Driving Behaviour and Driver Assistance at Traffic Light Intersections

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Zusammenfassung

Die wachsende Bedeutung umweltfreundlicher und effizienter Mobilität hat zur zunehmenden Entwicklung von Technologien geführt, die Fahrer bei der Umsetzung eines effizienten Fahrstils unterstützen.

Die vorliegende Arbeit beinhaltet die Entwicklung eines Ampelassistenten aus verkehrspsychologischer Sicht. Das System unterstützt Fahrer bei der effizienten Annäherung an Ampelkreuzungen. Drei Fahrsimulatorstudien betrachten die inhaltlichen Forschungsfragen zur Analyse von nicht-assistiertem Fahrverhalten, der Wahrnehmung der Interaktion zwischen verschiedenen Verkehrsteilnehmern mit und ohne Assistenzsystem und der Informationsstrategie in der Mensch-Maschine Schnittstelle des Systems. In Fahrsituationen mit wechselnden Ampelphasen oder Sichtverdeckung initiieren Fahrer Verhalten, das im Hinblick auf die Ampelphase bei Ankunft an der Kreuzung unangemessen ist. Diese Situationen bieten das größte Potential für eine Unterstützung durch das Assistenzsystem. Die weiteren Studien zeigen, dass der Ampelassistent das Fahrverhalten beeinflusst. Hierbei spielt die Erwartung, die Fahrer an die emotionalen Reaktionen nachfolgender Fahrer in der Kolonne haben, eine Rolle. In Situationen, in denen Fahrer erwarten andere zu behindern, sinkt die Bereitschaft sich an die Empfehlungen des Systems zu halten. Die Abweichungen des Fahrverhaltens vom Zielverhalten der Funktion sind am geringsten, wenn Handlungs- und Geschwindigkeitsempfehlungen gegeben werden. Information zur Ampelphase stellt für die Fahrer subjektiv eine wichtige Informationseinheit dar. Die Ergebnisse legen nahe, alle drei Informationen zur Kommunikation des Zielverhaltens zu präsentieren.

Der methodische Teil der Arbeit beschäftigt sich mit der Messung des Informationsbedarfs für dynamische Reize. Um Entscheidungen für das angemessene Fahrverhalten zu treffen, müssen Fahrer bestimmte handlungsrelevante Informationen erfassen. Eye Tracking ist eine Standardmethode um den Informationsbedarf für fahrrelevante Reize zu messen. Die im Zuge der Arbeit entwickelte MARS (Masking Action Relevant Stimuli) Methode misst den Informationsbedarf durch Verdeckung. Der Fahrer kann die Verdeckung des Reizes durch Tastendruck für einen limitierten Zeitraum lösen. In zwei Fahrsimulatorstudien wurde die MARS Methode auf die Ampelschaltung und die Darstellung im Display des Ampelassistenten angewendet. Die Ergebnisse zeigen, dass die MARS Methode die experimentellen Variationen des Informationsbedarfs abbilden kann. Die Ergebnisse sind vergleichbar mit der Variation in Fixationen gemessen durch Eye Tracking. Aufgrund ihrer einfachen Umsetzung ist die MARS Methode als Forschungsinstrument vielversprechend.

Executive Summary

The increasing importance of environmental friendly and efficient transportation guides the interest of researchers and car manufacturers towards the development of technologies that support an efficient driving style.

This thesis presents the development of a traffic light assistance system with the focus on human factors. The system aims on supporting drivers in approaching traffic light intersections efficiently. In three driving simulator studies, the content related research covered the investigation of the unassisted driving task, the influence of the system on the driver's perception of the interaction with other road users and the information strategy of the human machine interface. When the traffic light phase changes or when visibility is limited, drivers prepare driving behaviour that is not appropriate for the traffic light phase at arrival at the intersection. These situations offer the greatest potential for the assistance system. The traffic light assistant is able to change driving behaviour. However, the expectation of other road user's emotional reactions influences driver compliance. In situations in which drivers expected to bother others with their driving behaviour, compliance to the traffic light assistant was low. Further, the deviations of driver behaviour from the target strategy of the traffic light assistant are lowest when the HMI includes the two information units target speed and action recommendations. Traffic light phase information in the HMI is a subjectively important information for drivers. The results point towards the presentation of all three information units.

The method related research covered the development of a method for measuring drivers' information demand for dynamic stimuli. While driving, specific stimuli are action relevant for drivers, i.e. they need to be processed in order to decide on the appropriate driving behaviour. Eye tracking has been the standard method for measuring information demand while driving. The novel MARS (Masking Action Relevant Stimuli) method measures information demand by masking the dynamic action relevant stimulus in the driving environment or in the vehicle. To unmask the stimulus for a fixed interval, drivers press a button at the steering wheel. In the present thesis, two driving simulator studies evaluated the MARS method. They included measuring information demand for the traffic light phasing and the in-vehicle display of the traffic light assistant. The analyses demonstrate that variations in the experimental conditions influence the information demand measured with the MARS method qualitatively similar to the influences on fixations measured by eye tracking. Due to its simple application, the MARS method represents a promising tool for transportation research.

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1 Introduction

In transportation research, there has been an increasing industrial and scientific interest in a development towards environmentally friendly driving. One of the major goals has been to increase driving efficiency by reducing fuel consumptions and emissions. In the United States, the transportation sector is the second largest human related source for carbon emissions (Malakorn & Park, 2010). Emissions from personal vehicles “are the largest single contributor to household/individual emissions” (Barkenbus, 2010). Emissions and air pollution in urban traffic affect human health and have detrimental effects on the environment (El-Shawarby, Ahn, & Rakha, 2005). European legislation on vehicle emissions has been a main driver in encouraging car manufacturers to invest in advanced in-vehicle technologies that aim at reductions in emissions and fuel consumptions (Bell, 2006). Besides the implications for the environment, the limitations in the required resources, the trade with fossil fuels and the national dependence of the production of oil have pushed the development towards technologies that support reductions in fuel consumption.

Especially urban traffic contributes to emissions and fuel consumption. “In 2011, congestion caused urban Americans to travel 5.5 billion hours more and to purchase an extra 2.9 billion gallons of fuel for a congestion cost of $ 121 billion” (Schrank, Eisele, & Lomax, 2012). Due to the interruptions of traffic flow and delays caused by stop/start events, especially traffic lights trigger accelerations and decelerations that negatively influence efficiency. When a vehicle is in motion, emission rates are lower compared to when the traffic light intersection causes a delay (Pandian, Gokhale, & Ghoshal, 2009). Researchers have shown that stop and go traffic flow at signalised intersections contributes largely to the emission rates of specific road sections (Unal, Frey, & Rouphail, 2004). Nevertheless, traffic lights represent inevitable components of urban traffic, because they allow for clear right of way rules in complex intersection scenarios. Moreover, traffic light intersections offer a great potential for efficient driving strategies (Qian, 2013) by reducing accelerations and decelerations when approaching the intersection. The new technical developments in intelligent traffic management and increasing integration and connectivity between road users and infrastructure offer opportunities for adaptations in driving behaviour. Importantly, Höltl and Trommer (2012) mentioned that the differences between efficient and non-efficient individual driving styles are not based on conscious behaviour, but on missing knowledge of a low emission and fuel consuming way of driving.

The increasing technical possibilities along with the driver's individual influence on the success of efficient driving advance new driver assistance systems. This thesis deals with the human factors in the development of a traffic light assistance system. The traffic light assistance system supports drivers with information that promotes driving efficiency when approaching traffic light intersections. For that, the focus is on the driver, his behaviour and interactions with the system in the specific driving situation. The research aims at understanding driving behaviour at traffic light intersections and the influence the system has on driving behaviour and the interactions with other road users. Further, the information strategy for supporting the driver when approaching traffic light intersections is identified. Finally, the thesis examines the information demand drivers have for both, the traffic light as dynamic stimulus in the road environment and for the dynamic in-vehicle display communicating traffic light information to the driver. The methodological research covers the question on how to measure this information demand. In sum, the thesis covers the relevant steps for the development of the driver assistance system from a human factors perspective.

The structure of the thesis is as follows. After the formulation of the research questions in chapter 2, the thesis consists of two main parts: the content related research and the methods related research. Each part presents a literature background along with the respective experimental driving studies. The chapter presenting the content related research (chapter 3) starts with the presentation of the literature on driving behaviour at traffic light intersections and the crucial relation between driving behaviour and efficiency of driving. The following chapter outlines the first experiment and results of the investigation of unassisted driving behaviour (Study 1). Subsequently, the theoretic and technical background for traffic light assistance systems is given. Two further experiments investigate the influence of the traffic light assistant on the perceived interaction of road users in platoon driving (Study 2) and the information strategy for the traffic light assistant (Study 3). After that, chapter 4 presents the method related research. Eye tracking for measuring information demand and the novel MARS (Masking Action Relevant Stimuli) method are introduced and evaluated. The MARS method aims on measuring the information demand drivers have for the traffic light and the in-vehicle display of the traffic light assistant (Study 4 and Study 5). Finally, the thesis concludes with a general discussion on the main contents. An overall framework discusses and summarises the results relevant for the potentials of assistance and the development of the Human Machine Interface (HMI) concept of the traffic light assistant. The chapter also includes the evaluation of the MARS method and its applicability for different research questions.

2 Research questions

The increasing demand for improvements in driving efficiency has guided researchers and car manufacturers to develop urban driving structures (e.g. adapt traffic light phasing) and to invest in technical improvements of vehicle and engine properties (e.g. stop/start systems). Besides this focus on the technical improvements, the individual driving style has a large influence on the efficiency of driving. A driver’s knowledge of and motivation for efficient driving offers a great contribution to changes in fuel consumptions and emissions.

Therefore, there has been an increasing technical development and research effort towards driver assistance systems supporting individual drivers with efficient driving. The technical conditions advance and offer improvements in sensor systems, algorithms and the presentation of this enriched information to the driver. For the technical development, it is crucial to define how specific information can be used to calculate the most efficient driving strategy and which parameters are relevant for that. Moreover, and that is the focus of the current thesis, human factors research demands evolve from the possibilities and challenges that come along with the new information that is available from the assistance systems. In the development of the assistance system, the focus should be to adapt technical properties towards the needs and characteristics of the human driver (Jordan, 1998; Tango & Montanari, 2006).

The thesis presents the development of the Human Machine Interface of a traffic light assistance system. Based on wireless communication between the traffic light and the vehicle approaching the intersection, the vehicle receives information from the traffic light. Using that information, the system calculates a driving strategy for an efficient approach to the intersection. This includes either avoiding stops at the intersection or initiating efficient standstills in case of unavoidable red phases. The system presents driving recommendations to the driver by an in-vehicle display. The success of the system depends on the ability and motivation of the driver to change his driving behaviour according to the recommendations.

The system allows that information about the driving environment is available earlier than previously possible, which enables an anticipation of the traffic situation in a way that has not been known before from the driving task. The drivers get informed about events in the environment that they cannot yet perceive (e.g. because a traffic light is behind a curve), that happen in future (e.g. a traffic light change) or both. Along with that, the driver assistance system aims on modifying driving behaviour. The expectation is that the consciousness with which the driving task is performed and the perception of one’s own role in the social system traffic change. Therefore, it is important to identify which information the system presents to the driver, under which conditions it is beneficial to support and how driver behaviour changes while interacting with the system.

Figure 1 depicts the frame for the investigation of driving behaviour at traffic light intersections and the development of the driver assistance system. The driver interacts with the system via the HMI. The HMI communicates the target values for efficient driving at the traffic light intersection to the driver. The driver processes this information along with information in his environment in order to come to the correct decision on the required driving behaviour. In turn, the driver’s behaviour influences the system output and the surrounding road environment. The research presented in this thesis gives detailed considerations on the factors influencing the depicted interaction and it describes and varies the relevant processes and variables. In the end, the presented research contributes to a comprehensive concept of driving behaviour at traffic light intersections and the characteristics of the traffic light assistance system.

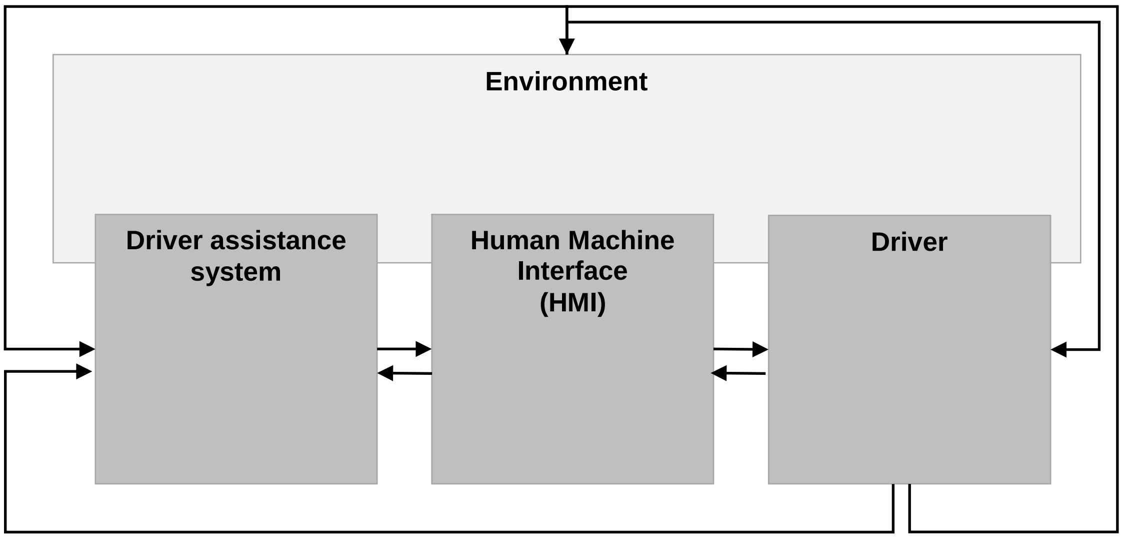


Figure 1. Framework of the interaction between driver assistance system, human machine interface and the driver within the road environment. Adapted from Bruder and Didier (2012) and Zarife (2014).

The thesis bases upon data from five studies that cover content and method related research questions. Within the process of the content and method related research, each study evolved from the results gained from the previous study and the relevant literature background presented before each empiric chapter. Each study focusses on specific factors of the framework for the interaction between driver, system and environment. Table 1 shows an overview of the conducted studies and the related research questions.

Table 1. Overview of the conducted studies and related research questions.

No	Study title	Main research questions	Main research focus	Setting
1	Baseline study	How do drivers approach traffic light intersections without assistance? (Chapter 3.1.2)	Content related	Single driver simulator
2	Interaction between road users	How do drivers experience the interaction with other road users when driving with the traffic light assistant? (Chapter 3.2.2) What are minimum speed thresholds for the system recommendations? (Chapter 3.2.2.3)	Content related	Multi driver simulator
3	HMI evaluation	What information strategy should be used for the HMI of the traffic light assistant? (Chapter 3.3.2)	Content related	Single driver simulator
4	Information demand for the traffic light	Can the MARS method measure the information demand for the traffic light phase as dynamic stimulus in the road environment? (Chapter 4.2.1)	Method related	Single driver simulator
5	Information demand for the HMI display	Can the MARS method measure the information demand for the HMI display as dynamic stimulus in the vehicle? (Chapter 4.2.2)	Method related	Single driver simulator

Studies 1, 2 and 3 are relevant for answering the content related research questions on the development of the driver assistance system. First, unassisted driving behaviour at traffic light intersections is investigated. The goal is to extend the knowledge of driving behaviour in different traffic and environmental conditions. The analysis of driving behaviour in specific situations represents an important tool of transportation research (Liu & Ozguner, 2007). In order to support drivers with in-vehicle assistance systems, understanding unassisted driving behaviour is inevitable (Berndt, Wender, & Dietmayer, 2007). Especially, efficient driving affects basic driving behaviours (e.g. operating pedals to modify driving speed) that in general are highly trained for experienced drivers. Influencing these behaviours through an informing driver assistance system requires changes in the well-known rules that drivers apply. A literature review identifies the relevant factors for the evaluation of driving behaviour at traffic light intersections. Subsequently, the factors varied in Study 1 are expected to support the development of a general understanding of driving behaviour. Further, the conclusions of the first study summarise the influences on more or less efficient driving behaviour. It is then possible to identify the parameters of situations in which the support of a traffic light assistant could be potentially beneficial and how crucial the changes in driving behaviour might be. This represents a necessary justification for the development of the system.

Second, a first version of the traffic light assistant is introduced to the drivers. The design of the assistant should maximise comfort, acceptance and willingness to use the system. Influential are hereby for example the understanding of the information presented in the HMI and the degree of impact the system has on normal driving behaviour. This is especially relevant when the success of the driver assistance system depends on the driver’s willingness to stick to the provided recommendations. Additionally, traffic is a social system and road users have assumptions and expectations on the driving behaviour of others, as well as they have anticipations on how their own behaviour is perceived by others. Based on the results gained from Study 1 it is expected that the traffic light assistant modifies normal driving behaviour. By this, the traffic light assistant has the potential to influence the interactions between road users. Therefore, Study 2 focuses on the evaluation of drivers own perception of their influence on other drivers when driving with the traffic light assistant. The goal is to identify situations in which it is difficult for drivers to stick to the recommendations of the traffic light assistant, because of the social influences in platoon driving. Furthermore, Study 2 also allows identifying what drivers’ assumptions on efficient traffic light approaches are and which thresholds drivers have for minimum driving speeds. This is valuable information for the parameterisation of the algorithm of the traffic light assistant.

Third, the algorithm and the HMI concept of the traffic light assistant are improved according to the results from Study 2. In general, the target values transferred by the assistance system allow for the presentation of a great number of different information units. Therefore, the goal of Study 3 is to identify relevant, accepted and safe information units that enable drivers to follow the recommended driving profiles. For that, the experiment compared eight different HMI versions. There are two main research questions: (1) Which information units should be communicated in the HMI? (2) Does the presentation of a combination of multiple information units lead to a deterioration of driver performance because of information overload? Alternatively, does the combination of information units lead to redundancy gains and with that to improvements in driver performance? Furthermore, Study 3 discusses the influence of the HMI concepts on driving safety. Conflicts or safety critical situations might occur, when the driving behaviour required by the environmental conditions and the target behaviour recommended by the driver assistance system contradict.

During the research process, the operationalisation of constructs and the definition of parameters to measure certain driver behaviour defines the quality of the conclusions drawn from the research results. Therefore, in the current thesis Study 4 and Study 5 state a methodological research question. It concerns the measurement of the information demand that drivers have for dynamic stimuli in the driver environment and the vehicle. In particular, when approaching traffic light intersections, drivers need to know about the current traffic light state in order to come to the right decision on proceeding or stopping at the intersection. Therefore, they have an information demand for the traffic light phasing, which indicates the relevance of the traffic light phasing for the current decisions on driving behaviour. As a standard method, eye tracking identifies when and to what extent drivers attend to the traffic lights. However, the literature review and experiences in the reported experiments identify limitations of the eye tracking method for measuring information demand. Therefore, this thesis introduces the novel MARS (Masking Action Relevant Stimuli) method. The MARS method measures the information demand that drivers have for the traffic light by means of masking the traffic light phasing. Drivers press a button to initiate the unmasking for a fixed interval. In order to evaluate the new method, the results compare data gained from the MARS method and data gained from the recording with the eye tracker. The data of Study 1 and Study 4 were recorded within the same experimental procedure. Study 1 presents the results relevant for the investigation of unassisted driving behaviour; Study 4 presents the results relevant for the evaluation of the MARS method.

After the application of the MARS method to an external dynamic stimulus in Study 4, Study 5 aims on the application of the MARS method to the in-vehicle HMI display of the traffic light assistant. While driving with a traffic light assistant, drivers have a demand for the information presented by the assistant in order to follow the instructed behaviour. Using the MARS method includes masking the relevant information in the display. Based on the results of Study 3, the MARS method should distinguish the information demand that drivers have for different HMI concepts. Additionally, methodological considerations lead to the application of eye tracking and MARS method simultaneously. A detailed analysis investigates the relation between information demand measured by the MARS method and driver fixations. The goal is to show that the MARS method is an appropriate method to measure information demand for the in-vehicle display.

In summary, the thesis describes the process of the development of a traffic light assistance system from a human factors perspective. Unassisted driving behaviour, the HMI strategy and a method for measuring the information demand drivers have for the traffic light and the HMI display are the key contents of the conducted studies. The results will contribute to the framework of the interaction between system, HMI and driver within the influence of the road environment.

3 Content related research

3.1 Driving behaviour at traffic light intersections

The goal of this chapter is to investigate driving behaviour at traffic light intersections. Understanding unassisted driving behaviour and estimating the impact a system might have on human behaviour represents an important motivation for its development. The theoretic background presents literature on models of the driving task, which enables a first understanding of the driving behaviour considered in this thesis. Following this, the previous literature on driving behaviour at traffic light intersections states important concepts and parameters for the description of driving behaviour. Importantly, the theoretic background includes the relation between specific driving behaviours and efficiency. This explains the operationalisation of efficient driving in the current thesis. Subsequently, the methods and results of Study 1 are detailed. The goal of the study is to identify parameters that describe situations in which drivers show more or less efficient driving behaviour. The conclusions of the study discuss the factors influencing efficient driving and state the main phases of driving behaviour when approaching traffic light intersections.

3.1.1 Theoretic background

3.1.1.1 Models of the driving task

There has been a variety of models describing the driving task. In the frameworks of cognitive models, the problem solving task of driving is explained in a hierarchical structure consisting of usually three levels (Michon, 1985). The strategic level subsumes the general trip planning and choices concerning costs, risks and comfort (Figure 2). The input for this level comes from top-down driving information. The manoeuvring level describes the tactical behaviour and the managing of current situations and driving manoeuvres. Examples for driving behaviour on this level are gap acceptance, obstacle avoidance or overtaking. Finally, the control level includes automatic action patterns, in which for each specific moment appropriate values for critical driving parameters are chosen (e.g. speed or steering angle). Input on the control level comes from bottom-up information in the stimulus environment. Figure 2 shows that the levels represent different time frames. Moreover, individual skills and experiences shift the major parts of the driving task towards more or less control, manoeuver or strategic based driving. This comes along with an anticipatory regulation in the manoeuvring level (i.e. drivers anticipate which behaviour is appropriate without receiving immediate feedback), whereas a compensatory regulation takes place in the control level. Further, the levels interfere and naturally, behaviours on the manoeuvring and control level match the general goals of the strategic level and changes in control or manoeuvring may lead to changes in the strategic level.

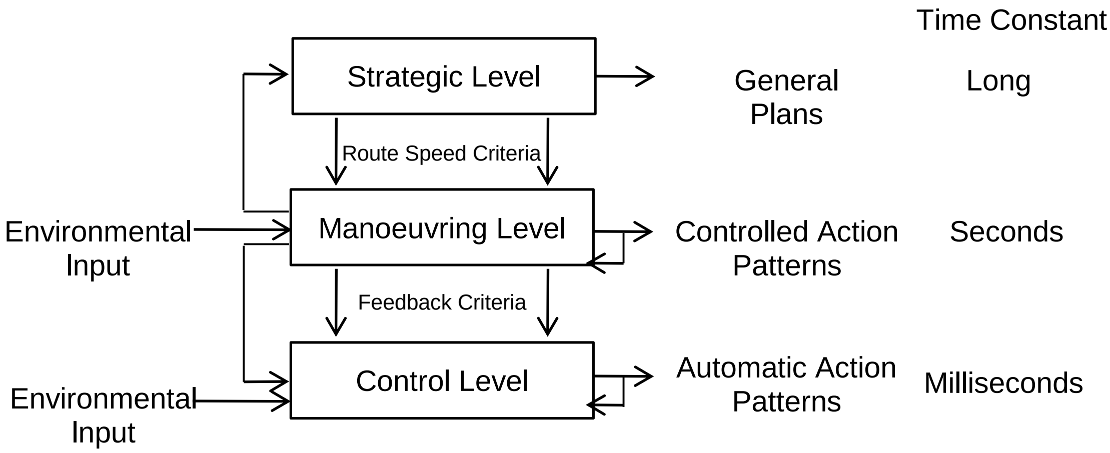


Figure 2. Hierarchical model of the driving task (Michon, 1985).

Other hierarchical models explained driving behaviour in terms of a goal-directed activity (Rasmussen, 1983). Driving divides into three hierarchical levels. On the knowledge-based level, identification of unknown situations, decision making and conscious planning of actions are the relevant activities. Rule-based behaviour includes the activation of associations between well-learned rules and the relevant behaviour. On the skill-based level, unconsciously performed vehicle control behaviour takes place.

The two models have been related to each other (Ranney, 1994). Within Table 2, an experienced driver in everyday driving might operate mainly in the diagonal from the upper left to the lower right field, whereas novice drivers initially use knowledge-based behaviour for the control tasks. Similarly, unexpected situations can interrupt the skill-based processes, because they require knowledge-based performance.

It is assumed that driving at urban traffic light intersections in general takes place on a manoeuvring and control level. The vehicle handling in terms of initiating accelerations and decelerations or estimating stop distances takes place on a control level. On a manoeuvring level, the traffic light phasing as well learned stimulus and the anticipation of the traffic situation at arrival at the intersection trigger the decisions on the required manoeuvre (e.g. proceeding or stopping).

As will be outlined in the course of this thesis, efficient driving represents a strategic goal. Planning efficient driving behaviour takes place on a knowledge-based level. Hence, increasing driver's awareness of the appropriate driving behaviour by a driver assistance system changes the level of the performed driving task. These changes in the driving goals and strategy also influence driving behaviour on the manoeuvring and control level.

Table 2. Relation of the hierarchic models of Michon (1985) and Rasmussen (1983) with classified examples (adapted from Ranney, 1994).

	Strategic	**Manoeuvring**	**Control**
Knowledge	Navigation in unfamiliar area	Controlling skid	Novice in first lesson
Rule	Choice between familiar routes	Passing other vehicles	Driving unfamiliar vehicle
Skill	Route used for daily commute	Negotiating familiar intersection	Vehicle handling on curves

3.1.1.2 Unassisted driving behaviour at traffic light intersections

Traffic light intersections are inevitable components of urban traffic. They regulate complex traffic situations and by that aim to ensure that all road users safely pass the scenario. Traffic lights differ from intersections regulated by traffic signs. The traffic light phasing indicates the right of way rules that can change unexpectedly and multiple times within a single traffic light approach. Drivers approaching traffic light intersections are faced with a dynamic decision making task in which they need to response to variable conditions (Liu, 2006). At typical German traffic light intersections there are four different relevant traffic light phasing scenarios: (1) The traffic light remains solid green, which requires proceeding. (2) The traffic light is initially red and changes to a combined yellow/red state and subsequently to green, which requires proceeding. (3) The traffic light remains solid red, which requires stopping. (4) The traffic light is initially green and changes to yellow and subsequently to red, which requires stopping. The driver in every situation makes the decision to brake and stop or to proceed through the intersection. The traffic light phasing might change at any time during a traffic light approach. Therefore, drivers can experience a certain level of uncertainty. This uncertainty can be associated with anxiety (Kikuchi & Riegner, 1992) and increased workload (Kaul & Baumann, 2013) that can result in workload compensation by reducing driving speed while approaching the intersections (Harms, 1991; Rataj & Vollrath, 2006).

Research on driving at traffic light intersections has mainly focused on the specific situation when the traffic light changes from green to red during the approach. The driver decision in this situation has been formulated as the dilemma zone problem (Gazis, Herman, & Maradudin, 1960). In the dilemma zone, the driver is forced to make the binary decision to either proceed or to stop, i.e. decide between two conflicting action alternatives. Others defined the dilemma zone as the area in which neither safe stopping nor proceeding before the red light appears is possible (Newton, Mussa, Sadalla, Burns, & Matthias, 1997). More recently, the transitional zone was defined as starting with yellow onset and putting the driver in the forced-pace condition of having to decide whether to proceed or to stop (Goh & Wong, 2004). Rakha et al. (2011) defined that the driver is trapped in a dilemma zone when the minimum stopping distance (d_s) is greater than the maximum distance at which the vehicle can clear the intersection before the end of the yellow interval (d_r = running distance). The option zone defines the zone in which the driver is farer away from the intersection than the minimum stopping distance and closer to the intersection than the maximum running distance at yellow onset (Figure 3).

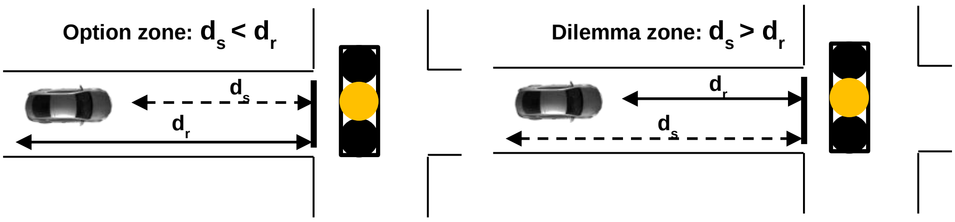


Figure 3. Option and dilemma zone at yellow onset as defined by Rakha et al. (2011); d_s represents the minimum safe stopping distance, d_r represents the maximum running distance.

Degani (2004) incorporated the safe braking zone and the safe proceeding zone. The black overlap in Figure 4 shows that there are situations in which safe braking and safe proceeding are possible. In certain distance and speed combinations, neither safe stopping nor safe braking can be realised. The threshold for the safe braking area was defined by the maximum braking performance of the vehicle and a driver reaction time of 1.5 s starting at yellow phase onset.

A frequently mentioned concept in the definition of traffic light timing and intersection design is the perception-reaction time (PRT). The PRT describes the time from yellow phase onset to brake pedal onset and thereby includes the mental processing time and the movement time (Green, 2000). Different studies suggested different PRTs between 1 s and 1.9 s (Rakha et al., 2011). Caird, Chisholm, Edwards, and Creaser (2007) give a good literature summary on reported PRTs and presented results from a driving simulator study. Different times to stop line (TSL) at yellow onset were implemented.

Figure 5 shows the cumulative frequencies for the different TSL values. The authors conclude that at a PRT value of 1.01 s, approximately 90 % of the drivers have responded to the traffic light change. Drivers delay their response, when more time is available at longer TSL values. Hence, assuming a PRT of 1.0 s appears reasonable. Interestingly, the PRT has also been applied for the investigation of driver's reaction to the green light while waiting at a red traffic light (Li, Zhang, Rong, Ma, & Guo, 2014).

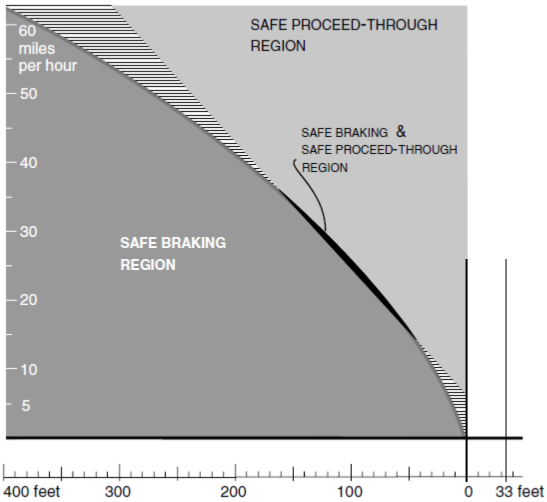


Figure 4. Safe braking and safe proceeding region when approaching a traffic light that changes from green to red (Degani, 2004).

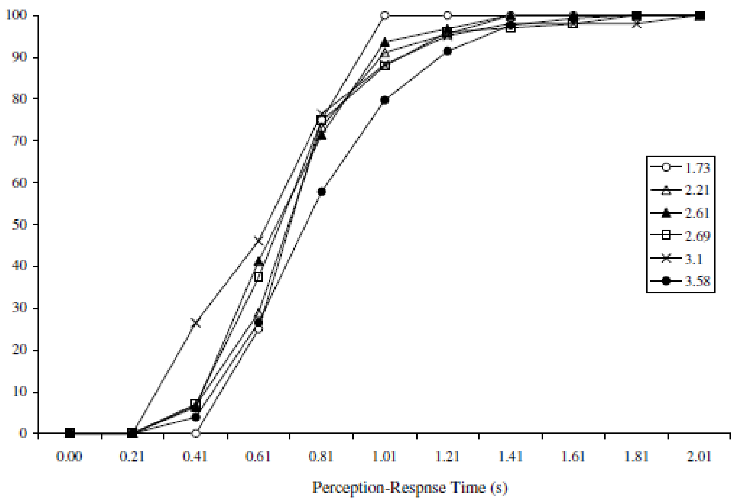


Figure 5. Cumulative percentage of drivers responding with a given perception-response time (PRT) for the range of different time to stop line values (TSL; Caird et al., 2007).

Furthermore, several studies investigated decelerations for the initiation of stops at intersections. Typically, decelerations for initiating stops start with low values and increase gradually. Maximum deceleration rates can be expected at 5 s or less before stopping (Wang, Dixon, Li, & Ogle, 2005). El-Shawarby, Rakha, Inman, and Davis (2007) analysed overall 821 traffic light intersection approaches at the onset of yellow.

Participants drove with 72 km/h on a controlled field track. The measured decelerations ranged between -1.51 m/s² and -7.47 m² with a mean of -3.27 m/s². The distance to the stop line at yellow onset influenced the strength of deceleration. The shortest distance to the stop line (1.6 s) led to decelerations around -5.6 m/s², whereas the longest distance resulted in decelerations around -2.2 m/s². Hence, drivers used more time to decelerate, when they were further away from the stop lines at yellow onset. A comparison of deceleration values measured in different real traffic intersection approaches is offered by Gates, Noyce, Laracuente, and Nordheim (2007). Figure 6 shows that the deceleration values reported in the investigated studies are comparable. -3.05 m/s² represented approximately the 52nd percentile of measured deceleration values. Caird et al. (2007) reported deceleration behaviour at yellow onset based on their aforementioned driving simulator study. They found effects for time to stop line and age group. Generally, the researchers reported mean deceleration values between -5.5 m/s² and -2.5 m/s².

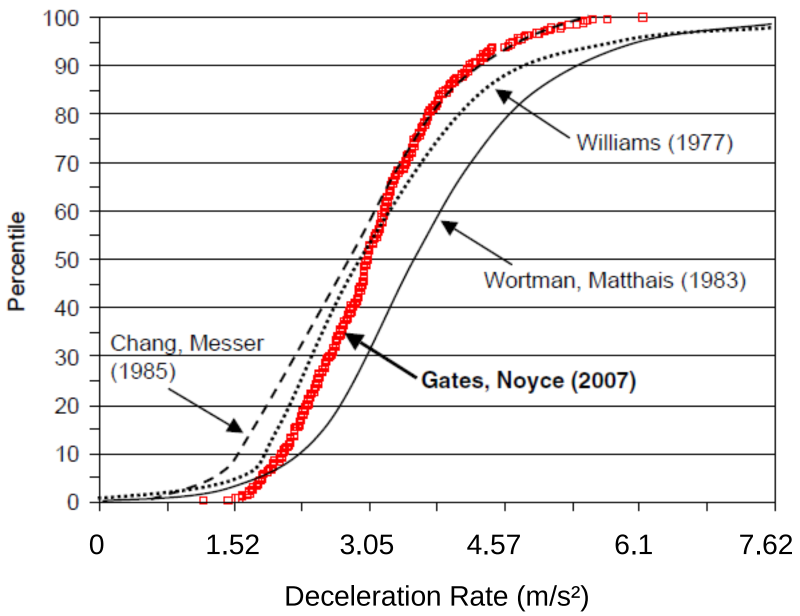


Figure 6. Deceleration rates measured when approaching changing green to red traffic lights as compared by Gates et al. (2007). The comparison refers to Chang, Messer, and Santiago (1985), Williams (1977) and Wortman and Matthias (1983).

Berndt et al. (2007) measured 270 driving profiles when approaching traffic lights by means of a laser scanner installed alongside an urban intersection. They differentiated different driving styles, vehicle types and weather conditions. Figure 7 shows the difference in speed profiles between an early and a late traffic light change from green to red. Naturally, sharp braking was necessary when the traffic light turned red in short distance to the traffic light (blue solid and blue mixed dashed and dotted line). When the traffic light changed to red in far distance to the intersection (red dashed and red dotted line), the majority of drivers reduced speed slightly over the 60 m of traffic light approach. Nevertheless, some drivers still initiated strong decelerations. The study of normal driving behaviour showed that there is a potential for more efficient driving (i.e. less strong decelerations) when drivers know earlier about the traffic light state at which they would arrive at the intersection. Nevertheless, the distance range that the researchers investigated was shorter than the Car-to-Infrastructure communication range. In addition, adaptations of driving speed due to the traffic light might occur already at larger distances to the intersection.

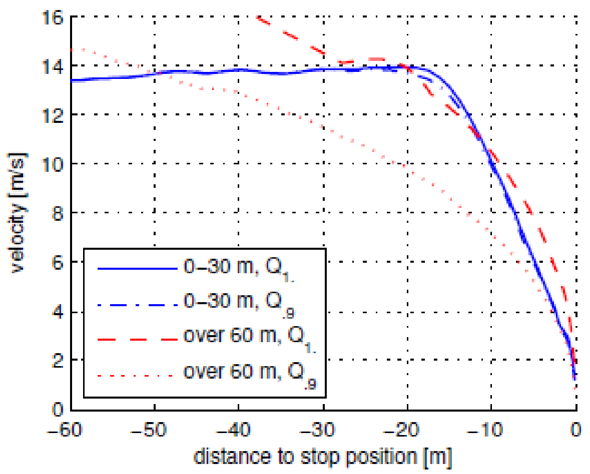


Figure 7. Speed profiles depending on the distance of the vehicle to the traffic light at which the traffic light turned from green to red (Berndt et al., 2007).

Importantly, researchers have investigated the influence of different factors on driving behaviour when approaching intersections. For example, driving behaviour changes with gender and age (Caird et al., 2007; Konecni, Ebbeson, & Konecni, 1976), vehicle type (Gates et al., 2007), traffic density and driving environment (Liu, 2006), driving style and driver states (Doerzaph, 2004), initial speed (Haas, Inman, Dixson, & Warren, 2004) or certain kinds of distraction (Liu, Chang, Tao, Hicks, & Tabacek, 2008). Yang and Najm (2007) classified the factors related to red light running into driver-related, intersection-related and traffic-and-environment-related factors. Male and young drivers were most likely to run the intersection. Shorter yellow timings increased the likelihood for a red light violation. Finally, at higher traffic densities at the intersection red light violations occurred more frequently, but with lower likelihoods for speed violations.

Furthermore, lead vehicles influence driving in intersection situations. El-Shawarby, Rakha, Amer, and McGhee (2011) conducted a study in a controlled field test setting. Occasionally, a lead or a following vehicle appeared. In 50% of the trials, the traffic light remained green, whereas in the other 50% of the trials the light changed from green to yellow/red. When the traffic light changed from green to red, drivers decelerated stronger when following a lead vehicle that legally proceeded through the traffic light compared to a single approach. No difference in decelerations occurred depending on the presence of a following vehicle. Additionally, a lead vehicle seems to reduce driving task difficulty when approaching traffic light intersections. Kaul and Baumann (2013) investigated cognitive load by means of pupil dilation as indicator for workload. Increased workload is associated with increased pupil dilation. Participants approached traffic light intersections that changed from green to yellow/red in a driving simulator setting. With a lead vehicle, drivers showed better performance in a secondary task and there was a tendency for more pupil dilation without a lead vehicle compared to driving with a lead vehicle. The authors concluded that following a lead vehicle might base on bottom-up processes and therefore requires less cognitive resources when approaching traffic lights compared to traffic light approaches without lead vehicle.

In general, the visibility of the intersection is an important influence on driving behaviour. Rataj and Vollrath (2006) varied visibility in their driving simulator study by placing up to four buildings at the edges of non-signalised intersections. They found that the time drivers needed to pass the intersection increased when the view of the upcoming intersection was blocked. This was interpreted as an increase in difficulty. Additionally, researchers have reported that adverse visibility conditions come along with increased risk taking of younger drivers (Clarke, Ward, & Truman, 2005), with modified visual search strategies (Konstantopoulos, Chapman, & Crundall, 2010), with increases in reaction times (Plainis & Murray, 2002) or with changes in driving speed (Trick, Toxopeus, & Wilson, 2010). Thus, adverse visibility conditions can lead to increases in the number of accidents. Werneke, Kassner, and Vollrath (2008) mentioned fog as a negative visibility condition that produces strain in drivers. Therefore, in fog, a driver assistance system could support drivers. However, no study reported driving behaviour in relation to visibility of the traffic light at traffic light intersections.

3.1.1.3 Efficient driving

Driving efficiency can relate to a number of target values, e.g. noise production, travel times, or throughput. For example, eco driving has been defined as a behaviour “that allows the driver to optimise his/her driving behaviour in order to reduce pollution emissions and save fuel” (Cristea, Paran, & Delhomme, 2012). Other researchers defined the term ‘driving economy’, which includes reductions in petrol consumption, air pollution and greenhouse gas emissions (Li & Gao, 2013). Mensing, Bideaux, Trigui, Ribet, and Jeanneret (2014) distinguished between economic driving by referring to fuel saving and ecologic driving by referring to the reduction in pollutant emissions. In line with this, efficient driving in the current context is defined as an adaptation of driving behaviour that leads to low fuel consumptions and emissions. Efficient driving only includes driving behaviour relevant during vehicle operation. Drivers can show efficient driving behaviour without conscious intent to do so.

In this thesis, driving efficiency is not measured explicitly by measuring fuel consumptions and emissions. Absolute fuel consumptions and emissions strongly depend on the vehicle model, engine characteristics, a large number of external factors and the drivers vehicle handling with a specific vehicle (Bandeira et al., 2014; Ericsson, 2001; Frey, Zhang, & Rouphail, 2008; Li & Gao, 2013). It is widely accepted that specific driving behaviours relate to fuel consumptions and emissions (Madireddy et al., 2011). At the same time, it is expected that the general direction of the effects of the specific driving behaviours on emissions and fuel consumptions are robust between different types of vehicles (Ericsson, 2001; Pandian et al., 2009; Unal et al., 2004). Hence, the background for the analysis and the interpretation of the results presented in this thesis bases upon the relation between dynamic driving parameters and emission and fuel consumption values. The following paragraph presents literature demonstrating this relation.

In general, Kamal, Mukai, Murata, and Kawabe (2010) emphasised that the anticipation of the traffic situation leads to low accelerations, little braking, the optimal choice of speed and long coasting times before stops. In turn, the authors named these driving behaviours as crucial for efficient driving. Barkenbus (2010) listed moderate acceleration, anticipation of traffic flow and signals, avoiding sudden starts and stops, maintaining an even driving pace, driving at the speed limit and the elimination of excessive idling as crucial behaviours defining an eco-driving style. Similarly, Bell (2006) emphasised the strong relation between speed, strength of acceleration and strength of deceleration and efficient driving behaviour. Rakha and Kamalanathsharma (2014) mentioned that 7 % of the energy of a vehicle is lost during braking. Li, Boriboonsomsin, Wu, Zhang, and Barth (2009) emphasised that braking events represent a waste of kinetic energy that is transformed into heat. Stevanovic, Stevanovic, Zhang,and Batterman (2009) concluded that a reduction in the number of stops is beneficial for reductions in fuel consumptions and emissions.

Specifically, driving studies in real traffic conditions point towards the relation of driving behaviour and efficient driving. For example, De Vlieger (1997) analysed emissions of carbon monoxide (CO), nitric oxide (NO_x), hydrocarbon (HC) and carbon dioxide (CO_2)

and fuel consumption in seven petrol vehicles. Besides type of vehicle and road type, the study compared the three driving styles calm, normal and aggressive. Calm driving included the anticipation of the traffic situation and avoidance of sudden acceleration and heavy braking. Normal driving included moderate acceleration and deceleration. Aggressive driving in urban and rural traffic led to up to four times higher emissions and 30 to 40% higher fuel consumption compared to normal driving. Even though the vehicles observed in this study were around 20 years old, the general relation between driving behaviour and consumption transfers to modern engines. In a frequently cited study reported in Ericsson (2001) and in Brundell-Freij and Ericsson (2005) driving profiles were recorded in five different vehicles driven each for two weeks by 29 different families on their daily routes. The relation of driving patterns with fuel consumptions and emissions of CO_2, HC, and NO_x was determined based on real driving data and consumption models. The factor and regression analyses identified nine factors that relate to consumption and emissions. Four of the factors related to acceleration and power demand, three describe gear changing behaviour, while two further factors relate to driving speed (including the occurrence of stops). As a conclusion, the authors summarised that the environmental conditions and individual driving styles need to be adapted towards an avoidance of heavy acceleration. Unal et al. (2004) identified hot spots as road sections in which real world measured emissions (CO, HC, NO_x and CO_2) are at least twice as high as in free-flow conditions. Test vehicles were equipped with on-board measurement equipment. Especially indicators describing traffic flow conditions like for example average speed, average acceleration, standard deviation of speed, minimum speed, and maximum acceleration had significant effects on vehicle emissions. Also based on real driving data El-Shawarby et al. (2005) pointed out that a major influence on the relation between acceleration and emission values is the duration and the distance of the acceleration manoeuvre. Strong accelerations over a fixed distance result in the observation that increasing accelerations lead to increases in emissions of NO_x, HC, CO and CO_2. Finally, Berry (2010) reported that especially reductions in accelerations lead to increases in efficiency in terms of increased fuel savings. Thereby, the individual driving style influences the amount of savings, because for aggressive drivers the potential for improvements is larger compared to moderate drivers.

In sum, the presented research emphasises the relation between driving behaviour described by driving speed, acceleration and deceleration and efficient driving in terms of fuel consumptions and emissions. It has been a commonly used approach to predict efficiency of driving with accelerations, decelerations and driving speed (Rakha &

Kamalanathsharma, 2014). Importantly, efficient driving behaviour relates to the anticipation of traffic conditions. With a correct anticipation of the upcoming traffic situation, driving speed can be maintained constant or adapted in advance so that strong accelerations and decelerations are not necessary (Arama, Balos, & Mosoiu, 2010; Cristea et al., 2012; Li & Gao, 2013). Traffic light intersections have the potential to influence driving efficiency negatively. This is because they only provide limited possibilities for anticipating the traffic situation and they require variations in acceleration and deceleration or even trigger the initiation of stops.

3.1.2 Study 1: Baseline study[1]

Study 1 investigates driving behaviour at traffic light intersections without traffic light assistance system. The knowledge of unassisted driving behaviour represents a first crucial step in the development of the driver assistance system. It allows determining the parameters that characterise situations in which more or less efficient driving behaviour occurs. This demonstrates the potential of the traffic light assistant and identifies the magnitude of changes that are necessary in order to achieve efficient intersection approaches.

In the experiment, drivers approach various traffic light intersections. Chapter 2 introduced the framework for the research conducted in this thesis. The bold frames in Figure 8 highlight the relevant factors covered by Study 1. The focus of Study 1 is on the driver and his behaviour in the road environment. For that, the model of information processing stages by Wickens and Hollands (2000) is included in the framework. While driving, the driver processes information from the environment, selects from a set of well-learned responses and executes those. Dynamic parameters are measured as indicators for driving behaviour, i.e. the response execution. In line with the presented definition, efficient driving behaviour is characterised by constant speed profiles and low acceleration and deceleration values. Further, gaze behaviour is analysed in order to gain insights into drivers' information processing in relation to the traffic light and the speedometer display.

The variations in the environment included the traffic light phasing, the presence of a lead vehicle and visibility. As outlined above, the previous research on driving behaviour when approaching traffic light intersections clearly focused on the specific situation of traffic lights changing from green to red during the approach. The current experiment enhances this by introducing situations with all four possible traffic light states, i.e. solid green and solid red traffic lights and changing red to green and green to red traffic lights. All four possible traffic light phases are relevant for the traffic light assistant. Moreover, changing traffic light phases in general reduce the possibility to anticipate the required driving behaviour correctly. Therefore, it is expected that when the traffic light changes during the approach, participants might prepare a different driving behaviour than the traffic situation requires when arriving at the intersection. With that, changing traffic light phases demonstrate the potential of a traffic light assistant. Thereby, the current study

[1] Parts of this study are published in Rittger, Schmidt, Maag, and Kiesel (in press).

targets on non-critical driving situations, i.e. the traffic light phase changes occur so that drivers do not experience dilemma zone scenarios and decisions on how to proceed are obvious. In line with this, a hypothesis is that driver fixations between solid and changing traffic light phases differ: A traffic light change during the intersection approach gives a clear indication of the traffic light phase at arrival, whereas with a solid traffic light there remains a chance for a traffic light change. Therefore, it is expected that the driver attends to the traffic light more often when the traffic light is solid compared to changing traffic lights.

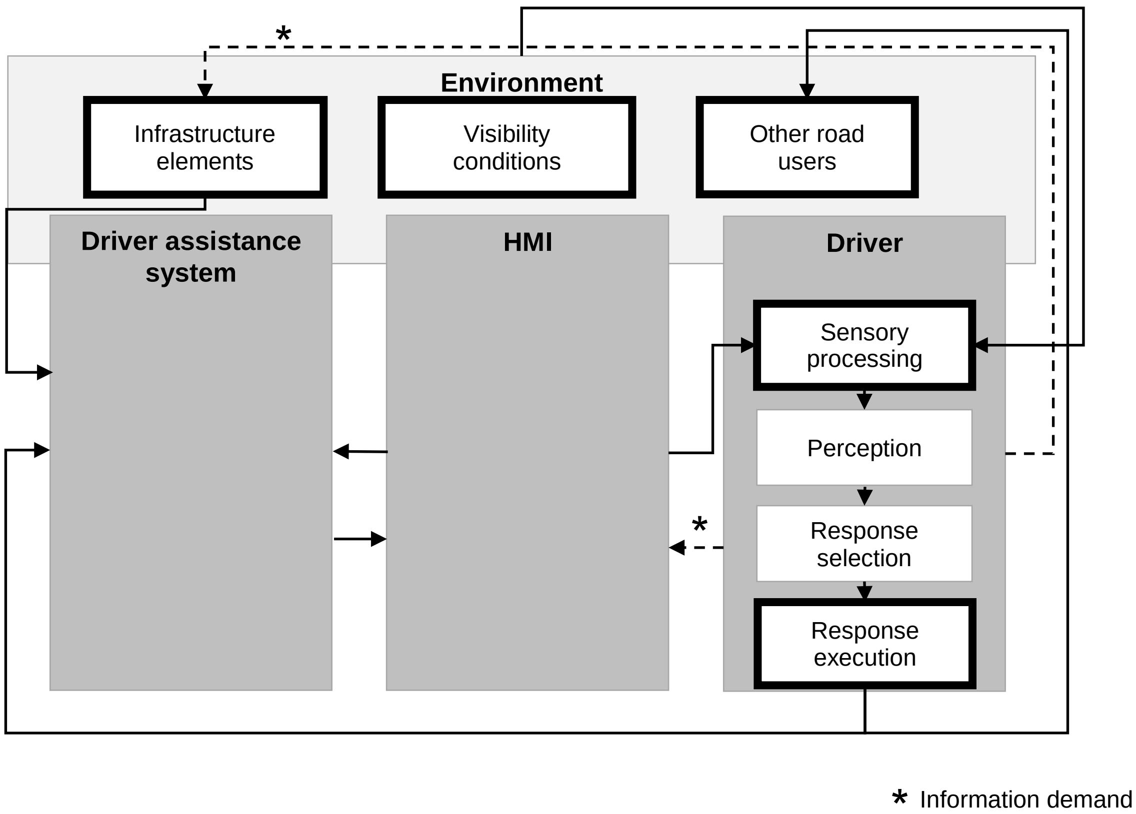


Figure 8. Relation of the factors considered in the present thesis. Bold frames indicate factors investigated in Study 1. Adapted from Bruder and Didier (2012), Wickens and Hollands (2000) and Zarife (2014).

Furthermore, based on the presented literature review it is expected that lead vehicles influence the driving behaviour when approaching traffic light intersections. Naturally, vehicles in front limit the driver's own driving style and the lead vehicle's behaviour offers an orientation for the required driving behaviour. Additionally, cognitive load differs between traffic light approaches with and without lead vehicle (Kaul & Baumann, 2011). In case the lead vehicle serves as a source of information in car following, the number of fixations on the traffic light should be lower when following a vehicle compared to free driving conditions. Concluding from this, with lead vehicle the potential for improvements in driving efficiency could decrease compared to driving without lead vehicle, because the lead vehicle might have a more important impact in the selection of appropriate driving behaviours than the traffic light assistant.

Finally, previous research has shown that earlier traffic light phase changes and based on that more anticipative driving behaviour increased driving efficiency. In turn, it can be expected that a lack of early information on the presence of the traffic light reduces driving efficiency. In the present study, the visibility of the traffic light is manipulated by introducing fog in the test track. Van der Hulst, Rothengatter, and Meijman (1998) successfully manipulated visibility conditions and described adaptations in driving behaviour due to difficulties in the anticipation of the driving scene. For the current setting, the expectation is that with worse visibility conditions, driving behaviour becomes less anticipative and therefore less efficient compared to good visibility conditions.

In sum, the described variations in the environment are introduced in order to identify situations that lead to more or less efficient driving behaviour. This allows determining the characteristics of situations in which the support of the driver assistance system is potentially beneficial. The following chapters detail the methods and the results of the experiment, before the discussion presents the description of unassisted driving behaviour and its implications for the traffic light assistance system.

3.1.2.1 Methods

Participants

Twelve (four female) participants took part in the study. The mean age was 26.8 years (sd = 6.6). Their self-reported annual driving experience was on average 13775 km (sd = 9344.8). They had experienced 37.5% (sd = 22.3) of their annual driving in urban environments. The WIVW GmbH (Wuerzburg Institute for Traffic Sciences) recruited the participants from its test driver panel. Due to a standardised driver training, all participants were well experienced with driving in the static driving simulator. All participants had normal or corrected to normal vision.

Apparatus

The experiment took place in the static driving simulator of the WIVW. The simulator had a 300° horizontal field of vision, with five image channels, each one with a resolution of 1024x768 pixels and an update frequency of 60 Hz. In addition, there were two TFT displays representing the rear view mirror and the left outside mirror. One LCD display depicted the speedometer behind the steering wheel (1024x768 pixels). A 5.1 Dolby Surround System presented the vehicle motor sound. Overall there were nine PCs (Intel

Core 2 Duo, 3 GHz, 4 GB Ram, NVidia GeForce GTS 250) connected via a 100 Mbit Ethernet. The data recording took place with 120 Hz. The driving simulation software used in the experiment was SILAB. The mock-up based on a sprinter-class vehicle (Figure 9, left). The ego-vehicle model was an automatic transition vehicle. Therefore, drivers only used accelerator and brake pedal. The steering wheel had two buttons positioned at the left and the right side on the level of the conventional thumb position. During the procedure, the experimenter observed all driver views on separate display screens and communicated with the participants via intercom. The head mounted eye tracking system Dikablis of Ergoneers GmbH was used (Figure 9, right). It had an update rate of 25 Hz. Pupil movements and eye fixations were tracked with a camera pointing towards the participants left eye and a field oriented camera.

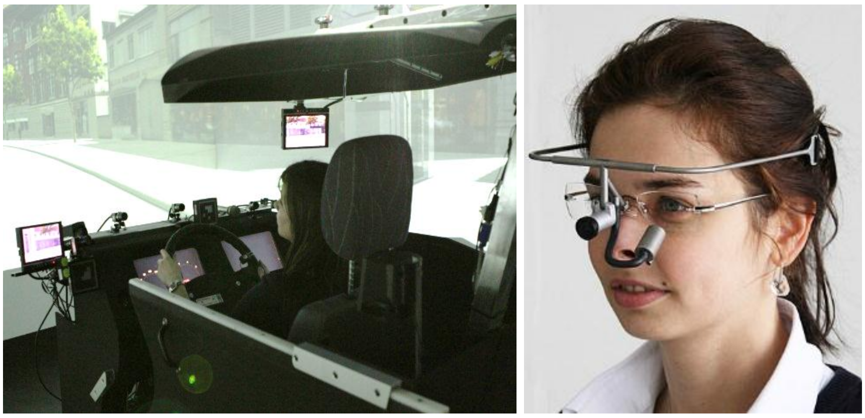


Figure 9. Driving simulator mockup (left, picture from WIVW GmbH) and head mounted eye tracker (right, picture from Ergoneers GmbH).

