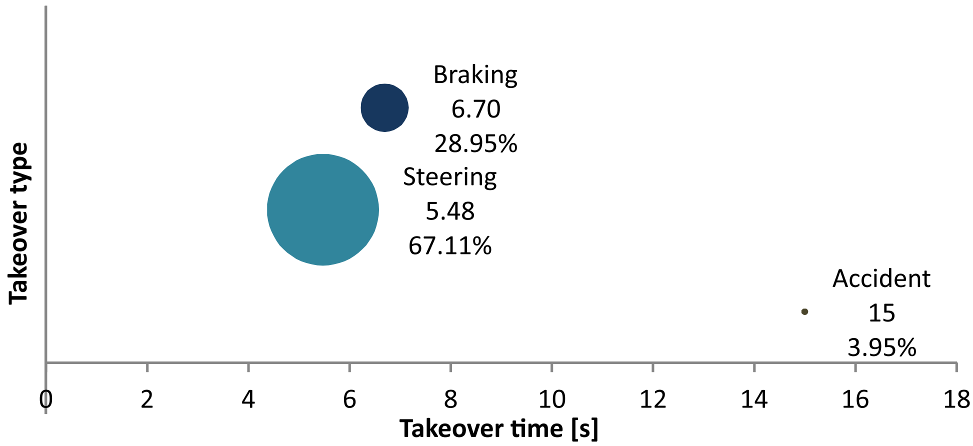


Figure 6.10: Takeover behavior

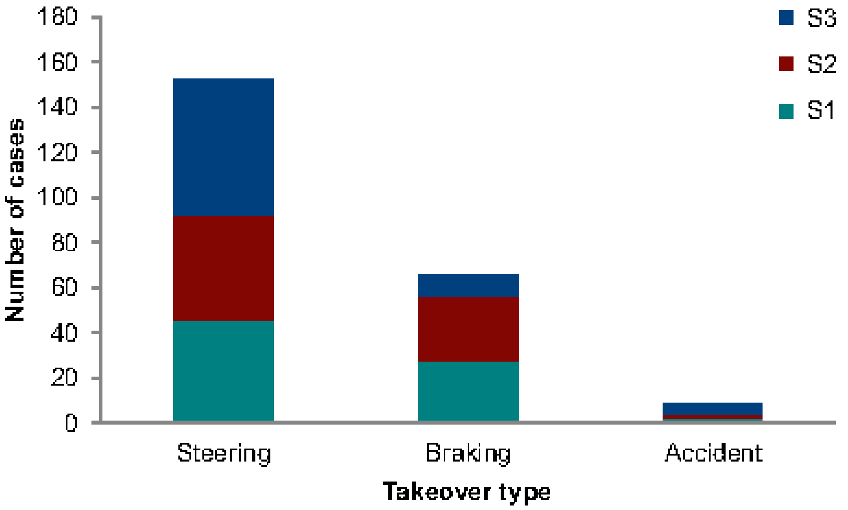


Figure 6.11: Number of cases for three takeover types

results of using the same method show no significant association between type of takeover behavior and interface ($\chi^2(2) = .178.\ p > .05$).

The number of cases for each situation is illustrated in Figure 6.10. The number on the second row near the circle represents the takeover time. The size of the circle in Figure 6.10 denotes the related percentage of each behavior, which is also detailed as the number on the last row near to each circle. The number of cases for three takeover types is depicted in Figure 6.11.

Performance of non-driving-related task

Three independent variables, which are driving scenario, driving mode, and interface, were considered. Three-way ANOVA was conducted for the evaluation. Results show no significant 3-way interaction. A significant 2-way interaction of driving scenario and mode ($F(4{,}683) = 6.9$, $p < .001$, $\eta^2 = .02$) is obtained. Main effects for the driving scenario ($F(2{,}683) = 21.0$, $p < .001$, $\eta^2 = .03$) and the driving mode ($F(2{,}683) = 251.6$, $p < .001$, $\eta^2 = .41$) are detected. Post hoc tests using Tukey's HSD were performed. For both interfaces, S2 is significantly different to S1 ($p < .001$) as well as to S3 ($p < .001$), whilst no significant difference between S2 and S3 is obtained. The pairwise comparison for driving mode showed that the performance of NDRT is significantly different in all three driving modes ($p < .001$). This means that more NDRT could be performed with higher automated driving level. Results are illustrated in Figure 6.12.

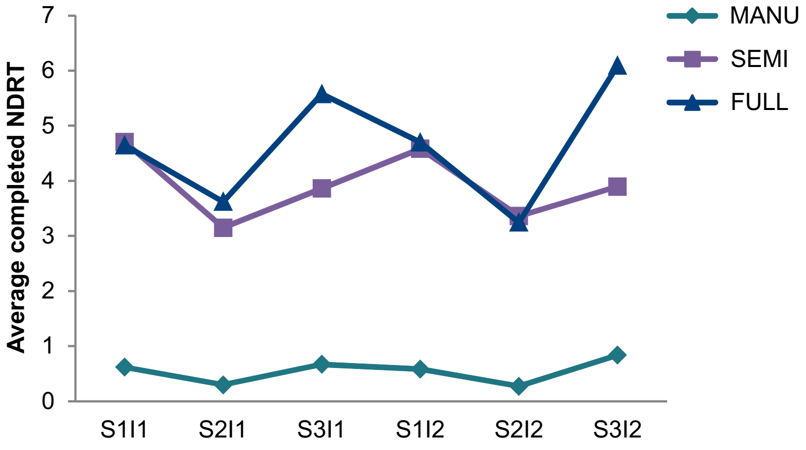


Figure 6.12: Performance of non-driving-related task (NDRT)

Relation between takeover time and performance of non-driving-related task

Taking both takeover time and performance of non-driving-related task (NDRT) in FULL driving mode into consideration, it was expected that better performance of NDRT could be achieved by compromising the takeover time. In other words, the more distracted or the more intensive by the NDRT, the longer the takeover time. The results depicting the relation between them are shown in Figure 6.13. In Figure 6.13(a),the relation is represented based on the combination of scenario and interface, while Figure 6.13(b) shows the one based on the sequence of drives. The tendency among the four drives from S1 to S2 is shown in Figure 6.13(a). It can be clearly detected that the S1 (simpler scenario with lower speed by takeover) needs more takeover time, while the ones with increased complexity and higher speed by takeover (S2) needs less. The reason for the "good" behavior (better performance of NDRT and shorter takeover time) with respect to S3 may due to the circumstance that S1 and S2 require the similar driving strategy, which is at relative constant high speed. The S3 consists of several transition segments between motorways, in which the allowed maximum speed is 30 km/h. Most drivers did the NDRT only during the transition segments not on the motorway. As shown in Figure 6.13(b), the longest takeover time and the minimum number of realized NDRT are achieved in the first drive, because the drivers were not familiar with the tasks. In the subsequent drives, the takeover time and number of completed NDRT during FULL driving mode do not show significant differences. From this it can be concluded that the takeover time is between 5 to 6 s, which includes the time requested for the driver to understand the scenario and to suitably handle the takeover. It should also be noted that the takeover time of the non-experienced driver (all drivers experiencing TOR for the first time) is 9 s.

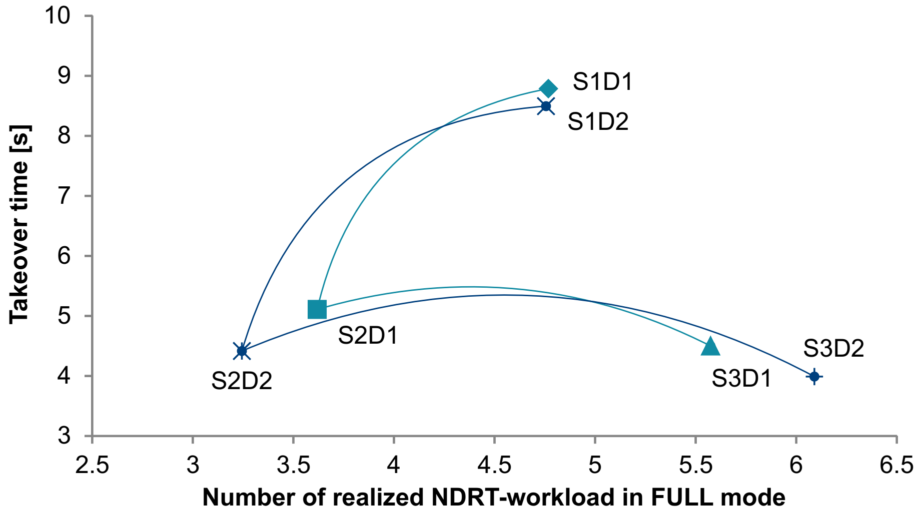
Situation/Mode awareness

Results show no significant interaction between the effects of driving scenario and interface on the total score of the questionnaire. However, significant main effect for the driving scenario ($F(2{,}227) = 9.9$, $p < .001$, $\eta^2 = .08$) can be obtained. No significant main effect for the interface can be detected. Results from post hoc tests using Tukey's HSD show that, S2 is significantly different to S1 ($p < .005$) as well as to S3 ($p < .001$). No significant difference between S1 and S3 can be obtained. The total score of the questionnaire is illustrated in Figure 6.14.

