Technische Universität München

Fakultät für Maschinenwesen

Lehrstuhl für Ergonomie

Design and Evaluation of an Automated Lane Change in Dense Traffic from Interacting Human Drivers' Perspective

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Vollständiger Abdruck der von der Fakultät für Maschinenwesen der Technischen Universität München zur Erlangung des akademischen Grades eines Doktor-Ingenieurs (Dr.-Ing.) genehmigten Dissertation.

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Prüfer der Dissertation:	1.	Prof. Dr. phil. Klaus Bengler
	2.	Prof. Dr. rer. nat. Hermann Winner

Die Dissertation wurde am 19.04.2021 bei der Technischen Universität München eingereicht und durch die Fakultät für Maschinenwesen am 18.07.2021 angenommen.

Danksagung

Die vorliegende Dissertation ist im Rahmen meiner dreieinhalbjährigen Promotionszeit bei der Audi AG im Bereich der Vorentwicklung automatisiertes Fahren als INI.TUM Kooperationsdoktorand entstanden.

Als Erstes möchte ich mich bei meinem Betreuer bei der AUDI AG Dr. Karl-Heinz Siedersberger bedanken. Vielen Dank, dass du besonders am Anfang der Arbeit immer wieder Zeit gefunden hast dich mit mir über mein Promotionsvorhaben auszutauschen. Zudem danke ich dir für die Rückendeckung, die es ermöglicht hat für jede der Studien drei Versuchsträger und das Testgelände der Audi AG in Neuburg zu nutzen - ohne diese wäre die Durchführung der aufwendigen Studien nicht möglich gewesen. Und nicht zuletzt dafür, dass ich meine Ideen im Rahmen der Promotion immer frei entfalten durfte.

Besonderer Dank gebührt der Vorentwicklung für automatisiertes Fahren der Audi AG, ohne die die Durchführung der Studien nicht möglich gewesen wäre. Besonders möchte ich mich bei Sebastian Bayerl dafür bedanken, dass du immer ein offenes Ohr für die Beantwortung von Fragen zur Entwicklung der notwendigen Software zur Durchführung der Versuche hattest. Auch möchte ich mich besonders bei Stephan Bultjes für die Zeit zur Inbetriebnahme der Fahrzeuge auf dem Testgelände und das Einstellen der Regler bedanken. Nicht zu vergessen sind die Masteranden Magdalena Feuerbach, Sophie Feinauer und Philipp Hartl sowie die Praktikanten Karlijn Labrujere und Mareike Schüle.

Besonders möchte ich mich bei Herrn Prof. Bengler bedanken, ich danke Ihnen für die vielen konstruktiven Gespräche - besonders sind mir die Testfahrten vor dem ersten und zweiten Versuch in Erinnerung - in denen wir intensiv über das ideale Einfädelverhalten diskutiert haben und verschiedene Variationen direkt erleben konnten - diese Testtage waren sicherlich ein Highlight meiner Promotionszeit. Des Weiteren gilt mein Dank Prof. Winner für das Interesse an meiner Arbeit und die Übernahme der Aufgabe des Zweitprüfers und Herrn Prof. Lienkamp für die Übernahme des Prüfungsvorsitz.

Auch möchte ich mich bei meinen Doktorandenkollegen Frank Dierkes, Stefan Krämer, Henrik Bey, Michael Rettenmeier, Alexander Feierle und Tanja Fuest für die vielen interessanten Diskussionen bedanken - die Konferenzen in Paris und Auckland waren ihre Reise wert.

Auch möchte ich meiner Partnerin und meiner Familie danken. Vielen Dank, dass ihr mich während der Promotionszeit immer unterstützt habt, vielen lieben Dank für die vielen ausgedehnten Telefonate auf dem langen Arbeitsweg zwischen München und Ingolstadt und nicht zuletzt vielen Dank für das Korrekturlesen der Arbeit.

Abstract

The fact that the replacement of human drivers with Automated Driving Systems is still a future vision and especially first Automated Driving Systems have to interact with them, motivates the investigation of the communication between those traffic participants. Especially in dense traffic an automated vehicle's (AV's) lane changes cannot be executed without cooperation of interacting human drivers. To systematically analyse the desired AV's driving style from the perspective of interacting human drivers five steps need to be evaluated to design the AVs driving style in dense mixed traffic lane changes: 1. analyse, 2. communicate, 3. interpret, 4. start, 5. execute. Implications for step two, four and five to design an AV's driving style are derived within the scope of this thesis based on three different real vehicle studies on the test track. Within those studies a similar scenario considering a lane change into an adjusted gap between slower human drivers in front of the AV is investigated.

The first study examines the second step to systematically design the AV's driving style to communicate the intention to change lanes in a within-subjects design (with 40 participants). Different factors to announce a lane change like the time to set the turn signal, different braking strength to the adjusted gap or a lateral offset in advance of the lane change are investigated. Moreover, the influence of the lane change direction as well as the velocity of the adjusted gap are analysed. The study illustrates that not only the turn signal is crucial to announce a lane change, but also hard braking to the adjusted gap influences the predictability of the AV's driving style as well as cooperation of interacting human drivers. Other factors, such as a lateral offset in advance of a lane change are evaluated as less important. In addition, the study implies higher cooperation and an influence of the lane change direction at slow velocities. The second study examines the fourth step to systematically design the AV's driving style at the start of the AV's lane change in a within-subjects design (with 39 participants). The participants validate different distances between the lag (participant's) vehicle of the adjusted gap and the AV in different scenarios (velocity and lane narrowing) as start condition and start the lane change of the AV themselves out of an interacting vehicle, at the time they expect it to change lanes. The results show that participants prefer an AV's start of the lane change with small distances to vehicles forming the adjusted gap. Compliance with safety distances is not decisive. The required distance between the AV and interacting human drivers decreases with higher velocity and in lane narrowing scenarios. The third study examines the fifth step to systematically design the AV's driving style for the execution of the AV's lane change in a within-subject design (with 37 participants), considering different possibilities to establish safety distances on the target lane. Moreover, different lane change durations and the influence of the perspective of the lead or lag vehicle of the adjusted gap are evaluated. The results show that even light braking of the AV during and after the lane change should be avoided, but almost no influence whether, at what time or to which extent the distance to the lead vehicle is increased. Lane change durations at the lower limit of the passenger's comfort comparable to human driving style and not longer lane change durations with lower lateral dynamics are preferred and low impact of the perspective is shown.

Kurzfassung

Der Fakt, dass der Austausch menschlicher Fahrer durch selbstfahrende Autos noch eine Zukunftsvision ist und insbesondere die ersten selbstfahrende Autos mit diesen interagieren müssen, macht die Untersuchung der Kommunikation zwischen diesen beiden Verkehrsteilnehmern interessant. Insbesondere bei dichtem Verkehr kann ein Fahrstreifenwechsel eines automatisierten Fahrzeuges ohne die Kooperation der interagierenden menschlichen Fahrer nicht durchgeführt werden. Zur systematischen Analyse des gewünschten Fahrstils von automatisierte Fahrzeugen aus der Perspektive interagierender menschlicher Fahrer müssen fünf Schritte zur Gestaltung des Fahrstils in dichten gemischten Verkehr untersucht werden: 1. Analysieren, 2. Kommunizieren 3. Interpretieren, 4. Starten, 5. Ausführen. Für die Phasen zwei, vier und fünf werden in Rahmen dieser Arbeit Implikationen zur Gestaltung des automatisierten Fahrstils in drei verschiedenen realen Fahrzeugstudien auf dem Testgelände abgeleitet. In diesen Studien wird mit einem Fahrstreifenwechsel in eine Lücke zwischen langsameren menschlichen Fahrern vor dem automatisierten Fahrzeug ein ähnliches Szenario betrachtet.

Die erste Studie untersucht den ersten Schritt zur systematischen Gestaltung des automatisierten Fahrstils, die Kommunikation des Fahrstreifenwechselwunsches, mit einer Within-Subject Studie (mit 40 Probanden). Es werden verschiedene Faktoren zur Ankündigung eines Fahrspurwechsels wie der Blinkzeitpunkt, unterschiedliche Stärken der Bremsungen auf die Ziellücke oder eine Annäherung an den Fahrstreifenrand vor dem Fahrstreifenwechsel beleuchtet. Darüber hinaus wird der Einfluss der Wechselrichtung sowie der Geschwindigkeit analysiert. Die Studie veranschaulicht, dass nicht nur ein ausreichend früher Blinkzeitpunkt entscheidend ist, um die Intention eines Fahrstreifenwechsels zu kommunizieren, auch stärkere Bremsungen auf die Ziellücke beeinflussen die Erwartungskonformität des Fahrstils des automatisierten Fahrzeuges positiv und erhöht die Kooperation der interagierenden menschlichen Fahrer. Andere Faktoren, wie eine Annäherung an den Fahrstreifenrand vor dem Fahrstreifenwechsel, werden als weniger wichtig bewertet. Darüber hinaus impliziert die Studie eine höhere Kooperation und einen Einfluss der Wechselrichtung bei langsamen Geschwindigkeiten. Die zweite Studie untersucht den vierten Schritt zur systematischen Gestaltung des automatisierten Fahrstil, den Start des automatisierten Fahrstreifenwechsels, ebenfalls mit einer Within-Subject Studie (mit 39 Probanden). Die Teilnehmer validieren unterschiedliche Abstände zwischen dem vom Probanden gefahrenen und dem automatisierten Fahrzeug, als Starbedingung für den Fahrstreifenwechsel, in verschiedenen Szenarien (Geschwindigkeit und Fahrbahnverengung) und starten den Fahrstreifenwechsel des automatisierten Fahrzeuges selbst aus dem hinteren Fahrzeug der Fahrzeuge die die Ziellücke bilden heraus, genau an dem Zeitpunkt an dem sie diesen erwarten würden. Die Ergebnisse zeigen, dass die Probanden den Beginn eines automatisierten Fahrstreifenwechsels mit kleinen Abständen zu den Fahrzeugen, die die Ziellücke bilden, bevorzugen. Die Einhaltung von Sicherheitsabständen ist nicht entscheidend. Der erforderliche Abstand zwischen dem automatisierten Fahrzeug und den interagierenden menschlichen Fahrern nimmt mit höherer Geschwindigkeit und in Szenarien mit Fahrbahnverengung ab. Die dritte Studie untersucht den fünften Schritt zur systematischen Gestaltung des automatisierten Fahrstil, die Durchführung des Fahrstreifenwechsels, mit einer Within-Subject Studie (mit 37 Probanden) unter Berücksichtigung verschiedener Möglichkeiten zur Festlegung von Sicherheitsabständen auf den Zielfahrstreifen. Darüber hinaus werden verschiedene Fahrstreifenwechselzeiten und der Einfluss der Perspektive des vorderen und hinteren Fahrzeuges der Ziellücke beleuchtet. Die Ergebnisse zeigen, dass selbst ein leichtes Abbremsen des automatisierten Fahrzeuges während und nach dem Fahrstreifenwechsel vermieden werden sollte und fast kein Einfluss ob, zu welchen Zeitpunkt oder wie groß der Abstand zum vorderen Fahrzeug der Ziellücke vergrößert wird. Darüber hinaus werden Fahrstreifenwechselzeiten an der unteren Grenze des Komforts, vergleichbar zu menschlichen Fahrstreifenwechselzeiten, und nicht längere Fahrstreifenwechselzeiten mit geringeren Querdynamiken bevorzugt und es zeigt sich ein geringer Einfluss der Perspektive.

Publications

The author of this thesis published as first author the following thesis related articles:

- Potzy, J., Goerigk, N., Heil, T., Fassbender, D., & Siedersberger, K.-H. (2019). Trajectory Planning for Automated Merging on Highways. In Proceedings of the 5th international conference on vehicle technology and intelligent transport systems (pp. 283–290). SCITEPRESS - Science and Technology Publications. doi: 10.5220/0007585602830290

- Potzy, J., Feuerbach, M., & Bengler, K. (2019). Communication Strategies for Automated Merging in Dense Traffic. In 2019 ieee intelligent vehicles symposium (iv) (pp.2291–2298). IEEE. doi: 10.1109/IVS.2019.8813835

- Potzy, J., Feinauer, S., Siedersberger, K.-H., & Bengler, K. (2019). Manual Drivers' Evaluation of Automated Merging Behavior in Dense Traffic: Efficiency Matters. In 2019 ieee intelligent transportation systems conference (itsc) (pp. 3454–3460). IEEE. doi: 10.1109/ITSC.2019.8917346

Supervised Master's theses

The following Master's theses, supervised by the author, contributed significant scientific to this thesis. Thanks to all students for their support to this research.

- Feuerbach, M. (2018). Evaluation automatisierter Einfädelvorgänge aus Sicht der interagierenden Verkehrsteilnehmenden (Master's thesis). Friedrich-Alexander-Universität Erlangen-Nürnberg.

- Feinauer, S. (2019). Außenwirkung automatisierten Fahrverhaltens: Evaluation des automatisierten Einfädelzeitpunktes im Mischverkehr aus der Sicht interagierender Verkehrsteilnehmer (Master's thesis). Juluis-Maximilians-Unversität Würzburg.

- Hartl, P. (2020) Bewertung eines automatisierten Fahrstreifenwechsels aus der Sicht der interagierenden Fahrer (Master's thesis). Technische Universität München.

Contents

1 Introduction

Due to a manageable complexity (Bengler et al., 2014), first Automated Driving Systems will most likely be registered on highways (SAE-level 3-5 (SAE, 2016)). The automation on the highway is considered to be most useful as it supports the driver in a monotonous scenario (Sommer, 2013). On highway driving a lane change is with a frequency of 20 %, one of the most important manoeuvres (Bellem et al., 2016). To realize an automation on the highway with a wide possible range of applications, it is necessary to investigate requirements for automated lane changes from the point of view of interacting human drivers. Therefore, requirements for automated lane changes in a dense traffic scenario are investigated within the scope of this thesis. The scenario illustrated in Figure 1.1, serves as an example for the investigation of a lane change scenario in dense traffic and is examined in three studies based on each other. The Figure shows a lane narrowing scenario, with definitions according to

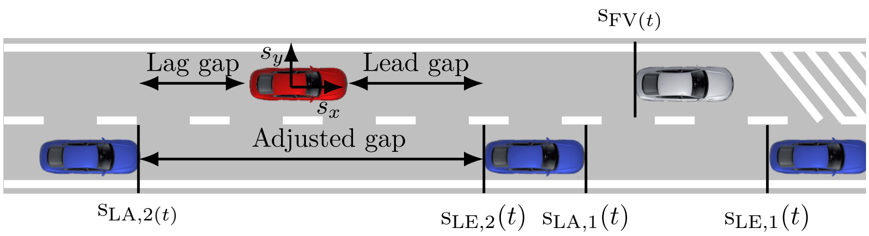


Figure 1.1: Lane change scenario underlying the work.

Toledo et al. (2003) and Toledo and Zohar (2007). The AV (red vehicle) is forced to change lanes to the right in between interacting human drivers (blue vehicles) on the target lanes. The front vehicle (gray vehicle) at the AV's starting lane is blocking the first gap on the target lane, between the lead vehicle $s_{LE,1}(t)$ and the lag vehicle $s_{LA,1}(t)$. The AV selects an adjusted gap on the target lane, between the lead vehicle $s_{LE,2}(t)$ and the lag vehicle $s_{LA,2}(t)$. The coordinate system (s_y, s_x) of the AV is placed at its mid.

1.1 Motivation

AVs promise many advantages, e.g. increasing road safety, traffic flow and reducing emissions (Sivak and Schoettle, 2015). However, new AVs introduced on public roads are confronted with an unprecedented number of road users, as this number is increasing (Fitschen and Nordmann, 2017). In the year 2019 a new maximum of approx. 47 096 000 vehicles have been registered in Germany. This implies an increase of registered vehicles of approx. 11.38 % since 2010, of approx. 34.85 % since 1990 and even of approx. 90.47 % since 1960 (Statista, 2020). At the same time the length of traffic jams on German roads increases. In 2018, drivers on German highways were stuck in 1 527 905 km traffic jam (2017: approx. 1 450 000 km), by an existing total highway length of 13 009 km (ADAC, 2019). Even considering that in 2007 the number of registered vehicles 46 570 000 in Germany was already close to the new record of the year 2019 (Statista, 2020). Those facts allow one to easily understand that AVs need to interact with other human drivers on public roads.

By the use of driver assistant systems, besides the improvement of traffic flow and the reduction of fuel consumption, traffic accidents are considerable reduced (Benmimoun et al., 2012). The introduction of Automated Driving Systems (SAE-level 3-5 SAE (2016)), should once again improve the accident statistics (Bartels and Ruchatz, 2015). Taking a closer look at the distance behaviour of human drivers in car-following and the required distances by law (cf. section 3.2) shows that human lane changes in dense traffic are taking place in the field of tension between small lag and lead gaps at the adjusted gap and the asserting of the individual interests. That this is not free of dangers can be seen in the accident statistics.

Than especially lane changes in dense traffic are prone to accidents (Bie et al., 2013). In 2014, 13 % of accidents with injuries and 5.3 % of all accidents on highways took place in lane change scenarios (Statistisches Bundesamt, 2016). If lane changes are carried out from the automation, this does not lead automatically to a lower complexity of the scenario and to a lower amount of accidents. The automation is most likely still interacting with a human driver. Because, even though AVs are rapidly developing, it is a future vision that they replace human transport (Sivak and Schoettle, 2015). Thus, already during the development of the first Automated Driving Systems, it is necessary to investigate how they must interact with human drivers. According to Gründl (Gründl, 2005, p.66), 30 % of accidents occur because of the humans drivers' wrong determination of distances in the longitudinal direction and tailgating of a faster vehicle to a slower one. It is assumed that an AV, that changes lanes into too small adjusted gaps or with lower velocity than the lag vehicle of the adjusted gap, brings the human driver of the lag vehicle of the adjusted gap into a difficult situation. Also, the fact that a lot of accidents occur due to the wrong expectations of the behaviour of other road users (Gründl, 2005, p.67), clarifies the necessity to communicate the intention to change lanes before the execution. The danger of accidents caused by rear-end collisions due to late interpretation of an AV's lane change is further aggravated by the unambiguous attribution of blame when leaving the lane. As a rule, it can be assumed that the lane changer is solely responsible. A joint liability of the lag vehicle of the adjusted gap only arises if the intention to change lanes is clearly detectable with a sufficient period of time (Heß, 2020, par.33).

To generate a suitable adjusted gap on the target lane in dense traffic to perform a lane change with the lowest risk of collision possible, AVs need a driving style that is easy interpretable for interacting human drivers and increases their willingness to cooperate.

1.2 Research objectives

To design an AV's lane change it is important to consider already known aspects as a framework for the design of the AV's driving style and to analyse the situations to be expected on the target lane.

In order to investigate the communication, that should lead to cooperation of interacting human drivers systematically, a communication model for a cooperative lane change between an AV and interacting human drivers is derived. The communication model is used to define five steps that an AV passes through during a cooperative lane change. Based on the steps, leading research questions are formulated, which are examined more closely in the context of this thesis. To define implications for the AV's driving style out of interacting human drivers' perspective, a challenging scenario to investigate before the introduction of lane changing Automated Driving Systems on highways in dense traffic is defined. Therefore, an AV is based on an existing functional architecture enabled to perform a lane change on the test track into small adjusted gaps on the target lane.

Each research question (cf. section 4.1.2) is investigated in an individual real vehicle study in the defined scenario (cf. section 1.1), separately. Based on the results of the studies, implications for the driving style of AVs are derived, which provide general and to the scenario specific design recommendations for an automated lane change.

1.3 Outline of the thesis

In chapter 2 characteristics of the involved interacting agents, presented in Figure 1.1, are introduced. The human-driver-vehicle control loop, relevant to analyse the information processing process on the target lane, is discussed in detail and the human-driver-automation-vehicle control loop, with the different levels of interaction between the human driver and the automation of the vehicle, is introduced.

Chapter 3 presents the framework to design an automated lane change in order to classify the addressed lane change type in this thesis. The expected human driving style on the target lane is analysed and the human lane change style, as a possible example for the AV, is depicted. Human driving in lane following and lane change scenarios are related to road traffic regulations on German highways and dynamical and distance requirements for AVs from passengers perspective are summarized.

In chapter 4 importance of communication for cooperation of individual agents is outlined. Using a communication model between AVs and human drivers, the main research questions dealt within this thesis are derived. Furthermore, the scenario considered in this thesis and the prototypical implementation of the automation system and the equipment used to carry out the studies are presented.

Chapters 5 to 7 contain the series of studies carried out in the context of this thesis. Chapter 5 investigates different possibilities to communicate the AV's intention to change lanes to interacting human drivers. Chapter 6 deals with different starting conditions of the automated lane change under different urgency of the lane change. Chapter 7 compares different variations to execute the actual lane change.

Chapter 8 summarizes the derived implications to be considered by designing an AV's driving style for lane changes from interacting traffic's perspective, limitations of the method used in the series of studies are discussed and suggestions for future work are given.

2 Theoretical foundation

The theoretical foundations take a closer look at the traffic participants interacting in mixed-traffic lane changes, with focus on a lane changing AV and human drivers on the target lane, presented in Figure 1.1. The human-driver-vehicle control loop (cf. section 2.1) and the information processing process of the interacting human drivers (cf. section 2.1.1) is analysed. Additionally, the human-driver-automation-vehicle control loop with focus on the different interaction variations between the human driver and the automation of the vehicle (cf. section 2.2) is presented and an overview of functional system architectures of AVs known from literature is depicted.

2.1 Human-driver-vehicle control loop

System theoretically it is possible to describe the driving task with the system human driver and vehicle as control loop. The human driver influences over corresponding actuators the lateral and longitudinal dynamics of the vehicle and receives feedback over its motion, as illustrated in Figure 2.1. The environment includes interacting vehicles as well as the road

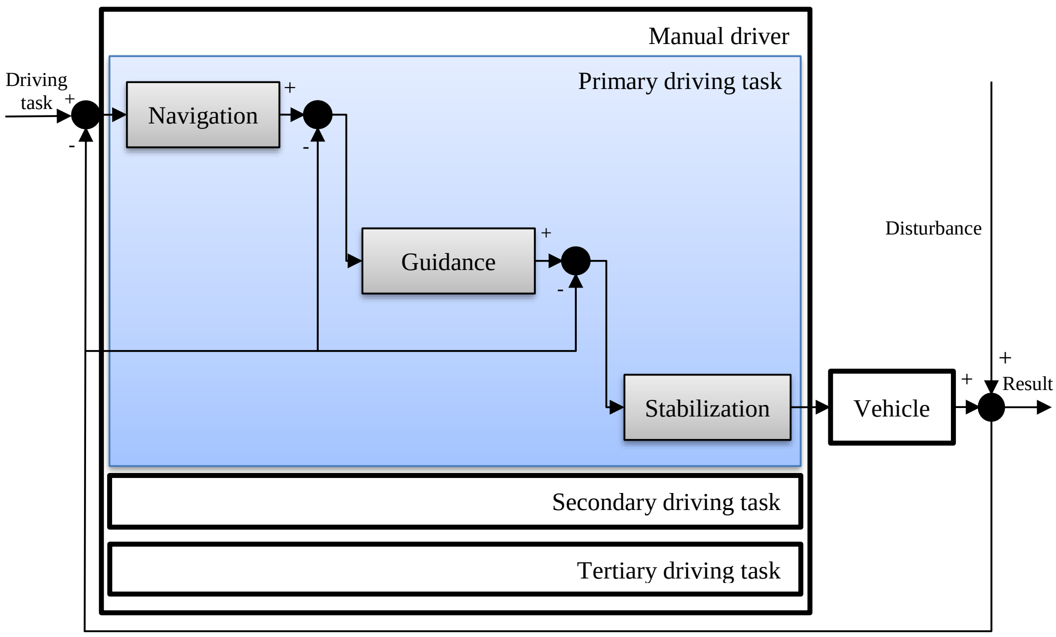


Figure 2.1: Human-driver-vehicle control loop according to Bubb (Bubb et al., 2015, p.29).

network, topology and driving space and acts as disturbance to the control loop (Bubb et al., 2015, p.29). The human driver compares the feedback of the vehicle and the disturbance to the driving task and eventually adjusts its input. The primary driving task, according to Bubb (Bubb et al., 2015, p.29) of the human driver includes navigation, guidance and stabilization. On the navigation level the human driver determines the desired route, while the guidance level comprises the manoeuvre planning, like lane following or lane changing, and the determination of the vehicle's driving trajectory. On stabilization level ensures the human driver with steering movement and with throttle and brake pedal actuation to stay at the desired trajectory. Activating, e.g. the vehicle's lights, the turn signal or the horn is classified as the secondary driving task. The tertiary driving task satisfies the comfort level of the human driver, e.g. by operating the air conditioning system. In order to understand the behavioural repertoire of the human driver to react to the intention of an AV to change lanes, with respect to the primary and secondary driving task, the following section describes the human drivers' information processing process.

2.1.1 Information processing process

The human driver has to select and execute a response from the evaluation of the detected information. Basically, it is possible to divide the information processing process into three steps: information perception, perception and information processing and response execution (Bubb et al., 2015, p.68). According to Wickens (2015), information perception includes the short-term sensory store and perception, the information processing (cognition), the working memory, and the decision and response selection. Both processes depend on information stored in the long-term memory. In order to perform the driving task, the information perception depends on four of six stimuli, mainly: the visual, acoustical, kinetic and tactile sense (Bubb et al., 2015, p.68). Subsequent, information is considered to get a consistent representation of the environment and to predict the own and actions of other traffic participants. In information processing an adequate reaction is chosen and prepared. Finally, the selected response is forwarded to the vehicle by the upper or lower extremities. The human driver can divide its attention resource to the three different stages of the information processing process. A sufficient distribution of the attention resource must be learned for every task, and a false one may result in errors (Abendroth, 2015). Moreover, the processing of information is restricted by the capacity of the working memory. This is compensated by simultaneously processing informations from different perception channels (Wickens, 2015). Therefore, the human driver is capable to parallel fulfil the driving task and to have a conversation with passengers.

The behaviour level model according to Rasmussen (1983), can be used to understand the time constrains of the information processing process. The model divides human drivers' responds in skill-based, rule-based and knowledge-based behaviour. The skill-based behaviour is dominated by automated action patterns, based on intuitive performed reaction on detected information. Rule-based behaviour requires to process the detected information and to associate a repertoire of trained behavioural rules, comparable to mental models (cf. section 2.1.1.2). Knowledge-based behaviour dominates the information processing process in unknown situations. Here, the relevance of the detected information according to the driving tasks need to be identified and options for actions need to be balanced and to be planed actively. Donges (2016) relates the driving tasks navigation (determining the route), vehicle guidance (selection of lane and target velocity) and stabilization (input at steering wheel, brake paddles and throttle) to knowledge-based, rule-based and skill-based behaviour, respectively. According to Bubb (Bubb et al., 2015, p.121), the respond times for skill-based behaviour lies between 0.1 s and 0.3 s, the respond time for rule-based behaviour is approx. 2 s and the time expenditure for knowledge-based behaviour lies between several seconds and hours.

Since, the human driver of the lag vehicle of the adjusted gap has the chance to adjust his velocity to the vehicle that wants to change lanes before it is passing the lane marking, the reaction of the same human driver due to an emergency brake of the lane changing vehicle is most likely with comparable respond times to a braking front vehicle. Habenicht (Habenicht, 2012, p.32) suggests in such situations a respond time of 0.5 s in order to analyse the potential criticality of a lane changing scenario. Simmerbacher (Simmerbacher, 2013, p.47) summarizes response times of the human driver due to reactions to vulnerable road user, obstacles or front vehicles. A study of Mücke and Breuer (2007) found respond times between 0.4 s and 0.6 s and a study of Krochmann (1979) (cited after Simmerbacher (2013)) respond times to braking front vehicles, between 0.57 s and 0.9 s (5 %-percentile, 99 %-percentile), at day and slightly longer respond times, between 0.69 s and 1.15 s (5 %-percentile, 99 %-percentile), at night. Stanczyk and Jurecki (2008) states that respond times decrease with the urgency of a reaction. Those respond times suggest that the respond to a breaking front vehicle is according to Rasmussen (1983) dominated by skill-based behaviour.

2.1.1.1 Information perception

The detection of the surrounding at the driving task is dominated by the visual perception (Bubb et al., 2015, p.81) (90 % of the important information for driving are detected by the visual perception channel (Lachenmayer, 1996)). Thus, objects can mostly only be detected if they are in the visual field of the human driver. This area is restricted through the geometry of the vehicle. The interested reader finds further details to the restriction of the vehicle geometry in the dissertation of Hudelmaier (2003) and Woyna (2014).

In order to detect surrounding traffic and road infrastructure light reflected from objects reaches the cornea of the eye and illustrates an upside down picture of the object at the retina through light refraction of the vitreous body and the lens. Directly in front of the lens is a circular muscle. The departure, adjusted through the circular muscle, is called pupil, which adjusts the incident light on the retina. The lens itself is connected to the ciliary muscle, which adjusts the focal length (accommodation) of the lens to gain a sharp image of the object. The eye, as visual perception channel, registers the surrounding objects sharp in a very small area 2°-3° of the retina only. This area is called fovea and has high concentration of cones, responsible for colour perception. The part of the retina outside the foveal area, is called peripheral vision. Here are the most light sensitive rods to detect movements of objects or contrasts. The nerve cords connected to the receptor cells, cones and rods, are leaving the eye at a common point, the blind spot. (Bubb et al., 2015, p.83)

The turned assembled picture of the surrounding is registered in the brain in a not closer known way (Goldstein, 2015, p.47). Hartmann (1970) mentions five conditions making it possible to detect an object, provided that defective vision has been corrected: a minimum contrast in opposite of the surrounding, a minimum size, a minimum light density, sufficient adjustment of the eye to the light density and a minimum presentation time. According to Schmidtke (1989) needs the human driver a minimum of:

$$T_{\text{Detect}} = 100\,\text{ms}, \tag{2.1}$$

to detect an object over the visual perception channel. Gengenbach (1997) believes in a balance of received and emitted information with a maximum stimulation time of an external stimulus of around 3 s - 4 s.

The peripheral vision is used for the continual visual control of the own vehicle motions to determine the size as well as the moving direction of objects (Schweigert, 2003). Only the cone receptors concentrated in the fovea reach a good vision. Thus, this area needs to be realigned to an AOI for closer examination. It is only the confirmation of the already discovered (Rockwell, 1972). To consciously perceive AOI's the fixation has to be from 0.08 s - 0.1 s up to several seconds (Young and Sheena, 1975). The alignment of the foveal area to an object (fixation) is performed by motions with up to 500 °/s (Bruce et al., 2003, p.260). The time necessary for the eye movement is calculated according to Schweigert (2003) and is given in equation (2.2). The expression is considering the eye-movement latency (D_0 = 21 ms), the time necessary to move the fovea one degree (d = 2.2 ms/°) and the amplitude of the movement A in degree:

$$T_{\text{EyeMovement}} = D_0 + d \cdot A. \tag{2.2}$$

It is assumed that the fixation period is related to the time necessary to interpret the information (Gengenbach, 1997). A long period of successive fixations at an object or in the environment of a previously defined place indicates a difficulty to capture the information of the object (Rantanen and Goldberg, 1999). According to Gengenbach (1997) a human driver fixates up to 0.8 - 5 objects per second. In case it is not possible to predict the behaviour of other traffic participants, they have to be steadily observed (Rensink et al., 1997). In contrast, human drivers have gaze conversions of up to 2 s, as soon as they believe to know how the scene will develop (Bubb et al., 2015, p.107).

To keep interesting objects in the sharp seeing part, the eye is aligned again and again. Therefore, is advanced after the principle of the smallest compulsion. As the object leaves our visual field first the eyes move. If those movements are not enough, the object is kept with movements of the head and thereafter with movements of the torso in the sharp seeing part. (Hudelmaier, 2003, p. 22)

In this way arise approx. a dozen different representation of the visual scene. These are continuously updated and contain the following information: outlines, velocity, and moving direction of the AOI's as well as shady and bright areas. The brain uses these representations for processing of information. (Bubb et al., 2015, p.107)

2.1.1.2 Perception and information processing

Based on the representation of the visual scene and other senses the human driver decides the necessity of a response. A comprehension process builds a knowledge network of associations between detected and in long-term memory stored informations (Baumann and Krems, 2007; Krems and Baumann, 2009). This is done in two phases: a construction and an integration phase (Baumann et al., 2006). In the construction phase, the undirected activation of knowledge structures in long-term memory takes place through the extracted features of the visual scene. In the integration phase a coherent mental representation of knowledge is created. The knowledge network is comparable to a mental model of the scenario. Wilson & Rutherford (Wilson and Rutherford, 1989, p. 619) define the mental model as follows:

'(. . .) a mental model is a representation formed by a user of a system and/or task, based on previous experience as well as current observation, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance.'