Design

The experiment had a full within subjects design with three factors: traffic light phase, lead vehicle and fog. The four different traffic light phases were solid green, solid red, changing red to green or changing green to red. A lead vehicle was either present or not present. The visibility was manipulated by presenting fog or no fog. The fog reduced the distance at which the traffic light was visible. There was a randomised order of the factor combinations within the test track. The randomised order was the same for all participants. The drivers repeatedly approached the intersections in each condition. The non-fog conditions occurred three times, while the fog conditions were repeated twice. In sum, every driver approached a total amount of 40 traffic light intersections. With the intention to investigate the dependent variables in relation to the distance to the traffic light, each traffic light approach divided into distance sections of 10 m. In the following, each segment will be referred to by its upper border (e.g. 60 for the distance segment

60 – 50 m in front of the intersection). The dependent variables were dynamic driving data and gaze behaviour. Table 3 gives a summary of the dependent variables.

Table 3. Overview of the dependent variables recorded in the experiment.

Dependent variable	**Unit**	**Description**
Speed	km/h	Speed with which the vehicles proceeds
Acceleration	m/s²	Acceleration when increasing speed
Deceleration	m/s²	Deceleration when decreasing speed
Accelerator pedal usage	press vs. no press	Usage of the accelerator pedal with the binary distinction between pedal pressed vs. pedal not pressed
Brake pedal usage	press vs. no press	Usage of the brake pedal with the binary distinction between pedal pressed vs. pedal not pressed
Fixation intervals on an area of interest	%	Proportion of time fixating an area of interest in relation to the total duration of driving in a specific distance section

Test track

Participants drove through an urban test track with 40 intersections with the same X - junction layout. The road environment varied by buildings, landmarks and plants. The track was approximately 25 km long, with approximately 500 m between two traffic light intersections. Driving through the test track once took approximately 40 min. Each intersection approach consisted of three lanes, one for each driving direction (Figure 10). The traffic light phasing was identical for each driving direction. Participants and the lead vehicle always drove straight on the middle lane. In order to control for cues that could be obtained from other road users in the intersection area, there was no other traffic than the lead vehicle in the respective conditions. The traffic light phasing was according to the German road traffic regulations. The red phase always ended with a combined presentation of red and yellow, whereas the green phase ended with a single yellow state. The single yellow light lasted approximately 1.8 s and the combined red and yellow phase lasted approximately 1.2 s. The red phase following the single yellow state lasted for 16 s. The traffic light changes always occurred when drivers passed a landmark 80 m in front of the intersection. This distance allowed for sufficient time to either avoid a stop at red in case of a change from red to green or to initiate a safe stop at red in case of a change from green to red.

Figure 10. Screenshots of the test track with lead vehicle (upper left and bottom left) and fog (upper left and upper right).

Before the main experiment started, participants evaluated the visibility of the traffic light in the track. They approached the traffic light intersection with and without fog. They were instructed to press a button at the steering wheel as soon as they could see the traffic light for the first time. The average distance at which participants were able to see the traffic light without fog was 182.3 m (sd = 42.8) in front of the intersection, with a 95^{th} percentile of 230 m. When there was fog in the track, visibility reduced on average to 90.9 m (sd = 10.4) in front of the intersection with a 95^{th} percentile of 102 m.

At a distance of 300 m in front of the intersection, the lead vehicle appeared in front of the drivers. It followed the standard vehicle models implemented by the SILAB software. The driving speed was 46.8 km/h (13 m/s). The lead vehicle always followed the traffic rules. When the traffic light changed from green to red, it initiated a stop by decelerating with around -3 m/s^2. When the traffic light changed from red to green, it proceeded through the intersection without a stop. After crossing the intersection, the lead vehicle left the scene by strong acceleration.

Procedure

Participants completed a data privacy statement and received instructions about the objectives of the study. They were familiarised with the test track by driving a practice track consisting of six traffic light intersections with different combinations of traffic light phases, lead vehicle and fog conditions. Subsequently, the experimenter calibrated the eye tracking system. The following experimental block consisted of 40 intersection approaches within a single test drive. Before the test drive, the experimenter instructed the participants to stick to the traffic rules while driving.

3.1.2.2 Results

Data preparation and check for order and learning effects

Before the data analysis, the correlation between time during the experiment and the dependent variable speed was investigated. Therefore, mean speed during each traffic light approach was correlated with the starting point in time when the new traffic light approach started. Figure 11 shows the respective scatterplot. The correlation was r = .060 and not significant. This showed that driving behaviour did not change with increasing duration of the experiment.

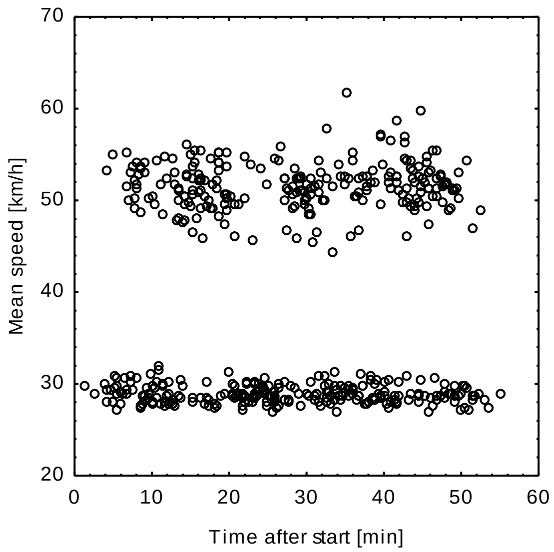


Figure 11. Relation between time at the start of the traffic light approach and mean speed in each traffic light approach.

Additionally, pre-tests compared the mean driving speed in traffic light approaches with identical conditions. For example, mean driving speed between the first traffic light approach with green traffic light, lead vehicle and fog was compared to the second repetition of the same condition. Eight t-tests were conducted for traffic light approaches with fog and eight Analyses of Variance (ANOVAs) were conducted for traffic light approaches without fog. Only one effect was significant. When the traffic light changed from red to green and there was fog and a lead vehicle in the track, participants drove on average 1.3 km/h faster in the second repetition compared to the first repetition, $t(11) = -2.23$, $p = .048$. The absolute difference in speed was small and therefore negligible. As a conclusion, no order effects occurred.

For the analyses, data were averaged over repeated traffic light intersection approaches for each participant. The ANOVAs considered the repeated measurements design. Data for the approach area of 230 m in front of the intersection were included and divided into the 10 m segments. The analyses were conducted separately for traffic light approaches without a stop (i.e. green and red to green traffic light phases) and traffic light approaches with a stop (i.e. red and green to red traffic light phases). Data were processed and analysed with the software Statistica and Excel.

As preparation of the eye tracking data, the recorded videos were reviewed manually frame-by-frame for each 40 ms frame. A rectangle around the cluster display defined the speedometer as area of interest (Figure 12). Ellipses around the traffic light defined the traffic light as area of interest. The size of the ellipses changed during the 230 m of the traffic light approach. There was no differentiation between fixations on the top traffic light or the right traffic light (Figure 13). A fixation was defined when the fixation point was in the area of interest for at least two consecutive frames, i.e. 80 ms. As soon as participants moved their eyes away from the area of interest, the fixation ended. Any further fixation of the speedometer or the traffic light counted as new fixation.

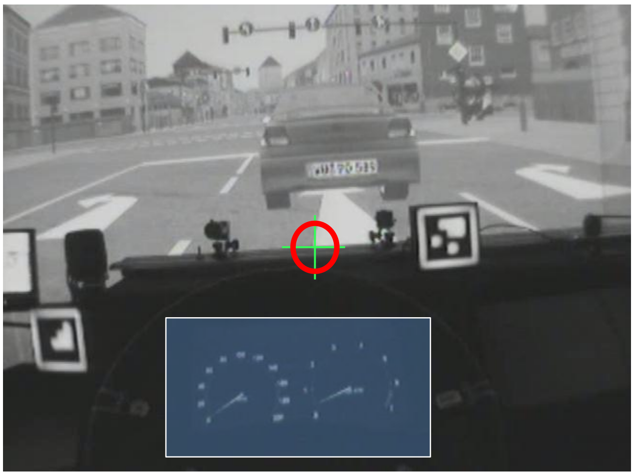


Figure 12. A rectangle around the cluster display defined the speedometer as area of interest. The red circle represents the fixation point as determined by the eye tracker.

Figure 13. Ellipses around the traffic light defined the traffic light as areas of interest, depicted for two different distances during the traffic light approach. The red circle represents the fixation point as determined by the eye tracker.

Speed

Speed profiles for traffic light approaches without a stop were investigated (Figure 14). In general, when the traffic light was solid green, adaptations of driving speed were low over the course of the traffic light approach. When approaching a changing red to green traffic light, drivers reduced their speed before accelerating back to their driving speed of slightly above 50 km/h after the traffic light change had occurred.

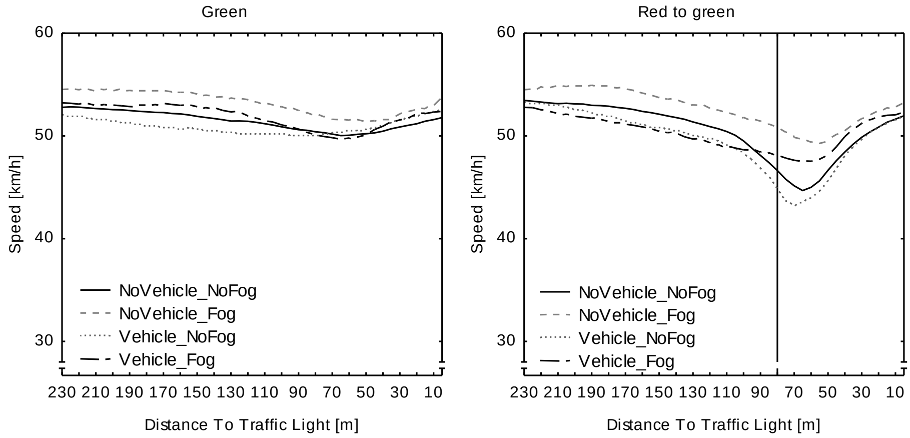


Figure 14. Mean speed in the distance segments 230 to 10 m in front of the intersection for the different fog and lead vehicle conditions separated by the traffic light phases solid green (left) and red to green (right). The vertical black line indicates the distance at which the traffic light phase change occurred.

Mean driving speed was investigated individually for each of the 23 distance segments within the 230 m traffic light approach. The independent variables for each of the 23 ANOVAs were traffic light phase, lead vehicle and fog. The alpha level was adjusted to $p = .0011$ according to Bonferroni, because overall 46 ANOVAs were conducted with the same data material (23 ANOVAs for the comparison green and red to green, and 23 ANOVAs for the comparison red and green to red traffic lights; the latter see below). Table 4 shows that driving speed differed between the two traffic light phases in the distance sections 120 to 50 m in front of the intersection. When the traffic light changed from red to green, driving speed was lower compared to when the traffic light was solid green. With lead vehicle, driving speed was lower between 120 and 110 m compared to without lead vehicle. Fog influenced driving speed especially between 80 and 70 m in front of the intersection, leading to higher driving speeds when there was fog compared to no fog in the track.

Table 4. ANOVA results (*p*-values) for each distance section of 10 m. The factor traffic light phase distinguishes between solid green and changing red to green traffic lights. The alpha level was Bonferroni corrected to $p = .0011$. Bold numbers indicate significant effects. TLP = traffic light phase, LV = lead vehicle, F = fog.

Effect	230-140	130	120	110	100	90	80	70	60	50	40-10
TLP	all *ps* >.007	.002	**.001**	**.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	all *ps* >.089
LV	all *ps* >.002	.001	**.001**	**.001**	.001	.003	.010	.026	.068	.283	all *ps* >.703
F	all *ps* > .011	.027	.025	.016	.005	.003	**.001**	**<.001**	.011	.094	all *ps* >.143
TLP*LV	all *ps* > .114	.127	.116	.096	.135	.194	.183	.243	.327	.384	all *ps* >.470
TLP*F	all *ps* > .003	.042	.138	.473	.598	.074	.010	.004	.008	.070	all *ps* >.156
LV*F	all *ps* > .076	.078	.044	.019	.005	.005	.014	.020	.075	.250	all *ps* >.206
TLP*LV*F	all *ps* > .105	.223	.251	.363	.571	.902	.387	.340	.328	.485	all *ps* >.579

Next, driving speed was investigated for traffic light approaches with a stop (Figure 15). In all conditions, participants reduced driving speed and initiated the stop in the final distance sections in front of the stop line. The reduction in driving speed in the green to red situation occurred after the traffic light change in all four conditions.

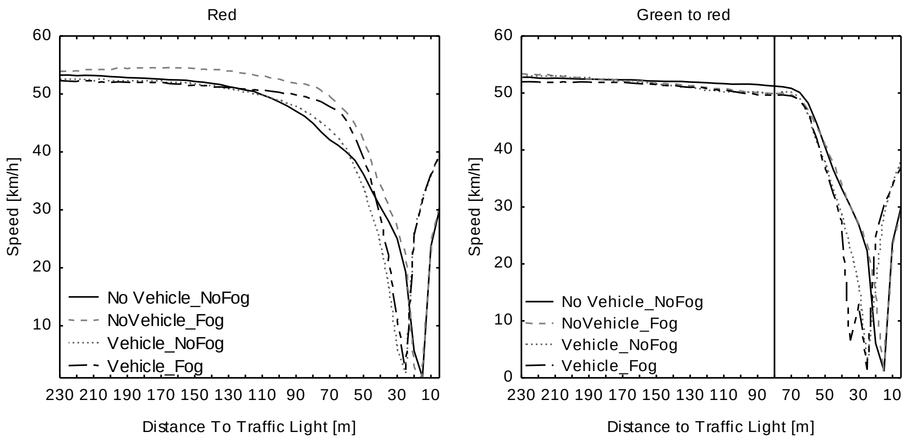


Figure 15. Mean speed in the distance segments 230 to 10 m in front of the intersection for the different fog and lead vehicle conditions separated by the traffic light phases solid red (left) and green to red (right). The vertical black line indicates the distance at which the traffic light phase change occurred.

Similar to the analysis of traffic light approaches without a stop, mean driving speed was investigated separately for each of the 23 distance sections (Table 5). In the distance sections 90 to 70 m in front of the intersection, participant’s driving speed was lower when the traffic light was solid red compared to the changing green to red traffic light. In these distance sections, drivers initiated the stop at red when the solid red light was visible. This main effect was qualified by the interaction between traffic light phase and fog in the distance section 110 to 50 m in front of the intersection. Fog only influenced the initiation of the stop at red in the solid red light condition, but not in the changing green to red condition. When the traffic light was solid red and there was fog in the track, drivers postponed the speed reduction compared to the solid red condition without fog. The lead vehicle influenced driving speed in the final distance sections (distances < 50 m in front of the intersection), because naturally the distance at which drivers stopped in front of the intersection was larger when there was a lead vehicle in front.

Table 5. ANOVA results (*p*-values) for each distance section of 10 m. The factor traffic light phase distinguishes between solid red and changing green to red traffic lights. The alpha level was Bonferroni corrected to *p* = .0011. Bold numbers indicate significant effects. TLP = traffic light phase, LV = lead vehicle, F = fog.

Effect	230-120	110	100	90	80	70	60	50	40	30	20	10
TLP	all ps >.013	.742	.076	**.001**	**<.001**	**<.001**	.001	.153	.102	.158	.017	.138
LV	all ps >.005	.008	.022	.072	.264	.252	.001	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
F	all ps >.246	.186	.120	.039	.006	.010	.013	.004	.188	.292	.045	.880
TLP*LV	all ps >.040	.654	.965	.966	.864	.949	.555	.463	.047	.077	.302	.258
TLP*F	all ps >.005	**.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**.001**	.064	.340	.830	.249
LV*F	all ps >.107	.267	.187	.082	.035	.433	.855	.764	.220	.943	.629	.465
TLP*LV*F	all ps >.028	.012	.006	.007	.018	.043	.466	.240	.495	.668	.017	.836

Acceleration and deceleration

First, an ANOVA investigated the maximum acceleration for traffic light approaches without a stop. In line with the previous analysis, the independent factors were traffic light phase, lead vehicle and fog. The maximum acceleration was larger when the traffic light phase changed from red to green compared to a solid green traffic light, $F(1,11) = 17.691$, $p = .001$, $\eta^2_{partial} = .617$. When there was fog in the track, the maximum acceleration was larger compared to conditions without fog, $F(1,11) = 5.500$, $p = .039$, $\eta^2_{partial} = .333$. The interaction between traffic light phase and fog indicated that the difference in maximum acceleration between foggy and non-foggy traffic light approaches was limited to the changing red to green traffic light and did not occur when the traffic light was solid green, $F(1,11) = 7.587$, $p = .019$, $\eta^2_{partial} = .408$. Second, an ANOVA for traffic light approaches to green and red to green lights included the maximum deceleration as dependent variable. The maximum deceleration was larger, when the traffic light changed from red to green compared to the maximum deceleration when the traffic light was solid green, $F(1,11) = 18.102$, $p = .001$, $\eta^2_{partial} = .622$. When there was no fog in the track, participants decelerated stronger compared to the foggy condition, $F(1,11) = 5.041$, $p = .046$, $\eta^2_{partial} = .314$. The significant interaction between traffic light phase and fog showed that when the traffic light changed from red to green, the maximum deceleration was stronger when there was no fog in the track compared to when there was fog in the track, $F(1,11) = 7.008$, $p = .023$, $\eta^2_{partial} = .389$. Figure 16 depicts the described effects. Third, a further ANOVA showed that when the traffic light was red or changed from green to red, the maximum acceleration occurred after waiting at the red light. When drivers started behind a lead vehicle, the maximum acceleration was stronger compared to starting without lead vehicle, $F(1,11) = 7.061$, $p = .022$, $\eta^2_{partial} = .390$. Fourth, ANOVA results indicated that when the traffic light changed from green to red, the maximum deceleration was stronger compared to the maximum deceleration in the solid red traffic light conditions, $F(1,11) = 8.972$, $p = .012$, $\eta^2_{partial} = .449$. When there was a lead vehicle compared to no lead vehicle in the track, the maximum deceleration was larger, $F(1,11) = 12.486$, $p = .005$, $\eta^2_{partial} = .532$, as well as when there was fog compared to no fog in the track, $F(1,11) = 11.743$, $p = .006$, $\eta^2_{partial} = .516$. No other effects were significant. Figure 17 depicts the described effects.

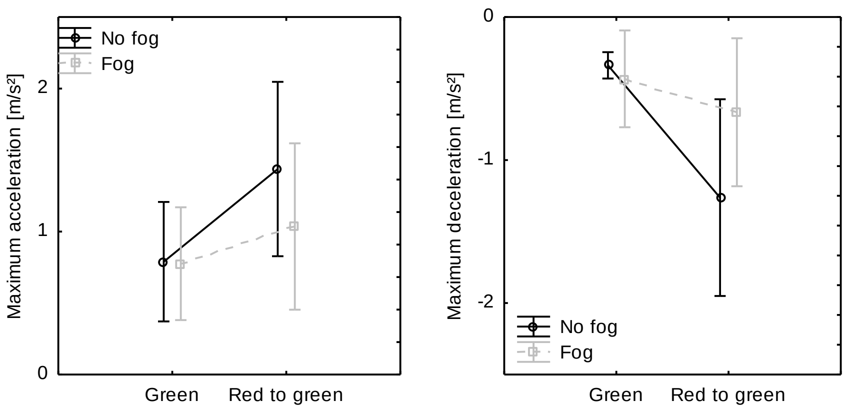


Figure 16. Maximum acceleration (left) and maximum deceleration (right) depending on the factors traffic light phase and fog for traffic light approaches with solid green and changing red to green phase. Graphs show means with 95% confidence intervals.

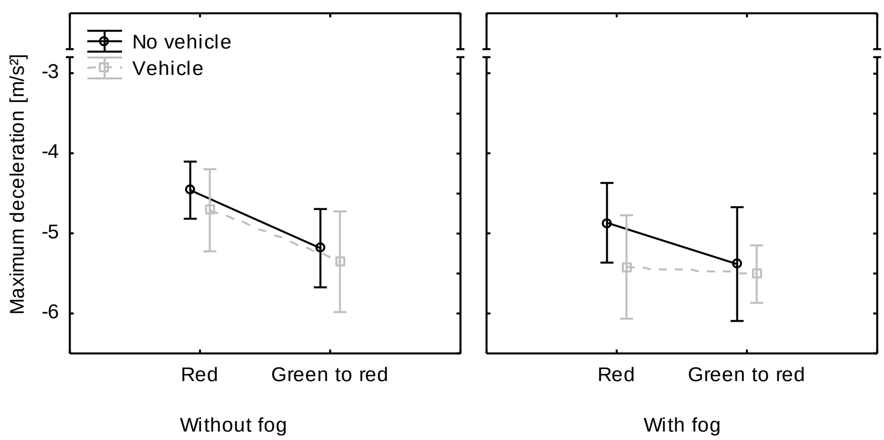


Figure 17. Maximum deceleration depending on the factors traffic light phase, lead vehicle and fog for traffic light approaches with solid red and changing green to red phase. Graph shows means with 95% confidence intervals.

Pedal usage

The number of traffic light approaches in which drivers released the accelerator pedal completely and the number of traffic light approaches in which drivers pressed the brake pedal was determined. The numbers were related to the total amount of traffic light approaches conducted in each of the conditions. For traffic light approaches with a stop, this analysis resulted in 100% probabilities for releasing the accelerator pedal and for using the brake pedal, because no driver accidently crossed the red light without a stop.

Table 6 summarises the results for the traffic light approaches to solid green and changing red to green traffic lights. In overall 50 % of the traffic light approaches to a solid green light, drivers released the accelerator pedal at some point in the approach. The number of traffic light approaches with brake onset is low in this condition. When the traffic light phase changed from red to green and there was no fog in the track, drivers released the accelerator pedal in almost all traffic light approaches and pressed the brake pedal in around 50% of the cases. The number of brake onsets reduced clearly, when there was fog in the track.

Table 6. Frequencies [%] of traffic light approaches in which drivers released the accelerator pedal and pressed the brake pedal depending on the factors traffic light phase, lead vehicle and fog. The table does not include red and green to red traffic lights, because in these conditions, the frequencies for releasing the accelerator pedal and pressing the brake pedal were 100%.

Traffic Light	**Vehicle**	**Fog**	**Accelerator release**	**Brake onset**
Green	No Vehicle	No Fog	38.89	2.78
	No Vehicle	Fog	54.17	4.17
	Vehicle	No Fog	41.67	2.78
	Vehicle	Fog	62.50	4.17
Red to green	No Vehicle	No Fog	94.44	47.22
	No Vehicle	Fog	66.67	16.67
	Vehicle	No Fog	94.44	50.00
	Vehicle	Fog	66.67	4.17

Fixations on the speedometer

The percentage of time fixating the speedometer was determined. Figure 18 shows the percentage of time drivers spent with fixating the speedometer in each of the 23 distance sections over the course of the 230 m traffic light approach. At solid green traffic lights, drivers fixated to the speedometer on average 7% of the time in each distance section. When the traffic light changed from red to green, drivers did not fixate the speedometer in the distance section in which the traffic light change occurred. In the subsequent distance sections, the time fixating the speedometer increased. When the traffic light was red, the proportion of fixation time reduced while participants initiated the stop at the red light in the distance sections 90-30 m in front of the intersection. When the traffic light was red or changed from green to red, the time fixating the speedometer increased when drivers started after waiting at the red light.

Two ANOVAs were conducted separately for green and red to green lights and for red and green to red lights. The independent factors were traffic light phase, lead vehicle and fog. The dependent variable was the mean proportion of time fixating the speedometer over the course of the 230 m traffic light approach. When the traffic light was green or changed from red to green, drivers fixated the speedometer for longer periods of time when there was no lead vehicle compared to when there was a lead vehicle, $F(1,11) = 21.039$, $p < .001$, $\eta^2_{\text{partial}} = .657$. No other effects were significant.

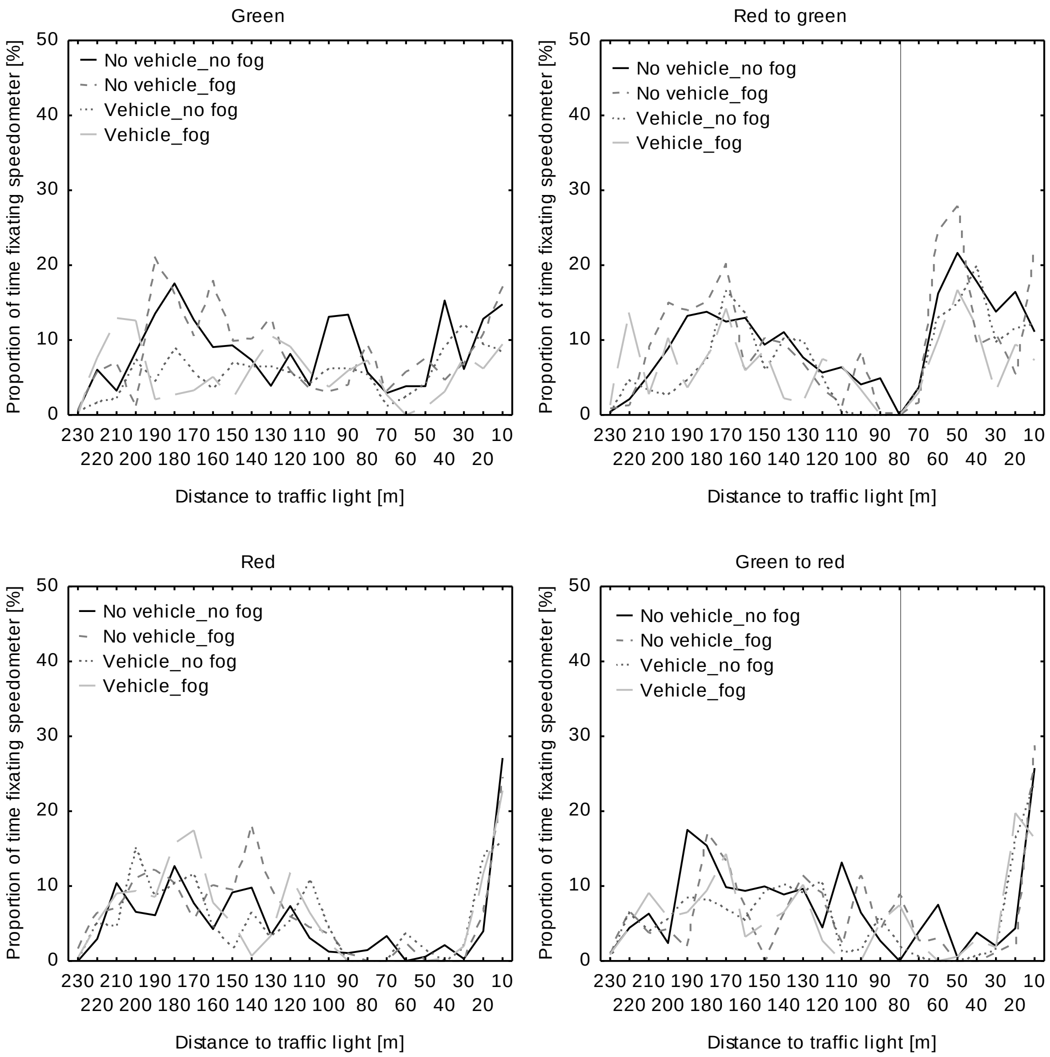


Figure 18. Mean proportion of time drivers fixated the speedometer in each distance section for the different traffic light phase, lead vehicle and fog conditions.

Fixations on the traffic light

The percentage of time fixating the traffic light in each distance section was determined and plotted as shown in Figure 19. With decreasing distance to the traffic light, the percentage of time fixating the traffic light increased up to a peak around 80 m in front of the intersection. In the fog condition, the increase occurred delayed, because the traffic light can only be fixated starting at approximately 120 m. After the traffic light change in the red to green and green to red condition, the proportion of time fixating the traffic light decreased more rapidly compared to the solid green and the solid red condition. Descriptively, the proportion of time fixating the traffic light was slightly lower when there were lead vehicles ahead compared to no lead vehicles. Two ANOVAs were conducted for green and red to green traffic lights, and red and green to red traffic lights. The independent factors were traffic light phase, lead vehicle and fog. The dependent variable was the proportion of time fixating the traffic light over the course of the whole 230 m traffic light approach. In the analysis of green and red to green traffic lights, all main effects were significant: Traffic light phase $F(1,11) = 36.207$, $p < .001$, $\eta^2_{partial} = .767$, lead vehicle $F(1,11) = 8.689$, $p = .013$, $\eta^2_{partial} = .441$ and fog $F(1,11) = 22.276$, $p < .001$, $\eta^2_{partial} = .669$. Drivers fixated the traffic light more often when the traffic light phase was solid green compared to red to green, when there was no lead vehicle compared to with lead vehicle and when there was no fog in the track compared to with fog. Further, there was a significant hybrid interaction between traffic light phase and fog, $F(1,11) = 18.762$, $p = .001$, $\eta^2_{partial} = .630$. The main effect fog can be interpreted globally. However, when there was fog in the track, no difference between the duration of fixations on the traffic light occurred between green and red to green lights (Figure 20 left).

When the traffic light was red or changed from green to red, the three main effects were significant: Traffic light phase $F(1,11) = 11.445$, $p = .006$, $\eta^2_{partial} = .510$, lead vehicle $F(1,11) = 26.792$, $p < .001$, $\eta^2_{partial} = .709$, and fog $F(1,11) = 11.214$, $p = .006$, $\eta^2_{partial} = .505$. Drivers fixated the traffic light for longer periods of time when it was solid red compared to changing green to red, when there was no vehicle in front compared to when there was a vehicle in front and when there was no fog in the track compared to with fog in the track (Figure 20, right).

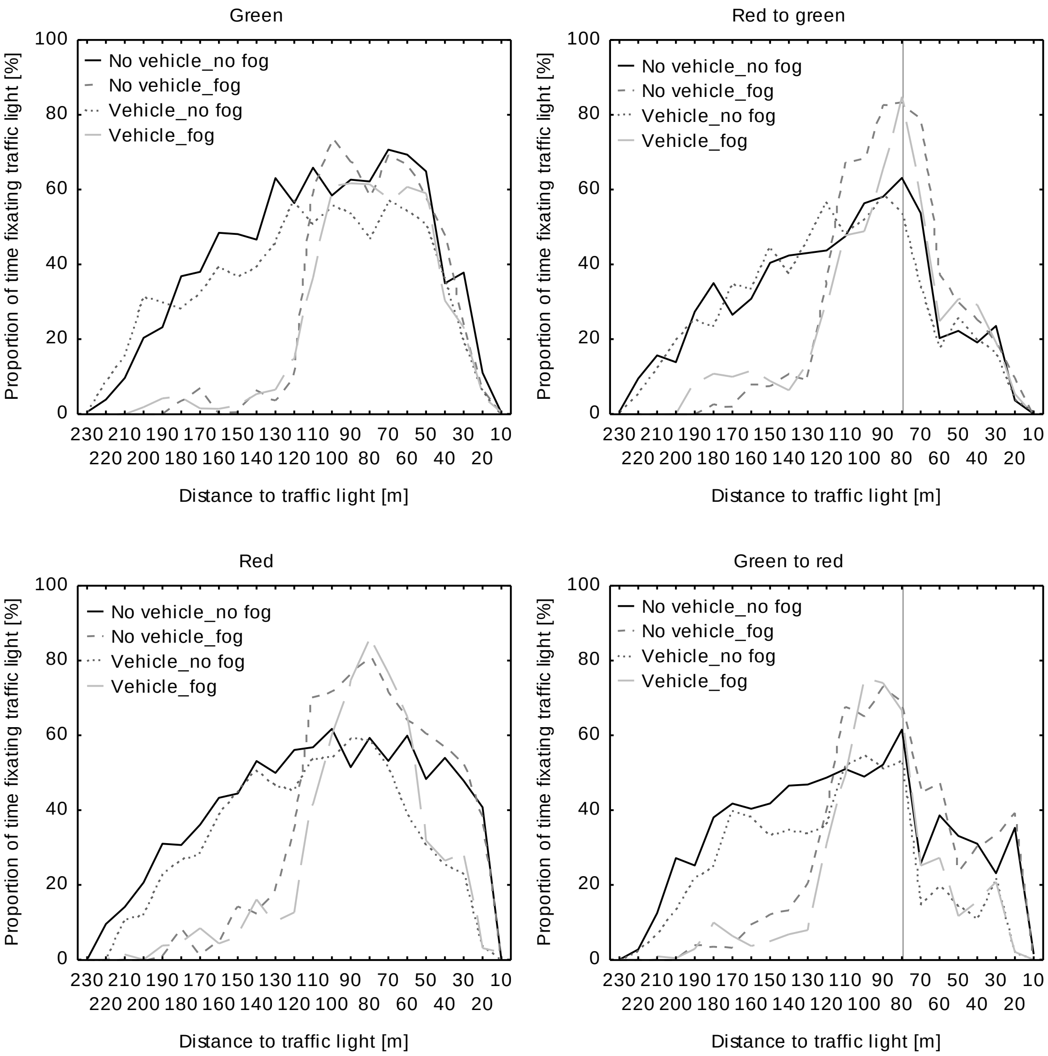


Figure 19. Mean proportion of time drivers spent fixating the traffic light in each distance section for the different traffic light phase, lead vehicle and fog conditions.

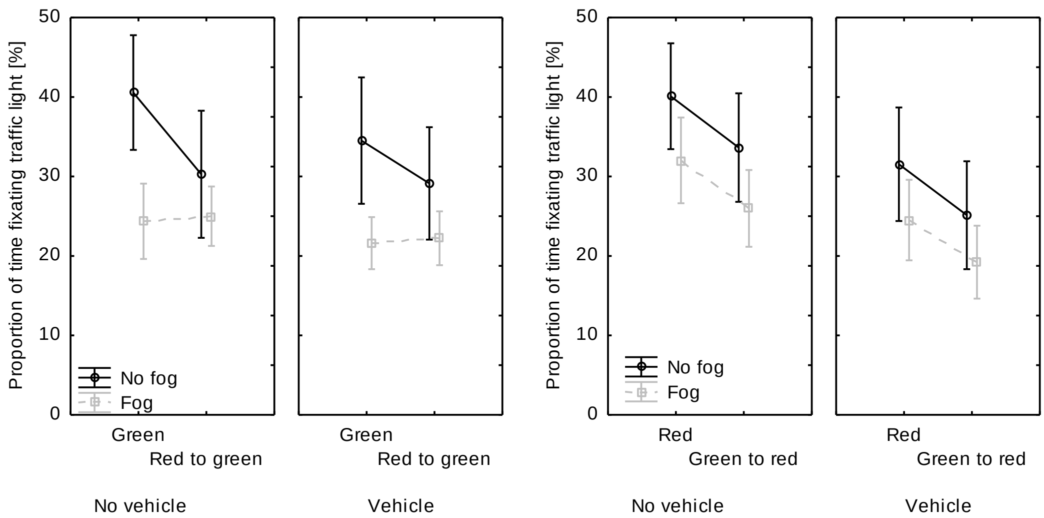


Figure 20. Proportion of time fixating the traffic light depending on the factors traffic light phase, lead vehicle and fog for traffic light approaches with solid green and changing red to green phase (left), and solid red and changing green to red phase (right). Graph shows means with 95% confidence intervals.

3.1.2.3 Summary and discussion

Study 1 investigated unassisted driving behaviour at traffic light intersections. Drivers approached traffic light intersections with varying traffic and visibility conditions. Traffic and visibility varied in order to identify the relation between situation parameters and driving efficiency. Hence, the study aimed at defining which situation characteristics lead to more or less efficient driving behaviour. Efficiency was measured indirectly by driving behaviour. Drivers' gaze behaviour was recorded in order to investigate the information processing and to identify when and to what extent drivers attend to the traffic light and the speedometer.

In general, drivers approached the traffic light intersections with initially slightly over 50 km/h driving speed. The crucial distance segments were approximately 130 m to 50 m in front of the intersection. At greater distances to the intersection, drivers did not yet adapt driving behaviour. At distances 40 m and closer to the intersection, the speed profiles between lead vehicle and fog conditions assimilated. When the traffic light was red or changed to red, all drivers stopped at the intersection. Additionally, between 100 and 60 m in front of the intersection, the attention drivers allocated to the traffic light peaked. In this phase of the traffic light approach, the information from the traffic light seemed to be crucial for the decision on how to proceed. The fixed traffic light phase change that occurred around 80 m in front of the intersection probably determined this distance section. Drivers might have learned during the experiment when it is worthwhile to attend to the traffic light.

At solid green traffic lights, the driving speed between distance sections showed only slight variations. The analysis of pedal usage indicated that in around 50% of the traffic light approaches to solid green lights drivers released the accelerator pedal. This might reflect the uncertainty about a possible traffic light phase change for which drivers might have prepared (Wickens & Hollands, 2000). When the traffic lights changed from red to green, drivers reduced speed and decelerated by using the brake pedal. Subsequently, after the traffic light change had occurred drivers accelerated back to their desired driving speed of 50 km/h. Hence, the traffic light phase change happened later than the participants' threshold for a safe and comfortable stop at red. Supporting this, drivers reduced speed earlier in the solid red traffic light condition compared to the changing green to red condition. When the traffic light changed from green to red, deceleration was stronger and started at closer distances to the traffic light compared to solid red lights. As a conclusion, the traffic light phase change delayed drivers' reaction because it occurred later than drivers naturally start their reaction to the traffic light. Even though the current drives took place in a static driving simulator setting, the measured maximum deceleration values were in line with previously reported deceleration values.

A similar effect was observed in the fog conditions. The fog only allowed participants to see the traffic light starting around 120 m in front of the intersection. Therefore, the fog conditions postponed drivers' reaction to the traffic light. This was beneficial in cases where an earlier adaptation of driving speed was inappropriate because the traffic light changed during the approach (e.g. at red to green traffic lights), and it was not beneficial in cases where an early adaptation of speed was appropriate (e.g. at solid red traffic lights).

Especially in adverse visibility conditions, the lead vehicle served as an orientation for selecting the driving speed. When there was no lead vehicle ahead, the influence of fog was increased. Naturally, participants could not drive faster than 50 km/h when the lead vehicle was present. When passing through a green or red to green light, the lead vehicle served as an orientation for choosing the driving speed and participants reduced the number of speedometer fixations compared to driving without lead vehicle. Similarly, the lead vehicle served as a source of information, as drivers reduced the amount of time checking the traffic light when there was a lead vehicle in front. The lead vehicle always behaved correctly and was therefore a reliable orientation for drivers.

The fixation durations to the traffic light were higher, when the traffic lights were solid compared to when the traffic light changed. When drivers experienced the traffic light change, they could anticipate the traffic light status at arrival at the intersection, because a further traffic light change was unlikely. Therefore, the progress of the upcoming situation was clear. Contrary, when the traffic light was solid during the traffic light approach, a phase change could be possible any time and the information demand for the traffic light was high. The presence of fog reduced the duration of fixations on the traffic light. However, this was because the traffic light was only visible at closer distances to the intersection compared to the no fog condition. No fixations on the traffic light were possible while drivers were in the distance sections in which the traffic light was covered with fog. As soon as the traffic lights became visible starting around 120 m in front of the intersection, drivers fixated the traffic light frequently. Hence, the information demand drivers had for the traffic light was higher than what was offered in the foggy conditions.

Based on the current data, approaching traffic light intersections divides into the three stages orientation, preparation and realisation (Figure 21). In the orientation phase, the traffic light is visible, but drivers do not yet adapt their driving behaviour. This is reasonable, because a traffic light phase change could still change the required behaviour. As outlined by Caird et al. (2007), at sufficient distances to the traffic light, drivers postpone their reaction to the traffic light. During the preparation phase, drivers start preparing for external triggers that give the indication on how to proceed at the intersection. The preparation phase started earliest at around 150 m in the current study. During the preparation phase, the attention to the traffic light increases, because the traffic light phasing defines the required behaviour. The decision on how to proceed defines the end of the preparation phase. At this point, the driver decides to stop or proceed through the intersection. In the present study, the realisation started at farer distances to the intersection than the traffic light phase changes occurred. Therefore, the realisation phase was already initiated and drivers had to correct their decision on proceeding or stopping in case the traffic light changed afterwards. When fog obscures the traffic light drivers are in a free driving state until the traffic light becomes visible. As soon as drivers see the traffic light, the orientation and preparation phases take place with an increased attention to the traffic light, before the traffic light phase change occurs and the final realisation phase starts. In that case, the orientation and preparation phase might follow each other in a short sequence and differences in driving behaviour are difficult to identify. During the realisation phase, the attention to the traffic light decreases. After a decision to proceed through the intersection (Figure 21, left), the realisation phase comes along with an increased attention to the speedometer, because drivers assess if their driving speed is appropriate for the realisation of the selected behaviour. When initiating a stop at a red light (Figure 21, right), drivers' attention is allocated to the driving scene rather than the speedometer information about the driving speed. During deceleration for stopping, estimating the distance to the stop line or the lead vehicle is more important than one's own driving speed. The presence of a lead vehicle facilitates the driver's decision on proceeding or stopping at the intersection. For example, with lead vehicle the influence of fog on driving behaviour decreased. In line with the findings of Kaul and Baumann (2013), following a lead vehicle requires less cognitive resources than free driving, because the lead vehicle serves as a source of information.

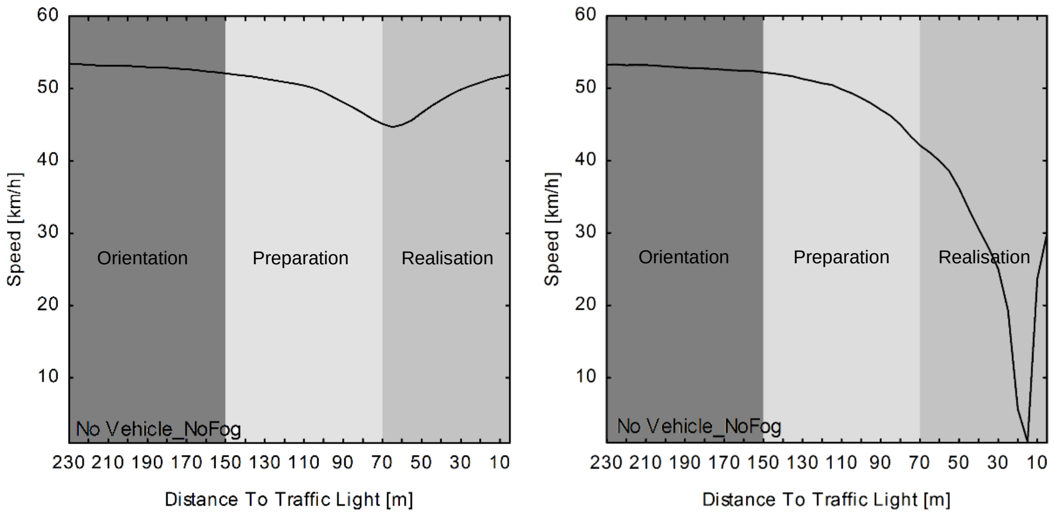


Figure 21. Speed profiles for approaching a red to green traffic light (left) and a solid red traffic light (right). The background colours highlight the three approach areas orientation, preparation and realisation.

The results showed that there is a potential for more anticipatory and with that more efficient driving at traffic light intersections. Driving speed and acceleration differed according to the variations in traffic conditions and fog. The factors traffic light phase and visibility operationalised drivers' foresight and anticipation of the situation. The driver assistance system should promote changes in these parameters. When drivers saw the traffic light earlier, they adapted their behaviour earlier. However, as pointed out, the early adaptation was not beneficial as long the traffic light phase subsequently changed. Therefore, additional information on possible traffic light phase changes or future traffic lights states could be beneficial. This could reduce the uncertainty about the traffic light phasing that naturally appears. Additionally, it could help drivers to decide on the required driving behaviour at comfortable distances to the traffic light or even at distances at which drivers naturally do not see or react to the traffic light. In turn, this more anticipative driving behaviour could increase driving efficiency. Moreover, the results also showed that drivers did not adapt their driving behaviour in the orientation phase. Besides the earlier knowledge of traffic light phasing, there is a potential for improving specific driving behaviours in the different situations. For example, all drivers braked to reduce speed when approaching red or green to red traffic lights. Instructing drivers to reduce speed early by the initiation of coasting could meet the criteria for an efficient driving style. Similarly, at red to green traffic lights drivers accelerated after deciding to proceed through the intersection instead of keeping speed constant.

In sum, the study showed that a traffic light assistant would influence the normal driving behaviour and natural gaze behaviour at traffic light intersections. A driver assistant system could improve drivers' anticipation of the upcoming traffic situation and could influence the driving behaviour in different phases of the traffic light approach. Besides that information, driving recommendations in terms of driving speeds or required driving behaviour as well as information on the traffic light phasing seem to be appropriate information units to guide drivers to more efficient driving at traffic light intersections. The drivers' orientation on driving behaviour of the lead vehicle leads to the expectation that using a traffic light assistance system might be especially difficult in conditions with surrounding traffic.

3.2 Traffic light assistance

The following paragraphs introduce concepts for traffic light assistance. This includes a literature overview of different approaches for increasing driving efficiency at traffic light intersection and the assumptions for individual driver support. Additionally, the technical background for the traffic light assistant used in the present study is given. The influence of traffic light assistance on the interaction between road users is detailed. Subsequently, Study 2 presents the investigation of the interaction between road users when using the traffic light assistant. Study 1 demonstrated that in order to increase driving efficiency, drivers need to adapt their normal behaviour. The goal is to identify situations in which drivers do not feel comfortable with using the traffic light assistant, based on variations in system parameters and surrounding traffic.

3.2.1 Theoretic background

3.2.1.1 Assisting efficient driving at traffic light intersections

Different approaches have been chosen to increase efficiency at traffic light intersections. A global strategy has been to optimise traffic signal timing. For example, an early approach that is widely known as the “green-wave” allows vehicles to cross intersections at green when choosing a certain driving speed. Drivers are informed about the required driving behaviour by elements in the infrastructure, for example by additional traffic signs containing static or dynamic speed recommendations (Van Leersum, 1985). This concept can lead to reductions in emissions of around 10 % (Madireddy et al., 2011). In some traffic systems in worldwide traffic, countdown timers have been used to indicate the remaining green or red phase duration. By these digital timers, drivers are supported with their decision on acceleration or deceleration (Kidwai, Karim, & Ibrahim, 2005; Koukoumidis, Peh, & Martonosi, 2011). More advanced is the concept to control traffic lights on demand. The traffic light controller therefore uses a sensor (e.g. cameras, loop detectors) to detect vehicles approaching the intersection. The traffic light phasing can then be adapted, average waiting times decrease and individual vehicles are able to avoid stops (Khakhutskyy, 2011; Stevanovic et al., 2009). To reduce the likelihood for a dilemma zone situation it has been suggested to switch the traffic light whenever no vehicle is currently approaching to the intersection (Li et al., 2009). With these global traffic management strategies, a large number of vehicles can benefit from the adapted traffic light control without the necessity of specific technical equipment in the vehicles. Controlling traffic lights on demand could also be approached by Car-to-Infrastructure communication, i.e. the traffic light could receive the information on approaching traffic by receiving wireless messages from the vehicles themselves (Gradinescu, Gorgorin, Diaconescu, Cristea, & Iftode, 2007). A disadvantage of the global approaches to increases in efficiency at traffic light intersections is that they do not consider individual vehicle characteristics and driver behaviours. Wu, Boriboonsomsin, Zhang, Li, and Barth (2010) compared stationary information in terms of variable message signs as part of the infrastructure and in vehicle integration of a traffic light assistant. They concluded that even though both kinds of driver support led to savings in fuel consumption and emissions, the in vehicle system led to the largest improvements.

By means of increasing efficiency in individual vehicles, car manufacturers have invested in improving engine and car body properties in order to prepare for stops at intersections. For example, stop/start systems enable to turn off the car engine automatically when reaching standstill. Like this, fuel consumptions and emissions while waiting at a red light are reduced (Opel, 2015). Furthermore, some vehicle lines introduce eco systems to the market that enable the isolation of the engine from the drive train (BMW, 2014).

Importantly, efficiency of driving has been considered in the frame of individual driving styles. The goal is to provide individualised feedback for single drivers in order to influence driving behaviour. Numerous national and international research projects focused on the development of traffic light assistance as individual vehicle application (e.g. eCoMove, PReVent Intersafe, ecoDriver, AKTIV and recently UR:BAN). The technical background of such traffic light assistance application can either be wireless communication between vehicle and infrastructure or mobile communication networks that require smartphones in the vehicle (Koukoumidis et al., 2011). The idea is to influence the dynamic driving behaviour of the individual driver approaching the traffic light intersection. As mentioned before, crucial for an efficient driving style is the anticipation of the traffic situation. The dynamic traffic light phasing naturally limits the possibilities for predictions of the driving scene. Therefore, individual in vehicle traffic light assistant systems support drivers to achieve an improved anticipation of the situation. The systems increase drivers’ knowledge of the driving situation by time (i.e. information on the traffic light phasing is earlier available than drivers usually see the traffic light), by space (i.e. the distance at which drivers know about the traffic light is increased), and by quality (e.g. drivers get additional information that cannot be seen in the actual traffic light). Hence, the traffic light assistant supports drivers’ judgments and decisions in driving by giving “value-added” information (Iglesias, Isasi, Larburu, Martinez, & Molinete, 2008; Kamal et al., 2010; Seong & Bisantz, 2008). The system aims on presenting necessary information to the driver in order to support a coherent decision making (Armand, Filliat, & Ibanez-Guzman, 2013). To achieve the benefits of the traffic light assistant, the adaptation of driving behaviour might be required either when drivers cannot yet see the respective traffic light, or when they cannot anticipate the relevant traffic light state. Therefore, information processing, action selection and execution in reaction to the traffic light start earlier than in unassisted driving (Figure 22).

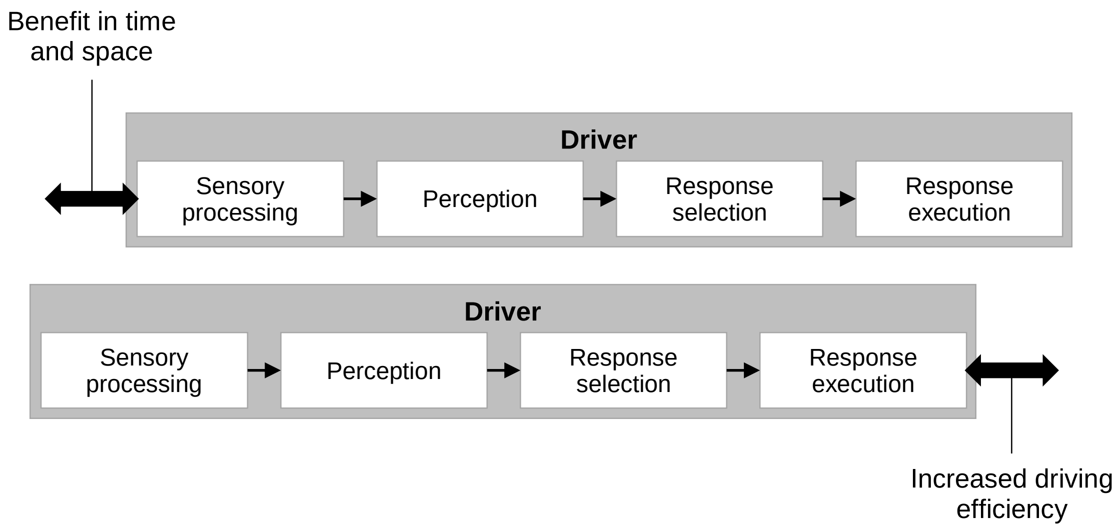


Figure 22. Benefits in time and space gained by a traffic light assistant lead to anticipative behaviour and increased driving efficiency in individual drivers (adapted from Popiv, 2012; Wickens & Hollands, 2000).

In terms of the models of the driving task mentioned in chapter 3.1.1.1, efficient driving represents a strategic goal. The additional information offered by a driver assistance system triggers a conscious decision to drive efficiently. This emphasises knowledge based behaviour on a strategic level. Further, the traffic light assistant modifies available rules that drivers apply and that relate the driving situation to sensory motor patterns. In addition to the stimuli in the environment that usually trigger decisions on the required manoeuvres (e.g. stopping, proceeding), the information from the assistant is now included in the anticipation of the traffic situation and the selection of the required behaviours. This information might change well-learned rules for approaching the intersection. Drivers need to understand and learn the new relation between the presented information and the relevant behaviour. Finally, the efficient driving behaviour manifests on a control level and becomes measurable in dynamic driving parameters (Figure 23). Hence, the increases in driving efficiency are achieved by benefits that influence driving behaviour at all three levels of the driving task (Popiv, 2012).

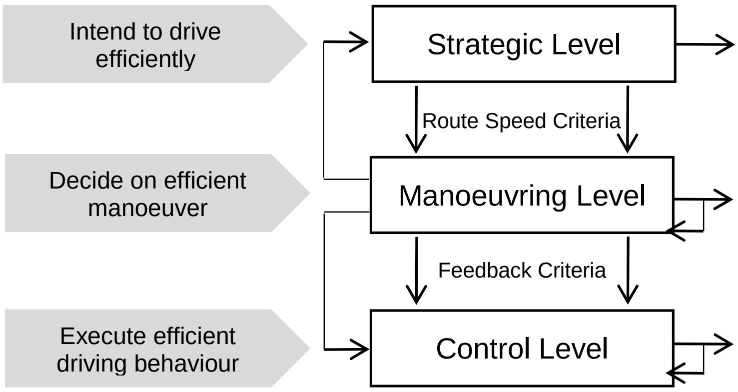


Figure 23. Influence of the traffic light assistant on different levels of the driving task defined by Michon (1985).

General evidence for the benefits of the traffic light assistant for emissions and fuel consumption comes from traffic simulation studies. Tielert et al. (2010) showed savings achieved with a traffic light assistant based on Car-to-Infrastructure communication. Depending on the number of vehicles in the scenario and the start distance for the communication of the traffic light phase to the approaching vehicles, individual vehicles saved up to 22 % compared to unequipped vehicles. Rakha and Kamalanathsharma (2014) simulated a traffic light assistant at a real intersection scenario. The traffic light assistant was supposed to communicate information on the next traffic light phase to the approaching vehicles. The researchers reported reductions of around 30 % by increasing the average travel speed of all approaching vehicles. Furthermore, adaptive cruise control systems have integrated the traffic light assistant. With that, the target speed of the adaptive cruise control adapts towards the required driving speed to cross the intersection at green. Asadi and Vahidi (2011) adapted the driving speed of a cruise control system so that at the time of arrival at the intersection the traffic light was green. Their simulations with a single vehicle, multiple vehicles and baseline vehicles showed fuel consumption reductions of 47% and reductions in emissions by 56% after crossing nine traffic light intersections. Malakorn and Park (2010) demonstrated this approach in an interactive system, where the adaptive cruise control adapted driving speed towards the required conditions and the traffic light phasing adapted towards the requirement of the approaching vehicles. The traffic simulation results showed that the cooperative scenario has benefits in terms of CO_2 emissions and fuel consumption compared to a fixed traffic light phasing in a non-cooperative scenario.