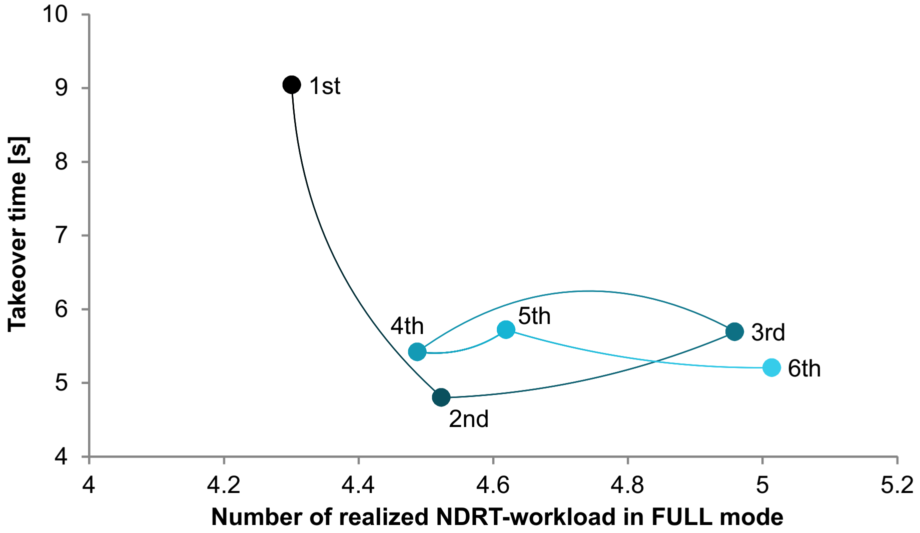
Considering the results separately, no significant interaction between the effects of driving scenario and interface on the questionnaire regarding SAW can be obtained either. However, significant main effects for the driving scenario ($F(2{,}227) = 9.8$, $p < .001$, $\eta^2 = .08$) and the interface ($F(1{,}227) = 5.0$, $p = .03$, $\eta^2 = .02$) are obtained. Results from post hoc tests using Tukey's HSD show that, S2 is significantly different to S1 ($p < .005$) as well as to S3 ($p < .001$). No significant difference between S1 and S3 can be obtained. No significant difference in correctly answered question regarding MA for the three scenarios and the two interfaces can be obtained, but still, they show the similar tendency as the ones in the questions regarding SAW. This means that the complexity of the driving scenario influences the SAW of the driver and could also cause lack of MA.

Pupil diameter

As introduced in section 4.2.2, the pupil diameter could be used to evaluate the perceived mental workload. The analysis of this variable is based on the data from 24 participants, because the gaze data from the rest of the participants were obtained based on iris contour. The two independent variables: driving scenario and interface, are considered. Results show no significant interaction between the effects of driving scenario and interface on pupil diameter. A significant main effect for the driving scenario ($F(2{,}143) = 4.9$, $p < .01$, $\eta^2 = .07$) can be obtained. Post hoc tests were



(a) Scenario related



(b) Sequence related

Figure 6.13: Relation between takeover time and performance of non-driving-related task (NDRT)

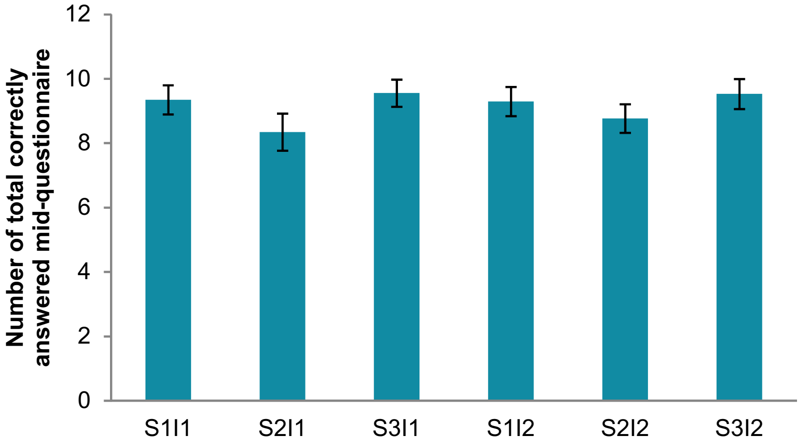


Figure 6.14: Comparison of correctly answered questions in mid-questionnaire

performed using Tukey's HSD. For both interfaces, S1 is significantly different to S2 ($p = .02$) as well as to S3 ($p = .02$). No significant difference between S2 and S3 can be obtained. Results are shown in Figure 6.15.

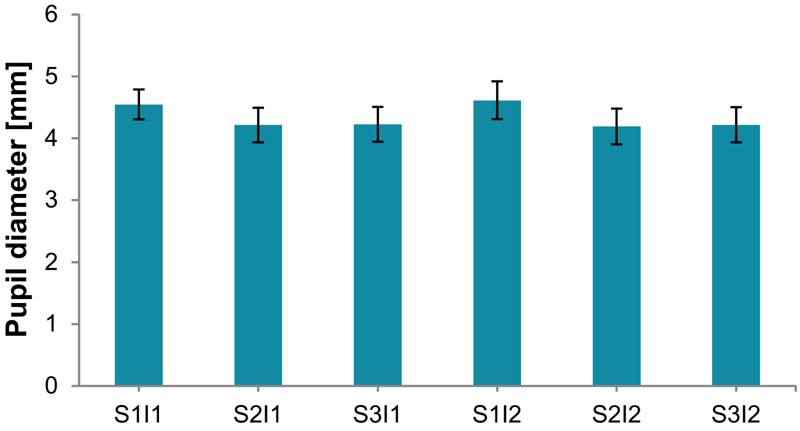


Figure 6.15: Pupil diameter based on combination of scenario and interface

Workload

The results show no significant interaction between the effects of driving scenario and interface on total NASA-TLX score. A significant main effect for the driving scenario ($F(2, 227) = 6.6$, $p < .005$, $\eta^2 = .06$) can be obtained, but no effect for the interface can be detected. Tukey's HSD post hoc tests were performed. For both interfaces, S2 is significantly different to S1 ($p = .003$) as well as to S3 ($p = .01$). No significant difference between S2 and S3 can be obtained. The internal consistency of the workload assessment with Cronbach's alpha is reliable in each test drive (S1I1:

.801; S2I1: .779; S3I1: .850; S1I2: .867; S2I2: .848; S3I2: .877). The total score of NASA-TLX questionnaire is illustrated in Figure 6.16).

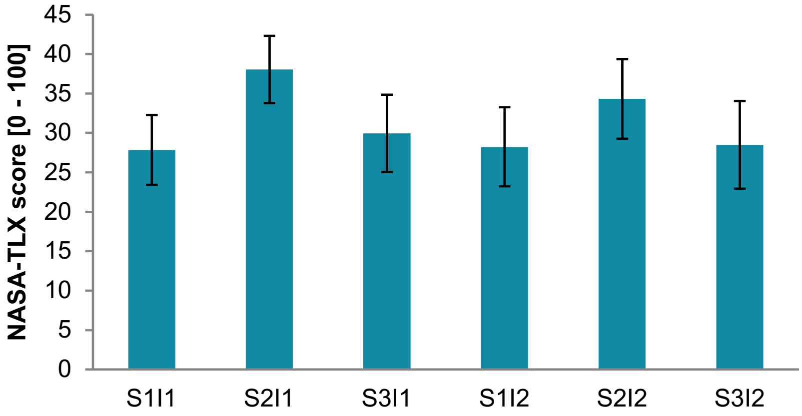


Figure 6.16: Comparison of workload in six drives

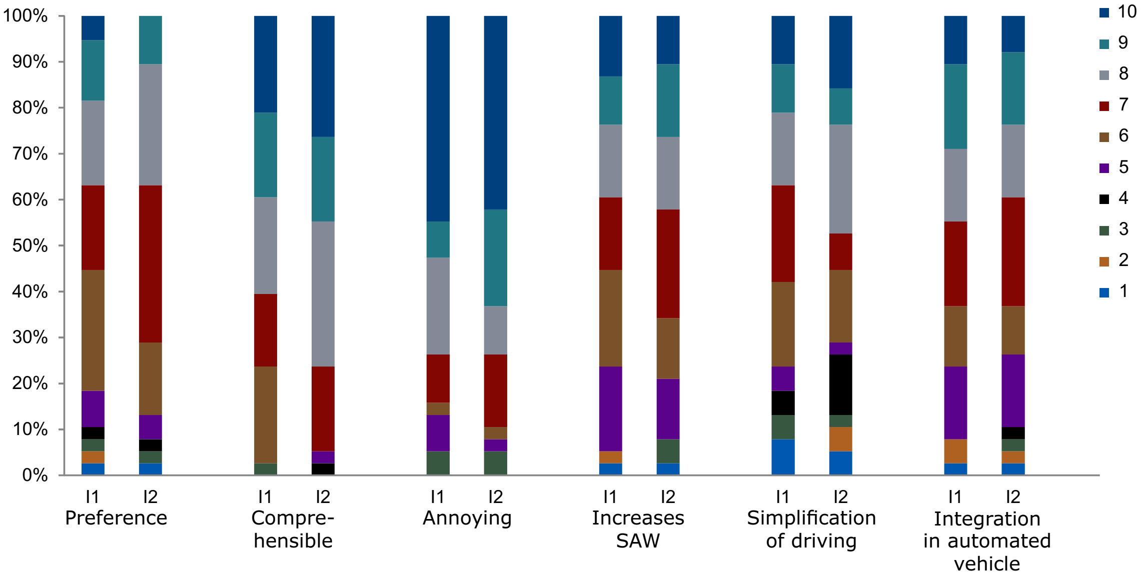


Figure 6.17: Subjective ratings of two DVIs

6.2.2 Subjective results

In the post-questionnaire, the participants were asked with questions using 10-point Likert scale about preference, comprehensibility, annoyance, increment of SAW, simplification of driving, and willingness of integration in automated vehicle of two interfaces (Figure 6.17). It is worth mentioning that the interface is less annoyance with larger scale. There is no obvious difference of the preference between the two interfaces. Most of the participants stated that the interface is helpful to increase

Table 6.6: Hypotheses verification in E3 with regard to takeover time and behavior

Focuses	Hypotheses	
Experiencing sequence	H0: The takeover time does not depend on the sequence of experiencing the critical situation.	×
	H1: The takeover time depends on the sequence of experiencing the critical situation.	√
Critical situation	H0: The takeover time does not depend on the critical situation.	×
	H1: The takeover time depends on the critical situation.	√
	H0: The takeover behavior does not depend on the critical situation.	×
	H1: The takeover behavior depends on the critical situation.	√
Interface	H0: The takeover time does not depend on the interface.	√
	H1: The takeover time depends on the interface.	×
	H0: The takeover behavior does not depend on the interface.	√
	H1: The takeover behavior depends on the interface.	×

their SAW and would like to integrate them into an automated vehicle. Some of the participants stated that the representation of lane change command by clicking on the lane in I1 is more convenient than in I2, but some stated exact the opposite. Some thought that the separation of driving modes and function area using different sizes in S1 is easier to operate, because the switch of driving modes is not realized often; others declared that the larger buttons for driving modes in S2 are easier to touch.