As these mental models are flexible, new experiences can be integrated into the human drivers' models of the scenario (Wilson and Rutherford, 1989) and therefore a human driver can get used to a behaviour patterns, e.g. of an initially unusual AV's driving style in lane change scenarios.

The following decision-making process selects the action promising greatest benefit under variation of the external circumstances, by taking into account the associated own risk (Abendroth, 2015, p.7) by the activation of schemata stored in the long term memory

(Baumann et al., 2006; Endsley, 2000). The activation of a schemata is founded on a present trigger based on experience (Krems and Baumann, 2009), compromising typical, less typical and prototypical events (Rauch, 2009).

The information perception influences the perception and information processing, but at the same time perception and information processing influence the perception of information (Goldstone R.L. and Barsalou L.W., 1998). By the huge amount of information in our environment, it is necessary to select important stimuli from the surrounding (Lamme, 2000), because the attention resource is limiting the perception and information processing (Wickens and McCarley, 2019, p.2). The human driver can focus its attention to a particular task, perception channel or environment information, using the most suitable perception channel, declaring other task or distractions as irrelevant. To carry out different task simultaneously for which for example the visual perception channel is necessary, the human driver needs to switch from one task to another - for example keeping its vehicle on the desired lane and extracting information from the navigation system, called visual scanning (Wickens and McCarley, 2019, p.2). Divided attention allows to process different tasks parallel (multitasking) - for example to process two aspects of the visual perception channel, by dividing its attention to process the information generated by a glance at the navigation system and or the road's curvature (Wickens and McCarley, 2019, p.3). Tasks using stimuli from the same perception channel compete for the same attention resources and weaken the human driver's performance, while tasks that are requiring stimuli from different perception channels can be executed simultaneously with only small reduction of performance (Wickens, 2008).

The probability of the allocation of the visual attention for information acquisition in visual scanning is based on four characteristics of the stimuli: salience (extent to which a visual stimulus is different from its surrounding), effort (physiological costs caused by the distance between a previously fixated AOI and a current AOI), expectancy (characterizes the tendency to allocate attention to areas with relevant AOIs to solve a specific driving task) and value (describes that areas with relevant AOIs to solve a specific driving task are viewed more often), named Salience-Effort-Expectancy-Value-Model (SEEV-model) (Wickens, C.; Helleberg, J.; Goh, J.; Xu X.; Horrey, 2001).

Wickens et al. (Wickens, C.; Horrey, 2008) differentiates between top-down and bottom-up processes. Bottom-up processes are dominated by salience and effort of the SEEV-model, e.g. a turn signal of a vehicle on the neighbour lane that is different from its surrounding and close to a previous AOI that was most likely somewhere on the road already. Top-down processes are dominated by expectancy and value of the SEEV-model, e.g. a driving scenario in which the human driver is passing an on-ramp and the association that on the on-ramp might be vehicles that have the intention to change lanes.

2.1.1.3 Response execution

The response is executed by the upper and lower extremities and is given over the steering wheel, the break or throttle as input to the vehicle. The response to a lane changing vehicle in front or back of a human driver's vehicle is dominated by using the break pedals or throttle over the lower extremities. The time necessary to execute the response depends amongst other things on the driving scenario. Schmidtke (1989) states, that the human driver takes more time to get his foot from the throttle to the break pedal in a comfort break scenario than in an emergency brake scenario. Davies et al. (Davies and Watts, 1969, 1970) reports a mean time span around 309 ms to get the foot from the throttle to the brake pedal in an emergency brake scenario. Schmidtke (1989) outlines a time span around 600 ms in a comfort brake scenario. Response times in a comfort brake scenario for only pressing the break pedal are with 250 ms smaller (Schmidtke, 1989).

2.2 Human-driver-automation-vehicle control loop

In the human-driver-automation-vehicle control loop the automation replaces partly or completely the automation system, according to the concept of Cooperative Guidance and Control (Flemisch et al., 2014), by generating the manipulated variables of the vehicles. In order to use the capabilities of the automation without reaching their limits. The control loop is illustrated in Figure 2.2. Similar to the human-driver-vehicle control loop is the result influenced by disturbance, by weather, road infrastructure or interacting traffic participants.

The SAE (2016) divides between six automation levels (Level 0-5), where either the human driver or the automation systems executes the driving task of at least the longitudinal or lateral dynamics. At Level 0 the human driver executes the driving task alone and represents human driving. In further automation levels the responsibilities of the human driver are reduced and the system capabilities are expanded step-wise. Advanced Driver Assistant System (ADAS) are represented by Level 1-2 and Automated Driving System (ADS) by Level 3-5. A Level 1 ADAS executes the longitudinal or lateral control of a vehicle assisted by a human driver fulfilling the remaining driving tasks. From Level 2 upwards, the ADAS or ADS conducts the longitudinal and lateral dynamics on its own. However, at Level 2 the human driver still needs to monitor the driving environment and take back control over the vehicle at all times. From Level 3 upwards (Conditional Automation) the ADS has responsibility for monitoring and the human driver just maintains as backup in case of malfunction as minimal risk condition. Other taxonomies refer to this level as Limited Self Driving Automation (NHTSA, 2013) or Highly Automated Driving (Gasser et al., 2012). From Level 4 (High Automation) upwards, the human driver as backup is no longer necessary and the ADS is

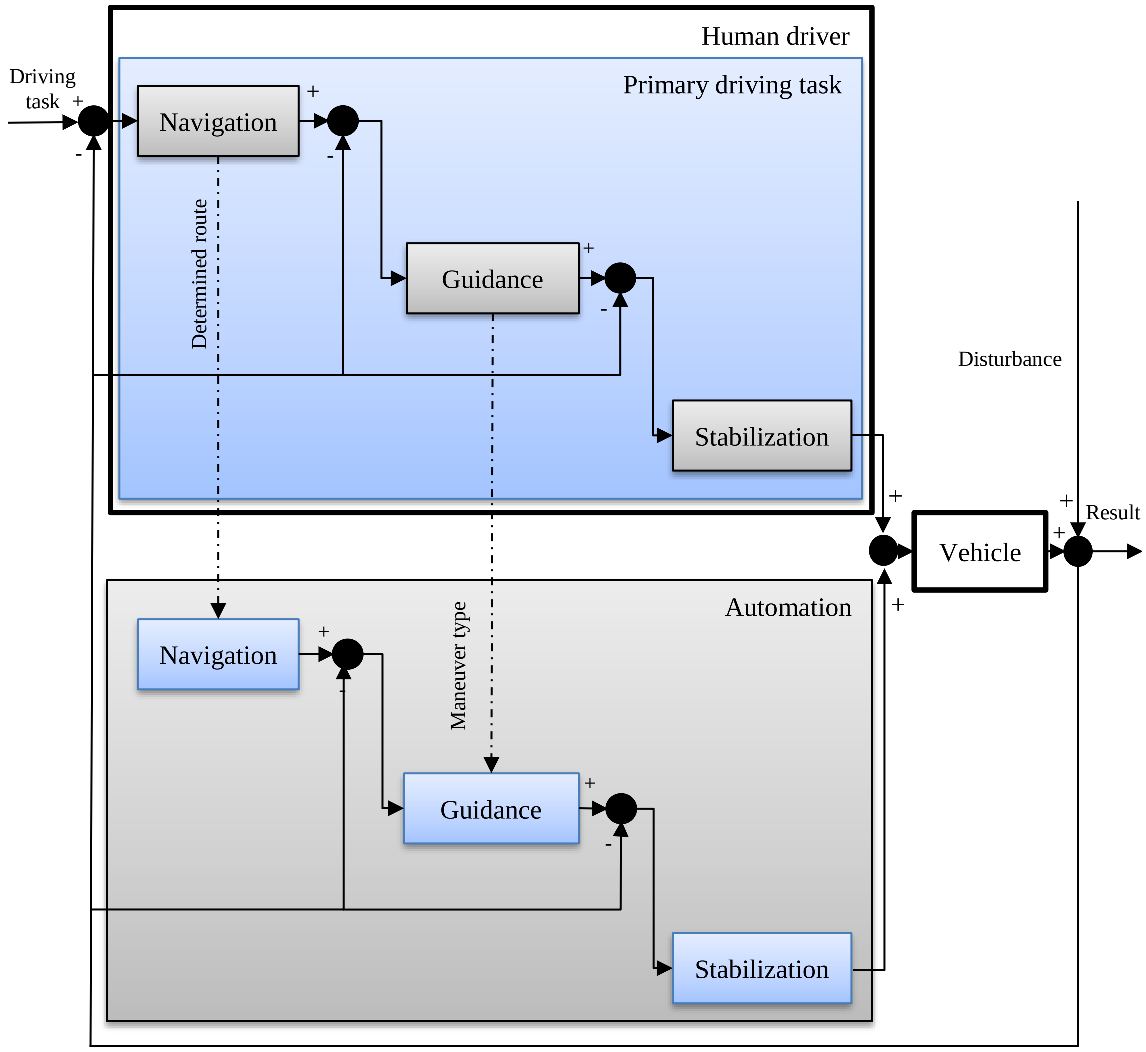


Figure 2.2: Human-driver-automation-vehicle control loop: The automation replaces or shares the control task with the human driver.

able to achieve a minimal risk condition itself. However, the ADS's capability is still reduced to certain driving modes. Thus, the human driver still has an advantage if he could regain control of the vehicle to get on its own to its exact desired destination that could not be reached by the automation by itself that only works at determined roads. At Level 5 (Full Automation), the ADS works at all available roads that are navigable by a human driver.

The automation system could use the driving task or the desired route as input at the navigation level of the human driver. But it is also possible to define the desired manoeuvre at the manoeuvring layer. Examples for this approach are called Conduct-by-Wire systems (Franz et al., 2016). Here, the human driver is specifying the manoeuvrer type and the automation is planing the trajectory at the manoeuvring layer and is performing the vehicle control in order to stabilize the vehicle. The manoeuvres are divided in explicit and implicit (Schreiber et al., 2010). Explicit manoeuvres are activated through the human driver, like a lane change at a highway. After the lane change the automation is changing to lane following automatically and therefore such kind of manoeuvre are called implicit. There are not only approaches where either the automation or the human driver is in charge of control of the longitudinal and lateral dynamics, separately. Examples for such systems are haptic shared control and H-mode approaches. Haptic shared control allows the human driver and the ADAS to exert inputs to the vehicle, while the human driver feels the input and the functional limitations of the ADAS and can decide to overrule it (Mulder et al., 2012; Petermeijer et al., 2015). H-mode allows the human driver and the automation to share the driving task in a tight or loose rein mode (Flemisch et al., 2014; Cramer et al., 2015). In tight rein mode, the automation acts with only low force at the haptic interface. In loose rein mode the vehicle is guided and controlled by the automation, mainly. However, the human driver still gets haptic feedback over the input of the automation to the vehicle.

All studies are made with a Level 2 system (cf. section 2.2) with a human safety driver, monitoring the driving environment at all times. The special task of developing Level 2 systems, in which it is especially necessary to keep the human driver in the loop to regain control over the vehicle at any time (for further information take a closer look at Lange (2017) or Cramer (2019)) is neglected. Since, it is assumed that from the perspective of an interacting human driver the automation Level plays not a decisive role, in the following the term AV instead of ADAS or ADS is used.

2.2.1 Functional system-architecture

The main challenge by designing a functional system-architecture is to manage its complexity in order to ensure the system is testable, maintainable and scaleable (Matthaei and Maurer, 2018, p.95). Matthaei proposes a system-architecture (Matthaei, 2015, p.57) and gives a good overview about existing ones (Matthaei, 2015, p.25-33). These and other architectures, e.g. Behere and Törngren (2015); Tas et al. (2016); Ulbrich et al. (2017), essentially have the following layers: self & environment perception and mission accomplishment. The system architectures according to Matthaei (Matthaei, 2015, p.57), under consideration of the HMI framework according to Bengler et al. (2020) are illustrated in Figure 2.3.

The self & environment perception provides information about the AV's states and its surroundings. Environment sensors such as lidar, radar, ultra-sonic or camera and vehicle sensors are used in order to gain information about the AV itself including state-estimations like yaw rate, velocity and acceleration (Winner et al., 2009, sec.15). In Ulbrich et al. (2017) and Matthaei (Matthaei, 2015, p.57) the AV's localization and the map provision is realized in additional layers, not visualized in Figure 2.3. Based on sensor information and eventual based lane markings from the localization and map provision relevant features of the surrounding are extracted. Based on the features and the lane network from the localization and map provision the context is derived and a scene is modelled, as defined in Ulbrich

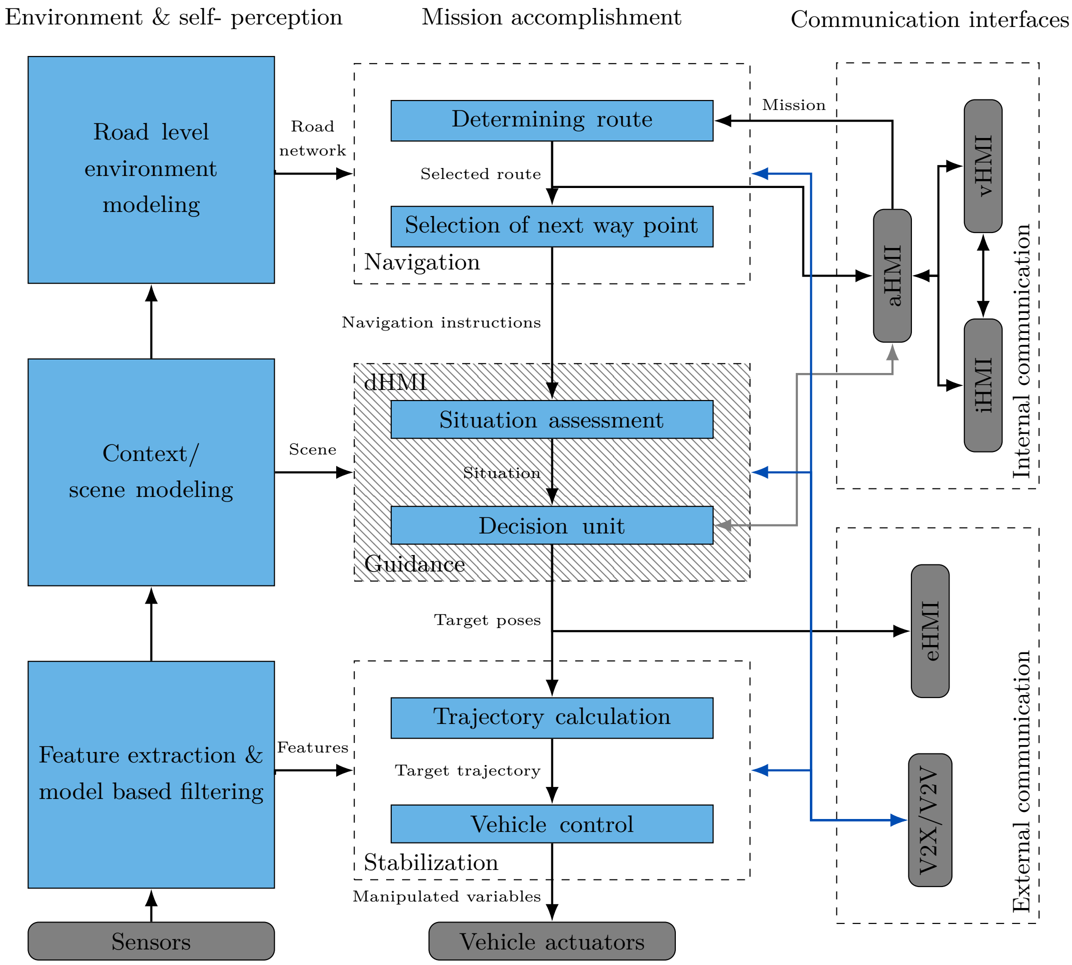


Figure 2.3: Functional system-architecture according to Matthaei (Matthaei 2015, p.57; Matthaei et al. 2016, p.1540) with integrated Human-Machine-Interface (HMI) components, dynamic (dHMI), automation (aHMI), vehicle (vHMI), infotainment (iHMI) and external (eHMI) HMI based on Bengler et al. (2020), considering Vehicle-to-Infrastructure (V2X) and Vehicle-to-Vehicle (V2V) communication.

et al. (2015). Due to the context, the actual scene and the road network relative to a global positioning system from the localization and map provision a road network relative to the AV's current environment is built.

In several functional-architecture designs (Matthaei, 2015; Ulbrich et al., 2017; Behere and Törngren, 2015; Tas et al., 2016) the mission accomplishment layer consists of three basic levels analogue to the three-levels of the human driving task of Donges (2016): navigation, guidance and stabilization. However, the assignment of the trajectory calculation to the three levels of human driving tasks is not clear. Matthaei (2015) and Ulbrich et al. (2017) locate the trajectory calculation on the stabilization level, while the trajectory planing at the three-levels of the human driving task, as well as in the functional system architectures of Behere and Törngren (2015), Tas et al. (2016) and in this thesis (cf. section 4.2.2) is located at the guidance level. Lange (Lange, 2017, p.15) provides for the interested reader a good overview of the assignment of the three levels of the mission accomplishment layer to the three levels of the human driving task in various other functional system architectures.

On navigation level the AV plans the desired route and the next way point, while it contains information about the abilities of the underlined guidance level (Ulbrich et al., 2017). On the guidance level the situation, as defined in Ulbrich et al. (2015), is assessed based on the scene, provided by the environment & self-perception layer and navigation instructions, calculated by the navigation level. Based on the situation the decision unit calculates a set of target poses, containing a target position, orientation, velocity and reference lane etc., for different manoeuvres (Ulbrich et al., 2017). One or more target poses can be handed over to the trajectory calculation module (Ulbrich et al., 2017), where a longitudinal and lateral component of the trajectory is calculated. The different set of target poses may cause a switch between algorithm, as mentioned in Maurer (Maurer, 2000, p.74), on the stabilization level. The vehicle control compensates for disturbances and inaccuracy of the automation, e.g. in the dynamical model of the AV the trajectory planning, and keeps the vehicle at the desired trajectory. The vehicle controller sets the manipulated variables, comprising the desired torque at the steering wheel or the desired moment at the brake or thrust. Therefore, the vehicle controller meets hard real-time requirements for simultaneity and timeliness to communicate with the vehicle bus.

According to Bengler et al. (2020), Human-Machine-Interfaces (HMI) are divided in internal and external communication. The dynamic HMI (dHMI) can be used for internal, as well as external communication, by the parametrisation of the target poses, to either communicate to the passengers of the AV, that the automation is changing lane (Lange, 2017; Cramer, 2019) or to interact with other human road users, e.g. in crossing scenarios (Fuest et al., 2018; Dietrich et al., 2018). Further examples are to cooperate in a lane change scenario in order to enable human drivers to change lanes (Kauffmann et al., 2018a) or to communicate the AV's intention to change lanes itself (Kauffmann et al., 2018b) (cf. chapter 5-7).

The internal communication further includes an automation HMI (aHMI), a vehicle HMI (vHMI), and an infotainment HMI (iHMI). The passengers of the AV communicate over the aHMI with the automation and are determining its mission or specify the desired manoeuvre. The vHMI contains the vehicle states like the current velocity and the iHMI contains the infotainment system, especially interesting for ADS, in which the human driver is at least temporarily allowed to stay out of the human-driver-automation-vehicle control loop, illustrated in Figure 2.2.

Moreover, the automation can communicate, besides the dHMI, over external HMIs (eHMI), vehicle to vehicle (V2V) as well as vehicle to infrastructure (V2X) communication with other road users or infrastructure. The eHMIs are designed to communicate with human road users. Common well-established examples for eHMIs are legally required turn signals and brake lights. Still there is a lot of research to improve the communication of AVs in specific traffic situations with additional eHMIs, e.g. in bottleneck scenarios (Rettenmaier et al., 2019, 2020). Over V2V/V2X interfaces, the automation communicates its current states (situation, selected manoeuvre, target trajectory or manipulated variables) to other vehicles or the infrastructure and can consider states of other vehicles or information from the infrastructure, like traffic accidents or a red traffic light ahead, on the guidance and/or stabilization level of the AV (Ploeg and de Haan, 2019). Besides the more likely communication between AVs, V2V communication can also be used to interact with other human drivers, e.g. to coordinate and motivate cooperative actions in lane change scenarios (Zimmermann et al., 2014a; Lütteken et al., 2016).

3 Framework: Design of an automated vehicle's lane change

In this section, a framework for the design of an AV's driving style in lane change scenarios is introduced. Driving style differs from driving behaviour to the extent that it is maintained over a longer period of time, while driving behaviour depends on the scenario (Bellem, 2018). Thus, driving behaviour can be seen as an observable manifestation of the driving style (Griesche et al., 2016). Sagberg et al. (2015) defines the term driving style as relatively stable, habitual and internalised, different between drivers and as a deliberate choice. According to French et al. (1993) and Elander et al. (1993) the driving style is characterized by the driver's velocity preference, acceleration profiles, risk taking at overtaking or tailgating and following traffic road regulations. In the context of this work general criteria are to be defined. For this reason it is spoken of the AV's driving style.

To define the application scenario, first the lane changes are classified and the considered type is defined (section 3.1). To illustrate the existing scenarios on highways, the legal framework for lane following and lane changes on German highways is analysed (section 3.2) and compared with expected human driving style on the target lane (section 3.2.1) and at lane changes (section 3.2.2). Although, this thesis focuses on the design and evaluation of the AV's driving style in lane change scenarios from the perspective of interacting human drivers, it is important to consider as well the passengers' perspective. Thus, design requirements for the AV's driving style from passengers' perspective are summarized (section 3.3).

3.1 Classification of lane changes an addressed scenario

Toledo et al. (2003) divides lane changes in mandatory lane changes and discretionary lane changes. Mandatory lane changes are performed when a driver needs to leave the current lane. Discretionary lane changes are performed to improve driving conditions. Lee et al. (2004) divides naturalistic lane changes in 11 types including types that could not be categorized. As discretionary lane change it is possible to categorize lane changes due to a slow lead vehicle, a tailgating vehicle, added lane, unintended lane change, return lane change (end of passing scenario) or to give way to a cut-in vehicle. As mandatory lane change it is possible to categorize lane change types to reach an exit or in preparation to exit, to enter a highway, because of a lane drop or to avoid an obstacle. Lane changes due to a slow lead vehicle (37 %), exit or in preparation to exit (23.3 %), return (17.9%), and enter highway scenario (7.9%) types were most common 86.3 % (7,475) of all recorded. Hidas (2005) differentiates between three types of lane changes: free, forced and cooperative lane changes. At a free lane change there is no noticeable change in the relative adjusted cap between the lead and lag vehicle. At a forced lane change the adjusted gap is either constant or narrowing before the start of the lane change and the cut-in vehicle forces the lag vehicle to slow down. At a cooperative lane change the drivers of the lead and lag vehicle increase the adjusted gap before the start of the lane change of the cut-in vehicle.

In the addressed lane change scenario the AV interacts with human drivers. This takes place in a cooperative mandatory lane change scenario to reach an exit or in preparation to exit the highway. Thus, the AV is not able to change lanes without the cooperation of interacting human drivers.

3.2 Disparity between road traffic regulations and human driving

The road traffic regulations on German highways stipulate that the distance to the front vehicle needs to be as big as the distance required to stop behind a sudden braking vehicle even if the front vehicle is braking without a predictable cause (Burmann, 2020, par.2). The minimum gap required to the front vehicle depends on the velocity, locality, weather, and traffic conditions. Under normal conditions the safety distance to the front vehicle needs to be significantly greater than the distance travelled (time headway) in 1.5 s (Burmann, 2020, par.3). An exposure of the front vehicle takes place if the time headway is not only temporally smaller than the endangering distance of 0.8 s. Because undercutting of the endangering distance risks an aversion response of the driver of the front vehicle (Burmann, 2020, par.11). In dense traffic the driver is allowed to follow the front vehicle with a time headway as short as 0.75 s (Burmann, 2020, par.12), in case it is ensured that there are no obstacles in front of the front vehicle and with short response times. In high traffic density the driver does not need to expect a sudden braking front vehicle (Burmann, 2020, par.13).

In the USA according to the 'assured clear distance ahead' (ACDA) - rule, the driver must be able to stop in time behind any obstacle that appears in its path (Leibowitz et al., 1998). In dynamic following tailgating is not allowed. Tailgating, similar to German road traffic regulations, is not leaving sufficient distance to stop behind a sudden braking vehicle. The timely minimum safety distance to the front vehicle should be at least 2 s. Ohta (1993) divides between four headway zones: the danger zone (under 0.6 s), the critical zone (under 1.1 s), the normal driving zone (under 1.7 s), and the pursuit zone (over 1.7 s).

In car-following it is only necessary to pay attention to the distances to the front vehicle. This is not the case in a lane change scenario. A cut-in vehicle according to German road regulations has to act without endangering drivers in following vehicles. Minor deficiencies, decisive is the traffic density, of following vehicles are allowed, in case those drivers had the chance to prepare to the cut-in vehicle (Heß, 2020, par.33). When a cut-in vehicle changes the lane to the right between two vehicles a gap size in sum of 3 s plus the cut-in vehicle's length between the lead and lag vehicle of the adjusted gap is required (Heß, 2020, par.39). The activation of the turn signal before the start of the lane change is compulsory and the turn signal needs to be deactivated instantly after reaching the target lane (Heß, 2020, par.43).

3.2.1 Target lane: Interacting human drivers' driving style

In order to analyse the expected scenarios on the target lane this section summarizes the bandwidth of human driving style in car-following.

Required distances by law are standing in contrast with the actually measured behaviour of human drivers as given in Table 3.1. In particular at high traffic density the following

source	**mean**	**std**	**range**
Wagner (2015)	1.4 s	-	0.25 s - 5 s
Friedrich (2015)	1 s	-	0.5 s** -
Brackstone et al. (2009)	1.2 s - 2.6 s	-	0.80 s - 2.54 s
Taieb-Maimon and Shinar (2001) comfortable time headway	0.98 s	0.36 s	0.45 s* - 1.68 s***
Taieb-Maimon and Shinar (2001) minimum safety distance	0.66 s	0.26 s	0.26 s* - 1.04 s***
Ahmed (1999)	1.47 s	-	1.1 s - 1.9 s

Table 3.1: Distance behavior in car-following: *5th percentile, **15th percentile, ***95th percentile

distances fall below the required safety distances. According to Wagner (2015), the most common distance lies by 1.1 s, in which the mean of distance is found at 1.4 s. Moreover, he reports a large bandwidth of headway distributions for every individual human driver (Wagner, 2012), fluctuations between 0.5 s and 1.5 s are considered normal. Friedrich (2015) also reports that the following distance reduces with higher traffic density. Here, at high traffic density human drivers keep time headway around 1 s. The 15 %-percentile is even under 0.5 s. In a study of Taieb-Maimon and Shinar (2001) participants adjusted their comfortable time headway with a mean of 0.98 s, with a significant reduction for increasing velocities. As self adjusted minimum safety distance he reports a mean of 0.66 s, in which a high percentage 25 % of the participants adjusted a save time headway of 0.5 s or less with no significant velocity dependent changes. Brackstone et al. (2009) found by using on-road data, that the time headway to the front vehicle is also reduced at higher velocities. Moreover, he reported that larger vehicles are followed closer and implies a day to day effect between human drivers. Moon and Yi (2008) found smaller time headway for younger human drivers (1 s), than for middle aged human drivers (1.5 s) and for older human drivers (2 s), with significant differences. Van Der Hulst et al. (1999), found that human drivers increase their time headway to the front vehicle, if its more likely that the front vehicle is decelerating. The response time is shorter for small following distances (Jurecki et al., 2017) and expected braking of the front vehicle (Van Der Hulst et al., 1999). Moon and Yi (2008) report that 90 % of the deceleration and acceleration ranged between $-1.03\,\mathrm{m\,s^{-2}}$ and $0.91\,\mathrm{m\,s^{-2}}$, with maxima between $-5.08\,\mathrm{m\,s^{-2}}$ and $3.07\,\mathrm{m\,s^{-2}}$. Bosetti et al. (2014) report decelerations lower $-2.0\,\mathrm{m\,s^{-2}}$

The human drivers' distance behaviour and road traffic regulations for lane changes show that the AV needs to cooperate with the human driver on the target lane, especially at mandatory lane changes and high dense traffic on the target lane. This is considered particularly important by taking a look at accidents statistics (cf. section 1.1) and the human drivers' response times (cf. section 2.1.1).

According to Ehmanns (2002), the willingness of surrounding traffic to cooperate depends on the clearance of the necessity and the intention to change lanes to interacting traffic. Thus, in a scenario in which the vehicle is on an acceleration lane surrounding traffic cooperates more than if the motivation of the lane change is not reasonable to surrounding traffic (Stoll et al., 2018; Benmimoun et al., 2004; Ehmanns, 2001). Human drivers of the lag vehicle of the adjusted gap cooperate with accelerations between $-0.5\,\mathrm{m\,s^{-2}}$ and $-1.5\,\mathrm{m\,s^{-2}}$ with response times between approx. 2 s, if the turn signal is set, and over 5 s, if the turn signal is not set (Ehmanns, 2002, p.76). Participants react faster to velocity changes of a cut-in vehicle in case it is already at the participants' lane (Fu et al., 2019).

3.2.2 Lane change: Human driving style as an example

Human drivers solve lane change scenarios in dense traffic every day in great numbers. Since, there are no ADS on public roads yet and first series developed ADS may be integrated in low numbers on public roads at the beginning, the mental models of human drivers (cf. section 2.1.1.2) are most likely dominated by human driving style. Thus, in order to design the driving style of an AV's lane change from the perspective of interacting human drivers it may be expedient to adapt human driving style. Therefore, this section summarizes the bandwidth of human driving style as an example for the AV.

Also in lane change scenarios, human drivers do not always follow road regulation and indicate the lane change with the turn signal. The turn signal is often not used to communicate the intention to change lanes to interacting human drivers, as given in Table 3.2. According to

source	**percentage**
Beggiato and Krems (2013)	89 %
Ponziani (2012)	52 %
Lee et al. (2004)	56 %
Salvucci and Liu (2002)	50 %

Table 3.2: Lawful turn signal usage at lane changes in percentage

Ponziani (2012) human drivers use the turn signal only in 52 % of scenarios lawfully. Lee et al. (2004) report a slightly higher turn signal usage of 56 %, with a high in between subject variance from 0 % to 92 %. The results show that the turn signal is used more often at lane changes to the right 65 % than to the left 52 %. Also in a study of Salvucci and Liu (2002), only half of the participants activated the turn signal at the beginning of the lane change. However, the activation rate increased 1.5 s to 2 s after the start of the lane change to 90 %. Beggiato and Krems (2013) reports with 89 % a higher turn signal usage. But their participants were the only ones aware of being recorded on video.