Individual traffic light assistance has also been investigated in driving simulators and real traffic conditions. For example, Thoma, Lindberg, and Klinker (2007) investigated a traffic light assistant in a driving simulator. As can be seen in Figure 24, with traffic light assistant, drivers decelerated less strong and reacted earlier to the traffic light when they drove with assistance system compared to a baseline drive without traffic light assistant.

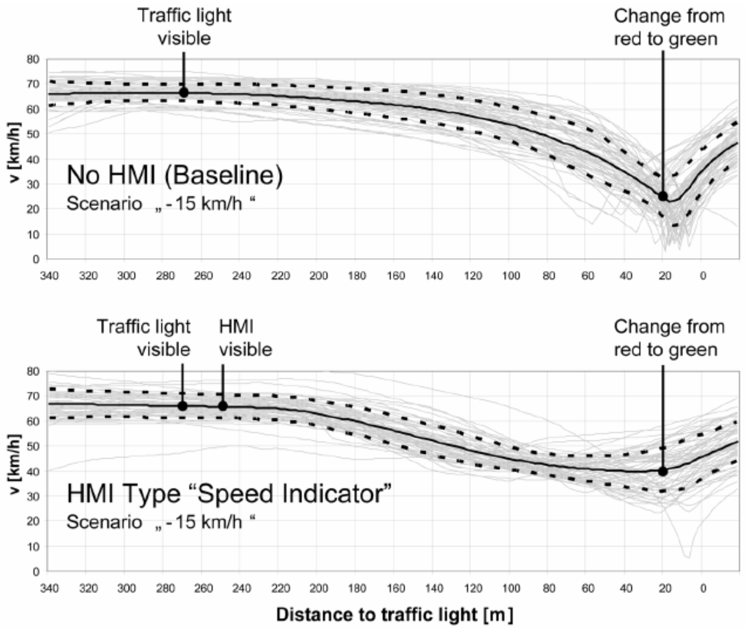


Figure 24. Speed profiles when driving with (lower graph) and without (upper graph) traffic light assistant (Thoma et al., 2007).

Wu, Zhao, and Ou (2011) tested an acceleration assistant for traffic light approaches with a small sample in a real traffic situation. Drivers received visual information on how strong acceleration and decelerations should be in order to drive efficiently. In specific situations, the researchers measured fuel savings up to 31 %. Koukoumidis et al. (2011) implemented a Green Light Optimal Speed Advisory (GLOSA) function by means of a smartphone application, which did not require a communication structure between infrastructure and vehicle, because it based on the smart phone camera. The system was tested at three consecutive traffic light intersections in Cambridge. Driving with the GLOSA system led to a reduction in the number of stops at the intersection and to fuel savings of on average 20.3 %. Importantly, Li et al. (2009) emphasised that even though the benefits of each individual assisted traffic light approach might be small and very specific for the investigated scenario, the cumulative savings gained by a larger number of repeated traffic light approaches can lead to meaningful changes in emissions and fuel consumption.

In sum, a traffic light assistant communicates value-added information to the driver. This in turn leads to changes at all levels of the driving task. By that, driving efficiency of the individual vehicle increases when approaching the traffic light intersection.

3.2.1.2 Technical background of the traffic light assistant

According to the classification in the German research project UR:BAN[2], driver assistance systems are described in three groups (Petermann-Stock & Rhede, 2013). (1) Systems that increase safety by warnings and automatic interference in critical situations. (2) Systems that increase efficiency and/or comfort by continuous overtaking of parts of the driving task. (3) Systems that increase efficiency and/or comfort by informing drivers about appropriate driving behaviours or a system status (Figure 25).

In the present thesis, the traffic light assistance system is a recommendation system with no system interference in longitudinal vehicle control. Therefore, it belongs to group (3) in the right branch of the UR:BAN classification. The system focuses on driving recommendations for the traffic light approach and does not consider speed profiling past the intersection.

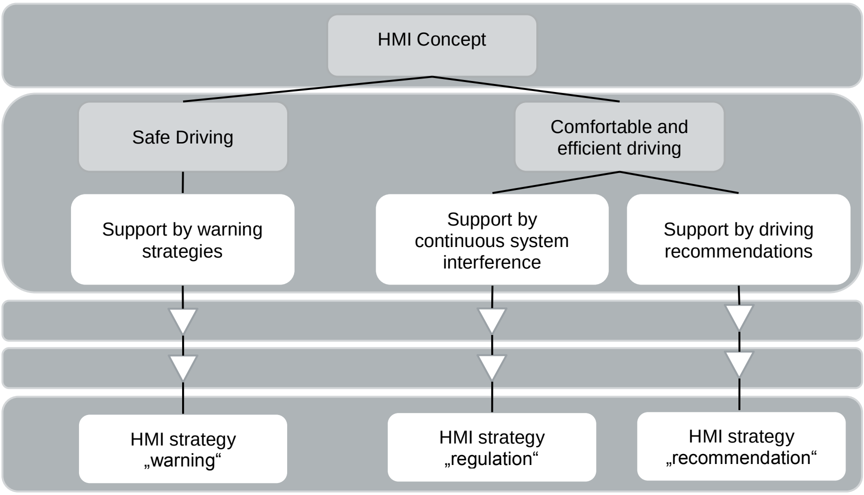


Figure 25. Categorisation of driver assistance systems according to the German research project UR:BAN.

The technical background of the traffic light assistant is the Car-to-Infrastructure communication structure. The vehicle as well as the infrastructure are equipped with wireless communication units that allow data transfer. In the present research, the system bases on the 802.11p standard of IEEE. It is limited to the transfer of information from the traffic light to the vehicle (not vice versa). The traffic light sends the information about the currently active traffic light phase and the duration of the current and the next traffic light phase. Furthermore, the traffic light communication unit contains information

[2] The current thesis was conducted in the research project UR:BAN Urbaner Raum: Benutzergerechte Assistenzsysteme und Netzmanagement, funded by the German Federal Ministry of Economics and Technology (BMWi) in the frame of the third traffic research programme of the German government.

about the GPS traces of the different driving lanes. This information is used to match the defined GPS traces to the current GPS position of the approaching vehicle in the track and by that determine the traffic light for the relevant driving direction. Depending on the surrounding environment (buildings, curves etc.), the information can be transmitted up to 1000 m in front of the intersection. The current settings considers approach areas up to 400 m as reasonable range in urban environments.

The Adam Opel AG developed an on board algorithm in the progress of the UR:BAN project. The algorithm is responsible for the prediction of the traffic light state at arrival at the intersection. The algorithm receives information from the roadside unit at the traffic light and includes input from in-vehicle information about the current driving speed and driving behaviour. The latter is received from the CAN Bus, a network area connecting different control units in the vehicle. The algorithm then calculates the time and traffic light phase at arrival at the stop line. By this, it deduces a target driving strategy, identifies the current deviations from the target, and recommends necessary adaptations in driving behaviour (Figure 26). The update frequency of the traffic light assistant is 5 Hz, i.e. every 200 s the dynamic system calculates a new target value. The assistant is dynamic, i.e. it adapts to the actual driving behaviour of the individual driver. As mentioned in Tulusan, Soi, Paefgen, Brogle, and Staake (2011), the feedback system therefore results in an information cycle: The system influences the driving behaviour, and the driving behaviour influences the output of the system.

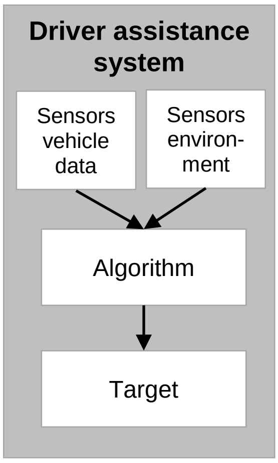


Figure 26. Schematic depiction of the functioning of the traffic light assistant.

The traffic light assistant has two main goals. First, drivers should adapt their driving behaviour so that they do not need to stop at the intersection. Figure 27 shows speed profiles as expected without and with the traffic light assistant. The information about the traffic light phasing is extended by time, distance and/or quality. With the recommendations of the traffic light assistant, driving behaviour can be adapted so that the traffic light is green at arrival at the intersection. Efficiency of driving increases by avoiding strong accelerations and decelerations and reducing variability of driving speeds. Second, in cases of unavoidable stops, the traffic light assistant supports drivers with an efficient initiation of the stop (Figure 28). Based on the outputs of the algorithm the traffic light assistant concludes that a safe crossing of the intersection is not possible within the current speed limits. This information is earlier available than in unassisted driving. As outlined above, efficient stops are associated with less strong decelerations and an earlier reduction in driving speed.

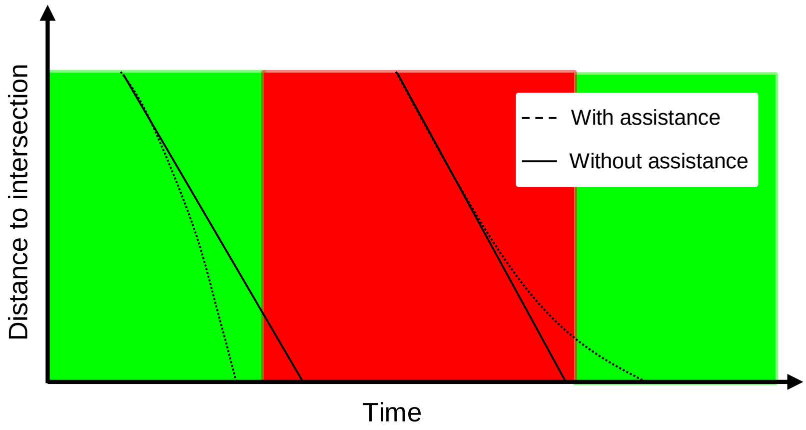


Figure 27. Visualisation of example profiles with and without traffic light assistant for the support in achieving a green light (adapted from Rakha & Kamalanathsharma, 2014).

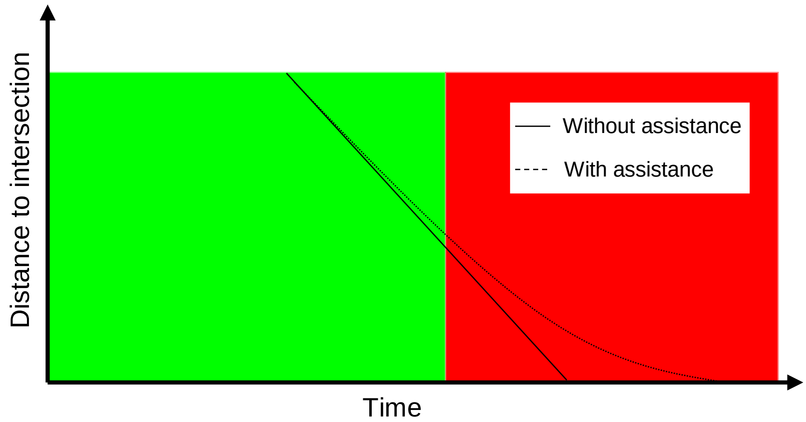


Figure 28. Visualisation of an example profile with and without traffic light assistant for the support in approaching a red traffic light (adapted from Rakha & Kamalanathsharma, 2014).

3.2.1.3 Influences on the interaction between road users

Traffic is a social system with frequently occurring interactions between road users. Therefore, researchers have investigated the effectiveness and acceptance for driver assistance systems in interaction with other road users. Qian (2013) pointed out that the evaluation of the effects of an efficient driving style needs to take place in a global perspective considering the effects that a single driver has on other road users, especially following road users. For example, Li and Gao (2013) stated that the future of driver assistance for efficient driving lays in the synchronisation of driving behaviours. By means of a traffic simulation tool, they investigated fuel consumption for six vehicles in a platoon in which either only the lead vehicle followed an efficient driving style or all vehicles shared the speed information of the lead vehicle. Fuel consumption improved by more than 4 % in the synchronised condition compared to conditions without information sharing. Also, positive effects on efficient driving in mixed platoons have been reported, even though the penetration rates were low (Xia, Boriboonsomsin, & Barth, 2013). In a traffic simulation study Sanchez, Cano, and Kim (2006) showed that when only the leading car of a platoon of 10 cars was equipped with a traffic light assistant, overall fuel consumption was reduced by 30% compared to the condition driving without any assistant. Contrary, Qian and Chung (2011) conducted traffic simulations in which eco-driving profiles in an intersection scenario were investigated. They pointed out that the benefits of eco-driving strongly depend on penetration rates and that eco-driving can have negative influences on the environmental performance in congested traffic. Other researchers argued that in congested traffic conditions drivers' attention is on safe driving rather than efficient driving. Therefore, the potential for efficient driving is reduced when drivers are not in a free flow driving situation (Wu et al., 2011). Hence, based on the dynamic characteristics and influences vehicles have on each other, the effects of efficient driving can be modified in platoon driving compared to free driving.

In addition, interactions between car drivers are characterised by limited communication structures and an egocentric perspective of the individual road user (Maag, 2013). Anger or even aggressive episodes in driving occur frequently and drivers experience expressions of anger or driving behaviours representing other drivers' anger (Underwood, Chapman, Wright, & Crundall, 1999). Conflicts between road users at traffic light intersections especially occur when different drivers come to different decisions on how to approach the current intersection (Liu, 2006). In the warning context it has been shown that there can be negative influences on surrounding vehicles when drivers incorrectly interpret warning information (Armand et al., 2013). Therefore, the emotional climate has been introduced as an evaluation criterion for a driver assistance system (Maag, 2013). It is expected that emotional reactions of drivers and the expectations about emotional reactions of surrounding drivers influence the acceptance of the traffic light assistant. In turn, decreasing acceptance for the traffic light assistant or recommended driving behaviours will reduce drivers' willingness to comply with the recommendations. Cristea et al. (2012) reported from their questionnaire study that social pressure played an important role when drivers decided to stick to the speed limits in order to apply an efficient driving style. They pointed out that the beliefs on other drivers' expectations and driving behaviours influence their own driving behaviour in terms of speed choice and time headways.

Even in case of a fast introduction of the Car-to-Infrastructure technology to the market, the penetration rates of the traffic light assistant will be mixed for a considerable period. During that time, road users equipped with traffic light assistant will interact with road users not equipped with a traffic light assistant. This situation creates a discrepancy of knowledge that drivers have of the upcoming right of way rules at the intersection. Drivers without traffic light assistant conclude on the required driving behaviour based on the currently visible traffic light state. Drivers with traffic light assistant conclude on driving behaviour based on the enhanced information they receive from the assistance system. Hence, different drivers approaching the same intersection come to different conclusions on appropriate driving behaviour based on different quality and reliability of the data from the environment (Iglesias et al., 2008). The resulting diverging driving behaviours represent a potential for negative emotional reactions and conflicts between road users. In turn, the frustrating situations experienced during conflicts with other road users can lead to aggressive or dangerous driving behaviours like tailgating or red light violations (Deffenbacher, Lynch, Oetting, & Swaim, 2002; Guéguen, Meineri, Martin, & Charron, 2014; David Shinar, 1998; Stephens & Groeger, 2014).

In a driving simulator study Mühlbacher (2013) investigated the influence of a traffic light assistant on the anger experience of four drivers driving in a platoon. The penetration rates for the traffic light assistant were either 0, 25, 50, 75 or 100 %, i.e. between 0 and all drivers were equipped with the traffic light assistant. The experimental setting controlled the order of the vehicles in the platoon. The results showed that in mixed penetration rates of the traffic light assistant the number of anger events reported by the drivers in the platoon was higher compared to a more homogenous penetration rate. The highest number of anger events occurred, when two drivers received information from the traffic light assistant while the two other drivers in the platoon did not drive with traffic light assistant. The lowest number of anger events occurred, when no driver had a traffic light assistant, i.e. when all drivers drove unassisted. Figure 29 shows the occurrence of an anger episode: The traffic light assistant recommended driving with 50 km/h while the lead vehicle decelerated to less than 30 km/h. Hence, the anger episode took place, when a driver with traffic light assistant was hindered in sticking to the recommendations. Additionally, the results also showed that anger occurred when drivers did not understand why others decelerated or drove slower than normal when approaching the green traffic light.

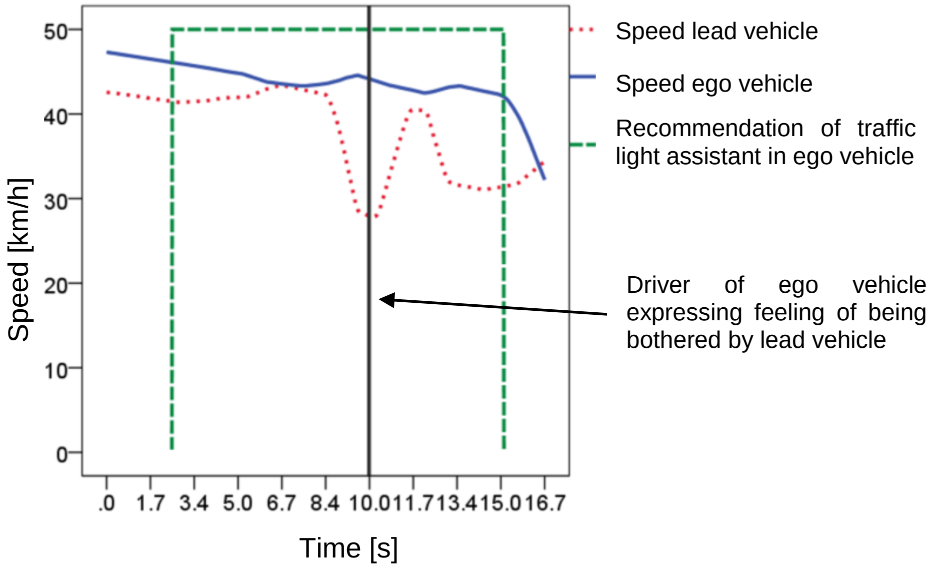


Figure 29. Scenario in which the driver of the ego vehicle receives a speed recommendation (50 km/h) from the traffic light assistant and expresses his feeling of being bothered by the lead vehicle (vertical black line; Mühlbacher, 2013).

In summary, it is expected that the dynamic and social characteristics of platoon driving influence the efficiency of a traffic light assistant system. Along with that, drivers who are not equipped with a traffic light assistant might experience anger when they interact with drivers equipped with a traffic light assistant, even though there is a chance that they benefit from the behaviour of an equipped lead vehicle. The presented study by Mühlbacher (2013) focused on the expression of anger episodes. In addition, based on previous driving experiences drivers might anticipate negative emotional reactions of other road users because of their own deviations from their usual driving style. These expectations might in turn influence the willingness to use the traffic light assistant, which could reduce the beneficial effects of the system.

3.2.2 Study 2: Interaction between road users[3]

Study 2 investigates driving behaviour when driving with a traffic light assistant. The study has two main parts that both take place in a multi-driver simulator setting. The multi-driver simulator allows that real drivers interact in controlled virtual environments.

The focus of the first part is the influence of situation and system parameters on the interaction between road users. Research has shown that benefits for the reductions in fuel consumption and emission rates can be reached when the traffic light assistant is activated up to 600 m in front of the intersection (Tielert et al., 2010). Additionally, the initial system algorithm allows for driving recommendations within the whole speed frame of 0 km/h to the maximum allowed speed limit (50 km/h). Depending on the traffic situation, the system might therefore recommend very low driving speeds at very large distances to the driver. While this might be the most efficient way to approach the intersection, it might also decrease the drivers' acceptance and willingness to comply with the recommendations.

The literature review showed that traffic is a social system. Based on the results of Study 1, it is expected that the traffic light assistant changes normal driving behaviour. The traffic light assistant allows for time shifts in information processing and response execution. The acceptance for the traffic light assistant might therefore not only depend on the experienced impact on one's own driving behaviour, but also on the expected impact on other road users. At the first introduction of the system to the market, there will be mixed penetration rates. Hence, road users driving with traffic light assistant will interact with road users who are not equipped with the traffic light assistant. As outlined above, there will be a discrepancy of knowledge about the upcoming traffic situation at the lights and a discrepancy of assumptions on the appropriate driving behaviour. For road users without traffic light assistance, the difference between desired driving speed and actual driving speed could come along with the experience of anger (Stephens & Groeger, 2014). Drivers with traffic light assistant might have the expectations of bothering other road users because of their driving behaviour. These emotional expectations on other drivers' reactions might lead to less compliance to the traffic light assistant. An important aspect when considering driver compliance is whether drivers

[3] Parts of this study are published in Rittger, Muehlbacher, Maag, and Kiesel (2015), Muehlbacher, Rittger, and Maag (2014) and Rittger, Muehlbacher, and Kiesel (2014).

have to stick to the recommendations of the traffic light assistant or whether they can follow the recommendations whenever they want.

In conclusion, in the first part of Study 2, drivers approach traffic light intersections in a platoon of four drivers. Half of the drivers are equipped with a traffic light assistant, because previous research has shown that greatest influences on driver interaction appear with mixed equipment rates (Mühlbacher, 2013). Different positions in the platoon are realised for each driver. Participants driving with traffic light assistant receive different instructions on the obligation to stick to the recommendations. The traffic light assistant is activated either 200 m or 400 m in front of the intersection. The main research questions are: Under which situational circumstances and system states do participants driving with a traffic light assistant feel that they are bothering other road users? In which situational circumstances and systems states are participants less compliant to the recommendations of the traffic light assistant? Under which situational circumstances and system states do participants driving without traffic light assistant express that they feel angered by other road users?

The second part of the study aims on identifying what minimum driving speeds are acceptable for drivers when receiving recommendations from the traffic light assistant and how drivers themselves perform an efficient approach to a red traffic light (“speed threshold drive”). Therefore, drivers approach traffic light intersections with the instruction to drive the minimum acceptable driving speed for passing a green light. Further, they approach red traffic lights by applying their own assumption of efficient initiations of stops. This covers some basic questions for the parameterisation of the algorithm of the traffic light assistant and offers input for the improvements of the traffic light assistant. The results will be included in the thresholds and parameters, in order to adapt the system towards driver’s comfort and high acceptance.

In Figure 30 the bold frames highlight the factors considered in Study 2. The traffic light phasing, the presence and the position of surrounding vehicles represent the variations in the road environment. The second part of Study 2 covers specific parameters of the algorithm of the traffic light assistant. During the drives in the first part of Study 2, the traffic light assistant recommends different target speeds and behaviours. The distance at activation of the traffic light assistant varies the start of the recommendations. Consistent with Study 1, the dynamic driving behaviour measures the driver’s response execution. Additionally, button presses at the steering wheel operationalise the feelings of anger and bother.

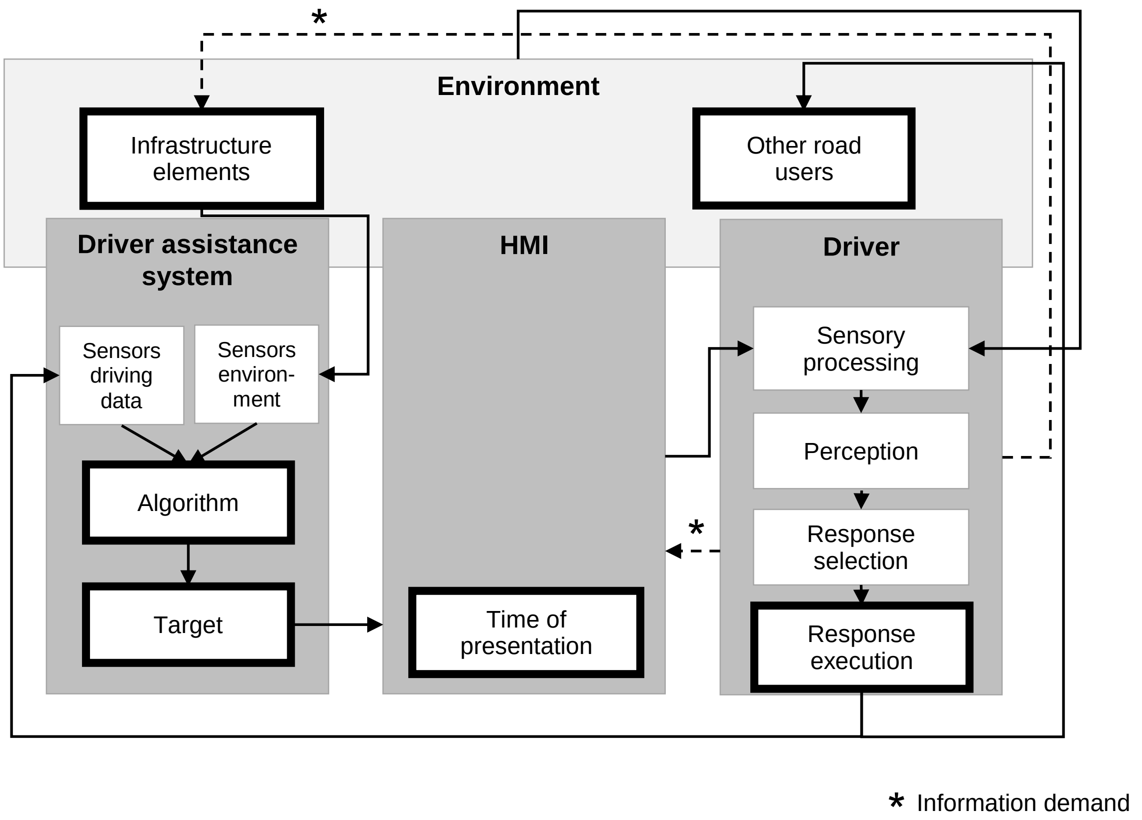


Figure 30. Relation of the factors considered in the present thesis. Bold frames indicate factors investigated in Study 2. Adapted from Bruder and Didier (2012), Popiv (2012), Schmidtke and Bernotat (1993), Wickens and Hollands (2000) and Zarife (2014).

3.2.2.1 Methods

Participants

44 participants (28 female) took part in the study. Due to technical problems, the HMI display of one driver did not correctly show the driving recommendations. Data of the respective platoon of four drivers were not included in the analysis and the experimental condition was repeated with a different platoon. Hence, the following descriptions include data of 40 participants. All 44 drivers were included in the analysis of the subjective preferences for the HMI design. The mean age was 38.6 years (sd = 15.8). The recruited participants belonged to the WIVW test driver panel and were well experienced with driving in the multi driver simulator. No driver had previous experience with a traffic light assistant. All participants had normal or corrected to normal vision.

Apparatus

The study took place in the multi driver simulator at WIVW. The multi driver simulator consisted of four driving stations that were used simultaneously in the experiment.

Hence, four drivers drove at the same time in the same virtual environment. No simulated traffic was present. Each driving station consisted of three 22” LCD displays with a resolution of 1680x1050 pixels, offering a 150° horizontal field of vision. The left display represented the field of vision as experienced in the left window, including the left side mirror. The middle and right display depicted the windscreen view, including the centre and right side mirror. All mirrors had a size of 11x6 cm. An additional 10” LCD display with 800x400 pixels positioned next to the steering wheel showed the HMI of the traffic light assistant. The simulator ran with the SILAB software. The data recording took place with 60 Hz. The mock-ups consisted of steering wheels with force feedback and a commercially available pedal system. The vehicle included automatic transition. Therefore, drivers only used accelerator and brake pedal. There were two levers at the left and the right side of the steering wheel, which could be pulled comfortably with index and/or middle finger. Curtains separated the driving stations so that drivers could not see each other (Figure 31). During the study, participants wore headsets with which they could hear the vehicle motor sound. The headsets also enabled the individual communication between driver and experimenter. Two experimenters supervised the test drives. One experimenter operated the simulator while the other took care of the communication with the participants.

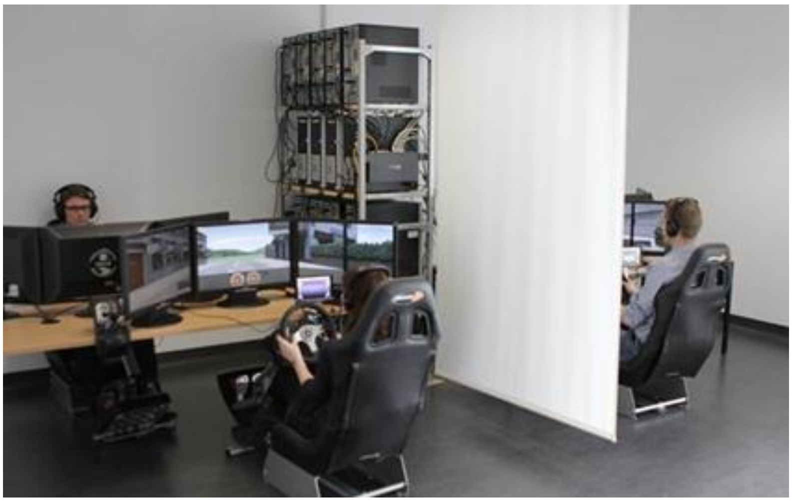


Figure 31. The multi driver simulator. Three of the four driving stations are visible in the picture.

For the subjective evaluation of driving with the traffic light assistant, a questionnaire consisting of 10 statements was used. Drivers expressed their agreement to the statements on a scale from 1 (do not agree at all) to 7 (totally agree). Three further questions about the start distances for the different recommendations were included, to which drivers could either agree or disagree.

Traffic light assistant

The algorithm considered the duration of the current and the next traffic light phase and driver's speed and distance to the traffic light. Based on that the algorithm calculated target speeds. First, the goal was to guide drivers to achieve the required driving speed to pass the green light without a stop. Only speed reduction scenarios were included. In order to pass the intersection at green and without a stop, the scenarios required that drivers reduced speed sharply by braking to 30 km/h and subsequently reducing speed by coasting to around 20 km/h. Second, when drivers could only arrive at the intersection at red, the goal was to guide drivers to follow a predefined speed profile to initiate the stop. This included decreasing driving speed by braking to around 30 km/h and subsequently coasting to 0 km/h by releasing accelerator and brake pedal. Shortly before arriving at the stop line, the system recommended braking to 0 km/h in order to make drivers press the brake pedal while waiting at the red light. The update frequency of the traffic light assistant was 5 Hz.

The HMI screen presented the recommendations of the traffic light assistant. They contained a combination of action and speed suggestions. Action recommendations were either coast, brake or drive. Speed recommendations were either 0, 20 or 30 km/h. The threshold for achieving a certain speed was 5 km/h. For example, when the recommendation was to drive 20 km/h, the driver was in the correct mode as long as he drove between 15 and 25 km/h. The recommendations contained text in German with distinctive colours (Figure 32).

Figure 32. Driving recommendations in the HMI display. "Drive" was depicted in green, "coast" was depicted in white, and "brake" was depicted in amber. The original recommendations contained German text ("Fahren", "Ausrollen", and "Bremsen").

Design

The experiment had a mixed between-within subjects design. The between subjects variables were system equipment and instruction condition. The within subjects variables were position in the platoon and start of the recommendations of the traffic light assistant.

Two of the four drivers in each platoon drove with a traffic light assistant whereas two did not receive recommendations. Participants received individual instructions. Drivers without traffic light assistant were instructed to pull the lever at the steering wheel whenever other road users angered them. These drivers did not know about the existence of a traffic light assistant in other vehicles within the platoon. Drivers with traffic light assistant were instructed to pull the lever whenever they had the feeling of bothering other road users. These drivers did not know whether other vehicles in the platoon also received the recommendations from a system. In every second platoon, the drivers with traffic light assistant were instructed to always stick to the recommendations ("must" condition). In the other half of the platoons, drivers with system were instructed that they could stick to the recommendations whenever they wanted ("can" condition). Drivers did not know about any of the instructions the other three drivers in the group received.

Every participant could drive in any of the four positions in the platoon. Four different orders were realised during the experiment (Figure 33). The four orders were defined so that every driver experienced driving at each of the four positions, that the drivers with system always followed drivers without system and vice versa, and that the combinations of lead and following vehicle differed. Finally, the recommendations of the traffic light assistant started either at 200 m or at 400 m in front of the intersection.

The dependent variables of the experiment consisted of objective and subjective data (see Table 7 for an overview). The driving simulator software recorded the objective data.

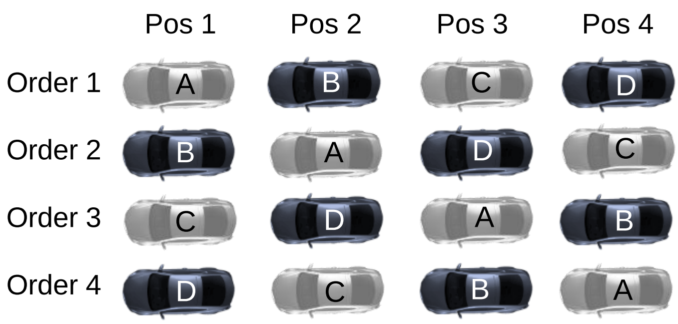


Figure 33. Four orders were realised during the experiment. Vehicles A-D represent to the four drivers of one platoon. Drivers A and C received recommendations from the traffic light assistant. Drivers B and D did not drive with traffic light assistant.

Table 7. Overview of the dependent variables recorded in the experiment.

Dependent variable	Unit	Description
Speed	km/h	Speed with which the vehicles proceeds
Coasting time	%	Percentage of time drivers coasted during a specific traffic light approach area
HMI activation	s	Duration of the presentation of a specific driving recommendation in the HMI
Lever pull	Pull vs. no pull	Occasions when drivers pulled the lever at the steering wheel; drivers with traffic light assistant expressed bother experience by lever pulls, drivers without traffic light assistant expressed anger experience by lever pulls
Questionnaire item agreement	1 = do not agree, 7 = totally agree	Nine questionnaire items for which drivers expressed their agreement: I drove uninterrupted; I was bothered by drivers in front; I was influenced by drivers in front; The ride was fun; I was bothered by drivers following me; I was influenced by drivers following me; Others hampered me to drive like I wanted; I was very attentive; I paid lots of attention to other road users One question that the experimenter explained to the drivers and they expressed their agreement: If other drivers knew that I had a traffic light assistant, I still would have felt like bothering them (for drivers with system); If I had known about the traffic light assistant in other drivers I would have still be angered by them (for drivers without system)
Questionnaire item agreement	Yes vs. no	Three questions only for drivers with traffic light assistant focused on the start distance for the specific driving recommendations: I would stick to drive 20/coast to 20/coast to 0/brake to 30 if the recommendation was given 100 m/200 m/300 m in front of the intersection A list of information units for drivers with traffic light assistant asked which information unit was desirable for the HMI of a traffic light assistant

Test track and procedure

Each participant received instructions about the objectives of the study, while the other three participants were waiting in a separate room. They did not talk to each other about their instructions. During the instructions, they drove a short practice track without any surrounding traffic, in order to practice pulling the lever at the steering wheel and to get to know the basic layout of the urban test track. In the experimental drive, the four participants drove in the same virtual environment. The test track consisted of 16 traffic light intersections resulting from a repetition of the eight different conditions (two start distances combined with four platoon positions). The order of the 16 traffic light approaches was randomised and the same for all platoons of drivers. The traffic light approaches were about 600 m long and participants always drove straight. All intersections had the same X-junction layout. The traffic in the track consisted of the four vehicles without any further road users. Driving through the test track took around 30 min. The traffic light phasing was according to German road traffic regulations. In the scenarios, drivers either had to reduce speed in order to cross the intersection at a green light, or they had to reduce speed to initiate an efficient stop at red. For scenarios in which the traffic light changed to green during the approach, the red phase was between 40 and 52 s long. Drivers could only reach the traffic light without a stop when sticking to the driving recommendations given in the HMI screen. For scenarios in which drivers had to stop at red, the traffic light was red for the whole approach time and changed to green after drivers waited in front of the traffic light. There were eight green and eight red traffic lights in the track. After completing each traffic light approach, the order of the vehicles in the platoon changed. For that, drivers approached a traffic sign showing their next position in the platoon (Figure 34). As soon as all participants parked in the correct position, the platoon started for the next traffic light approach, with the very left vehicle starting first and the very right vehicle following on the last position.

After completing the test drive, the experimenters unravelled the objectives of the experiment and explained the goals of the traffic light assistant to all four drivers in the platoon. Subsequently, the experiment continued with the speed threshold drive (see chapter 3.2.2.3). Before the session ended, the experimenter supported the participants with filling in the questionnaire. Overall, the experiment took approximately two hours.

Figure 34. Traffic sign showing the position of the vehicles in the platoon. Drivers parked in the required position and subsequently started the next section of the test track from left to right (also see Mühlbacher, 2013).

3.2.2.2 Results

If not stated differently, data from 10 platoons with overall 40 participants were included in the analyses. 20 participants drove without traffic light assistant, 20 participants drove with traffic light assistant. Of the latter, 10 received the recommendation to stick to the recommendations whenever possible, while 10 received the recommendation that they can stick to the recommendation whenever they wanted.

Percentage of stops

To determine how well drivers performed in achieving the major target of the traffic light assistant, the percentage of traffic light approaches with stops at the traffic light was determined for each condition. In the scenarios, drivers either could cross the intersection at green by adapting speed or initiated an efficient stop at red. Based on that, the deviation from predicted percentage of stops as planned from the structure of the scenarios and the actual percentage of stops for each condition was identified. It was assumed that the predicted value was identical for drivers with and without assistant. Reaching a driving speed of less than 1 km/h defined a stop. An ANOVA included the deviation of actual percentage of stops from predicted percentage of stops as dependent variable. The between factors were system equipment (with, without system) and instruction (“can”, “must”), the within factors were notification distance (200 m, 400 m) and position in the platoon (1, 2, 3, 4). Table 8 summarises the results.

Drivers with traffic light assistant crossed the intersection without stop more often compared to drivers without assistance system. When the recommendations started at 200 m in front of the intersection, the deviation from the predicted percentage of stops was lower compared to the 400 m start condition. The more on the back of the platoon participants drove, the lower was the deviation between predicted and actual percentage of stops. In drivers without traffic light assistant, the difference in the percentage of stops between the 200 m and 400 m start condition was larger compared to drivers with assistant. The interaction between notification distance and instruction was hybrid. With that, the main effect for notification distance was interpreted globally. In the 200 m condition, there were less stops in the “must” condition compared to the “can” condition. In the 400 m condition, there were more stops with “must” compared to “can” instruction. The interaction between position and notification distance expresses that the increase in the number of avoided stops from position 1 to position 4 was stronger when the recommendations started 400 m in front of the intersection compared to the 200 m condition. Concluding from the four-way interaction, least stops occurred when drivers received recommendations from the system at 400 m in front of the intersection when driving in the fourth position and being instructed to stick to the recommendations whenever they wanted. The highest number of stops occurred when drivers without system were in the first position of the platoon in the 400 m start condition (Figure 35).

Table 8. Summary of ANOVA results for the deviation of actual percentage of stops from predicted percentage of stops. Bold numbers mark significant effects.

Effect	Df effect	Df error	*F*	*p*	$\eta^2_{partial}$
System (SYS)	**1**	**36**	**8.142**	**.007**	**.184**
Instruction (I)	1	36	0.686	.413	.019
Notification distance (ND)	**1**	**36**	**99.858**	**<.001**	**.735**
Position (P)	**3**	**108**	**13.754**	**<.001**	**.276**
I x SYS	1	36	0.008	.927	.000
ND x SYS	**1**	**36**	**8.736**	**.005**	**.195**
P x SYS	3	108	0.708	.549	.019
ND x I	**1**	**36**	**9.299**	**.004**	**.205**
P x I	3	108	1.010	.391	.027
P x ND	**3**	**108**	**3.424**	**.020**	**.087**
I x ND x SYS	1	36	0.971	.331	.026
I x P x SYS	3	108	0.785	.505	.021
ND x P x SYS	**3**	**108**	**4.457**	**.005**	**.110**
I x ND x P	3	108	.900	.444	.024
SYS x I x ND x P	**3**	**108**	**2.849**	**.041**	**.073**

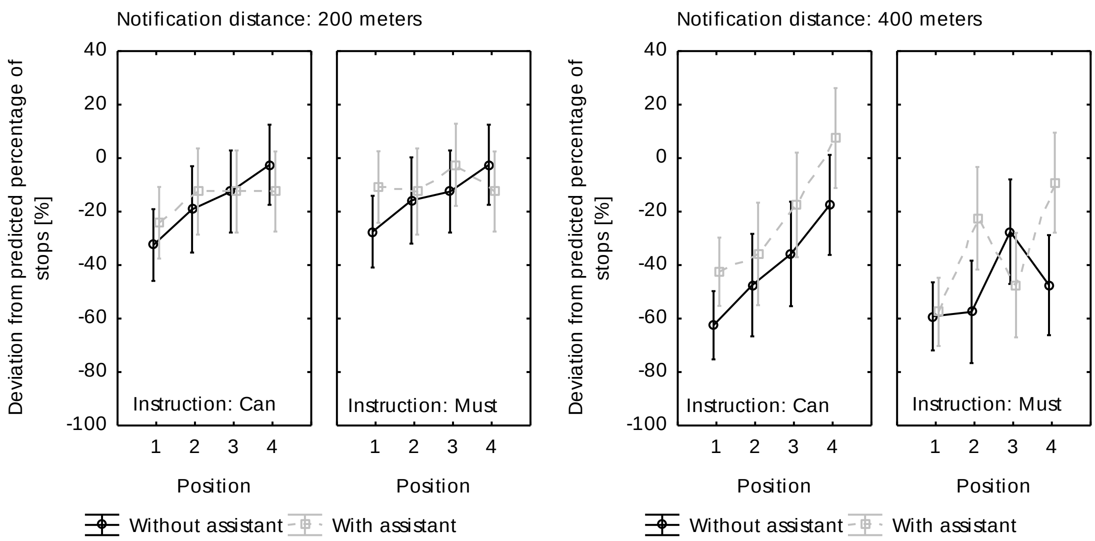


Figure 35. Deviation of percentage of observed stops from percentage of predicted stops in the different factor combinations. Graphs show means with 95% confidence intervals.

Feeling of bothering others

Drivers with traffic light assistant expressed their feeling of bothering other drivers by pulling the lever at the steering wheel. The number of traffic light approaches in which drivers with traffic light assistant pulled the lever was related to the total amount of traffic light approaches in each condition. An ANOVA included this relation as a dependent variable. To investigate the influence of the distance to the intersection, the traffic light approaches were separated into the distance sections 0-200 m and 200-400 m in front of the intersection. Hence, the ANOVA model consisted of four variables: The between subject variable instruction (“can”, “must”) and the within-subject variables notification distance (200 m, 400 m), position in the platoon (1, 2, 3, 4) and distance section during the approach (0-200 m, 200-400 m). Table 9 presents the ANOVA results.

There were significant main effects for the factors instruction, notification distance and position. Drivers expressed the feeling of bothering others more often in the “can” compared to the “must” condition and when the recommendations started 400 m in front of the intersection compared to the 200 m condition. Post-hoc tests showed that drivers expressed significantly less often that they feel like bothering others when driving in the fourth position compared to all other positions in the platoon (all *ps* <.028) and when driving in the third compared to the second position in the platoon (p = .028).

Table 9. Summary of ANOVA results for the percentage of traffic light approaches with lever pull to express the feelings of bothering others. Bold numbers mark significant effects.

Effect	**Df effect**	**Df error**	***F***	***P***	**$\eta^2_{partial}$**
Instruction (I)	**1**	**18**	**20.098**	**<.001**	**.528**
Notification distance (ND)	**1**	**18**	**36.699**	**<.001**	**.671**
Position (P)	**3**	**54**	**12.203**	**<.001**	**.404**
Distance section (DS)	1	18	3.860	.065	.177
ND x I	1	18	3.315	.085	.156
P x I	3	54	1.713	.175	.087
DS x I	1	18	.095	.762	.005
ND x P	3	54	.816	.491	.043
ND x DS	**1**	**18**	**18.051**	**<.001**	**.501**
P x DS	**3**	**54**	**3.195**	**.031**	**.151**
ND x P x I	3	54	.420	.739	.023
ND x DS x I	**1**	**18**	**8.294**	**.009**	**.315**
P x DS x I	3	54	.133	.94	.007
ND x P x DS	3	54	1.825	.154	.092
I x ND x P x DS	3	54	1.069	.370	.056

Figure 36 depicts the interaction effects. Drivers only pressed the button to express the feeling of bothering others when the traffic light system was active. When the system recommendations started 200 m in front of the intersection, hardly any driver pressed the button between 200 – 400 m. Between 0 – 200 m, the differences in lever pulls between positions in the platoon was exaggerated compared to the 200 – 400 m distance section. Positions one and two resulted in higher numbers in lever pulls compared to positions three and four. The three-way interaction between notification distance, distance section and instruction does not limit the global interpretation of the explained effects.

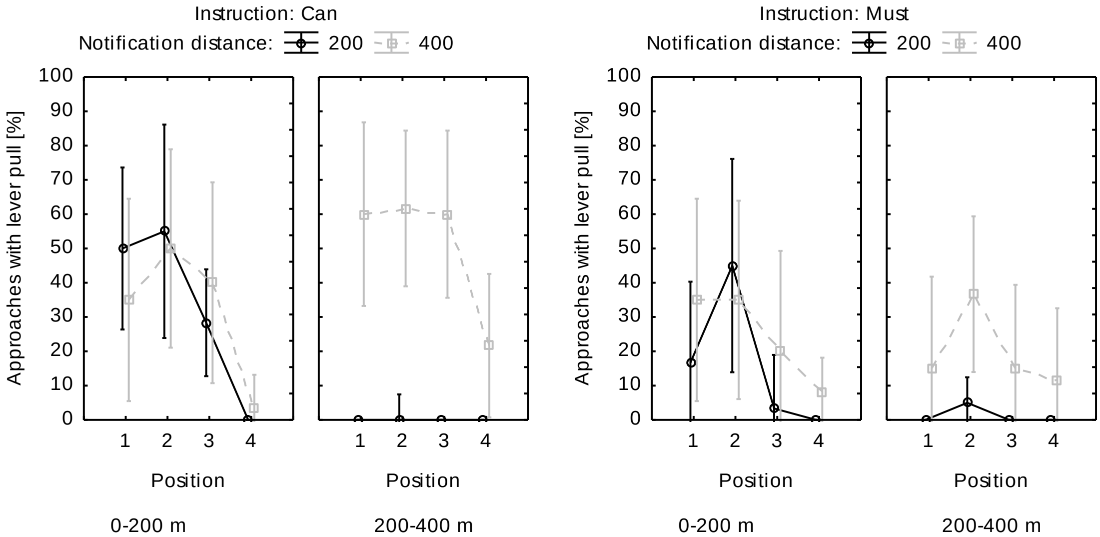


Figure 36. Mean percentage of traffic light approaches with lever pulls to express the feeling of bothering others by participants driving with traffic light assistant in relation to the factors position in the platoon, notification distance and distance section in front of the intersection differentiated for the factor instruction (left and right). Graphs show means with 95% confidence intervals.

Influence of the type of recommendation

The relation between number of lever pulls in drivers with traffic light assistant and the type of recommendation the drivers received was investigated. First, the total activation time of each of the five recommendations during the 16 traffic light approaches was determined for each participant and averaged over participants (Figure 37). The duration of the recommendation presentation differed based on the algorithm of the traffic light assistant and based on participants compliance with the recommendations. The “drive 20 km/h” recommendation was presented as long as participants actually drove between 15 and 25 km/h. Hence, it only varied within a traffic light approach when drivers were faster or slower than these margins. The “coast to 20 km/h” recommendation was presented until drivers reached the speed of lower than 25 km/h and could therefore represent a measure of drivers’ compliance in the respective situations. The “coast to 0 km/h” recommendation was presented as long as drivers reached a speed lower than 10 km/h. The coasting episodes could last over large parts of the traffic light approach. Therefore, the “coast to 0 km/h” recommendations achieved long presentation durations. The “brake to 30 km/h” recommendation was presented to prepare further coasting episodes and could be realised rapidly by the drivers, which led to short presentation durations. Finally, the “brake to 0 km/h” recommendation was active while drivers were waiting in standstill and therefore resulted in long presentation durations.

Second, the number of times at which at least one lever pull occurred while a specific recommendation was active was identified. For each participant and type of recommendation, the number of episodes in which a lever pull occurred was related to the total time spent with activated recommendation. Figure 37 presents the resulting ratios. Additionally, in a within subjects ANOVA the independent variable was the type of recommendation; the ratio was the dependent variable. The ratio differed according to the type of recommendation, $F(4,76) = 11.409$, $p < .001$. $\eta^2_{partial} = .375$. The “coast to 20 km/h” recommendation led to significant more lever pulls than all other recommendations (all *ps* <.033). During the “coast to 0 km/h” recommendation, drivers pulled the lever significantly more often compared to the “brake to 0 km/h” recommendation ($p = .016$).

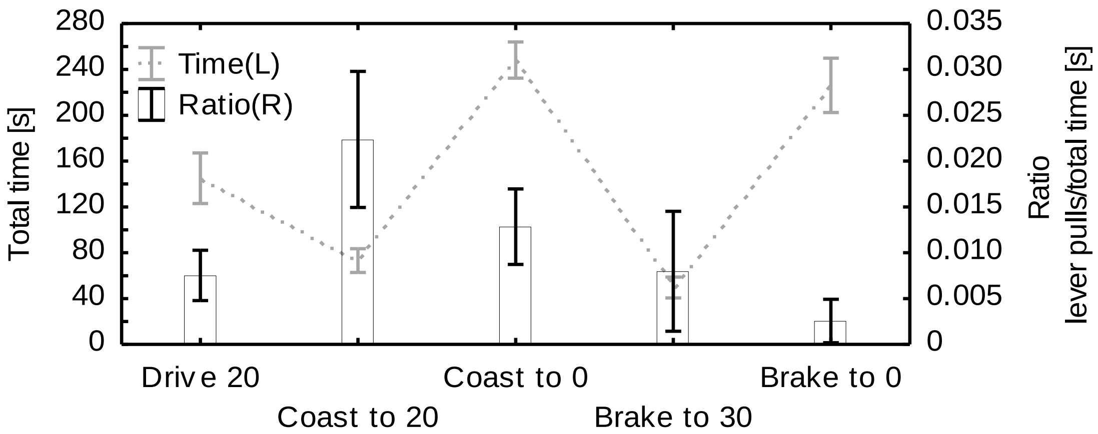


Figure 37. Total time with activated recommendation (left axis) and ratio of number of episodes with at least one lever pull in relation to total activation time (right axis) of the five different recommendations. Graph shows means with 95% confidence intervals.

Feeling angry about others

Participants driving without traffic light assistant expressed their feeling of being angered by others by pulling the lever at the steering wheel. The number of traffic light approaches with lever pull was related to the total number of traffic light approaches in each condition. The traffic light approaches were separated in two distance sections. An ANOVA was conducted, with the between-subjects factor instruction (“can”, “must”) and the within-subjects factors notification distance (200 m, 400 m), position in the platoon (1, 2, 3, 4) and distance section during the approach (0-200 m, 200-400 m). The variables instruction and notification distance varied in drivers with traffic light assistant and the impact of the variations was assessed for drivers without traffic light assistant. Table 10 presents the ANOVA results. Figure 38 depicts the interaction effects.

Table 10. Summary of ANOVA results for the percentage of traffic light approaches with lever pull to express anger about other road users. Bold numbers mark significant effects.

Effect	Df effect	Df error	*F*	*p*	$\eta^2_{partial}$
Instruction (I)	1	18	3.728	.069	.172
Notification distance (ND)	**1**	**18**	**15.886**	**<.001**	**.469**
Position (P)	**3**	**54**	**11.389**	**<.001**	**.388**
Distance section (DS)	1	18	4.366	.051	.195
ND x I	1	18	2.179	.157	.109
P x I	3	54	2.516	.068	.123
DS x I	1	18	4.366	.051	.195
ND x P	**3**	**54**	**3.928**	**.013**	**.179**
ND x DS	**1**	**18**	**10.407**	**.005**	**.366**
P x DS	3	54	1.672	.184	.085
ND x P x I	3	54	.432	.737	.023
ND x DS x I	1	18	.15	.703	.008
P x DS x I	3	54	.786	.507	.042
ND x P x DS	**3**	**54**	**3.747**	**.016**	**.172**
I x ND x P x DS	3	54	1.203	.318	.063

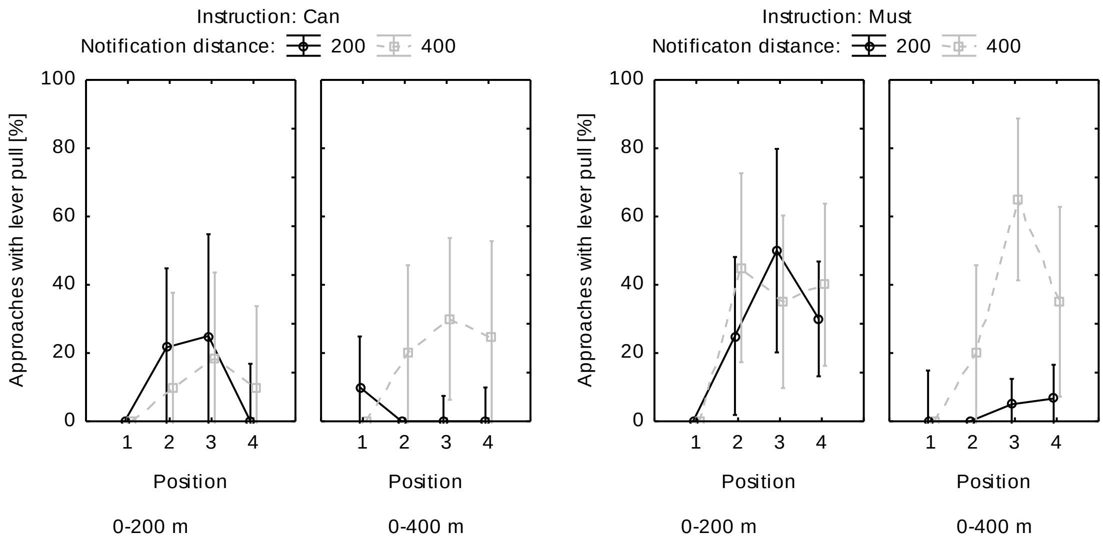


Figure 38. Mean percentage of traffic light approaches with lever pulls to express the feeling of being angered by others by participants driving without traffic light assistant in relation to the factors position in the platoon, notification distance and distance section in front of the intersection differentiated for the factor instruction (left and right). Graphs show means with 95% confidence intervals.

Drivers more often expressed being angered by others when the recommendations started 400 m in front of the intersection compared to the start at 200 m. Participants expressed being angered less often when driving in the first position of the platoon compared to the second, third and fourth position of the platoon (all *ps* < .006).

The difference in lever pulls between the two notification distance conditions was exaggerated when drivers were in the distance section 200-400 m and when driving in the positions two to four. When the recommendations started 200 m in front of the intersection, hardly any driver pulled the lever between 200-400 m in front of the intersection.

Relation between bother and anger feelings

The investigation of the relation between anger and bother feelings contains the number of traffic light approaches with lever pulls for drivers following each other. First, the number of traffic light approaches was identified in which participants driving with traffic light assistant in the first, second and third position of the platoon pulled the lever. Second, from these traffic light approaches, the number of approaches was determined, in which the directly following driver without traffic light assistant in the second, third and fourth position pulled the lever, too (to express his anger about others). Table 11 shows the data for three pairs: a driver with system on position one followed by a driver without system on position two, a driver with system on position two followed by a driver without system on position three and a driver with system on position three followed by a driver without system on position four.