6.3 Verification of hypotheses and discussion

Based on the results described in section 6.1.1, the hypotheses posed in chapter 5 could be verified. They are summarized in Table 6.6, Table 6.7, Table 6.8, and Table 6.9.

6.3.1 Limits

Takeover time and related consequences

One of the questions stated at the beginning of this chapter is: Is one general TOR time suitable regardless drivers, takeover situations, and experiencing of the takeover? The TOR in the experiment is given to the driver visually and acoustically 8 s before the automated driving system fails. The mean takeover time measured is 5.93 s. According to [GDLB13], the takeover time is proportional to the TOR

Table 6.7: Hypotheses verification in E3 with regard to performance of NDRT

Focuses	Hypotheses	
Automated driving level	H0: The automated driving level does not influence the performance of NDRT.	×
	H1: The automated driving level influences the performance of NDRT.	√
Complexity of scenario	H0: The complexity of scenario does not influence the performance of NDRT.	×
	H1: The complexity of scenario influences the performance of NDRT.	√
Interface	H0: The interface does not influence the performance of NDRT.	√
	H1: The interface influences the performance of NDRT.	×

Table 6.8: Hypotheses verification in E3 with regard to SAW and MA of driver

Focuses	Hypotheses	
Complexity of critical situation	H0: The complexity of critical situation does not influence the SAW of the driver.	×
	H1: The complexity of critical situation influences the SAW of the driver.	√
	H0: The complexity of critical situation does not influence the MA of the driver.	√
	H1: The complexity of critical situation influences the MA of the driver.	×
Interface	H0: The interface does not influence the SAW of the driver.	×
	H1: The interface influences the SAW of the driver.	√
	H0: The interface does not influence the MA of the driver.	√
	H1: The interface influences the MA of the driver.	×

Table 6.9: Hypotheses verification in E3 with regard to workload of driver

Focuses	Hypotheses	
Complexity of scenario	H0: The pupil diameter dose not depend on the complexity of scenario.	×
	H1: The pupil diameter depends on the complexity of scenario.	√
	H0: The workload rating dose not depend on the complexity of scenario.	×
	H1: The workload rating depends on the complexity of scenario.	√
Interface	H0: The pupil diameter dose not depend on the interface.	√
	H1: The pupil diameter depends on the interface.	×
	H0: The workload rating dose not depend on the interface.	√
	H1: The workload rating depends on the interface.	×

time, which may explain why the average takeover time is higher than observed by others [LDS+16] [MRD+15]. The larger TOR time provides the driver more time to analyze the situation and thus to make a more correct decision. It should be noticed that the mean takeover time for the first drive is about 9 s (Table 6.5), which is significantly larger than those for the following takeover maneuvers. The drivers were not ready to deal with the takeover situation in the first drive although they were previously told of the failure of the system in the introduction part. Obviously the experience of the upcoming takeover situations influences the takeover time. There were totally 9 accidents, 6 of them happened in the first drive. However some drivers could manage the takeover at the first time, which possibly indicates that also the experience of the driver effects the takeover result. In some cases, the takeover time was larger than the TOR time and no accident happened, because the automated driving was still working from the time point of TOR to the time point of system failure. For only 8 s the automated system could detect the dangerous situation and respond if there could be a collision. However, if the driver did not react at all or too late, the forward collision could not be avoided. The takeover time measured in the second drive is almost half of the one in the first drive, which shows a strong learning or anticipation effect and therefore also individual adaption behavior. Once the drivers experienced the critical situation, they became more attentive. After a successful takeover, they became less attentive again. That is why the takeover time curve shows a zigzag form as shown in Figure 6.8. Results show also that the takeover time is various in different critical situations. As conclusion it can be stated that the answer to the aforementioned question about one general TOR time is negative: one general TOR time seems not to be suitable.

The performance of NDRT is used to denote how helpful the SEMI and FULL driving modes are. The results show significantly higher score with increasing automated driving level. Using automated driving did indeed reduce the workload by driving. The drivers could spend more time for NDRTs. Comparing it within three driving scenarios, S2 has the lowest score because it has higher traffic density, which requires the driver to monitor the driving environment and the system more often. Driving in more complex scenario (S2), the drivers preferred to monitor the behavior of the system more, such as: how the system performs an overtaking maneuver. During driving on the ramps between two motorways in S3, the drivers could concentrate on the NDRTs more because of the low-speed included less complexity. No significant relation between the activity in NDRT and the takeover time could be obtained in this experiment. The reason could be the effects of experiencing sequence, driving speed, and differences in the critical situations on takeover time and performance of NDRT. Due to the non-stochastically mixed arrangement of the scenarios with increasing complexity regarding to traffic density (from S1/S3 to S2) it can be concluded that the skilled drivers (training was done before with different levels of interaction) need for unexpected TOR about 9 seconds, whilst knowing the new tasks less time (about 5 to 6 seconds). In brief, after familiarizing the new task (taking over from FULL to MANU) the drivers varied their awareness to what is required to solve the takeover scenario and which potential for increasing the NDRT. The combination of the scenario and NDRT does not completely require the available cognitive resources from perspectives of cognitive workload due to perception, thinking, planning etc., so a new balance according to a given individual risk awareness appears, for which 5-6 s (Figure 6.8 for the second and subsequent events) as takeover time results as an accepted time potential doing the unknown driving task successfully. Moreover, the total number of completed arithmetic tasks results from the activity of the driver for a long time range. It is not suitable to describe the relation between the takeover time and the performance of NDRT, because the period of time from TOR to take over is relatively short.

Based on the experimental results with respect to the takeover time two open issues are given defining the limits of nowadays research:

- As discussed before it can be concluded that the shown 5-6 s takeover time results from a combination of what is really required (to solve the vehicle control task) and what is assumed to be required (on an individual base). The second point is still open to be discussed. One of the goals of automated driving is to free the drivers from driving so that they could be able to focus on other tasks. The NDRT could be any activity of the driver except sleeping and driving. The critical situation for TOR could be various, because the failure of the automated system is random. The following questions arise: How could the takeover time/behavior be improved when both of them (doing NDRT and taking over) are involved? To study this question, how the NDRT influencing the takeover time/behavior qualitatively and quantitatively should be first studied as well as the takeover behavior of the driver facing different critical situations. Moreover, the question if it is possible to guide the human drivers' risk awareness to the required level should be answered, because the distribution of drivers' focus could vary depending on various NDRTs and critical situations.

- As shown from the results, a strong adaption of the human behavior can be observed. Even increasing the scenario complexity from S1/S3 to S2 the takeover time is reduced. This result is independent of the interfaces used. Understand the TOR as a rare event so the probability of its occurrence can be assumed as very low. The first takeover maneuvers based on the shown experiments can be characterized by a high probability to fail (accidents) with the takeover time about 9 to 10 s, which appears as non-suitable for critical situations. In reality it is not possible to train the drivers with several trials to get familiar with TOR and critical situations. The question arises: How could a TOR be designed to ensure a stable and successful takeover behavior of the driver regardless with or without experience of such incident?

Effects of driven speed and critical situation on takeover time

Takeover time also depends on the critical situation. Comparing the takeover time after the driving scenario in Figure 6.9, it can be stated that the one from S1 is significantly longer than the ones from S2 and S3. The scenario S1 is the easiest but it took the longest takeover time. The reason could be that the vehicle by taking over in S1 was driving with 70 km/h, whilst the ones in S2 and S3 were 80 km/h. In spite of same length of TOR, the smaller velocity gives obviously the impression to the driver that the situation is not as critical as the ones in other scenarios.

The takeover time by steering is more than 1 s larger than those by braking (Figure 6.10). This could be caused by higher familiarity with strong steering in comparison with braking. The takeover time by accident was set to 15 s in Figure 6.10 only to denote the difference to the real takeover behavior. In S3, because of the scenario design, the steering is required for takeover, which explains why the takeover time in this scenario is slightly smaller than it in S2. Also here questions arise:

- How can the risk awareness of the driver be affected to avoid the misinterpretation of the relation between driven speed and level of danger?
- How should the TOR be designed for critical situations different to those simple critical situation such as avoidance of stopped frontal vehicle?

Effects of interface on SAW/MA

At the beginning of this chapter, a question about using DVI to increase SAW/MA is posed. Two DVIs are proposed to display various automated driving levels and corresponding functionalities. The main difference between these two DVIs is the way of displaying the driving environment. One uses bird-view perspective and the other driver-view perspective. Results from the experiment show no difference between these two DVIs from takeover time, performance of NDRT, pupil diameter, and workload. Difference in perceived SAW is obtained. Results show that the I2 is more helpful in increasing SAW. No difference in increasing MA is obtained. The preference, the comprehensibility, and less annoyance of I2 with driver-perspective can be seen from the subjective ratings. Therefore it is possible to use DVI to show the status of automated driving level and its limitations to increase the SAW.