The trajectory of cut-in vehicles can be separated in a longitudinal and lateral component. In the longitudinal direction the distance to the lead and lag vehicle of the adjusted gap is decisive and the relative velocity plays an important role (Toledo et al., 2003). Also in the longitudinal direction safety distances are not kept. As illustrated in Table 3.3 human drivers allow themselves closer distances than their response times would require (cf. section 2.1.1) in order to force their way on the target lane. Daamen et al. (2010) found adjusted gap sizes between 0.5 s and 8.75 s at the start of a lane change at on-ramps of a highway. This results in small lead and lag gaps with a minimum of 0.25 s (Daamen et al., 2010), with smaller accepted distances at the end of an on-ramp. Bham (2009) and Ehmanns (2001) found a comparable gap size mean, standard deviation and range. The accepted adjusted gap sizes found by Gurupackiam and Lee Jones (2012) are also comparable to the findings of Daamen et al. (2010). Fastenmeier et al. (2001) rates himself a lag and lead gaps under 0.6 s as critical in case of same velocities of the cut-in and the lead and lag vehicle of the adjusted gap and reports that this boundary is undercut in 20 % of the 1095 analysed lane changes. At higher congestion human drivers accept smaller lag gaps (Choudhury et al., 2007; Hwang and Park, 2005; Toledo et al., 2003). It seems that human drivers even take the smallest gap available and therefore human drivers always find a suitable gap to change lanes in congestions. But this risk seems to be taken mainly only temporally. Daamen et al. (2010) stated that the mean time headway is growing by 42 % to the lead vehicle of the adjusted gap from the

source	value	mean	std	range
Gurupackiam and Lee Jones (2012) recurrent congestion[1]	t_A	4.04 s	1.61 s	1.60 s - 7.80 s
Gurupackiam and Lee Jones (2012) non-recurrent congestion[1]	t_A	3.502 s	1.20 s	1.87 s - 7.84 s
Daamen et al. (2010)[2]	t_A	3.52 s	2.1 s	0.5 s - 8.75 s
Daamen et al. (2010)[2]	t_{LE}	1.14 s	0.93 s	0.25 s - 4.75 s
Daamen et al. (2010)[2]	t_{LA}	1.62 s	1.2 s	0.25 s - 4.75 s
Bham (2009)	t_{LE}	1.17 s	0.91 s	-
Bham (2009)	t_{LA}	1.26 s	0.93 s	-
Ehmanns (2001)	t_{LE}	-	-	0.3 s - 3.0 s
Ehmanns (2001)	t_{LA}	-	-	0.3 s - 1.7 s

Table 3.3: Gap acceptance at lane changes: [1] at urban streets, [2] lane change on highways with time headway for the adjusted gap size t_A, lead gap size t_{LE} and lag gap size t_{LA} at the start of the lane change.

moment the vehicle started the lane change, in case both vehicles are following each other on the target lane. According to Salvucci and Liu (2002) starts the relaxation already with the start of the lane change.

The analysis of the lateral component of the trajectory at lane changes shows an asymmetrical trajectory, in which the driver is steering more into the lane than to straighten the vehicle on the target lane (Sporrer et al., 1998; Salvucci and Liu, 2002). A characteristic criterion for the lateral dynamic is the lane change duration, which is closer investigated by many authors, summarized in Table 3.4. The summarized authors found lane change duration between 0.7 s and 13.3 s with mean duration between 2.5 s and 6.28 s. Lane change durations of more than 10 s are seldom (Kreisel, 2016) and those are shorter at fast than slow velocities (Sporrer et al., 1998). Moreover, is the lane change duration longer with decreasing lag gaps, increasing lead gaps and to the left than to the right (Toledo and Zohar, 2007).

3.3 Design requirements from passengers' perspective

Hartwich et al. (2015) names as most important factor for driving comfort the velocity, acceleration and deceleration profile. Scherer et al. (2015) adds the time headway to a front vehicle, the steering behaviour and the usage of the turn signal. In order to design an AV's driving style it is not only possible to influence the vertical forces and force changes applied to the passenger influenced by road disturbance and the vehicle's chassis (Bär, 2014), but

source	mean	std	range
Wang et al. (2019)[1,2]	3.91 s	2.34 s	0.7 s - 12.4 s
Gurupackiam and Lee Jones (2012) recurrent congestion[1]	4.19 s	0.81 s	2.6 s - 6.0 s
Gurupackiam and Lee Jones (2012) non-recurrent congestion[1]	4.71 s	0.90 s	2.7 s - 6.5 s
Toledo and Zohar (2007)[2]	4.6 s	2.3 s	1.0 s - 13.3 s
Thiemann et al. (2008)[2]	4.01 s	2.31 s	-
Lee (2006)[2]	6.28 s	2 s	-
Fastenmeier et al. (2001)[2]	2.5 s	-	1.7 s - 4.9 s
Sporrer et al. (1998)	-	-	3.5 s - 10.5 s

Table 3.4: Lane change duration: [1] at urban streets, [2] on highways.

also the forces in the longitudinal and lateral direction, by influencing the corresponding lateral and longitudinal acceleration and jerk. It is possible to differentiate between different resulting forces and force changes in a certain range (Doshi and Trivedi, 2010) and those are influencing the driving comfort (Turner and Griffin, 1999), while human drivers are more sensitive to high jerk than to high acceleration (Scherer et al., 2016; Murphey et al., 2009; Gianna et al., 1996). Influencing the corresponding lateral and longitudinal acceleration and jerk also helps to achieve, further important aspects, like the relation between expected and actual driving, apparent safety and to prevent motion sickness (Elbanhawi et al., 2015). In the following, limit values of the comfortable design of an AV's driving style are discussed in more detail.

The dynamics of the vehicle percepts the AV's passengers mostly over the vestibular perception channel (Baloh et al., 2011). The passengers are able to detect longitudinal accelerations as well as decelerations from a range between $0.02\,\mathrm{m\,s^{-2}}$ and $0.8\,\mathrm{m\,s^{-2}}$ and lateral accelerations as well as decelerations from a range between $0.05\,\mathrm{m\,s^{-2}}$ and $0.1\,\mathrm{m\,s^{-2}}$ (Heißing et al., 2000, p.13). Müller (2015) found as difference threshold for longitudinal deceleration, a difference passengers detected at 50 % of cases, a value of $0.08\,\mathrm{m\,s^{-2}}$ and as difference threshold for longitudinal acceleration a value of $0.12\,\mathrm{m\,s^{-2}}$. For a more detailed overview the interested reader may refer to Festner (Festner, 2019, p.31-34) and Cramer (Cramer, 2019, p.23-27).

Festner et al. (2016) reports higher comfort at a lower dynamical realization of decelerations of the AV's driving style, especially relevant if passengers are performing a non-driving related task. Moreover, he gives a broad overview of guidelines and limit values for a comfortable

AV's driving style (Festner, 2019, p.51-55). At country roads Radke (Radke, 2013, p.115) reports, a comfortable acceleration range between $1\,\mathrm{m\,s^{-2}}$ and $2.3\,\mathrm{m\,s^{-2}}$. This is confirmed by Scherer et al. (2016), who reports that steady accelerations up to $1.5\,\mathrm{m\,s^{-2}}$ are comfortable. Martin and Litwhiler (2008) rate accelerations up to $-1\,\mathrm{m\,s^{-2}}$ as comfortable in public transportation. In the study of Bosetti et al. (2014) human drivers realized accelerations with up to $-2\,\mathrm{m\,s^{-2}}$ on a road with high curvature. Ammon (2013) finds decelerations of human drivers up to $-2.5\,\mathrm{m\,s^{-2}}$. This deceleration is classified in a study of Scherer et al. (2016), which aims to evaluate how passengers should be driven by the automation, as slightly too high.

That a low dynamic does not necessarily lead to a better evaluation of the AV's driving style shows Lange (Lange, 2017, p.84-85) in the evaluation of different lane change duration from passengers' perspective. In this study the maximum accepted lateral dynamics for the application of ADS are set by the passengers on the test ground. The participants accept significant longer lane change durations at $30\,\mathrm{km\,h^{-1}}$ (with a mean of M = 4.4 s, range between 3.6 s and 6.6 s) than at $60\,\mathrm{km\,h^{-1}}$ (with a mean of M = 4.6 s, range between 3.6 s and 6.6 s) and a mean self-selected acceleration at $60\,\mathrm{km\,h^{-1}}$ of M = $0.88\,\mathrm{m\,s^{-2}}$ and at $30\,\mathrm{km\,h^{-1}}$ of M = $0.75\,\mathrm{m\,s^{-2}}$. A comparison with Table 3.4 leads to the conclusion that even higher automation levels (ADS) should not necessarily be designed to be less dynamical than human drivers change lanes themselves. Similar maximum lateral acceleration values are known from trains (Persson and Kufver 2010; Förstberg 2000, p.223). Those values are a good example for ADS, because passengers of a train are often busy with activities comparable to non-driving related tasks and do not receive a permanent visual feedback about the vehicle movement.

According to ISO 15622 (2018) minimum time headway for intelligent transportation systems are 0.8 s and at least one time headway in the range between 1.5 s and 2.2 s shall be provided. Human drivers in a study of Tscharn et al. (2018) rated different short time headway, variate between 0.7 s , 1.1 s and 1.5 s, at slower velocities as significant more critical than at faster velocities. ADS vehicle could realize a time headway with a minimum between 0.4 s and 0.5 s (Friedrich, 2015).

4 Method: Cooperation in mixed-traffic lane changes

The accidents statistics (cf. section 1.1) and the unambiguous attribution of blame (cf. section 3.1) in lane change scenarios cause that AV's lane changes in dense traffic cannot be executed without the cooperation of interacting human drivers. This is especially important in a cooperative mandatory lane change scenario (cf. section 3.1). Section 4.1 introduces the concept to design cooperation between an AV and human drivers in an AV's lane change scenario. Therefore, the importance of communication for cooperation is motivated and a communication model between the AV and interacting human drivers is derived. Based on a communication model, steps are derived that need to be evaluated to design the AV's driving style in dense mixed-traffic lane changes and research questions are formulated that are evaluated in this thesis. Section 4.2 defines a scenario that is used to examine the formulated research questions more closely and the used test track is presented. Moreover, a prototypically implemented automation system and equipment is introduced, used to bring an automation to live, that is enabled to execute lane changes automatically in a small adjusted gap and can be evaluated out of interacting human drivers' perspective.

4.1 Cooperation requires communication

Initiating for cooperation is, that multiple agents are sharing one resource, while following their individual interfering goals (Hoc, 2001). Cooperation itself arises if the involved agents adapt their own actions in order to try to overcome this interference (Hoc, 2001). This requires to take another's perspective (Krappmann, 2000). The willingness to cooperate depends largely on the perceived fairness and time pressure of interacting human traffic (Zimmermann et al., 2018). To increase the cooperation of interacting human traffic it is important to explicitly address hypothetical cooperation partners, in order to clearly assign the responsibility for cooperation (Baumann et al., 2014) and to ensure to exchange the information via suitable interfaces (Kelsch et al., 2015). According to the functional requirements, summarized by Matthaei (2015), the automation needs to react to the intentions of other traffic participants and has to communicate its own intentions to interacting traffic.

Communication is defined as transfer of information, new findings, data or knowledge between different subjects (Stangl, 2020). Thus, communication lays the foundation to interact with other traffic participants in a targeted manner and to cooperate. The communication model according to Shannon and Weaver (1964) consists of six components: the information source, the transmitter, a potential noise source, a communication channel, a receiver, and a destination. The automation as a driver is a new traffic participant, that plays the role of information source and destination in public transportation, besides human traffic participants.

Human drivers, as information source, communicate over formal or informal communication (Färber, 2015). To communicate formally and therefore directly, its possible to use established signals as transmitter, like the turn signal to communicate a lane change or the brake lights to communicate brake usage to interacting traffic (Färber, 2015). Moreover, a human driver has three possibilities to communicate informally (Merten (1977), cited after (Färber, 2015)): one direct way and two indirect ways. To communicate informally the context of the situation is highly relevant (Sivak and Schoettle, 2015). This form of communication needs to be applied especially in dense traffic (Färber, 2015). The direct way of informal communication is to communicate non-verbal and use eye contact, facial expression, gestures or body movements, e.g. to wave past a pedestrian. There are also indirect ways to communicate informally. For this kind of communication, as in formal communication, the vehicle is used as transmitter of the human drivers' intentions.

Human traffic participants, as destination, receive information in traffic mainly through the visual perception channel (cf. section 2.1.1.1). Based on frequently experienced behaviour patterns of other traffic participants human traffic participants built mental models (cf. section 2.1.1.2) in order to predict their future states. Thus, in contrast to the new agent to public transport, the ADS, human drivers' driving styles are well know by other human traffic participants. Those driving styles have a wide bandwidth and do not always meet traffic road regulations on public roads (cf. section 3.2), which is especially true in car-following (cf. section 3.2.1), as well as in lane change scenarios (cf. section 3.2.2). The ability to predict the behaviour of others does not automatically lead to a higher acceptance of their behaviour and to an increase of the own cooperation, if they need it. Thus, the question arises, how far human traffic should serve as an example for AVs. Due to the wide bandwidth of human driving style, its open which behaviour patterns do actually influence other drivers positively.

The cooperation increases in scenarios in which the necessity to cooperate is more reasonable for surrounding human drivers (cf. section 3.2.1). Thus, the cooperativeness of interacting traffic may also increase with a clear and distinct interpretable AV's driving style, as dHMI (cf. section 2.2.1), to approach to the adjusted gap. Especially important, if the navigation of the AV requires a lane change to reach an exit in a few kilometres which is not directly applicable for interacting human drivers. Since, the willingness of surrounding traffic to cooperate depends on the explicitness of the intention to change lanes, undermines the importance of clear communication. Communication is fundamental for traffic flow (Daimler, 2013) and traffic safety (Bie et al., 2013), as well for rates of cooperation (Kollock, 1998). It increases trust (Matthews et al., 2017) and perceived safety (Lundgren et al., 2017) of interacting road users. Thus, the investigation of communication is crucial for the acceptance of ADS in mixed-traffic (Fuest et al., 2018).

If human drivers on the target lane behave cooperative and enlarge the adjusted gap they lose time and comfort, whereby the cut-in vehicle, profits directly from the cooperation. This results in an asymmetry in cooperation between the drivers on the target lane and the cut-in vehicle (Zimmermann et al., 2015). Nevertheless, successful cooperation increases positive feelings (Benmimoun et al., 2004; Zimmermann et al., 2015) and the overall traffic profits from cooperation, that decreases the overall traffic's energy consumption and increases the overall traffic's driving comfort (Lütteken et al., 2016). Thus, it is also important to develop a cooperative AV's driving style that minimizes the asymmetry in cooperation between the drivers on the target lane and the cut-in vehicle, in a way that interacting drivers on the target lane have to cooperate as few as possible. This is especially important for AVs, not at least because interacting traffic has to expect a similar AV's driving style in future lane change scenarios. Thus, an AV's driving style that requires too much cooperation of interacting traffic could decrease the probability that interacting traffic cooperates with an AV in future scenarios.

4.1.1 Communication model for cooperative mixed-traffic lane changes

In order to analyse the communication between an AV and interacting human drivers systematically in a series of studies a communication model between AVs and human drivers is derived. The communication model is visualized in Figure 4.1. As explained above (cf. chapter 4), the automation has various possibilities to communicate. To design an AV's driving style in a cooperative lane change scenario five basic steps need to be evaluated: 1. analyse (scenario), 2. communicate (lane change), 3. interpret (detect cooperative or uncooperative behaviour), 4. start (reaction), and 5. execute (lane change or select new space).

In order to analyse the situation and to initiate the lane change the AV has to find the most preferable space to execute a lane change. Figure 4.2 predicts a previous scene of the scenario defined in Figure 1.1 and illustrates that a lane change is only possible into the second gap on the target lane. If the AV can carry out a free lane change (cf. section 3.1) no further actions are required. But also for AVs it must be expected that situational even the adjusted gap size of the most preferable gap is too small to allow the AV to execute its lane change directly. Especially in dense traffic, as it should be the case for human drivers (cf. section 3.2). Thus, the question rises what happens if the used planning algorithm

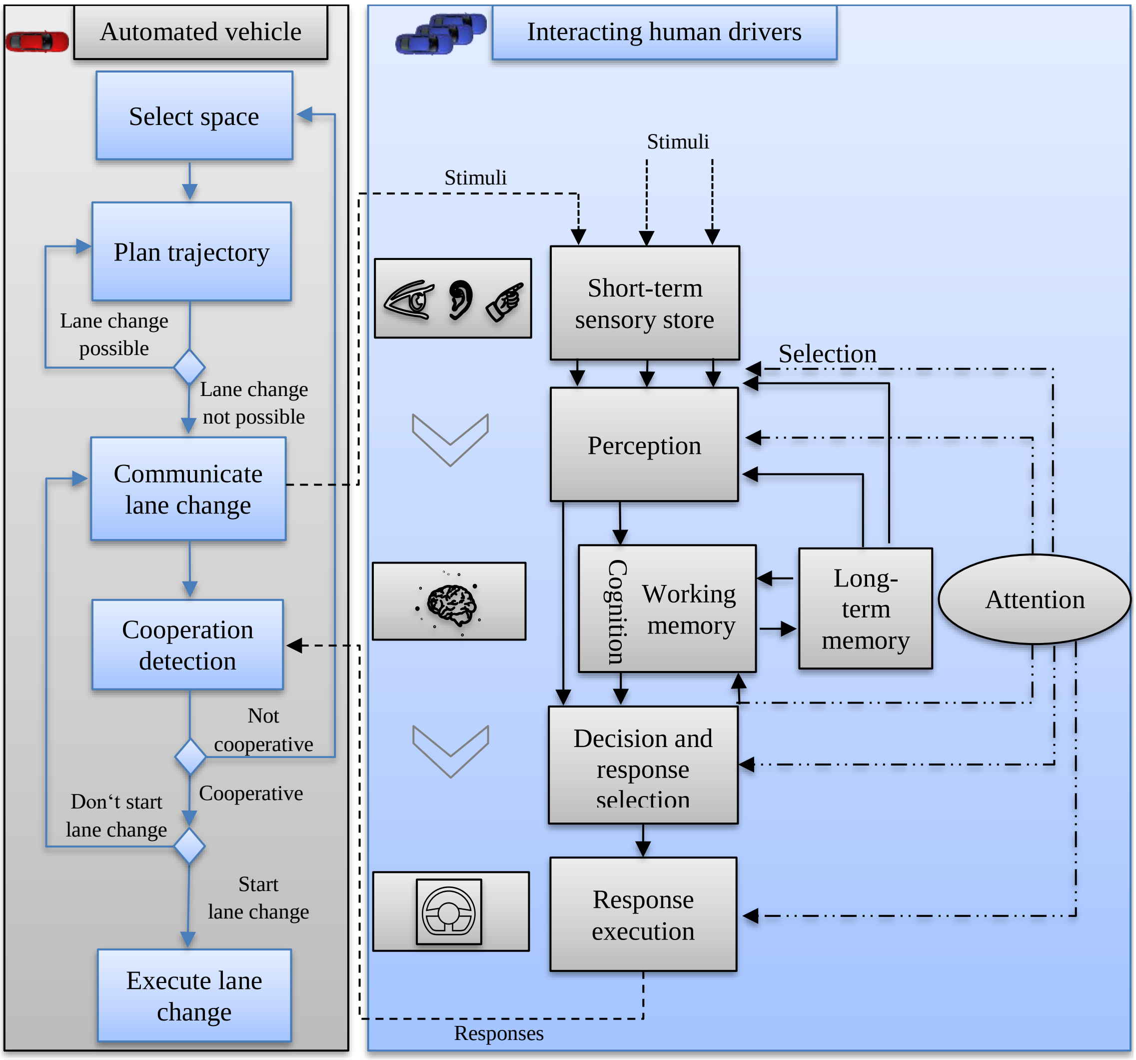


Figure 4.1: Communication model between the AV that wants to change lanes and interacting human drivers as an iterative process with an information processing process of human drivers according to Wickens (2015) (cf. section 2.1.1).

finds no solution for the lateral component of the trajectory, in difference to the trajectories illustrated in Figure 4.3, and the AV is only able to plan a longitudinal component of the trajectory to approach to the adjusted gap and cooperation of interacting traffic is required to execute the lane change. In such cases, the AV needs to communicate its own intention to interacting human drivers. The interacting human drivers detect and percept the perceived intention to change lanes. Depending on the resources the intention is further processed using the long- and short-term memory and a respond is selected and executed (cf. section 2.1.1). Thereafter, the AV has to interpret the behaviour of interacting traffic and to decide if its cooperative or not. Then the AV starts and executes its reaction to show interacting traffic that the AV is able to understand their respond. In an uncooperative case the AV has to choose a new adjusted gap to execute the lane change. In a cooperative case the AV is able to execute its lane change.

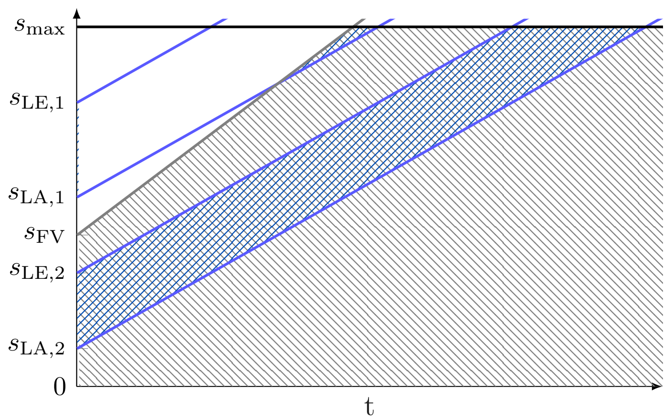
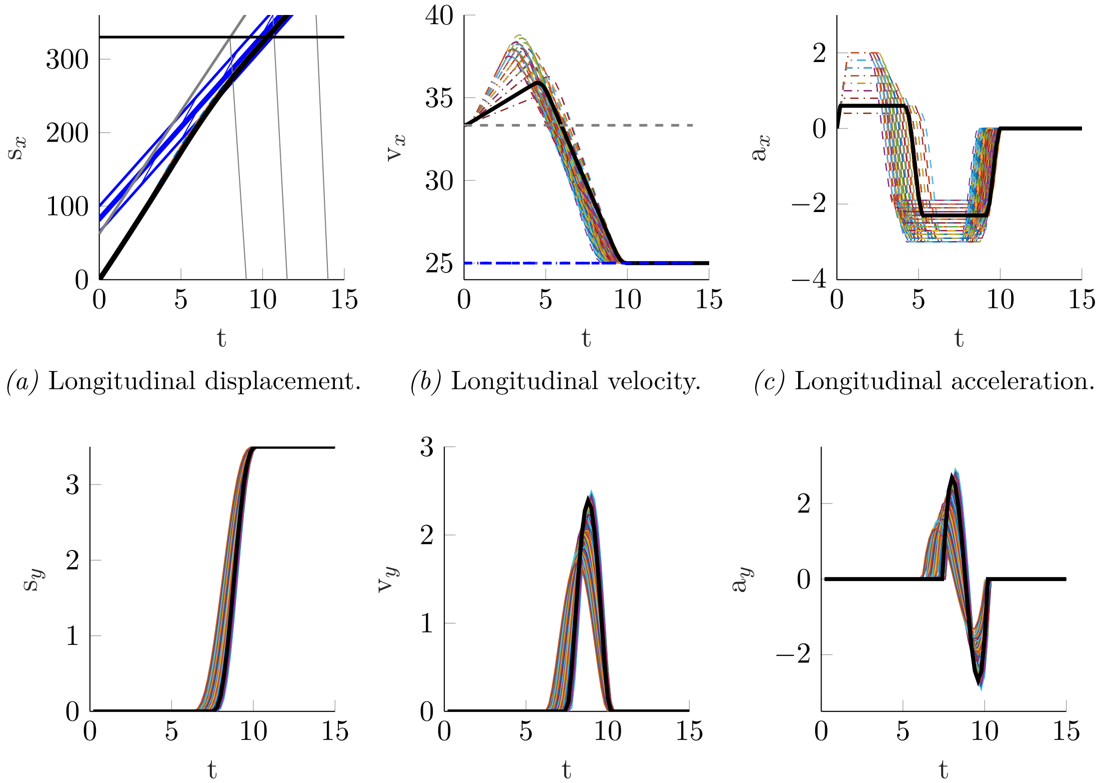


Figure 4.2: The grey dashed area virtualizes the displacement of the space between the AV and the front vehicle. The blue dashed area visualizes areas, in which a lane change to the target lane into the first or the second target gap could be possible using a algorithm proposed in (Potzy et al., 2019c). The first gap is built between the rear of the first gap's lead vehicle $s_{\mathrm{GF},1}(t)$ and the front of the first gap's lag vehicle $s_{\mathrm{GB},1}(t)$ and the second gap is built between the rear of the second gap's lead vehicle $s_{\mathrm{GF},2}(t)$ and the front of the second gap's lag vehicle $s_{\mathrm{GB},2}(t)$, on the target lane. Also the rear of the AV's front vehicle $s_{\mathrm{GF},0}(t)$ and a possible lane end $s_{\max}$ on the starting lane is taken into account.



(a) Longitudinal displacement. *(b)* Longitudinal velocity. *(c)* Longitudinal acceleration.

(d) Lateral offset. *(e)* Lateral velocity. *(f)* Lateral acceleration.

Figure 4.3: Longitudinal and lateral component of the set of trajectories in Frenet coordinates using the algorithm proposed in Potzy et al. (2019c). The thick black trajectory represents the optimum one.

4.1.2 Research questions

Based on the procedure to design an AV's driving style in a cooperative lane change scenario due to three steps (communicate, start and execute) research questions are formulated. Each of these steps result in a different driving study. To analyse the situation a possible algorithm is provided in Potzy et al. (2019c). During the driving studies, standardized cooperative lane change scenarios are realized on the test track for simplification (cf. section 4.2.1).

Driving study I - Communicate the lane change (cf. chapter 5). How should the AV communicate its intention to change lanes to interacting human drivers? At what time should the AV activate its turn signal? What influence has an AV's lateral offset in advance of a lane change or a different AV's braking strength to the adjusted gap? Do interacting human drivers prefer different AV's driving styles at different lane change directions or target velocities?

To evaluate research questions of the driving studies two and three it is precondition, that the participants that drive the interacting vehicles are cooperating. This is accomplished by study instructions, requesting that the participants act similar cooperative as they would in real traffic. Thus, the third step of the above introduced procedure is simplified, as the interacting human drivers act always cooperative.

Driving study II - Start the lane change (cf. chapter 6). At what time would interacting human drivers expect the AV to start its lane change? Which time headway should the AV adhere to the lag vehicle of the adjusted gap before the AV's lane change should be started out of interacting human drivers' perspective? Which impact does the urgency of the lane change, the velocity of the adjusted gap and the AV's deceleration to communicate the lane change have?

Driving study III - Execute the lane change (cf. chapter 7). Whether, at what time or to which extent should the AV increase the distance to the lead vehicle of the adjusted gap from the perspective of interacting human drivers? Does it make a difference how large the distance to the lead vehicle of the adjusted gap is expanded and at what time? Are braking interventions permitted to increase the target time headway? Do interacting human drivers prefer long or short lane change durations?

4.2 Scenario, test track, automation system and equipment

4.2.1 Scenario and test track

It is assumed that a cooperative mandatory lane change scenario in dense traffic (cf. section 3.1) to reach e.g. an exit that is not yet visible in a few kilometres is of high importance for an AV, but not replicable to surrounding traffic. As a result, the AV changes lane in a small adjusted gap with lower velocity in front of the AV. In every study, a similar reproducible scenario as illustrated in Figure 4.4 is realized. In order to realize a cooperative lane change

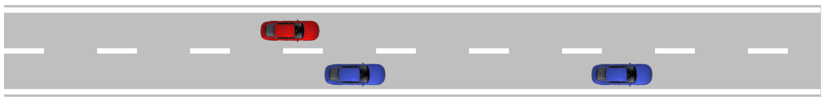


Figure 4.4: Evaluated scenario: Cooperative mandatory lane change to reach an exit.

scenario (cf. section 3.1) with a distance on the target lane that is likely in high traffic density the adjusted gap size was approx. 1 s (cf. section 3.2.1).

The studies took place on a three-lane oval test track with a length of 1400 m, as illustrated in Figure 4.5. In all studies the middle lane built the AV's starting lane and the left side of

Figure 4.5: Areal view of the FASIS test track in Neuburg (AUDI AG, 2018).

the oval test track is used to perform the lane change manoeuvre. In the first and second study, the adjusted gap was built on the outer lane of the left side of the test track. The right side of the test track is used to answer questionnaires and study instructions. In the third study only the left side of the test track is used. Thus, the evaluated lane changes to the right due to the adjusted gap are performed on the inner or outer lane on the left side of the oval test track, depending on the driving direction. After every manoeuvre, the vehicle platoon changed direction by turning at end of the test route. Because of the short length of the straight of the test track (approx. 650 m) velocities of the adjusted gap of $30\,\mathrm{km\,h^{-1}}$ and $50\,\mathrm{km\,h^{-1}}$ are evaluated.

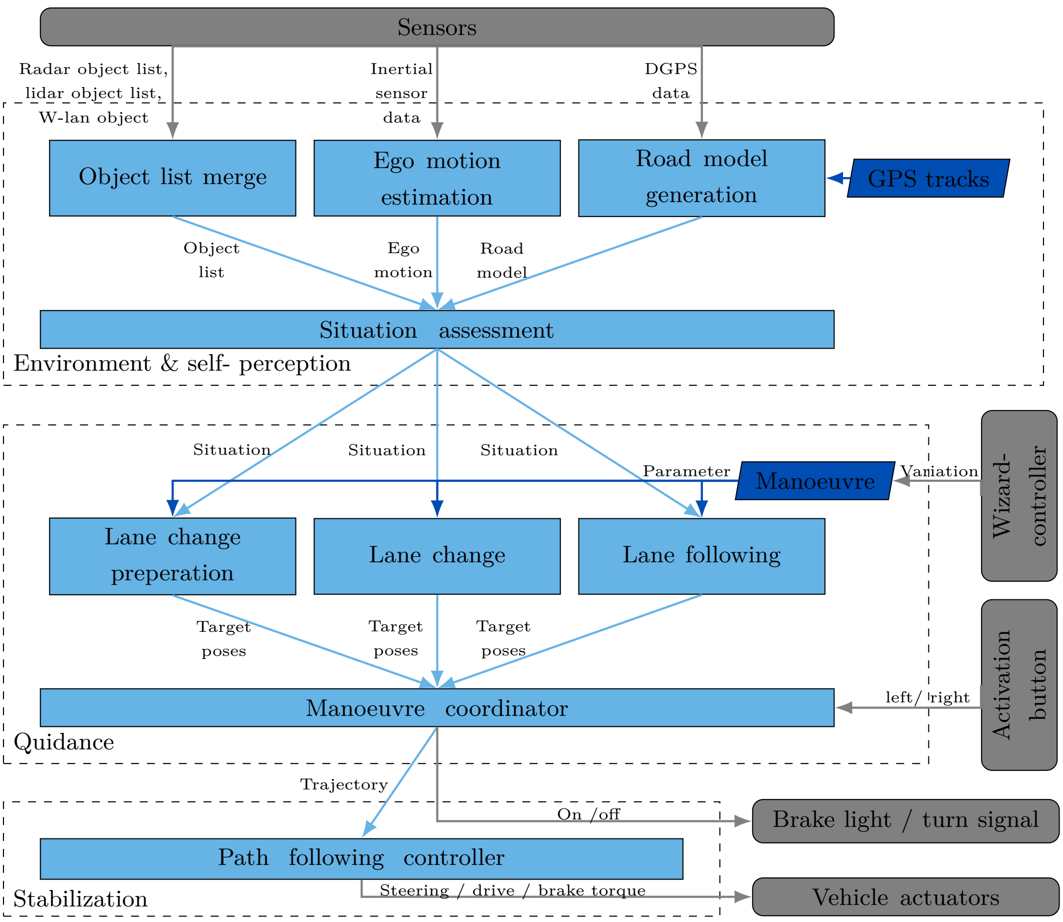


Figure 4.6: Prototypical implemented software architecture.

4.2.2 Automation system and equipment

To percept the environment and motion of the AV, as illustrated in Figure 4.6, a highly accurate inertial sensor platforms supported with DGPS (Differential Global Positioning System) (iMAR GmbH, 2012), integrated in the AV, is used to localize the AV to the center of the target lane, described by GPS tracks. Based on the DGPS data and the GPS tracks a road model is generated and the motion of the AV is determined based on inertial sensor data.

To generate a merged object list, a radar object list of a front, rear and side sensor, as well as a lidar object list of a front sensor are merged. The AV has no sufficient capabilities to percept vehicles laterally to the AV and in order to detect the driving states of the lag vehicle of the adjusted gap precisely, the lag vehicle of the adjusted gap is also equipped with inertial sensor platforms supported with DGPS (iMAR GmbH, 2012), in order to locate the vehicle at the given GPS tracks. The position of the lag vehicle of the adjusted gap is sent to the AV via W-lan connection. The set-up is based on an approach of (Strasser, 2013, p.58-59). The W-lan object, is considered highly prioritized to build the merged object list. Based on the object list the motion of the AV (Ego motion) and the road model a situation defined according to Ulbrich et al. (2015), is calculated in a situation assessment module.