Overall, in 40.4 % of the traffic light approaches in which a driver with system expressed the feeling of bothering others the directly following driver also expressed the feeling of anger about other drivers. Table 11 shows again that drivers pressed the button more often when receiving the instruction that they “can” stick to the recommendations compared to the “must” condition. As well, drivers more often had the feeling of bothering others when receiving the information 400 m in front of the intersection compared to when receiving the information 200 m in front of the traffic light. When a driver with assistant drove in the second position, he most often expressed that he had the feeling of bothering others and the following driver most often expressed that he was also bothered. In this situation, the driver in the third position saw that the first vehicle proceeded as expected, and only the second one was blocking. For drivers without traffic light assistant driving in the third and fourth position the measurement cannot distinguish between the feeling of being angered by only the directly leading vehicle or the feeling of being angered because of the drivers in front of the leading vehicle.

Table 11. Number of traffic light approaches with lever pull of participants driving with traffic light assistant in positions one, two and three of the platoon and percentage of traffic light approaches in which the directly following participant without traffic light assistant also pulled the lever to express anger about others.

Independent variable		**Number of approaches with lever pull of drivers with system []**			**Proportion of approaches with pairs pulling the lever [%]**		
Instruction	**Notification distance**	**Position 1**	**Position 2**	**Position 3**	**Pair 1/2**	**Pair 2/3**	**Pair 3/4**
“Can”	**200**	12	9	8	41.66	33.33	0.00
	400	12	21	11	33.33	42.85	36.36
“Must”	**200**	4	6	1	0.00	83.33	0.00
	400	7	13	5	57.14	76.92	80.00

Subjective evaluations

Drivers evaluated driving in the group of four drivers and driving with the traffic light assistant. Figure 39 shows the results, differentiated for drivers with and without system. For drivers with system the graph differentiates between the two instruction conditions “can” and “must”. T-tests for independent groups compared drivers with and without traffic light assistant. Both groups consisted of statements by 20 participants. T-test for independent groups were conducted to compare the two different instruction conditions, with n=10 for each group. Deviations in degrees of freedom occurred when a driver did not respond to a specific statement.

No differences in the level of agreement between the groups occurred in the following statements: “I drove uninterrupted”, “I was influenced by drivers in front of me”, “the ride was fun”, “I was influenced by drivers following me”, “I was very attentive”, and “I paid lots of attention to other road users”. Participants experienced that they drove quite easily through the track, felt that the drivers in front of them influenced them and expressed a medium level of fun during the ride. The influence of drivers following themselves was low and participants drove very attentive. Finally, drivers expressed that they paid lots of attention to other road users.

Statement 7 (“others hampered me to drive like I wanted”) showed that participants without traffic light assistant subjectively felt more hindered by others than participants driving with traffic light assistant, $t(37) = -2.103$, $p = .042$. Drivers without traffic light assistant were also more bothered by drivers in front of them (statement 2), $t(38) = -2.276$, $p = .029$. Drivers with system were more bothered by drivers following them (statement 5) compared to drivers without traffic light assistant, $t(38) = 2.248$, $p = .030$.

Statement 2 reveals that in the “must” condition, participants were less bothered by drivers in front of them than drivers in the “can” condition, $t(18) = -2.193$, $p = .042$.

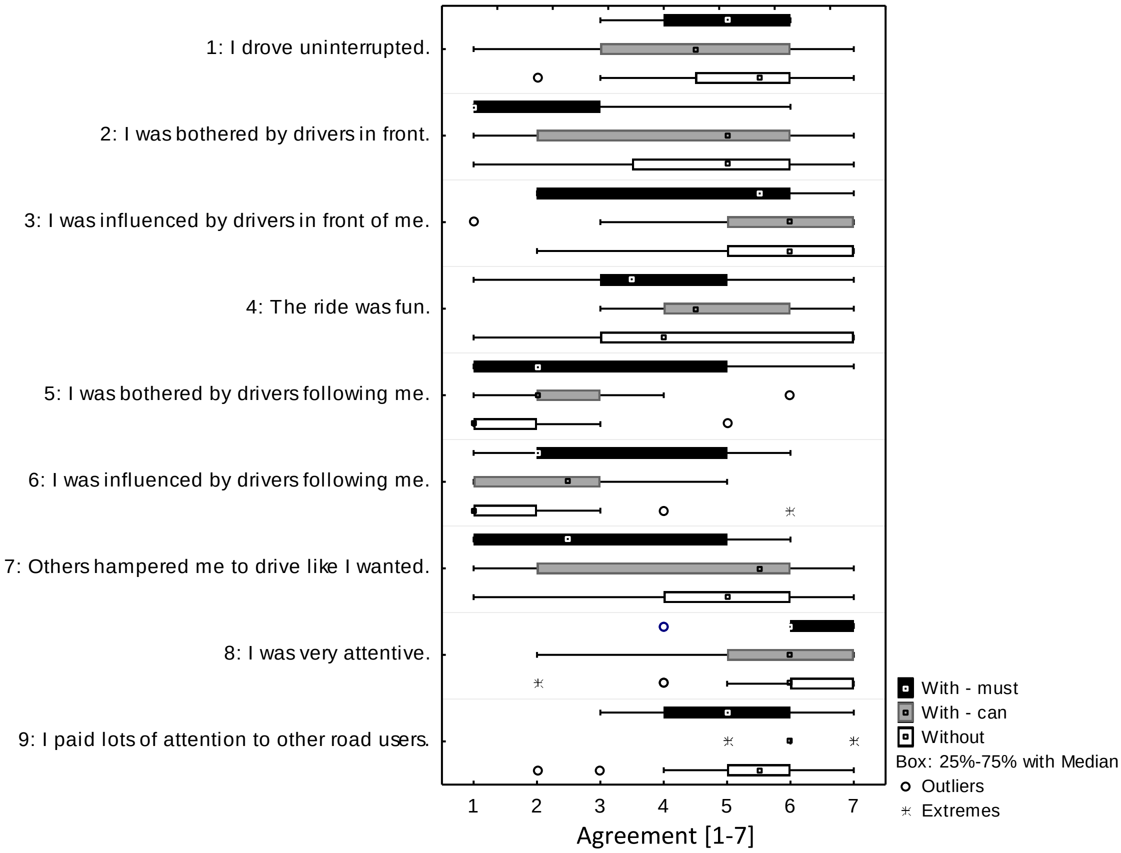


Figure 39. Participants’ responses to nine statements on a scale from 1 (do not agree) to 7 (totally agree). Graph shows boxplots with median [n=40].

After the test drive, the experimenter asked the participants to imagine that cars had an information at the back of the vehicle, for example a sticker, informing about the existence of the traffic light assistance in the vehicle. Participants driving without traffic light assistant stated whether they still felt anger about vehicles in front in case they would have known about the assistance system in these vehicles. Participants driving with traffic light assistant stated whether they still felt like bothering others in case the other road users would have known about their system. The agreement to this statement was medium high for both groups of drivers and showed large variations, $p = .917$ (Figure 40).

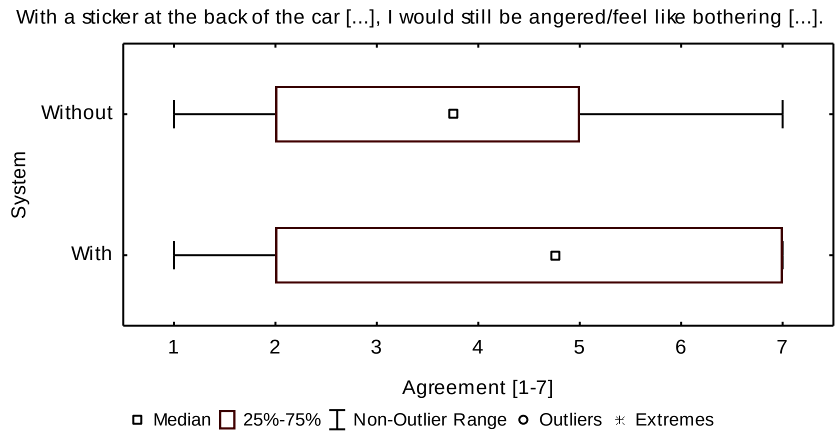


Figure 40. Participants' agreement to the statement: "If other drivers knew about the assistance system, I still would have been angered by others/ feeling like bothering others". 1 indicates that their bother/anger would have been reduced. 7 indicates that their anger would have been the same. Graph shows boxplots with median [n=40].

Participants who had experienced the traffic light assistant during the experiment answered whether they would stick to the specific recommendations in real traffic when the recommendations started 100 m, 200 m, or 300 m in front of the intersection. Data of all 22 participants who received instructions for the traffic light assistant were included. Figure 41 shows the number of participants agreeing that they would stick to the respective recommendations.

In general, when the distance to the traffic light increased, drivers' willingness to stick to the recommendations decreased. The most accepted recommendation for all distance sections was the "brake to 30 km/h" recommendation. A reason for that might be that drivers experienced during the test drive that the "brake to 30 km/h" recommendation initiated a sequence of recommendations and a variety of other recommendations could follow (e.g. "coast to 20 km/h", "coast to 0 km/h").

Finally, drivers who had previously experienced the traffic light assistant chose from a list of information units. The list contained information units that could possibly occur in the HMI of a traffic light assistant. The participants chose the desirable information units. Figure 42 shows the results. The most desired information units were the duration of the current traffic light phase, speed recommendations and action recommendations.

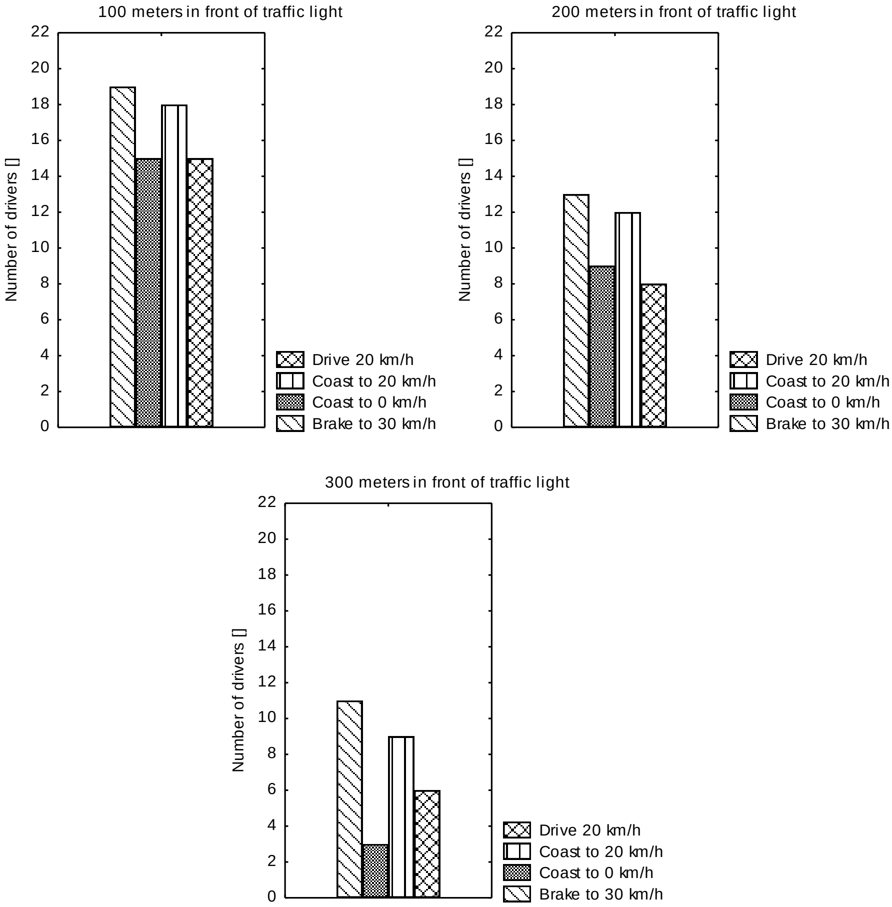


Figure 41. Number of drivers expressing that they would stick to the respective recommendation in case it started 100 m, 200 m and 300 m in front of the intersection [n=22].

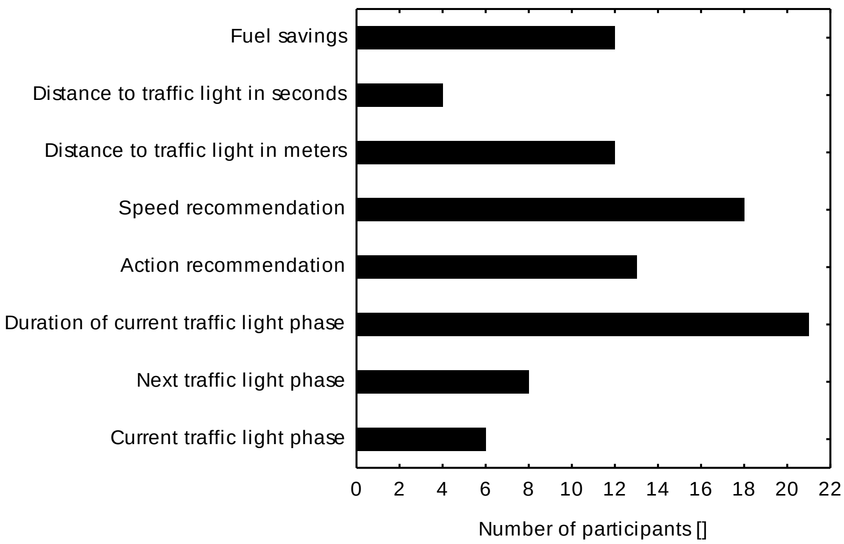


Figure 42. Number of participants evaluating the respective information unit as desirable for a depiction in the HMI of the traffic light assistant [n=22].

3.2.2.3 Speed threshold drive

Methods

After completing the main part of the experiment, drivers were instructed that there was an additional short test track, in which they drove each in their own virtual environment without traffic light assistant. The track consisted of two traffic lights that were green and subsequently two traffic lights that were red. The intersections had the same layout as the intersections in the main test track. For the green traffic lights, all drivers were instructed to choose the minimum driving speed that they would accept as a recommendation from a traffic light assistant. For the red traffic lights, drivers were supposed to choose an approach strategy that would be most efficient in their point of view. In one of the two green traffic light approaches and in one of the two red traffic light approaches, there was a simulated vehicle following the participant. A traffic sign placed around 400 m in front of the intersection indicated the start of the traffic light approach. At this point drivers could start adapting their driving behaviour in preparation for the upcoming traffic light.

Results

The data analysis based on the 400 m traffic light approach. Figure 43 left shows the speed profiles for the four traffic light approaches. When drivers approached the green traffic lights, they reduced speed to on average of approximately 35 km/h. When approaching a red traffic light, drivers showed a continuous reduction in speed to approximately 25 km/h, before initiating the stop by strong deceleration.

Figure 43 right shows boxplots for the minimum driving speed drivers chose. On average, drivers did not reduce their driving speed below around 35 km/h during the approach of solid green lights. The median for the minimum speed drivers chose was slightly below 30 km/h. No differences in minimum driving speed occurred between traffic light approaches with and without following vehicle for the green light condition, $t(39) = 1.754$, $p = .087$, and for the red light condition, $t(39) = .655$, $p = .143$. No differences in minimum driving speed occurred between drivers who had previously experienced the traffic light system and drivers who had not previously experienced the traffic light assistant, $t(38) = .221$, $p = .484$. Naturally, the minimum driving speed when approaching red lights was 0 km/h.

When approaching the red traffic lights, the majority of drivers chose to coast in order to drive efficiently. Figure 44 shows the percentage of time drivers coasted, determined by the episodes during which the participants used neither the accelerator nor the brake pedal. When approaching the red traffic lights, drivers coasted most of the time. No differences in the percentage of time spent with coasting occurred between the two green traffic light approaches, $t(39) = .354$, $p = .725$, and no differences occurred between the two red light approaches, , $t(39) = .908$, $p = .37$. No differences in the time spent with coasting occurred between drivers who had driven with traffic light assistant in the previous experimental test run compared to drivers who had not received recommendations, $t(38) = .655$, $p = .516$.

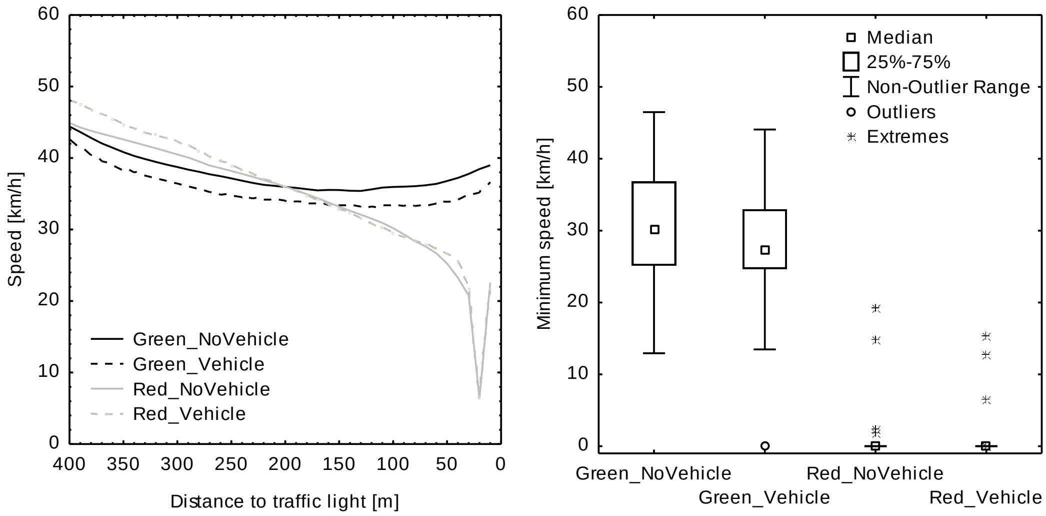


Figure 43. Mean speed (left) and minimum driving speed (right) drivers chose when approaching the traffic light intersections with the instruction to reduce speed to the minimum acceptable level when the traffic light was green (with and without following vehicle) and to approach in the most efficient way when the traffic light was red (with and without following vehicle).

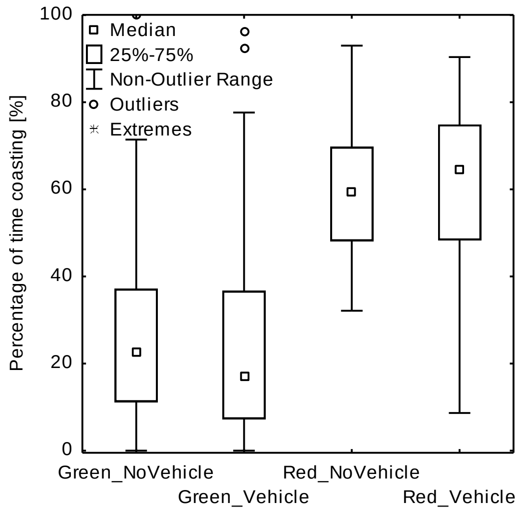


Figure 44. Percentage of time coasting when approaching the traffic light intersections with the instruction to reduce speed to the minimum acceptable level when the traffic light was green (with and without following vehicle) and to approach in the most efficient way when the traffic light was red (with and without following vehicle).

3.2.2.4 Summary and discussion

Study 2 investigated drivers' emotional reactions and system compliance depending on traffic conditions and system parameters of the traffic light assistant. The multi-driver simulator setting allowed for the investigation of interactions between real drivers in a controlled laboratory setting.

In general, driving with the traffic light assistant has the potential to improve efficiency when approaching intersections. Drivers with traffic light assistant were more likely to cross the intersection without stop than drivers who did not receive the recommendations. However, the results showed that certain conditions reduced the efficiency of the traffic light assistant. Drivers were less compliant to the system when driving in the front positions of the platoon. The influence of position was stronger, when the recommendations started in greater distance to the traffic light. The beneficial effects of an early start of the recommendations at 400 m in front of the intersection were only realised when drivers were in the back positions of the platoon. Naturally, drivers without traffic light assistant benefited from drivers with system driving in front of them.

The emotional reactions measured in the study could explain the decreasing compliance to the recommendations in certain situations. The traffic light assistant has the potential to induce anger in drivers without assistant and the feeling of bothering others in drivers with traffic light assistant. The feeling of bothering others related to system activation; drivers only expressed the feeling of bothering others in distance sections in which the traffic light assistant was activate.

Drivers without assistant were especially angered when driving in the back positions of the platoon and when the system turned on at far distances to the traffic light. Drivers with system especially felt like bothering others in the front positions of the platoon, i.e. when a larger number of drivers was following them. In addition, the feeling of bothering others was expressed more often when the recommendations started at far distances to the intersection compared to close distances. The coast recommendations had the highest potential to trigger the feeling of bothering others. A reason might be that with the recommendations “coast to 20 km/h” and “coast to 0 km/h” the deviations from the maximum speed limit were largest. Further, the traffic light assistant presented the recommendations consecutively. It might be that drivers expressed their feeling of bothering others in the “coast to 20 km/h” situation and did not repeat it afterwards (when for example “drive 20 km/h” followed). Compared to that, the higher acceptance for the “brake to 30 km/h” expressed in the questionnaire could demonstrate a general acceptance for the 30 km/h as lower speed limit.

While the instruction on the obligation to stick to the recommendations did not influence driving behaviour, the feeling of bothering others occurred more often when the instruction was that drivers “can” follow compared to “must” follow the assistant. It is assumed that in the “must” condition, drivers attributed their adapted driving behaviour to the system. Therefore, they felt less like bothering others with “must” instruction than with “can” instruction. In the “can” condition, they decided themselves to drive as recommended by the system, which might have made themselves feel more responsible for bothering others. The lever presses then served to express that drivers, even though they followed the recommendations, did not feel comfortable with it.

The results revealed that drivers with assistant more often expected to bother drivers than the directly following drivers expressed that they were angered. Even though there are conditions in which drivers with and without traffic light assistant both pressed more often (e.g. when recommendations started 400 m compared to 200 m in front), the feeling of bothering others does not necessarily come along with the feeling of being angered by others. However, it is the expectation on negative emotional reactions by others that might reduce the benefits of the system. This shows that considering the emotional reactions in the dynamic situations is an important evaluation criterion. Furthermore, increasing drivers acceptance for the system based on that criterion is necessary to achieve the maximum benefits. A possible solution to the discrepancy between the self-perception and the perception others have might be to inform others about the traffic light assistant in the vehicles. Research has shown that anger in others can be larger when drivers do not see the reasons for the reductions in driving speed of the lead vehicle (Stephens & Groeger, 2014). Supporting this, in the current setting, the percentage of lever pulls because of anger and bother that occurred together was highest in situations in which drivers without assistant experienced two drivers in front, one with modified and one with expected driving behaviour (in the third position in which drivers with and without assistant preceded in the second and first position). In these situations, the contrast between desired and actual driving behaviour was largest and there was no obvious reason for the lead vehicle to drive slowly. The participants’ answers showed that the sticker at the back of the vehicle could potentially reduce anger and bother. The sticker could emphasise that even without traffic light assistant, one could benefit from following a lead vehicle with traffic light assistant. More information exchange and elucidation on other drivers’ motives and backgrounds could address the egocentric perspective that drivers have when interacting in traffic.

In addition, even though the efficiency benefits are largest when the recommendations started in 400 m distance to the intersection, the results showed that subjective acceptance might increase with a reduction of the start distance. This is especially recommended in conditions with busy traffic. Along with that, the speed threshold drive showed that drivers only accept a minimum threshold of 30 km/h for the recommendations of the traffic light assistant. The future algorithm should consider this. Interestingly, drivers coasted to initiate an efficient stop at red. For stops, drivers seem to have a correct assumption on how to apply an efficient driving style, as long as they can be sure that the light remains solid red until arrival at the intersection.

As preparation for the HMI versions of the traffic light assistant, the questionnaire showed that the three preferred information units are speed recommendations, action recommendations and information on traffic light phasing. The preference for action and speed recommendations might not be surprising, as this were the units presented in the test drives. Nevertheless, drivers confirmed the applicability of this information. The further development of the HMI concept will consider traffic light phase information.

In summary, emotional reactions and driving behaviour showed situations in which it is difficult for drivers to stick to the recommendations. The expectation on other drivers' reaction to one's own driving behaviour could explain the lower system compliance. For the parameterisation of the traffic light assistant, it is important to aim for a trade-off between maximum efficiency and maximum driver acceptance in order to maximise drivers' willingness to stick to the recommendations of the traffic light assistant and by that maximise its beneficial effects.

3.3 HMI concept for traffic light assistance

3.3.1 Theoretic background

3.3.1.1 HMI information strategy

The traffic light assistant communicates with the driver via the Human Machine Interface (HMI). Hence, the HMI represents a major part of the experience drivers have with the system. The major human factors challenge in the development of the traffic light assistant is the depiction of information in the HMI. Consequently, researchers and developers have stated requirements for the place of presentation, the form of presentation, the time of presentation, and the information content (Bruder & Didier, 2012; Popiv, 2012; Schmidtke & Bernotat, 1993). This includes the questions on where the HMI presents information, how the HMI presents information, when the HMI presents information, and which information the HMI should present.

The place of information presentation in the vehicle is limited to available technologies (e.g. availability of display concepts like the head-up display). Further, considerations on the place of presentation include decisions on the modality of communication (i.e. visual, auditory or haptic). The traffic light assistant represents a mere information system. When the driver does not stick to the recommendations, no safety critical situation or safety disadvantage occurs compared to unassisted driving. From the perspective of the introduction of the system to the market, it is important to keep the number of auditory outputs (especially for information systems) small. Visual information also offers the possibility to present detailed information by using multiple codes (e.g. colour, symbols, and text). Along with that, visual information is presented as long as the system is active, which allows drivers to re-evaluate the information multiple times. Krause, Knott, and Bengler (2014) showed, that the combination of visual and acoustic information presentation for a traffic light assistant did not influence driving and gaze behaviour compared to a mere visual presentation. Thus, for the HMI strategy discussed in the present thesis, the focus on visual information presentation is adequate. Furthermore, Bley et al., 2011 recommended the presentation of speed related information near the speedometer in order to facilitate the acquisition and comparison of the different visual information units. Based on the higher consciousness of the driving task, it might be that driving with the traffic light assistant leads to increases in attention to the driving speed depicted in the speedometer. The presentation of the information of the traffic light assistant close to the speedometer prevents additional visual effort by comparing different display locations.

Questions on the form of presentation concern the design of the depicted information. For visual information presentation in in-vehicle displays, graphic designs for the relevant information units need to be defined and evaluated. For example, in the HMI of a traffic light assistant, Krause, Knott, and Bengler (2014) compared different sizes for the depiction. Increased display sizes led to reductions in glance durations, while the percentage of time the drivers attend to the display did not decrease. In general, the graphic designs in the HMI should correspond to specific guidelines and requirements for display design (e.g. for the meaning of colours), which were not the focus of the present thesis. For the implementation of graphics in the present experiments, graphic designers were consulted.

Requirements for the timing of information contain aspects like reaction times for perception of information, decision making and performing the required action. Importantly, the type and design of the presented information should improve driver's awareness of the relations between actions and environmental events. The information should show clearly, if and how the preconditions for future actions are reached (Noyes, Masakowski, & Cook, 2012; Popiv, 2012). In addition, Popiv (2012) mentioned that information for anticipatory driver assistance systems should be presented in a continuous manner. Hence, during activity of the traffic light assistant in the intersection approach, the information presentation of the traffic light assistant should be active. As outlined before, the major benefit of the traffic light assistant is that information is available earlier than drivers usually see or anticipate the traffic light phase. Therefore, from a technical point of view, the information should be presented as soon as available (the limitation is the technical communication range between vehicle and infrastructure). Contrary, from a human factors perspective, drivers could feel uncomfortable with long system interventions, especially when long coasting periods are necessary (Dorrer, 2004). Study 2 included the question about the distance of activation of the system in relation to driver's willingness to stick to the recommendations of the system.

Information content

The following paragraphs cover the definition of information content for the HMI display. Based on the technically available information of the traffic light assistant, the HMI can potentially present a large number of information units to the driver. The research on eco driving assistance systems in general and traffic light assistance systems in particular has reported different information contents. First, a simple solution is to inform drivers about the existence of an upcoming traffic light along with the current traffic light states. This is beneficial as long as the drivers cannot yet see the real traffic light in the track. The additional presentation of traffic light phase timings (i.e. the remaining duration of the current traffic light phase) further increases the anticipation of the upcoming driving situation. The expectation is that with this information, drivers are able to adapt their driving behaviour according to their interpretation of the relation between phase durations and necessary adaptations in driving behaviour (e.g. speed). As depicted in the example of Figure 45, presenting the phase durations does not include the actual required driving behaviour.

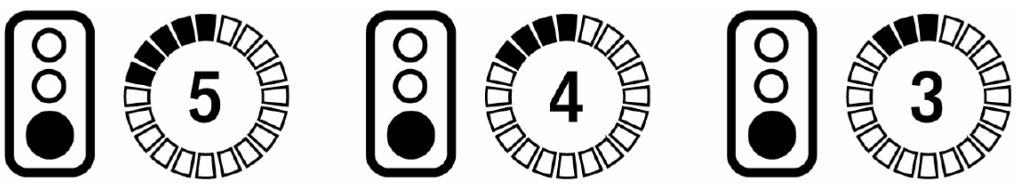


Figure 45. Information about the duration of the current traffic light phase (Thoma et al., 2007).

Second, drivers received action recommendations. From the literature, action recommendations have mostly been mentioned in eco-driving systems that included support for traffic light intersections amongst other traffic situations. For example, action recommendations can instruct the reduction in speed before curves or choosing the right acceleration when crossing slopes. Hence, for the traffic light approaches action recommendations might be particularly relevant when decelerations at traffic lights are necessary. Most frequently, action recommendations included symbolic depictions of the required action (Figure 46, left) and verbal prompts (Figure 46, right).

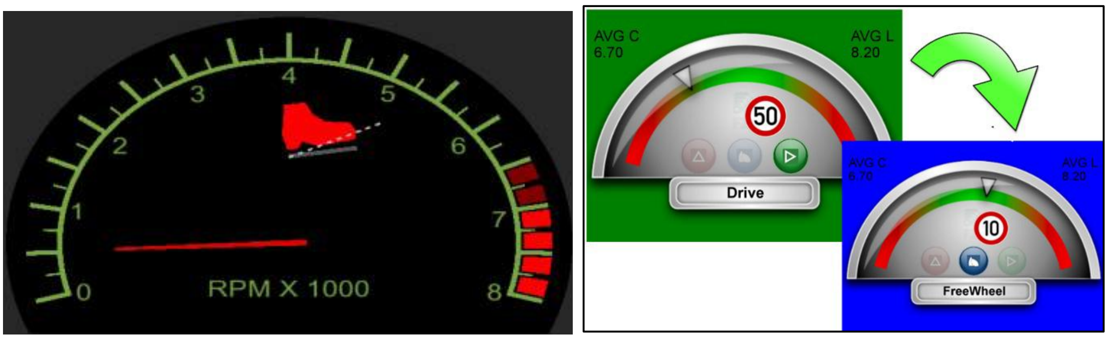


Figure 46. Action recommendations presented by a symbolic representation of the foot on the accelerator pedal on the left (here representing that pressure on the pedal is excessive and should be reduced; Jamson, Hibberd, & Jamson, 2015) and the text based presentation of the action recommendations “drive” and “freewheel” on the right (Bär, Kohlhaas, Zollner, & Scholl, 2011). Both versions include an additional colour coding.

Third, system developers used speed recommendations to present the information of the traffic light assistant. The speed recommendation communicates the required driving speed to cross the traffic light at green. There have been various concepts for the presentation of driving speed (e.g. Figure 47). These included for example marked areas in the speedometer or speed carpets, which involve minimum and maximum allowed driving speeds, or numeric presentation of the required speed (Krause & Bengler, 2012).

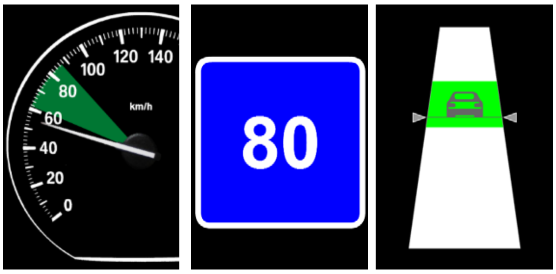


Figure 47. Different concepts for the presentation of speed recommendations. The left picture shows markings in the speedometer, the middle picture shows the target speed as recommended by the traffic light assistant, the right picture represents a speed carpet showing the driving speed for passing green including the current speed of the vehicle (Krause & Bengler, 2012).

Table 12 gives a summary of studies that reported the HMI concept for a traffic light assistance system and studies in which the eco or safety assistance system contained traffic light support. The summary does not include studies using traffic simulation tools (e.g. Ferreira & d'Orey, 2012). It further neither contains systems that used autonomous interference in longitudinal vehicle control (Bley et al., 2011) nor systems which interfere in dynamic driving behaviour solely by active pedals (Hjälmdahl & Várhelyi, 2004; Larsson & Ericsson, 2009). Evaluations of traffic light assistant systems that did not include a driving study (e.g. Wong, 2008) and driving studies on efficient driving that did not include traffic light intersections (Bär et al., 2011) were not inserted in the summary.

Table 12 shows that most research focused on the technical implementation of the traffic light assistant, without reporting an evaluation of the HMI concept. The studies reporting HMI investigation focused on the presentation of one specific information unit or the comparison of different graphic designs including the comparison with baseline drives. In some approaches, different information units were used for specific traffic light state conditions. For example, Fujimaki et al. (2012) divided the GLOSA feature in three sub-functions: a signal passing assist service, a signal stopping assist service, and a mild acceleration assist service. Depending on the sub-function, they suggested using different information units. An active signal passing assist presents speed recommendations, while a signal stopping assist indicates action recommendations. Georgiev (2013) compared different designs for presenting speed and traffic light phase information for a GLOSA application on a mobile device. He evaluated the presentation of the duration of the current traffic light phase only as reasonable, when the traffic light is currently red or changing to red soon.

Table 12. Summary of research reporting HMI concepts for a traffic light assistant.

Authors (year)	Information unit	Place of presentation	Comparison
Braun et al. (2009)	Traffic light information: countdown timer for red; speed recommendation	In-vehicle display	No HMI evaluation
Caird, Chisholm, and Lockhart (2008)	Traffic light information: red traffic light ahead; static action recommendation	Head-up display	Traffic light ahead vs. prepare for stop
Duivenvoorden, Schaap, van der Horst, Feenstra, and van Arem (2007)	Static speed recommendation	Road/ infrastructure and in-vehicle display	Speed for green wave in-vehicle vs. speed for green wave along the road vs. no speed recommendation
Fujimaki, Kinoshita, and Inoue (2012)	Speed recommendation; action recommendation	In-vehicle display	No HMI evaluation
Georgiev (2013)	Traffic light phase information: countdown timer for red and green; speed recommendation	Mobile device	Different graphic designs
Hoffmann (1991)	Speed recommendation	In-vehicle display	Different graphic designs
Hoyer (2012)	Traffic light phase information: countdown timer for red and green	Smartphone	No HMI evaluation
Kidwai et al. (2005)	Traffic light phase information: countdown timer for red	Road/ infrastructure	No HMI evaluation
Kosch and Ehmanns (2006)	Traffic light phase information: current state; speed recommendation for green lights; warning for red light violation	Head-up display	No HMI evaluation
Krause and Bengler (2012)	Speed recommendation; traffic light phase information: countdown timer for red	Smartphone	Different graphic designs for speed recommendations
Krause, Knott, and Bengler (2014)	Traffic light phase information: countdown timer for all phases; speed recommendation	Smartphone	Different screen sizes
Krause, Rissel, and Bengler (2014)	Traffic light phase information: countdown timer for all phases; speed recommendation	Smartphone	Personalisation of displayed information
Li et al. (2014)	Traffic light information: countdown timer for red	Road/ infrastructure	No HMI evaluation
Nestler, Duschl, Popiv, Rakic, and Klinker (2009)	Traffic light information: red traffic light ahead	In-vehicle display	No HMI evaluation

Table 12. Summary of research reporting HMI concepts for a traffic light assistant (continued).

Authors (year)	Information unit	Place of presentation	Comparison
Olaverri-Monreal, Gomes, Silveria, and Ferreira (2012)	Traffic light information: traffic light state	Head-up display	No HMI evaluation
Popiv, Rommerskirchen, Rakic, Duschl, and Bengler (2010)	Action recommendation	In-vehicle display	Different graphic designs
Rijavec, Zakovšek, and Maher (2013)	Traffic light information: countdown timer for all phases	Road/ infrastructure	No HMI evaluation
Rommerskirchen, Helmbrecht, and Bengler (2014)	Traffic light information: red traffic light ahead; action recommendation	In-vehicle display	No HMI evaluation
Thoma et al. (2007)	Traffic light information: countdown timer for red; speed recommendation	In-vehicle display	Countdown timer vs. different graphic designs for speed recommendations
Trayford and Crowle (1989)	Speed recommendation	Road/ infrastructure	No HMI evaluation
Trayford, Doughty, and van der Touw (1984)	Speed recommendation	In-vehicle display	No HMI evaluation
Wu et al. (2011)	Action recommendation	In-vehicle display	No HMI evaluation

Evidence for the benefits of the presentation of specific information units in the human factors context comes from systematic investigations in aviation research. Crocoll and Coury (1990) presented status information, action recommendations and the combination of status and action recommendations in an aircraft identification task. The results showed no difference between the display versions as long as the presented information was correct. However, when reliability dropped, performance in the recommendation group dropped more sharply compared to the performance in the status information group. One conclusion was that participants' compliance to the presented information was higher with recommendation information compared to status information. Barnett (1990) found no difference in performance between two levels of support for participants in an air controller context. However, participants felt more confident when using situation assessment aids (representing status information) compared to response aids (representing action recommendations). Sarter and Schroeder (2001) investigated command and status information for a decision support system in the aviation context. They concluded that both information levels led to good performance as long as the information was accurate. With decreasing reliability of the system information, status information should be preferred. Wickens and Hollands (2000) reviewed status and command displays and concluded that the command displays were especially helpful in conditions of high stress and time pressure (characteristics that certainly transfer to urban traffic at intersections). Rovira, Zinni, and Parasuraman (2002) presented different information units to assist operators in a system monitoring task. There was either information automation (information about the location of a malfunction, i.e. status information) or decision automation (information on the required correction, i.e. action recommendation). Additionally, the authors manipulated automation reliability. Again, differences between information and action recommendations were greater in cases of unreliable automation, with beneficial effects for the information automation compared to action recommendations.

In a driver assistance context, Lee, Gore, and Campbell (1999) compared message style of advanced traveller information systems (e.g. “icy road ahead” as notification style vs. “slow down” as command style). They concluded that command messages led to higher compliance in drivers than notification messages. For the presentation of driver warnings for obstacle situations, Cao et al. (2010) varied modality and level of assistance. The latter implicated either action suggestions (e.g. change lanes) or no action suggestions. The researchers concluded that messages with action suggestion were more beneficial in different subjective and objective measures compared to messages without action suggestions. The authors further remarked that for non-time critical situations, drivers might prefer to be informed early, but without action commands in order to decide about the appropriate driving behaviour themselves. Additionally, they recommended that when action suggestions are presented, they should be combined with relevant information about the situation. Finally, Kassner (2008) compared information and warning display in longitudinal warning situations. She concluded that the assistant including information showed the best driving behaviour, the highest traffic safety and the best subjective evaluations when compared to the assistant showing warnings with specific brake recommendations.

In summary, the literature from the aviation context shows a basic distinction between status and command information. The research from the driver assistance context uses terms like notification style or info-assistance to express that status information is given and terms like warning assistance to express that command information is given. In general, for command messages a higher level of automation is necessary compared to status information, because the system needs to integrate more information sources and parameters in order to recommend appropriate behaviour. The distinction between status and command information transfers to the information units relevant for the HMI concept of the traffic light assistant. Information on the traffic light phase represents status information. Drivers receiving that information need to interpret which driving behaviour is required. Speed recommendations represent an increased level of automation, because they inform drivers about the correct choice of speed. Finally, action recommendations transfer directly to command information, because they include concrete driving behaviours. For the choice of the correct driving behaviour, no interpretation of the given information is necessary. The literature shows that there might be a benefit for the driver performance during the presentation of action recommendations compared to status information. The research from the driver assistance context points towards subjective preference of status information. Study 3 aims to show whether this conclusion transfers to the traffic light assistant.

Presentation of multiple information units

Besides the direct comparison between different single information units, the combination of different information units is possible. Thereby, two opposing hypotheses are stated.

A classic effect in the research on divided attention is that participants respond faster to redundant compared to single stimuli (Egeth & Mordkoff, 1991; Kiesel, Miller, & Ulrich, 2007; Raab, 1962). Figure 48 visualises this effect: When multiple target stimuli are present, the reaction times for detecting the target decrease compared to the presentation of a single target stimulus.

The possible information units of the traffic light assistant are redundant to a certain extent. For example, an action recommendation to keep speed implies that the currently active speed is correct. The additional presentation of the target speed would be a redundant information. At the same time, in the described case, drivers assume that the traffic light assistant recommends the behaviour in order to guide drivers through the traffic light at green. The additional presentation of an arrival at green information would be redundant information. Hence, in case the redundancy gains found in the stimulus processing and attention research transfer to HMI displays in the dynamic driving situation, it is expected that driver performance improves when multiple information units are presented compared to the presentation of a single information unit. A related hypothesis would be that the gaze durations for gaining the information of the traffic light assistant reduce, because drivers understand the required behaviour faster.

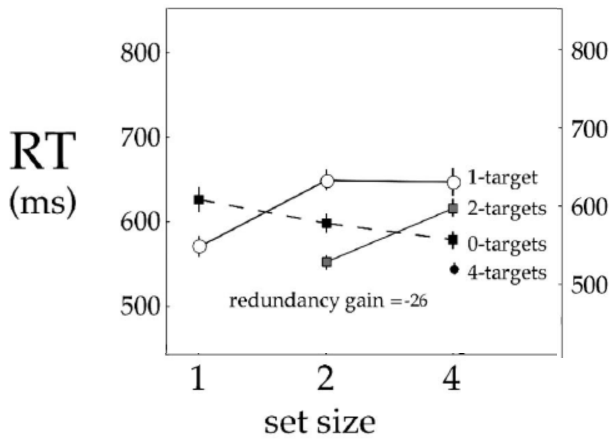


Figure 48. Redundancy gain shown for 1-4 targets in different set sizes. The presence of more than one target led to reductions in reaction time (Thornton & Gilden, 2007).

On the contrary, when the number of information units presented in the in-vehicle display increases there might be the danger of overloading the driver. Based on the classic resource model of Wickens (2008), the extent to which two tasks use the same resource defines how well both tasks can be performed simultaneously (Figure 49). Ideally, the secondary task of following the traffic light assistant should be designed so that it draws on “residual capacities” that are available next to the primary driving task (Wickens, 2008). Overload occurs when task demands exceed the available mental capacities (e.g. when a complex traffic situation requires different behaviour than the recommendation of the assistant). As a consequence, performance will break down (Green, 2008; Oberholtzer et al., 2007; Wickens & Hollands, 2000; Wickens, 2008) and the primary task of driving cannot be performed as required. Hence, when the driver is not able to prioritise his tasks adequately and adapt to an increased workload, the worst consequence would be safety critical driving behaviour. In line with this, Wickens and Hollands (2000) outlined that the decision quality does not necessarily increase with increasing number of information sources. Moreover, driving is predominantly a visual task and information presented in in-vehicle displays draws on the visual processing resources. Besides the potential conflicts in the execution of driving behaviour, the presentation of more information in the display could distract drivers from the primary visual field. More information units could relate to longer processing times and with that to longer periods of time in which drivers’ attention is allocated to the traffic light assistant display instead of the road environment. This leads to conflicts in visual processing capacities.

In summary, previous research on traffic light assistance focused on the three information units traffic light phase information, speed recommendations and action recommendations. Study 2 showed that drivers subjectively prefer these information units. There has not yet been a systematic investigation of the benefits of each information unit by comparing them within a single experiment. Besides the benefits of the presentation of each single information unit it is crucial to determine, whether a combination of information units is beneficial or leads to driver overload.

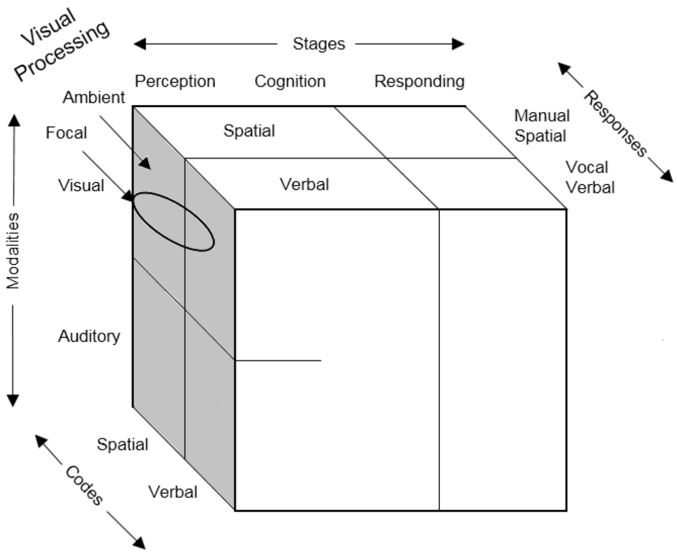


Figure 49. The 4-D multiple resources model by Wickens (2008).

3.3.1.2 Safety aspects in efficient driving

While driving, drivers have multiple goals. At any point in time these goals might conflict (e.g. safety, target speed, efficient driving). Driving behaviour is then planned according to the appraisal of these conflicts (Groeger, 2000). In general, researchers have assumed that increases in efficiency of driving come along with increases in driving safety (Barkenbus, 2010; Nouveliere, Mammar, & Luu, 2012; Young, Birrell, & Stanton, 2011). This implies that the two goals do not conflict. Haworth, Symmons, and Bureau (2001) reported that the fuel consumption of vehicles that were involved in crashes was higher than the fuel consumption of vehicles that were not involved in crashes. After drivers received an eco-driving training, fuel consumptions decreased by around 11 %, emissions by up to 50%, and accidents around 35%. Others showed that accident rates dropped by around 40% after drivers received an eco-driving training, while fuel consumption improved by over 50% (Hedges & Moss, 1996; cited in Young et al., 2011).

Contrary, other researchers explained that drivers might neglect driving safety when using a support tool for efficient driving (Wu et al., 2011) and that eco-driving feedback increased drivers workload with affecting mental demand, effort and frustration (Lee, Lee, & Lim, 2010). Also, it might be that the eco-driving information could lose its optional character and have an increasing affordance for the driver to attend to the information (Kircher, Fors, & Ahlstrom, 2014). For approaching traffic light intersections in particular, a potential critical behaviour are red light violations, which represent a serious danger to road safety (Green, 2003).

In general, different evaluation criteria are able to estimate the impacts of a traffic light assistance system and the HMI concept on safety. The major guidelines for the design of in-vehicle information systems distinguish between safety critical and non-critical gaze behaviour in the interaction with the system. The background of these guidelines is that the in-vehicle information competes with the driving task over limited visual resources (Horrey, Wickens, & Consalus, 2006). The Alliance of Automobile Manufacturers requires that the 85^{th} percentile of single gaze durations should not exceed 2 s (AAM, 2006). The ISO 15005:2002 requires that maximum dwell times to capture information from the display should not exceed 1.5 s (ISO, 2002). A definition of thresholds for the gaze behaviour was provided by Monk et al. (2000). Based on a literature review, expert evaluations and four on-road field studies, 1.6 s single glance duration was defined as affecting driver performance, while 2.0 s were defined as substantially affecting driver performance. Similarly, based on the results of the 100-car study, Klauer, Dingus, Neale, Sudweeks, and Ramsey (2006) reported that glances longer than 2 s led to significant increases in near-crash and crash risk.

Importantly, Kircher et al. (2014) pointed out that in the evaluation of the potential distraction of an eco-driving system it should be focused when and how drivers sample information from the system, rather estimating whether the system is attended per se (as this is the purpose of the system). In their study, the glance frequency and duration to the in-vehicle display increased. However, with mean glance durations of around 1 s, they identified no safety critical behaviour. Importantly, they observed that in visually demanding situations (e.g. construction sites, motorway entrance) glance duration and frequency to the display was lower. This is an indication that drivers are able to consider the driving situation in their decision to follow the driving recommendations. For the different display versions of a traffic light assistant, Krause and Bengler (2012) concluded that based on the 2 s rule of the AAM and the 1.5 s rules of the ISO 15005:2002, all display versions were safe. Interestingly, the HMI version that led to the shortest gaze durations was the one least appealing in subjective ratings of the drivers. Thoma et al. (2007) summarised for their traffic light assistant that with on average eight glances to the traffic light assistant, the number of glances is quite high, even though the duration of glances did not exceed the aforementioned thresholds.

Furthermore, behaviour in potentially safety critical situations when drivers use the driver assistance system can serve as an evaluation criterion for the impact on safety. For example, researchers tested an eco-driving feedback system (which either consisted of a haptic pedal system or visual action recommendations) in high and low traffic density conditions. They evaluated whether drivers were able to increase attention to driving safety when the traffic situation requires it and thereby neglect the less important eco-driving goals. In the study, drivers were able to prioritise safe driving over efficient driving in both, dynamic driving behaviour and gaze behaviour. The authors argued that drivers could manage well their resources depending on the demand of the driving situation and "took responsibility for their own distraction" (Jamson et al., 2015). Rouzikhah, King, and Rakotonirainy (2013) compared driving with a system supporting driving efficiency to other secondary tasks. Amongst other criteria, they evaluated driver workload and the response to the peripheral detection task (PDT). Receiving eco-driving messages led to more missed responses compared to baseline. Changing CD or a navigation task led to significantly more driver workload and higher missed rates than baseline and eco-driving feedback. The authors concluded that the eco-driving system offers the potential for driver distraction and might influence driving performance. However, this influence was less strong than the influence of well-known secondary tasks while driving.

In sum, research on driving safety when being supported by a driver assistance system that aims on increasing driving efficiency has led to mixed results. From general research on eco-driving systems, it is concluded that drivers are able to prioritise their attention to safe driving, while the eco-driving system still represents a threat to driver attention. In terms of gaze behaviour, the traffic light assistant seems to be a safe system. To extend the safety evaluation, driving behaviour in a potentially safety critical traffic situation when receiving information from a traffic light assistant should be investigated.

3.3.2 Study 3: HMI evaluation

The goal of Study 3 is to evaluate which information units help the driver to achieve the driving strategy of the traffic light assistant and at the same time are subjectively accepted and safe for the usage during driving. The study contains a driving simulator experiment. Based on the results of Study 2, the algorithm of the traffic simulator is adapted. Based on the literature review and confirmed by the results from Study 2, the evaluated HMI strategy considers the information units traffic light phase information, action recommendations and speed recommendations.

The speed recommendations represent a target state that the driver should achieve in order to realise the goals of the traffic light assistant. Speed recommendations in the display do not consider how the driver achieves the target speed and whether the drivers are already in the correct target state. The action recommendations result from comparing current with required driving behaviour. With that, the system recommends “keep it”, otherwise acceleration or deceleration are instructed. The traffic light phase information informs the driver of the current traffic light state and its expected length. Additionally, drivers learn about the traffic light state at which they would arrive at the intersection. With that status information it is up to the drivers to adapt driving behaviour accordingly without communicating what the relevant behaviour is. Considering the appropriateness of the specific information units based on the literature, the hypothesis is that speed and action recommendations lead to better driving performance than traffic light information. Better driving behaviour implies that deviations from target behaviour are lower. The subjective preferences point towards the presentation of traffic light phase information as status information. Furthermore, two opposing hypotheses arise when the different information units are combined. The presentation of multiple information units leads to redundancy gains. Hence, with combined presentation of information units, driver performance improves and gaze durations reduce. Contrary, an increasing number of information units might lead to increases in cognitive load, which could result in the deterioration of driver performance and safety critical gaze behaviour.

In the driving simulator experiment, drivers experience overall eight different HMI versions that are built by the combination of the three information units. The evaluation criteria are driving behaviour, gaze behaviour and subjective evaluations. Questionnaires record the subjective preferences of drivers. The dynamic driving behaviour operationalises if drivers manage to achieve the target behaviour of the traffic light assistant. The gaze behaviour serves as an indicator for the general information usage in the interaction with the different HMI versions. For the important evaluation of safety aspects, the gaze behaviour is evaluated according to the relevant thresholds. Moreover, the results investigate the number of red light violations and driving behaviour in a potentially safety critical situation involving an emergency vehicle. The bold frames in Figure 50 highlight the relevant factors in Study 3. In summary the research questions are: Which of the three information units or combinations of them are suitable for presenting information of the traffic light assistant in terms of driver acceptance and performance? Do specific information units or combinations of them lead to safety critical driver behaviour?

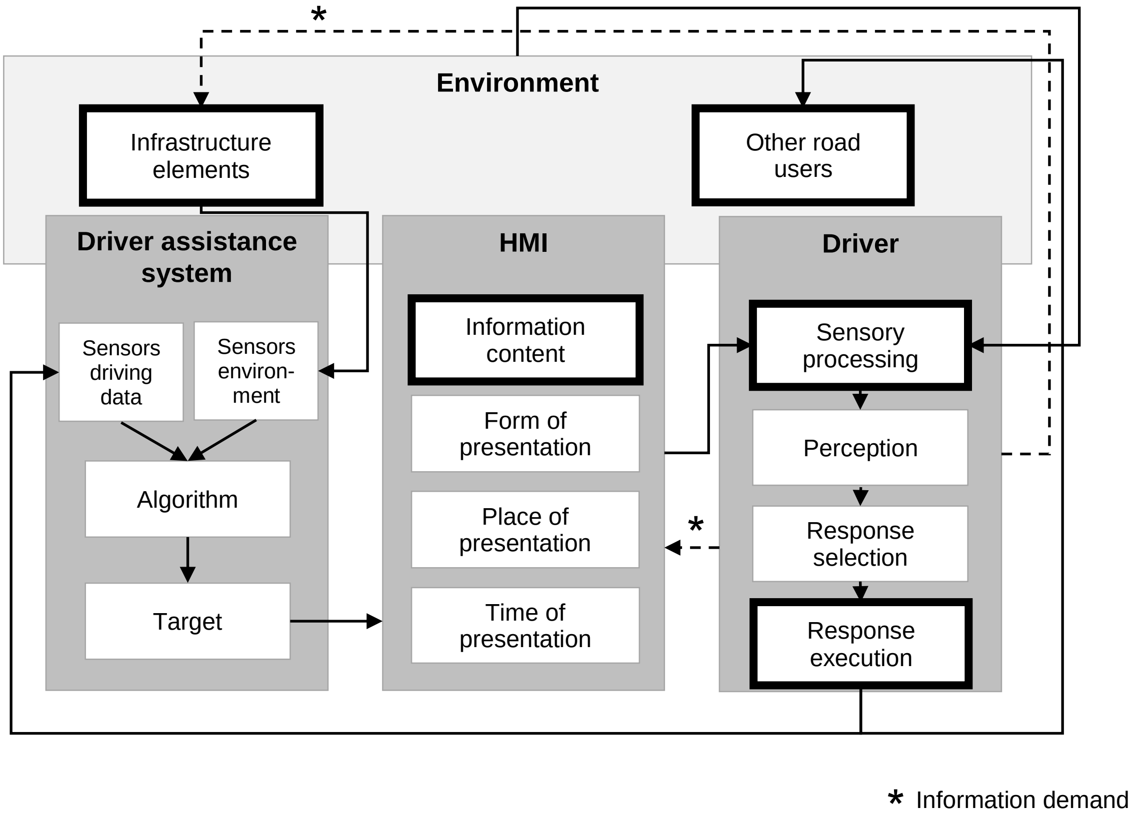


Figure 50. Relation of the factors considered in the present thesis. Bold frames indicate factors investigated in Study 3. Adapted from Bruder and Didier (2012), Popiv (2012), Schmidtke and Bernotat (1993), Wickens and Hollands (2000) and Zarife (2014).