6.3.2 Trends

Interface design with respect to the driver's task

Based on the literature review, most of the studies apply one general TOR time for investigating the takeover behavior or evaluation of TOR [LDS$^+$16] [Pet17]. However, based on the results from this study, it can be concluded that the takeover time depends on various variables. Moreover, studies about individual behavior, influences from surroundings, various complexity of NDRT, and the activity of driver in NDRT should be further performed. Furthermore, the experimentally concluded mean takeover time from previous studies are limited to the simulation equipment and environment, the experimental design, etc. It seems to be difficult to apply the specifically observed results for more general real driving situations. From this an open question remains: Can a maximal or general TOR time be defined or it is situation- and/or driver-dependent?

The drivers could take over the vehicle control by either pressing the brake pedal or steering. As shown in Table 6.5 and Figure 6.11, more drivers chose to steer, especially in S3. Most drivers perceived the indicator signal and took the exit to leave the motorway, but 4 drivers did hear the indicator sound but did not understand the meaning so that they did nothing. As also concluded from the literature review part, the DVI should not only be able to interpret the driving situation but also the status of the system. It might be helpful to highlight the geometrical position of critical situations, the intention of the automated driving systems (if available), and more complex but also important option(s) for the driver. Similar to the newest existing fighter interfaces (F22 (Raptor)) [BWJ01], a suitable information reduction to those of relevances (what is behind the critical situation and what are the options) might be helpful.

Interface design with respect to the driver's workload

The perceived workload was assessed using NASA-TLX questionnaire. The statistical analysis of the total score represents that S2 is perceived as more difficult for drivers to accomplish compared with S1 and S3. Same as the assessment of SAW, the score of S2 is significantly lower than the ones of S1 and S3. This assessment matches the results of performance of NDRT as well as the ones of workload. Most of the drivers could only answer one question correctly about the driving and set velocities. By asking about the surrounding vehicles, most wrong answers were about the existence, the number, and the position of vehicles behind. This shows that the situation recognition of the driver to the critical time point is focused on one specific area, either the main monitor, the rear view mirror, or the touchpad. As a conclusion it could be stated that the useful information related to the critical situation should be displayed to the driver adaptively according to where the driver is looking at, or should appear in all related interfaces.

Further aspects

The takeover from automated driving has been studied since about one decade. The first SAE level 3 vehicle was introduced by Audi [Aud17]. Assume all the functions could be used on road, could the drivers really be able to take over the vehicle control from automated mode in the real environment, briefly: does the existence of related functionality guarantee the suitable use of the driver sitting in front of the interface of the system? Of course the answer is “No”. Related research can not be detected, as well as research denoting the dependency of the new system on the (situational) abilities of the driver. The individual driving behavior plays an important role in the TOR design. The time left to the driver to take over depends on several variables. The road condition, such as rough road surface or skid surface because of raining or snow, which is known as influencing factor [CSL17] but typically not considered in most driving simulator studies. In real driving environment, the traffic situation may be more complex than it within simulator studies. Furthermore, the participants, who were willing to take part in the simulator study, were mostly healthy and vigilant during the study. After daily work or party, drivers would not be in the same status as those who participated the simulator study. Simulator study results generate best cases based on typical boundary conditions not reflecting all differences related to real environmental and driver conditions. Also here the assumption of only one general TOR time could lead to not sufficient recognition in complex situations or inattention in simple situations. More research should be investigated.

6.4 Subsequent adaption of DVIs based on previous studies

In the previous studies, the DVIs using HUD, dashboard, and touch 1 (Figure 4.1) are investigated separately. The information is displayed statically to the driver, which means the position for the specific information is fixed. Based on the collected comments and suggestions from previous studies, two modified DVIs considering dynamic displayed information are introduced in this section.

Two DVIs (I1' and I2') are proposed based on the ones introduced in section 6.1.1 with the same applied automated driving levels and the realized functions. The two proposed DVIs have two different layouts. The other difference is that the I2' uses the eye tracker to obtain the gaze position of the driver, so some of the displayed information is dynamic based on the direction of the glance.

In Table 6.10, the details of displayed information, driving modes, situations for display, and positions of the two proposed DVIs are summarized. The "ET" standing for "Eye Tracker" shown in the table denotes the information is displayed when the gaze is on the corresponding interface.

6.4.1 DVI I1'

Dashboard

In I1', the information about actual velocity displayed in both speedometer and digital form, the tachometer, the actual steer number, the indicator, the activity of assistance systems, the SOC, and the distance to empty are shown on the dashboard (Figure 6.18). The driving environment is displayed in the middle of the dashboard showing the dangerous vehicle in the surrounding (Figure 6.19). Parts of the speedometer and the tachometer are overlapped by the displayed driving environment, but the current velocity could be read by the digital representation.

Figure 6.18: Dashboard with basic information in DVI I1'

Table 6.10: Summarization of displayed information

Functions	Driving mode	Situation for display	HUD		Dashboard		Touch 1		Acoustic	
	I1'/I2'	I1'/I2'	I1'	I2'	I1'	I2'	I1'	I2'	I1'	I2'
FCW amber	MANU SEMI	TTC and distance to frontal vehicle between two thresholds	√	ET		ET		ET		
FCW red	MANU SEMI	TTC and distance to frontal vehicle smaller than threshold	√	ET		ET		ET	Beep tone	Beep tone
SOC	MANU SEMI FULL	Continuously		√	√					
Suggested efficiency optimal velocity	MANU SEMI FULL	Continuously	√	√		√		ET		
Feedback of lane change not possible in SEMI mode	SEMI	Lane change command activated and vehicles in blind spot areas	√			√			Beep tone	Beep tone
Feedback of execution of lane changing	SEMI FULL	Ego-vehicle changing lane autonomously	√			√			Feedback sound of indicator	Feedback sound of indicator
Recognized traffic sign	MANU SEMI FULL	Continuously		√	√		√	ET		Verbal
Activity of DAS	MANU SEMI FULL	Continuously			√	√	√	√		
TOR	FULL	Automated driving not available	√	√	√	√	√	√	Verbal	Verbal

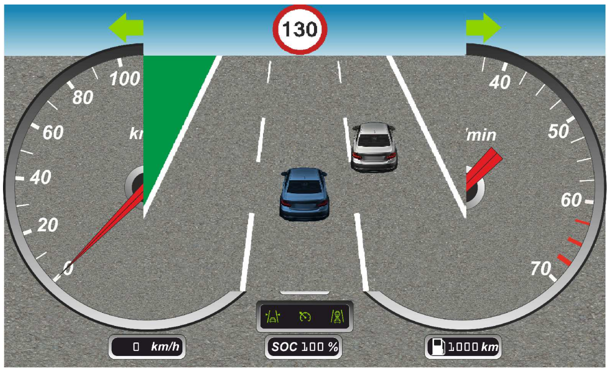


Figure 6.19: Dashboard displaying driving environment in DVI I1'

HUD

The FCW is displayed on the HUD with two colors (amber and red) to show the levels of emergency based on predefined TTC and distance to the frontal vehicle

(Figure 6.20). The efficiency optimal velocity is abstracted with the arrow and a horizontal bar (Figure 6.21(a)) and displayed with the suggested behavior (Figure 6.21(b)), when the driving situation is not dangerous. The later one is hidden when the FCW is shown.

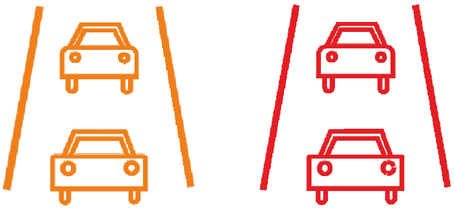
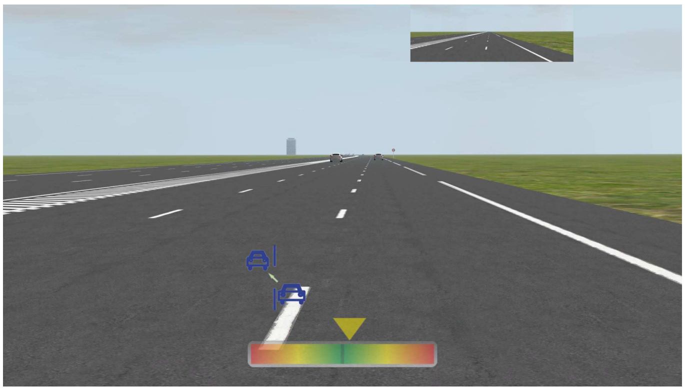
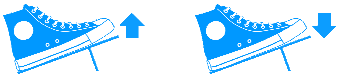


Figure 6.20: FCW on HUD in DVI I1'



(a) Suggested efficiency optimal velocity



(b) Suggested efficiency optimal behavior

Figure 6.21: Efficiency optimal velocity and suggested behavior displayed on main monitor in DVI I1'

In SEMI driving mode, the feedback of the execution of lane changing command is displayed on the HUD in Figure 6.21(a). When the driver activates the lane changing maneuver but the situation not allows, a feedback of "lane change not possible" as shown in Figure 6.22 is displayed on the HUD.

The TOR in FULL driving mode is improved to be situation dependent. The displayed suggested takeover behavior could be hands on the steering wheel, press the

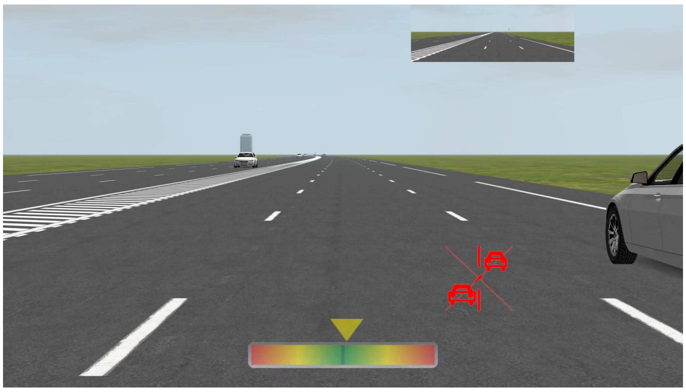


Figure 6.22: Illustrated feedback of changing lane not possible in SEMI driving mode as HUD in DVI I1'

brake pedal, or both of them. One example of the latest situation is shown in Figure 6.23.