It is possible to divide automated driving at highways in a lane following and a lane change manoeuvre to the left and to the right (Lange, 2017, p.65). To execute a lane change into a small adjusted gap, on the guidance level an additional manoeuvre is introduced to enable the automation to select and positions itself on a variable position of the adjusted gap on the starting lane, named lane change preparation manoeuvre (cf. (Lange, 2017, p.65) and (Ardelt et al., 2012)). To select different parametrised manoeuvre variations a Wizard-controller is used in the AV. Every manoeuvre calculates a parameter space, that is sent to the manoeuvre coordinator. The downstream implemented manoeuvre coordinator, coordinates the active manoeuvre, as illustrated in Figure 4.7 and calculates a target trajectory that is sent to a path following controller. In addition, the manoeuvre coordinator transmits the desired status of

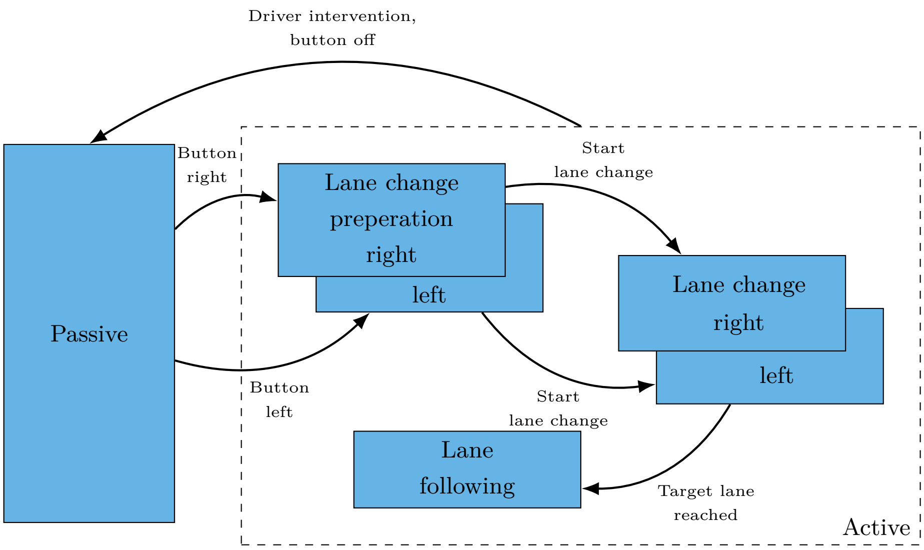
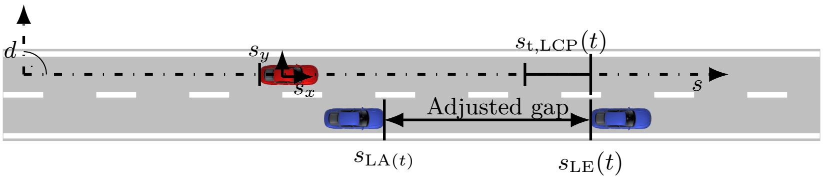


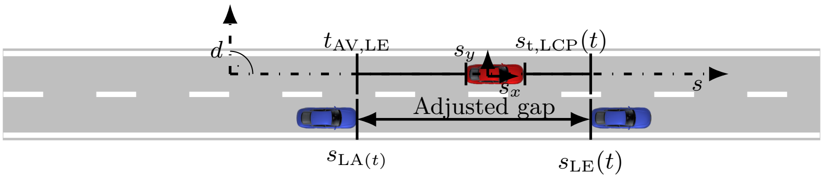
Figure 4.7: Prototypical implemented manoeuvre coordinator.

the turn signal and brake light to the vehicle. The path following controller, ensures that the AV stays at the longitudinal and lateral component of the trajectory and sends the desired steering, drive, and brake torque to the vehicle actuators.

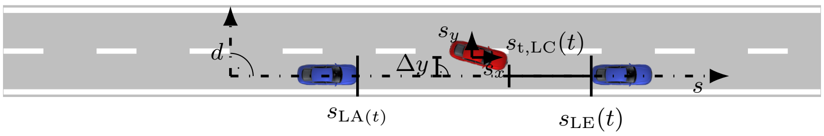
Figure 4.8 demonstrates the manoeuvre, defining the parameter space, including the target positions, velocity and reference lane in Frenet coordinates (Werling et al., 2010). The Frenet coordinate system is positioned at the AV's reference lane in a defined distance in longitudinal direction behind the AV. To use the length of the straight as good as possible the AV is accelerated by an experimenter to the target velocity. Aiming to realize standardized experimental conditions the automated driving function is activated by pressing an activation button. Depending on the type of the activation button the lane change preparation module to the right or left lane is activated, an adjusted gap is determined and a target position is calculated, illustrated in Figure 4.8a. The target position is calculated considering the



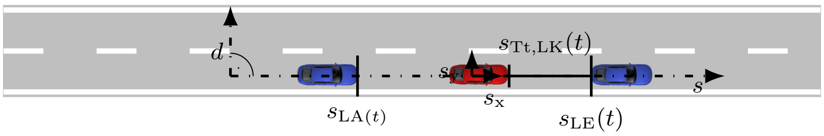
(a) Lane change preperation manoeuvre.



(b) Transition between lane change preperation and lane change manoeuvre: $t_{\mathrm{AV,LE}} > t_{\mathrm{R}}$.



(c) Transition between lane change and lane following manoeuvre: $\Delta y < y_{\mathrm{T}}$.



(d) Lane following manoeuvre.

Figure 4.8: Adjustable lane change strategy due to the adjusted gap in front of the AV on the target lane with manoeuvre transitions.

position $s_{\mathrm{t},0}$ and the velocity v_{t} of the target vehicle, a minimum safety gap s_{min} and a adjustable time headway τ_{t}, as given in equation 4.1:

$$s_{\mathrm{t}}(t) = s_{\mathrm{t},0} + v_{\mathrm{t}}(t) \cdot t - \max(v_{\mathrm{t}} \cdot \tau_{\mathrm{t}}, \Delta_{\mathrm{min}}). \tag{4.1}$$

The time headway τ_{t} can be parametrised separately in the lane change preparation $\tau_{\mathrm{t,LCP}}$, lane change $\tau_{\mathrm{t,LC}}$, and lane keep manoeuvre $\tau_{\mathrm{t,LK}}$. This leads to a different absolute distance in longitudinal direction to the lead vehicle of the adjusted gap in the lane change preparation $s_{\mathrm{t,LCP}}$, lane change $s_{\mathrm{t,LC}}$, and lane keep $s_{\mathrm{t,LK}}$ manoeuvre. In the evaluated use-case the target vehicle is the lead vehicle (LE) of the adjusted gap. In case, the time headway between the AV and the lag vehicle of the adjusted gap, as shown in Figure 4.8b, is large enough $t_{\mathrm{AV,LE}} > t_{\mathrm{r,AV,LE}}$, the lane change to the left or right lane, with respect to the selected lane change preparation direction, is executed. The time headway is calculated according to equation 4.2:

$$t_{\mathrm{AV,LE}}(t) = \frac{s_{\mathrm{AV},0}(t) - s_{\mathrm{LA},0}(t)}{v_{\mathrm{LA},0}(t)}, \tag{4.2}$$

with the actual position of the AV $s_{\mathrm{AV,0}}$, the actual position of the lag vehicle of the adjusted gap $s_{\mathrm{LA,0}}$ and its velocity $v_{\mathrm{LA,0}}$. In case, the AV has reached the target lane $\Delta y < y_T$, as illustrated in Figure 4.8d, the lane following manoeuvre is activated. It uses the current lane as reference lane and the target position s_{LC}, due to a front vehicle at the reference lane and velocity restriction to calculate the lateral and longitudinal component of the target trajectory. Every driver intervention or pressing the automation off button changes every active state to passive state. At manoeuvre coordinator's passive state no steering, drive or brake torques from the automation are processed by the vehicle actuators and therefore the AV's safety driver regains full control over the vehicle.

To plan the longitudinal component of the trajectory, a separate planning approach for the case with and without target vehicle is used. Without target vehicle the longitudinal component in Frenet coordinates depends on velocity restrictions. To calculate the longitudinal component of the trajectory a solution with three components is used. The function consists of two cubic and one constant acceleration part, using the equations given in Potzy et al. (2019c), whereby the constant acceleration part is placed in the middle of the two cubic acceleration parts. The target acceleration a_{T} of the constant acceleration part, as well as the maximum and minimum jerk for the cubic acceleration parts j_{EXT} can be defined separately, in order to realize different characterisations of the AV's driving style. With front vehicle the three-parted acceleration profile, introduced above, is solved for the target acceleration a_{T} of the constant acceleration part to reach target velocity v_{T} at the target position s_{T}. The solution for a_{T} is calculated numerically. The planning approach can also take n target points into account and selects the longitudinal component of the trajectory with minimum acceleration $a_{\mathrm{T}} = \min(a_{\mathrm{t,1}}, a_{\mathrm{t,2}}, ..., a_{\mathrm{t,n}})$. To reduce the reactions of velocity changes of the target vehicles, target acceleration a_{T} outside a settable minimum and maximum value are executed only. Via the settable minimum and maximum value it is possible to adjust different deceleration characteristic of the AV. To solve the equations numerically is only possible, in case the target position is in front of the AV with lower velocity or behind the AV with higher velocity. Thus, it is necessary to combine the planning approaches with and without front vehicle in order to increase the distance to the front vehicle at the starting lane or the lead vehicle of the adjusted gap, caused for example by different parametrizations of the time headway t_{T} in the different manoeuvres. At first, the AV's velocity is reduced under the velocity of the target vehicle and afterwards increased in a way to reach a higher AV's velocity than the target velocity v_{T} behind the target point s_{T} using the planning approach without target vehicle to full-fill the conditions to solve for the target acceleration a_{T} using the planning approach with target vehicle (Hartl, 2020, p.27-28). To plan the lateral component of the trajectory the lateral planing approach to reach the reference lane, according to (Heil et al., 2016), is used.

5 Driving study I - Communicate the lane change

The driving study and its results are pre-published in Potzy et al. (2019b). Some parts of the written text are taken from these article. Figures, tables, and statistics are adapted for an overall consistent representation throughout this thesis. Magdalena Feuerbach helped in designing and conducting the driving study as part of her Master's thesis (Feuerbach, 2018). For this Doctoral thesis the data was evaluated separately.

In driving study I, different variations to communicate an AV's intention to change lanes to interacting human drivers are performed on a test track and evaluated (N = 40) in a within-subjects design in order to answer the research question, respective to *Communicate the lane change*, formulated in section 4.1.2: How should the AV communicate its intention to change lanes to interacting human drivers? To gain standardized scenarios all lane change manoeuvrers are executed automatically (cf. section 4.2.2) in a similar scenario on the test ground (cf. section 4.2.1). During the study different factors to communicate the intention to change lanes, as the time to set the turn signal, hard or light braking to the adjusted gap, or a lateral offset in advance of the lane change are investigated. Additionally, the influence of the lane change direction as well as the velocity of the adjusted gap are analysed.

5.1 Hypotheses and exploratory questions

To gain cooperative behaviour to the intention to change lanes, explicit communication in the form of a turn signal plays an important role (cf. section 3.2.1). However, human drivers tend to not set the turn signal before the execution of the lane change (cf. Table 3.2). To evaluate direct communication, an early use and a late use of the turn signal are compared. In the late use the turn signal is activated by executing the lane change. In case of an early use, the turn signal is activated if the AV and the lag (participant's) vehicle of the adjusted gap are at same height. The following hypotheses (H1) is verified:

- Setting the turn signal as the AV and the lag vehicle of the adjusted gap are at the same height (early), leads to a higher *predictability* (H1.1) of the AV's intention and higher *cooperation* (H1.2) and *acceptance* (H1.3) of the AV's driving style from the perspective of interacting human drivers, in comparison to AV's driving styles that are setting the turn signal at the start of the lane change (late).

The late use of the turn signal gives also the possibility to analyse the effects of indirect ways of communication only. To evaluate indirect ways to communicate the AV's intention to change lanes the longitudinal and lateral driving strategy can be varied. In the present scenario it is imperative to brake to the velocity of the adjusted gap. But the braking strength is designed separately. It is distinguished between an AV's driving style with hard and light braking. As both braking variations are visible to the interacting human driver we assumed that a higher stimulus leads to a faster perception and information processing (Nissen, 1977). As demonstrated by Fuest et al. (2018), who found that pedestrians detect the intention of vehicles to give them right of way faster, in case the vehicle is braking hard than if its braking weak. The following hypotheses (H2) is formulated:

- AV's driving styles with hard braking to the adjusted gap lead to a higher *predictability* (H3.1) of the AV's intention and higher *cooperation* (H3.2), and higher *acceptance* (H3.3) of interacting human drivers, in comparison to AV's driving styles with light braking to the adjusted gap.

A previous study executed in a driving simulator showed, that a lateral offset to the target lane in advance of the lane change leads to a cooperative behaviour of the AV (Kauffmann et al., 2018a). Thus, the same driving style is evaluated in a real driving situation. The following hypotheses (H3) is set up:

- AV's driving styles with a lateral offset in advance of a lane change lead to a higher *predictability* (H2.1) of the AV's intention and higher *cooperation* (H2.2) and *acceptance* (H2.3) of interacting human drivers, compared to AV's driving styles without a lateral offset in advance of a lane change.

The direction of the lane change influences the gaze behaviour (Lee et al., 2004) and the relative increase of the time headway to the front vehicle decreases with higher velocities (Abendroth, 2015). Moreover, human drivers use the turn signal at lane changes to the right more often than at lane changes to the left (Lee et al., 2004). Thus, the following exploratory questions (Q1-Q2) are evaluated:

- Does a different *velocity* (Q1) of the adjusted gap or lane change *direction* (Q2) lead to a disparate *predictability* of the AV's intention and *cooperation* and *acceptance* of interacting human drivers?

5.2 Methods

5.2.1 Test scenario

The study took place in June 2018. The experimental cars on the test ground are illustrated in Figure 5.1. During the manoeuvres the participants were driving the lag vehicle of the

Figure 5.1: Experimental cars on the test track.

adjusted gap. They were introduced to follow the lead vehicle of the adjusted gap with the lowest Adaptive Cruise Control time distance (1 s). The lead vehicle of the adjusted gap was driving with Cruise Control. The AV was accelerated by an experimenter to the target velocity. Thereafter, the automated driving function was activated and every lane change of the AV was performed automatically. The AV overtook the lag (participant's) vehicle and communicated the intention to change lanes in different variations. At the point the AV was at the height of the participant's vehicle the mean adjusted gap size was M = 1.28 s (SD = 0.18 s). The lane change was performed when the participant cooperated and the distance to the front vehicle and the participant's vehicle was larger than a minimum time headway. The mean time headway at the start of the AV's lane change between the AV and the lag (participant's) vehicle during the study was M = 0.83 s (SD = 0.31 s).

5.2.2 Procedure and study design

The overall duration of the study was approx. 90 minutes per participant and was structured in an pre- and post-test, a first study part (within-subjects design) and a second study part (exploratory design) as followed:

Pre-test and instructions: At first participants answered an online questionnaire in order describe the sample, given in Appendix A.2.1. At the test ground they were informed about the content and their tasks during the study, as shown in Appendix A.1.

Part I: The participants were asked to follow the lead vehicle of the adjusted gap. The AV communicated the lane change to the interacting human driver of the lag vehicle of the adjusted gap in different variations in a within-subject design. After halfway of the manoeuvres, a collaborative change of direction was performed. The participants were informed to react to the AV's intention to change lanes the same way they would in real traffic. After every manoeuvres the participants completed a questionnaire with the subjective measures (see section 5.2.4) via interview guided by an experimenter at the front passengers seat of the participant's vehicle.

Part II: In the second part of the study, participants choose their preferred AV's driving strategy to communicate the intention to change lanes and rated the relevance of the selected parameter. Therefore, the participants were shown manoeuvres at $50\,\mathrm{km\,h^{-1}}$. At first they could choose between a strategy with and without lateral offset and thereafter with hard or light braking. Last the participants set a trigger at the time the participants expected the AV's turn signal to be set to their preferred driving strategy to communicate the intention to change lanes.

5.2.3 Independent variables

At $50\,\mathrm{km\,h^{-1}}$ the lane change direction, the AV's braking strength to the adjusted gap, the time to set the turn signal, as well as AV's driving styles with and without lateral offset in advance of the lane change were evaluated, as illustrated in Table 5.1. In order to realize a

Independent variables	Variations	Operationalization
Lateral offset	with without	AV's lateral offset before the start of the lane change
Braking	hard light	strength of AV's braking to adjust velocity to adjusted gap's velocity
Turn signal	early late	AV and lag (participant's) vehicle at same height; start of the lane change
Direction	left right	lane change direction

Table 5.1: Independent Variables and their operationalization in the first part of the study at $50\,\mathrm{km\,h^{-1}}$ (2x2x2x2 within-subject designs).

lateral offset in advance of the lane change in order to communicate the intention to change lanes to interacting human drivers, the reference lane is shifted in Frenet coordinates in the lane change preparation manoeuvre to the left or the right with a distance of $\Delta s_y = 0.5\,\mathrm{m}$, from the point the time headway between the AV and the lag vehicle of the adjusted gap was larger than $t_{\mathrm{AV,LA}} > 0.2\,\mathrm{s}$. The perspective from the lag vehicle of the adjusted gap, illustrating a variation with and without lateral offset is shown in Figure 5.2. The AV's

(a) Variation with lateral offset.

(b) Variation without lateral offset.

Figure 5.2: View form the lag (participant's) vehicle of the adjusted gap.

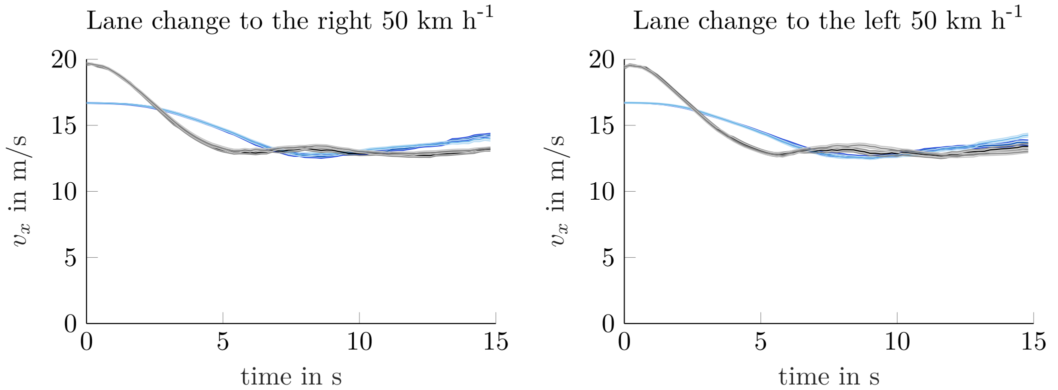
velocity until the start of the lane change at $50\,\mathrm{km\,h^{-1}}$ is illustrated in Figure 5.3a. The AV's acceleration is illustrated in Figure 5.3b. The AV's lateral offset in advance of the lane change is illustrated in Figure 5.3c.

So that the duration of the study remained within an acceptable limit, different longitudinal decelerations were not varied at $30\,\mathrm{km\,h^{-1}}$, as illustrated in Table 5.2. Thus, 24 different variations were evaluated. The AV's driving styles were shown the participants in permuted variation. Because of the big number of possibilities the permutation was restricted with the groups velocity and direction. The change of direction took place in the mid of the first part of the study, to reduce the number of turns during the study with all vehicles to a minimum.

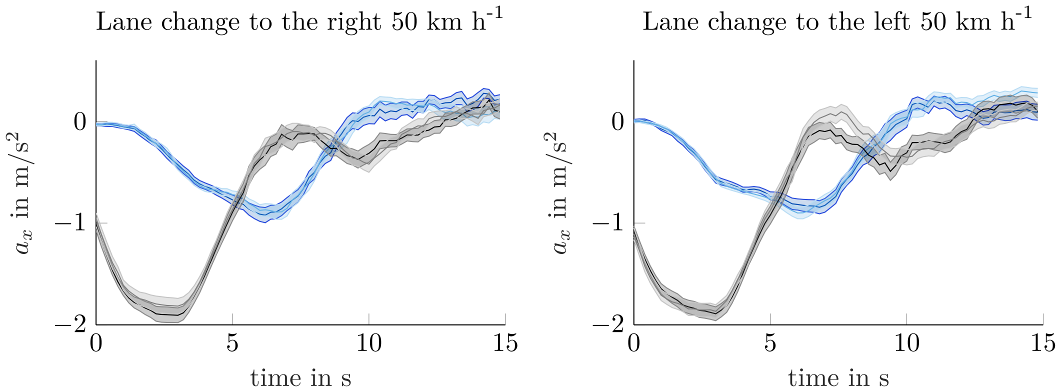
Independent variables	Variations	Operationalization
Lateral offset	with	AV's lateral offset
	without	the start of the lane change
Direction	left	lane change
	right	direction
Turn signal	early	AV and lag (participant's) vehicle at same height;
	late	Start of the lane change

Table 5.2: Independent Variables and their operationalization in the first part of the study at $30\,\mathrm{km\,h^{-1}}$ (2x2x2 within-subject design).

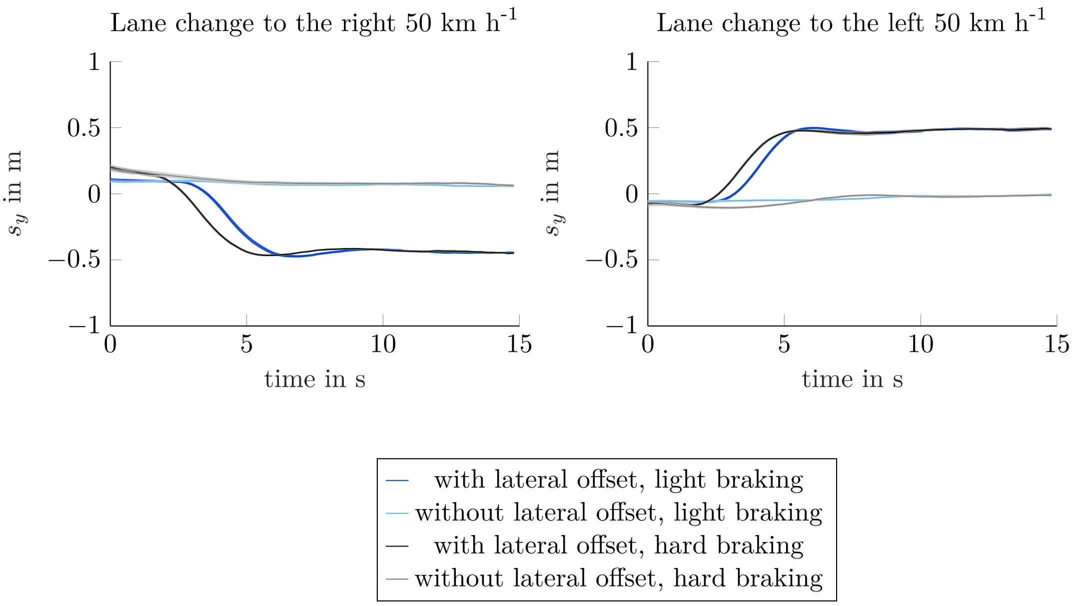
The AV's velocity until the start of the lane change at target velocity $30\,\mathrm{km\,h^{-1}}$ is illustrated in Figure 5.4a. The AV's acceleration is illustrated in Figure 5.4b and AV's lateral offset in advance of the lane change in Figure 5.4c. At a target velocity $50\,\mathrm{km\,h^{-1}}$ and light braking was the mean minimum acceleration $\mathrm{M}(\min(a_x)) = -1.23\,\mathrm{m\,s^{-2}}$ with a standard



(a) AV's velocity in longitudinal direction.

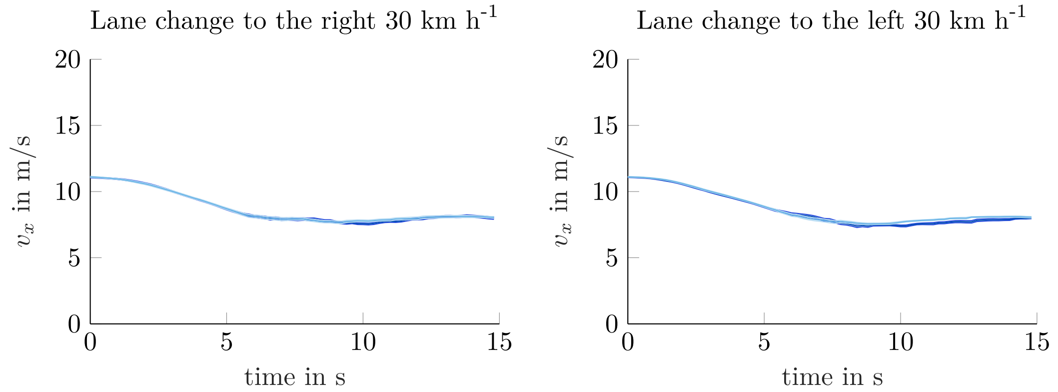


(b) AV's acceleration in longitudinal direction.

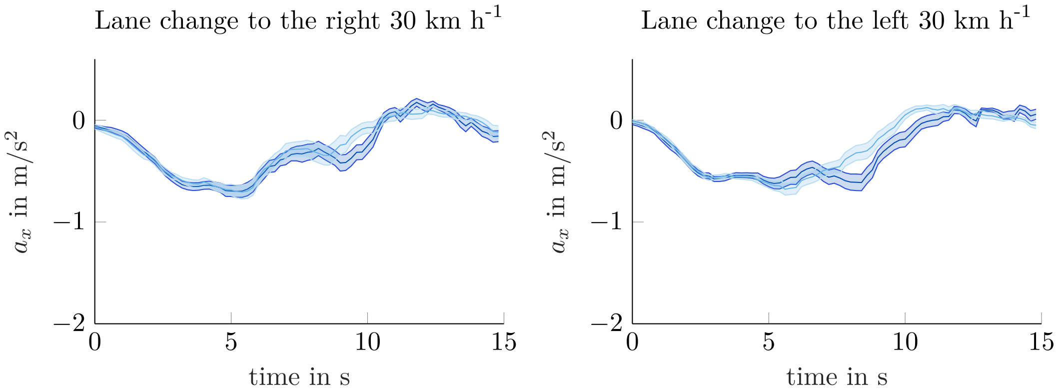


(c) AV's lateral offset before the start of the lane change

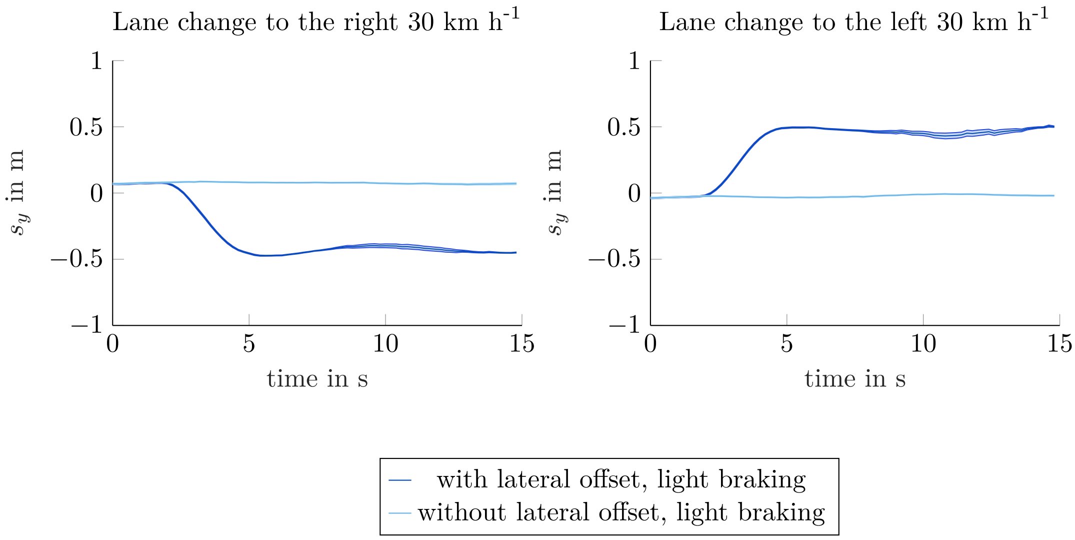
Figure 5.3: Means (centre line) and errors (pale area) in Frenet coordinates over time at target velocity of 50 km h^{-1}. At time equal to zero the AV and the lag vehicle of the adjusted gap are at same height.



(a) AV's velocity in longitudinal direction.



(b) AV's acceleration in longitudinal direction.



(c) AV's lateral offset before the start of the lane change

Figure 5.4: Means (centre line) and errors (pale area) in Frenet coordinates over time at target velocity of 30 km h^{-1}. At time equal to zero the AV and the lag vehicle of the adjusted gap are at same height.

deviation of $\mathrm{SD}(\min(a_x)) = 0.05\,\mathrm{m\,s^{-2}}$. At a target velocity $50\,\mathrm{km\,h^{-1}}$ and hard braking was the mean minimum acceleration $\mathrm{M}(\min(a_x)) = -2.08\,\mathrm{m\,s^{-2}}$ with a standard deviation of $\mathrm{SD}(\min(a_x)) = 0.06\,\mathrm{m\,s^{-2}}$. The mean minimum acceleration at a target velocity of $30\,\mathrm{km\,h^{-1}}$ was $\mathrm{M}(\min(a_x)) = -1.17\,\mathrm{m\,s^{-2}}$ with a standard deviation of $\mathrm{SD}(\min(a_x)) = 0.04\,\mathrm{m\,s^{-2}}$.

5.2.4 Dependent variables

The whole questionnaire is represented in the appendix A.2.

5.2.4.1 Part I

Predictability. In order to anticipate the behaviour of interacting vehicles, the consistency of the mental model and the observed behaviour play an important role (cf. section 2.1.1.2). It is important to evaluate which strategy is congruent with the human drivers' expectations. This is surveyed with the *predictability* (Lichtenthaler et al., 2012) and the *clarity* of the AV's intention to change lanes. The questions were answered on a seven-point rating scale. In addition, we asked the participants after every manoeuvre, what they recognized as communication of the intention to change lanes. To measure the objective predictability, participants had to push a button in the moment they understood the AV's intention to change lanes. The button is illustrated in Figure 5.5. Time was measured relative to the

Figure 5.5: Button harassed on the index finger or thumb (Cramer, 2019).

moment as the AV and the lag (participant's) vehicle of the adjusted gap were at same height. The participants could decide not to press the button, if the intention to change lanes was not distinct. However, this decision had to be made intentionally. To evaluate this, the participants were asked about their intentions.

Cooperation. Aim of the series of studies presented in this thesis was to generate an AV's lane change behaviour that increase the cooperation of interacting human drivers on the target lane. Thus, it was important to visualize different participants' cooperative behaviour. Therefore, the participants were advised to rate their-own cooperative behaviour from the perspective of an observer. For objective assessment performances measures, as quality over time as given in Schmidtke (1989), were designed. The performance measure is calculated by comparing the adjusted gap size Δs_t with the actual gap size s_a, given in equation 5.1:

$$\Delta s_t(t) = 3\,\mathrm{s} \cdot v_{\mathrm{LA}}(t) + L_{\mathrm{AV}}, \qquad \Delta s_a(t) = s_{\mathrm{LE}}(t) - s_{\mathrm{LA}}(t), \tag{5.1}$$

in which s_{LE} is the position of the adjusted gap's lead vehicle, s_{LA} and v_{LA} the position and the velocity of the adjusted gap's lag (participant's) vehicle and L_{AV} is the length of the AV. The adjusted gap size Δs_{t} is orientated on traffic's road regulations on German highways (cf. 3.2). The setting of the required adjusted gap size is taken as the interacting human drivers' overall task to cooperate. To standardize this measure between one and zero and to get its maximum per manoeuvre variation, the maximum quality measure $Q_{\max}$ is formulated in equation 5.2:

$$Q_{\max} = 1 - \min\left(\frac{\Delta s_{\mathrm{t}}(t) - \Delta s_{\mathrm{a}}(t)}{\Delta s_{\mathrm{t}}(t)}\right). \tag{5.2}$$

To take into account the time when the maximum was reached a performance measure L_s given in equation 5.3 is used to compare different cooperative behaviour of the participants due to the different AV's driving style:

$$L_s = \frac{Q_{\max}}{t_{Q\max}}. \tag{5.3}$$

At $t_{Q\max}$ the quality measure is at its maximum $Q_{\max}$. The time $t_{Q\max}$ is equal to zero at the time the AV and the lag vehicle of the adjusted gap are at same height.