3.3.2.1 Methods

Participants

32 participants (16 female) took part in the study. Their mean age was 31.6 years (sd = 11.7), with a minimum age of 21 years and a maximum age of 55 years. On average, participants drove 13757 km (sd = 10855) over the course of the past year, with on average 38.72 % (sd = 19.48) in urban areas. All drivers were recruited from the test driver panel of the WIVW. Due to a standardised driver training, they were well

experienced with driving in the static driving simulator. Only participants who had not participated in the previously conducted multi-driver simulator study were included. All drivers had normal or corrected to normal vision.

Apparatus

The study took place in the driving simulator described in chapter 3.1.2.1. The driving simulator was static and had a 300° horizontal field of vision. The display in the centre console presented the navigation information. The display behind the steering wheel presented the speedometer and the HMI information.

The eye tracker of Smart Eye AB recorded the gaze behaviour. Four infrared cameras captured head and eye movements of the drivers in a non-invasive way. The update frequency of the eye tracker was 60 Hz. A virtual model represented the driver environment in terms of available screens and instruments (Figure 51).

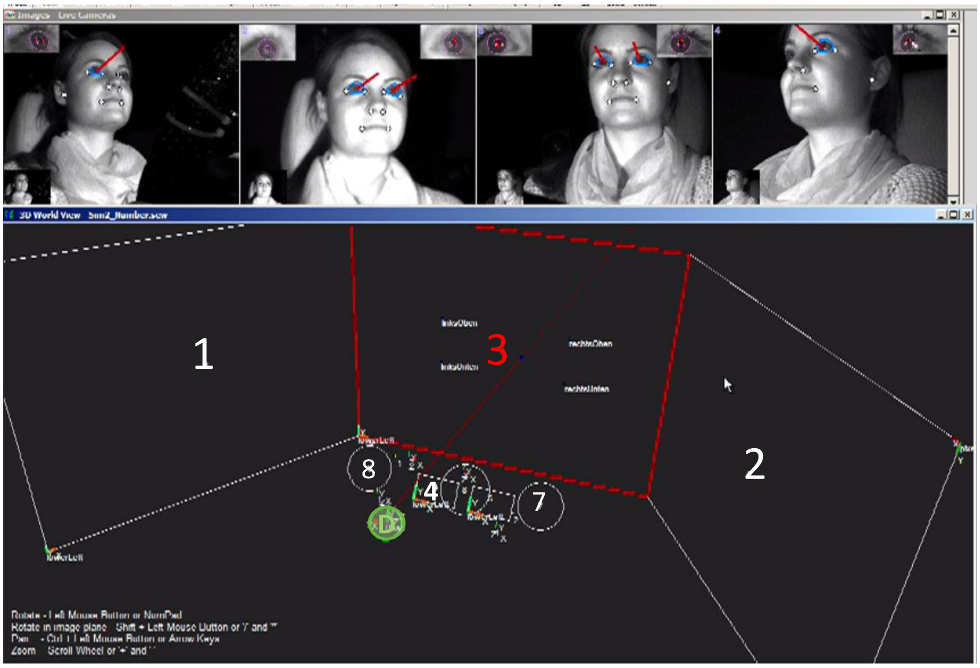


Figure 51. Operator screen of the Smart Eye AB eye tracking system. The upper pictures show the recording of the driver face with red and blue colour coding for the detection of gaze direction. The lower picture shows the model of the participant (D) in the driver environment with the areas of interest front view (3), left view (1), right view (2), side view mirrors (7 and 8) and the cluster display (4). The red marking shows that the driver is currently fixating on the centre screen.

The defined areas of interest were front view (3), left view (1), right view (2), side view mirrors (7 and 8) and the cluster display (4). The cluster display contained the speedometer and the HMI information. In the data analysis, only fixations made to the cluster display (4) were relevant. The data logs for the Smart Eye data were synchronised with the data logs recorded by the SILAB software.

A questionnaire consisting of five items captured the subjective evaluations of driving with the traffic light assistant. Participants answered the subjective questions on a verbal-numeric scale from 0 (do not agree at all) to 15 (very strongly agree; Figure 52).

Not at all	Very little			Little			Some			Strong			Very strong		
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Figure 52. Verbal-numeric scale for expressing the level of agreement to the statements in the questionnaires. The original version contained German text.

Traffic light assistant and HMI concept

The traffic light assistant received information on the current traffic light phase, the duration of the current traffic light phase and the next traffic light phase from the traffic light controller. Additionally, the algorithm used the vehicle’s current driving speed, the distance to the stop line and the driving direction as indicated by the navigation system. Based on that information the target speed was calculated. By comparing the target speed to the current driving speed and driving behaviour, the algorithm identified whether deceleration, acceleration or keeping the current speed was required. The first goal of the traffic light assistant was to avoid a stop at the intersection. The maximum driving speed was the current speed limit of 50 km/h (normal speed limit for urban driving in Germany). The minimum accepted driving speed was 30 km/h. In the case of an unavoidable stop at the red light, the assistant recommended driving behaviour for an efficient stop at red. The HMI of the traffic light assistant turned on when drivers were 300 m in front of the intersection.

The cluster display included the HMI of the traffic light assistant (Figure 53). The information was lane specific, i.e. drivers received the driving recommendations related to their current direction.

The HMI concept considered three different information units. First, information about the traffic light contained the colour of the current traffic light phase (Figure 54). The current traffic light phase was either red or green. The yellow traffic light phase was not depicted. The duration of the yellow phase added to the red phase. Eight seconds before termination of the current traffic light phase, the filling of the traffic light phase started reducing as a countdown timer counting by quarters. A quarter of the coloured filling related to two seconds. Additionally, an arrow next to the traffic light indicated at which traffic light phase drivers would arrive at the intersection in case they continued driving as currently recorded and as recommended by the traffic light assistant.

Figure 53. Cluster display with speedometer and basic HMI structure. Information for all three possible driving directions was depicted lane specific by highlighting the lane (left pictures shows driving straight, right picture shows turning right).

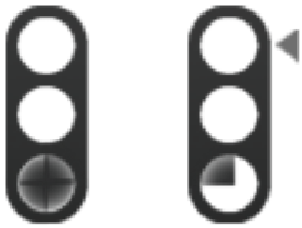


Figure 54. Schema of the traffic light phase information as depicted in the HMI concept. The left traffic light showed the current traffic light state. The right traffic light showed the remaining time in the current traffic light with one quarter representing 2 s. The arrow next to the traffic light highlighted the traffic light phase at which the driver arrived at the intersection (right picture: arrival at red, remaining time in green 2 s).

Second, action recommendations contained the recommendations "coast", "brake", "drive" (i.e. keep speed) and "accelerate". Braking was required when decelerations stronger than $-2\ m/s^2$ were necessary to reach the target speed. When the target behaviour required decelerations above $-2\ m/s^2$, the HMI showed coasting. Each action recommendation was implemented with a symbolic depiction (Table 13).

Table 13. Symbols used for depicting the four different action recommendations in the HMI concept.

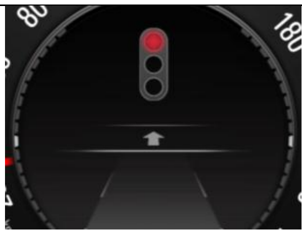
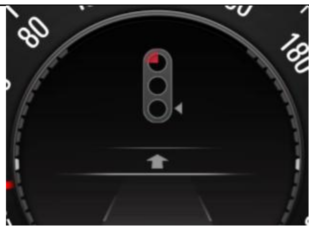
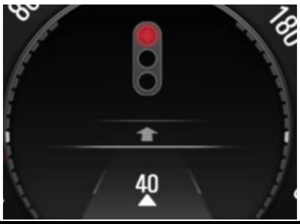
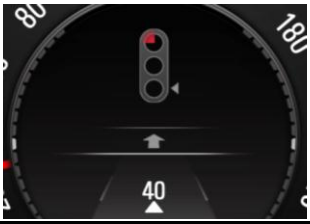
Symbol	Action recommendation
▲	Accelerate
▼	Brake
▽	Coast
⧗	Drive; keep speed

Third, target speeds were presented with numeric text (e.g. 30 for 30 km/h). The accuracy was 5 km/h. Hence, the possible speed recommendations were 30, 35, 40, 45 and 50 km/h.

Design

The study had a full within-subjects design. Each participant drove with eight different HMI versions. The HMI versions resulted from a combination of traffic light phase information (not present, present), action recommendations (not present, present) and speed recommendations (not present, present). Table 14 gives an overview of the different versions. When the traffic light information was not present, the HMI contained a traffic light showing the current traffic light phase without timing information or information on the phase of arrival (Figure 54, left).

Table 14. Eight HMI versions resulted from a combination of traffic light phase information, action recommendations and speed recommendations.

Recommendations		**Traffic light information**	
Action	**Speed**	**No**	**Yes**
No	**No**		
Yes	**No**		
No	**Yes**		
Yes	**Yes**		

Participants drove through the test track once with each of the HMI versions resulting in eight drives. The order of the eight drives was permuted between participants according to a Latin Square. Hence, four of the 32 participants experienced the same order of HMIs. Additionally, within each drive participants approached traffic light intersections with different states. The traffic light was either solid green or solid red, or changed from red to green or from green to red. Each traffic light approach was repeated twice within the test track, resulting in eight traffic light approaches. In these traffic light approaches, the navigation system indicated driving straight. In addition, in every drive participants crossed two intersections by turning left or right. The turning manoeuvres were included randomly between the eight straight traffic light crossings in order to diversify the driving task. The order of the overall ten traffic light approaches in the test track was permuted by a Latin Square, of which eight sequences were randomly chosen. Hence, drivers experienced each HMI version with a different sequence of traffic light phases in the test track.

The dependent measures consisted of dynamic driving behaviour, gaze behaviour and subjective evaluations. The SILAB software recorded the objective data. Table 15 summarises the dependent variables.

Table 15. Overview of the dependent variables recorded in the experiment.

Dependent variable	**Unit**	**Description**
Speed	km/h	Speed with which the vehicles proceeds
Acceleration	m/s²	Acceleration when increasing speed
Deceleration	m/s²	Deceleration when decreasing speed
Fixation duration	ms	Duration of a fixation on an area of interest
Fixation intervals on an area of interest	%	Proportion of time fixating on an area of interest in relation to total duration of driving in a specific distance section
Number of fixations on an area of interest	[]	Number of fixations on an area of interest in a defined distance segment
Questionnaire items	0 = do not agree at all, 15 = totally agree	Five questionnaire items for which participants expressed their agreement: I got along well with the display; The display was complex; The display contained enough information; The display was helpful; I performed well with respect to the required driving behaviour
HMI preference	1,2,3; 7,8	Participants' ranking of the best (1), second best (2), third best (3) HMI version, and the worst (8) and second worst (7) HMI version

Test track

Participants drove through an urban test track with ten traffic light intersections. All traffic light intersections had the same three-way layout with variable buildings and environments. The navigation system indicated drivers to either drive left, straight or right. Within their own lane, drivers did not experience other road users while approaching the traffic light intersection. On other lanes and intersection directions, minor traffic was present.

The traffic light phasing was according to German road traffic regulations. The red phase always ended with a combined presentation of red and yellow light, whereas the green phase ended with an only yellow state. The yellow phase and the combined red and yellow phase lasted approximately 1.8 s. The red phase following the single yellow state lasted for 16 s. The traffic light phase changes occurred when drivers were approximately 50 m in front of the intersection.

Critical driving situation

A final test drive consisted of five intersection approaches including the critical driving situation. 17 participants drove with the HMI version that did not show any of the three information units. 15 participants drove with the HMI that showed all three information units. At the fifth intersection approach, the traffic light was solid green, so that drivers could pass the intersection at green with 50 km/h. During the traffic light approach, an emergency vehicle drove towards the X-junction from the left side and crossed the intersection. The situation should trigger deceleration in attentive drivers, which could prevent a collision with the emergency vehicle. It was expected that drivers who were distracted by the traffic light assistant would collide with the vehicle (Figure 55).

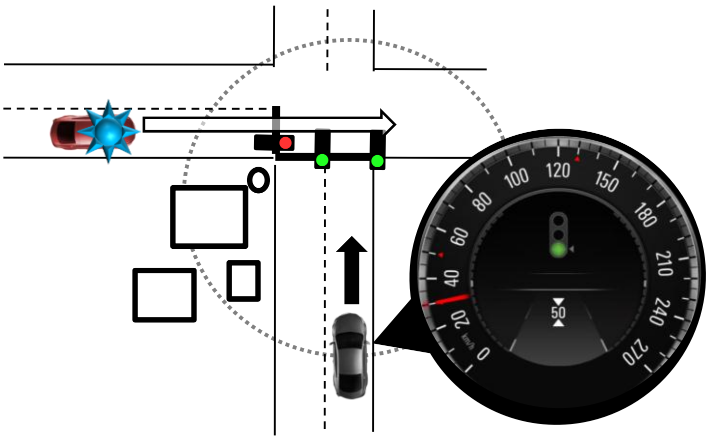


Figure 55. Schematic depiction of the critical situation. Drivers approached a solid green traffic light. The emergency vehicle approached from the left side of the X-junction while drivers received recommendations from the traffic light assistant. The HMI showed either all three information units (depicted here) or no information unit.

For the objective evaluation of driver performance in the critical situation, the number of collisions was determined along with dynamic driving data like maximum decelerations and reaction times from emergency vehicle onset to accelerator pedal release. For the subjective evaluation of the critical driving situation, drivers stated how critical the situation was, how well they solved the situation and if they felt distracted by the display. The subjective evaluation was made according to the 16-point verbal-numeric scale (Figure 52).

Procedure

Participants completed a data privacy statement and received instructions about the objectives of the study. Before the experiment started, the experimenter calibrated the eye tracking system. Participants were familiarised with the test track by driving a short practice track consisting of traffic lights with different traffic light states and intersections with different navigation directions. In the practice drive, no traffic light assistant was active. The experiment started by thoroughly introducing the first HMI version. The goal of the instruction was to ensure that the participants correctly understood all depicted information units. Participants were instructed to stick to the recommendations of the assistant as closely as possible. After completing each experimental drive consisting of ten intersections with one HMI version, the experimenter interviewed the participants. Then, the second HMI version was introduced and the procedure was repeated with all eight HMI versions. Each experimental drive took approximately 10 min. Before the final test ride including the critical situation, the experimenter mentioned that drivers would now drive a second time with either the full HMI or the no information HMI version. This final drive took approximately 5 min. Participants were allowed to take breaks whenever they wanted between drives. The experiment ended after around 2 hours with the final questionnaire.

3.3.2.2 Results

Data preparation

As preparation for the analysis of gaze behaviour, a fixation on an area of interest counted whenever it was longer than 100 ms. Depending on the anatomy and movements of the participants, the eye tracker occasionally recorded missing data when the participants fixated on the cluster display (Figure 56). Therefore, data were recoded by defining that missing data occurring between two display fixations counted as display fixation. 17 traffic light approaches (out of overall 2048) were excluded, because the percentage of missing data after recoding was still larger than 30%. In additional 18 traffic light approaches (all from the same driver), the participant did not look at the HMI at all. Hence, gaze data analysis related to overall 2013 traffic light approaches.

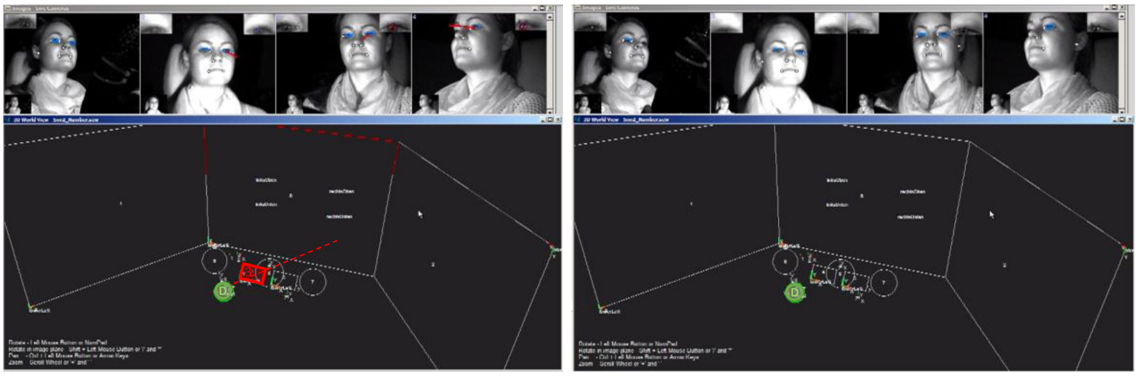


Figure 56. Example screenshots from the operator view of the eye tracking software. The left picture shows a correctly determined fixation on the cluster display. The right picture shows a recording of missing data because the eye tracker did not detect the fixation on the cluster display.

For the data analysis, dynamic driving and gaze data were averaged over repeated traffic light approaches for each participant. The ANOVAs considered the 2x2x2 repeated measurements design. The analysis included data for the approach area of 300 m in front of the intersection. Further, the analysis of objective data was separated between traffic light approaches to green, red to green, red and green to red traffic light phases.

Subjective evaluation

Figure 57 gives an overview of the agreement that drivers expressed for the five items of the questionnaire separated by HMI version.

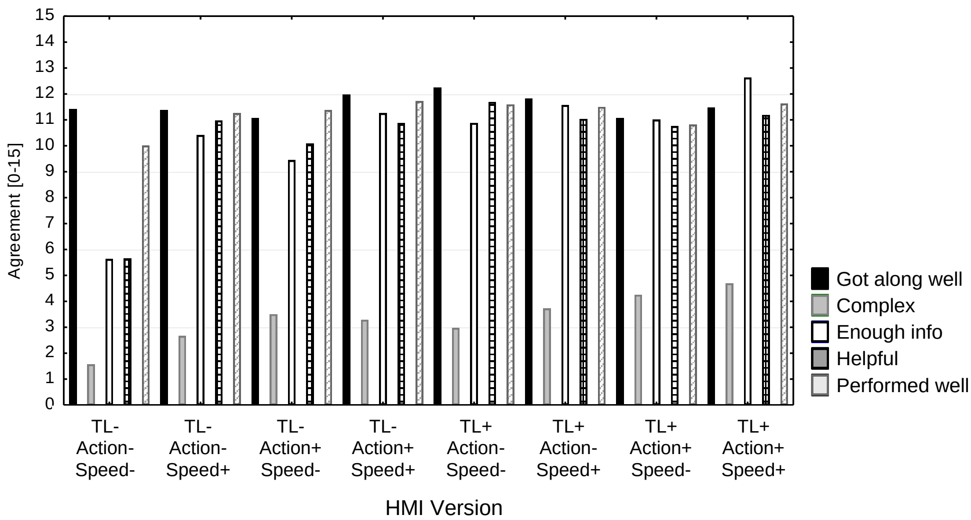


Figure 57. Agreement to the five statements evaluating the HMI versions. The items were: I got along well with the display, the display was complex, the display contained enough information, the display was helpful and I performed well with the display. The HMI versions are described by either containing (+) or not containing (-) each of the three information units traffic light phase information (TL), action recommendations (Action) and speed recommendations (Speed).

In general, participants expressed that they got along well with all of the displays and that all displays had low complexity. All HMI versions but the HMI version without any information unit subjectively contained enough information. The system was rated as helpful as long as at least one information unit was presented. Drivers experienced that they performed well with all of the HMI versions.

The ANOVAs conducted for each questionnaire item included the independent factors traffic light phase information, action recommendations and speed recommendations. The dependent variable was the agreement drivers expressed on the scale from 0 to 15. Figure 58 depicts the effects for each item.

For the item “I got along well with the display” no significant differences occurred between HMI versions. For the item “the display was complex” there were main effects for traffic light information, $F(1,31) = 14.865$, $p < .001$, $\eta^2_{partial} = .324$, and action recommendations, $F(1,31) = 16.907$, $p < .001$, $\eta^2_{partial} = .353$. The display was more complex when there was traffic light information compared to no traffic light information, and when there were action recommendations compared to no action recommendations. Concerning the item “the display contained enough information” all three main effects were significant: traffic light information $F(1,31) = 49.119$, $p < .001$, $\eta^2_{partial} = .613$, action recommendations $F(1,31) = 63.651$, $p < .001$, $\eta^2_{partial} = .672$, speed recommendations $(1,31) = 55.463$, $p < .001$, $\eta^2_{partial} = .641$. The agreement to the statement was larger, when each of the information units was present compared to not present. Additionally, the interaction between traffic light information and action recommendation, $F(1,31) = 11.791$, $p = .001$, $\eta^2_{partial} = .276$, and the interaction between traffic light information and speed recommendation, $F(1,31) = 13.791$, $p < .001$, $\eta^2_{partial} = .308$, were significant. Finally, there was a significant three-way interaction for this item, $F(1,31) = 14.544$, $p < .001$, $\eta^2_{partial} = .319$. Adding each of the three information units to the display increased drivers’ agreement to the statement. The agreement was lowest when no information was present, while the agreement was highest when all three information units were present. The analysis of the agreement to the statement “the information was helpful” showed that all effects were significant: Traffic light information $F(1,31) = 21.074$, $p < .001$, $\eta^2_{partial} = .405$, action recommendation $F(1,31) = 13.776$, $p < .001$, $\eta^2_{partial} = .308$, speed recommendation $F(1,31) = 17.262$, $p < .001$, $\eta^2_{partial} = .358$, traffic light information x action recommendation $F(1,31) = 28.092$, $p < .001$, $\eta^2_{partial} = .475$, traffic light information x speed recommendation $F(1,31) = 59.098$, $p < .001$, $\eta^2_{partial} = .656$, action recommendation x speed recommendation $F(1,31) = 13.997$, $p = .001$, $\eta^2_{partial} = .295$, traffic light information x action recommendation x speed recommendation $F(1,31) = 29.184$, $p < .001$, $\eta^2_{partial} = .485$. The display helped most in the HMI version presenting only traffic light information, whereas it helped least in the condition without any information unit. Without speed recommendations no difference between traffic light information or action recommendations occurred.

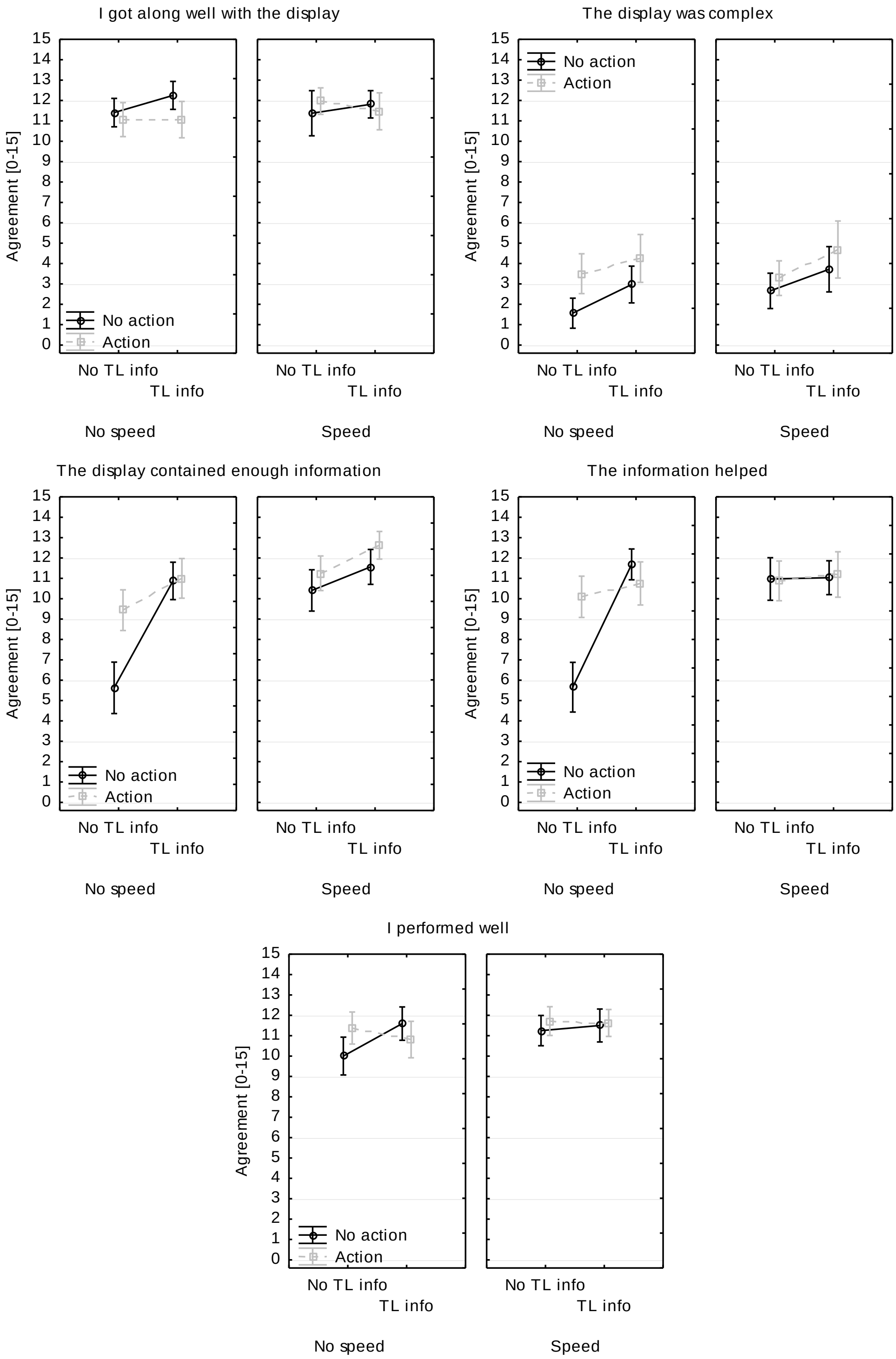


Figure 58. Agreement to the five statements evaluating the HMI versions. The items were: I got along well with the display, the display was complex, the display contained enough information, the display was helpful and I performed well with the display. Graphs show means with 95% confidence intervals.

Finally, driver's evaluation of their own performance changed with respect to speed recommendations, $F(1,31) = 9.391$, $p = .004$, $\eta^2_{partial} = .233$, the interaction between traffic light information and action recommendations, $F(1,31) = 7.789$, $p = .009$, $\eta^2_{partial} = .201$, and the three-way interaction between traffic light information, action recommendations and speed recommendations, $F(1,31) = 8.787$, $p = .006$, $\eta^2_{partial} = .221$. Lowest agreement to the statement was expressed when the HMI showed no information unit compared to all other combinations.

After completing all test drives, participants rated which HMI version they liked best, second best and third best. Along with that, the drivers identified the worst and second worst HMI version. The ratings were weighted by giving three points to the best HMI version, two points to the second best HMI version and one point to the third best HMI version. Similarly, the second worst HMI version received one point while the worst HMI version received two points. Figure 59 presents the sum of all weighted ratings. The HMI version containing all information units received the best score. In general, HMI versions with traffic light information received high ratings. The HMI version that did not contain any information units received the lowest number of "best" evaluation and the highest number of "worst" evaluations. The HMI version only showing action recommendations was the second worst version.

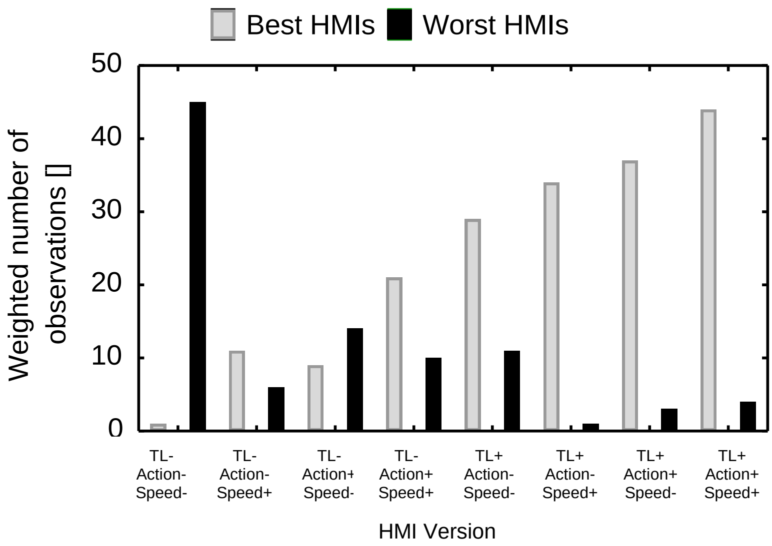


Figure 59. Weighted number of observations for the forced choice to determine the best [score 3], second best [score 2] and third best [score 1] HMI version and to indicate the worst [score 2] and second worst [score 1] HMI. The HMI versions are described by either containing (+) or not containing (-) each of the three information units traffic light phase information (TL), action recommendations (Action) and speed recommendations (Speed).

Deviations from target speed

Driving speed was averaged for 10 m distance segments over the course of the 300 m traffic light intersection approach. Figure 60 shows the speed profiles for the eight different HMI versions and the target speed as calculated by the traffic light assistant.

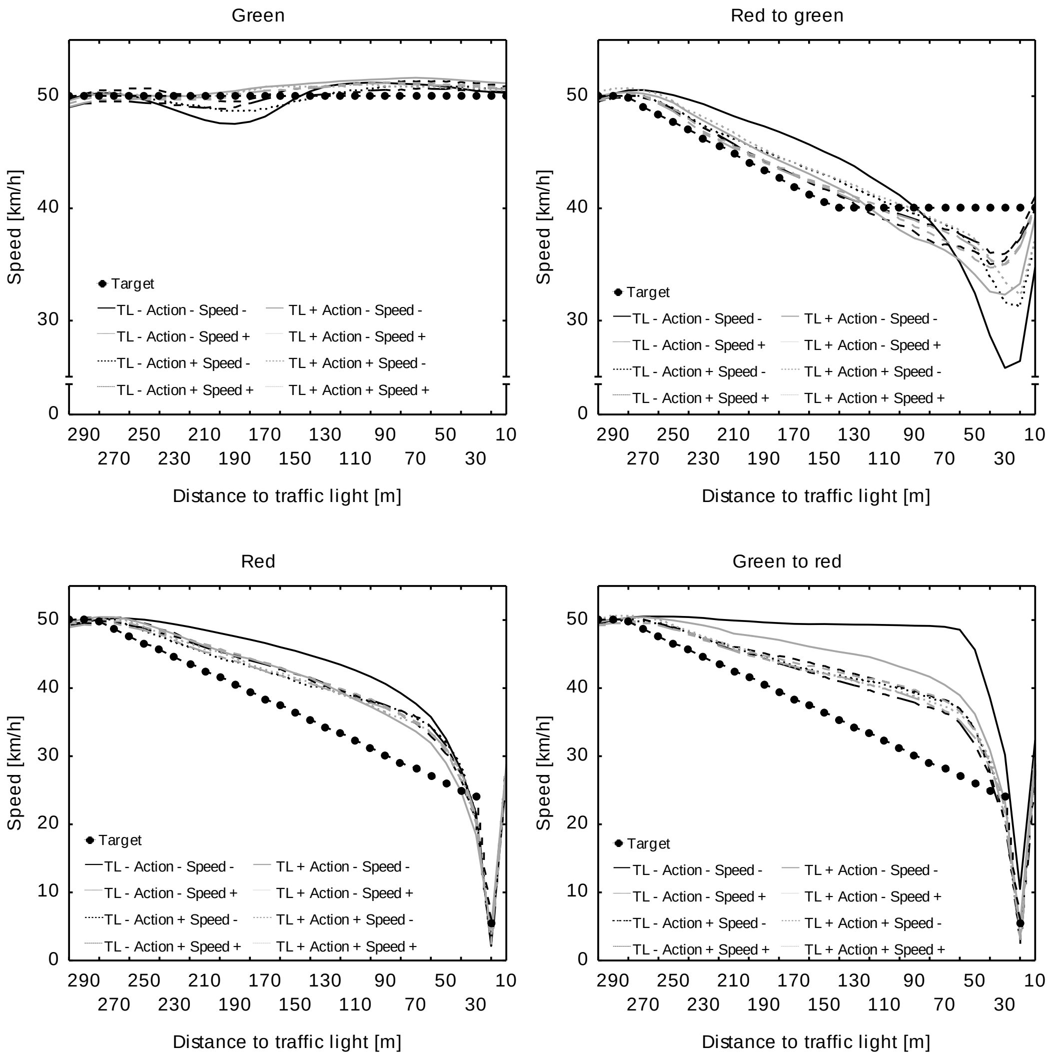


Figure 60. Mean driving speed for the 30 distance sections during the 300 m traffic light approach for the eight different HMI versions and the target speed as calculated by the traffic light assistant. The four graphs show speed for the traffic light phases solid green, changing red to green, solid red and changing green to red. The HMI versions are described by either containing (+) or not containing (-) each of the three information units traffic light phase information (TL), action recommendations (Action) and speed recommendations (Speed).

When approaching solid green traffic lights drivers kept speed stable and deviations from the target speed were in general low. When approaching red to green traffic lights, driving speed reduced according to the recommendations of the traffic light assistant. Shortly before entering the intersection, driving with all HMI versions led drivers to decrease speed stronger than recommended by the traffic light assistant. When approaching the solid red or changing green to red traffic lights, the driving speed was in general higher than the target speed. Due to drivers' reaction time from HMI activation to start of coasting, the reduction of speed by coasting started later than the deceleration in the target profile. In all traffic light approaches, HMI versions containing at least one information unit led to lower deviations from the target speed compared to the HMI version that did not contain any information unit.

The squared deviations of the actual driving speed from the target speed were determined and accumulated for each traffic light approach. Figure 61 presents the average sum of squared deviations for each HMI version. As expected, the deviations from target speed were overall largest when participants drove with the HMI version that did not contain any information unit. The HMI versions that led to the lowest deviations from target speed were the ones containing a combination of action and speed recommendations.

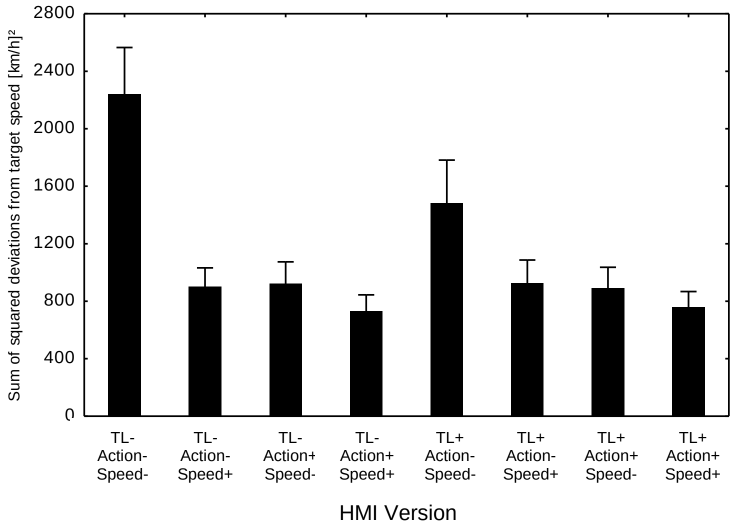


Figure 61. Sums of squared deviations of actual driving speed from target speed as calculated by the traffic light assistant for the eight different HMI versions. The HMI versions are described by either containing (+) or not containing (-) each of the three information units traffic light phase information (TL), action recommendations (Action) and speed recommendations (Speed). Graph shows means with 95% confidence intervals.

The sum of squared deviations was the dependent variable in the ANOVAs that were conducted separately for each of the four possible traffic light phases. The independent variables were traffic light information, action recommendations and speed recommendations. Table 16 summarises the results of all four ANOVAs. For the solid red and the green to red traffic light phase, deviations for the last distance section (10 to 0 m in front of the intersection) and during standstill (speed < 1km/h) were not considered in the analysis.

When approaching green traffic lights, there was no influence of any information unit on the deviation from the target speed. When approaching changing red to green traffic lights, there were main effects for action recommendations and speed recommendations, indicating that the deviations from the target speed were lower with speed and action recommendations respectively. The interaction between action and speed recommendations indicates that with speed recommendations the influence of action recommendations was small.

Table 16. Summary of ANOVA results (*p*-values) with the dependent variable sum of squared deviations from target speed conducted separately for the four traffic light phases. Bold numbers mark significant effects.

Effect	Green	Red to green	Red	Green to red
TL Info	$p = .153$	$p = .295$	**$p = .035$**	**$p = .027$**
Action	$p = .664$	**$p < .001$**	**$p = .004$**	**$p < .001$**
Speed	$p = .086$	**$p < .001$**	**$p = .004$**	**$p < .001$**
TL Info x Action	$p = .258$	$p = .404$	$p = .888$	**$p = .004$**
TL Info x Speed	$p = .497$	$p = .105$	$p = .501$	**$p < .001$**
Action x Speed	$p = .056$	**$p = .006$**	**$p = .008$**	**$p < .001$**
TL Info x Action x Speed	$p = .971$	$p = .526$	$p = .227$	**$p = .017$**

For solid red traffic lights, all three main effects were significant. This indicates that the presentation of each information unit led to reductions in the deviations from the target speed. The significant interaction between action and speed recommendations shows that when one of the two information units was present, the additional impact of a second information unit on the deviation from the target speed was lower. Thereby, the influence of the action recommendation was larger than the influence of the speed recommendation.

When approaching traffic lights that changed from green to red, the effects of all information units and interactions were significant. The main effects express that all three information units led to reductions in the deviation from the target speed. The interactions qualified these conclusions. With action recommendations, there was no additional beneficial influence of traffic light phase information. Similar, a combined presentation of speed recommendations with traffic light information did not lead to larger reductions in the deviation from the target speed compared to a mere presentation of speed recommendations. Contrary, a combined presentation of speed and action recommendations led to the lowest deviations from the target speed compared to all other conditions. Figure 62 depicts the described effects.

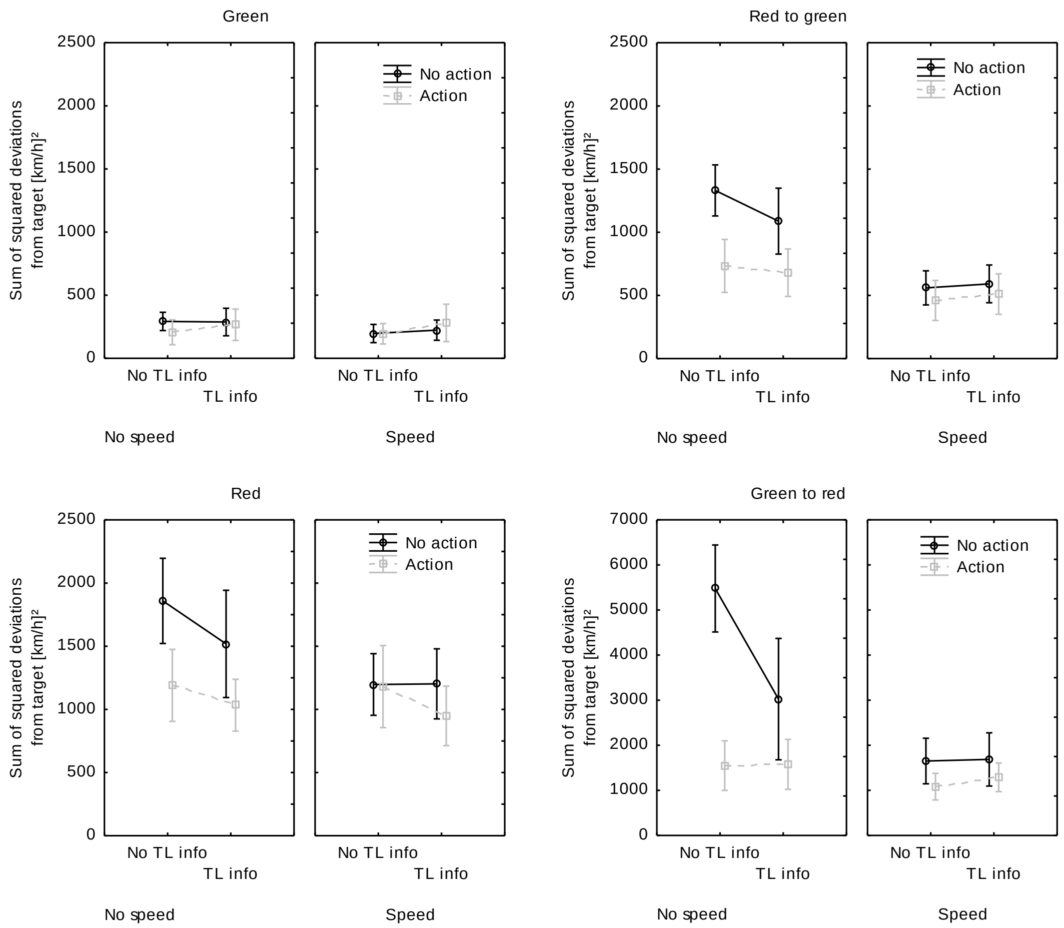


Figure 62. Sum of squared deviations from target speed with different information units presented in the HMI display (TL info = traffic light information) when approaching different traffic light phases. Note that the scaling of the x-axis for green to red traffic lights differs from the remaining graphs. Graphs show means with 95% confidence intervals.

Information usage

The analysis investigated the amount of time drivers spent fixating the cluster display. The time was a product of number and duration of display fixations. It was related to the total duration of the traffic light approach. For example, a value of 5 expresses that 5% of the time of a traffic light approach was spent with fixating the display. ANOVAs were conducted separately for the four traffic light phases, with the three independent variables representing the three information units in the HMI display: traffic light phase information (not present, present), action recommendations (not present, present) and speed recommendations (not present, present). Table 17 and Figure 63 show the ANOVA results and the related interaction graphs.

Drivers fixated the HMI display longer with traffic light phase information compared to without traffic light phase information in all traffic light phase conditions. The three-way interaction in solid green lights does not limit this interpretation. However, due to two three-way interactions, this effect is not globally valid. When the traffic light changed from red to green during the approach and when there were speed recommendations and no action recommendations, there was no difference in the fixation durations for approaches with compared to without traffic light phase information. When the traffic light was solid red and action recommendations were present but no speed recommendations, no difference in the fixation durations occurred between HMI versions with and without traffic light phase information.

Table 17. Summary of results for ANOVAs (*p*-values) with the dependent variable percentage of time fixating the HMI conducted separately for the four traffic light phases. Bold numbers mark significant effects.

Effect	Green	Red to green	Red	Green to red
TL Info	**$p < .001$**	**$p < .001$**	**$p < .001$**	**$p < .001$**
Action	**$p < .001$**	**$p < .001$**	**$p = .009$**	**$p = .007$**
Speed	$p = .111$	**$p < .001$**	**$p < .001$**	**$p = .008$**
TL Info x Action	**$p = .013$**	$p = .234$	**$p = .005$**	$p = .231$
TL Info x Speed	**$p = .021$**	**$p < .001$**	**$p = .039$**	**$p = .016$**
Action x Speed	**$p = .002$**	**$p < .001$**	$p = .772$	**$p = .049$**
TL Info x Action x Speed	**$p = .024$**	**$p = .003$**	**$p < .001$**	$p = .129$

The main effects for action recommendation indicate that participants fixated the HMI display for longer periods of time when an action recommendation was present compared to when it was not present in all traffic light phase conditions. This was qualified by two- and three-way interactions. When the traffic light was solid green, the effect of presenting the action recommendations was stronger, when no traffic light phase information or no speed recommendations were additionally present. When the traffic light changed from red to green during the approach, no increases in fixation durations occurred between conditions with and without action recommendations when the speed recommendation was active. With speed recommendations and without traffic light information, drivers fixated the HMI for longer periods in the no action condition compared to the action recommendation condition. When the traffic light was solid red, drivers fixated the HMI longer in the no action recommendation condition when the traffic light info was present with no information on speed compared to the action recommendation condition with traffic light and without speed information. Finally, when the traffic light changed from green to red, there was no difference in the duration of HMI fixations between conditions with and without action recommendations, any time a speed recommendation or traffic light phase information was present.

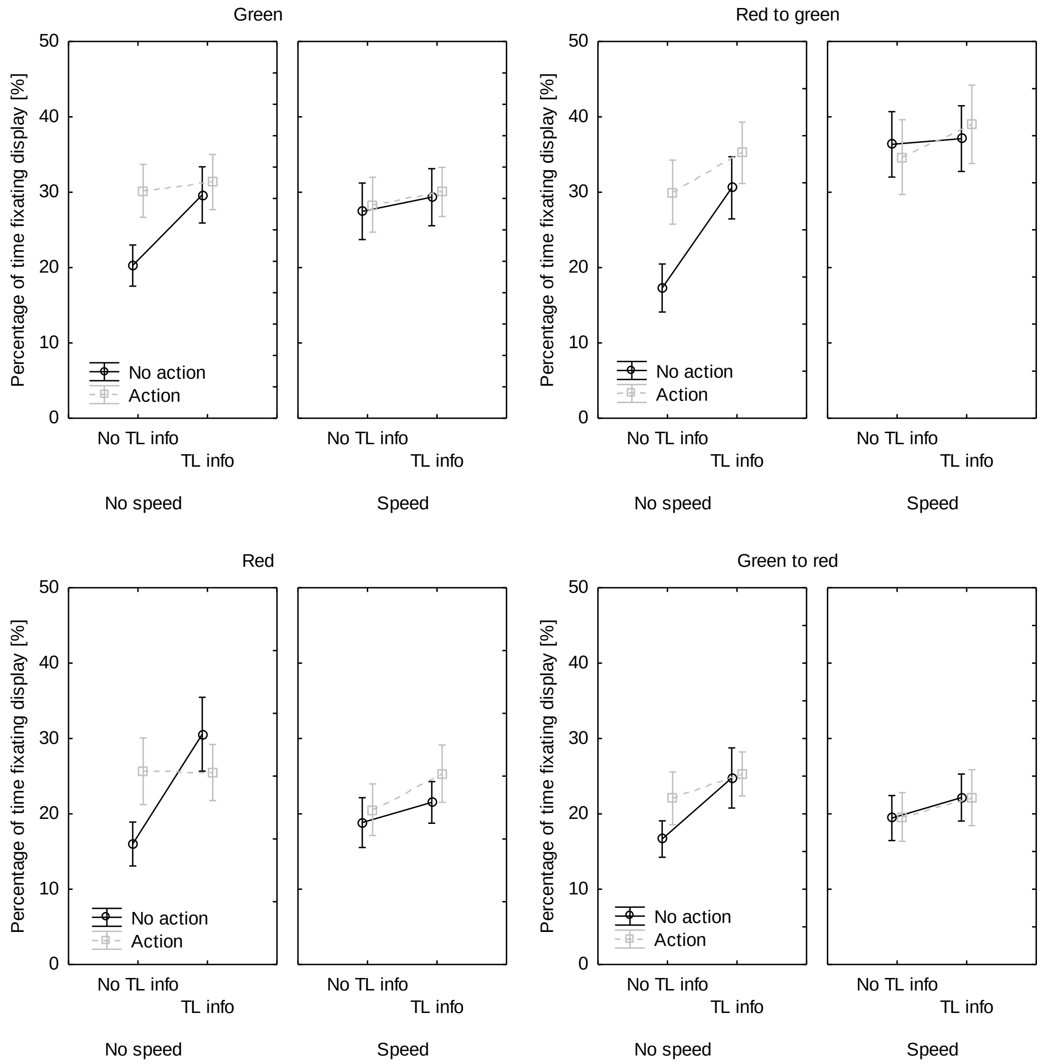


Figure 63. Percentage of time fixating the HMI when approaching solid green, red to green, solid red and green to red traffic lights when presenting the different information units in the HMI. Graphs show means with 95% confidence intervals.

There were significant main effects for speed recommendations in all but the green traffic light phase condition. When the traffic light changed from red to green participants fixated the HMI version with speed recommendations longer compared to the versions without speed recommendation. When the traffic light was red or changed from green to red participants fixated the HMI version with speed recommendations shorter compared to the version without speed recommendations. Two- and three-way interactions qualify the main effects. With speed recommendations in solid green lights, the fixation durations only increased compared to the no speed recommendations when no traffic light phase information or when no action recommendation was present. With speed recommendations in the red to green condition, the main effect for speed recommendations is valid globally. Interestingly, when the speed recommendations were given in the solid red condition, drivers fixated the display shorter than without speed recommendations, in case the display additionally either showed traffic light information or action recommendations. When either no other information unit was present or both other information units were present, no difference between the two speed recommendation conditions occurred. In the green to red condition, drivers fixated the HMI display for shorter periods of time when speed recommendations were present compared to without speed recommendations, as long as any other information was also present.

Safety evaluation

First, the distribution of fixation durations to the display provides information for the safety evaluation of the HMI versions. Descriptive statistics for the average duration of fixations on the display were determined (Table 18). Importantly, the 85% percentile was below 1.4 s and the 95% percentile was below 1.7 s for all HMI versions. The longest average fixation durations occurred for the HMI versions showing a combination of traffic light phase information and action recommendations. The shortest average fixation durations were observed for the HMI version showing no information units, followed by the version containing action and speed recommendations.

Figure 64 shows the distribution of fixation durations for the different HMI versions. For the basic HMI version without any information unit, fixations were overall shorter and with lower standard deviations. HMI versions with traffic light phase information (grey lines) triggered higher frequencies of fixations with longer than 1.2 s compared to the HMI versions without traffic light phase information (black lines).

Table 18. Descriptive statistics for the average duration of fixations on the display in the different HMI versions. The HMI versions are described by either containing (+) or not containing (-) each of the three information units traffic light phase information (TL), action recommendations (Action) and speed recommendations (Speed).

HMI version	N	Mean number of fixations []	Mean fixation duration [ms]	Median fixation duration [ms]	85% Percentile fixation duration [ms]	95% Percentile fixation duration [ms]
TL – Action – Speed –	254	7.205	652.845	629.861	968.333	1156.250
TL – Action – Speed +	254	9.673	774.939	716.666	1179.167	1502.381
TL – Action + Speed –	251	10.386	771.587	742.708	1100.000	1550.758
TL – Action + Speed +	252	10.230	746.611	741.666	1097.500	1458.333
TL + Action – Speed –	252	10.877	788.498	741.987	1185.185	1526.389
TL + Action – Speed +	253	10.17	817.454	768.055	1229.167	1632.292
TL + Action + Speed –	250	11.056	843.680	756.423	1320.833	1597.917
TL + Action + Speed +	247	11.126	804.317	714.166	1243.056	1616.667

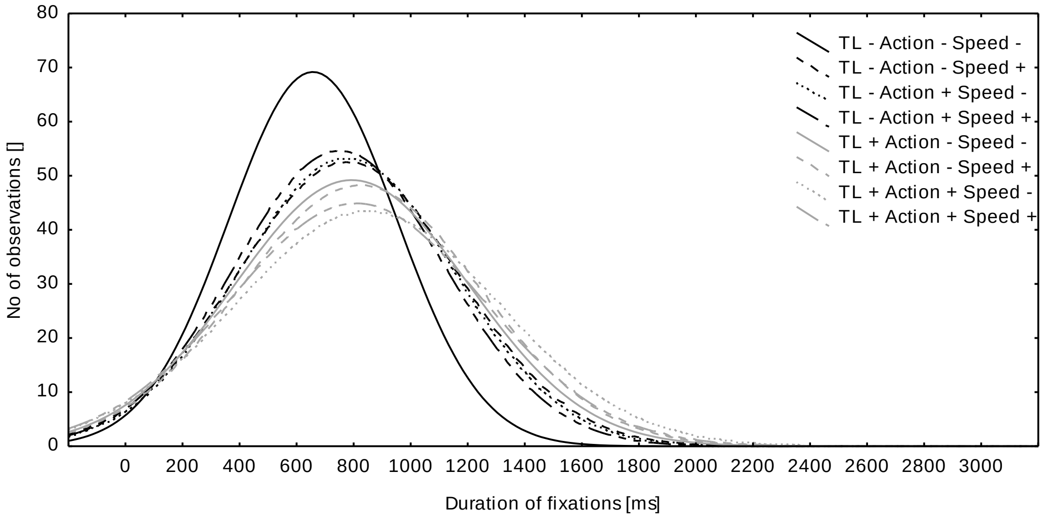


Figure 64. Distribution of fixation duration to the display for all HMI versions. The HMI versions are described by either containing (+) or not containing (-) each of the three information units traffic light phase information (TL), action recommendations (Action) and speed recommendations (Speed).

Second, the number of stops that participants initiated at the traffic light indicates how well drivers were able to achieve the global goal of the traffic light assistant. This is safety relevant for two reasons. First, when drivers stop at traffic lights right before turning green, they could increase the risk for a crash with following vehicles. Second, avoided stops at red traffic lights indicate red light violations, which represent a major thread to driving safety of all traffic participants at the intersection.

Table 19 shows the number of unnecessary stops at green and red to green traffic lights and the number of avoided stops at red and green to red traffic lights. A driving speed < 1 km/h classified a stop. When the traffic light was green, all drivers passed every intersection without a stop. When the traffic light changed from red to green, in overall ten traffic light approaches, eight different drivers did not manage to cross the intersection without a stop. Four drivers did not manage to avoid the stop with the HMI providing action recommendations in combination with traffic light phase information.

Table 19. Number of unnecessary stops when approaching green and red to green traffic lights and number of times drivers did not stop at a red or green to red traffic light. The HMI versions are described by either containing (+) or not containing (-) each of the three information units traffic light phase information (TL), action recommendations (Action) and speed recommendations (Speed).

Category	Traffic light phase	Traffic light information -				Traffic light information +			
		Action - Speed -	Action - Speed +	Action + Speed -	Action + Speed +	Action - Speed -	Action - Speed +	Action + Speed -	Action + Speed +
Unnecessary stops	**Green**	0	0	0	0	0	0	0	0
	Red to green	1	0	2	0	2	0	4	1
Avoided stops (by red light violations and/or speed violations)	**Red**	0	0	0	0	3 (0)	0	0	0
	Green to red	10 (10)	0	1 (1)	0	3 (3)	1 (1)	2 (1)	1 (0)

When the traffic light was solid red, two different drivers avoided a stop in overall three traffic light approaches when only traffic light information was present. In these cases no red light violation occurred. Contrary, drivers adapted their speed significantly by reducing it below 20 km/h (Figure 65, left). With that, they postponed their arrival at the intersection and the traffic light changed back to green before drivers came to standstill. Similar approach patterns occurred in two traffic light approaches by two different drivers when the traffic light changed from green to red and participants were driving with the HMI version containing traffic light information in combination with action recommendations and when driving with the HMI version containing all information units. Like this, drivers approached the traffic light with lower speeds than the speed thresholds considered in the traffic light assistant algorithm would allow recommending. Moreover, when the traffic light changed from green to red, in 16 traffic light approaches 14 different drivers crossed the intersection without a stop due to speed limit violations and red light violations. The majority of speed and red light violations occurred when drivers did neither receive traffic light phase information nor action nor speed recommendations. Figure 65 depicts examples for the described traffic light approaches. The left graph shows a driver avoiding a stop at the red light; the right graph shows a driver conducting speed and red light violations.