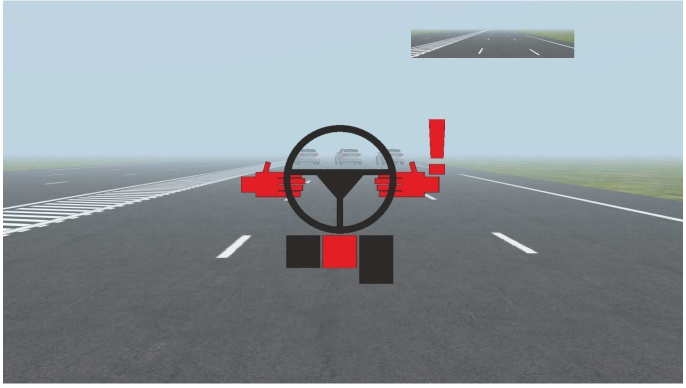
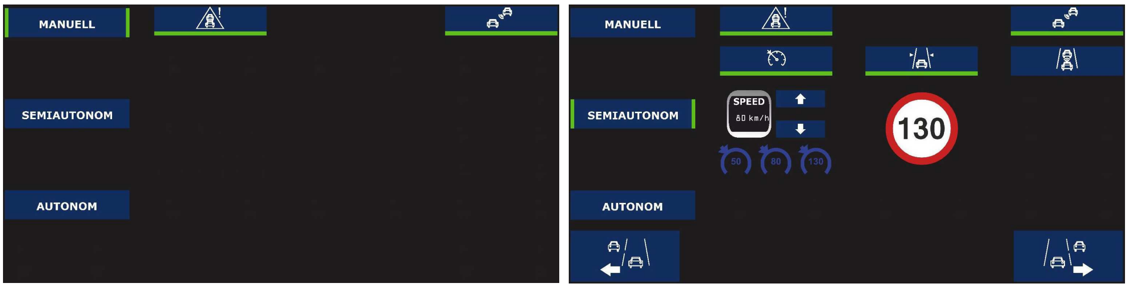


Figure 6.23: TOR as HUD in DVI I1'

Touch 1

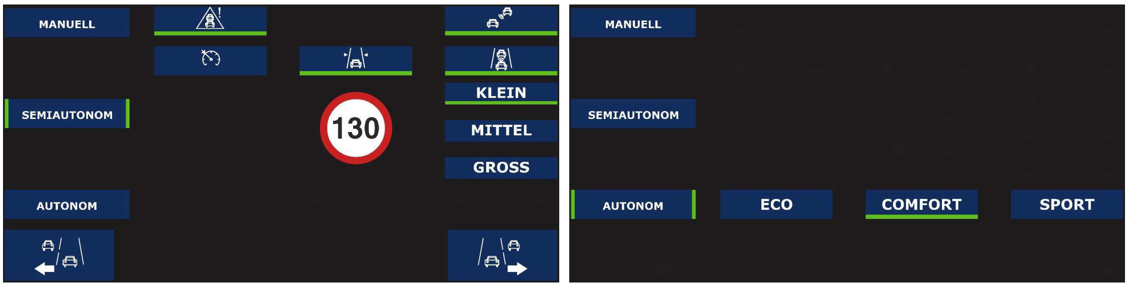
The idea is to group the driving mode and related functionalities in one horizontal area. As illustrated in Figure 6.24(a), the top row shows the MANU mode button and mode relevant functions, which are to activate or deactivate the assistance systems FCW and BSW. The buttons of possible driving modes to be switched to are displayed on the left column.

The SEMI mode and its three related functions are displayed in the second row. When the function ACC is activated (Figure 6.24(b)), the desired velocity, the buttons of arrows, and the three buttons labeled with 50, 80, and 130 are displayed to set the desired velocity. The arrows enable the driver to increase or decrease the desired velocity with the sector 10 km/h. To realize the velocity, which has



(a) MANU driving mode

(b) SEMI driving mode with activated ACC



(c) SEMI driving mode with activated vehicle-following function

(d) FULL driving mode

Figure 6.24: Touch display in different driving modes in DVI I1'

MANUELL: Manual
SEMIAUTONOM: Semi-automated
AUTONOM: Automated
KLEIN: Small
MITTEL: Middle
GROSS: Large

a large difference to current velocity, the driver could set with the three buttons labeled with often used velocities. When the function ACC is deactivated, the related functions are also hidden. The vehicle-following function is followed with three buttons labeled with “Groß” (Large), “Mittel” (Middle), and “Klein” (Small), when it is activated (Figure 6.24(c)). The buttons on the left-bottom and right-bottom corners realize the lane change maneuvers. They are displayed only when the SEMI mode is activated.

In the third row, the FULL mode and its options are displayed, when it is activated (Figure 6.24(d)). The buttons labeled with “ECO”, “COMFORT”, and “SPORT” distinguish the driving styles of the automated system based on the velocity and distance to frontal vehicle.

The activity of the driving mode is denoted with two green bars on the left and right margins of the button, whilst the activity of the mode related functions are denoted with one green bar on the bottom margin of the button. The space between buttons ensures the symmetry and the grouping of the functions.

6.4.2 DVI I2'

Dashboard

The basic layout of the dashboard in I2' is displayed in Figure 6.25. The FCW with two levels of emergency is displayed between the speedometer and the tachometer (Figure 6.26). The corresponding suggestion to be aware of the distance ("VORSICHT!") and to brake ("BREMSEN!") are provided to the driver. The efficiency optimal velocity is displayed on the speedometer so that it could be easier to be compared with actual velocity in MANU mode.

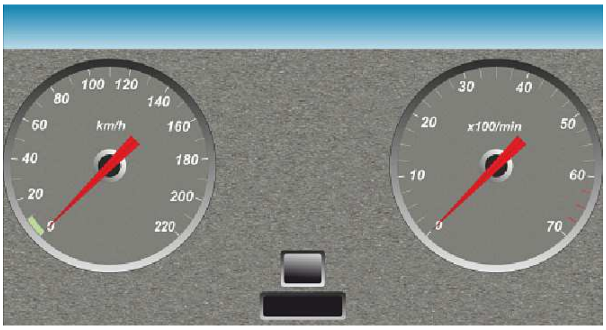


Figure 6.25: Dashboard with basic information in DVI I2'

Figure 6.26: Two levels of FCW on dashboard in DVI I2'

BREMSEN: Brake
VORSICHT: Caution

In SEMI driving mode, the speedometer and the tachometer are replaced by the symbol of showing the feedback of the execution of lane changing to left and right commands respectively (Figure 6.27), because the velocity is displayed redundantly on the HUD and the number of revolutions is secondary information. The corresponding feedback of “lane change not possible” is displayed on the same position (Figure 6.28).

Figure 6.27: Feedback of execution of lane changing in SEMI driving mode on dashboard in DVI I2’

AUTONOMER SPURWECHSEL AKTIV: Autonomous lane changing active

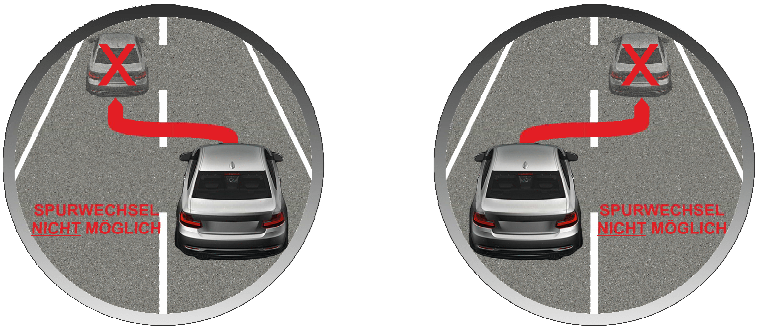


Figure 6.28: Feedback of changing lane not possible in SEMI driving mode on dashboard in DVI I2’

SPURWECHSEL NICHT MÖGLCH: Lane changing not possible

The situation-dependent TOR is shown on the dashboard when the system is not able to handle the critical situation. The reason for takeover and suggested behavior for the takeover are displayed in the middle between the speedometer and the tachometer. The TOR could be changed when the critical situation is different (Figure 6.29).

HUD

On the HUD, the traffic sign, the actual and suggested efficiency optimal velocities, as well as the SOC, are displayed continuously (Figure 6.30 but without TOR). The

Figure 6.29: Situational TOR on dashboard in DVI I2’

AUTONOMER FAHRMODUS FEHLGESCHLAGEN: Autonomous driving mode failed
AUTONOMER FAHRMODUS VERLASSEN: Autonomous driving mode off

actual velocity and the SOC are represented in white with digital form based on a gray background so that the information could be obtained instantly and precisely [BSD96]. The color of the horizontal bar displaying the current SOC changes to amber and red, when the SOC reaches the critical state and is empty respectively.