Acceptance. Initially, after every manoeuvre the participants had the possibility to rate the AV's driving style according to a traffic light. The 'red' light stands for a bad AV's driving style that is rated 'rather negative', a 'yellow' light represents a behaviour that is rated 'neutral' and the 'green' light was representing an AV's driving style that is 'rather positive'. The acceptance of the AV's communication was measured by two questions referring to the scales introduced by Van Der Laan et al. (1997), referring to the *usefulness* and *satisfying* of the AV's driving style. The questions were answered on a seven-point rating scale.

5.2.4.2 Part II

The participants surveyed questions due to the ‘importance’ on a seven point rating scale and the ‘strength of the characteristic’ (‘way too strong’, ‘too strong’, ‘just right’, ‘too weak’, ‘way too weak’) of the selected driving style. The participants were asked to mark the time slot at which the AV should set the turn signal, using the button illustrated in Figure 5.5 due to their preferred AV’s driving style.

5.2.5 Sample

The study was carried out with N = 40 participants compromising 17 females and 23 males. They were between 20 and 54 years old (M = 36.13, SD = 9.69). They had their driver’s licence for 3 to 37 years (M = 18.25, SD = 9.37) and the average driven mileage per week was 290.83 km (SD = 282.55km). 16 participants had a non-technical profession (9 females and 7 males) and 24 participants had a technical profession (8 females and 16 males). Participants had an average Adaptive Cruise Control experience between 0 and 15 years (M = 4.18, SD = 3.70). They were driving 41% on highways, 31% in the inner city and 27% on country roads. 35 participants were employees of the AUDI AG. Furthermore, participants rated themselves on a scale of the prosocial and aggressive driving inventory (Harris et al., 2014) as pro-social drivers (M = 4.77, SD = 0.46).

5.2.6 Data preparation and statistical analysis

To replace missing information in the collected data, Expectation Maximization analysis is used (Little and Rubin, 2002). The premise for the method is that MCAR-test according to Little does not lead to significant findings, which implies that the missing values accrue randomly. In the subjective evaluation, a few questions are not reported over all participants. Therefore, 10 of 7680 answers are replaced by Expectation Maximization analysis. In two cases, the recording of the button was not working and thus the analysis of the objective processing of the information was done with N = 38 participants. Several participants stated, that they forgot to press the button after recognizing the AV’s intention to change lanes. Thus, 43 of 671 values are replaced by Expectation Maximization analysis. The analysis of the objective cooperation was done with N = 39 participants, because the recording of the AV dynamics was not working for one participant. A few recording errors occurred. Thus, 24 of 887 values of the performance measure as well as the time to detect the wish to change lanes are refunded by Expectation Maximization analysis.

The surveyed evaluations via rating scale are equidistant and therefore are assumed as interval scaled variables (Döring and Bortz, 2016, p.244-245). Moreover, normal distribution of the data is assumed, because of sample sizes N > 30 (Bortz and Schuster, 2010, p.87). In the statistical analysis values for univariate and multivariate tests (Pillai's trace) are reported and a statistical significance level of $\alpha = .05$ is applied if not stated otherwise.

5.3 Results

5.3.1 Part I: Standardized tests

5.3.1.1 Predictability

In 98.54 % the turn signal and in 37.57 % the lateral offset is detected as communication of the intention to change lanes. Moreover, in 3.44 % the AV's light braking and in 23.44 % the AV's hard braking is identified as communication of the intention to change lanes.

The subjective utilization of the item predictability and clarity at target velocity $50\,\mathrm{km\,h^{-1}}$ is illustrated in Figure 5.6. A four-way Multivariate Analysis of Variance (MANOVA) for repeated measure design (turn signal x braking x lateral offset x direction) at target velocity $50\,\mathrm{km\,h^{-1}}$ (Table 5.3), shows significant results for the main effects lateral offset and turn signal. The main effects braking and direction are not significant. The interaction between the lateral offset and the time to set the turn signal, considering Bonferroni-correction ($\alpha/2$), implies that the difference between AV's driving styles with (wO) and without (nO) lateral offset is only significant if the turn signal is set late (predictability: $\Delta M_{\mathrm{wO,nO}} = 0.281$, SE = 0.118, $p = .023$; clarity: $\Delta M_{\mathrm{wO,nO}} = 0.656$, SE = 0.162, $p < .001$) and not if the turn signal is set early (predictability: $\Delta M_{\mathrm{wO,nO}} = 0.137$, SE = 0.099, $p = .178$; clarity: $\Delta M_{\mathrm{wO,nO}} = 0.085$, SE = 0.047, $p = .080$).

The subjective utilization of the items predictability and clarity at target velocity $30\,\mathrm{km\,h^{-1}}$ is illustrated in Figure 5.7. A three-way MANOVA for repeated measure design (turn signal x lateral offset x direction) at target velocity $30\,\mathrm{km\,h^{-1}}$ (Table 5.4), shows significant results for the main effects lateral offset and turn signal. The main effects braking and direction are not significant. The significant interaction between the lateral offset and the time to set the turn signal implies, considering Bonferroni-correction ($\alpha/2$), that the difference between AV's driving styles with (wO) and without (nO) lateral offset is only significant if the turn signal is set late (predictability: $\Delta M_{\mathrm{wO,nO}} = 0.737$, SE = 0.93, $p < .001$; clarity: $\Delta M_{\mathrm{wO,nO}} = 0.850$, SE = 0.227, $p = .001$) and not if the turn signal is set early (predictability: $\Delta M_{\mathrm{wO,nO}} = 0.063$, SE = 0.173, $p = .720$; clarity: $\Delta M_{\mathrm{wO,nO}} = 0.025$, SE = 0.082, $p = .762$).

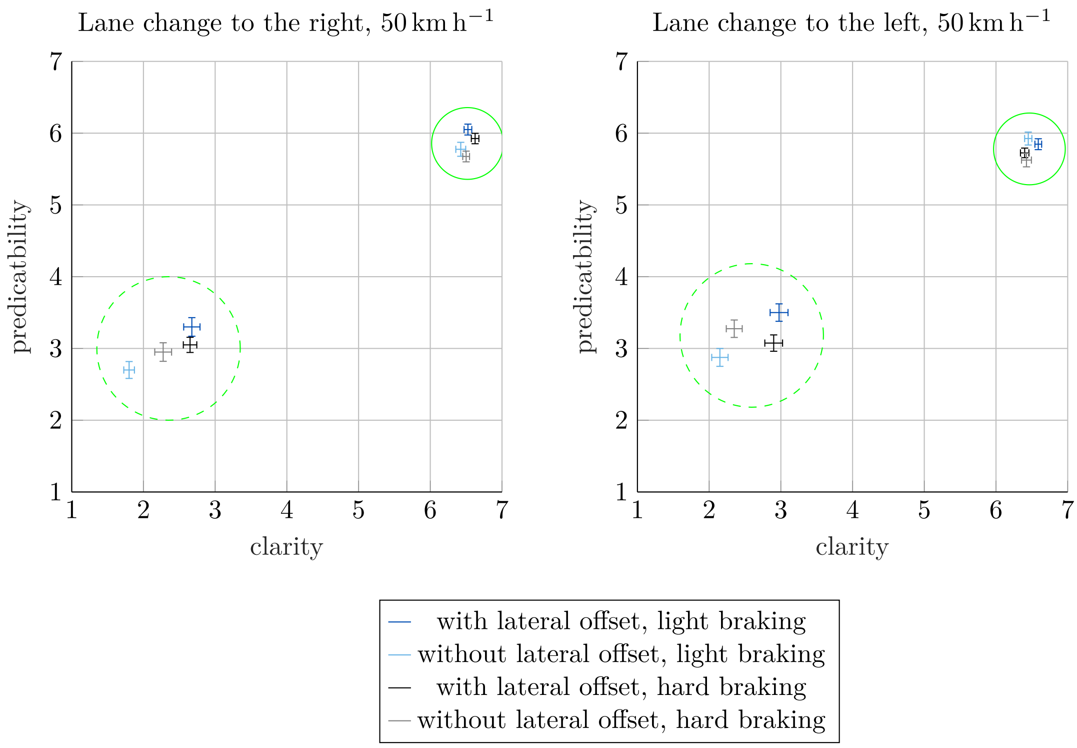


Figure 5.6: Means and errors of subjective *predictability* ratings the scales predictability and clarity [from 1 to 7]. The dashed green circles are around AV's driving styles in which the turn signal is set late and the solid green circles are around AV's driving styles in which the turn signal is set early.

Independent variable	$F(2,38)$	p	η_p^2
Lateral offset	8.67	.001	.313
Braking	1.78	.182	.09
Turn signal	256.37	$<$ .001	.93
Direction	0.70	.505	.04
Lateral offset * braking	2.48	.097	.12
Lateral offset * turn signal	6.11	.005	.24
Braking * turn signal	.863	.430	.04
Lateral offset * braking * turn signal	2.79	.074	.13
Lateral offset * direction	.57	.569	.03
Braking * direction	1.12	.337	.06
Lateral offset * braking * direction	.03	.969	$<$ .01
Turn signal * direction	1.83	.174	.09
Lateral offset * turn signal * direction	0.108	.898	.01
Braking * turn signal * direction	0.043	.958	$<$ .01
Lateral offset * braking * turn signal * direction	1.509	.234	.07

Table 5.3: Results of the MANOVA (2 (lateral offset) x 2 (braking) x 2 (turn signal) x 2 (direction)) for the surveyed predictability and clarity at 50 km h^{-1}.

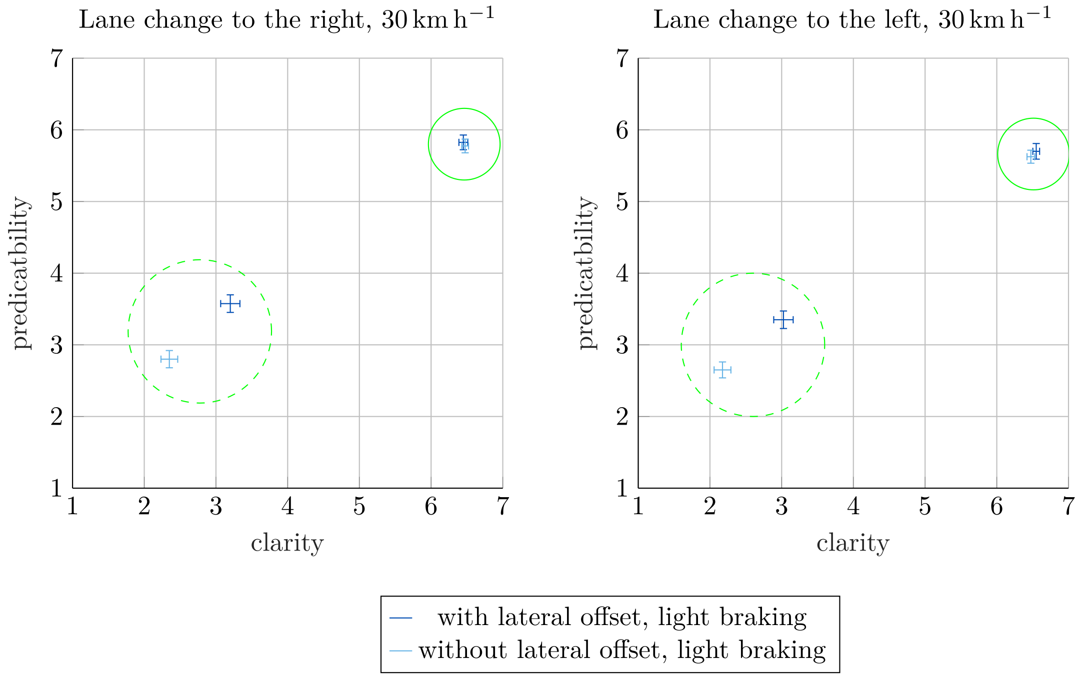


Figure 5.7: Means and errors of subjective *predictability* ratings of the scales predictability and clarity [from 1 to 7]. The dashed green circles are around AV's driving styles in which the turn signal is set late and the solid green circles are around AV's driving styles in which the turn signal is set early.

Independent variable	$F(2, 38)$	p	η_p^2
Lateral offset	5.55	.008	.23
Turn signal	190.97	.001	.91
Direction	1.03	.367	.05
Lateral offset * turn signal	8.04	.001	.30
Lateral offset * direction	0.05	.954	$< .01$
Turn signal * direction	0.54	.587	.03
Lateral offset * turn signal * direction	.04	.947	$< .01$

Table 5.4: Results of the MANOVA (2 (lateral offset) x 2 (turn signal) x 2 (direction)) for the surveyed predictability and clarity at 30 km h^{-1}.

A four-way MANOVA for repeated measure design (turn signal x lateral offset x direction x velocity) for all AV's driving styles with light braking with Bonferroni-correction ($\alpha/2$), shows significant findings for the main factors lateral offset and turn signal (Table 5.5). The significant interaction between the lateral offset and the time to set the turn signal, considering Bonferroni-correction ($\alpha/4$) once again, confirms the findings at $50\,\mathrm{km\,h^{-1}}$ and $30\,\mathrm{km\,h^{-1}}$. The difference between AV's driving styles with (wO) and without (nO) lateral offset is only significant if the turn signal is set late (predictability: $\Delta \mathrm{M}_{\mathrm{wO,nO}} = 0.675$, $\mathrm{SE} = 0.147$, $p < .001$; clarity: $\Delta \mathrm{M}_{\mathrm{wO,nO}} = 0.850$, $\mathrm{SE} = 0.172$, $p < .001$) and not if the turn signal is set early (predictability: $\Delta \mathrm{M}_{\mathrm{wO,nO}} = 0.080$, $\mathrm{SE} = 0.102$, $p = .434$; clarity: $\Delta \mathrm{M}_{\mathrm{wO,nO}} = 0.072$, $\mathrm{SE} = 0.049$, $p = .148$). As participants needed a very long time to

Independent variable	$F(1,37)$	p	η_p^2
Lateral offset	11.57	$< .001$	.378
Turn signal	245.36	$< .001$	.93
Direction	1.14	.330	.06
Velocity	3.66	.035	.162
Lateral offset * turn signal	11.90	$< .001$	.39
Lateral offset * direction	0.16	.856	.01
Turn signal * direction	0.127	.881	.01
Lateral offset * turn signal * direction	.217	.806	.01
Lateral offset * velocity	0.01	.839	.01
Turn signal * velocity	1.91	.162	.09
Lateral offset * turn signal * velocity	0.26	.773	.01
Direction* velocity	2.44	.101	.11
Lateral offset * direction * velocity	0.07	.930	$< .01$
Turn signal * direction * velocity	2.02	.147	.10
Lateral offset * turn signal * direction* velocity	0.292	.748	.02

Table 5.5: Results of the MANOVA (2 (lateral offset) x 2 (turn signal) x 2 (direction) 2 x (velocity)) for the surveyed predictability and clarity for all AV's driving styles with light braking.

identify the AV s intention to change lanes in AV's driving styles with a late turn signal and in average 13 participants (32.5 %) per scenario did not detect the intention to change lanes at all, the objective analysis is done in two parts. First, to evaluate the AV's driving styles with a late turn signal, the number of participants that did not press the button deliberately per scenario are analysed. Second, the time the participants needed to recognize the AV's intention to change lanes is investigated for the AV's driving styles with an early turn signal. The number per AV's driving styles with a late turn signal, in which the participants did not press the button intentional is illustrated in Figure 5.8. Using a Mc-Nemar test shows a significant influence of the lateral offset ($\chi^2(1.480) = 29.60$, $p < .001$) and the AV's braking strength ($\chi^2(1.320) = 8.16$, $p = .004$).

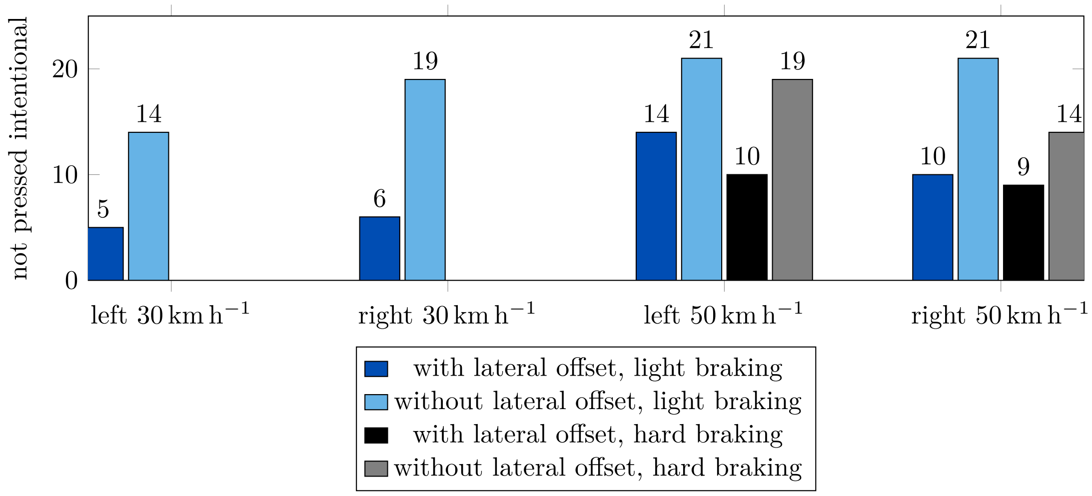


Figure 5.8: Numbers per scenario, in which the participants were not pressing the button intentionally. Only AV's driving styles, with a late turn signal are illustrated. Since, at AV's driving styles with an early turn signal no participant pressed the button unintentionally. The dashed bars are AV's driving styles with hard, the others with light braking.

The objective *predictability* measure of AV's driving styles with an early turn signal and the time participants' needed to detect the AV's intention to change lanes is illustrated in Figure 5.9. A three-way Univariate Analysis of Variance (ANOVA) for repeated measure design (braking x lateral offset x direction) for all AV's driving styles with early turn signal at 50 km h^{-1} shows only a significant main effect for braking (Table 5.6). The influence of the lateral offset or the lane change direction is not significant. The AV's intention is detected at AV's driving styles with hard braking after an average time span of $M = 2.39s$ ($SD = .09s$) and with light braking after an average time span of $M = 3.04s$ ($SD = .09s$).

Independent variable	$F(1, 37)$	p	η_p^2
Lateral offset	0.28	.603	.01
Braking	0.553	$< .001$	.553
Direction	< 0.01	.973	$< .01$
Lateral offset * braking	0.03	.271	.03
Lateral offset * direction	1.99	.167	.05
Braking * direction	0.03	.334	.03
Lateral offset * braking * direction	0.01	.649	.01

Table 5.6: Results of the ANOVA (2 (lateral offset) x 2 (braking) x 2 (direction)) of the time necessary to identify the AV's intention to change lanes, for all AV's driving styles in which the turn signal is set early (objective *predictability*) at 50 km h^{-1}.

A two-way ANOVA for repeated measure design (lateral offset x direction) for all AV's driving styles with early turn signal at 30 km h^{-1} shows that lane changes to the left are detected significantly faster than lane changes to the right. AV's driving styles with lateral

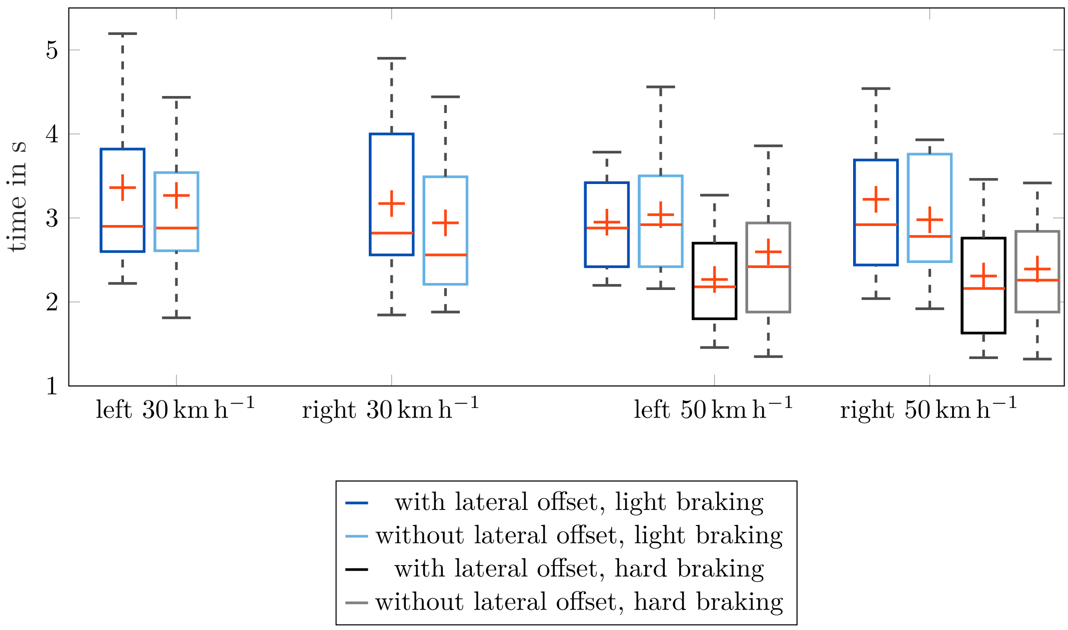


Figure 5.9: Time necessary to identify the AV's intention to change lanes, for all AV's driving styles in which the turn signal is set early (objective *predictability*). At time = 0, the lag (participant's) vehicle of the adjusted gap and the AV was at same height.

offset are not detected significantly faster.

Independent variable	$F(1, 37)$	p	η_p^2
Lateral offset	0.22	.603	.01
Direction	4.14	.049	.10
Lateral offset * direction	.48	.491	.01

Table 5.7: Results of the ANOVA (2 (lateral offset) x 2 (direction)) of the time necessary to identify the AV's intention to change lanes, for all AV's driving styles in which the turn signal is set early (objective *predictability*) at 30 km h^{-1}.

A three-way ANOVA for repeated measure design (lateral offset x direction x velocity) for all AV's driving styles with early turn signal and light braking with Bonferroni-correction ($\alpha/2$), shows no significant findings (Table 5.8).

A lateral offset and hard braking to the adjusted gap increases the chance to detect the intention to change lanes in case the turn signal is set late. The time to process the intention to change lanes decreases significantly with setting the turn signal early. Also the scales predictability and clarity of the intention increases. Thus, hypothesis H1.1 is accepted. If the turn signal is set early, hard braking makes a significant difference in the objective measure. However, participants are not recognizing this effect and are not rating AV's driving styles with hard braking with significant higher predictability and clarity than AV's driving styles with light braking. Due to the results of the objective measure hypothesis H1.3 is accepted.

Independent variable	$F(1,37)$	p	η_p^2
Lateral offset	0.65	.427	.02
Direction	0.032	.275	.0
Velocity	1.48	.232	.04
Lateral offset * direction	1.83	.184	.05
Lateral offset * velocity	1.99	.945	.05
Direction * velocity	5.08	.030	.121
Lateral offset * direction * velocity	0.154	.697	$< .01$

Table 5.8: Results of the ANOVA (2 (lateral offset) x 2 (turn signal) x 2 (velocity)) for the objective *predictability* at $30\,\mathrm{km\,h^{-1}}$.

A lateral offset only makes a difference if the turn signal is set late. Hypothesis H1.2 is only accepted for AV's driving styles in which the turn signal is not set to communicate the intention to change lanes. At $30\,\mathrm{km\,h^{-1}}$ (Q1), lane changes to the right are detected significantly faster than lane changes to the left (Q2). This effect is only found in the objective measures and not at $50\,\mathrm{km\,h^{-1}}$

5.3.1.2 Cooperation

The participants' self-assessment of their-own cooperation at $50\,\mathrm{km\,h^{-1}}$ is illustrated in Figure 5.10. A three-way ANOVA for repeated measure design (turn signal x deceleration x

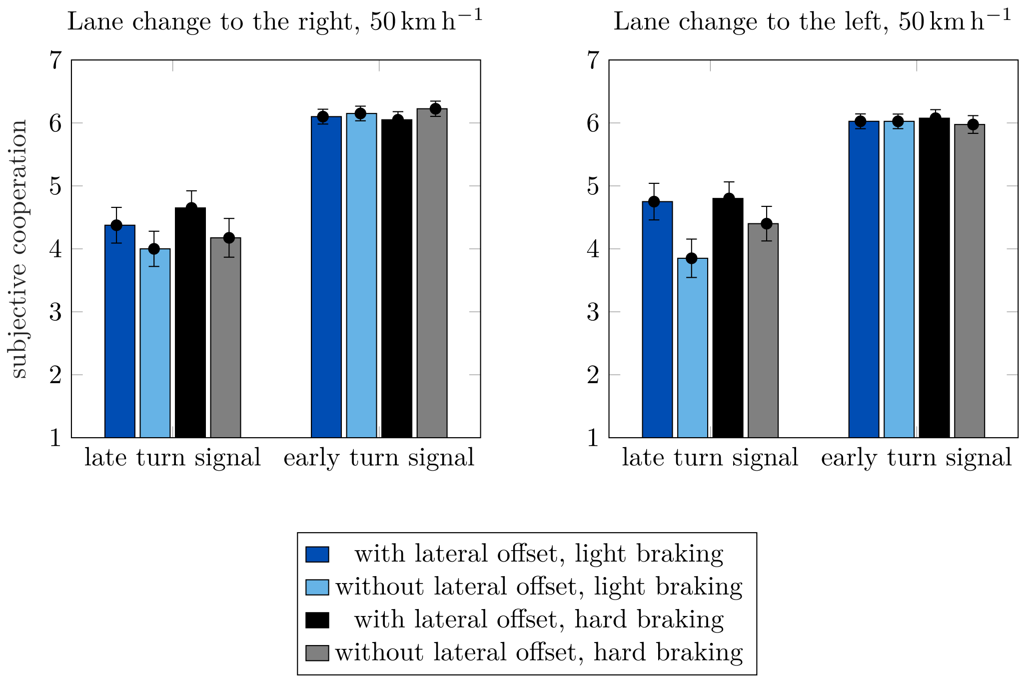


Figure 5.10: Means and errors of the surveyed participants' self-assessment of their-own *cooperation* at $50\,\mathrm{km\,h^{-1}}$ [from 1 to 7].

lateral offset x lane change direction) is used to analyse the surveyed self-assessment of the participants' cooperation (Table 5.9). AV's driving styles with early turn signal, lateral offset

Independent variable	$F(1, 39)$	p	η_p^2
Lateral offset	8.42	.006	.18
Braking	5.58	.023	.13
Turn signal	65.07	$< .001$	.63
Direction	0.07	.788	$< .01$
Lateral offset * braking	0.49	.49	.01
Lateral offset * turn signal	13.13	.001	.25
Braking * turn signal	3.34	.075	.25
Lateral offset * braking * turn signal	0.34	.566	.01
Lateral offset * direction	2.74	.106	.07
Braking * direction	0.04	.839	$< .01$
Lateral offset * braking * direction	0.36	.553	$< .01$
Turn signal * direction	2.12	.153	.05
Lateral offset * turn signal * direction	0.06	.809	$< .01$
Braking * turn signal * direction	0.10	.759	$< .01$
Lateral offset * braking * turn signal * direction	1.95	.171	.05

Table 5.9: Results of the ANOVA (2 (lateral offset) x 2 (braking) x 2 (turn signal) x 2 (direction)) for the surveyed *cooperation* at $50\,\mathrm{km\,h^{-1}}$.

and hard braking result in significant higher participants' cooperation. Only the influence of the lane change direction is not significant. The lateral offset interacts dis-ordinal with the time to set the turn signal for the subjective measure. Considering Bonferroni-correction ($\alpha/2$) the difference between AV's driving styles with (wO) and without (nO) lateral offset is significant if the turn signal is set late ($\Delta \mathrm{M}_{\mathrm{wO,nO}} = 0.538$, SE = 0.152, $p = .001$) and not in cases the turn signal is set early ($\Delta \mathrm{M}_{\mathrm{wO,nO}} = -0.030$, SE = 0.066, $p = .651$).

The participants' self-assessment of their-own cooperation at $30\,\mathrm{km\,h^{-1}}$ is illustrated in Figure 5.11. A three-way ANOVA for repeated measure design (turn signal x lateral offset x lane change direction) is used to analyse the surveyed self-assessment of the participants' cooperation (Table 5.10). Setting the turn signal early results in significant higher participants' cooperation. The influence of a lateral offset or a different lane change direction is not significant. The lateral offset interacts dis-ordinal with the time to set the turn signal. Considering Bonferroni-correction ($\alpha/2$), the difference between AV's driving styles with (wO) and without (nO) lateral offset is significant if the turn signal is set late ($\Delta \mathrm{M}_{\mathrm{wO,nO}} = 0.563$, SE = 0.171, $p = .002$) and not if the turn signal is set early ($\Delta \mathrm{M}_{\mathrm{wO,nO}} = -0.212$, SE = 0.109, $p = .058$).

A four-way ANOVA for repeated measure design (turn signal x lateral offset x direction x velocity) for all AV's driving styles with light braking with Bonferroni-correction ($\alpha/2$),

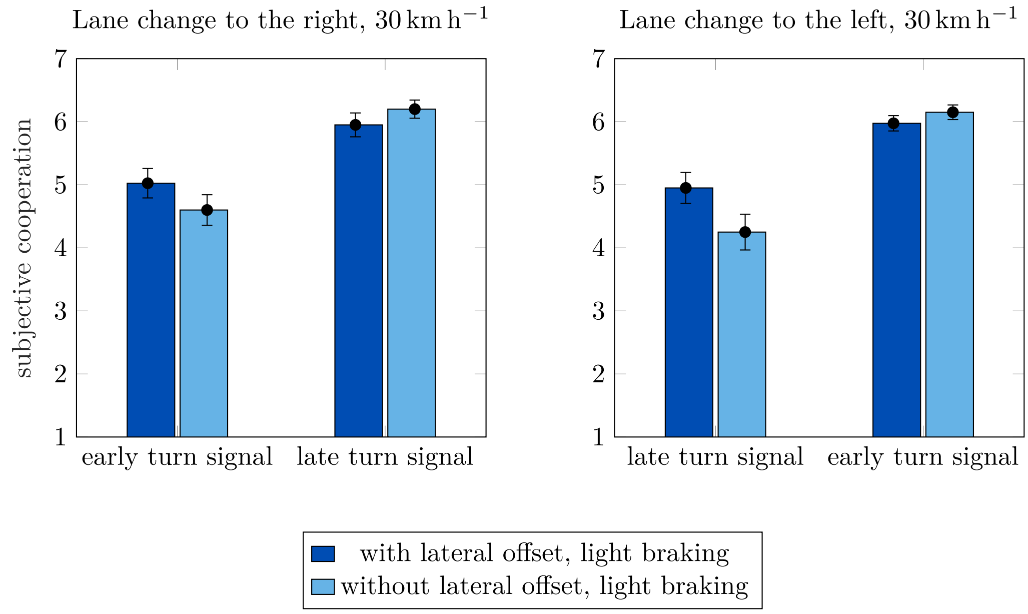


Figure 5.11: Means and errors of the surveyed participants' self-assessment of their-own *cooperation* at 30 km h^{-1} [from 1 to 7].