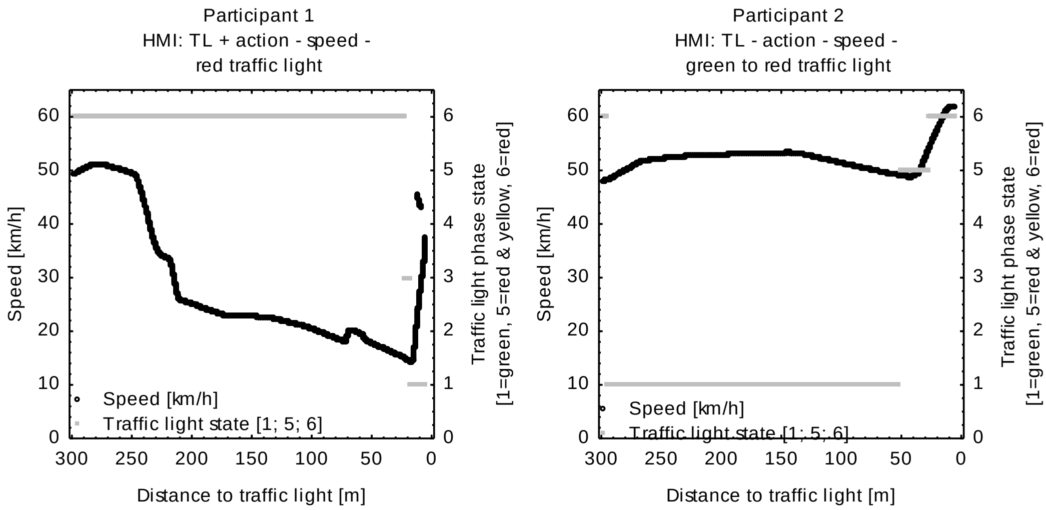


Figure 65. Speed profile of a participant approaching a solid red traffic light with receiving traffic light phase information (left). Speed profile of a participant approaching a green to red traffic light with receiving no information from the traffic light assistant (right).

Third, the performance in the critical driving situation was evaluated according to the subjective evaluations of drivers, the number of collisions and dynamic driving behaviour. The evaluation compared the simple HMI version without any information units to the complex HMI version containing all information units. 17 drivers experienced the critical situation with the simple HMI version and 15 drivers experienced the critical situation with the complex HMI version. After the critical situation drivers expressed their agreement to the statements “the situation was critical”, “I solved the task well” and “I was distracted”. T-tests for independent samples for each item compared the evaluations for the different HMI versions. No significant differences appeared, all *ps* > .215 (Figure 66). In general, drivers rated their distraction as low, thought that they solved the task quite well and experienced the situation as critical.

Finally, the number of collisions was determined. Overall, 9 collisions with the emergency vehicle were observed, of which five occurred when participants were driving with the simple HMI version and four occurred when participants were driving with the complex HMI version. The complex HMI version did not increase the risk for a collision. Two separate t-tests for independent samples compared the maximum decelerations and reaction times from emergency vehicle onset to accelerator pedal release and brake pedal onset. No differences were found for any parameter between the two HMI versions, all *ps* > .572. This indicates that the complex HMI version containing all information units does not change driving behaviour compared to the HMI version not containing any information. As a conclusion, the complex HMI version does not lead to inappropriate behaviour in the critical driving situation

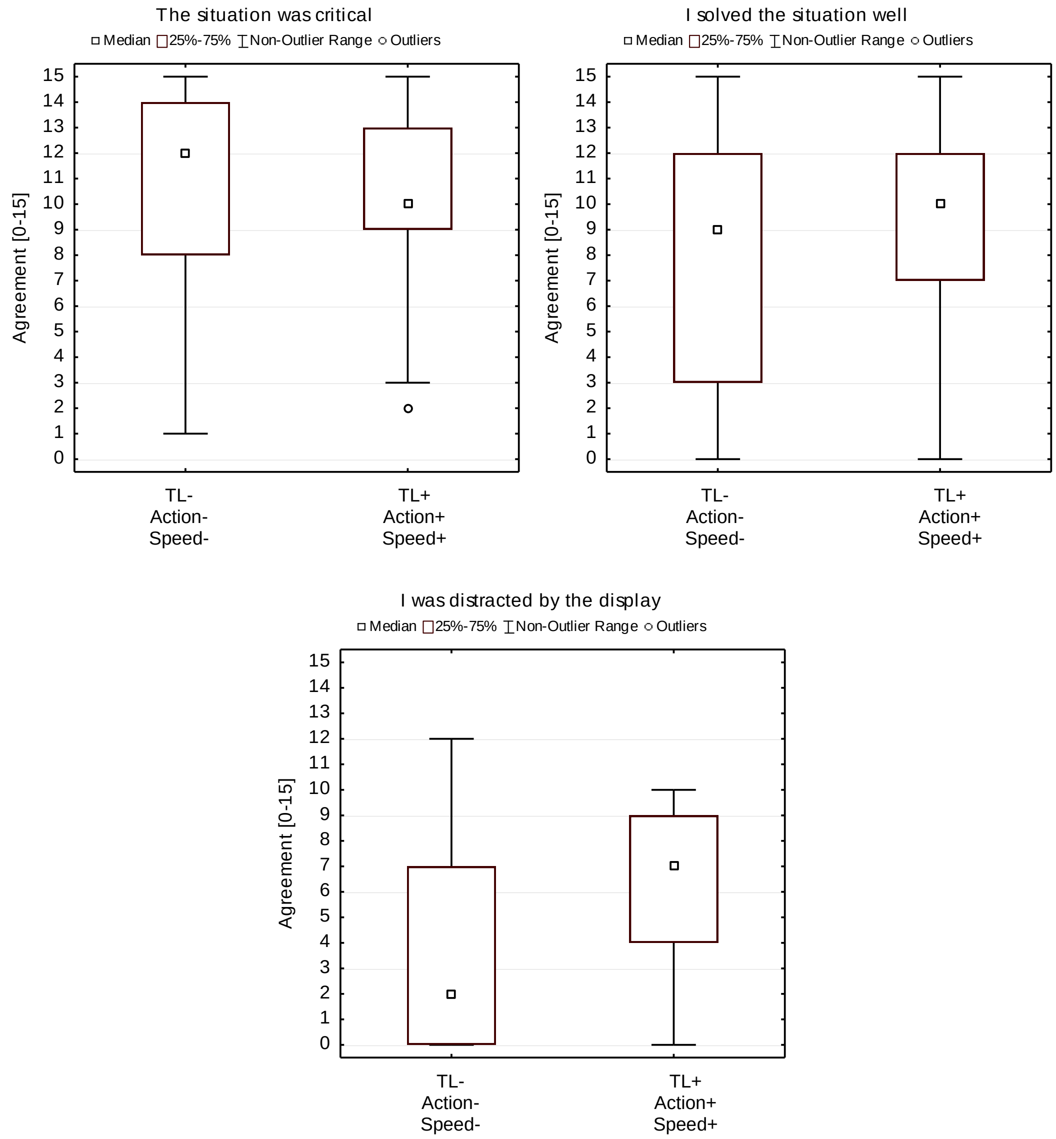


Figure 66. Agreement to the statements evaluating the critical situation. The HMI versions are described by either containing (+) or not containing (-) each of the three information units traffic light phase information (TL), action recommendations (Action) and speed recommendations (Speed). Graphs show boxplots with median.

3.3.2.3 Summary and Discussion

Study 3 investigated the HMI strategy for the traffic light assistant. The evaluation criteria were the subjective assessment of participants, the efficiency of the system by means of driving profiles, the information usage in terms of gaze behaviour, and the influence of the HMI versions on driving safety. The experimental design included the different information units traffic light phase, action recommendations and speed recommendations. Two main research questions were stated: Which information units are suitable to support the drivers? Does a combination of information units lead to redundancy gains, i.e. an improved performance, or does the combination of information units lead to overload, i.e. deterioration of performance? Overall, four main conclusions are drawn from the results:

- The three information units traffic light phase information, action recommendations, and speed recommendations should be presented in the HMI.
- The combination of information units leads to improved driver performance. This supports the redundancy gain hypothesis.
- No HMI version led to safety critical behaviour.
- The traffic light assistant is especially beneficial in situations when the traffic light phase changes.

Subjectively, drivers preferred HMI versions that contained information on traffic light phasing. As an explanation, the traffic light phase information directly visualises the benefits of the system. Knowing about the phase timing and the phase at arrival demonstrates the increased quality of information that is available from the system. Additionally, without traffic light phase information the recommended driving behaviours could contradict with the driving behaviour that the real traffic light might require (e.g. the system recommends driving 50 km/h, while the real traffic light is still red). The drivers might value the traffic light phase information in the display as an additional explanation for the speed and action recommendations. This is in line previous research (e.g. Cao et al., 2010). Further, in the forced choice situation, most drivers prefer the HMI concept containing all three information units. Increasing from zero to any one information unit increased drivers' ratings of helpfulness and information richness. More information units did not lead to much better ratings, which shows that any one of the information units is able to satisfy drivers' subjective evaluation of the display.

Over all driving situations, the deviations of driving speed from target speed were largest without any information unit in the HMI. The presentation of any one information unit reduced the deviations from target. Hence, any information in the HMI has the potential to modify driving behaviour to some extent. The results are in line with previous research indicating that driver's performance in reaction to the recommendations is better with command information (i.e. action or speed recommendations) compared to status information. In particular, to follow the predetermined driving strategy, the combination of speed recommendations and action recommendations was most beneficial. Speed recommendations were especially beneficial, when drivers crossed the intersection (in red to green conditions). Additionally, the number of unnecessary stops was lowest with speed recommendations. In the situations in which drivers are able to pass the intersection without stop, the main target is reaching and holding a required driving speed. Thereby, the speed recommendations trigger the well-trained behaviour of modulating driving speed towards a target. Contrary, with action recommendations that are supposed to guide drivers to the correct driving speed, excessing and undercutting the required driving speed might happen. In turn, action recommendations supported stopping at red lights better than the other information units. Speed recommendations were only relevant when no action recommendations were present. When initiating stops at red, action recommendations (e.g. coast) seem to be the more plausible and therefore more helpful information unit than the 0 km/h included in the speed recommendations. The traffic light phase information was only relevant for reductions in the deviations from the target speed when the traffic light was red or changed from green to red and no other information unit was present. Receiving traffic light information requires some trial and error in order to find out about the appropriate driving behaviour for the respective traffic light state. This can be beneficial when drivers are willing to exceed or undercut certain thresholds for deceleration or driving speed. As the results showed, some participants reduced their driving speed extensively when they received traffic light phase information. These drivers explored the assistant in varying their driving speed (some while neglecting the action and speed recommendations in the display). They found out at which driving speed the status changed from arrival at red to arrival at green. By this, they were able to apply the HMI to situations that were not considered in the experimental setting, because they were willing to reduce their driving speed significantly below the lower speed threshold in the algorithm of the traffic light assistant. Hence, the status information offers the potential for drivers to decide self-determined on the extent of changes in driving behaviour. Thresholds for speed or maximum deceleration in the algorithm do not influence the traffic light information.

Moreover, presenting any of the three information units led to longer times fixating the display compared to presenting no information units. When the traffic light changed from red to green, the speed recommendations were so important for drivers that no differences in percentage of time fixating the display occurred between HMI versions with and without traffic light information. When the traffic light changed from green to red, the action recommendations were important for drivers and no difference between the traffic light phase information conditions was measured. For solid red and green to red traffic lights, the speed recommendations decreased the percentage of time fixating the display compared to no speed recommendations, when additional action recommendations or traffic light phase information was present. Moreover, the HMI version presenting a combination of speed and action recommendations led to the shortest fixation durations of all HMI versions containing at least one information unit.

Overall, the results support the redundancy hypothesis. In terms of driver performance, the combination of information units led to improvements in the target behaviour of participants. However, the reason for the facilitation of sticking to the target behaviour remains unclear. It might be that drivers decide which information unit is helpful in any moment. As outlined above, for situations in which drivers pass the intersection without stop, speed recommendations are most beneficial. For situations in which drivers have to initiate a stop at a red traffic light, action recommendations are most beneficial. The presentation of all information allows drivers to choose the information that is most beneficial for them. Alternatively, the information units represent a certain level of redundancy. The information units supplement each other and dependent on each other. For example, during the rides drivers could learn that speed recommendations of 0 km/h are associated with the recommendation to coast to 0 km/h. The potentially irritating recommendation of 0 km/h then represented the same driving behaviour as the recommendation to coast. In terms of Wickens and Hollands (2000), speed and action recommendations have a high processing proximity expressing that the extent to which the two information sources are used within the same task is high. Then, with the combination of information units, the level of detail of the instructions increases, which facilitates the understanding of the required driving behaviour and triggers the improved performance.

In terms of gaze behaviour, the results partially confirm the redundancy hypothesis. In situations in which drivers stopped at the intersection at red or green to red, the combined presentation of action and speed recommendations lead to lower gaze durations compared to the single presentation of speed or action recommendations. The combination of these two information units accelerated the information processing. However, the traffic light phase information as status information increased the fixation durations compared to solely presenting speed and action recommendations. Apparently, this status information implies an additional quality of information that requires longer processing times. Additionally, in the display the spatial distance of the traffic light phase information to the other two information units was larger compared to the distance between speed and action recommendations. Hence, in combination with additional traffic light phase information, more information units did not lead to facilitations in information processing and the redundancy hypothesis was not confirmed.

Nevertheless, the results can rebut the overload hypothesis. Driver fixation durations in all HMI versions matched the 1.5 s criterion for the 85th percentile level of the ISO 15005:2003. Surprisingly, even though the study took place in a laboratory setting, drivers violated traffic rules by speeding and/or violating red lights. This mostly occurred without any information in the HMI. Presenting one information unit or presenting combinations of information units decreased the risk for red light violations. In line with this, presenting all three information units did not negatively influence driving behaviour in the critical situation compared to the baseline. Differences occurred neither in dynamic parameters nor in the number of collisions. Drivers were able to prioritise safe driving over efficient driving as recommended by the system. However, for the critical situation in the experiment needs to be considered that it allowed for a large range of driving behaviours that would have helped to avoid the crash (e.g. accelerating to leave the intersection before the emergency vehicle occurred, or coming to standstill at various distances in front of the intersection). This resulted in high variations in observed dynamic driving parameters. For a further investigation of driving behaviour, the HMI information strategy should be tested in a wider range of potentially critical situations. Nevertheless, the results show that even in the most complex HMI version, the visual load was on an appropriate level. Additionally, driver performance in sticking to the recommendations, red light violations and reactions in the safety critical situation improved with the presentation of information units in the display. Supporting this, drivers subjectively rated no HMI version as highly complex and they were not overstrained by any combination of information units. Overall, the results of the study showed no evidence for driver overload.

Generally, the traffic light assistant resulted in the greatest benefits when the traffic light changed compared to remaining solid. In line with Popiv et al. (2010) the assistance for anticipatory driving especially helps drivers when the deceleration situation cannot be seen in advance. For green traffic light approaches, the HMI versions had no influence on the deviations from target speed. This is because the assistant in this situation recommended driving 50 km/h, which is the desired driving speed for participants (Mühlbacher, 2013). The speed plots for the other traffic light phases confirmed the expectations from Study 1: Without traffic light assistant, drivers prepared and realised driving behaviour that was not appropriate for the traffic light phase at arrival. Adaptations and corrections to the initiated behaviour (e.g. acceleration to avoid the already initiated stop) were then necessary and led to decreases in efficiency of driving. Also, in the changing green to red traffic light phase, most red light violations and speed violations occurred. This situation is well known from everyday traffic, in which drivers try to challenge the traffic light and assume to be able to cross the traffic light at green when increasing driving speed. However, in the current setting, crossing the intersection at green required speed violations. The traffic light assistant reduced the number of safety critical driving events in these situations.

In summary, the present data point towards the presentation of all three information units for communicating recommendations to the driver. Even though the benefits for adding multiple information units only slightly increased when adding a second or third information unit compared to a single one, different driving situations benefited from different information units. In presenting all information units, drivers can rely on the most useful information unit in any specific situation. The traffic light phase information was the most important according to the subjective evaluations and did not negatively influence driving performance. Command information in terms of speed and action recommendations led to the best driving performance. Importantly, presenting all information units does not threat safety (in terms of gaze behaviour) and in some situations even increases safety (in terms of red light violation) compared to the baseline condition.

4 Method related research

In the investigation of driving behaviour at traffic light intersections and the HMI strategy for the traffic light assistant, a methodological research question occurred. During driving and in the interaction with the traffic light assistant, drivers have an information demand for certain stimuli. In the presented content related research, the information demand was measured by eye tracking. This offered valuable information on drivers understanding and decision making in driving. However, the evaluation of the eye tracking method results in some flaws and limitations. Within the frame of the content related research questions covered in this thesis, a novel method for measuring information demand for action relevant stimuli by masking them, the MARS (Masking Action Relevant Stimuli) method, was developed and evaluated.

The following chapters include a theoretic background for the measurement of information demand by means of eye tracking. Subsequently, they introduce the MARS method. The studies following the theoretic background outline the application of the MARS method to a dynamic stimulus outside the vehicle, i.e. the traffic light phasing, and to a dynamic stimulus inside the vehicle, i.e. the HMI display of the traffic light assistant.

4.1 Theoretic background

4.1.1 Definition of information demand

In general, planning a motor action is influenced by action relevant features of related objects in the environment (Bekkering & Neggers, 2002). Especially in complex dynamic situations like driving, it is efficient to apply task-specific visual strategies (Shinoda, Hayhoe, & Shrivastava, 2001). The drivers cannot anticipate and process all information available in their driving environment (Ullman, 1984). The different tasks performed while driving (e.g. steering, braking, turn manoeuvres, car following) require different information units from the driving scene (Shinoda et al., 2001). Therefore, the experience and expectations drivers have in specific driving situations influence the importance of certain information in the road environment.

In line with that, when approaching traffic light intersections, certain elements of the driving scene have direct action implications. In order to perform the driving task correctly, the driver processes the action relevant information and selects an appropriate response. Crucial action relevant information is the traffic light phasing. Based on the perception of that information drivers decide about the necessity to initiate a stop at the intersection. Similarly, in the interaction with the traffic light assistant, the driver must process the information presented in the HMI in order to drive according to the recommendations.

Therefore, drivers have a demand for the obtained information units. That is, they make the conscious decision to attend to the source of information. Information demand relates to action relevance: In order to come to a decision on the desired or appropriate behaviour, the information from the relevant stimulus is required. The more action relevant an information is for solving the current driving task, the higher is the information demand for that information. Importantly, the information demand results in conscious decisions to attend to a stimulus. Information demand does not include unconscious bottom-up triggered attention on stimuli.

The knowledge about the relevance of specific stimuli for the driver represents an important input for transportation research. The complexity of traffic and the amount of information that drivers need to process increase. Details on driver’s information demand help explaining decisions while driving and might be able to predict certain driving behaviours. Consequently, information about whether and when drivers have an information demand for specific elements of the driving scene gives input to the research on basic principles of information processing while driving. Additionally, measuring information demand supports the development of driver assistance systems and can initiate improvements in the infrastructure and road design.

4.1.2 Eye tracking for measuring information demand

Information demand has been measured by means of eye tracking. A large number of research has shown the relation between attention and fixations (Corbetta, 1998; Konstantopoulos et al., 2010; Shinar, 2008). Just and Carpenter (1980) stated general assumptions on the relation between eye movements and cognitive processes. The assumptions based upon research on cognitive processing and gaze behaviour while reading. The Eye-Mind Assumption states that fixated objects are cognitively processed. The Immediacy Assumption states that fixated objects are processed immediately. The Sequence Assumption states that the sequence of fixations indicates the sequence of processing steps.

In the driving context, the eye tracking method includes the recording of eye movements, saccades and fixations with camera systems. The analysis of eye tracking data focuses on specific defined areas of interest. Different parameters are analysed in relation to these areas of interest, for example the number and duration of eye fixations.

Information needed for solving the driving task is mainly visual (Gelau & Krems, 2004; Van Der Horst, 2004). Therefore, eye movements to specific areas of interest in the driving scene have been interpreted in terms of information demand. Strategies considering the task context, goals and expectations influence the visual search patterns in driving (Engström, 2011). The strategies allow the acquisition of relevant information from the driving scene and the anticipation of demanding driving conditions (Shinoda et al., 2001; Underwood, 2007). A driver will sample a certain area of interest more frequently when he expects relevant information there (Horrey et al., 2006). For example, Horrey et al. (2006) described situations with high and low information bandwidth. In situations with low bandwidth (e.g. a smooth road without curves), less frequent sampling of a specific information (e.g. lane position) is necessary compared to situations with high information bandwidth (e.g. a curvy road). Pradhan et al. (2005) recorded eye movements in order to measure drivers abilities to “acquire and assess” the relevant information from the driving scene. The authors assume that the higher risk for accidents in younger and novice drivers relates to the ability to attend to risk relevant elements in the environment. In a further study, experienced and novice drivers watched videos of driving scenes (Underwood, Chapman, Bowden, & Crundall, 2002). The number and length of fixations on the relevant areas indicated the correct understanding of the driving scene. Based on this analysis, the authors concluded that novice drivers have poor mental models of the driving situations. Contrary, experienced drivers showed appropriate scanning patterns. Furthermore, a driving simulator study showed the relation between fixations and action relevance (Sullivan, Johnson, Rothkopf, Ballard, & Hayhoe, 2012). The researchers manipulated the priorities of different driving tasks. The instruction for drivers was either to prioritise keeping a certain speed or to follow a lead vehicle in a specific distance. The results showed that the task priority was the main factor influencing the probability of gazes to the task relevant areas of interest and the fixation durations. When keeping the defined speed limit was the primary task, the probability for gazes to the speedometer increased. When keeping the defined distance to the lead vehicle was preferred, the probability for gazes to the lead vehicle increased (Figure 67).

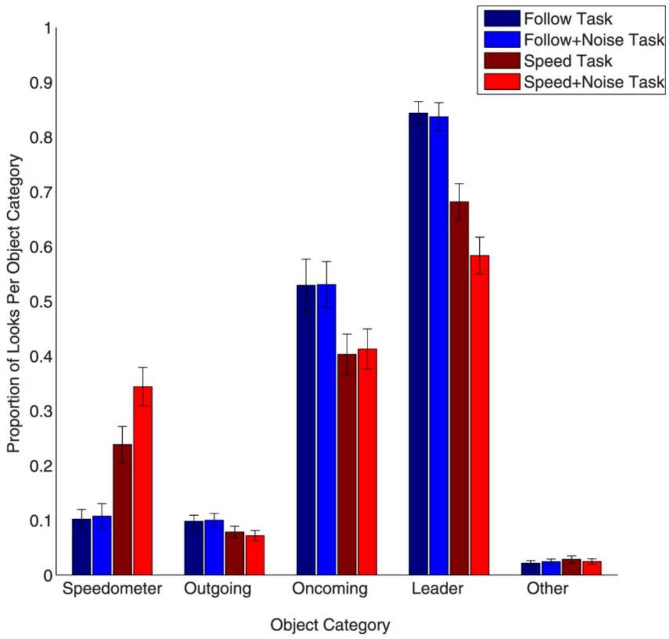


Figure 67. Mean percentage of gazes to different areas of interest in the study of Sullivan et al. (2012), depending on the instruction of priorities for certain tasks (keeping distance in car following vs. keeping speed). Leader means lead vehicle as area of interest.

Shinoda et al. (2001) varied the location and relevance of task-specific information. While driving through the test track in a driving simulator, a no-parking sign was replaced occasionally by a stop sign. The behavioural relevance of the signs was manipulated by instruction (follow the lead vehicle vs. adhere traffic rules while following) and by the position of the stop sign (at an intersection vs. not at an intersection). They found that with the instruction to follow the traffic rules, the proportion of time fixating on the side of the road increased compared to without that instruction. Furthermore, when the stop sign appeared at the intersection, the probability for detecting the sign increased compared to the when the stop sign was placed along a straight road (Figure 68). The authors concluded that “perception appears to depend heavily on active search initiated by the observer, based on learnt probabilities". The target behaviour influenced the fixations occurring during driving.

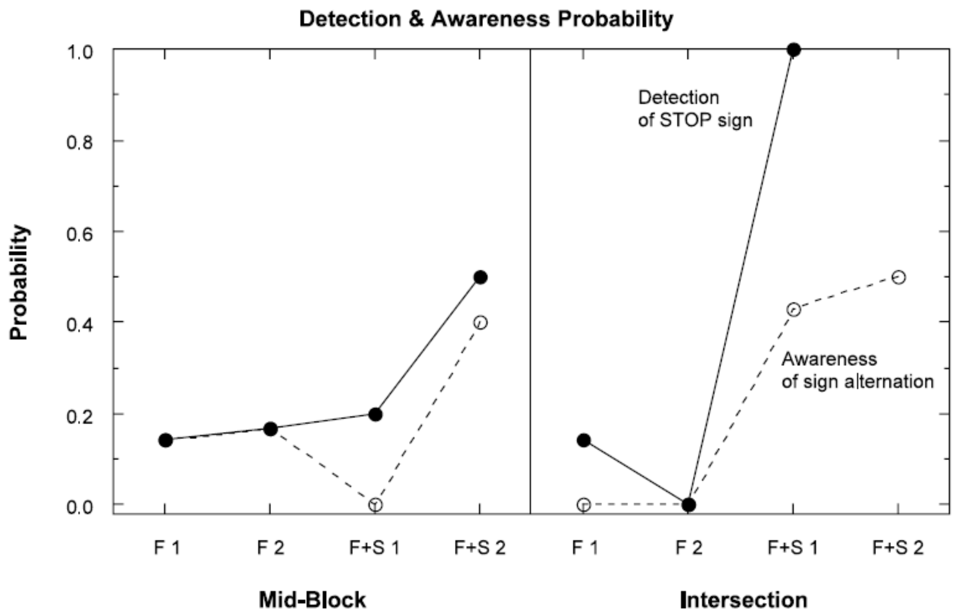


Figure 68. Results of Shinoda et al. (2001) for the two different sign locations (mid-block = presentation of the sign along a straight road) and for different instruction conditions (F = follow lead vehicle, F+S = follow lead vehicle and pay attention to traffic rules). Each instruction condition was repeated twice. The continuous line represent the probability for detecting the stop sign (predominantly based on fixations on the sign), the dashed line represents the probability for noticing that the stop sign changed to a no-parking sign and back.

Eye tracking has been a well-established method in transportation research and the summarised literature demonstrates the relation between fixations and action relevance. However, there are some limitations when measuring information demand by means of eye tracking. First, the assumptions made by Just and Carpenter (1980) do not generalise and transfer directly to the driving context. Fixating areas of interest does not necessarily include that drivers actually attend to the fixated locations. Shinar (2008) pointed out that "the open eyes always fixate somewhere in space", while the attention might be allocated elsewhere. This results in the frequently mentioned phenomenon of inattentional blindness. Inattentional blindness describes "the failure to see highly visible objects we may be looking at directly when our attention is elsewhere" (Mack, 2003). In the transportation context, the "looked-but-failed-to-see" failure represents as an example for visual fixation without attention (Greenberg et al., 2003). It describes situations in which drivers fail to notice relevant objects or events in their driving environment even though the direction of fixations was correct. Hence, a driver who fails to notice information might show the same gaze behaviour like a driver who actually processes the fixated information (Galpin, Underwood, & Crundall, 2009).

Second, even if the drivers fixate and attend to the specific area of interest, measuring eye movements cannot determine whether fixations occur because of action relevance and a conscious information demand for the attended object. Alternatively, drivers simply have to look somewhere in the road scene and fixations can occur without information demand. Kircher et al. (2014) defined these "convenience glances" as glances that occur without immediate requirement to fixate on the area. In that case, bottom up mechanisms might play a role. For example, some stimulus features such as colour or brightness could guide drivers' attention towards a certain object. Hence, eye movements do not necessarily serve as a distinct measure of information demand.

Third, attention can shift to a relevant location without fixating this location. In that case, the gaze position differs from the position of attention (Posner, 1980). Measuring eye fixations then could not indicate the actual information demand for the currently relevant area of interest. For example, a highly salient stimulus when approaching intersections is the traffic light. In that case, drivers might use peripheral vision and perceive the traffic light phase as relevant information without fixating it. Measuring eye fixations would then fail to reflect information demand.

Besides the limitations in the interpretation of eye tracking data, the method comes along with some technical disadvantages. Direct measurement of eye movements is typically difficult and expensive (ISO 16673:2007). For video-based eye trackers, individual calibration prior to recording is necessary. Depending on the used technology, this can be time consuming. Further, the quality of the recorded data depends on behaviour of the individual participants and characteristics of the setting. Due to the limited size of the camera lenses, specific movements might lead to interruptions of data recording. In addition, varying brightness and light conditions in the experimental setting challenge the quality of the recorded data. Characteristics like specific eye colour, face and body shape or the presence of glasses negatively influence the recording quality. Additionally, the intrusive equipment of some eye trackers can lead to limitations in study designs due to the restriction of experiment durations. Especially head or face-mounted systems can be uncomfortable for drivers and the quality of data recording can vary within drives due to changes in the eye tracker position. For the data analyses, eye tracking data have to be filtered and further processed (see for example chapter 3.2.2.2). Difficulties arise when researchers aim on differentiating between fixations on objects that are very small or in near proximity to each other. Conventional eye trackers are accurate within 0.5 – 1 degree, while accuracy can vary across the screen when analysing eye movements on displays (Sundstedt, 2012). Limitations to an efficient data analysis occur for objects with variable positions in the recorded picture frames, which is usually the case in dynamic driving.

In summary, eye tracking has been the dominant method to measure driver information demand for stimuli. In the present thesis, it was important to determine the information demand for different stimuli in the investigation of driving behaviour at traffic light intersections and in the evaluation of the HMI concept for the traffic light assistant. Due to the outlined challenges for the interpretation and analysis of eye tracking data, the methodological research question on the measurement of information demand arose. The goal was to find a supplement or alternative method for assessing how much information drivers request from objects in the driving environment.

4.1.3 The MARS Method

The MARS method was developed to supplement or substitute the recording and analysis of eye movements. The background for the implementation of the MARS method is the occlusion technique. Occlusion describes the “physical obscuration of vision” for total or major parts of the driving scene (Lansdown, Burns, & Parkes, 2004; Senders, Kristofferson, Levison, Dietrich, & Ward, 1967). Researchers have realised the occlusion for example by using specific spectacles (Van Der Horst, 2004), by applying curtains in the vehicle (De Vos, 2000) or by covering the lens of the projector in the driving simulator (Tsimhoni & Green, 1999). The de-occlusion usually occurs for fixed periods of time in predefined intervals (Van Der Horst, 2004). The goal of visual occlusion was to measure the visual demand of the driving task in relation to driving safety, the time drivers needed to process visual information to solve a secondary task satisfactorily and the effects of interruptions on the primary and the secondary task performance (Gelau & Krems, 2004). The ISO 16673:2007 recommends the occlusion method for the evaluation of in-vehicle systems. Periodically blocking the driver’s view of the display allows estimating whether drivers are able to resume to a task with partitioned visual information from the in-vehicle system.

Even though the MARS method is based on the concept of visual obscuration, the target of investigation differs from the occlusion technique. While occlusion techniques investigate visual distraction and workload, the MARS method studies the information demand that drivers have for a specific dynamic element of the driving scene.

In the MARS method, a single dynamic stimulus in the driving scene is masked. The stimulus itself is present, while the masking obscures the crucial action relevant information. Drivers can unmask the stimulus on demand (e.g. by pressing a button).

After demanding the information, the stimulus is unmasked for a fixed interval, before the masking returns. Drivers can initiate unmasking whenever and as often as they want. Thus, the masking is embedded in the normal driving scene. The MARS method then requires no other task for drivers than to drive normally. As dependent variable of the MARS method serves the number of information demands by button presses. Resulting from that, the duration of information demand time can be determined. The assumption is that the number of times the drivers require the information from the stimulus represents the degree of information demand drivers have for the specific stimulus. The demand occurs, because the stimulus is action relevant. Additionally, the MARS method allows for the interpretation of time or position of information demands. Like this, the researcher might be able to identify when drivers make decisions regarding their driving behaviour, and when specific information is relevant.

4.2 Studies

The MARS method was applied to the two main scenarios that were developed in the course of the content related research: Approaching traffic light intersections as baseline investigation and approaching traffic light intersections with traffic light assistant.

4.2.1 Study 4: Information demand for the traffic light[4]

In the first study applying the MARS method, the information demand drivers have for the traffic light as dynamic stimulus in the environment is measured. As pointed out previously, the traffic light phase is a crucial information that drivers need to process in order to come to the correct decision on proceeding or stopping at the intersection. Without knowing the traffic light state, red light violations or unnecessary stops might occur. Furthermore, the traffic light phasing is dynamic, which requires repeated reappraisal whether driving behaviour and traffic light situation are concordant. Hence, in the current setting, the traffic light state is the masked stimulus and drivers initiate the unmasking interval by pressing a button.

To evaluate the sensitivity of the MARS method, the experimental approach of Study 1 serves as a background. In Study 1, the variation of traffic light phases caused different driving behaviours. Hence, the hypotheses is that dynamics in the traffic light phasing (i.e. changing vs. solid traffic light phases) influence the information demand drivers have for the traffic light. Further, Study 1 showed that lead vehicles serve as source of information about the required driving behaviour. Therefore, it is expected that the information demand as measured by the MARS method varies between conditions with and without lead vehicle. Finally, visibility is limited in the track by means of fog. For the evaluation of the MARS method, the limitation of the visibility allows to investigate whether drivers actually relate their information requests to the stimulus, or whether drivers express their information demand irrespective of the visibility of the stimulus. The expectation is that drivers only request information from the traffic light by unmasking when the traffic light is actually visible and meaningful information can be retrieved from it. Contrary, drivers would not demand information as long as fog covers the traffic light. Figure 69 summarises the factors considered in the study.

[4] Parts of this study are published in Rittger, Kiesel, Schmidt, and Maag (2014).

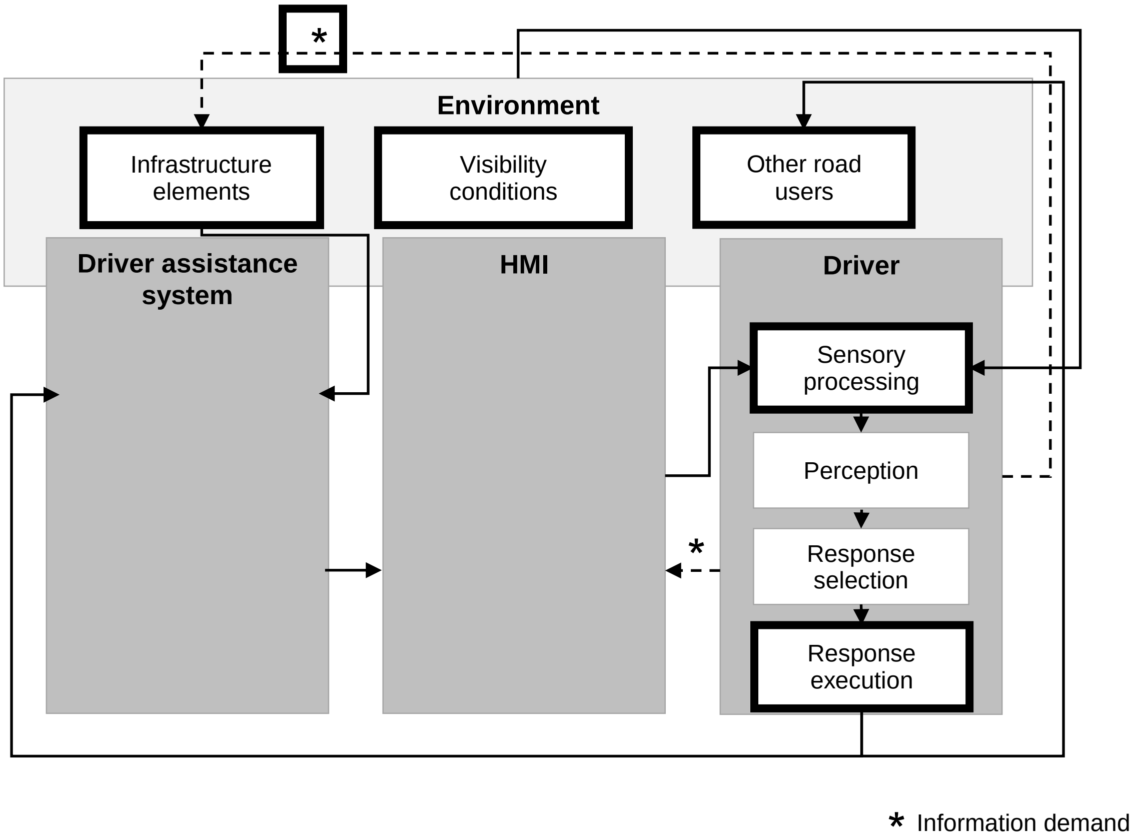


Figure 69. Relation of the factors considered in the present thesis. Bold frames indicate factors investigated in the evaluation of the MARS method during Study 4. Adapted from Bruder and Didier (2012), Wickens and Hollands (2000) and Zarife (2014).

For the further evaluation of the MARS method, the information demand measured by the number of unmasking intervals is compared to the measurement of information demand by means of eye tracking. The presented literature shows that eye tracking represents the standard method for measuring information demand in dynamic driving situations. Study 1 showed that the variations in traffic and environmental conditions varied drivers' fixations on the traffic light. It is expected that the variations in the track influence the information demand measured by the MARS method qualitatively similarly to the information demand measured by eye tracking. Increased number and duration of fixations on the traffic light should occur in the same conditions in which increased number of unmasking intervals occur when using the MARS method.

Moreover, a further investigation compares the driving behaviour recorded while using the MARS method and driving behaviour while recording gaze behaviour with the eye tracker. For the applicability of the MARS method for driving in the driving simulator, it is necessary to show that the MARS method does not alter normal driving behaviour. In general, it is widely accepted that driving with the eye tracker does not interfere with driving behaviour, i.e. that while recording eye movements drivers show normal driving behaviour. Therefore, this condition serves as a baseline for the investigation of driving behaviour with the MARS method. It is expected that the MARS method does not alter normal driving behaviour, because drivers are able to request the relevant information whenever it is necessary for them. Therefore, similar to conditions without masking, they come to the appropriate decisions on how to proceed.

Finally, the evaluation of the MARS method closes with a subjective evaluation of driving with the covered traffic light phasing. By that, subjective difficulty of using the MARS method is investigated. In order to operationalise the MARS method for measuring information demand, the method should not disturb drivers and it should be easy to learn how to request the information.

4.2.1.1 Methods

The first evaluation of the MARS method based on data recorded in Study 1. The MARS method was applied in a second drive conducted within the procedure of Study 1. The driving data discussed in chapter 3.1.2.2 served as a baseline to compare whether the MARS method causes changes in driving behaviour. The gaze behaviour in terms of fixations on the traffic light discussed in chapter 3.1.2.2 was compared to the information demand measured in terms of button presses in the MARS method. Therefore, the driving simulator setting, the test track and the participants used for the first evaluation of the MARS method are identical to the methods reported in chapter 3.1.2.1. The following chapters only include details that changed or further support the understanding of the methods in Study 4.

Apparatus

The study took place in the static driving simulator. The steering wheel of the driving simulator mock-up had two buttons positioned at the left and the right side. While driving, participants could press the buttons conveniently with the left and the right thumb.

Design

The experiment had a full within subjects design. The three varied factors were traffic light phase (green, red to green, red, green to red), lead vehicle (with vehicle, without vehicle) and visibility (with fog, without fog). The variations and repetitions of conditions resulted in 40 traffic light approaches within one test drive. Additionally, two conditions were distinguished within participants: The GAZE and the MARS condition. Each driver experienced the 40 intersections once in the GAZE condition and once in the MARS condition. The GAZE condition represented the baseline condition. It allowed for the analysis of unassisted driving behaviour at traffic light intersections and enabled to measure drivers' fixations on the traffic light. In the GAZE condition, the eye tracking system recorded drivers' fixations on the traffic light while the traffic light was always visible in the track. In the MARS condition, no eye tracking was active. When approaching the intersections, the traffic lights were masked while the traffic light programme was running as normal. Drivers pressed one of the two possible buttons at the steering wheel in order to unmask the traffic light for 800 ms before the masking returned. Pre-tests had shown that 800 ms offered sufficient time to process the information from the traffic light. Longer or repeated button presses within the unmasking interval did not lead to longer unmasking intervals. To unmask the traffic light again in masking intervals, drivers pressed the button again. Participants pressed the button as often they wanted and whenever they wanted. Figure 70 shows a schematic depiction of the MARS method.

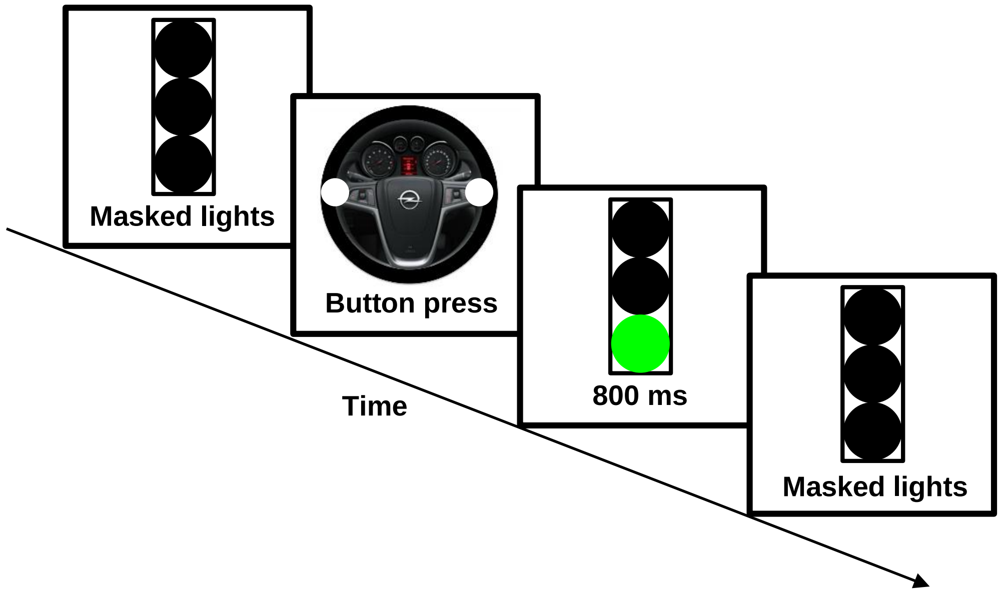


Figure 70. Schema of the MARS method. The traffic light was masked while driving. When pressing one of two buttons located at the steering wheel (indicated by the white dots), the traffic light unmasked for 800 ms before the masking returned. Note that the traffic light was embedded in a natural driving scene.

To compare the driver's information demand for the traffic light in the MARS and the GAZE condition, number and duration of button presses and fixations on the traffic light were analysed, respectively. For the determination of unmasking intervals when driving with the MARS method, the SILAB log files recorded an additional variable. The variable was coded binary and showed if the traffic light was visible and or not visible for drivers in each 8 ms data point. Driving behaviour in both conditions was compared in terms of speed and acceleration. For the subjective evaluation of driving with the MARS method, a questionnaire was used. It contained three closed items and three open questions.

Participants answered the closed items on the verbal-numeric scale (Figure 52). Further, drivers named situations in which driving with the masked lights was especially easy or difficult and mentioned if and which strategies they used for driving with the masked lights. Table 20 summarises the dependent variables investigated in the study.

Table 20. Overview of the dependent variables recorded in the experiment.

Dependent variable	Unit	Description
Speed	km/h	Speed with which the vehicles proceeds
Acceleration	m/s²	Acceleration when increasing speed
Deceleration	m/s²	Deceleration when decreasing speed
Button presses	Press vs. no press	Usage of the buttons at the steering wheel to unmask the traffic light
Unmasking intervals	%	Proportion of time with unmasked traffic lights in relation to total duration of a specific distance section
Number of fixations on the traffic light	[]	Number of fixations on the traffic light in a defined distance section
Fixation intervals on the traffic light	%	Proportion of time fixating on the traffic lights in relation to total duration of driving in a specific distance section
Evaluation of driving with the MARS method	Verbal-numeric scale from 0-15	Three questions evaluating the MARS method: It was difficult to drive with the masked traffic light; It was disturbing that the traffic light was masked; The more I drove with the masked traffic light, the easier was driving

Procedure

The two experimental conditions (GAZE, MARS) followed each other in two consecutive drives with counterbalanced order. Each drive consisted of 40 intersections. Before the GAZE condition started, the experimenter calibrated the eye tracking system for each participant. Before the MARS condition started, participants experienced a practice track with two intersection approaches with masked lights in which they practiced unmasking the lights. Before each experimental drive, participants were instructed to follow the traffic rules. After the MARS condition, participants filled out the questionnaire. The procedure took approximately two hours for each participant.

4.2.1.2 Results

For the analyses of the information demand during the traffic light approaches, data were averaged over repeated traffic light intersection approaches for each participant. ANOVAs considered the repeated measurements design. The data analysis included the approach distance of 230 m in front of the intersection. Analyses were conducted separately for traffic light approaches with and without a stop. The eye tracking data were prepared as described in chapter 3.1.2.2.

Number of information demands for the traffic light

The number of information demands was the number of fixations on the traffic light in the GAZE condition and the number of button presses in the MARS condition. Figure 71 shows descriptively that the information demand increased during the approach to the traffic light and peaked around 30-20 m in front of the intersection. Drivers came to standstill when the traffic light was red at this distance. The number of fixations on the traffic light in the GAZE condition exceeded the number of button presses in the MARS condition.

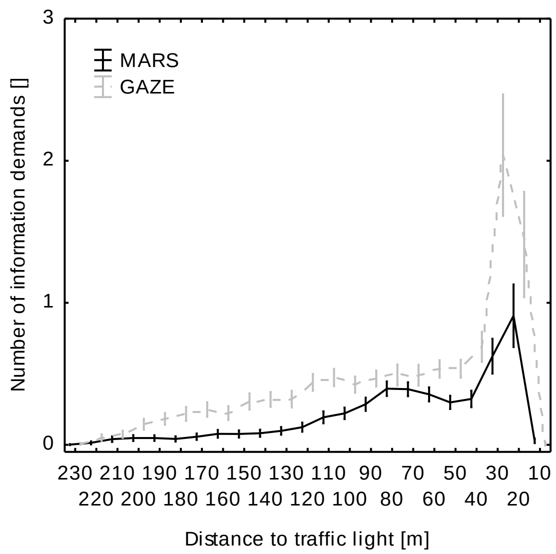


Figure 71. Number of information demands in the MARS and the GAZE condition averaged over all factor combinations. Graph shows means with 95% confidence intervals.

The number of information demands was averaged for the 230 m distance of the traffic light approach. Two ANOVAs included the independent variables condition (MARS, GAZE), traffic light phase (green and red to green, red and green to red), lead vehicle (with, without) and fog (with, without). The dependent variable was the information demand. Table 21 and Figure 72 show the ANOVA results for green and red to green traffic lights. Drivers fixated the traffic light more often in the GAZE condition than they pressed the button to unmask the traffic light in the MARS condition. When the traffic light changed from red to green, the number of information demands reduced compared to solid green lights. When there was a lead vehicle or fog in the track, the number of information demands was lower than when there was no lead vehicle or no fog in the track, respectively. The two ordinal interactions between the factors condition and lead vehicle and the factors condition and fog expressed that in the GAZE compared to the MARS condition, the difference between the two lead vehicle and the two fog conditions was greater.

Table 21. Summary of ANOVA results for the number of information demands for green and red to green traffic lights. Bold numbers mark significant effects.

Effect	Df effect	Df error	F	p	$\eta^2_{partial}$
Condition (C)	**1**	**11**	**6.401**	**.028**	**.368**
Traffic light phase (TLP)	**1**	**11**	**11.617**	**.006**	**.514**
Lead vehicle (LV)	**1**	**11**	**23.335**	**<.001**	**.680**
Fog (F)	**1**	**11**	**22.860**	**<.001**	**.675**
C x TLP	1	11	.408	.536	.036
C x LV	**1**	**11**	**17.928**	**.001**	**.620**
TLP x LV	1	11	4.769	.051	.302
C x F	**1**	**11**	**14.171**	**.003**	**.563**
TLP x F	1	11	.390	.545	.034
LV x F	1	11	.526	.484	.046
C x TLP x LV	1	11	.511	.378	.071
C x TLP x F	1	11	.291	.600	.026
C x LV x F	1	11	.087	.774	.008
TLP x LV x F	1	11	.992	.341	.083
C x TLP x LV x F	1	11	.047	.832	.004

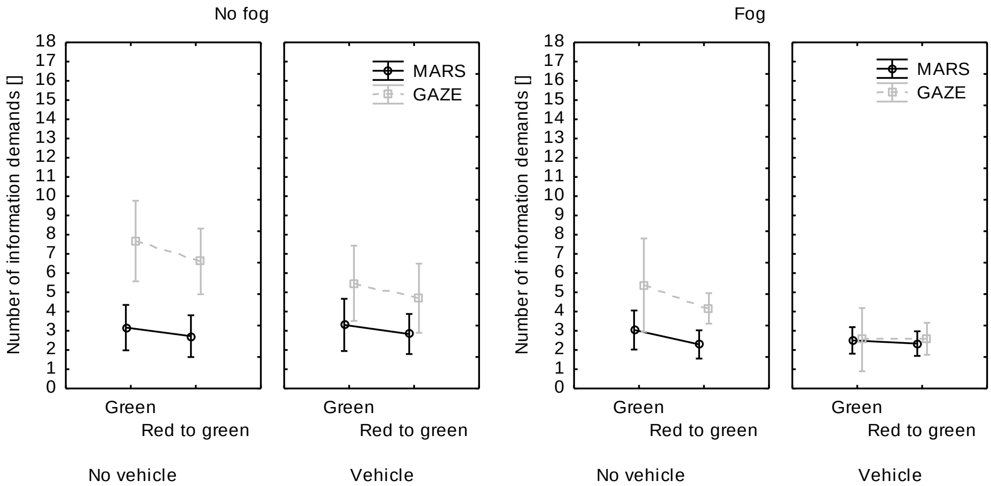


Figure 72. Number of information demands in the MARS and the GAZE condition depending on the factors traffic light phase, lead vehicle and fog for traffic light approaches with solid green and changing red to green phase. Graph shows means with 95% confidence intervals.

Table 22 and Figure 73 show the ANOVA results for red and green to red traffic lights. Drivers fixated the traffic light more often in the GAZE condition than they pressed the button to unmask the traffic light in the MARS condition. The information demand was higher when the traffic light was solid red compared to a changing green to red light. Without lead vehicle compared to with lead vehicle and without fog compared to with fog, the information demand was higher, respectively. Again, the ordinal interactions between the factors condition and lead vehicle, and the factors condition and fog express that in the GAZE condition, the differences in information demand were more exaggerated compared to the MARS condition. The ordinal three-way interaction between condition, traffic light phase and lead vehicle emphasised that in the GAZE condition, the information demand was higher than in the MARS condition, and that this effect was strongest, when the traffic light was solid red and there was no lead vehicle ahead.

Table 22. Summary of ANOVA results for the number of information demands for red and green to red traffic lights. Bold numbers mark significant effects.

Effect	Df effect	Df error	F	p	$\eta^2_{partial}$
Condition (C)	**1**	**11**	**13.137**	**.004**	**.544**
Traffic light phase (TLP)	**1**	**11**	**12.869**	**.004**	**.539**
Lead vehicle (LV)	**1**	**11**	**77.649**	**<.001**	**.876**
Fog (F)	**1**	**11**	**14.234**	**.003**	**.564**
C x TLP	1	11	.657	.435	.056
C x LV	**1**	**11**	**7.025**	**.023**	**.390**
TLP x LV	1	11	.010	.922	.001
C x F	**1**	**11**	**7.254**	**.021**	**.397**
TLP x F	**1**	**11**	**4.985**	**.047**	**.312**
LV x F	1	11	3.319	.096	.232
C x TLP x LV	**1**	**11**	**16.843**	**.002**	**.605**
C x TLP x F	1	11	1.299	.279	.106
C x LV x F	1	11	1.996	.184	.155
TLP x LV x F	1	11	.466	.509	.041
C x TLP x LV x F	1	11	2.151	.170	.164

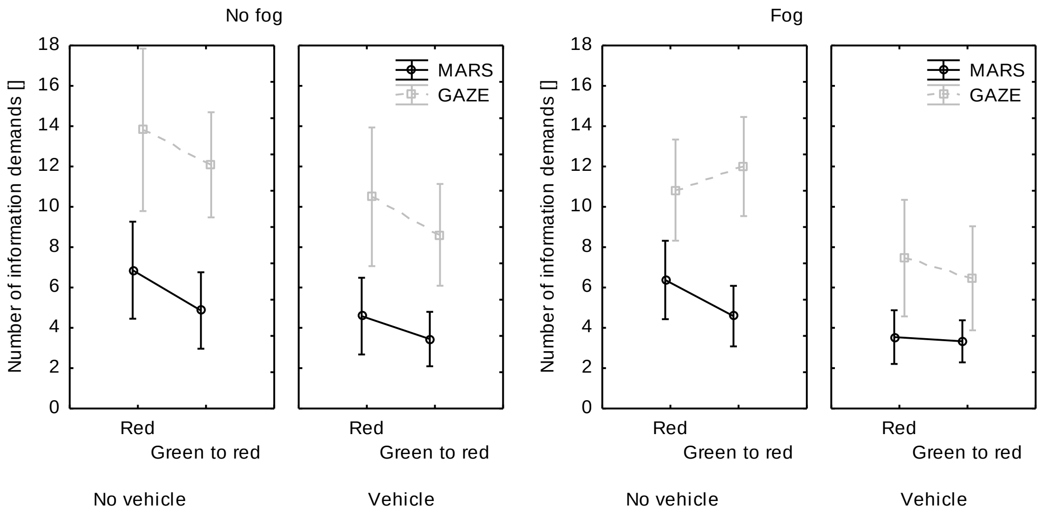


Figure 73. Number of information demands in the MARS and the GAZE condition depending on the factors traffic light phase, lead vehicle and fog for traffic light approaches with solid red and changing green to red phase. Graph shows means with 95% confidence intervals.

Intervals of information demand for the traffic light

The duration of information demands was determined as the proportion of time the traffic light was unmasked or fixated in relation to the total time spent in each 10 m distance section. As shown in Figure 74, the proportion of information demand intervals varied over the course of the traffic light approaches. With decreasing distance to the traffic light, the proportion of time fixating or unmasking the traffic light increased. The steep increase started in both conditions after the traffic light became visible in the fog conditions. After a peak around 70 m in front of the intersection, the number of information demands decreased with decreasing distance to the traffic light. Participants fixated the traffic light for longer periods in the GAZE condition than they unmasked the traffic light in the MARS condition.

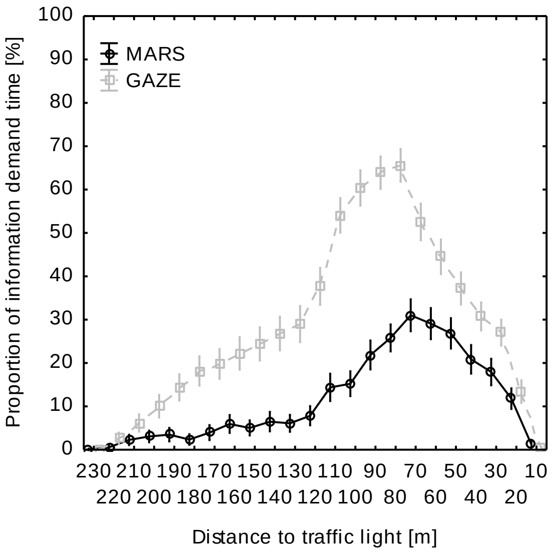


Figure 74. Proportion of time demanding the information in the MARS and the GAZE condition averaged over all factor combinations. Graph shows means with 95% confidence intervals.

Two ANOVAs separately analysed traffic light approaches to green and red to green traffic lights, and red and green to red traffic lights. The independent factors were condition, traffic light phase, lead vehicle and fog. The dependent variable was the proportion of information demand intervals over the approach distance of 230 m, i.e. the time that participants drove with unmasked or fixated traffic lights in relation to the total time of the traffic light approach.