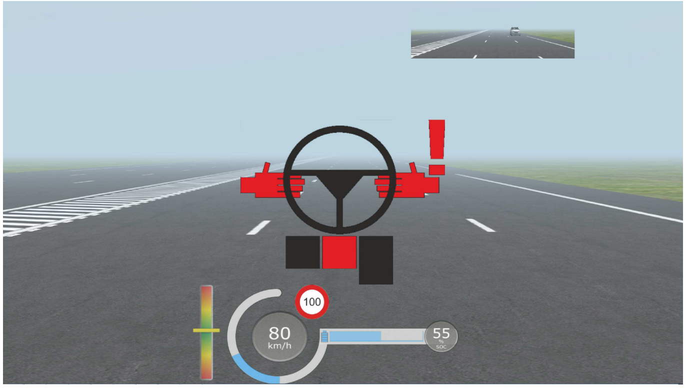
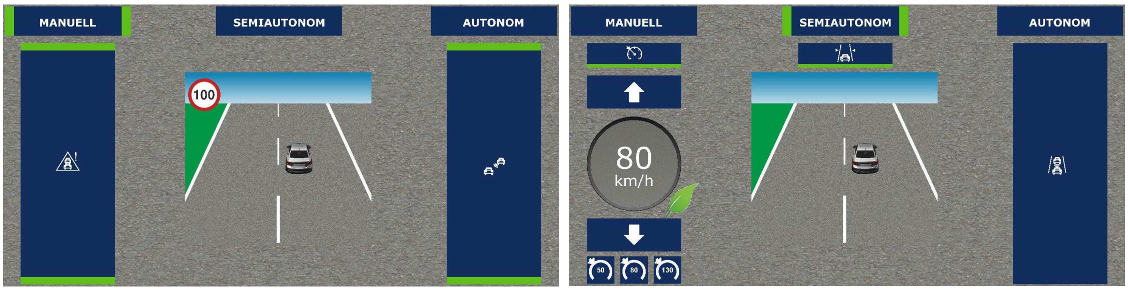


Figure 6.30: HUD with continuous information in DVI I2’

When the driving mode is switched from FULL to SEMI or MANU, the critical vehicles in the surrounding are highlighted with a blue box on the main monitor. This helps the driver to increase the SAW so that the takeover quality can be guaranteed. The situation-dependent TOR is displayed as HUD on the main monitor (Figure 6.30).

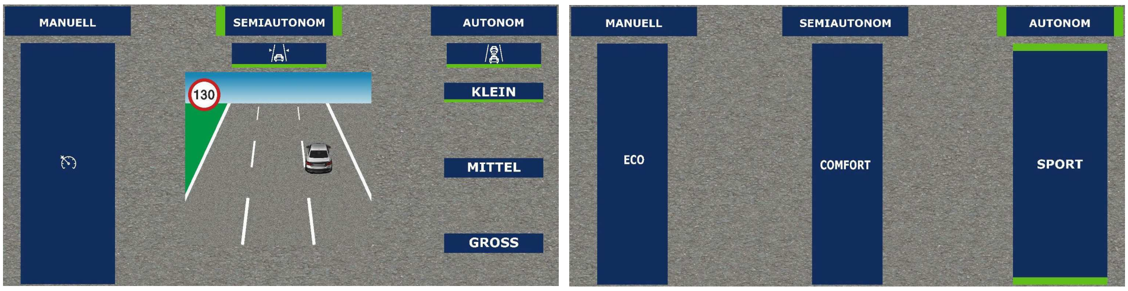
Touch 1

In the touch 1 of DVI I1’, the areas for each driving mode and related specific functions are fixed. This could lead to waste of the usable space. To improve the



(a) MANU driving mode

(b) SEMI driving mode with activated ACC



(c) SEMI driving mode with activated vehicle-following function

(d) FULL driving mode

Figure 6.31: Touch display in different driving modes in DVI I2'

MANUELL: Manual
SEMIAUTONOM: Semi-automated
AUTONOM: Automated
KLEIN: Small
MITTEL: Middle
GROSS: Large

utilization of the interface, the DVI I2' is designed using a vertical layout to realize a dynamic interface.

As shown in Figure 6.31(a), the top row displays the three driving modes. The related functions are distributed in the rest lower area. In MANU mode, the FCW and BSW are symmetrically placed on left and right sides of the interface. In the middle, the driving environment is displayed, which is adaptive to the current driving road.

When the SEMI mode is activated, the three related functions are displayed. The activated function is shown with smaller button whilst the deactivated one is with a larger button. When the ACC is activated, the space for displaying FCW in MANU

(a) Overspeed warning in SEMI driving mode

(b) Fuel efficiency suggestion in SEMI driving mode

(c) FCW in SEMI driving mode

(d) TOR in FULL driving mode

Figure 6.32: Popup windows on touch 1 in DVI I2’

MANUELL: Manual
SEMIAUTONOM: Semi-automated
AUTONOM: Automated
GESCHWINDIGKEIT REDUZIEREN: Reduce velocity
IDEALE GESCHWINDIGKEIT: Ideal velocity
VORSICHT: Caution
AUTONOMER FAHRMODUS FEHLGESCHLAGEN: Autonomous driving mode failed

mode is used for the set of desired velocity (Figure 6.31(b)). The driving efficiency suggestion is shown with a leaf near to the desired velocity, whose color changes from green to red by driving from efficiently to inefficiently. The DVI with activated vehicle - following function is shown in Figure 6.31(c).

In FULL mode, the driving environment is not necessary and therefore hidden. The space is used for displaying three driving styles as shown in Figure 6.31(d).

The popup windows (Figure 6.32(a)) on the touch 1 with increasing priority are used for displaying the situation-dependent suggestion about inefficient driving (Figure 6.32(b)), FCW (Figure 6.32(c)), over speed warning (Figure 6.32(a)), and TOR (Figure 6.32(d)). In each situation beside the TOR, the warning is displayed with suggested behavior to solve the problem. The driver has the opportunity either to remain the current situation by clicking the “OK” button or to follow the suggestion by clicking the corresponding symbol. The TOR on the touch 1 is displayed until the driver takes over the drive. The activity of the driving mode is denoted with two green bars on the left and right margins of the button, whilst the activity of the mode related functions are with one green bar on the bottom margin for the small buttons and also the top margin for large buttons.

7 Summary, discussion, and outlook

As mentioned in the introduction, the main objective of this work is to investigate and analyze the options and effects of DVI design as well as of automated systems on the driving behavior of human in varied situations based on simulator experiments. With studies of the developed DVIs for the increment of driving efficiency in HEV and the improvement of mode awareness in vehicles with multi-levels of automated driving, suitable design principles and requirements of DVIs for future developments could be concluded. In this chapter, the complete work and the experimental results are summarized in section 7.1. The design principles and requirements of DVIs for future developments are concluded in section 7.2 based on [WS]. The limitations of this work as well as the outlook for future work is given in section 7.3.

7.1 Summary

The DVI plays a crucial role in the interaction between the driver and the vehicle in different levels of automated driving to realize a safe and efficient driving. It is concluded in chapter 2 that guiding drivers with DVI to realize an efficient driving is possible for lower automated driving levels. The not exhaustive development of automated vehicles allows the consideration of a safe transition between two levels, especially from higher levels to lower levels. The mode error/confusion of the drivers caused by the vehicles with multi-levels of automated driving is noticeable, which should be considered and could be avoided with DVI. The effect of DVIs on human driver's behavior in various situations should be analyzed for the future development of the automotive industry.

In this thesis, the concept using the DVI to close the driver-vehicle-environment loop is introduced. The DVI could help the three components in the loop to understand each other and influence each other in a positive way.

Based on this concept, three experiments are conducted. The results and individual statements are statistically proved. In E1, DVIs showing the suggested velocity in digital, analog, and text forms as HUD are designed to assist the driver to improve the driving efficiency within an HEV. Experiments were conducted to compare the three ways of displays. It can be concluded from the results that the efficacy of the proposed DVIs in increasing driving efficiency are proved, such as the average fuel consumption and the matched velocity. From the experiments, it can be found that more efficient driving requires higher visual demand based on the measurements of blink duration. The cognitive workload is mainly caused by the conflict between the displayed efficiency optimal velocity and the allowed maximum velocity from the traffic sign.

To improve this and to understand other options for displaying efficiency-related information, a dashboard is used in E2. The effect of considering traffic sign into the suggestion is positively proved with the second experiment. The results show that this combination improves the fuel efficiency from the perspectives of total fuel consumption as well as the proportion of matched velocity. Considering traffic signs also reduces the perceived workload and improves the performance of the secondary task.

The continuously ongoing development of automated vehicles could bring the human a new experience of driving. Before it could be widely executed, related questions should be solved. In this transition phase, vehicles with several different automated driving modes are introduced. These vehicles could realize an automated driving, but only in predefined specific situations. The human driver should still be aware of the driving environment and ready to take over the vehicle control when the system is not able to handle the critical situations. In such case, the limits of the human should be investigated to assure a safe takeover. The mode error/confusion caused by multi-levels of automated driving should be avoided. In E3, two DVIs are proposed for such vehicles to display the automated levels and related functionalities. The results from E1 and E2 are applied in E3 for lower automated driving levels. The limit of the driver by taking over the driving task is studied during the experiments. Results show that the mean takeover time measured is 5.93 s. It should be noticed that the mean takeover time for the first drive is about 9 s, which is significantly higher than others. From the experiments with 38 participants, it can be clearly detected that the takeover time in the second drive is almost half of the one in the first drive, which shows a strong learning effect and adaption. This answers the question raised in section 1.1 regarding the insufficient sample size for statistical analysis in [HLK17]. Besides, it is also concluded that the takeover time depends on the driving velocity and the complexity of the critical situation, which answers the questions about influences of driven speed and complexity of the critical situation on takeover behavior [HLK17]. This indicates that the TOR time could not be designed only using a mean or median value for all cases. The individual driver, driving velocity, the activity of driver in NDRT, the difficulty of the critical situation, the influences from surroundings, etc. should be considered. Both of the proposed DVIs could help the drivers to increase the mode awareness and are accepted by most of the participants. Based on the analysis of the conducted experiments, the two interactive DVIs and unidirectional DVIs are combined to provide the driver a systematic view of the driving modes, warnings, suggestions, etc. The driving mode unrelated functionalities are hidden to avoid unnecessary superfluous information. Some of the information is displayed dynamically based on the gaze position of the driver, which is obtained from the eye tracker. The fuel efficiency suggested optimal behavior is integrated into the modified DVIs. The desired velocity adjustment for higher automated levels is modified to buttons with 10 km/h for each segment and several often used predefined velocities. The TOR is adaptive with critical situations displaying the reasons for the takeover, such as road construction, severe weather, missing lane marks, etc. as well as the suggestions for the behavior of taking over, which are hands on the steering wheel, press the brake pedal, or both of them.