Independent variable	$F(1,39)$	p	η_p^2
Lateral offset	2.73	.107	.07
Turn signal	41.67	$<.001$	.517
Direction	0.03	.311	.03
Lateral offset * turn signal	16.16	$<.001$	.29
Lateral offset * direction	0.59	.446	.02
Turn signal * direction	0.76	.390	.02
Lateral offset * turn signal * direction	0.24	.626	$<.01$

Table 5.10: Results of the ANOVA (2 (lateral offset) x 2 (turn signal) x 2 (direction)) for the surveyed *cooperation* at 30 km h^{-1}.

shows significant findings for the main factors lateral offset, turn signal and velocity (Table 5.11). The significant interaction between the lateral offset and the time to set the turn signal, considering Bonferroni-correction ($\alpha/4$) once again, confirms the findings at $50\,\mathrm{km\,h^{-1}}$ and $30\,\mathrm{km\,h^{-1}}$. The difference between AV's driving styles with (wO) and without (nO) lateral offset is only significant if the turn signal is set late ($\Delta\mathrm{M_{wO,nO}} = 0.600$, SE $= 0.132$, $p < .001$) and not if the turn signal is set early ($\Delta\mathrm{M_{wO,nO}} = -0.118$, SE $= 0.064$, $p = .076$). The significant interaction between the velocity and the time to set the turn signal, also considering Bonferroni-correction ($\alpha/4$), shows that the difference between AV's driving styles at $30\,\mathrm{km\,h^{-1}}$ (30) and at $50\,\mathrm{km\,h^{-1}}$ (50) is only significant if the turn signal is set late ($\Delta\mathrm{M_{30,50}} = 0.462$, SE $= 0.172$, $p = .011$) and not if the turn signal is set early ($\Delta\mathrm{M_{30,50}} = -0.007$, SE $= 0.066$, $p = .912$).

Independent variable	$F(1,39)$	p	η_p^2
Lateral offset	9.35	.004	.19
Turn signal	65.06	$< .001$	.63
Direction	0.43	.514	.01
Velocity	7.02	.012	.15
Lateral offset * turn signal	27.84	$< .001$	.42
Lateral offset * direction	2.23	.142	.05
Turn signal * direction	< 0.01	.978	$< .01$
Lateral offset * turn signal * direction	1.41	.243	.04
Lateral offset * velocity	0.00	.326	.03
Turn signal * velocity	5.74	.021	.13
Lateral offset * turn signal * velocity	.16	.688	$< .01$
Direction* velocity	0.75	.393	.02
Lateral offset * direction * velocity	.13	.718	$< .01$
Turn signal * direction * velocity	2.39	.130	.06
Lateral offset * turn signal * direction* velocity	.198	.658	.01

Table 5.11: Results of the ANOVA (2 (lateral offset) x 2 (turn signal) x 2 (direction) x 2 (velocity)) for the surveyed *cooperation* for all AV's driving styles with light braking.

The evaluation of the number of successful lane change AV's driving styles in which the AV communicated it's intention to change lanes with setting the turn signal late is illustrated in Figure 5.12. A Mc-Nemar analysis shows that AV's driving styles with lateral offset ($\chi^2(1.480) = 9.23$, $p = .002$) are significantly more successful. AV's driving styles with hard braking lead not to a significantly higher amount of successful lane changes ($\chi^2(1.320) = 2.84$, $p = .092$).

The performance measure used to evaluate the objective cooperative participants' behaviour due to the different AV's driving style variations at $50\,\mathrm{km\,h^{-1}}$ is illustrated in Figure 5.13. The objective analysis of a four-way ANOVA for repeated measure design (turn signal x

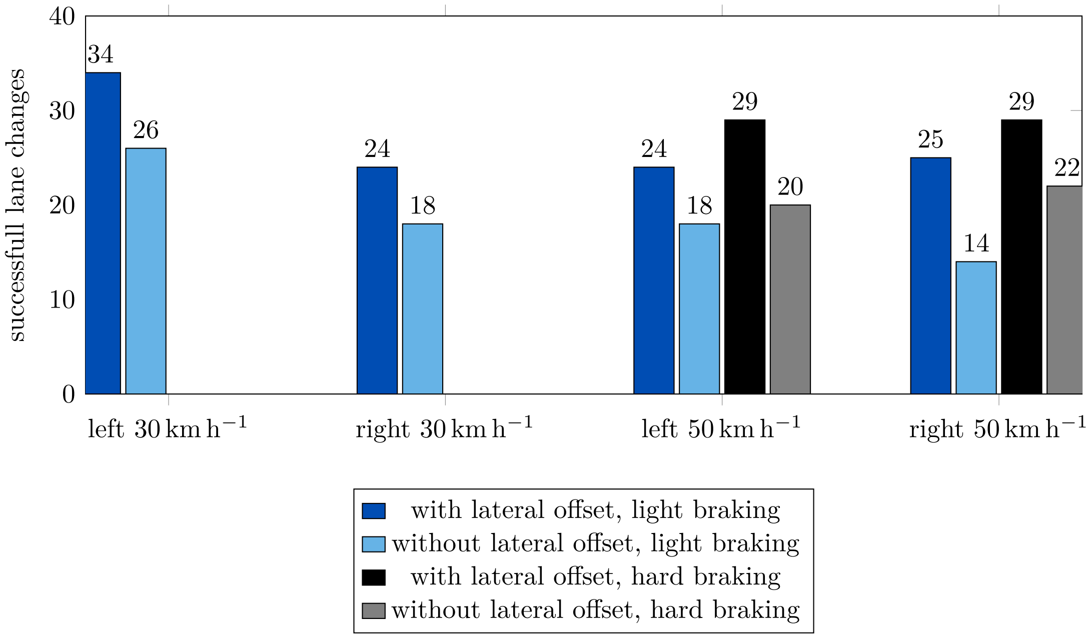


Figure 5.12: Numbers per scenario in which the lane change of the AV was executed successfully with an AV's driving style with late turn signal. With an AV's driving style with early turn signal 478 of 480 lane change were successful.

deceleration x lateral offset x lane change direction) for all AV's driving strategies at 50 km h^{-1} reveals significant results for the main effects (Table 5.12): lateral offset, braking and turn signal. AV's driving styles with lateral offset, hard braking and early turn signal cause significant more cooperation. The lateral offset interacts ordinal with the time to set the turn signal for the subjective measure. Considering Bonferroni-correction ($\alpha/2$), the difference between AV's driving styles with (wO) and without (nO) lateral offset is only significant if the turn signal is set late ($\Delta M_{wO,nO} = 0.008$, SE = 0.002, $p = .001$) and if the turn signal is set early ($\Delta M_{wO,nO} = 0.001$, SE = 0.001, $p = .333$).

The performance measure used to evaluate the objective cooperative participants' behaviour due to the different AV's driving style variations at 30 km h^{-1} is illustrated in Figure 5.14. A ANOVA for repeated measure design (turn signal x lateral offset x lane change direction) is used to analyse the data (Table 5.13). AV's driving styles with lateral offset, early turn signal and lane changes to the right cause significant more cooperation. The lateral offset interacts ordinal with the time to set the turn signal for the subjective measure. With Bonferroni-correction ($\alpha/2$) the difference between AV's driving styles with (wO) and without (nO) lateral offset is only significant if the turn signal is set late ($\Delta M_{wO,nO} = 0.021$, SE = 0.004, $p < .001$) and not in cases in which it is set early ($\Delta M_{wO,nO} = 0.004$, SE = 0.004, $p = .398$).

A four-way ANOVA for repeated measure design (turn signal x lateral offset x direction x velocity) for all AV's driving styles with light braking with Bonferroni-correction ($\alpha/2$), shows significant findings for the main factors lateral offset, turn signal and velocity (Table

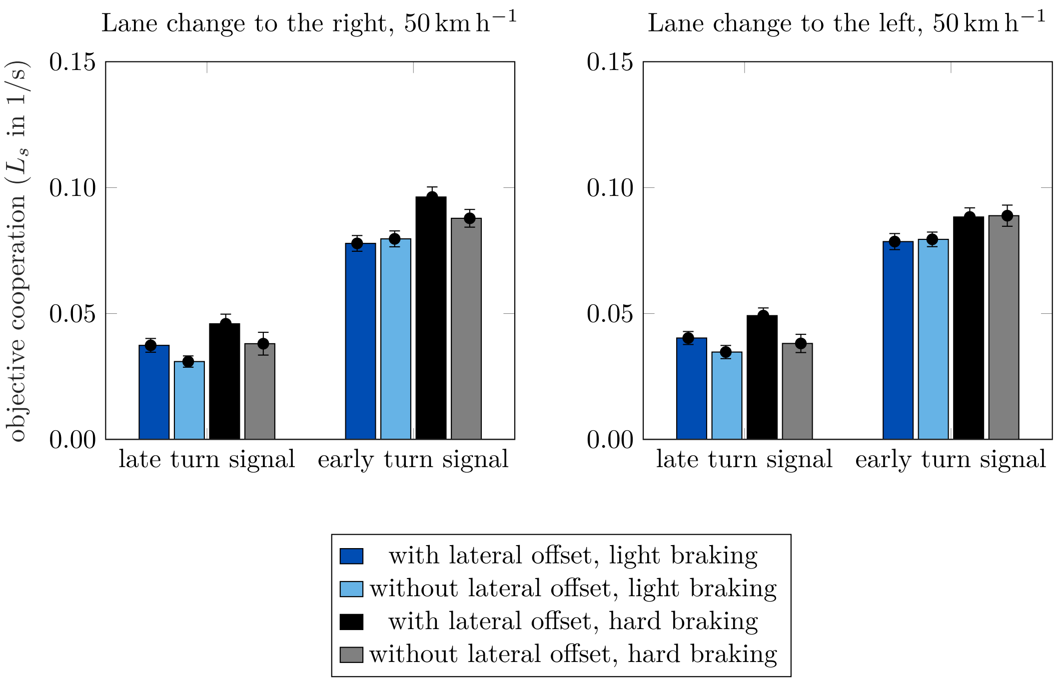


Figure 5.13: Means and errors of the objective measured participants' *cooperation* L_s as defined in section 5.2.4.1 at 50 km h^{-1}.

Independent variable	$F(1, 38)$	p	η_p^2
Lateral offset	14.76	$< .001$	.28
Braking	52.50	$< .001$	.58
Turn signal	170.00	$< .001$	.82
Direction	0.02	.897	$< .01$
Lateral offset * braking	3.16	.084	.08
Lateral offset * turn signal	5.44	.025	.13
Braking * turn signal	3.40	.073	.02
Lateral offset * braking * turn signal	0.17	.681	$< .01$
Lateral offset * direction	0.60	.444	.02
Braking * direction	1.06	.309	.03
Lateral offset * braking * direction	0.44	.510	.44
Turn signal * direction	3.18	.083	.08
Lateral offset * turn signal * direction	1.69	.202	.04
Braking * turn signal * direction	0.38	.540	.01
Lateral offset * braking * turn signal * direction	2.60	.115	.06

Table 5.12: Results of the ANOVA (2 (lateral offset) x 2 (braking) x 2 (turn signal) x 2 (direction)) for the objective cooperation at 50 km h^{-1}.

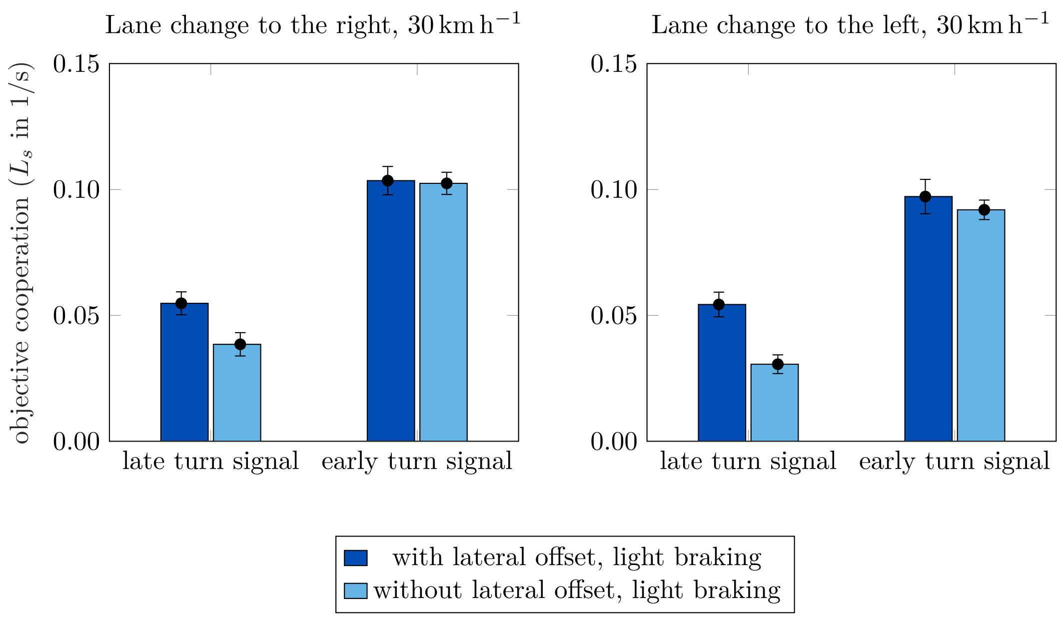


Figure 5.14: Means and errors of the objective measured participants' *cooperation* L_s as defined in section 5.2.4.1 at $30\,\mathrm{km\,h^{-1}}$.

Independent variable	$F(1,38)$	p	η_p^2
Lateral offset	18.22	$< .001$	.32
Turn signal	163.86	$< .001$	.91
Direction	4.34	.044	.10
Lateral offset * turn signal	10.22	.003	.21
Lateral offset * direction	1.51	.226	.04
Turn signal * direction	1.51	.226	.04
Lateral offset * turn signal * direction	.21	.650	.01

Table 5.13: Results of the ANOVA (2 (lateral offset) x 2 (turn signal) x 2 (direction)) for the objective measured *cooperation* at $30\,\mathrm{km\,h^{-1}}$.

5.14). The analysis, considering Bonferroni-correction twice ($\alpha/4$), shows four significant interactions. The significant interaction between the lateral offset and the time to set the turn signal confirms the findings at $50\,\mathrm{km\,h^{-1}}$ and $30\,\mathrm{km\,h^{-1}}$. The difference between AV's driving styles with (wO) and without (nO) lateral offset is only significant if the turn signal is set late ($\Delta\mathrm{M}_{\mathrm{wO,nO}} = 0.014$, SE $= 0.002$, $p < .001$) and not in cases in which it is set early ($\Delta\mathrm{M}_{\mathrm{wO,nO}} = 0.001$, SE $= 0.002$, $p = .628$). The significant interaction between the velocity and the turn signal, shows that the difference between AV's driving styles at $30\,\mathrm{km\,h^{-1}}$ and at $50\,\mathrm{km\,h^{-1}}$ is larger if the turn signal is set early ($\Delta\mathrm{M}_{30,50} = 0.021$, SE $= 0.003$, $p < .001$), than a late set of the turn signal ($\Delta\mathrm{M}_{30,50} = 0.009$, SE $= 0.003$, $p = .001$). In both cases the difference is significant. The significant interaction between the velocity and lateral offset implies, that the difference between AV's driving styles at $30\,\mathrm{km\,h^{-1}}$ and at $50\,\mathrm{km\,h^{-1}}$ is larger in cases with lateral offset ($\Delta\mathrm{M}_{30,50} = 0.020$, SE $= 0.003$, $p < .001$) than in cases without lateral offset ($\Delta\mathrm{M}_{30,50} = 0.010$, SE $= 0.002$, $p < .001$). But, in both cases the difference is significant. AV's driving styles with lateral offset (wO) only cause significantly more cooperation than AV's driving styles without lateral offset (nO) at $30\,\mathrm{km\,h^{-1}}$ ($\Delta\mathrm{M}_{\mathrm{wO,nO}} = 0.012$, SE $= 0.003$, $p < .001$) and not at $50\,\mathrm{km\,h^{-1}}$ ($\Delta\mathrm{M}_{\mathrm{wO,nO}} = 0.003$, SE $= 0.001$, $p = .062$). Since, the influence of the lane change direction is, as explained above, only significant at slow velocity, the expected interaction between lane change direction and velocity is found analysing all AV's driving styles with light braking. The difference between AV's driving styles at $30\,\mathrm{km\,h^{-1}}$ and at $50\,\mathrm{km\,h^{-1}}$ is larger at lane changes to the right ($\Delta\mathrm{M}_{30,50} = 0.019$, SE $= 0.003$, $p < .001$), than to the left ($\Delta\mathrm{M}_{30,50} = 0.011$, SE $= 0.003$, $p < .001$). In both cases the difference is significant. The difference between AV's driving styles to the right (R) and to the left (L) at $30\,\mathrm{km\,h^{-1}}$ ($\Delta\mathrm{M}_{\mathrm{R,L}} = 0.006$, SE $= 0.003$, $p = .044$) and $50\,\mathrm{km\,h^{-1}}$ ($\Delta\mathrm{M}_{\mathrm{R,L}} = -0.002$, SE $= 0.002$, $p = .478$) is not significant.

The cooperation of interacting human drivers increases with the main effects: early turn signal on the subjective and objective measures. Thus, hypothesis H2.1 is accepted. At $50\,\mathrm{km\,h^{-1}}$, the influence of AV's driving style with hard braking (H2.3) to the adjusted gap is significant as well on the subjective and objective measures. Thus, hypothesis H2.3 is accepted. The effect of the lateral offset only makes a difference if the turn signal is set late. Hypothesis H2.2 is only accepted for AV's driving styles in which the turn signal is not set to communicate the intention to change lanes. Interacting human drivers reacts more cooperative at slower velocities (Q1). This difference is even higher if the turn signal is set early to communicate the AV's intention to change lanes and is larger at lane changes to the right than to the left in the objective measure. The participants did not recognize a difference at different velocities. At slower velocities the reaction on lane changes to the left is more cooperative than on lane changes to the right (Q2) in the objective measures.

Independent variable	$F(1,38)$	p	η_p^2
Lateral offset	21.69	$<.001$	.36
Turn signal	206.20	$<.001$	.84
Direction	1.2ß	.280	.031
Velocity	46.90	$<.001$	.55
Lateral offset * turn signal	13.01	.001	.26
Lateral offset * direction	.94	.339	.02
Turn signal * direction	1.68	.203	.04
Lateral offset * turn signal * direction	.10	.753	$<.01$
Lateral offset * velocity	9.60	.004	.20
Turn signal * velocity	16.67	$<.001$	.31
Lateral offset * turn signal * velocity	3.06	.089	.07
Direction* velocity	6.52	.015	.156
Lateral offset * direction * velocity	.94	.340	.02
Turn signal * direction * velocity	0.15	.706	$<.01$
Lateral offset * turn signal * direction* velocity	.27	.608	.01

Table 5.14: Results of the ANOVA (2 (lateral offset) x 2 (turn signal) x 2 (direction) x 2 (velocity)) for the objective *cooperation* for all AV's driving styles with light braking.

5.3.1.3 Acceptance

The subjective ratings, based on traffic light, for all lane changes at 50 $\mathrm{km\,h^{-1}}$ are represented in Figure 5.15. The Figure illustrates that only AV's driving styles, in which the turn signal is set early, are rated in the green and therefore 'rather positive' area.

A four-way ANOVA for repeated measure design (turn signal x braking x lateral offset x direction) at target velocity 50 $\mathrm{km\,h^{-1}}$ (Table 5.15), shows significant results for the main effect turn signal. The main effects, lateral offset, braking and direction are not significant. The significant interaction between the lateral offset and the AV's braking strength, considering Bonferroni-correction ($\alpha/2$), shows no significant difference between AV's driving styles with (wO) and without (nO) lateral offset as well at light braking ($\Delta M_{\mathrm{wO,nO}} = 0.110$, SE = 0.049, p = .032), as hard braking ($\Delta M_{\mathrm{wO,nO}} = -0.025$, SE = 0.041, p = .544). Moreover, no significant difference between between AV's driving styles with hard braking (hB) and light braking (lB) for AV's driving styles with lateral offset ($\Delta M_{\mathrm{lB,hB}} = 0.054$, SE = 0.048, p = .269) and without lateral offset ($\Delta M_{\mathrm{lB,hB}} = -0.081$, SE = 0.056, p = .159) is found.

The subjective ratings, based on traffic light, for all lane changes at 30 $\mathrm{km\,h^{-1}}$ are represented in Figure 5.16. The Figure illustrates the same picture than at 50 $\mathrm{km\,h^{-1}}$: setting the turn signal early is essential for a good rating of the AV's driving style. A three-way ANOVA

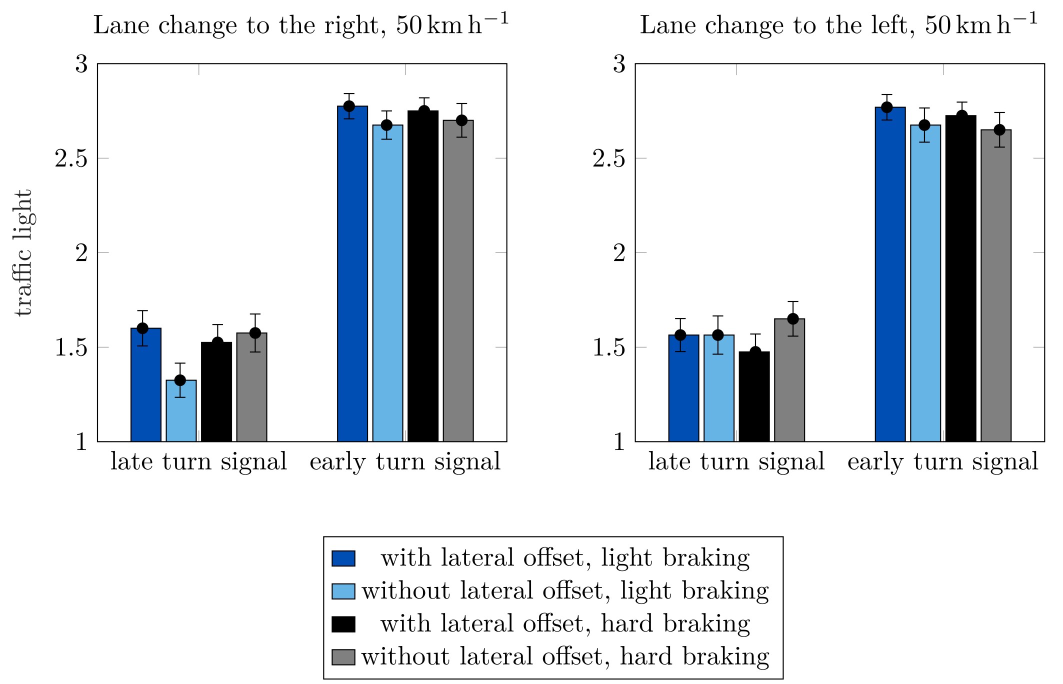


Figure 5.15: Means and errors of subjective measured *acceptance* of the AV's driving style based on a traffic light as defined in section 5.2.4.1 at $50\,\mathrm{km\,h^{-1}}$. In the Figure is the 'red' light represented with the value 1, the 'yellow' light with the value 2 and the 'green' light with the value 3.

Independent variable	$F(1,39)$	p	η_p^2
Lateral offset	1.58	.216	.04
Braking	0.10	.759	$< .01$
Turn signal	270.91	$< .001$	.87
Direction	0.19	.663	.01
Lateral offset * braking	5.00	.031	.11
Lateral offset * turn signal	1.30	.261	.03
Braking * turn signal	0.58	.450	.02
Lateral offset * braking * turn signal	2.57	.117	.06
Lateral offset * direction	2.72	.107	.07
Braking * direction	1.20	.281	.03
Lateral offset * braking * direction	0.42	.523	.01
Turn signal * direction	1.25	.271	.03
Lateral offset * turn signal * direction	1.88	.178	.05
Braking * turn signal * direction	0.19	.665	.01
Lateral offset * braking * turn signal * direction	0.23	.632	.01

Table 5.15: Results of the ANOVA (2 (lateral offset) x 2 (braking) x 2 (turn signal) x 2 (direction)) of subjective measured *acceptance* of the AV's driving style based on a traffic light at $50\,\mathrm{km\,h^{-1}}$.

for repeated measure design (turn signal x lateral offset x direction) (Table 5.16), shows significant results for the main effect turn signal. The main effects, lateral offset, braking and direction are not significant. There are no significant interactions.

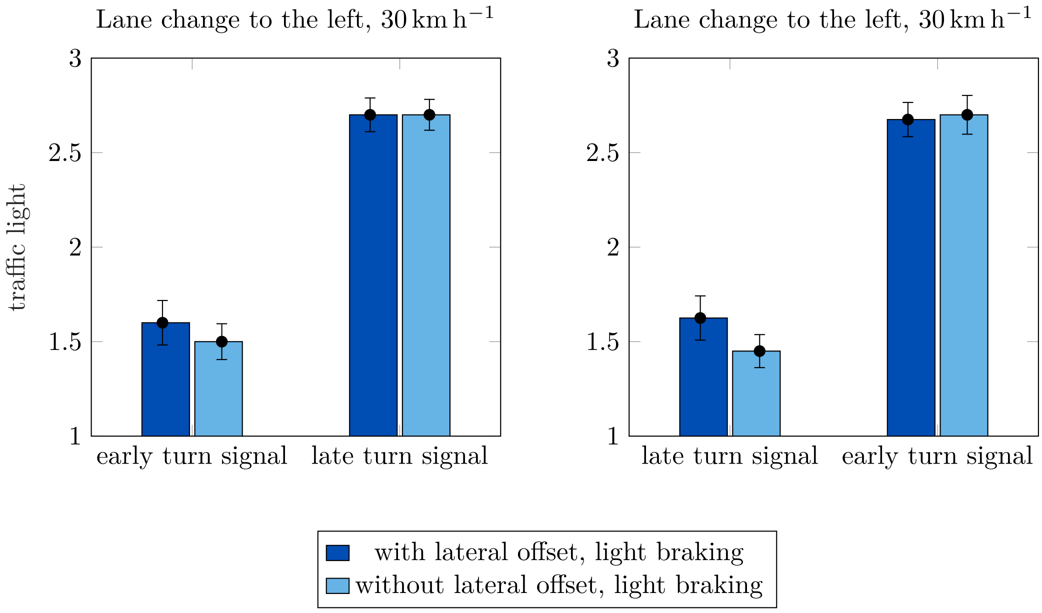


Figure 5.16: Means and errors of subjective measured *acceptance* of the AV's driving style based on a traffic light as defined in section 5.2.4.1 at $30\,\mathrm{km\,h^{-1}}$. In the Figure is the 'red' light represented with the value 1, the 'yellow' light with the value 2 and the 'green' light with the value 3.

Independent variable	$F(1,39)$	p	η_p^2
Lateral offset	0.77	.387	.02
Turn signal	156.00	$<.001$	.800
Direction	0.09	.772	$<.01$
Lateral offset * turn signal	1.23	.275	.03
Lateral offset * direction	0.07	.797	.002
Turn signal * direction	<0.01	1	$<.01$
Lateral offset * turn signal * direction	0.25	.618	.01

Table 5.16: Results of the ANOVA (2 (lateral offset) x 2 (turn signal) x 2 (direction)) of subjective measured *acceptance* of the AV's driving style based on a traffic light at $30\,\mathrm{km\,h^{-1}}$.

A four-way ANOVA for repeated measure design (turn signal x lateral offset x direction x velocity) for all AV's driving styles with light braking with Bonferroni-correction ($\alpha/2$), shows significant findings for the main factor turn signal (Table 5.17). The main effects, lateral offset, velocity and direction are not significant. There are no significant interactions.

The subjective utilization of the item *satisfying* and *usefulness* at target velocity $50\,\mathrm{km\,h^{-1}}$ is

Independent variable	$F(1,39)$	p	η_p^2
Lateral offset	4.01	.052	.09
Turn signal	203.36	$< .001$	.839
Direction	0.28	.597	.01
Velocity	$< .01$	.986	$< .01$
Lateral offset * turn signal	1.25	.271	.03
Lateral offset * direction	0.89	.350	.02
Turn signal * direction	0.66	.422	.02
Lateral offset * turn signal * direction	0.32	.575	.01
Lateral offset * velocity	0.30	.590	.01
Turn signal * velocity	0.81	.375	.02
Lateral offset * turn signal * velocity	.65	.426	.02
Direction* velocity	0.94	.339	.02
Lateral offset * direction * velocity	1.80	.187	.04
Turn signal * direction * velocity	.52	.47	.01
Lateral offset * turn signal * direction* velocity	3.39	.073	.08

Table 5.17: Results of the ANOVA (2 (lateral offset) x 2 (turn signal) x 2 (direction) x 2 (velocity)) of subjective measured *acceptance* of the AV's driving style based on a traffic light for all AV's driving styles with light braking.

illustrated in Figure 5.17. A four-way MANOVA for repeated measure design (turn signal x braking x lateral offset x direction) at target velocity 50 km h^{-1} (Table 5.18), shows significant results for the main effect turn signal. The main effects, lateral offset, braking and direction are not significant. The significant interaction between the lateral offset and the time to set the turn signal, considering Bonferroni-correction ($\alpha/2$), shows that the difference between AV's driving styles with (wO) and without (nO) lateral offset is only significant if the turn signal is set late for the surveyed usefulness ($\Delta M_{wO,nO} = 0.387$, SE = 0.135, $p = .007$), but not for the surveyed question satisfying ($\Delta M_{wO,nO} = 0.137$, SE = 0.114, $p = .233$). If the turn signal is set early, a lateral offset has no significant influence (usefulness: $\Delta M_{wO,nO} = -0.089$, SE = 0.119, $p = .458$; satisfying: $\Delta M_{wO,nO} = 0.028$, SE = 0.099, $p = .777$).

The subjective utilization of the item *satisfying* and *usefulness* at target velocity 30 km h^{-1} is illustrated in Figure 5.18. A three-way MANOVA for repeated measure design (turn signal x lateral offset x direction) (Table 5.19), shows significant results for all main effects lateral offset, turn signal and direction. AV's driving styles with early turn signal, with lateral offset and to the right are rated with significant higher acceptance. The significant interaction between the lateral offset and the time to set the turn signal, considering Bonferroni-correction ($\alpha/2$), that the difference between AV's driving styles with (wO) and without (nO) lateral offset is only significant if the turn signal is set late (usefulness: $\Delta M_{wO,nO} = 0.831$, SE = 0.183, $p < .001$; satisfying $\Delta M_{wO,nO} = 0.638$, SE = 0.187, $p = .002$). If the turn signal is set early both question show no significant influence (usefulness: $\Delta M_{wO,nO} = 0.013$, SE = 0.204,

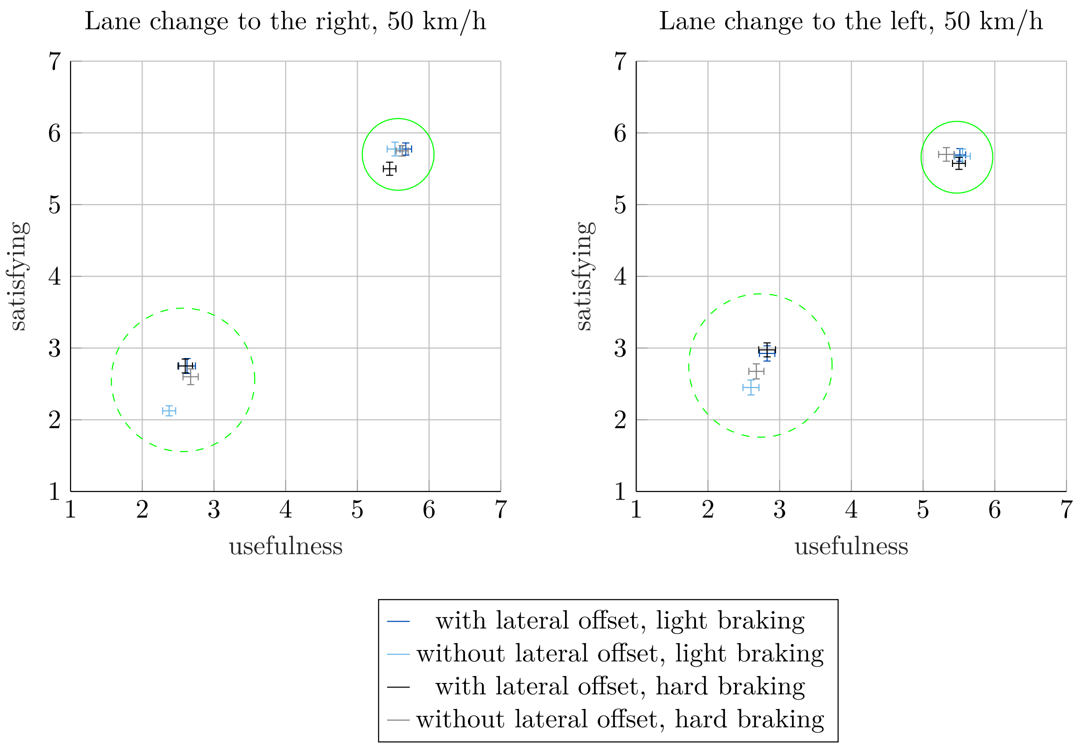


Figure 5.17: Means and errors of subjective *acceptance* ratings of the scales satisfying and usefulness [from 1 to 7]. The dashed green circles are around the AV's driving styles in which the turn signal is set late and the solid green circles are around AV's driving styles in which the turn signal is set early.