Table 23 shows the summary of ANOVA results for the comparison of green and red to green traffic lights. Drivers fixated the traffic light for longer durations in the GAZE condition than they drove with unmasked lights in the MARS condition. Drivers' information demand durations were longer, when the traffic light was solid green compared to the changing red to green condition, when there was no lead vehicle compared to the lead vehicle condition and when there was no fog compared to the fog condition. The significant two-way interaction between condition and fog was ordinal expressing that in the GAZE condition compared to the MARS condition the difference between the two fog conditions was greater. When there was no fog in the track, the difference between the two traffic light conditions was stronger compared to when there was fog in the track (interaction traffic light phase and fog). There was a three-way interaction between condition, traffic light phase and fog: When there was fog in the track, the duration of fixations on the traffic light was slightly higher when the traffic light changed from red to green compared to the solid green light. Contrary, when there was no fog in the track, the duration of fixations on the traffic light was higher when the traffic light was solid compared to when the traffic light changed from red to green (Figure 75).

Table 23. Summary of ANOVA results for the proportion of information demand intervals for green and red to green traffic lights. Bold numbers mark significant effects.

Effect	Df effect	Df error	F	p	$\eta^2_{partial}$
Condition (C)	**1**	**11**	**122.270**	**<.001**	**.917**
Traffic light phase (TLP)	**1**	**11**	**24.550**	**<.001**	**.691**
Lead vehicle (LV)	**1**	**11**	**15.613**	**.002**	**.587**
Fog (F)	**1**	**11**	**18.852**	**.001**	**.632**
C x TLP	1	11	4.189	.065	.276
C x LV	1	11	4.109	.068	.272
TLP x LV	1	11	2.084	.177	.159
C x F	**1**	**11**	**21.787**	**<.001**	**.664**
TLP x F	**1**	**11**	**12.3084**	**.005**	**.528**
LV x F	1	11	0.170	.688	.015
C x TLP x LV	1	11	0.560	.470	.048
C x TLP x F	**1**	**11**	**21.271**	**<.001**	**.659**
C x LV x F	1	11	1.692	.220	.133
TLP x LV x F	1	11	0.739	.409	.063
C x TLP x LV x F	1	11	2.086	.176	.159

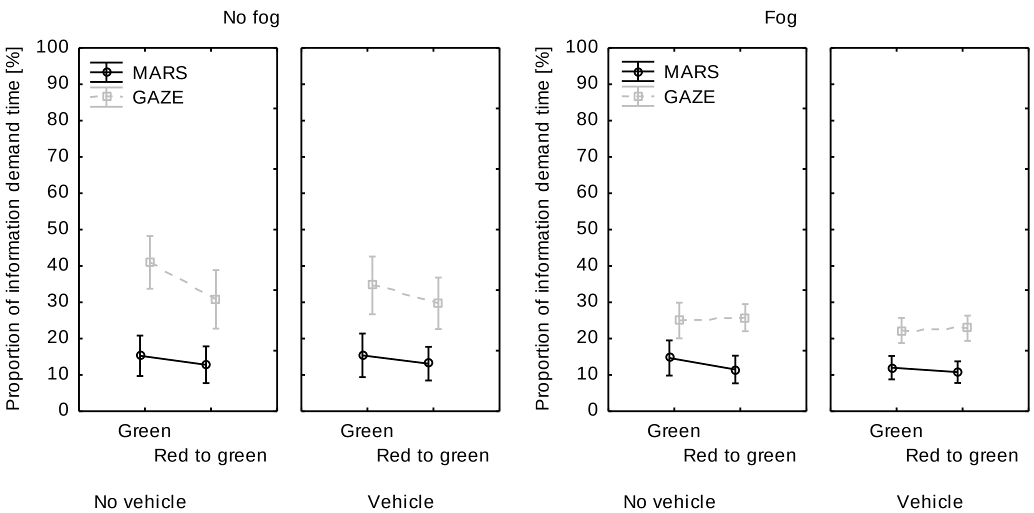


Figure 75. Proportion of information demand time in the MARS and the GAZE condition depending on the factors traffic light phase, lead vehicle and fog for traffic light approaches with solid green and changing red to green phase. Graph shows means with 95% confidence intervals.

For red and green to red traffic lights, three main effects were significant (Table 24, Figure 76). The information demand time was higher in the GAZE compared to the MARS condition, when the traffic light was solid red compared to changing green to red, and when there was no lead vehicle compared to with lead vehicle. The ordinal interaction between condition and lead vehicle expressed that the difference between the two lead vehicle conditions was stronger in GAZE compared to the MARS condition.

Table 24. Summary of ANOVA results for the proportion of information demand durations for red and green to red traffic lights. Bold numbers mark significant effects.

Effect	Df effect	Df error	F	p	$\eta^2_{partial}$
Condition (C)	**1**	**11**	**76.408**	**<.001**	**.874**
Traffic light phase (TLP)	**1**	**11**	**27.693**	**<.001**	**.716**
Lead vehicle (LV)	**1**	**11**	**49.866**	**<.001**	**.819**
Fog (F)	1	11	3.765	.078	.255
C x TLP	1	11	4.513	.057	.297
C x LV	**1**	**11**	**9.319**	**.011**	**.459**
TLP x LV	1	11	3.056	.108	.217
C x F	1	11	.624	.446	.054
TLP x F	1	11	.075	.789	.006
LV x F	1	11	.092	.767	.008
C x TLP x LV	1	11	1.198	.297	.098
C x TLP x F	1	11	.506	.492	.044
C x LV x F	1	11	.212	.173	.162
TLP x LV x F	1	11	.004	.952	<.001
C x TLP x LV x F	1	11	1.046	.328	.087

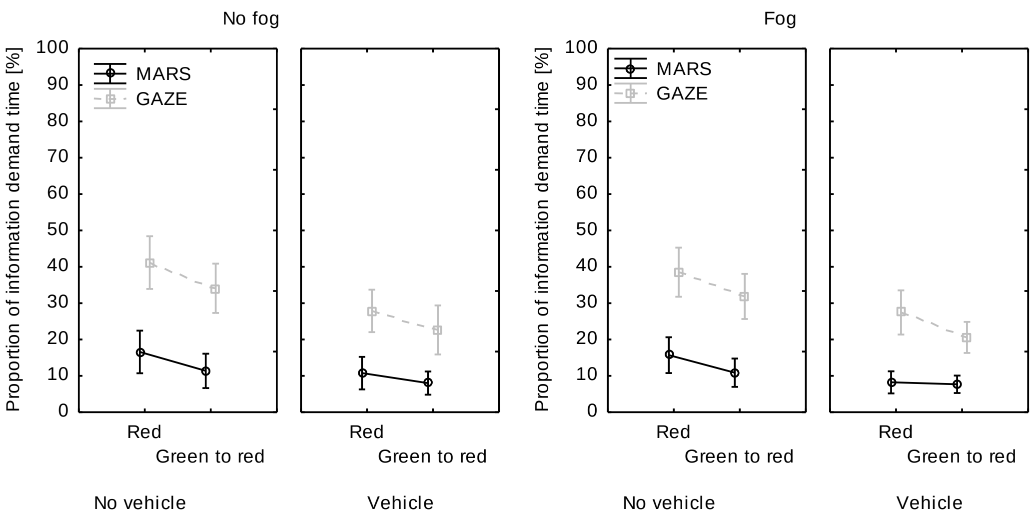


Figure 76. Proportion of information demand time in the MARS and the GAZE condition depending on the factors traffic light phase, lead vehicle and fog for traffic light approaches with solid red and changing green to red phase. Graph shows means with 95% confidence intervals.

Comparison of driving behaviour between MARS and GAZE condition

To determine the influence of the MARS method on driving behaviour, speed and acceleration were compared between MARS and GAZE condition. Figure 77 shows the speed profiles in the GAZE and the MARS condition averaged for fog and vehicle conditions differentiated for traffic light phase conditions. Descriptively, differences in driving speed were low between the GAZE and the MARS condition.

Two ANOVAs contained the factors condition, traffic light phase, lead vehicle and fog, separately for traffic light approaches to green and red to green lights, and red and green to red traffic lights. The dependent variable was mean driving speed during the approach distance of 230 m. For traffic light approaches to green and red to green lights, all main effects were significant: condition $F(1,11) = 5.422$, $p = .04$, $\eta^2_{partial} = .330$, traffic light phase $F(1,11) = 37.067$, $p < .001$, $\eta^2_{partial} = .771$, lead vehicle $F(1,11) = 6.583$, $p = .026$, $\eta^2_{partial} = .374$, and fog $F(1,11) = 14.733$, $p = .003$, $\eta^2_{partial} = .573$. The mean speed during the traffic light approach was approximately 1 km/h faster in the GAZE compared to the MARS condition. Participants drove slower when the traffic light changed from red to green, when there was a vehicle ahead and when there was no fog in the track compared to the respective opposite condition. There were two ordinal interactions between traffic light phase and fog condition, $F(1,11) = .14.873$, $p = .003$, $\eta^2_{partial} = .575$, and between lead vehicle and fog condition, $F(1,11) = 9.599$, $p = .010$, $\eta^2_{partial} = .466$. They expressed that the difference between the traffic light phase conditions was larger, when there was no fog in the track and that without fog, the difference between the lead vehicle conditions reduced. There was no interaction with the factor condition.

For the traffic light approaches to red and green to red lights, all main effects were significant: condition $F(1,11) = 5.716$, $p = .036$, $\eta^2_{partial} = .342$, traffic light phase $F(1,11) = 9.870$, $p = .009$, $\eta^2_{partial} = .473$, lead vehicle $F(1,11) = 15.397$, $p = .002$, $\eta^2_{partial} = .583$, and fog $F(1,11) = 17.948$, $p = .001$, $\eta^2_{partial} = .620$. In the GAZE condition, participants drove approximately 0.8 km/h slower than in the MARS condition. Participants drove faster when the traffic light changed from green to red, when the lead vehicle was present and when there was fog in the track compared to the respective opposite condition. There were significant two-way interactions between the factors condition and traffic light phase, $F(1,11) = 10.952$, $p = .007$, $\eta^2_{partial} = .499$, condition and lead vehicle, $F(1,11) = 8.476$, $p = .014$, $\eta^2_{partial} = .435$, and traffic light phase and fog, $F(1,11) = 50.011$, $p < .001$, $\eta^2_{partial} = .820$. Additionally, there were two three-way interactions between the factors condition, traffic light phase and fog, $F(1,11) = 14.872$, $p = .003$, $\eta^2_{partial} = .574$, and traffic light phase, lead vehicle and fog, $F(1,11) = 9.719$,

p = .010, $\eta^2_{partial}$ = .469. With lead vehicles, there was no difference between the MARS and the GAZE condition. When the traffic light phase changed from green to red, there was no difference between the fog conditions. When the traffic light was solid red, the difference in mean driving speed between MARS and GAZE condition was larger, when there was no fog in the track compared to the fog condition. When the traffic light changed from red to green, the difference between MARS and GAZE condition was larger when there was fog compared to no fog in the track. When the traffic light was solid red, the main effects for lead vehicle and fog are valid. When the traffic light changed from green to red, no difference between the fog conditions occurred when there was no lead vehicle in the track.

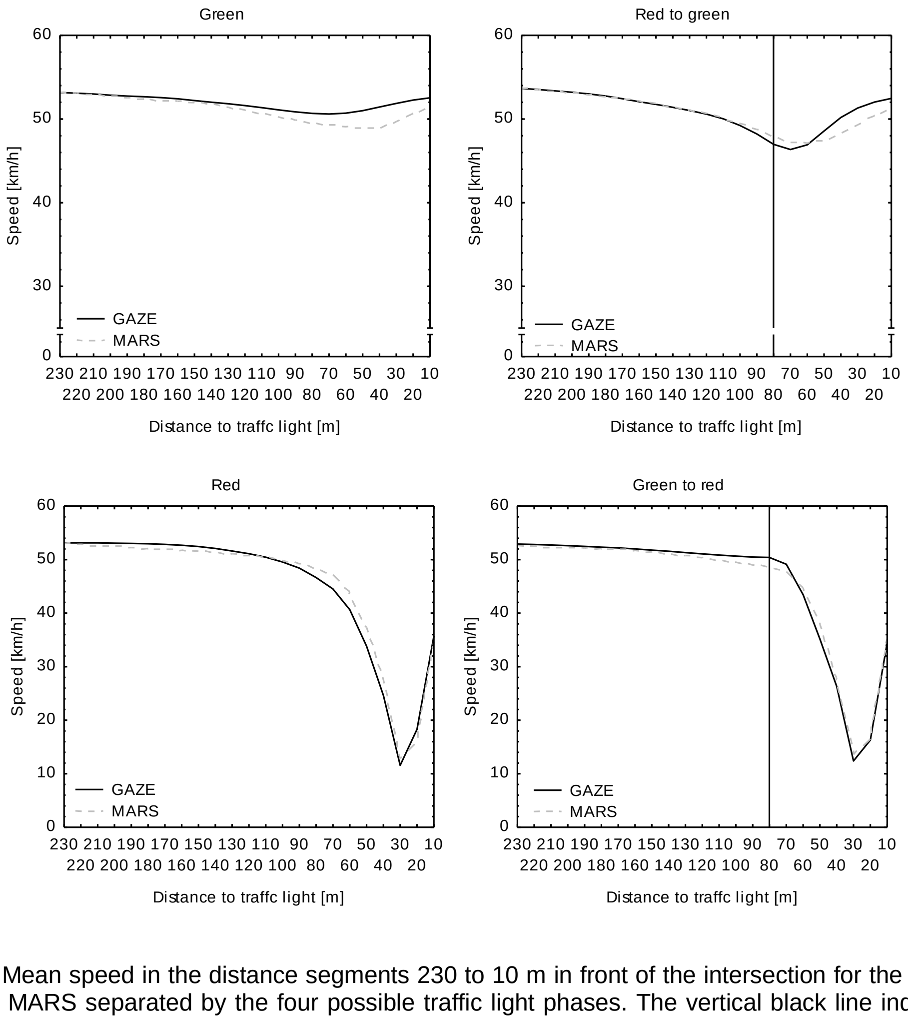


Figure 77. Mean speed in the distance segments 230 to 10 m in front of the intersection for the conditions GAZE and MARS separated by the four possible traffic light phases. The vertical black line indicates the distance at which the traffic light phase change occurred.

Two further ANOVAs analysed the mean acceleration separately for green and red to green lights, and red and green to red lights. The independent factors were condition, traffic light phase, lead vehicle and fog. For the green and red to green traffic lights, the main effects traffic light phase, $F(1,11)$ = 5.450, p = .040, $\eta^2_{partial}$ = .331, and lead vehicle, $F(1,11)$ = 12.106, p = .005, $\eta^2_{partial}$ = .524, were significant. When the traffic light changed from red to green, drivers accelerated stronger during the approach compared to when the traffic light was solid green. When there was a lead vehicle in the track, mean acceleration was stronger compared to when there was no lead vehicle. There was an ordinal interaction between condition and traffic light phase. When the traffic light changed from green to red, there was no difference between the MARS and the GAZE condition. When the traffic light was solid green, mean acceleration was approximately 0.1 m/s² stronger in the MARS condition compared to the GAZE condition, $F(1,11) = 7.268$, $p = .021$, $\eta^2_{partial} = .398$.

The ANOVA for solid red and green to red traffic lights revealed significant main effects for the factors traffic light phase, $F(1,11) = 11.148$, $p = .006$, $\eta^2_{partial} = .503$, and fog, $F(1,11) = 16.283$, $p = .002$, $\eta^2_{partial} = .597$. Mean acceleration was stronger when the traffic light was solid red compared to changing from green to red and when there was no fog in the track compared to fog in the track. The significant hybrid interaction between condition and vehicle, $F(1,11) = 5.656$, $p = .036$, $\eta^2_{partial} = .340$, expressed that without lead vehicle, mean acceleration was slightly stronger in the GAZE compared to the MARS condition. When there was a lead vehicle ahead, drivers on average accelerated slightly stronger in the MARS condition than in the GAZE condition. However, the absolute differences between MARS and GAZE condition were only around 0.05 m/s².

Finally, two ANOVAs were conducted separately for green and red to green traffic lights, and red and green to red traffic lights with mean deceleration as dependent variable. For the green and red to green traffic lights there were significant main effects for traffic light phase, $F(1,11) = 19.967$, $p = .001$ $\eta^2_{partial} = .645$, and fog, $F(1,11) = 9.901$, $p = .009$, $\eta^2_{partial} = .473$. Deceleration was stronger, when the traffic light changed from red to green compared to the solid green condition and deceleration was less strong when there was fog in the track compared to no fog. The interaction between traffic light phase and fog expressed that only when the traffic light changed from green to red there was a difference between the two fog conditions, $F(1,11) = 15.406$, $p = .002$, $\eta^2_{partial} = .583$.

When the traffic light was red or changed from green to red, mean deceleration was stronger when there was fog in the track compared to when there was no fog in the track, $F(1,11) = 14.911$, $p = .003$, $\eta^2_{partial} = .575$. There was a significant three-way interaction between the factors traffic light phase, lead vehicle and fog, $F(1,11) = 8.478$, $p = .014$, $\eta^2_{partial} = .435$. When there was fog in the track and the traffic light changed from red to green, no difference between the two lead vehicle conditions occurred. Hence for deceleration, no differences in the factor condition occurred.

In summary, the absolute differences between MARS and GAZE condition were small. The effects for the further factors were according to the expectations and in line with the analysis of driving behaviour at traffic light intersections presented in chapter 3.1.2.2.

Subjective evaluation of driving with the MARS method

Participants expressed their agreement to three statements concerning the evaluation of driving with the MARS method. Driving with the MARS method was not difficult for drivers. They expressed that the MARS method was only slightly disturbing. Finally, the majority of drivers agreed medium strongly that driving with the MARS method became easier with practice.

Many of the participants mentioned that they chose strategic points in the traffic light approach at which they pressed the button. For example, statements were “I pressed at the last point when I should brake in case of red” or “I pressed at the point when avoiding braking is possible in case the light changes from red to green”. Eight of the twelve drivers mentioned that driving with the masked lights was easier when there was a lead vehicle ahead.

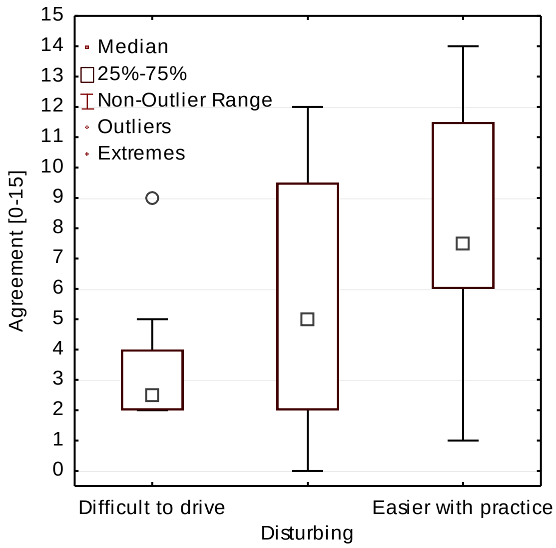


Figure 78. Drivers agreement to the statements “It was difficult to drive with the masked traffic light”, “It was disturbing that the traffic light was masked” and “The more I drove with the masked traffic light, the easier was driving”. The graph shows boxplots with medians.

4.2.1.3 Summary and discussion

The study investigated the information demand that drivers have for the traffic light as dynamic stimulus in the road environment. The variation of traffic and environment conditions allowed distinguishing between conditions with high or low information demand. The MARS method results reflected these differences. Furthermore, the MARS method results were compared to eye tracking data. The hypotheses was that the information demand measured by eye tracking and MARS method varies qualitatively similar.

The effects for number of information demands and proportion of information demand durations point to the same conclusions. The peaks and directions of effects were the same in the MARS and the GAZE condition. In general, effects in the number of information demands also occurred in the proportion of information demand time. This ensures that higher numbers of information demand related to higher frequencies of button presses. Only in the final distance sections when the traffic light was red or changed to red, higher numbers of information demand related to longer periods spent in these distance sections while drivers waited at the red light.

In general, the peaks of information demand occurred between 110 – 60 m in front of the traffic light. As mentioned in Study 1, in these distance sections drivers make the decision on how to proceed. In the current setting, this certainly relates to the fixed distance of 80 m at which the traffic light change occurred. At changing compared to solid traffic light phasing during the approach, drivers unmasked or fixated on the traffic light for shorter intervals. As soon as the traffic light changed during the approach, a further change was unlikely and drivers could be sure about the further progress of the situation. Then, the action relevance of the traffic light decreased because the decision to stop or proceed was clear. This is in line with Shinoda et al. (2001), who mentioned that as soon as a driver makes the decision to stop at a stop sign, the sign itself is not attended anymore.

With lead vehicle, driver’s information demand decreased compared to without lead vehicle. As mentioned in Study 1, the lead vehicle always drove according to the traffic rules and therefore, was a reliable source of information. Additionally, in any driving situation, a lead vehicle had action relevance. When the lead vehicle decreased driving speed, it was necessary to initiate deceleration, independent of the current traffic light state. While the information demand for the lead vehicle might have increased, the information demand for the traffic light decreased.

When there was fog in the track, the information demand decreased in the GAZE as well as the MARS condition. The traffic light was visible for shorter periods during traffic light approaches with fog. Drivers only saw the traffic light starting at distances lower than on average 90 m in front of the lights. The fact that drivers did not press the button as long as the traffic light was not visible supports that they understood the task well. The participants only pressed the button when they saw the possibility to receive meaningful information from it.

Overall, the effects were stronger in the GAZE compared to the MARS condition, i.e. the number of fixations exceeded the number of button presses. On the one hand, it seems as if measuring drivers' fixations to determine information demand for a stimulus was more sensitive than measuring number of button presses to determine information demand. On the other hand, one might also argue that the measurement of fixations overestimated the information demand to the stimulus. The scenarios were simple and drivers had to look somewhere in road environment. The traffic lights played an important role during the experiments. Hence, drivers fixated on the traffic light more often than was actually necessary. In the MARS condition, drivers solved the driving task correctly and no meaningful differences in driving behaviours between MARS condition and GAZE condition occurred. Therefore, the information retrieved by the button presses was sufficient to determine the correct action. The number and duration of fixations on the traffic light exceeded the actual information demand. Consequently, the MARS method might allow better estimating the real information demand, and whether and when the traffic light is action relevant compared to the GAZE condition.

Additionally, the lower number of button presses compared to number of fixations rebuts a possible flaw of the MARS method. Instructing drivers for the MARS method could increase the attention drivers pay to the traffic lights compared to the GAZE condition, in which no emphasis on the traffic lights was instructed. However, the findings showed no hint for an increased awareness for the masked object. Moreover, the MARS method could reduce the looked-but-failed-to-see phenomenon, because drivers consciously decide to press the button at strategic points during the approach. They do so, when they expect that the covered information might currently be action relevant.

For a future application of the MARS method, a precondition is that drivers understand their task when driving with the method. In the present study, participants evaluated that it was not difficult to drive with the MARS method and that learnability of the task is high. In the free comments, participants stated that they pressed the button at strategic points during the approach. This supports the interpretation of information demand in terms of action relevance. Participants pressed the button when decisions on driving behaviour were necessary.

The advantages of the MARS method concerning the experimental procedure and the analysis of data were apparent. The equipment only required a button, comfortably placed at the steering wheel. The instructions were simple and drivers learned quickly how to handle their task. No calibration of eye tracking was necessary. The button presses were recorded in the data logs. Due to the binary coding, data analysis was simple and the data quality was stable between participants.

In summary, the MARS method was able to measure the driver’s information demand for a specific dynamic stimulus. The method offered advantages in comparison to eye tracking regarding the interpretation of information demand and action relevance, as well as the experimental procedure and data analysis.

4.2.2 Study 5: Information demand for the HMI display[5]

Study 4 presented the first experiment evaluating the applicability of the MARS method to a dynamic stimulus in the road environment. However, further evaluation is necessary to determine the generalisability of the method to different stimuli and driving tasks. The MARS method defines fixed unmasking intervals. This does not allow to measure quick and consecutive information demands as for example measured by eye tracking. Drivers might fixate frequently within a single unmasking interval with varying fixation durations. Additionally, it might be that drivers did not fixate at all during the unmasking intervals. Even though drivers could still perceive the information without fixating to the stimulus, unmasking intervals without fixations would challenge the interpretation that button presses indicate information demand. Therefore, for a further evaluation of the MARS method, eye tracking and MARS method are applied within the same drives. This can determine the number of fixations within the unmasking intervals and allows the investigation of fixations during stimulus masking.

Study 5 investigates the information demand drivers have for the HMI display of the traffic light assistant by using the MARS method. Hence, the method is transferred to a dynamic stimulus in the vehicle. When drivers aim to stick to the recommendations of the assistant, the dynamic information in the display needs to be processed and repeated checks of the display are necessary. Therefore, the information presented in the display is action relevant. Additionally, applying the MARS method to a further stimulus indicates whether the method generalises to different contexts and driving tasks.

The results of Study 3 showed that the information demand as measured by eye tracking differs between the tested display versions. Depending on the level of support and the action relevance that the presented information offered, it made more or less sense for drivers to attend to the display. For example, when the display contained the information on the current traffic light phase, the action relevance of the information was low, because this information was also available from the real traffic light in the track. Contrary, when the display contained recommendations for driving speed and required actions, the action relevance of the display was high. Hence, drivers fixated the information more often when it contained more action relevant information. Greater

[5] The data reported for Study 5 were collected in the Master thesis of Katharina Reinmüller (Reimüller, 2015). The author of this doctoral thesis developed the research hypothesis and ideas for planning and conducting the study. The presented data were analysed by the author of this doctoral thesis.

action relevance increased the information demand for the display. For the evaluation of the MARS method, the hypothesis is that differences in the information demand can be measured by masking the relevant information in the display. Therefore, the HMI display of the traffic light assistant is masked and drivers can unmask the information for a fixed period by pressing a button. To evaluate the sensitivity of the MARS method to variations of the display content, two different HMI versions are compared. Based on the results of Study 3, Study 5 compares the version with the lowest action relevance, i.e. the version only showing the current traffic light phasing, to the version containing all three information units (traffic light phase information, speed recommendations, action recommendations). It is expected that the complex HMI version leads to a higher number of information demands compared to the simple HMI version, and that this occurs in button presses and fixations on the display. The bold frames in Figure 79 highlight the factors relevant in Study 5.

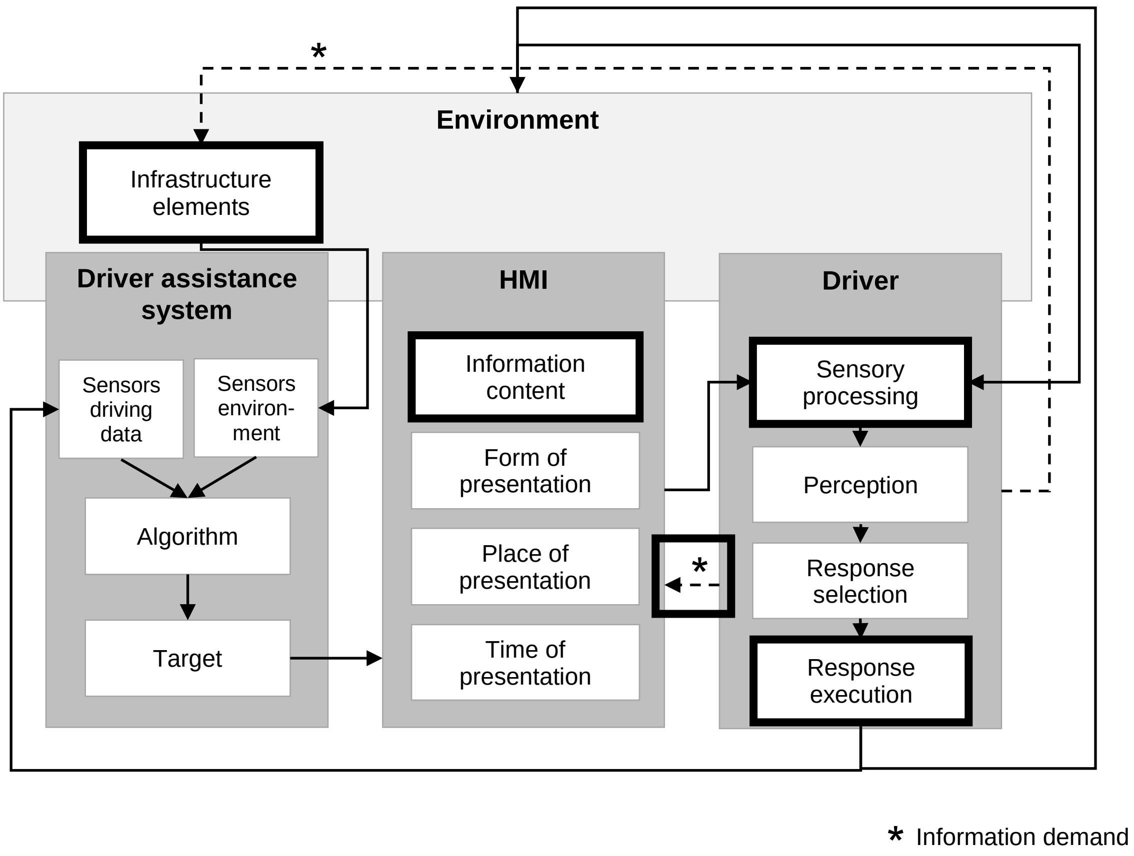


Figure 79. Relation of the factors considered in the present thesis. Bold frames indicate factors investigated in the evaluation of the MARS method during Study 5. Adapted from Bruder and Didier (2012), Popiv (2012), Schmidtke and Bernotat (1993), Wickens and Hollands (2000) and Zarife (2014).

In the HMI display, the information content varies. Depending on that, the expectation is that the information demand of the driver for the HMI display differs. The participant's driving behaviour and gaze behaviour is measured. In line with the previous studies, the traffic light phasing in the road environment changed within the experimental drives.

Similar to Study 4, the results compare the number of information demands by pressing the button in the MARS method to the information demands measured by eye tracking. Additionally, during the MARS method drives, the eye tracking records gaze behaviour. Like this, a detailed analysis and understanding of gaze behaviour while using the MARS method is possible. As mentioned before, this is essential to determine whether and how drivers fixate on the display during masking and during unmasking intervals. Finally, driving behaviour and subjective evaluations of the MARS method are also part of the analysis.

4.2.2.1 Methods

Participants

18 participants (10 female) took part in the study. Their mean age was 31.1 years (sd = 9.6), with a minimum age of 22 years and a maximum age of 54 years. All drivers were recruited from the test driver panel of the WIVW and were well experienced with driving in the static driving simulator. Only participants who had not participated in the previously conducted multi-driver simulator study were included. All drivers had normal or corrected to normal vision. Data of one participant were excluded from the analysis, because of major problems in understanding the instructions.

Apparatus

The study took place in the same single driving simulator used in the previous studies. As explained in chapter 3.1.2.1, the static driving simulator had a 300° horizontal field of vision. Besides the projected driving environment, drivers saw the cluster display, the mirrors and a navigation screen on separate LCD displays. The steering wheel had two buttons positioned at the left and the right side. Chapter 3.3.2.1 introduced the eye tracker of the Smart Eye AB Company.

Questionnaires were used to record subjective data. Three items covered the evaluation of the MARS method. Two questions evaluated the subjective appropriateness of the information demand. Six questionnaire items included the evaluation of the HMI versions. Participants answered the questions on the verbal-numeric scale from 0 to 15 (Figure 52).

Traffic light assistant

The traffic light assistant based on the same algorithm as described in chapter 3.3.2.1. The system used the information on the traffic light timing, current driving speed and the distance to the traffic light to calculate target speeds. Driving recommendations resulted from the comparison of current driving behaviour with target behaviour. The traffic light assistant supported crossing the intersection without stop. In cases of unavoidable stops, the system assisted with efficient stops at red.

The cluster display contained the HMI of the traffic light assistant. The two HMI versions used in the experiment were identical to two versions evaluated in Study 3. The simple HMI version showed the current traffic light phase (Figure 80, left). As long as drivers could see the traffic light in the road, the first version did not offer any additional information. The complex HMI version contained traffic light information, action recommendations and speed recommendations (Figure 80, right). With that, it showed the traffic light phase duration, the traffic light phase at arrival, the required driving speed and the action that drivers had to implement (e.g. coast). Chapter 3.3.2.1 includes a detailed description of the three information units. The HMI activated approximately 300 m in front of the intersection. Drivers noticed the activation of the HMI by the navigation information shown on the separate navigation display, because both displays were activated simultaneously.

Figure 80. HMI versions as used in the experiment. The simple version showed the current traffic light phase (left). The complex version showed information on the traffic light phase duration, phase at arrival, action and speed recommendations (right).

Design

The study had a full within-subjects design. The three factors were condition (MARS, GAZE), HMI version (simple, complex) and traffic light phase (green and red to green, red and green to red).

In the MARS condition, the HMI of the traffic light assistant was masked while the traffic light assistant was active. To unmask the information in the cluster display drivers had to press at least one of two buttons at the steering wheel. After pressing the button, the information in the HMI was unmasked for 1000 ms, before the masking returned. Pre-tests had shown that 1000 ms offered sufficient time to process the information in the display. In comparison to Study 4, the duration of unmasking intervals was increased by 200 ms, because unlike the masked traffic lights, the HMI display was not in the primary field of vision. Drivers could press the button to unmask whenever they wanted and as often as they wanted. Longer or repeated presses within an unmasking interval did not lead to longer unmasking intervals. Figure 81 shows a schematic depiction of the MARS method used for the HMI evaluation. In the GAZE condition, the HMI was unmasked constantly and drivers had no other task than driving according to the recommendations.

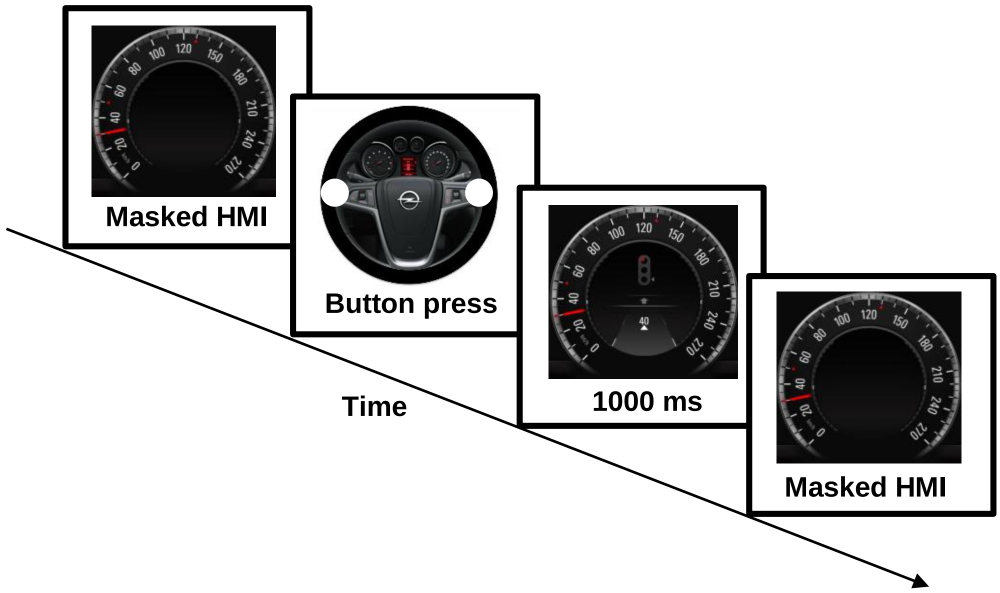


Figure 81. Schema of the MARS method. The HMI is masked while driving. When pressing one of two buttons located at the steering wheel (indicated by the white dots), the HMI unmasked for 1000 ms before the masking returned. Note that the display is located behind the steering wheel.

Conditions and HMI versions varied within drivers, resulting in four drives for each participant (MARS simple, MARS complex, GAZE simple, GAZE complex). In order to reduce the complexity of the instructions, the two drives with the same HMI version were conducted consecutively. The order of the two HMI versions and the order of the two conditions alternated between participants. Importantly, during all four test drives in the experiment, participants' fixations were recorded with the eye tracker.

The traffic light phase varied within the test drives. Participants approached intersections with either solid green or solid red traffic lights, or traffic lights that changed from red to green or from green to red. Every traffic light approach was repeated twice, resulting in a total number of eight traffic light approaches in each drive. There was a randomised order of the eight traffic light approaches with choosing four of the eight sequences resulting from a Latin square. Hence, drivers experienced each combination of HMI version and condition with a different sequence of traffic light approaches in the track.

The dependent variables consisted of dynamic driving behaviour, gaze behaviour, and subjective evaluations. Table 25 gives an overview of the dependent variables. The SILAB software recorded objective data. The SILAB data sheets included the eye tracking data.

Test track

The urban test track consisted of eight intersections with the same X-junction layout. The road environment varied by buildings, landmarks and plants. The test track was approximately 4.8 km long. Each intersection approach consisted of three lanes, one for each driving direction. Participants always drove straight on the middle lane. Nevertheless, the navigation system indicated the driving direction. There was crossing traffic at the intersection and traffic on the oncoming lane, but no traffic on drivers' own lane. The traffic light phasing was according to German road traffic regulations. The red phase ended with a combined presentation of red and yellow, the green phase ended with a single yellow state. The traffic light changes occurred when drivers were approximately 40 m in front of the intersection.

Procedure

Participants completed a data privacy statement and received instructions about the objectives of the study. Before the experiment started, the experimenter calibrated the eye tracking system. Subsequently, the four experimental drives followed. Before each first drive with a new HMI version, the experimenter explained the information units thoroughly and participants drove a short practice track consisting of two intersections. During the practice drives, the HMI was not masked. Before each drive, the instruction was to follow the traffic rules in general and to stick to the recommendations shown in the HMI. After each drive, participants filled in the respective questionnaires. The procedure took around 1 h for every participant. Participants made breaks whenever they wanted between drives.

Table 25. Overview of the dependent variables recorded in the experiment.

Dependent variable	Unit	Description
Speed	km/h	Speed with which the vehicles proceeds
Acceleration	m/s²	Acceleration when increasing speed
Deceleration	m/s²	Deceleration when decreasing speed
Button presses	Press vs. no press	Usage of the buttons at the steering wheel to unmask the HMI display
Unmasking intervals	%	Proportion of time with unmasked display in relation to total duration of a specific distance section
Number of fixations on the cluster	[]	Number of fixations on the cluster display in a defined distance section
Fixation intervals on the cluster	%	Proportion of time with fixated cluster display in relation to total duration of driving in a specific distance section
Evaluation of driving with the MARS method	Verbal-numeric scale from 0-15	Three questions evaluating the difficulty, disturbance and learnability of the MARS method: It was difficult to comply with the HMI information when driving with the masked display; It bothered me that the display was masked; The longer I drove with the masked display, the easier was driving
Evaluation of appropriateness of information demand	Verbal-numeric scale from 0-15	Two questions evaluating if information demand was more frequent than necessary: I pressed the button more often than necessary (in the MARS condition); I looked at the display more often than necessary (GAZE condition)
Evaluation of HMI versions	Verbal-numeric scale from 0-15	Six questions evaluating the HMI versions: I frequently looked at the display; I got along well with the information in the display; I performed well in adapting to the expected behaviour; The display contained enough information; The information in the display was helpful; The information in the display was complex

4.2.2.2 Results

Data preparation

In line with the descriptions in chapter 3.3.2.2, a fixation on the area of interest was at least 100 ms long. The area of interest was the cluster display. When missing data occurred between two display fixations, they were recoded to display fixations. In 12 traffic light approaches of one driver (9 in the GAZE condition, 3 in the MARS condition), the percentage of missing data was larger than 30% after recoding. These cases were excluded from gaze data analysis. Hence, gaze data analysis related to overall 263 traffic light approaches in the GAZE condition and 269 traffic light approaches in the MARS condition. All other analysis based on overall 544 traffic light approaches.

The information demand measured by the MARS method represents button presses to unmask the HMI information only. The information demand measured by the eye tracker represents fixations on the cluster display including the speedometer.

Number of information demands for the display

The number of button presses in the MARS condition and the number of fixations in the GAZE condition were plotted over the 300 m traffic light approach. Figure 82 shows that right after the activation of the HMI the number of information demands increased at around 290 m in front of the intersection. During the traffic light approach, the number of information demands remained stable. At 20 m in front of the intersection, i.e. shortly before crossing, the number of information demands increased again in both conditions.

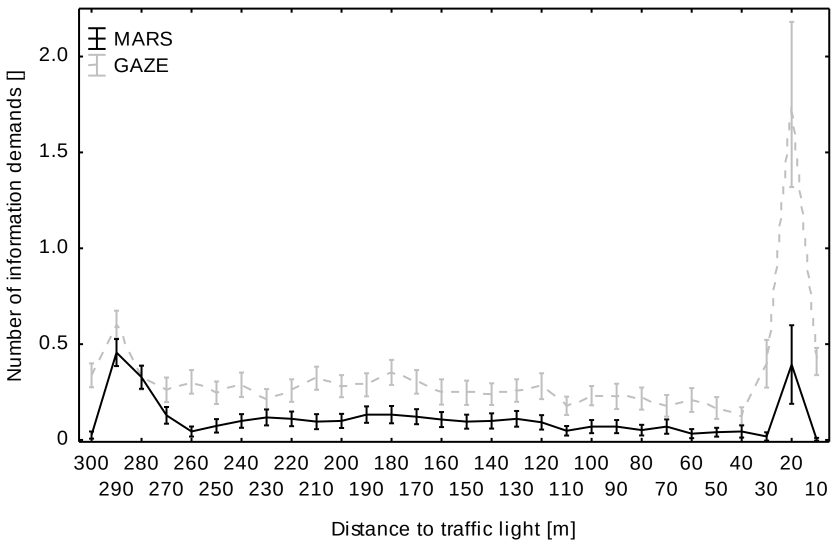


Figure 82. Number of information demands in the MARS and the GAZE condition averaged over all factor combinations. The graph shows means with 95% confidence intervals.

ANOVAs were conducted separately for solid green and red to green traffic lights and for solid red and green to red lights. The independent factors were the condition (MARS, GAZE), the HMI version (simple, complex) and the traffic light phase (green and red to green, red and green to red). The dependent variable was the number of information demands.

When the traffic light was green or changed from red to green all main effects were significant. The information demand measured in the MARS condition was lower compared to the information demand measured in the GAZE condition, *F*(1,16) =

130.693, $p < .001$, $\eta^2_{partial} = .891$. When participants drove with the complex HMI version, the information demand was higher compared to driving with the simple HMI version, $F(1,16) = 17.606$, $p < .001$, $\eta^2_{partial} = .524$. Approaching red to green traffic lights led to higher information demands for the display compared to approaching solid green traffic lights, $F(1,16) = 18.143$, $p < .001$, $\eta^2_{partial} = .531$. The interaction between HMI version and traffic light phase expressed that with the simple HMI version, no difference in the number of information demands occurred between the traffic light phases, $F(1,16) = 19.922$, $p < .001$, $\eta^2_{partial} = .555$. The three way interaction did not limit the interpretation of the described effects, $F(1,16) = 6.684$, $p = .020$, $\eta^2_{partial} = .295$. It showed that when the traffic light changed from red to green, the difference between simple and complex HMI version was stronger in the GAZE compared to the MARS condition (Figure 83, left).

When the traffic lights were red or changed from green to red, the number of information demands was higher in the GAZE compared to the MARS condition, $F(1,16) = 49.587$, $p < .001$, $\eta^2_{partial} = .756$. The information demand was also higher when participants received information from the complex HMI version compared to the simple HMI version, $F(1,16) = 20.172$, $p < .001$, $\eta^2_{partial} = .558$. The ordinal interaction between condition and HMI version expressed that the difference between HMI versions was stronger when the number of information demands was measured in the GAZE condition compared to the MARS condition, $F(1,16) = 6.554$, $p = .021$, $\eta^2_{partial} = .291$. No other effects were significant (Figure 83, right).

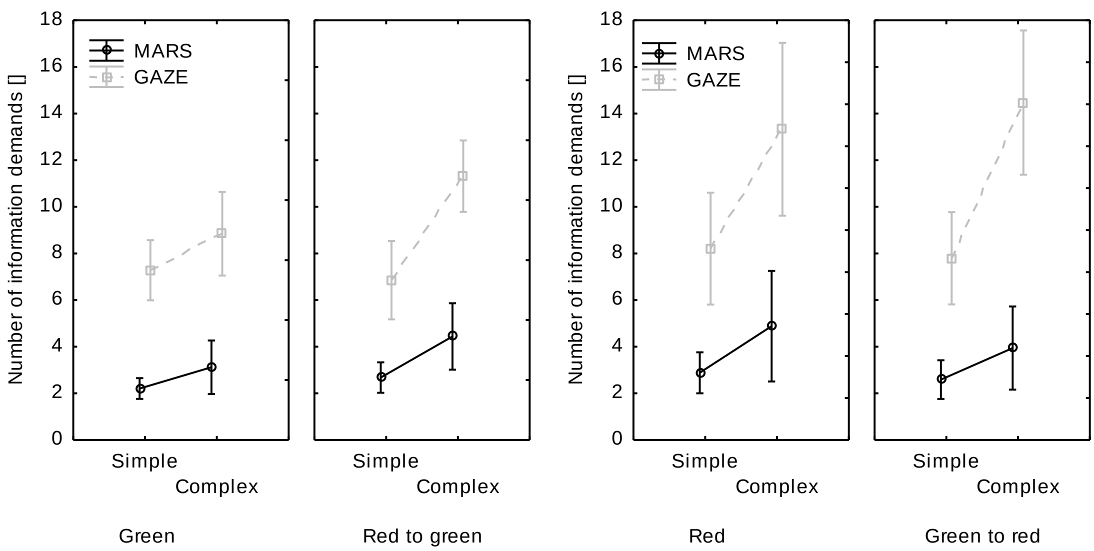


Figure 83. Number of information demands in the MARS and the GAZE condition depending on the factors HMI version and traffic light phase for traffic light approaches to solid green and changing red to green phase (left) and solid red and changing green to red phase (right). The graphs show means with 95% confidence intervals.

Intervals of information demand for the display

The proportion of information demand expressed the time during which the traffic light was unmasked in the MARS condition and fixated in the GAZE condition in relation to the total duration of the traffic light approach. Figure 84 shows the mean information demand duration averaged over all conditions for each 10 m distance section during the traffic light approach.

The figure confirms the initial high information demand measured by the number of button presses and number of fixations. After activation of the HMI, the information demand for the display was high in both conditions. In the final distance sections, the duration of information demand decreased in the MARS condition. Hence, drivers did not demand the display information with a higher frequency of button presses. Higher number of information demands resulted from longer times spent in the respective distance sections. The proportion of time fixating the display increased in the final distance sections.

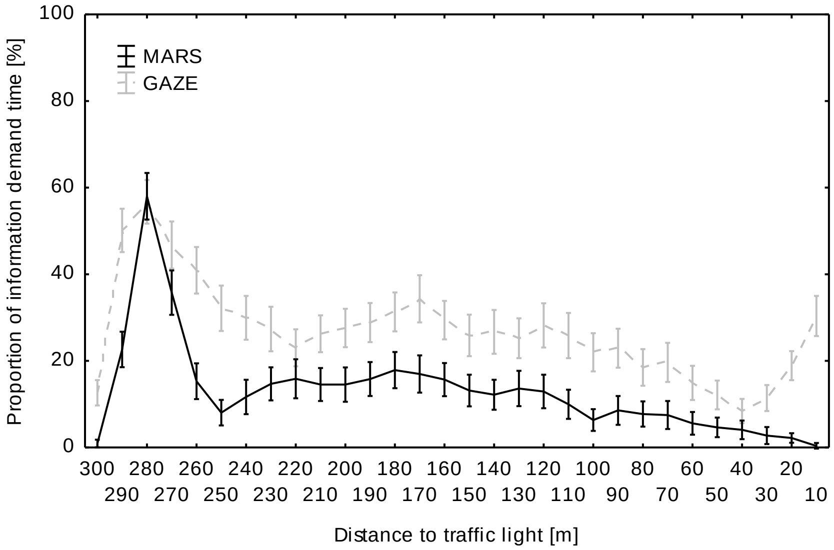


Figure 84. Proportion of time demanding the information in the display in the MARS and the GAZE condition in each distance section averaged over all factor combinations. The graph shows means with 95% confidence intervals.

ANOVAs were conducted separately for the traffic light phases green and red to green, and red and green to red. The factors were condition (MARS, GAZE), HMI version (simple, complex) and traffic light phase (green and red to green, red and green to red). The dependent variable was the proportion of information demand time.

When the traffic light was green or changed from red to green, all effects were significant. The proportion of time demanding the information from the display was higher in the

GAZE compared to the MARS condition, $F(1,16) = 65.325$, $p < .001$, $\eta^2_{partial} = .803$, when the complex HMI was activated compared to the simple HMI version , $F(1,16) = 57.560$, $p < .001$, $\eta^2_{partial} = .782$, and when the lights changed from red to green compared to the solid green light, $F(1,16) = 10.706$, $p = .004$, $\eta^2_{partial} = .401$. The two way interactions condition x HMI version and condition x traffic light phase were ordinal, $F(1,16) =30.321$, $p < .001$, $\eta^2_{partial} = .654$ and $F(1,16) = 5.609$, $p = .031$, $\eta^2_{partial} = .260$, respectively. This expressed that the differences between HMI versions and the differences between the two traffic light phases were larger when the information demand was measured in the GAZE compared to the MARS condition. The hybrid interaction between HMI version and traffic light phase showed that the main effect traffic light phase should not be globally interpreted $F(1,16) = 37.572$, $p < .001$, $\eta^2_{partial} = .701$. When driving with the simple HMI version, the information demand in the solid green and the changing red to green condition did not differ. The three-way interaction does not change these interpretations, $F(1,16) = 18.593$, $p < .001$, $\eta^2_{partial} = .537$. The information demand was highest when measured in the GAZE condition, when the HMI version was complex and when the traffic light changed from red to green (Figure 85, left).

When the traffic lights were red or changed to red, all three main effects were significant. Longer information demand times occurred in the GAZE compared to the MARS condition, $F(1,16) = 60.289$, $p < .001$, $\eta^2_{partial} = .790$, when the HMI version was complex compared to simple, $F(1,16) =26.855$, $p < .001$, $\eta^2_{partial} = .627$, and when the traffic lights changed from green to red compared to the solid red light, $F(1,16) = 5.945$ $p = .027$, $\eta^2_{partial} = .271$. The ordinal interaction between condition and HMI version expressed that the differences between the HMI versions were stronger in the GAZE compared to the MARS condition, $F(1,16) = 16.424$, $p < .001$, $\eta^2_{partial} = .507$. The hybrid interaction between condition and traffic light phase showed that the effect of traffic light phases could not be interpreted globally, $F(1,16) = 10.318$, $p = .005$, $\eta^2_{partial} = .392$. In the MARS condition, the proportion of information demand time did not differ between solid red and changing red to green lights. No other effects were significant (Figure 85, right).

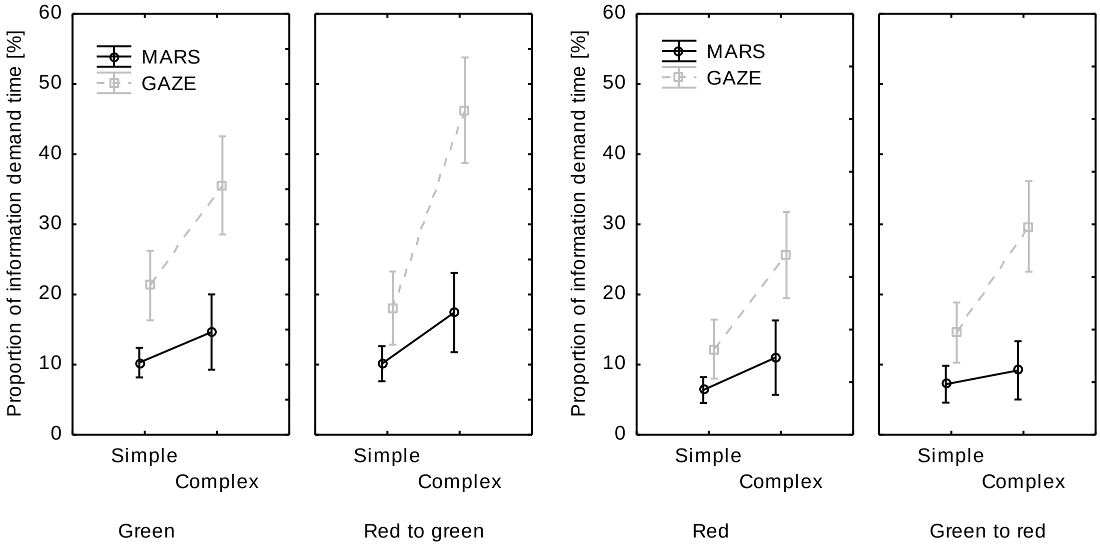


Figure 85. Proportion of information demand time in the MARS and the GAZE condition depending on the factors HMI version and traffic light phase for traffic light approaches to solid green and changing red to green phase (left) and solid red and changing green to red phase (right). The graphs show means with 95% confidence intervals.

Gaze behaviour in the MARS condition

During the MARS condition, the eye tracker detected and recorded participant's gaze behaviour. To evaluate whether the MARS method influences basic gaze behaviour in relation to the HMI display, the mean number of fixations on the display was plotted for the MARS and the GAZE condition (Figure 86). It shows that over the progress of the traffic light approach, the differences in the number of fixations on the display between MARS and GAZE condition were small. Two ANOVAs evaluated the differences in the average number of fixations on the display separately for the green and red to green lights, and the red and green to red lights. The independent variables were condition, HMI version and traffic light phase.

When the traffic light was green or changed to green, there were significant main effects for HMI version, $F(1,16) = 21.388$, $p < .001$, $\eta^2_{partial} = .572$, and traffic light phase, $F(1,16) = 20.523$, $p < .001$, $\eta^2_{partial} = .562$. With the complex HMI version, drivers fixated more often on the display compared to the simple HMI version. When the traffic light changed from red to green, drivers fixated the display more often than in the solid green condition. The main effect HMI version is globally valid. But, with the simple HMI version, no difference in fixations on the display occurred between solid green and red to green traffic light phase, $F(1,16) = 33.057$, $p < .001$, $\eta^2_{partial} = .674$. No significant differences occurred for the factor condition. In the red and green to red traffic light conditions, the number of fixations on the display was higher in the GAZE compared to the MARS condition, $F(1,16) = 12.083$, $p = .003$, $\eta^2_{partial} = .430$, and with complex compared to the simple HMI, $F(1,16) = 22.314$, $p < .001$, $\eta^2_{partial} = .582$. No other effects were significant, all *ps* > .052.

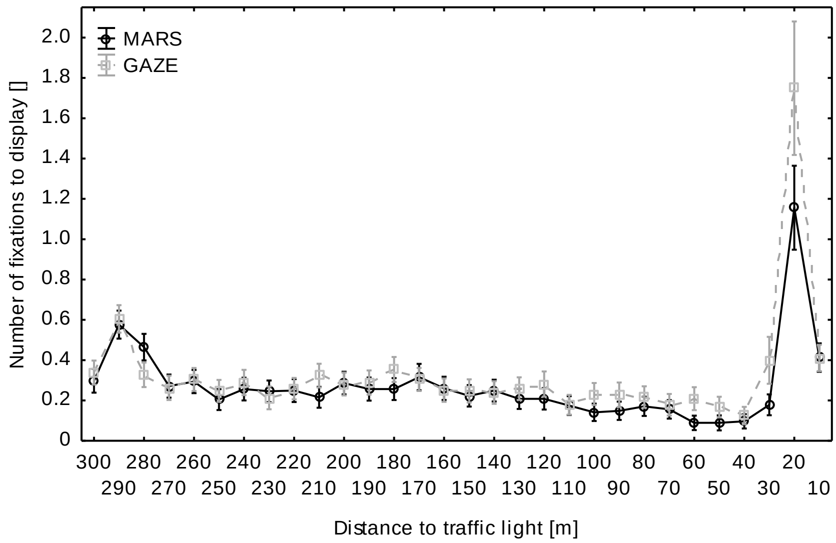


Figure 86. Number of fixations on the display in the MARS and the GAZE condition averaged over all factor combinations. The graph shows means with 95% confidence intervals.