The realized functions and specifications in the proposed interfaces are summarized in Table 7.1, which uses the similar criterion comparing to the Table 2.2 in chapter 2. The E1 stands for the interfaces “Image”, “Text”, and “Number” used in the first experiment, E2 for interfaces D1 and D2, and E3 for interfaces I1, I2, I1’, and I2’.

Table 7.1: Conclusion of realized functions and specifications in proposed interfaces

Functions		E1: Efficiency suggestion E2: Efficiency suggestion E3: Increasing SAW, SA, and efficiency for low level automated driving
Applied automated driving level		E1 and E2: SAE level 0 - 1 E3: SAE level 0 - 3
Goals	Safety relevant	E2 and E3
	Efficiency relevant	E1, E2, and E3
Method	Position of display	E1: HUD E2: Dashboard E3: Dashboard and touch screen as central console
	Modality	Visual and acoustic
	Judgment of driving behavior	E1 and E2
	Comparison between actual and optimal behavior	E1 and E2
	Suggested behavior	E1: Efficiency optimal velocity E2: Efficiency optimal velocity and gear
	Individualization	E2 and E3
	Adaption	E2 and E3

To conclude the contributions of this work, through the first experiment, it can be drawn that the most efficient driving could be achieved by appropriately designed DVI within HEV but with the most workload. This could be improved by combining the efficiency optimal behavior and the environmental distractions into the displayed suggestion, which is proved statistically by the second experiment. Within multi-levels automated driving, it is concluded from the third experiment that using one general TOR time for all drivers and critical situations is not suitable. It is found from the results that the takeover time is related to various factors, such as driven speed and complexity of the critical situation. Derived from the results obtained from the conducted experiments, new research questions are raised with respect to the realization of a safe takeover, comprehensively understanding of TOR, and distribution of attention between NDRT and takeover.

7.2 Discussion

Most vehicles in the market are still at "Level 2" or lower. Assisting the driver to realize a safe and efficient drive is the design goal. In combination with higher traffic density, higher velocity, less human competences (demography), assistance or automation can provide improvements. The strengths of human and machine should be combined and their weaknesses should be avoided to achieve a safe, efficient, and comfortable driving. Vehicles with multi-levels of automation are derivatives of the fully automated vehicle. With the development of the automated vehicles, the DVIs should also be adapted. Beside the ergonomic requirements [BSD96] [WB92] as well as the consideration of restrictions of each display area and functions of assistance systems [VM13] [KKHL14] [OMLT^{+}13] [OMH14] [TKP09] [BMB16], the following design goals and requirements regarding DVI and TOR are concluded based on the conducted studies in this thesis.

7.2.1 Inseparability between DVI and ADAS

The inseparable relation between the DVI and the ADAS is similar to the one between the "front-end" and "back-end" in software engineering. The correctness of the results of the algorithms in ADAS is essential for an effective use of the DVI within the driver-vehicle interaction. The driver would not follow the suggestion, if the displayed information is meaningless and not helpful. For an individual cognitive DVI, it should be able to learn the gaze pattern of the driver, such as to combine the visual workload and the displayed information to achieve a balanced safety awareness, so that the driver would not ignore the warning in case of multi-activities. To ensure this, the background learning algorithms are indispensable. This is also explained in the driver-vehicle-environment loop in chapter 3.

7.2.2 Learn individual driving behavior for better adjustment

The driving behavior of the human is individual. Therefore it can be concluded that the ADAS should consider the individual differences. The ADAS should be able to recognize the driver's individual driving behavior and, if necessary, to learn it and take it into account. As example, to increase the driving efficiency, the assistance system should know about the intentions of the driver. Based on this, a corresponding optimization of the behavior can be displayed/suggested to the driver in comparison to the consequences of the current behavior. In this case, the intention prediction of the driver becomes essential. Moreover, for the vehicles with multi-levels of automated driving, the transition between two levels directly influences the driving safety, especially from higher level to lower level. The individual limit of the driver should be learned to show the limits of the system.

7.2.3 Sufficient and correct representation of the situation including the current state of automation

The term “mode awareness” is discussed in section 2.1.3. As example the capability of ADAS includes performing tasks autonomously for a long time (e. g.: ACC). This could lead to that the activation or the function of the assistance system is no longer perceived or forgotten by the driver and thus causes lack of mode awareness. As summarized in [SWB97], the user can not correctly perceive or interpret the current state of the system and the current or future state of the total situation due to the lack of situation awareness. To avoid this the ADAS or DVI should be designed in such way that mode error/confusion can not be caused and therefore the driver should always be aware of the current situation. Redundancy about the state of automation should be allowed but limited.

7.2.4 Combination of situation, intention, and efficiency

The suggested optimal behavior from efficiency perspective should also consider the factors from safety’s perspective, such as: the allowed maximum velocity from the speed limit, the actual velocity of the preceding vehicle when overtaking is not allowed, etc. A combination of elements allowed from the current situation, the intention of the driver, and the efficiency-related suggestion should be suggested, so that the driver is distracted minimally due to the conflicts between the situation and suggestion.

7.2.5 Backward TOR design instead of forward

The TOR designs or studies of the takeover behavior of human drivers till now [GDLB13] [MRD$^+$15] [GKLB16] [LDS$^+$16] [MDT16] [WSH$^+$16] [HLK17] [MJMJ17] [Pet17] share the same strategy: forward. They study the takeover time by predefining the length of TOR time first. The results from them show a comparable TOR time and various takeover time of the drivers. However, the goal is to realize a safe takeover. Stimulated by the results of this work, a question arises: How should the TOR time/design be varied to realize a comparable safe takeover time? The backward design strategy sets the goal of achieving a predefined takeover time. To realize that, the individuality of the driver (experience of TOR, activity in NDRT, reaction time, etc.) and the environment (complexity of the critical situation, driven speed, characteristics of vehicles/roads, etc.) should be considered as variables/unknowns. Their relations should be found to obtain the constant/known (takeover time). In this way, a safe takeover could be ensured independently from the individuality and varying environment.

7.3 Limitations and outlook

The direct interaction between the human and the environment is not considered in the concept of human-vehicle-environment-interface interaction loop, such as the interaction between the driver and the pedestrian when they meet at an intersection without traffic light. In such situation, the eye contact or negotiation between both parties is required, in which the DVI in lower automated driving levels is not involved. However, this kind of situation should be considered in SAE level 3 or 4, because the system still cannot realize all driving modes. In other words, the DVI should be appropriately designed, so that the attention of the driver could be easily and suitably moved from NDRT to the driving.

Due to time restriction in each test slot, the results with regards to the SAW and MA of the drivers in the E3 are not compared to the result from a baseline interface, which shows no information about the surroundings. Therefore the effect of each part in the interfaces I1 and I2 on the SAW and MA could not be differentiated. As for future work, an experiment for detailed comparison between two interfaces is necessary.

The new research questions stated in section 6.3 based on conducted experiments should be answered in the future work. The quantitative and qualitative relations among the individual driver, the activity in NDRT, the factors from the environment and vehicle, and the takeover time could be explored. Based on this and the suggested design principles in section 7.2, an appropriate TOR could be designed to ensure a safe takeover regardless of the driver, vehicle, and environment.

The takeover behavior is studied in this thesis based on three driving scenarios with varied difficulties. The takeover scenarios are static critical situations because the critical object is standstills (stopped vehicle in front or exit of the motorway). These scenarios can only represent part of the critical situations in the real driving environment. The takeover behavior should be studied for more complex, dynamic, and critical scenarios.

As introduced in chapter 2, the sample size in each experiment fulfills the requirement. The results of the experiments conducted in this thesis are analyzed considering all participants as one group regardless of gender, age, etc. The behavior of the driver could be different due to the driving experience, age, gender, nationality, etc. To investigate the efficacy of the DVI as well as the interaction among the driver, the vehicle, and the environment more concretely, the results from the experiments should be analyzed based on different user groups categorized after driving experience, age, gender, etc. In other words, more participants should be recruited to perform more detailed and diverse analysis.

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This thesis is based on the results and development steps presented in the following previous publications:

Journal articles

[WS18] Wang, J.; Söffker, D.: Bridging gaps among human, assisted, and automated driving with DVIs: a conceptional experimental study. In *IEEE Transactions on Intelligent Transportation Systems*, PP (2018), pp. 1 - 13

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Workshop presentations

[WSW17] Wang, J.; Söffker, D.: Towards improving driving efficiency of HEV with a suitable designed feedback. *6. Interdisziplinärer Workshop Kognitive Systeme: Mensch, Teams, Systeme und Automaten*, München, March, 2017

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Other publications, which are not included in this thesis:

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In the context of research work at the Chair of Dynamics and Control, the following student theses have been supervised by Jiao Wang and Univ.-Prof. Dr.-Ing. Dirk Söffker. Development steps and results of the research work and the student theses are integrated with each other and hence are also part of this thesis.

[Ben17] Benjamin C. R., Entwicklung einer individualisierten adaptiven Mensch-Maschine-Schnittstelle am Fahrsimulator, Master Thesis, November 2017

[Tas16] Taskiran O., Konzeption und Realisierung einer Fahrzeugpositionsanzeige mittels Touchscreen am Fahrsimulator, Bachelor Thesis, November 2016

[Sak16] Sakalli E., Konzeption und Realisierung eines interaktiven Arbeitsplatzes für einen Fahrsimulator, Bachelor Thesis, October 2016

The following student theses have been supervised by Jiao Wang and Univ.-Prof. Dr.-Ing. Dirk Söffker, which are not included in this thesis:

[Dar18] Dargahi Nobari, K., Development of TOR to improve takeover behavior, Master Thesis, July 2018

[Hil17] Hillebrand. K., Entwicklung eines Fahrerassistenzsystems zur Erhöhung der Fahrsicherheit und -effizienz, Master Thesis, December 2017

[Xu16] Xu M., Driving situation recognition using classification methods for driving assistance system, Master Thesis, November 2016.