Independent variable	$F(2, 38)$	p	η_p^2
Lateral offset	1.23	.305	.06
Braking	.55	.584	.03
Turn signal	230.86	$< .001$	.92
Direction	.52	.600	.03
Lateral offset * braking	2.01	.147	.10
Lateral offset * turn signal	4.50	.018	.19
Braking * turn signal	2.04	.144	.10
Lateral offset * braking * turn signal	.16	.853	.01
Lateral offset * direction	.33	.724	.02
Braking * direction	.30	.740	.02
Lateral offset * braking * direction	.73	.489	.04
Turn signal * direction	1.08	.349	.05
Lateral offset * turn signal * direction	.06	.941	$< .01$
Braking * turn signal * direction	.83	.446	.04
Lateral offset * braking * turn signal * direction	.58	.564	.03

Table 5.18: Results of the MANOVA (2 (lateral offset) x 2 (braking) x 2 (turn signal) x 2 (direction)) for the surveyed *satisfying* and *usefulness* at 50 km h^{-1}.

p = .951; satisfying: $\Delta M_{wO,nO} = 0.025$, SE = 0.205, p = .902).

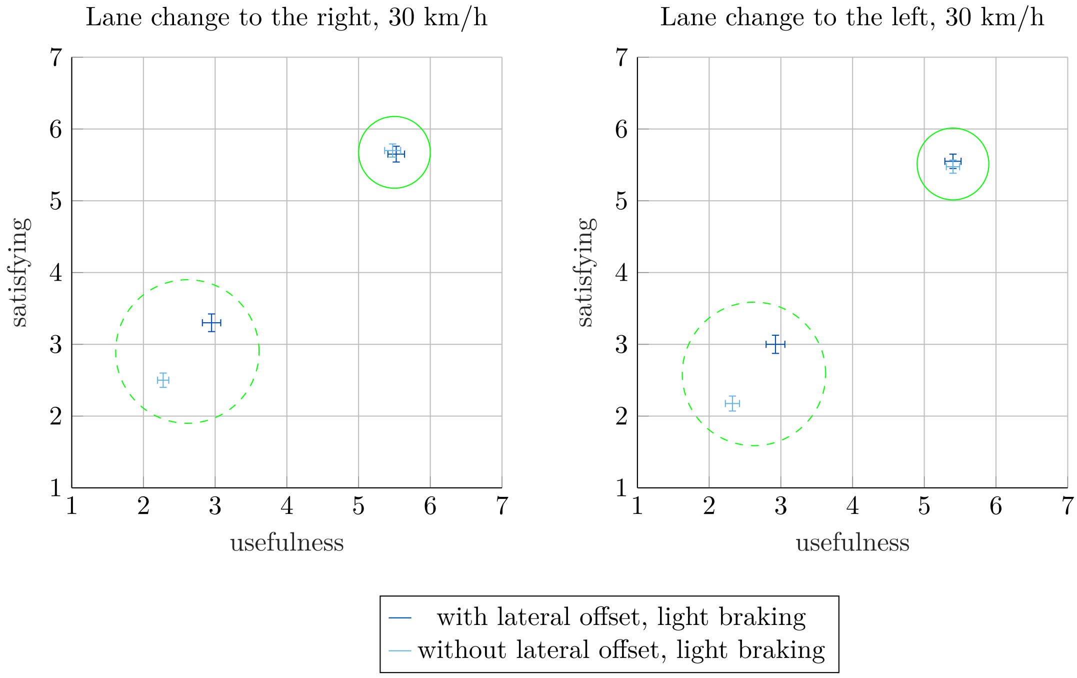


Figure 5.18: Means and errors of subjective *acceptance* ratings of the scales satisfying and usefulness [from 1 to 7]. The dashed green circles are around the AV's driving styles in which the turn signal is set late and the solid green circles are around AV's driving styles in which the turn signal is set early.

Independent variable	$F(2,38)$	p	η_p^2
Lateral offset	4.62	.016	.20
Turn signal	122.56	$<$ .001	.87
Direction	3.69	.034	.16
Lateral offset * turn signal	4.26	.021	.18
Lateral offset * direction	.42	.660	.02
Turn signal * direction	2.01	.148	.10
Lateral offset * turn signal * direction	.04	.958	$<$ .01

Table 5.19: Results of the MANOVA (2 (lateral offset) x 2 (turn signal) x 2 (direction)) for the surveyed *satisfying* and *usefulness* at $30\,\mathrm{km\,h^{-1}}$.

A four-way MANOVA for repeated measure design (turn signal x lateral offset x direction x velocity) for all AV's driving styles with light braking with Bonferroni-correction ($\alpha/2$), shows significant findings for the main factors lateral offset and turn signal (Table 5.20). The significant interaction between the lateral offset and the time to set the turn signal, considering Bonferroni-correction twice ($\alpha/4$), shows that the difference between AV's driving styles with (wO) and without (nO) lateral offset is only significant if the turn signal is set late (usefulness: $\Delta M_{wO,nO} = 0.681$, SE = 0.143, $p < .001$; satisfying $\Delta M_{wO,nO} = 0.438$, SE = 0.127, p = .001). If the turn signal is set early both question have no significant influence (usefulness: $\Delta M_{wO,nO} = 0.011$, SE = 0.117, p = .928; satisfying: $\Delta M_{wO,nO} = 0.041$, SE = 0.118, p = .732).

Independent variable	$F(2,38)$	p	η_p^2
Lateral offset	7.47	.002	.28
Turn signal	157.48	$< .001$	.89
Direction	1.61	.214	.08
Velocity	1.17	.322	.06
Lateral offset * turn signal	6.83	.003	.26
Lateral offset * direction	0.37	.693	.02
Turn signal * direction	0.82	.450	.04
Lateral offset * turn signal * direction	.37	.695	.02
Lateral offset * velocity	0.49	.616	.03
Turn signal * velocity	2.46	.099	.16
Lateral offset * turn signal * velocity	1.24	.302	.06
Direction* velocity	2.55	.092	.12
Lateral offset * direction * velocity	0.14	.866	.01
Turn signal * direction * velocity	3.70	.034	.16
Lateral offset * turn signal * direction* velocity	0.19	.826	.01

Table 5.20: Results of the MANOVA (2 (lateral offset) x 2 (turn signal) x 2 (direction) x 2 (velocity)) for the surveyed *satisfying* and *usefulness* for all AV's driving styles with light braking.

To communicate the intention to change lanes with an early turn signal is significantly better accepted, than a late usage of the turn signal. This confirms hypothesis H3.1. The braking strength to the target gap has no significant and thus hypothesis H3.3 is neglected. The influence of the lateral offset is only significant (H3.2) at the *acceptance* measured of the scales satisfying and usefulness if the turn signal is set late. Moreover, at slow velocity (Q1) lane changes to the right are better accepted than to the left (Q2). Both effects are not found on the AV's driving styles ratings based on a traffic light. Hypothesis H3.2 is only accepted for AV's driving styles in which the turn signal is not set to communicate the intention to change lanes.

5.3.2 Part II: Preferred driving strategy

75 % of the participants preferred an AV's driving style with lateral offset and rated the lateral offset as high relevant M = 4.98 (SD = 1.37). The decision of the deceleration was in contrast not distinct. Only 55 % percent chose an AV's driving style with hard braking strength. The participants rated the decision for the AV's braking strength as less relevant than the lateral

offset M = 4.85 (SD = 1.23). Some participants preferred the hard AV's braking strength. But, noted that the hard braking should be a little weaker. The opposite effect was found for some participants that preferred the light AV's braking strength. The optimum braking strength is supposed to lie somewhere in between. Setting the turn signal early was by far the most relevant parameter M = 6.88 (SD = 0.34). The time the participants would expect the AV to activate its turn signal is illustrated in Figure 5.19.

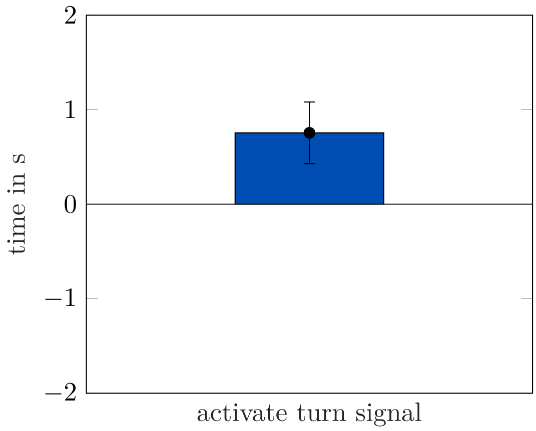


Figure 5.19: Means and errors of the time the AV should set its turn signal. At time equal to zero the AV and the lag (participant's) vehicle of the adjusted gap was at same height.

5.4 Discussion and conclusion

The present study investigates different variation to communicate the AV's intention to change lanes to interacting human drivers in a dense mixed-traffic scenario. The study focuses on a lane change to the right and to the left into a gap in front of the AV and was evaluated from the perspective of the lag vehicle of the adjusted gap (cf. section 4.2.1). The following section describes the behaviour patterns that should be considered for the design of an AV's driving style and those that don't have a significant influence to the evaluations of interacting human drivers by the key questions introduced in section 4.1.2, due to step *Communicate the lane change* of the procedure to designs an AV's driving style from interacting human drivers' perspective (cf. section 4.1.1).

At what time should the AV activate its turn signal?

To communicate the intention to change lanes the early usage of the turn signal (explicit communication) is absolutely necessary. This is confirmed by all metrics collected. Activating the turn signal does not only lead to significant higher *predictability* of the AV's driving style (cf. section 5.3.1.1). The results implicate, that AV's driving styles, in which the turn signal is activated early, are the only ones with high *acceptance* (cf. section 5.3.1.3). It seems that only a predictable and accepted AV's driving style really increases interacting human drivers' *cooperation* (cf. section 5.3.1.2). This is supported by the findings of Ehmanns (2001, 2002) and Stangl (2020), who found that interacting human drivers cooperate more as the necessity and the intention to change lanes is better predictable for them (cf. section 3.2.1).

To set the turn signal at the time the AV and the lag vehicle of the adjusted gap is at same height seems to fit the participants' expectation quite well (cf. Figure 5.19). Participants press the button to mark the time the turn signal should be activated in mean a bit later (cf. Figure 5.19). Probably, because the AV was a bit later more visible and better detectable by the participant (cf. section 2.1.1.1) and the participants needed time for the information processing process (cf. section 2.1.1), until they pressed the button.

What influence has an AV's lateral offset in advance of a lane change or a different AV's braking strength to the adjusted gap?

The pure communication over the driving style (implicit communication) can be classified as low. As explained above, it is necessary to activate the turn signal at a sufficiently large time interval in advance of the execution of the lane change in order to generate a predictable and accepted AV's driving style, as well as a cooperative behaviour of interacting human drivers.

In a study of Kauffmann et al. (2018a) it is found, that a lateral offset increases the cooperativeness of the AV's driving style from the point of view of interacting human drivers. In the present study an AV's lateral offset in advance of a lane change does only influence interacting human drivers' driving style and their rating if the turn signal is set late to communicate the AV's intention to change lanes. A lateral offset increases significantly the *predictability* (cf. section 5.3.1.1) and the *acceptance* (cf. section 5.3.1.3) of the AV's driving style. Moreover, the *cooperation* of interacting human drivers is significantly enlarged (cf. section 5.3.1.2). If the turn signal is activated early, a lateral offset has no significant influence to communicate the AV's intention to change lanes. Perhaps, this is due to the difference between driving simulator studies and studies in real vehicles, in which a lateral offset of 0.5 m, which according to Kauffmann et al. (2018a) is considered optimal, is too small. It is also possible that the turn signal itself is salient enough (cf. section 2.1.1.2) and the lateral offset in advance of the lane change to communicate the AV's intention is not necessary. That the majority of the participants prefer a strategy with lateral offset in the second part of the study, is an indication that a lateral offset in advance of a lane change does also not influence ratings negatively. During the study variations of the AV's driving style with hard and light braking are performed to adjust its velocity to the velocity of the adjusted gap. It should not be forgotten, that the here named 'hard' as well as the 'light' AV's braking strength (cf. Figure 5.3b) is realized in a comfortable area of longitudinal dynamics from passengers' perspective of the AV (cf. section 3.3). A hard AV's braking strength to adjust the velocity to the adjusted gap is detected significantly faster (cf. section 5.3.1.1) and ensures significantly higher *cooperation* of interacting human drivers compared to a light AV's braking strength (cf. section 5.3.1.2). Especially, if the turn signal is activated. Thus, this study corresponds to the trial of Fuest et al. (2018), that shows that pedestrians detect a hard braking strength significantly faster. The hypotheses that a hard braking strength increases the *acceptance* of the AV's driving style significantly must be discarded (cf. section 5.3.1.3). Hard braking to the adjusted gap does also not influence the *acceptance* of the AV's driving style significantly negatively. However, some participants commented that they would prefer a deceleration in between the varied ones, as a driving strategy to communicate the intention to change lanes. This could explain that only 55 % of participants chose the AV's drivings style with hard braking as their preferred variation in the second part of the study. But still gives this study reason to believe that interacting human drivers are more willing to cooperate in traffic scenarios in which the AV's lane change is more urgent and therefore it has to brake from a higher initial velocity in order the reach e.g. a highway, exit, or interchange.

Do interacting human drivers prefer different AV's driving styles at different lane change directions or target velocities?

Interacting human drivers seem to react significant more *cooperative* at $30\,\mathrm{km\,h^{-1}}$ than at $50\,\mathrm{km\,h^{-1}}$ (cf. section 5.3.1.2). This difference is even higher with an activated turn signal. Also at $30\,\mathrm{km\,h^{-1}}$ interacting human drivers react significantly more *cooperative* to lane changes of the AV to the left than to the right (cf. Figure 5.14 and Table 5.13). However, lane changes of the AV to the right are detected significantly faster (cf. Figure 5.9 and Table 5.7) and are rated with significantly higher *acceptance* (cf. section 5.3.1.3) than AV's lane changes to the left. Maybe, because it is mainly not allowed to overtake on the right and such a driving style is only common in high dense traffic to reach an exit or change lanes on an on-ramp or interchange, a scenario that is not evaluated explicitly in the current study.

6 Driving study II - Start the lane change

The driving study and its results are published in Potzy et al. (2019a). Some parts of the written text are taken from this article. Figures, tables, and statistics are adapted for an overall consistent representation throughout this thesis. Sophie Feinauer helped in designing and conducting of the driving study as part of her Master's thesis (Feinauer, 2019). For this Doctoral thesis the data was evaluated separately.

Since, in the first study (cf. chapter 5) the AV's driving style was parametrised very conservatively, without being asked, 57.5 % of the participants mentioned that the start of the lane change should be executed earlier. To gain an easy, distinct and interpretable AV's driving style for interacting human drivers this study investigates start conditions of lane changes into small gaps in a within-subject design on a test track with N = 39 participants, in order to answer the research question, pertaining *Start the lane change*, formulated in section 4.1.2: At what time would interacting human drivers expect the AV to start its lane change? To gain standardized scenarios all lane change manoeuvrers are executed automatically (cf. section 4.2.2) in a similar scenario on the test ground (cf. section 4.2.1). The study is divided into two parts. In a first part participants validate different time headway between the lag (participant's) vehicle of the adjusted gap and the AV as start condition of the lane change in different scenarios: velocity and existence of road work. In a second part, participants start the lane change of the AV themselves, when they expected it to start to change lanes out of the lag vehicle of the adjusted gap, also in different scenarios: deceleration to adjusted gap (weak and strong deceleration as evaluated in chapter 5), velocity and existence of road work.

6.1 Hypotheses and exploratory questions

To meet traffic road regulation on German highways (cf. section 3.2), intense cooperation of interacting human drivers is necessary before the AV can start its lane change. Human drivers change lanes if necessary with small time headway to interacting drivers (cf. section 3.2.2). Because interacting human drivers are faced with a fait accompli without being asked, their perspective still remains an open question. According to Zimmerman et al. (Zimmermann et al., 2014b, 2015), the driver opening the gap has a disadvantage in terms of cost compared to the cut-in vehicle. According to Lütteken et al. (2016) drivers do behave less cooperative, if they are aware of the overall costs of the cooperation. By reducing these costs the acceptance of AVs might be enhanced. Thus, we formulate the following hypothesises:

- AV's driving styles in which the lane change is started earlier (in terms of a smaller time headway between the AV and the lag vehicle of the adjusted gap) are rated with higher *predictability* (H1.1) of the AV's intention, higher *criticality* (H1.2), less *delaying* (H1.3), less *disturbing* (H1.4), and with higher *acceptance* (H1.5) from the perspective of interacting human drivers, compared to AV's driving styles in which the lane change is started later (in terms of a larger time headway between the AV and the lag vehicle of the adjusted gap).

At higher velocities the increase of the time headway to the front vehicle decreases (Abendroth, 2015; Wagner, 2012). But, in absolute distance the headway is increasing, which is assumed to attract human drivers' attention at repeated manoeuvres at different velocities. In addition, since interacting human drivers react more cooperatively at slow velocities (cf. chapter 5) manoeuvres are faster defused. The following hypothesises are formulated:

- AV's driving styles at a velocity of the adjusted gap of $30\,\mathrm{km\,h^{-1}}$ are rated with higher *predictability* (H2.1) of the AV's intention, higher *criticality* (H2.2), less *delaying* (H2.3), less *disturbing* (H2.4), and with higher *acceptance* (H2.5) from the perspective of interacting human drivers, than of $50\,\mathrm{km\,h^{-1}}$.

In lane narrowing scenarios, surrounding traffic is willing to cooperate more with a vehicle that wants to change lanes than in situations in which the motivation to change lanes is not obvious (Stoll et al., 2018; Benmimoun et al., 2004; Ehmanns, 2001, 2002). Moreover, at the end of an acceleration lane human drivers expect smaller gap sizes than at the beginning of the lane (Daamen et al., 2010), what leads to the following hypothesises:

- At high urgency (smaller distance from the AV to an upcoming lane end, e.g. due to road work), AV's driving styles are rated with higher *predictability* (H3.1) of the AV's intention, higher *criticality* (H3.2), more *delaying* (H3.3), more *disturbing* (H3.4), and with less *acceptance* (H3.5) from the perspective of interacting human drivers than at low urgency (without timely constraints for the lane change).

Interacting human drivers react more cooperative at small velocities and if the AV brakes harder to the target position (cf. chapter 5). Thus, we want to evaluate if those factors also influence the preferred start condition. The following exploratory questions are formulated:

- Which time headway (Q1) between the AV and the lag vehicle of the adjusted gap to start the AV's lane change do interacting human drivers prefer? Is there an influence of the dynamic of the lane change announcement (Q2), the urgency of the scenario (Q3) or the velocity of the adjusted gap (Q4)?

Hypothesis (H1-H3) are addressed in a first study part. To answer the questions (Q1-Q4) a second study part is conducted.

6.2 Method

6.2.1 Test scenario

The study took place in February 2019 and was executed on the test-ground described in section 4.2.1. The set-up on the test ground is illustrated in Figure 6.1a. Like in the first study, the participants drove the lag vehicle of the adjusted gap and were asked to follow the lead vehicle of the adjusted gap with a time headway of approx. 1 s, in order to gain an expected initial scenario in dense traffic on the target lane (cf. chapter 3.2.1). In order to generate a less artificial driving situation the participants were advised to do not use the Adaptive Cruise Control system to keep the required target distance, like in the first study (cf. chapter 5), but the participants were asked to orientated themselves at a customized marker at the windscreen, as illustrated in Figure 7.1b. The lead vehicle of the adjusted gap was driving with Cruise Control with either $50\,\mathrm{km\,h^{-1}}$ or $30\,\mathrm{km\,h^{-1}}$. The AV's starting lane was either restricted with obstacles, as illustrated in Figure 6.1b, or the AV had the whole straight to perform the lane change, as shown in Figure 6.1c. The AV was accelerated by an experimenter to the respective target velocity. Thereafter, the automated driving function was activated. Afterwards, the AV overtook the lag vehicle of the adjusted gap and aimed to get at the starting lane a target time headway of $t_{\mathrm{t,LE,AV}} = 0.4\,\mathrm{s}$ to the lead vehicle of the adjusted gap. From the point the appropriate conditions were fulfilled the AV started to change lanes. The driving function was deactivated shortly after the lane change was performed.

6.2.2 Procedure and study design

The study was structured in two parts, of which each part employed a within-subjects design, as well as a pre- and post-study questionnaire.

Pre-test. At first participants answered an questionnaire, in order describe the sample, given in Appendix B.2.1. At the test ground, they were informed about the content and their tasks during the study, as shown in Appendix B.1. Moreover, participants answered the pre-test

(a) Set- up on the test ground, reffering to Potzy et al. (2019a).

(b) High urgency.

(c) Low urgency.

questionnaire described in section 6.2.4.1.

Part I. The AV performed 12 lane change manoeuvres with a combination of parameters listed in Table 6.1. The participants were instructed to react to the AV's intention to change lanes the same way they would in real traffic. The start of the lane change was given if the time headway between the front of the lag (participant's) vehicle of the adjusted gap and the rear of the AV $t_{AV,LA}$ was larger than the value defined by $t_{r,AV,LA}$. After every manoeuvre the participants completed a questionnaire with the subjective measures described in section 6.2.4.2, via an interview guided by an experimenter at the front passenger's seat of the participant's vehicle.

Part II. The AV approached the adjusted gap eight times with a combination of parameters listed in Table 6.3. The participants released the lane change by pressing a button on the steering wheel out of the lag vehicle of the adjusted gap. The procedure was repeated until the participants were satisfied with the time they released the lane change (with a maximum of four trials).

Post-test. The participants answered the post-test questionnaire described in section 6.2.4.1.

The overall duration was approx. 120 minutes per participant. The first and second part of the study as well the AV's drivings styles variations were presented in randomized order.

6.2.3 Independent variables

This section summarizes the independent variables in study part I and II, representing different experimental conditions.

6.2.3.1 Part I

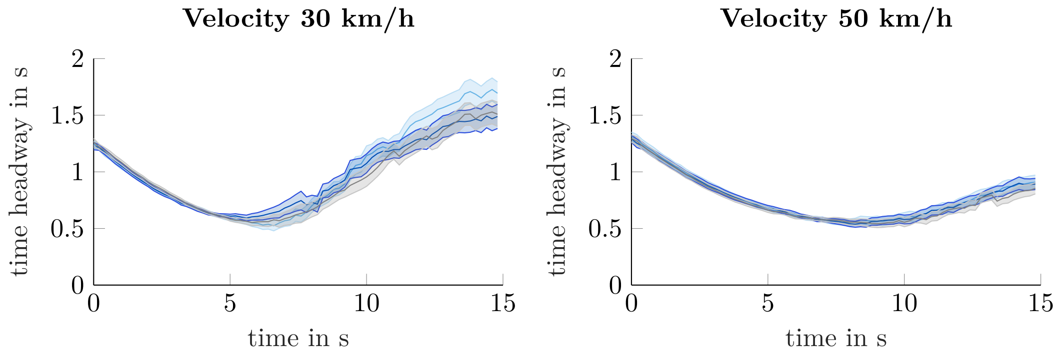
The independent variables of the first part of the study and their operationalization are illustrated in Table 6.1. During the first part of the study the target velocities, the urgency of the lane change and the start condition to start the AV's lane change was varied.

Independent variables	Variations	Operationalization
Velocity	$v_{LE} = 30\,km\,h^{-1}$ $v_{LE} = 50\,km\,h^{-1}$	velocity of lead vehicle
Urgency	high low	with/ without road work on left lane
Start condition	$t_{r,AV,LA} > 0.4\,s$ $t_{r,AV,LA} > 0.6\,s$ $t_{r,AV,LA} > 0.9\,s$	time headway between AV and lag (participant's) vehicle

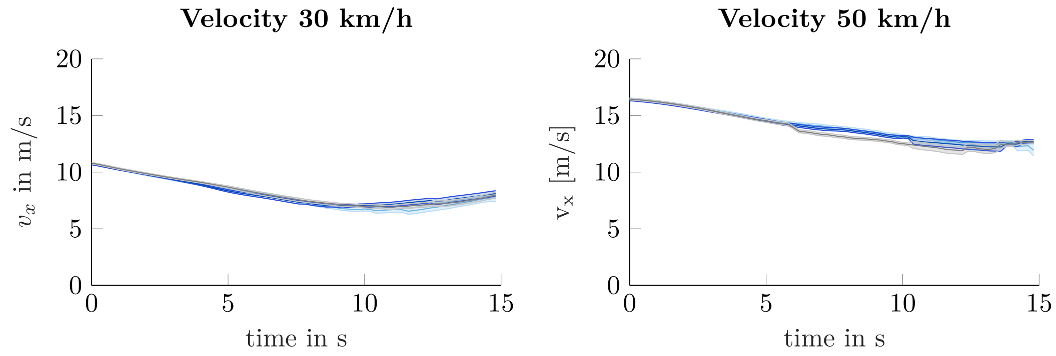
Table 6.1: Operationalization of independent variables of study part I (2x2x3 within-subject design)

Figure 6.1a illustrates the target time headway $t_{t,LE,AV}$ between lead vehicle of the adjusted gap and the AV during and after the lane change and shows a consistent AV's driving style at target velocity of $30\,km\,h^{-1}$ and $50\,km\,h^{-1}$. At different target velocities the driving style slightly defers. At a target velocity of $30\,km\,h^{-1}$ the AV had, shortly after the start of the lane change, a mean minimum time headway to the lead vehicle of the adjusted gap of $M(\min(t_{t,LE,AV})) = 0.33\,s$ with a standard error of $SE(\min(t_{t,LE,AV})) = 0.04\,s$. At a target velocity of $50\,km\,h^{-1}$ the AV had, shortly after the start of the lane change, a mean minimum time headway to the lead vehicle of the adjusted gap of $M(\min(t_{t,LE,AV})) = 0.45\,s$ with a standard error of $SE(\min(t_{t,LE,AV})) = 0.03\,s$. Thereafter, the target time headway increased. At a target velocity of $30\,km\,h^{-1}$ the mean maximum time headway was $M(\max(t_{t,LE,AV})) = 1.92\,s$ with a standard error of $SE(\max(t_{t,LE,AV})) = 0.11\,s$. At a target velocity of $50\,km\,h^{-1}$ the mean maximum time headway was $M(\max(t_{t,LE,AV})) = 1.36\,s$ with a standard error of $SE(\max(t_{t,LE,AV})) = 0.04\,s$.

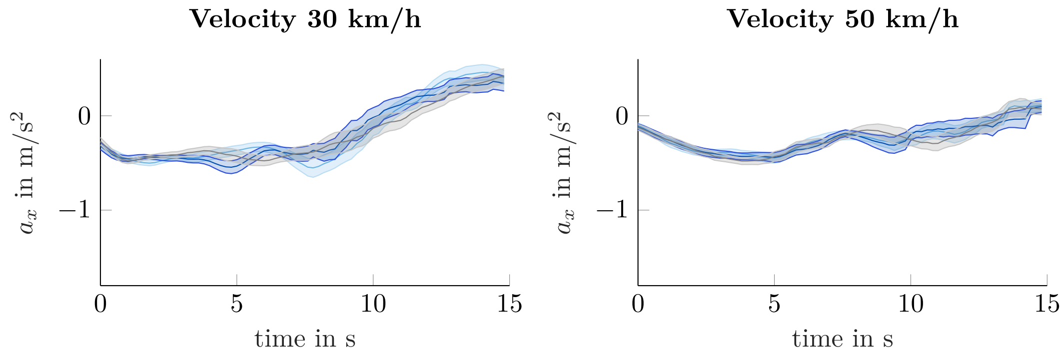
A closer look at Figure 6.1b and Figure 6.1c shows that the AV accelerated and therefore increased its velocity after the lane change. This rise occurred on one hand due to an



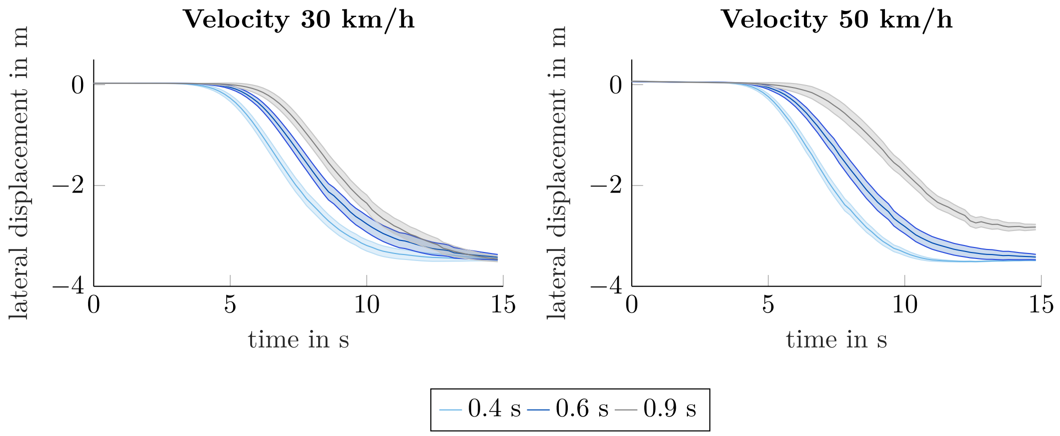
(a) time headway between AV and lead vehicle.



(b) AV's velocity in longitudinal direction.



(c) AV's acceleration in longitudinal direction



(d) AV's lateral displacement

Figure 6.1: Means (centre line) and errors (pale area) in Frenet coordinates over time. At time equal to zero the AV and the lag vehicle of the adjusted gap are at same height.

acceleration of the lead vehicle and on the other hand because the AV decreased its velocity during the lane change and aimed to reach its target velocity after the lane change. The braking to adjust AV's velocity to the velocity of the lead vehicle of the adjusted gap had an overall minimum over all conditions of $\mathrm{M}(\min(a_x)) = -1.09\,\mathrm{m\,s^{-2}}$ with a standard error of $\mathrm{SE}(\min(a_x)) = 0.07\,\mathrm{m\,s^{-2}}$. Here, the illustration deludes the mean acceleration over time. Figure 6.1d illustrates the AV's lateral displacement at the different factor levels. Not at all factor levels the AV reaches in mean the middle of the target lane. This can be explained by the fact, that especially, as shown in Table 6.2, at $50\,\mathrm{km\,h^{-1}}$ and high urgency a lot of lane changes could not be executed. In such situations the AV situational was manually stopped or steered to the target lane by the experimenter.

Start condition	Low urgency		High urgency	
	$30\,\mathrm{km\,h^{-1}}$	$50\,\mathrm{km\,h^{-1}}$	$30\,\mathrm{km\,h^{-1}}$	$50\,\mathrm{km\,h^{-1}}$
$t_{\mathrm{t,AV,LA}} \geq 0.4\,\mathrm{s}$	39 (100%)	39 (100%)	39 (100%)	39 (100%)
$t_{\mathrm{t,AV,LA}} \geq 0.6\,\mathrm{s}$	39 (100%)	39 (100%)	38 (97.4%)	33 (84.6%)
$t_{\mathrm{t,AV,LA}} \geq 0.9\,\mathrm{s}$	39 (100%)	38 (97.4%)	37 (94.9%)	20 (51.4%)

Table 6.2: Successful manoeuvres at different starting conditions $t_{\mathrm{t,AV,LA}}$ in the first part of the study.

In case the time headway to the lag vehicle of the adjusted gap was larger than $t_{\mathrm{t,AV,LA}}$ the AV started to change lanes. The Figure 6.2 shows that the factor levels were precisely met.