Furthermore, drivers gaze behaviour during unmasking intervals in the MARS condition was analysed. Figure 87 visualises the relevant parameters. The number of fixations starting before an unmasking interval had started (A), the number of fixations starting and ending within an unmasking interval (D) and the number of fixations starting within an unmasking interval and lasting into the masking interval were determined (C). Additionally, the analysis contained the number of times drivers pressed to unmask but did not fixate on the display (E).

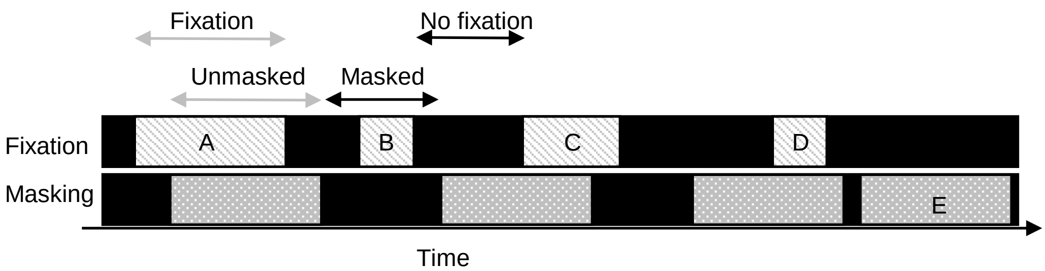


Figure 87. Visualisation of relevant parameters for the analysis of gaze behaviour when driving with the MARS method. [A] fixations on the display starting before the unmasking interval had started. [B] fixations on the display that occurred without unmasking interval. [C] fixations on the display that started within the unmasking interval and lasted beyond the end of the interval. [D] fixations on the display that started and ended within the unmasking interval. [E] unmasking intervals in which no fixation on the display occurred.

Table 26 presents the respective number of observations in all participants. The numbers reflect the sum of all observations made in all traffic light approaches of each condition. The number of unmasking intervals without fixation related to the total number of unmasking intervals showed that only 2.33 % of the unmasking events came along without any fixation. The number of fixations during unmasking intervals related to the total number of unmasking intervals showed that in total 1.05 fixations occurred per unmasking interval. There were slightly more fixations that started before drivers pressed the button (A) than fixations that started within the unmasking interval (C+D).

Table 26. Number of unmasking intervals, number of unmasking intervals without fixation, number of fixations starting before unmasking, number of fixations starting within unmasking and total number of fixations that occurred during unmasking intervals separated for the two different HMI versions and the four different traffic light phases.

HMI version	Traffic light phase	Unmasking intervals	Unmasking intervals without fixation (E)	Fixations starting before unmasking (A)	Fixations starting within unmasking (C + D)	Fixations during unmasking (A+C+D)
Simple	**Green**	75	3	40	46	86
	Red to green	91	0	46	46	92
	Red	98	4	56	43	99
	Green to red	88	5	50	38	88
Complex	**Green**	106	1	62	57	119
	Red to green	146	0	81	78	159
	Red	165	5	104	63	167
	Green to red	134	3	80	59	139
Sum		903	21	519	430	949

Two ANOVAs investigated whether differences in the number of fixations during unmasking occurred between the experimental conditions. Therefore, the dependent variable was number of fixations during unmasking intervals related to the total number of unmasking intervals, averaged for repeated conditions in each participant. The independent variables were HMI version (simple, complex) and traffic light phase (green and red to green, red and green to red). The number of fixations during unmasking neither differed in green and red to green light conditions, nor in red and green to red light conditions, all *ps* > .133.

Second, drivers gaze behaviour during masking intervals was analysed. Therefore, the total number of fixations when driving with the MARS method was determined. The number of fixations occurring during unmasking was deducted from the total number of fixations. Table 27 shows the respective number of observations added for all participants. Overall, 56.73 % of the fixations on the display in MARS method conditions occurred during display masking. Two ANOVAs evaluated differences in the relation of fixations during masking intervals and total number of fixations between the experimental conditions. The independent variables were HMI version (simple, complex) and traffic light phase (green and red to green, red and green to red). The dependent variable was the percentage of fixations during masking in relation to total number of fixations. One effect was significant. When the traffic light turned from green to red, the percentage of fixations during masking was higher compared to the solid red condition, $F(1,16) = 6.455$, $p = .022$, $\eta^2_{partial} = .287$.

Table 27. Total number of fixations and number of fixations occurring during masking intervals in the MARS condition separated for the different HMI and traffic light phase conditions.

HMI version	**Traffic light phase**	**Number of fixations (A+B+C+D)**	**Number of fixations during masking (B)**
Simple	**Green**	232	146
	Red to green	210	118
	Red	246	147
	Green to red	234	146
Complex	**Green**	279	160
	Red to green	361	202
	Red	316	149
	Green to red	315	176
Sum		2193	1244

Comparison of driving behaviour between MARS and GAZE condition

In order to evaluate whether driving with the MARS method changes normal driving behaviour, an analysis compared the driving behaviour between the MARS and the GAZE condition.

First, Table 28 contains the number of traffic light approaches with stop. Each participant experienced each condition twice, resulting in overall 34 traffic light approaches in each condition. Three different participants did not manage to avoid a stop when approaching a red to green intersection with the simple HMI version. Eight different drivers did not come to standstill when approaching a green to red traffic light in overall twelve different traffic light approaches. In these cases, drivers violated the red light. All red light violations occurred when participants drove with the simple HMI version. No differences occurred between MARS and GAZE condition and no differences occurred between the repetitions of conditions (seven red light violations in the first repetition, five red light violations in the second repetition of the respective conditions).

Table 28. Number of traffic light approaches with a stop. In total, there were n = 34 traffic light approaches in each condition.

Traffic light phase	MARS		GAZE	
	HMI simple	**HMI complex**	**HMI simple**	**HMI complex**
Green	0	0	0	0
Red to green	2	0	1	0
Red	34	34	34	34
Green to red	28	34	28	34

Second, the deviation of driving speed from the predicted target driving speed presents information on how well drivers preformed with respect to the traffic light assistant and whether this is influenced by the MARS method. Driving speed for the MARS and the GAZE conditions was plotted as depicted in Figure 88 (left). This shows that driving speed averaged over all HMI and traffic light phase conditions did not differ between the MARS and the GAZE condition.

For each traffic light approach, the squared deviation of current driving speed from target speed was determined for each distance section of 10 m. Figure 88 (right) depicts the average sum of squared deviations form target for the whole traffic light approach. As expected, the deviations from target were larger in the simple compared to the complex HMI version. Differences between the MARS and the GAZE condition were low.

The sum of squared deviations was the dependent variable in two ANOVAs. The independent factors were condition (MARS, GAZE), HMI version (simple, complex) and traffic light phase (green and red to green, red and green to red). When the traffic light was green or changed to green there were significant main effects for HMI version and traffic light phase, $F(1,16) = 60.154$, $p < .001$, $\eta^2_{partial} = .790$ and $F(1,16) = 29.124$, $p < .001$, $\eta^2_{partial} = .645$. The simple HMI version led to higher deviations from target speed compared to the complex HMI version and the red to green traffic light led to higher deviations from target speed compared to the solid green traffic light phase. The ordinal interaction of HMI version and traffic light phase supports the main effects, $F(1,16) = 8.934$, $p = .009$, $\eta^2_{partial} = .358$. When the traffic light changed from red to green the difference between HMI versions was larger compared to the solid green condition. When the traffic light was red or changed to red, the main effects HMI version and traffic light phase were significant, $F(1,16) = 68.315$, $p < .001$, $\eta^2_{partial} = .810$ and $F(1,16) = 50.050$, $p < .001$, $\eta^2_{partial} = .758$. The deviation from target speed was larger when the HMI version was simple compared to complex and when the traffic light changed from green to red compared to the solid red condition. The ordinal interaction showed that in the complex HMI version, the difference in deviation from target speed was very low between the two traffic light phases, $F(1,16) = 52.333$, $p < .001$, $\eta^2_{partial} = .766$. No main effect or interaction with the factor condition was significant, all *ps* > .142. Figure 89 shows the described effects.

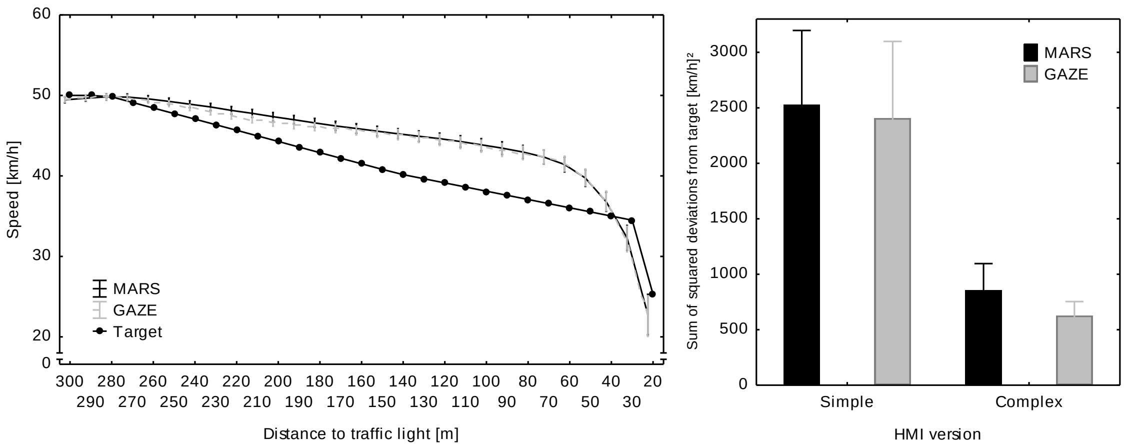


Figure 88. Mean driving speed for the 30 distance sections during the 300 m traffic light approach for the MARS and the GAZE condition and the target speed of the traffic light assistant (left). Sum of squared deviations from target speed for the MARS and the GAZE condition separated by HMI version (right).

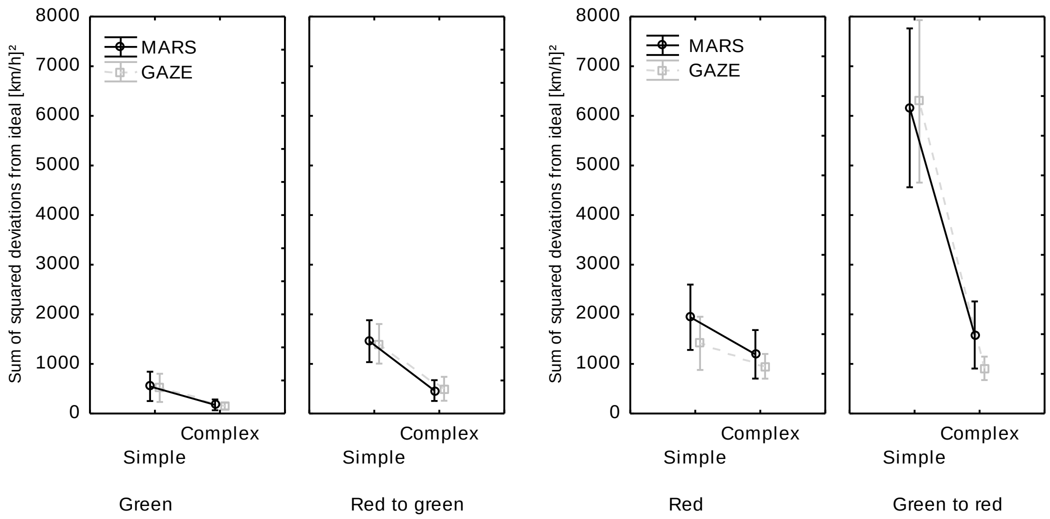


Figure 89. Sum of squared deviations for the MARS and the GAZE condition in the two HMI versions for green and red to green traffic light phases and red and green to red traffic light phases. Graphs show means with 95% confidence intervals.

Subjective evaluations

Drivers evaluated driving with the MARS method. Figure 90 shows the agreement to the statements for the three items examining driving with the MARS method separated by HMI version. In general, it was not very difficult to drive with the masked display and drivers expressed that they were not very bothered by the masked display. Participants agreed medium strongly to the statements that driving with the masked lights became easier with time. T-tests for dependent groups identified differences in the evaluation of the MARS method between HMI versions. Drivers expressed that it was more difficult to stick to the recommendations, when they had experienced the complex HMI version, $t(16) = 3.622$, $p = .002$. Drivers were significantly more bothered that the information was masked when they drove with the complex HMI version compared to the simple HMI version, $t(16) = 2.368$, $p = .031$. No difference occurred between the two HMI conditions concerning the evaluation of learnability, $t(16) = 1.241$, $p = .233$.

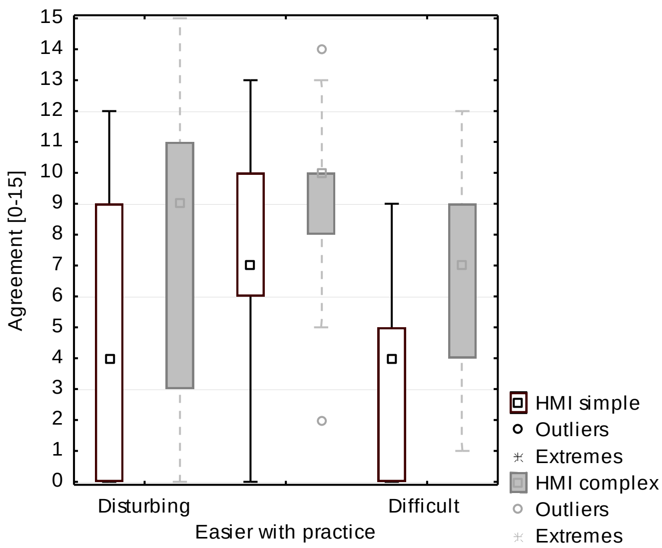


Figure 90. Drivers' agreement to the statements evaluating if driving with the masked display was disturbing, if it was easier with practice and if it was difficult to stick to the recommendations because of the masking. Graph shows boxplots with medians.

Drivers evaluated how appropriate their information demand for the display was after each MARS condition drive and each GAZE condition drive. Drivers responded to the statements "I pressed the button more often than necessary" and "I looked at the display more often than necessary". An ANOVA was conducted with the factors condition (MARS, GAZE) and HMI version (simple, complex) and the agreement to the statements as dependent variable. The interaction was marginally significant, $F(1,16) = 3.295$, $p < .088$, $\eta^2_{partial} = .171$, pointing to the tendency that drivers thought to have looked to the display slightly more often than necessary in the complex HMI version compared to the simple HMI version and compared to the button presses in the MARS condition (Figure 91).

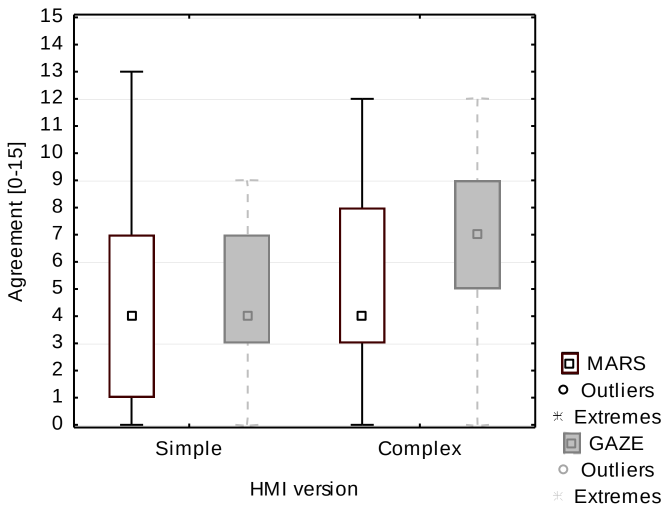


Figure 91. Drivers' agreement to the statements evaluating the appropriateness of information demand for the display in both conditions. After the MARS condition, the statement was "I pressed the button to unmask the display more often than necessary". After the GAZE condition, the statement was "I looked at the display more often than necessary". Graph shows boxplots with medians.

In the final interviews after the test drives, the experimenter asked about strategies used for applying the MARS method and about situations that might have been especially difficult when driving with the MARS method. The following statements were made (in parentheses the number of participants mentioning the statement): I used strategies (16); I pressed as soon as possible after activation (12); I used different strategies for simple and complex HMI versions (14); I only pressed the button as long as the real traffic light was not visible (13); I pressed the button to see the complex HMI multiple times during the traffic light approach (8); I used different strategies depending on the kind of action recommendations presented in the display (4); I mainly attended to the action recommendations in the display (3); I mainly attended to the speed recommendations in the display (3); I mainly attended to the traffic light phase information in the display (1); The MARS method was not explicitly difficult in any situation (10); The MARS method was challenging with the complex HMI (4); The MARS method was challenging when there was upcoming traffic (1); The MARS method was challenging when the traffic light changed from red to green (2).

Finally, drivers evaluated the two different HMI versions. For each of the six questions concerning the displayed information separate ANOVAs were conducted with the factors condition (MARS, GAZE) and HMI version (simple, complex). Neither significant main effects for the factor condition, nor significant interactions with the factor condition were found in drivers agreement to the statements, all *p*s >.086 and .470 respectively. The

HMI versions differed according to the evaluation of complexity, $F(1,16) = 21.952$, $p < .001$, $\eta^2_{partial} = .578$, the estimation of how helpful the HMI was, $F(1,16) = 19.709$, $p < .001$, $\eta^2_{partial} = .552$, the opinion on whether the HMI contained enough information, $F(1,16) = 83.959$, $p < .001$, $\eta^2_{partial} = .840$, and the experience that they looked at the display a lot, $F(1,16) = 10.397$, $p = .005$, $\eta^2_{partial} = .394$. The complex HMI version compared to the simple HMI version was rated as more complex (with generally low complexity ratings) and more helpful. Drivers experienced more strongly that the complex display contained enough information and that they looked at the display a lot. No differences occurred for the subjective evaluation of driving behaviour and how well drivers generally got along with the display, all *ps* > .163.

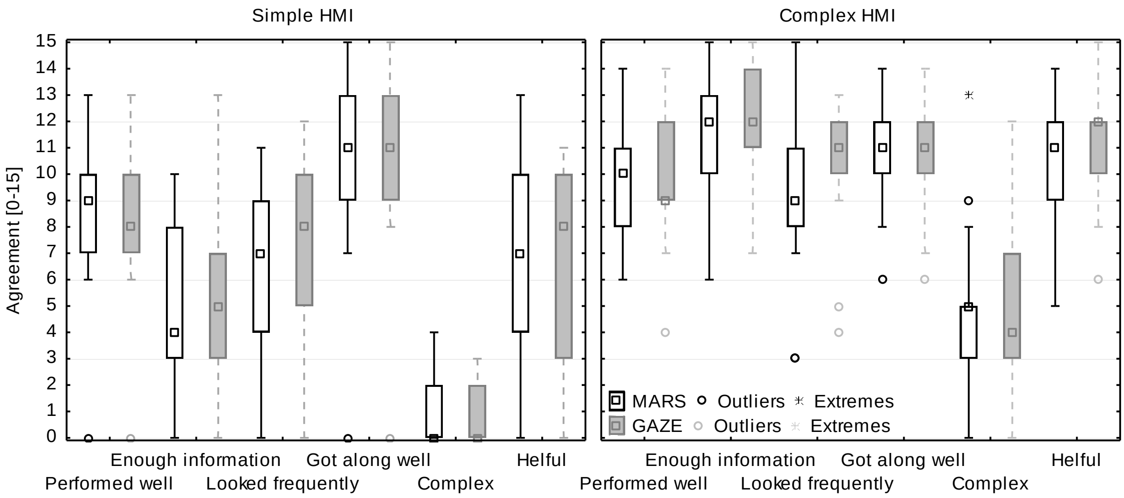


Figure 92. Drivers' agreement to the statements evaluating the HMI versions in the MARS and GAZE condition for the simple and the complex HMI version. The statements were: I performed well in adapting to the expected behaviour; The display contained enough information; I frequently looked at the display; I got along well with the information in the display, The display was complex; The display was helpful. Graphs show boxplots with medians.

4.2.2.3 Summary and discussion

The MARS method was applied to measuring the information demand for the dynamic HMI display of the traffic light assistant. In general, the results showed that the variations in HMI version and traffic light phases influenced the information demand measured in the MARS and the GAZE condition. In extension to the results discussed in Study 4, Study 5 offered the combination of eye tracking and MARS method. By that, it provided a comprehensive understanding of gaze behaviour during the MARS condition. This allows determining if drivers fixate on the display, and how often drivers fixate on the display during masking and unmasking intervals. Using MARS method and eye tracking simultaneously helps explaining possible differences between the number of fixations and the number of button presses. Therefore, the results represent a further progress in the evaluation of the MARS method.

In the MARS and the GAZE condition, the variations of HMI version and traffic light phase similarly influenced the information demand. As expected, with the complex HMI version the information demand was higher than with the simple HMI version. The complex HMI version contained the three different information units traffic light phase information, action recommendations and speed recommendations. The simple version only contained a depiction of the current traffic light state. With more information in the display and higher dynamics in the depictions, the information gains from attending to the complex display were higher than with the simple HMI version. Information needed to be retrieved from the display frequently to fulfil the task of sticking to the recommendations of the traffic light assistant.

When driving with the complex HMI version the information demand for the display was higher for a changing red to green traffic lights compared to the solid green traffic lights. First, when the traffic light changed during the approach, the traffic light phase at arrival marked in the display was different from the traffic light phase drivers saw on the road. Therefore, a more frequent checking if the arrival at green status was still correct took place. Second, the action and speed recommendations in changing traffic light conditions were more dynamic than in the solid green condition, because drivers had to reduce speed before keeping it stable at around 40 km/h. This might also be the reason why no differences between the red and the green to red conditions occurred. When the traffic light was red or changed to red, the recommendation was always to coast to 0 km/h and dynamics in the action and speed recommendations were low.

Similar to Study 4, the information demand measured by fixations in the GAZE condition was higher than the information demand measured by button presses in the MARS condition. A hypothesis was that higher number of fixations occurred because drivers fixated multiple times during a single unmasking interval. The investigation of gaze behaviour during unmasking and masking intervals allows rebutting this assumption. The results showed that button presses and fixations related to each other in the MARS condition. One button press came along with on average one fixation on the display. Hence, drivers hardly ever pressed the button without fixating the display and there were hardly any multiple fixations during a single unmasking interval. More fixations started before the drivers pressed the button to unmask. However, it seems to be an individual preference, if pressing the button or fixating the display comes first. Pleasing is that the experimental variations did not influence the relation between number of unmasking intervals and number of fixations during unmasking. Further, around 56% of the fixations on the display in the MARS condition occurred during display masking. In these cases, drivers probably checked the speedometer information. The analysis of eye tracking data did not distinguish between fixations on the HMI information and fixations on the speedometer, as they were presented in the same cluster display. This missing distinction could partially explain the higher information demand measured in the GAZE condition compared to the MARS condition. Especially the higher fixation durations in the final distance sections before crossing the intersection might result from drivers checking their speed before entering the intersection rather than observing the HMI of the traffic light assistant. It remains to be shown in future research whether the results can be confirmed with either a distinction of fixations on smaller areas of interest within the current HMI display or with using separate displays with separate locations for depicting speed and traffic light assistant HMI. The important conclusion from the Study 5 is that unmasking the display comes along with on average one fixation on it. Additionally, with the missing distinction of gazes to the speedometer and the HMI display, the number and duration of fixations on the display might overestimate the information demand for the HMI display.

Confirming the results from Study 4, the MARS method did not change driving behaviour significantly. There were neither differences in the number of red light violations nor differences in the deviation from target speed. The drivers were able to solve the task of sticking to the recommendations of the traffic light assistant correctly, independent of masked or permanently unmasked displays.

Additionally, the subjective evaluations of the HMI versions did not differ between the MARS and the GAZE condition. This is important for a potential future usage of the MARS method in the development of in-vehicle systems. The participants were able to distinguish between the MARS method as experimental tool and the actual HMI version.

In the evaluation of the MARS method, drivers expressed that the MARS method was more difficult when driving with the complex HMI version. That is a possible limitation of the MARS method, because the demands of the task should not vary between the experimental conditions. However, even though the subjective impression pointed towards a more difficult task with masked display, the objective and subjective comparison of the information demand and driver performance in the MARS and the GAZE method did not reflect these differences. Additionally, the majority of drivers could not identify any situation in which the MARS method was explicitly difficult. The individual explanations that the participants gave for driving with the MARS method point towards the interpretation that the MARS method measures information demand. For example, drivers mentioned that they pressed the button when the real traffic light was not visible yet or that they pressed multiple times during the approach, especially with the complex HMI version.

Finally, the study allowed confirming the results from Study 3. As expected, the complex HMI version was subjectively more complex than the simple version, while the latter did not contain enough information for participants. The deviations from target speed were lower with complex HMI version compared to the simple HMI version. The complex version helped to achieve the global goal of the traffic light assistant: There were no stops at red to green traffic lights and no red light violations at green to red lights when participants drove with the complex HMI version.

In summary, the MARS method was applicable for the evaluation of the information demand to the dynamic display information. The number of button presses offers the possibility to identify changes in the information demand according to different HMI concepts and environmental situations. At the same time, masking the relevant information did not change driving behaviour or subjective evaluations of the display concepts compared to driving with constant visible information. The methods applied in Study 5 allowed explaining gaze behaviour during unmasking intervals: unmasking the stimulus includes that drivers fixate the stimulus, with one unmasking coming along with one fixation. With the combination of MARS method and eye tracking, it is possible to distinguish drivers' information demand for the HMI information and the speedometer.

5 Discussion

Due to their importance for driving safety, traffic lights represent inevitable components of the traffic system. However, traffic lights cause delays and stop events, and by that negatively influence the efficiency of urban driving. The increasing demands for improvements of urban driving efficiency has promoted the development of driver assistance systems that aim to influence individual driving styles.

This thesis presents the development of a traffic light assistance system. The traffic light assistant aims on increasing driving efficiency by recommendations for driving behaviour. The focus of the thesis is on human factors. Hence, the research considers the characteristics of the human driver and evaluates adaptations of the technical system towards the human information processing while interacting with the system during traffic light approaches. Importantly, the research process described in this thesis covers the necessary steps to develop an extensive understanding of the relevant driving task and the factors influencing the effectiveness of the system in modifying driving behaviour.

In a human factors approach to the development of a driver assistance system, it is necessary to identify, quantify and describe the crucial parameters of the driver, the driving situation and the vehicle (König, 2012). Figure 93 summarises the factors considered in this thesis and states their assumed relation. The Car-to-Infrastructure communication allows that the traffic light assistant receives information on traffic light phasing from the infrastructure. Based on different sensor inputs, the algorithm calculates a target driving behaviour for either passing the intersection at green, or for initiating an efficient stop at red. The HMI receives input from the system and communicates the driving recommendations to the driver. Hereby, the current focus was on the investigation of information content presented in a visual HMI display. Based on the model of information processing stages by Wickens & Hollands (2000), the driver processes and perceives the information in the environment inside and outside the vehicle before he selects and executes a response. The thesis covers the investigation of the response execution in relation to stimuli in the environment during unassisted driving and in reaction to the system in assisted driving. The response execution is evaluated by means of dynamic driving parameters that relate to driving behaviour. Preceding the response execution, the driver has an information demand for specific stimuli in order to select the appropriate behaviour. The driver consciously attends to specific stimuli because of their action relevance. In particular, this thesis discusses the information demand for the dynamic traffic light phasing and the information presented in the in-vehicle HMI display. The considered factors in the environment are the traffic light as element of the infrastructure, visibility conditions operationalised by fog and other road users in the tracks.

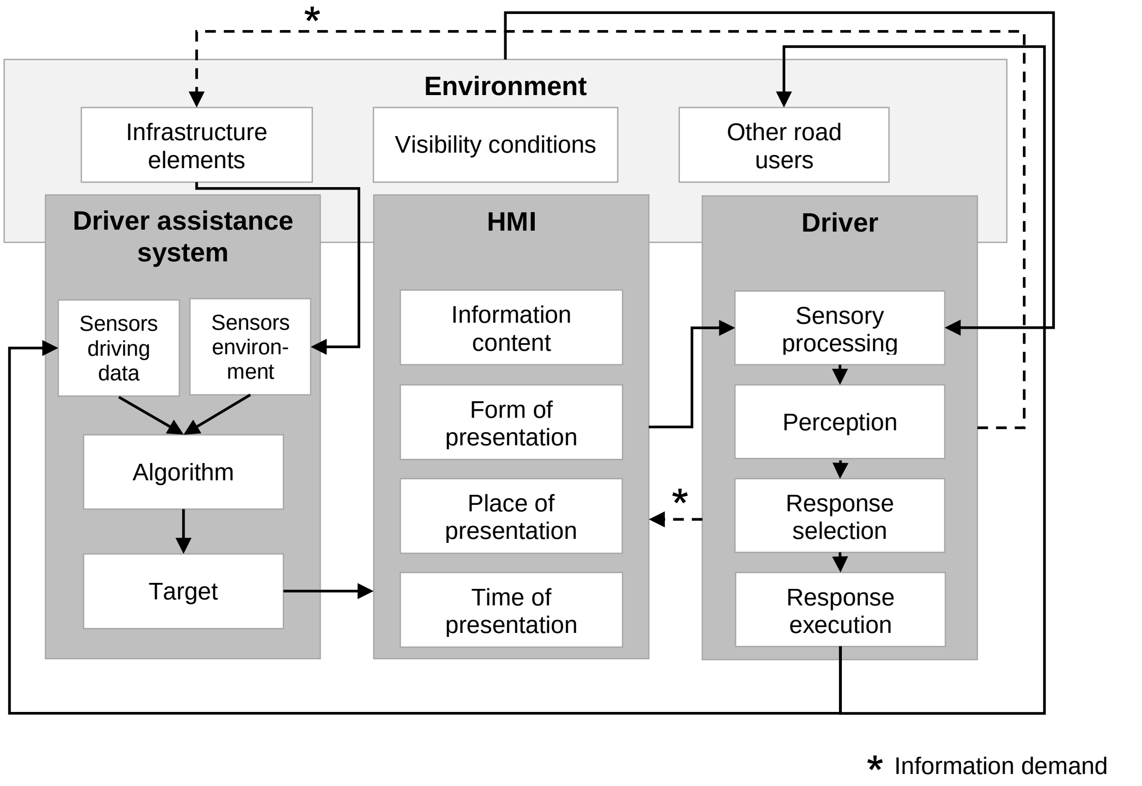


Figure 93. Framework showing the relation of the factors considered in the present thesis. Adapted from Bruder and Didier (2012), Popiv (2012), Schmidtke and Bernotat (1993), Wickens and Hollands (2000) and Zarife (2014).

The empiric part of the thesis presents five driving simulator studies. These include the investigation of unassisted driving behaviour, the influence of the system on the interaction between road users, the definition of the HMI information content and the measurement of the information demand that drivers have for the traffic light and the in-vehicle display. The main goal was to create a comprehensive picture of the driving situation that the system influences and the conditions that lead to good system understanding and compliance in drivers. Therefore, the influential factors depicted in Figure 93 were identified within the derivation of the research questions. The experimental designs of the conducted studies vary the factors of system, HMI and environmental conditions and measure variables in driver information processing. By that, the thesis divides into two main parts: Studies 1, 2 and 3 report the content related research on unassisted driving and the human factors influences on the development of the traffic light assistant. Studies 4 and 5 report the method related research that introduces the novel MARS method for measuring the information demand to dynamic stimuli while driving. To provide an overview, Table 29 summarises the main results covered in the five experiments. The following chapters summarise the main conclusions drawn from results of content related research and method related research.

Table 29. Overview of the conducted studies and the main results.

No	Study title	Main results
1	Baseline study	There is a potential for improvements in driving efficiency with increased anticipation of the traffic situation. Approaching traffic light intersections takes place in three phases: orientation, preparation and realisation.
2	Interaction between road users	Early recommendations of low driving speeds lead to the feeling of bothering other road users. Early recommendations of low driving speeds lead to low compliance with the recommendations of the traffic light assistant. The feeling of bothering others does not necessarily coincide with the feeling of anger in following drivers.
3	HMI evaluation	The HMI concept should provide traffic light phase information, action recommendations and speed recommendations. The combination of the information units leads to redundancy gains rather than driver overload.
4	Information demand for the traffic light	The MARS method is able to identify differences in information demand for the traffic light, depending on variations in traffic light phase, lead vehicle and visibility conditions.
5	Information demand for the HMI display	The MARS method is able to identify differences in information demand for the HMI display of the traffic light assistant, depending on traffic light phase conditions and complexity of the HMI display. One unmasking interval comes along with approximately one fixation. The combination of MARS method and eye tracking allows distinguishing the information demand for different details in the same display.

5.1 Discussion of content related research

The content related research in the present thesis focuses on the understanding of unassisted driving behaviour at traffic light intersections and the investigation of factors influencing driver compliance with the recommendations of the traffic light assistant.

First, the basic investigation of the driving task in Study 1 allowed justifying the development of the system. The varied factors in the experimental design were supposed to demonstrate the potential of improvements in driving efficiency. Driving efficiency was expressed in terms of dynamic parameters that relate to driving behaviour rather than specific consumption and emission values. This approach was justified by the literature background that demonstrated that gentle accelerations and decelerations as well as low variations in speed profiles relate to high efficiency of driving. The results showed that driving behaviour was less efficient when the traffic light changed compared to solid traffic light phases, and when there was no lead vehicle ahead compared to with a lead vehicle. Better visibility of the traffic light in conditions without fog in the track was only beneficial when the traffic light phase did not change during the approach. Hence, driving was less efficient when drivers prepared and realised driving behaviour for traffic conditions that subsequently changed. Consequently, the traffic light assistant has the potential to improve driving efficiency by influencing the driver's anticipation of the driving situation at arrival at the intersection.

Second, the main assumption in Study 1 was that in order to support drivers with a driver assistance system, it is necessary to gain knowledge and understanding of how drivers perform the relevant driving task. Before the actual introduction of the system to the drivers, it is possible to describe which parts of the driving task the system could influence and how significant the influence might be. The results in Study 1 showed that approaching traffic light intersections took place in three stages. In the orientation phase, drivers perceived the traffic light, but did not adapt their driving behaviour. The orientation phase started with first visibility of the traffic light. Adaptations of driving behaviour were not necessary, because the traffic light phase could still change until arrival at the stop line. In the preparation phase, drivers reduced driving speed and prepared for the cues in the environment that determined how to proceed. During the preparation phase, the information demand for the traffic light increased, because the traffic light phasing was the crucial cue for initiating a stop or proceeding through the intersection. Finally, in the realisation phase, the driver realised the selected driving behaviour, i.e. either initiated a stop at red or proceeded through the intersection without stop. When crossing the intersection at green in the realisation phase, drivers checked for their driving speed by attending to the speedometer.

Study 2, Study 3 and in parts Study 5 showed that the traffic light assistant influenced driver processing and behaviour in the three phases. While in unassisted driving the orientation phase started with the visibility of the traffic light, Study 5 indicated that driver's orientation phase was introduced by the activation of the traffic light assistant. The benefit in time and space that the traffic light assistant offered allowed that the information about the traffic light was available earlier than drivers could see the real traffic light. Therefore, the anticipation of the traffic situation was possible when the traffic light was not yet visible in the track. Drivers actually perceived and desired the information as soon as the presentation started. The increased information demand for the information from the traffic light assistant right after activation confirmed this conclusion.

In the preparation phase, the traffic light assistant supported the decision on which driving behaviour was required. Study 3 and Study 5 confirmed that a good HMI strategy of the traffic light assistant especially supported situations with changing traffic light phasing. With assistant, drivers were able to prepare driving behaviour for the estimated traffic light phase at arrival rather than the currently visible traffic light phase. This way to anticipate the traffic situation was exclusive to drivers equipped with the system. Additionally, the system recommended driving behaviour earlier than drivers usually react to the traffic light. Consequently, Study 2 showed that there were conditions in which drivers did not feel comfortable with sticking to the recommendations. The multi-driver simulator setting with four real drivers in the same virtual environment allowed identifying that these situations related to the interaction with other road users. When the deviations between normal driving behaviour and the system recommendations were too large (e.g. when speed adaptations were necessary at far distances to the lights or required very low speeds), drivers expected negative emotional reactions by others. These expectations in turn seemed to influence driving behaviour. Even in cases in which drivers were instructed to comply with the system whenever possible, they chose to violate the recommendations when they expected to bother other road users. Interestingly, in only 40 % of the traffic light approaches in which a driver with system expressed that he bothered a following vehicle, the driver of the following vehicle also expressed that others angered him. With that the number of times that two drivers with and without traffic light assistant following each other expressed anger and bother at the same time was lower than expected. As a solution, there are different ways to increase driver acceptance for the recommendations of the traffic light assistant. The algorithm should consider the speed and distance thresholds identified in Study 2. The system should not recommend driving speeds below 30 km/h. In particular, in busy traffic situations with high likelihood for following traffic, the system should abstain from low speed recommendations that start at far distances to the traffic light (e.g. 400 m in front). From a technical point of view, this option reduces the recommendation range of the traffic light assistant. When the system only allows recommending driving speeds between 30 and 50 km/h at short distances to the traffic light, the number of scenarios in which the traffic light assistant actually supports the drivers in the urban setting reduces dramatically. Therefore, addressing drivers' perception and emotional evaluation might be promising. To support the decision to stick to the recommendations in the preparation phase, elucidation and mutual understanding for the deviations from normal driving behaviour between different road users should be promoted. Especially the fact that to a certain extent following vehicles benefit from a vehicle with traffic light assistant in front could support that drivers feel comfortable in complying with the system. For a future evaluation of the traffic light assistant, it seems promising to address positive emotional reactions that drivers experience in interaction with the system. In the current setting, drivers were instructed to express anger and bother experiences by button presses. It might be that this leads to an overestimation of negative emotional reactions in relation to the system. Positive reactions might occur when for example drivers are able to catch a green light due to the information from the traffic light assistant. The positive reactions could be used to motivate drivers for using the system.

For the realisation of the target behaviour, Study 3 showed that in general, the traffic light assistant reduced the number of red light violations at the intersections. Hence, independent of the specific presented information unit in the HMI, the traffic light assistant supported the drivers with the correct decision on proceeding or stopping. The presentation of the three information units (traffic light information, action recommendations and speed recommendations) led to the highest acceptance and best performance in applying the driving strategy. For driver performance, speed and action recommendations were most beneficial. In particular, for initiating stops at the red light, action recommendations showed advantages. For proceeding through the green light, speed recommendations showed advantages. Subjectively, drivers valued information about the traffic light phase. With the combination of all three information units, the redundancy gains measured in subjective and objective data were higher than the disadvantages caused by the higher processing load of multiple information units. The gaze durations to the HMI display were within the standard thresholds for safe interaction with an in-vehicle display. The results suggested the confirmation of the redundancy hypothesis. The information units presented in the current studies included a certain degree of redundant content. For example, the speed recommendation “0 km/h” usually included a coast recommendation along with the information of arrival at red. Therefore, drivers could perceive the information faster and understood the presented information better. An alternative explanation for the improved driving performance with the combination of information units might be that the driver could rely on the specific information unit that was currently important in each specific situation (e.g. action recommendations for initiating the stop, speed recommendation for passing through, traffic light information while waiting at red). Additionally, the three information units offered different tolerances for drivers to explore the traffic light assistant. Using the traffic light phase information, some drivers were able to realise a driving behaviour that was not included in the action and speed recommendations. These drivers reduced their driving speed far below 30 km/h. By that, they managed to cross an intersection without stop, which in case of action or speed recommendations would have led to a stop at red. On the one hand, this shows that drivers understood the logic of the traffic light assistant and could use the timing information for their advantage. On the other hand, extreme adaptations of driving behaviour might lead to conflicts with other road users. With the presentation of all three information units, drivers can decide in any moment of the traffic light approach, whether and how strong they are willing to adapt their driving behaviour based on their preferred information. In relation to the results from Study 2, drivers would probably abstain from strong deviations from normal driving speed in case of following traffic. Nevertheless, future research should examine whether the presentation of multiple information units remains beneficial when more information (e.g. gear choice recommendations, efficiency statistics) is added to the display. Concluding from the present data, the drivers benefit from the combined presentation of information units and their driving performance and acceptance improves.

Finally, adding to the evaluation of driving behaviour with traffic light assistant, the current thesis presented the investigation of driver behaviour in a potentially critical driving situation. The situation required that drivers neglect the targets of the traffic light assistant in favour of a response adaptation to the potentially critical situation. The results showed that driver behaviour in the critical driving situation did not differ between the complex HMI version and the simple HMI condition. In general, the majority of drivers were able to decide in favour of driving safety, neglect the recommendation of the traffic light assistant and solve the situation correctly. Nevertheless, the critical driving situation evaluated in the current thesis allowed for a large range of different reactions in order to avoid a collision with the emergency vehicle. For future research, it is recommended to choose a driving situation that offers a distinct interpretation of driver's response selection based on driving data.

5.2 Discussion of method related research

The methodological focus of the thesis was to develop a method for measuring driver information demand for specific dynamic stimuli in the driving environment and the in-vehicle HMI display. The information demand is an indicator for conscious attention allocation to the stimulus. The information demand relates to action relevance. Hence, when drivers demand information from a stimulus by attending to it, the stimulus is required in order to select appropriate (driving) actions. Measuring gaze behaviour by means of eye tracking has been the standard method for measuring information demand. However, as outlined in this thesis, eye tracking data cannot necessarily be interpreted in terms of information demand. Drivers can covertly shift attention to a stimulus without fixating it. Further, increased number of fixations on a stimulus might occur because drivers just need to fixate somewhere in space or because of the salient role of the stimulus in the visual field. In both cases, fixations on a stimulus do not indicate action relevance. Finally, measuring eye tracking comes along with challenges for experiment procedure, data quality and data analysis. The MARS (Masking Action Relevant Stimuli) method measures information demand by covering the relevant stimulus. To unmask the stimulus, drivers indicate their information demand by pressing a button at the steering wheel. The driver's request to unmask leads to a limited unmasking interval (e.g. 800 ms) before the masking returns. The main dependent variables when analysing the MARS method data are the number of button presses initiated by the drivers.

The studies reported in this thesis investigated the information demand for the dynamic traffic light phasing and the dynamic HMI display of the traffic light assistant. The evaluation of the MARS method was based on two main criteria. First, the test designs introduced variations in the masked stimuli, as well as the environment conditions. It was expected that certain stimulus configurations and traffic conditions lead to more or less information demand of drivers for the specific stimulus. If the MARS method is able to measure information demand, it will distinguish between those conditions. Second, the unmasking intervals in the MARS method were compared to the fixation intervals as measured by the eye tracker. Based on the outlined relation between action relevance and eye fixations, the assumption was that the variations in the stimuli and the test track influence fixations and button presses qualitatively similar. Increases in number of button presses in the MARS condition should come along with increases in number of fixations measured by means of eye tracking (in the GAZE condition). Derived from that, increases in the time spent with unmasked stimulus should come along with increases in fixation durations.

Overall, the button presses to initiate unmasking intervals in the MARS condition were able to measure information demand for the traffic light. Information demand was higher, when the traffic light changed compared to solid lights. As an explanation, observing a traffic light change during the approach reduces the likelihood for a further change. Contrary, with solid lights, the information demand remains high until arrival at the intersection, because a phase change can occur at any time. The number of button presses was also higher, when there was no vehicle ahead compared to with lead vehicle, because the lead vehicle served as a source of information. Importantly, when fog obscured the visibility of the traffic light, drivers less often expressed an information demand compared to unlimited visibility. Participants only pressed the button when they could retrieve meaningful information from the stimulus. Hence, drivers understood the relation between button presses and the reception of required information. When the masking implied the HMI display, the number of button presses was higher with complex HMI version compared to the simple HMI version, because more action relevant information was depicted in the display. The high dynamics in the display at changing red to green traffic lights increased the number of information demands in the complex HMI version. As a conclusion, the number of button presses was able to distinguish between conditions with high and low information demand.

Furthermore, the comparison between MARS condition and GAZE condition showed that generally the button presses and fixations change qualitatively similar. Nevertheless, the number of fixations exceeded the number of button presses. Based on the results from Study 4, a possible hypothesis was that drivers fixate multiple times during a single unmasking interval and that therefore, the MARS method underestimates the information demand. However, measuring fixations in the MARS condition in Study 5 allowed rebutting this assumption: On average, drivers fixated on the display once in each unmasking interval. Consequently, it might be that solely interpreting driver fixations actually overestimates the information demand. In Study 4, drivers might have fixated on the traffic light more often than they pressed the button in the separate MARS condition, because the traffic light played an important role in the experiment, because it was always located in the central field of vision and because drivers always have to look somewhere in the driving scene. The measured gazes to the traffic light then do not indicate action relevance. In other words, while the MARS method measures conscious information demands for the stimulus, driver fixations include conscious and unconscious processes. Additionally, in Study 5, there was a tendency that drivers subjectively experienced that they attended to the display more often than necessary in the GAZE condition. Supporting this, there were no meaningful differences in driving behaviour between the MARS and GAZE conditions. The drivers did not miss any important information because of the masking and performed as well as without masking. For the correct solution of the driving task, there was no need to attend to the stimuli more often than measured in the MARS condition.

The stated overestimation of information demand for the traffic light by measuring fixations does not question previous research results reported from eye tracking studies. Usually, the relative difference between conditions is crucial for evaluation studies. However, the criteria for the evaluation of in-vehicle displays could also consider when and how much specific information is action relevant. Driver fixations on specific stimuli that occur without attention or with covertly shifting attention to other areas in the road scene are usually included in the analysis of fixations. These fixations might be less relevant for the evaluation of the interaction with a stimulus compared to the analysis of how much information drivers need from the stimulus in order to perform the driving task correctly. In line with that, the studies in the present thesis show that drivers are well able to focus their attention to specific stimuli when they evaluate them as action relevant and abstain from retrieving information from the stimulus as long as it is not action relevant. Hence, the information demand as measured by the MARS method could be included in the evaluation of information processing of specific elements inside or outside the vehicle.

In Study 5, an additional precondition needs to be considered: The recording of the gaze behaviour did not distinguish between fixations on the speedometer and fixations on the HMI display. For the HMI strategy, it was important to create the proximity of the HMI recommendations and the speedometer, because it was expected that recommending driving behaviour relates to checking the driving speed. Therefore, while gazes to the traffic light in Study 4 did not lead to any valuable information during masking, gazes to the display in Study 5 offered useful information. More than 50 % of the fixations on the display occurred during masking. In these cases, drivers might check the speedometer, rather than the HMI display area. This could explain the differences in fixations and button presses in general. While the eye tracker measured fixations on the display and the speedometer, the MARS method only measured information demands for the HMI display. Supporting this, shortly before crossing the intersection when driving with traffic light assistant, the information demand for the HMI display in the MARS method decreased while the information demand time increased in the GAZE condition during the same distance sections. At this point of the traffic light approach, the decision on how to proceed has already been made and further checking of the HMI display did not offer action relevant information. As outlined above, especially when deciding to proceed through the intersection, the driving speed represents an important information. Based on that interpretation, the combination of eye tracking and MARS method as used in Study 5 allows determining the information demand for multiple stimuli within the same area of interest. For the presented context, fixating on the area of interest without masking could imply that the speedometer information is action relevant. Fixating on the display with unmasking implies that the HMI display is relevant. Hence, the combination of MARS method and eye tracking method leads to results on the information demand for different stimuli within a single display. Nevertheless, research is necessary to evaluate the influence of the HMI version on the information demand for the speedometer and if gazes to the speedometer occur because of action relevance or, analogue to the gazes to the traffic light, without conscious information demand.

In general, the assumption of the MARS method is that drivers only press the button when they actually need the information from the stimulus. It could be argued that drivers press the button for curiosity or to comply with the experimenter’s instructions. Masking the relevant stimulus puts an emphasis on the stimulus and drivers might pay more attention to it than without that emphasis. However, as mentioned before, in both studies the number of fixations exceeded the number of button presses. Therefore, an overestimation of information demand in the MARS method seems unlikely. Supporting this, the investigation of gaze behaviour presented within Study 5 showed that there were no differences in the number of fixations on the area of interest between MARS and GAZE condition. The masking did not influence drivers normal gaze behaviour and the attention to the stimulus did not generally increase with the emphasis of the MARS method. In addition, the number of unmasking intervals in which drivers did not fixate on the display was very low. This supports the assumption that button presses come along with actually processing the action relevant information.

For the application of the MARS method in the experimental setting, it is important that participants understand their task and can handle it well. Besides the evidence on driving performance gained from dynamic parameters, participants subjectively stated that the task is low disturbing and that they learn quickly how to use it. Additionally, the free statements supported that drivers relate the button presses to decisions on driving behaviour. Ideally, participants perceive the MARS method similarly in the different experimental conditions. Study 5 showed, that the MARS method was slightly more difficult when driving with the complex HMI version compared to the simple HMI version. Future research needs to show how well the MARS method can be generalised to stimuli with different complexities and how this influences the experimental designs. Promising for a future usage is that the masking did not influence the evaluation of the HMI versions and the drivers were able to separate the HMI evaluation from the MARS method as a research tool.

A possible flaw of the MARS method is that it is not able to measure short and quick consecutive fixations. In both presented evaluation studies, the overall duration of unmasking intervals was compared to the overall duration of fixations. In analogy to the number of information demands, the duration of fixations exceeded the duration of unmasking intervals. Additionally, the variation of conditions similarly influenced the duration of information demand in the MARS and the GAZE condition. Further, Study 5 showed that drivers did not fixate frequently within a single unmasking interval. Nevertheless, the length and sequence of fixations on the specific stimulus might vary. In the current studies, the difference between information demand duration in the MARS and the GAZE condition was not identical between the distance sections during the traffic light approach. Especially, in more variable and difficult driving situations drivers might divide their information demand into more and shorter fixations. The MARS method is not able to cover for these frequently occurring short information demands, because unmasking intervals have a fixed pre-defined duration. Therefore, preparation of the MARS experiments requires careful consideration on the duration of the unmasking interval, and unmasking duration and characteristics of the masked stimulus might interact. Future research could investigate the information demands by unmasking depending on different durations of the unmasking intervals. A possible approach to the limitation of fixed unmasking intervals could be that drivers determine the length of the unmasking intervals by the length of button presses. In the current studies, this solution was not applied, because it was expected that drivers could keep the button pressed, independent of real information demand. The effort for leaving the thumbs on the buttons of the steering wheel was low and drivers could easily press the button constantly during the whole traffic light approach. Consequently, the unmasking intervals would not discriminate between conditions of high and low information demand. Yet, future research could investigate alternative concepts to operationalise the relation between button presses and unmasking duration.

Furthermore, the MARS method can only measure the information demand for a predefined, small number of stimuli, while the eye tracking technology allows for an exploratory investigation of drivers attention distribution to various stimuli. Future research could investigate the applicability of the MARS method to more than one stimulus within the same experiment. For example, considering the differentiation of the three information units in the HMI strategy (Study 3 and Study 5), it would be interesting how much information demand drivers have for the single information units during simultaneous presentation. Unclear remains the question whether drivers are able to handle multiple different buttons relating to different information units.

In general, the MARS method can be used for every dynamic action relevant stimulus in the vehicle. Masking dynamic stimuli in the road environment requires the usage of a driving simulator. Outside the vehicle, the MARS method can mask road signs, other road users and vehicles, or entire road sections. Inside the vehicle, mirrors, HMI displays and speedometer information can be covered (Table 30). Especially promising seems the application of the MARS method to information presented in head-up displays. For eye tracking, the determination of gaze behaviour when driving with a head-up display represents a challenge, because the discrimination between fixations on the head-up display and fixations on the environment is difficult. With the MARS method, the identification for information from the head-up display is simple. Further, in the context of automated driving, the MARS method could help to identify how important certain stimuli are for the driver's decision to attend to the road scene or how frequently drivers check the system status.

Table 30. Examples for possible applications of the MARS method.

Action relevant stimulus	**Masked**	**Unmasked**
Speedometer		
Rear view mirror		
Head-up display		

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5.3 Limitations

In general, all studies included driving simulator experiments. As stated by Shinoda et al. (2001), it is difficult to predict how especially attention measured in a specific experimental setting generalises to the real world. In order to draw clear conclusions form the variations in the independent factors, conditions were highly standardised and the simplified scenarios had limited variability and reduced complexity. Data collected in the driving simulator do not necessarily transfer directly to real world driving data. It is assumed that that the present results show relative validity (e.g. the situations that show a potential for assistance in the driving simulator will also show a potential for assistance in real traffic). Nevertheless, future research should test driving behaviour and the traffic light assistant in real traffic conditions. It might be that due to the simplicity of the scenarios the effects in more complex real traffic conditions are even stronger and that the current results underestimate the relationships between conditions. Moreover, in the present studies, the traffic light assistant was highly reliable, i.e. when the drivers complied with the recommendations, the predicted driving situation occurred. For future research, there should be a focus on highly dynamic traffic light controllers, which might decrease the reliability of the traffic light assistant. It remains to be shown how drivers react, when sticking to the recommendations of the system does not lead to the predicted driving situation. The plausibility of speed limits and recommendations plays an important role for driver acceptance and compliance (Schweigert, 2003).

Finally, driving efficiency was not measured directly by measuring fuel consumptions or emissions. The interpretation of results on unassisted driving based on the relation of driving behaviours with efficiency parameters, which has been outlined in the literature background. Efficiency when driving with the traffic light assistant was determined based on how well drivers achieved the goals of the traffic light assistant in terms how many stops at red could be avoided (in Study 2) and how much the driving profile deviated from the target profile of the assistant (in Study 3). For the evaluation of the HMI concept, absolute values for efficiency were not crucial. Essential for the evaluation in this thesis was, how well drivers were willing and able to follow certain recommendations, independent of whether these recommendations represented the most efficient strategy. Nevertheless, future research could cover the actual impact of driving behaviour and the assistant on efficiency. In line with this, driver performance in interaction with the system might relate to the driver’s desire to reduce fuel consumption and emissions and to the mental models that drivers have of efficient driving behaviour (Pampel, Jamson, Hibberd, & Barnard, 2015).

6 Conclusions

The research in this thesis investigated driving behaviour at traffic light intersections. It was demonstrated that especially situations in which the anticipation of the traffic light phase at arrival is difficult have a potential for improvements in driving efficiency. This is the case when visibility is limited or the traffic light phase changes during the traffic light approach. In turn, the traffic light assistant is able to influence driving behaviour when approaching traffic light intersections. Driver compliance, understanding and acceptance for the traffic light assistant depend on factors in the environment and characteristics of the HMI. To increase driver's acceptance for the recommendations of the traffic light assistant, the algorithm should include the determined speed and distance thresholds. Mutual elucidation of driving targets could reduce negative emotional reactions. The HMI of the traffic light assistant should show information on traffic light phasing, action recommendations and speed recommendations and. In the current setting, no negative effects on driving safety occurred when driving with the traffic light assistant.

In the process of the content related research, a methodological research question evolved. Two experiments showed that the information demand that drivers have for the dynamic traffic light phasing and the dynamic in-vehicle display of the traffic light assistant can be measured by the novel MARS method. The method allows measuring how action relevant the traffic light phasing or the HMI display are in any moment of the traffic light approach. Hence, the MARS method supports developing an understanding of basic information processing while driving. As a substitute or supplement of measuring gaze behaviour, the MARS method can serve as a research tool in the evaluation of HMI concepts.

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