[Mar16] Marques M. F., Erstellung eines Szenario zur Analyse und Evaluierung von Assistenz- und Entscheidungsunterstützungssystemen, Bachelor Thesis, July 2016

[Ji16] Ji Q., Development of a filtering and processing tool for driving simulator and eye tracker data, Bachelor Thesis, March 2016

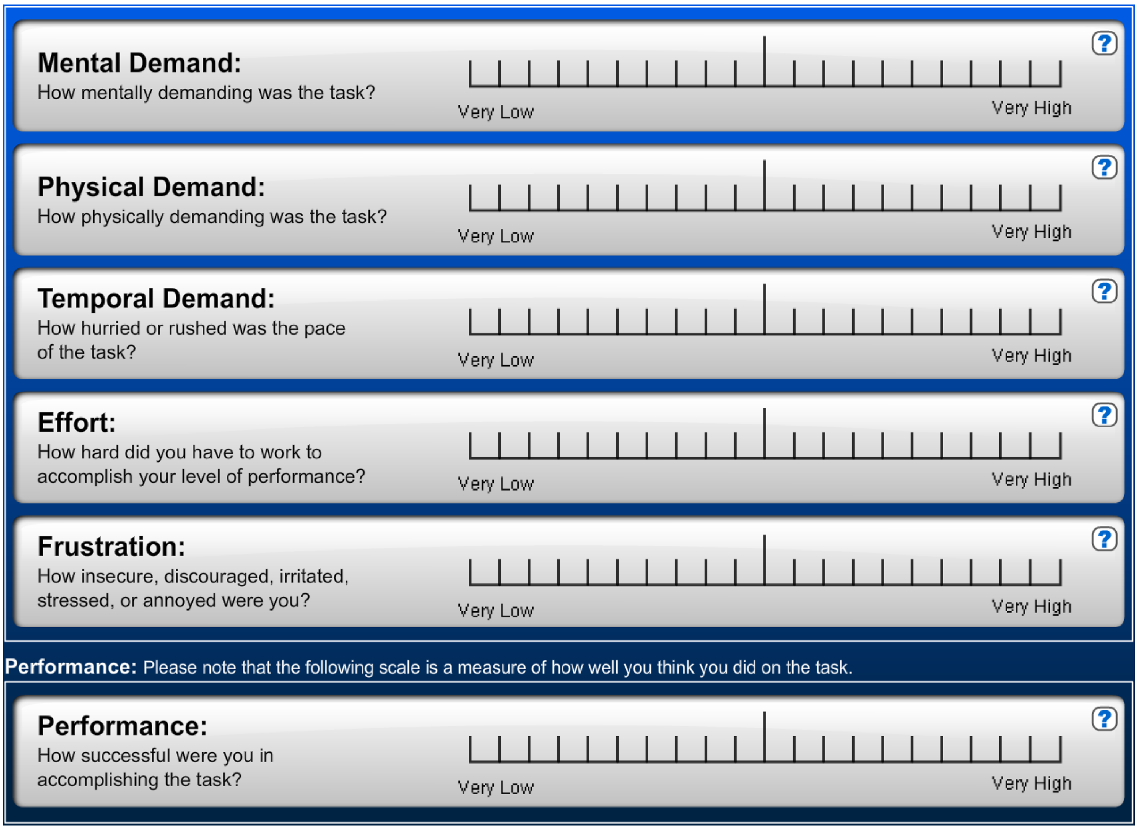
[Den14] Deng Q., Experimental determination of user specific stochastic state machine using driving simulation, Master Thesis, November 2014

Appendices

NASA-TLX questionnaire

English

NASA-TLX questionnaire about the whole driving including the secondary task or NDRT [ShaNC]



Mental Demand:
How mentally demanding was the task?
Very Low — Very High

Physical Demand:
How physically demanding was the task?
Very Low — Very High

Temporal Demand:
How hurried or rushed was the pace of the task?
Very Low — Very High

Effort:
How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration:
How insecure, discouraged, irritated, stressed, or annoyed were you?
Very Low — Very High

Performance: Please note that the following scale is a measure of how well you think you did on the task.

Performance:
How successful were you in accomplishing the task?
Very Low — Very High

German

Geistige Anforderung: Gering – Hoch

Wie viel geistige Anforderung war bei der Informationsaufnahme und bei der Informationsverarbeitung erforderlich (z.B. Denken, Entscheiden, Rechnen, Erinnern, Hinsehen, Suchen ...)? War die Aufgabe leicht oder anspruchsvoll, einfach oder komplex, erfordert sie hohe Genauigkeit oder ist sie fehlertolerant?

Körperliche Anforderung: Gering – Hoch

Wie viel körperliche Aktivität war erforderlich (z.B. ziehen, drücken, drehen, steuern, aktivieren ...)? War die Aufgabe leicht oder schwer, einfach oder anstrengend, erholsam oder mühselig?

Zeitliche Anforderung: Gering – Hoch

Wie viel Zeitdruck empfanden Sie hinsichtlich der Häufigkeit oder dem Takt mit dem die Aufgaben oder Aufgabenelemente auftraten? War die Aufgabe langsam und geruhsam oder schnell und hektisch?

Anstrengung: Gering – Hoch

Wie hart mussten Sie arbeiten, um Ihren Grad an Aufgabenerfüllung zu erreichen?

Frustration: Gering – Hoch

Wie unsicher, entmutigt, irritiert, gestresst und verärgert (versus sicher, bestätigt, zufrieden, entspannt und zufrieden mit sich selbst) fühlten Sie sich während der Aufgabe?

Leistung: Gut – Schlecht

Wie erfolgreich haben Sie Ihrer Meinung nach die vom Versuchsleiter (oder Ihnen selbst) gesetzten Ziele erreicht? Wie zufrieden waren Sie mit Ihrer Leistung bei der Verfolgung dieser Ziele?

Post-questionnaire in E1

1.	Did the displayed suggested velocity influence your driving behavior?	Yes	No	Maybe	
2.	Did the displayed bars/arrows influence your driving behavior?	Yes	No	Maybe	
3.	Did the displayed suggested driving behavior influence your driving behavior?	Yes	No	Maybe	
4.	Which interface is the easiest to understand?	Number	Image	Text	
5.	In your opinion, using which interface leads to increment of fuel efficiency?	Number	Image	Text	
6.	Would you like to integrate the tested interfaces onto the windshield of a hybrid electric vehicle? If yes, which one?	Number	Image	Text	No
7.	Do you have general suggestions to the interface or the experiment?				

Post-questionnaire in E2

1.	How did you like the displayed interface?	Very bad	1	2	3	4	5	Very good
2.	The description is comprehensible.	Not at all	1	2	3	4	5	Yes very
3.	The interface disturbed my driving.	Not at all	1	2	3	4	5	Yes very
4.	The interface influenced my driving behavior.	Not at all	1	2	3	4	5	Yes very
5.	The interface leads to distraction because of the conflict between suggested and allowed velocities.	Not at all	1	2	3	4	5	Yes very
6.	How would you like to integrate such system into a hybrid electric vehicle?	Not at all	1	2	3	4	5	Yes very
7.	What is especially good in this interface?							
8.	What should be absolutely improved in this interface?							
9.	Which of the two interfaces would you prefer?	Battery form	Curve form					
10.	Do you have general suggestions to the interface or the experiment?							

Questionnaires in E3

Mid-questionnaire regarding situation awareness

1.	Was there any vehicle in front of you on your lane? If yes, how many?	No	Yes	Not sure	Number:	Not sure
2.	Was there any vehicle behind you on your lane? If yes, how many?	No	Yes	Not sure	Number:	Not sure
3.	Was there any vehicle on your left lane? If yes, how many and where?	No	Yes	Not sure	Position:	Not sure
4.	Was there any vehicle on your right lane? If yes, how many and where?	No	Yes	Not sure	Position:	Not sure
5.	Which driving mode were you in?	Manual	Semi-autonomous	Full autonomous	Not sure	
6.	Was the ACC on?	No	Yes	Not sure		
7.	Was the distance keeping assistance system on?	No	Yes	Not sure		
8.	Was the lane keeping assistance system on?	No	Yes	Not sure		
9.	What was the actual speed?		Not sure			
10.	What was the set speed on the touchpad?		Not sure			
11.	On which lane were you driving?	Left	Middle	Right	Not sure	
12.	What happened?					

Post-questionnaire

1.	How do you like the displayed touch interface?	Very bad	1	2	3	4	5	6	7	8	9	10	Very good
2.	The description is comprehensible.	Not at all	1	2	3	4	5	6	7	8	9	10	Very good
3.	The touch interface disturbed my drive.	Very strong	1	2	3	4	5	6	7	8	9	10	Not at all
4.	The touch interface helped me to increase my situation awareness.	Not at all	1	2	3	4	5	6	7	8	9	10	Very much
5.	The touch interface simplifies my drive.	Not at all	1	2	3	4	5	6	7	8	9	10	Yes very
6.	Would you like to integrate this interface into an autonomous vehicle?	Not at all	1	2	3	4	5	6	7	8	9	10	Yes very
7.	What is especially good in this touch interface	Not at all	1	2	3	4	5	6	7	8	9	10	Yes very
8.	What should be absolutely improved?												
9.	Which of the two interfaces would you prefer?	Bird-view	Driver-view										
10.	Do you have general suggestions to the interface or the experiment?												