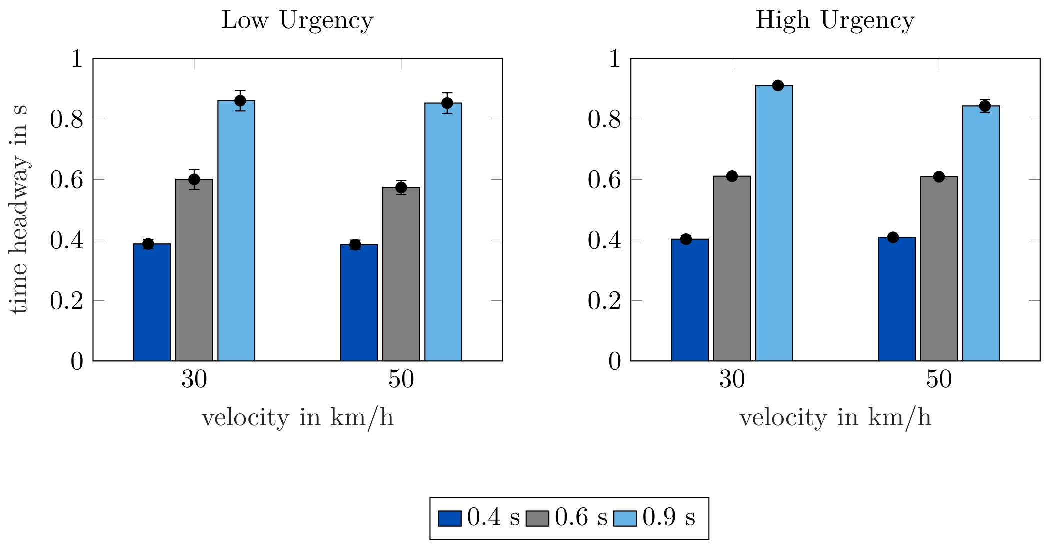


Figure 6.2: Means and errors of the time headway $t_{\mathrm{t,AV,LA}}$ between the AV and the lag vehicle of the adjusted gap at the start of the AV's lane change.

The factor level urgency is illustrated in Figure 6.3. To reach comparable distances at the lane end the lead and lag vehicle of the adjusted gap started to accelerate to target velocity from a standing start at defined locations. This let to comparable distances at the time point when the AV and the lag vehicle of adjusted gap were at same height to end of the lane at the factor levels low and high urgency for all variations of the AV's driving style. At the factor level high urgency a similar distance at a target velocity of $30\,\mathrm{km\,h^{-1}}$ and $50\,\mathrm{km\,h^{-1}}$ was reached. To realize different distances to the lane end at high urgency it was necessary to realize time restricted experimental conditions. At a target velocity of $50\,\mathrm{km\,h^{-1}}$, due to the faster velocity, the AV needed a longer distance available to position itself at the adjusted gap in order to realize the lane change than at $30\,\mathrm{km\,h^{-1}}$.

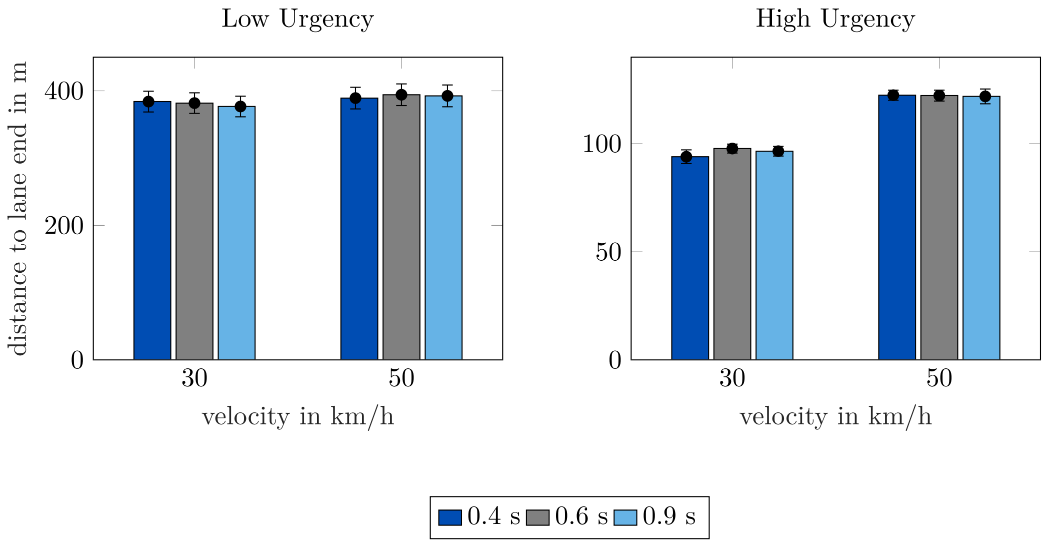


Figure 6.3: Means and errors of the distance to the lane end, when the AV and lag vehicle of adjusted gap were at same height in the first part of the study.

6.2.3.2 Part II

In the second part of the study the participants started the AV's lane change themselves out of the lag vehicle of the adjusted gap by pressing a button at the steering wheel (Figure 6.6b). As illustrated in Table 6.3 the urgency of the lane change and the AV's communication of the intention to change lanes, in terms of different realized decelerations to adjust the AV's velocity to the adjusted gap, was varied.

Figure 6.5a illustrates the time headway $t_{\mathrm{t,LE,AV}}$ between the lead vehicle of the adjusted gap and the AV during and after the lane change and shows a consistent AV's driving style at a target velocity of $30\,\mathrm{km\,h^{-1}}$ and $50\,\mathrm{km\,h^{-1}}$. At different target velocities the AV's driving style slightly defers. At a target velocity of $30\,\mathrm{km\,h^{-1}}$ the AV had, shortly after the start of the lane change, a mean minimum time headway to the lead vehicle of the adjusted gap of $\mathrm{M}(\min(t_{\mathrm{t,LE,AV}})) = 0.42\,\mathrm{s}$ with a standard error of $\mathrm{SE}(\min(t_{\mathrm{t,LE,AV}})) = 0.03\,\mathrm{s}$. At a target velocity of $50\,\mathrm{km\,h^{-1}}$ the AV had, shortly after the start of the lane change, a mean minimum

Independent variables	Variations	Operationalization
Communication of the lane change	$\Delta v_{E,PR} = 25\,\mathrm{km\,h^{-1}}$, $a_E \leq -1.5\,\mathrm{m\,s^{-2}}$; $\Delta v_{E,PR} = 10\,\mathrm{km\,h^{-1}}$, $a_E \leq -0.5\,\mathrm{m\,s^{-2}}$	strength of AV braking to target gap

Table 6.3: In study part II, in analogue to study part I, the factors target vehicle's velocity and urgency are varied. Additionally, the factor communication of the lane change is altered. This leads to a 2x2x2 within-subjects design. In part I only a light braking is performed.

time headway to the lead vehicle of the adjusted gap of $\mathrm{M}(\min(t_{\mathrm{t,LE,AV}})) = 0.46\,\mathrm{s}$ with a standard error of $\mathrm{SE}(\min(t_{\mathrm{t,LE,AV}})) = 0.02\,\mathrm{s}$. Thereafter, the target time headway increased. At a target velocity of $30\,\mathrm{km\,h^{-1}}$ the mean maximum time headway was $\mathrm{M}(\max(t_{\mathrm{t,LE,AV}})) = 1.97\,\mathrm{s}$ with a standard error of $\mathrm{SE}(\max(t_{\mathrm{t,LE,AV}})) = 0.11\,\mathrm{s}$. At a target velocity of $50\,\mathrm{km\,h^{-1}}$ the mean maximum time headway was $\mathrm{M}(\max(t_{\mathrm{t,LE,AV}})) = 1.30\,\mathrm{s}$ with a standard error of $\mathrm{SE}(\max(t_{\mathrm{t,LE,AV}})) = 0.04\,\mathrm{s}$. Both results are comparable to the first part of the study.

In case, of light braking the mean minimum deceleration, as illustrated in Figure 6.5c, was $\mathrm{M}(\min(a_x)) = -1.12\,\mathrm{m\,s^{-2}}$ with a standard error of $\mathrm{SE}(\min(a_x)) = 0.07\,\mathrm{m\,s^{-2}}$. In case of hard braking the mean minimum deceleration was $\mathrm{M}(\min(a_x)) = -1.87\,\mathrm{m\,s^{-2}}$ with a standard error of $\mathrm{SE}(\min(a_x)) = 0.04\,\mathrm{m\,s^{-2}}$. Figure 6.5b shows the AV's corresponding velocity and Figure 6.1d the AV's lateral displacement at different factor levels.

The distance to the lane end, at the point the AV and the lag vehicle of adjusted gap was at same height, illustrated in Figure 6.4, shows comparable conditions to the first part of the study (cf. Figure 6.3).

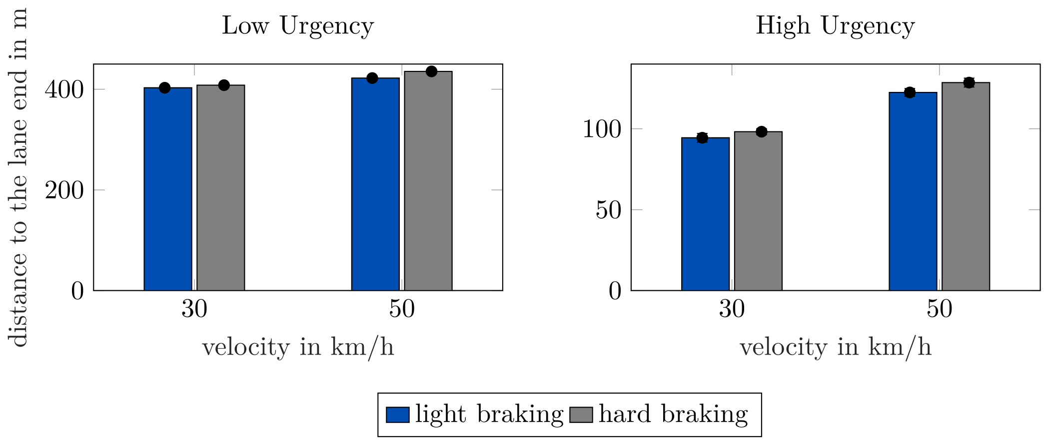
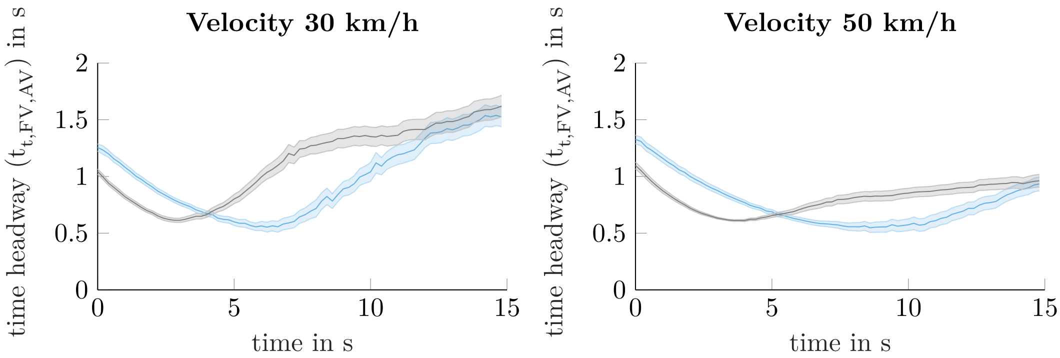
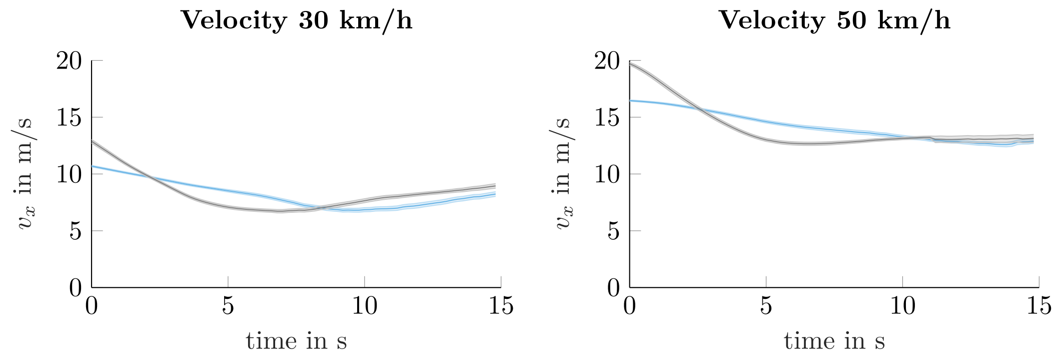


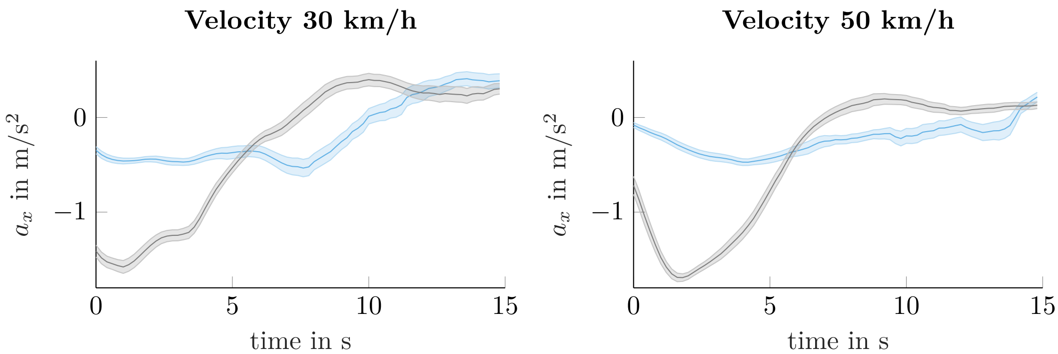
Figure 6.4: Means and errors of the distance to the lane end, when the AV and lag vehicle of adjusted gap were at same height in the second part of the study.



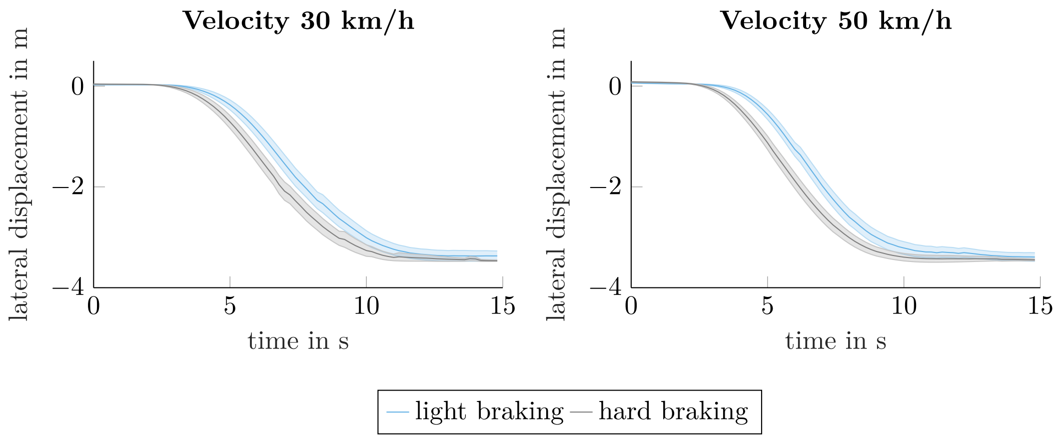
(a) time headway between AV and lead vehicle.



(b) AV's velocity in longitudinal direction.



(c) AV's acceleration in longitudinal direction



(d) AV's lateral displacement

Figure 6.5: Means (centre line) and errors (pale area) in Frenet coordinates over time. At time equal to zero the AV and the lag vehicle of adjusted gap are at same height.

6.2.4 Dependent variables

6.2.4.1 Pre-, post-test

Expectations concerning the AV's driving style at lane changes (pre- and post-test), before and after the study were raised, as given in the appendix B.2.5. Participants were instructed to state their desired AV's driving style from the perspective of the interacting human driver. Driving styles were 'efficient' (AV uses small gaps to enhance overall traffic efficiency), 'cost-reducing' (AV uses small gaps to reduce costs of interaction for the interacting human driver) and 'safe' (AV maintains safety distances to the human driver). These driving styles were assessed for the lane change steps ('start of the lane change', 'execution of the lane change', 'after execution of the lane change'), resulting in 9 items in total, measured on a 7-point rating scale. General expectations due to AV's driving style were also queried, similar to chapter 5.

6.2.4.2 Part I

In the first part of the study metrics were attached at the armatures of the lag vehicle of the adjusted gap as visualized in Figure 6.6.

(a) Part I: Questionaires.

(b) Part II: Button at the steering wheel to start the lane change.

Figure 6.6: Insight of the lag vehicle of the adjusted gap.

The whole questionnaire is represented in the appendix B.2.

Predictability. Measured due the argumentation of section 5.2.4.1 using a comparable subjective measure according to the predictability of AV's driving style only. To assess to which degree the AV's driving style was in accordance with the participants' expectations, participants were asked after each manoeuvre when they would have expected the AV to change lanes. A seven-point semantic differential was used, ranging from -3 ('earlier') via 0 ('just right') to 3 ('later'). To record objective data, the participants had to press a button at the time they expected the lane change. The analysis is done by the time difference the trigger is set and the actual start.

Cooperation. Cooperation was measured for consistency in the questionnaire in difference to the previous study (cf. 5.2.4.1) with a semantic differential from ‘not cooperative’ to ‘very cooperative’ and not with a rating scale.

Acceptance. The acceptance scale (Van Der Laan et al., 1997), in the German version (Kondzior, 1997), was used to assess acceptance of the AV’s driving style. The scale contains 9 Items on a 5-point semantic differential, resulting in a usefulness and satisfying score.

Criticality. Automated driving promises the avoidance of accidents and therefore enhanced safety on public roads (Maurer et al., 2015). To avoid those, criticality of the AV’s driving style needs to be evaluated. Subjective criticality was measured using the 10-point Scale by Neukum and Krüger (2003). It is a uni-dimensional scale that uses five verbal labels as anchoring points (‘imperceptible’ to ‘uncontrollable’).

Delay. To measure how strongly participants felt delayed by the AV, a questionnaire item of Zimmermann et al. (2014a) was used. Participants stated their opinion after each manoeuvre on a five-point semantic differential ranging from ‘delaying’ to ‘time-saving’. The objective measure was the time difference the AV was at the same height as the participants’ vehicle and the actual lane change.

Disturbance. Disturbance was measured using an item from Zimmermann et al. (2014a) as well. Participants stated their opinion after each manoeuvre on a 5-point semantic differential ranging from ‘disruptive’ to ‘helpful’.

The subjective metrics were attached at the armatures of the lag vehicle of the adjusted gap as visualized in Figure 6.6a. Moreover, the participants had the possibility to leave their impression of the influence of the urgency and the velocity of the lead vehicle of the adjusted gap to the time headway the AV should start its lane change after the first part of the study was completed.

6.2.4.3 Part II

The second part of the study focused on gaining objective data describing the participants’ reaction in relation to the experimental factors until the participants’ released the AV’s lane change, by pressing a button at the steering wheel, illustrated in Figure 6.6b, driving the lag vehicle of the adjusted gap. In order to derive and verify the starting conditions of the lane change evaluated in the first part of the study the time headway at the AV’s start of the lane change and the time span between the AV and the lag vehicle of the adjusted gap was at same height and the start of the lane change is displayed. Moreover, the participants reaction is analysed and the participants were asked to evaluated their own cooperativeness after each manoeuvre. The whole questionnaire is given in the appendix B.2.2. To analyse objective cooperation values are introduced in section 5.2.4.1. At the end of the second part of the study participants had the possibility to state their criteria to start the AV's lane change and had to give their opinion about the influence of the independent variables braking and urgency on the start of the lane change. Moreover, the participants had the possibility to leave improvement suggestions pertaining the AV's driving style.

6.2.5 Sample

The study was carried out with N = 39 participants (five female). The participants were recruited from research and development departments of automated driving and driver assistance systems of the Audi AG. They were on average 31.9 Years old (SD = 9.69) and had their driver's licence on average since 13.8 years (SD = 6.5). Their median driven mileage per week was 300 km. 37 participants had a technical profession and all participants were working at a development department for automated driving since M = 4.8 years (SD = 3.7), with a working experience between a minimum of 0.5 and a maximum of 16 years. The participants drove 48 % on highways, 28 % on country roads and 24 % in cities. All participants were experienced with Adaptive Cruise Control and 26 with the Lane Assist (LA). The participant stated to use those systems in everyday life as illustrated in Table 6.4. Only 2 participants never participated in test drives of Level 2 and 3 AVs (definition

	never	seldom	occasionally	often	always
Adaptive Cruise Control (N = 39)	-	7.7%	33.3%	36.0%	23.1%
LA (N = 26)	2%	8%	11%	8%	7%

Table 6.4: Relative frequency of usage of Adaptive Cruise Control and Lane Assist.

cf. section 2.2), 9 participated every half year, 5 participated less than every half year, 2 between every two and three month, 4 once a month and 12 even more often than once a month. Furthermore, participants rated themselves on the respective scale of the Prosocial Scale and Aggressive Driving Inventory Harris et al. (2014) as prosocial drivers (M = 4.65, SD = 0.63).

6.2.6 Data preparation and statistical analysis

In the first part of the study no objective data could be recorded for three participants. Thus, the analysis of the objective measures is done with 36 participants only. In the second part of the study for one participant no data could be collected and therefore here the analysis is done with 38 participants only. To replace missing information in the collected data, due to recording malfunction during the study, Expectation Maximization analysis is used (Little and Rubin, 2019, p.187-188). The premise for the method is that MCAR-test according to Little does not lead to significant findings, which implies that the missing values accrue randomly. Moreover, 20 of 432 in the objective predictability measures were replaced by Expectation Maximization analysis.

The surveyed evaluations via rating scale are equidistant and therefore are assumed as interval scaled variables (Döring and Bortz, 2016, p.244-245). Moreover, normal distribution of the data is assumed, because of sample sizes N $>$ 30 (Bortz and Schuster, 2010, p.87). In case of more than two factor stages of a independent variable Mauchly's test for spherity is performed and if its violated, the Greenhouse-Geisser corrected values are reported. In the statistical analysis values for univariate and multivariate tests (Pillai's trace) are reported and a statistical significance level of $\alpha = .05$ is applied if not stated otherwise.

6.3 Results

6.3.1 Pre- and post-test

To analyse the pre- and post-tests a two factorial repeated measures ANOVA for each lane change phase is executed with the within factors 'time of measurement' (pre- vs. post-test) and 'driving style' ('cost-reducing' vs. 'efficient' vs. 'safety'). Results are illustrated in Figure 6.7. Multivariate tests at the 'start of lane change' shows significant findings for 'driving style' ($F(2, 37) = 16.261$, $p < .001$, $\eta_p^2 = .468$). Post-hoc tests with Bonferroni-correction yields significant results for all comparisons between the respective factor levels ('cost-reducing', 'efficient', and 'safe'). The main effect of the factor 'time of measurement' was not significant ($F(2, 37) < 1$). The disordinal significant interaction between the 'driving style' and the 'time of measurement' ($F(2, 37) = 5.643$, $p = .007$, $\eta_p^2 = .234$) indicates that the driving style 'efficient' and 'cost-reducing' are preferred, especially after participants experienced the different AV's driving styles; in contrast ratings of approval for 'safety' decrease afterwards. At the phase 'execution of the lane change' no significant results were found (all $ps > .064$). At the phase 'after execution of the lane change' there is a significant main effect of 'driving style' ($F(2, 37) = 27.755$, $p < .001$, $\eta_p^2 = .600$), indicating that participants prefer the strategies

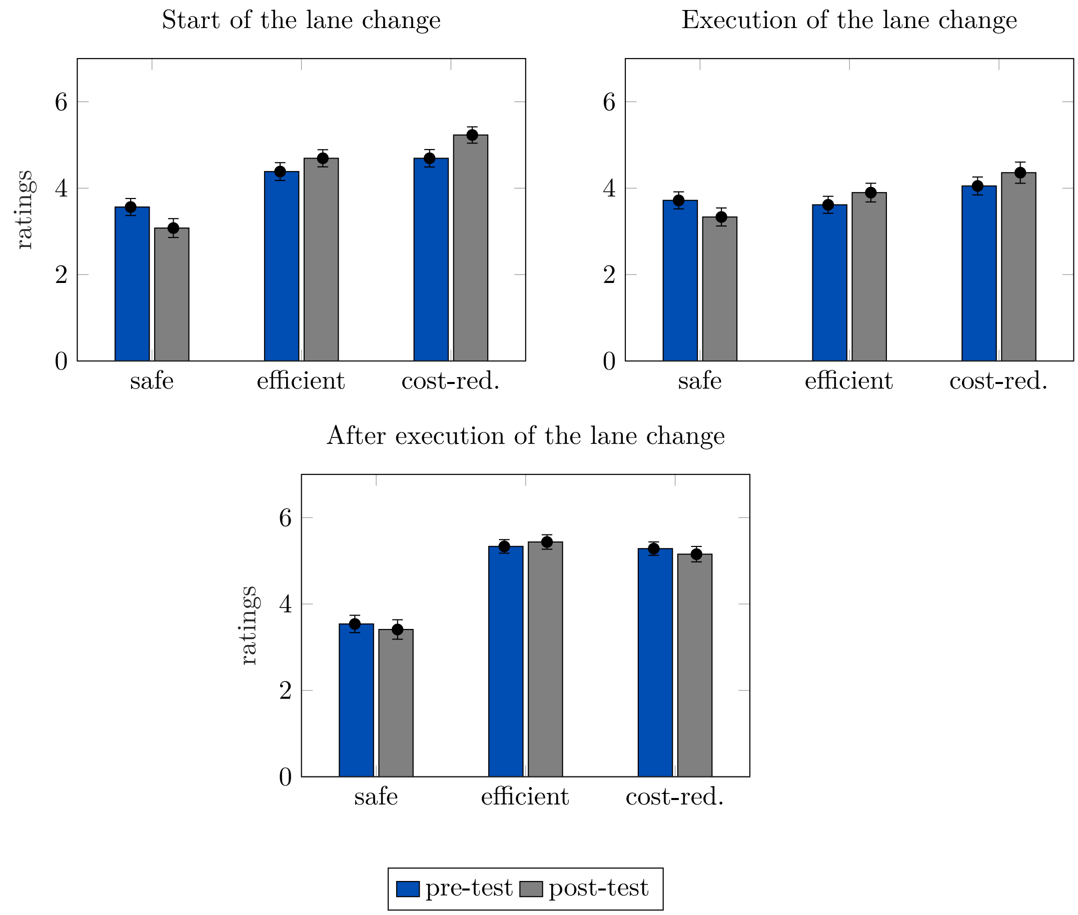


Figure 6.7: Means and errors of the pre- and post-test questionnaire at the phases start of the lane change, execution of the lane change, and after execution of the lane change from [1 to 7].

'efficient' and 'cost-reducing' over 'safety'. The 'time of measurement' ($F(1, 38) < 1$) is not significant.

6.3.2 Part I: Standardized tests

6.3.2.1 Predictability

The surveyed *predictability* is provided in Figure 6.8. A three-way ANOVA for repeated measure design is conducted (Table 6.5). All three main effects are significant: velocity, urgency, and start. Using a post-hoc analysis with Bonferroni-correction (α) shows significant results between all factor stages of the start condition: 0.4 s and 0.6 s ($\Delta M_{0.4,0.6} = 0.673$, SE = .096, $p < .001$), between 0.6 s and 0.9 s ($\Delta M_{0.6,0.9} = 0.756$, SE = 0.097, $p < .001$) and between 0.4 s and 0.9 s ($\Delta M_{0.4,0.9} = 1.429$, SE = 0.83, $p < .001$).

The interaction illustrates at velocities of $50\,\mathrm{km\,h^{-1}}$ and high urgency that the lane change is expected earlier than at low urgency. Also by considering Bonferroni-correction ($\alpha/2$) this difference is significant ($\Delta M_{IU,HU} = 0.632$, SE $= 1.07$, $p < .001$). At $30\,\mathrm{km\,h^{-1}}$ the difference between high and low urgency is not significant ($\Delta M_{IU,HU} = 0.162$, SE $= 0.116$, $p = .170$), but shows descriptive the same influence.

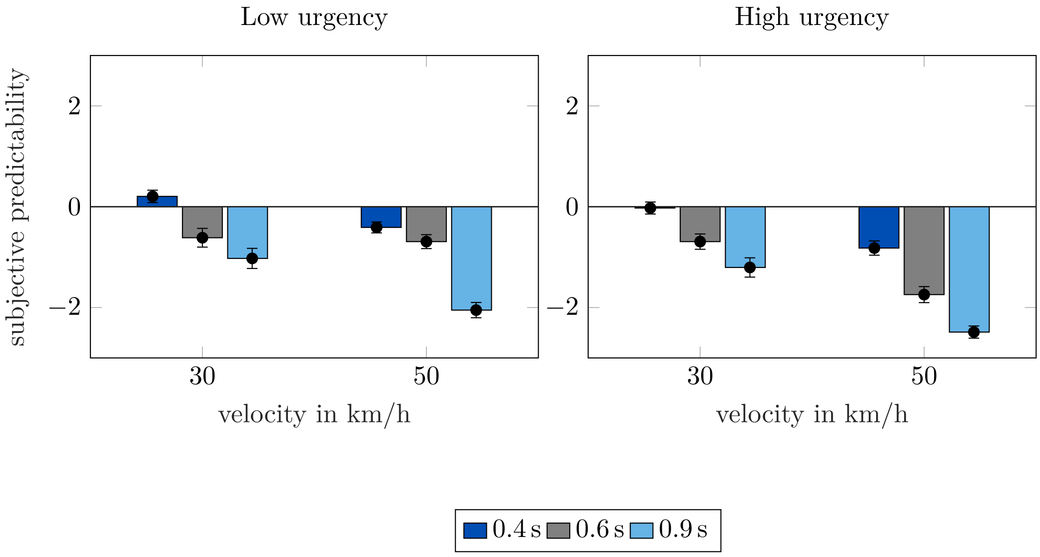


Figure 6.8: Means and errors of subjective *predictability* ratings (perceived time difference the participants expected the AV to change lanes to the actual lane change) from [-3 'earlier' to 3 'later'].

Independent variable	F	p	η_p^2
Velocity	$F(1, 38) = 84.67$	$< .001$	.69
Urgency	$F(1, 38) = 25.29$	$< .001$	.40
$t_{r,AV,LA}$	$F(2, 37) = 145.73$	$< .001$	.89
Velocity * urgency	$F(1, 38) = 8.84$	.005	.19
Velocity * $t_{r,AV,LA}$ (Greenhouse-Geisser)	$F(1.665, 63.281) = 3.86$	.033	.09
Urgency * $t_{r,AV,LA}$	$F(2, 37) = 0.92$	.408	.05
Velocity * urgency * $t_{r,AV,LA}$	$F(2, 37) = 2.25$	.120	.11

Table 6.5: Results of the ANOVA (2 (velocity) x 2 (urgency) x 3 (start $t_{r,AV,LA}$)) for the surveyed *predictability*.

The objective *predictability* is exhibited in Figure 6.9. A three-way ANOVA for repeated measure design is conducted (Table 6.6). The ANOVA yields significant findings for the main effects velocity and start condition. The main effect for urgency of the lane change is not significant. Using a post-hoc analysis with Bonferroni-correction shows significant results between all factor stages of the start condition: 0.4 s and 0.6 s ($\Delta M_{0.4,0.6} = 1.037$, SE $= .121$, $p < .001$), between 0.6 s and 0.9 s ($\Delta M_{0.6,0.9} = 1.196$, SE $= 0.147$, $p < .001$) and between 0.4 s and 0.9 s ($\Delta M_{0.4,0.9} = 2.233$, SE $= 0.82$, $p < .001$).

The analysis shows a dis-ordinal significant interaction between urgency and start condition. The results show that at low urgency and a start condition of 0.9 s a later lane change is expected, than at high urgency. Considering Bonferroni-correction ($\alpha/2$) this difference is not significant ($\Delta M_{\text{lU,HU}} = 0.308$, SE = .109, $p = .060$). However, at the start condition 0.4 s the results are pointing into the opposite direction. At high urgency participants expect the AV to change lanes later than at low urgency. Here, the difference after Bonferroni-correction ($\alpha/2$) is significant ($\Delta M_{\text{lU,HU}} = 0.321$, SE = .120, $p = .011$).

The ordinal interaction between velocity and start condition shows that at velocity of 50 km h^{-1}, especially for start condition 0.9 s an earlier lane change is expected than at 30 km h^{-1}. This difference is also with Bonferroni- correction ($\alpha/2$) significant ($\Delta M_{30,50} = 1.428$, SE = .195, $p < .001$).

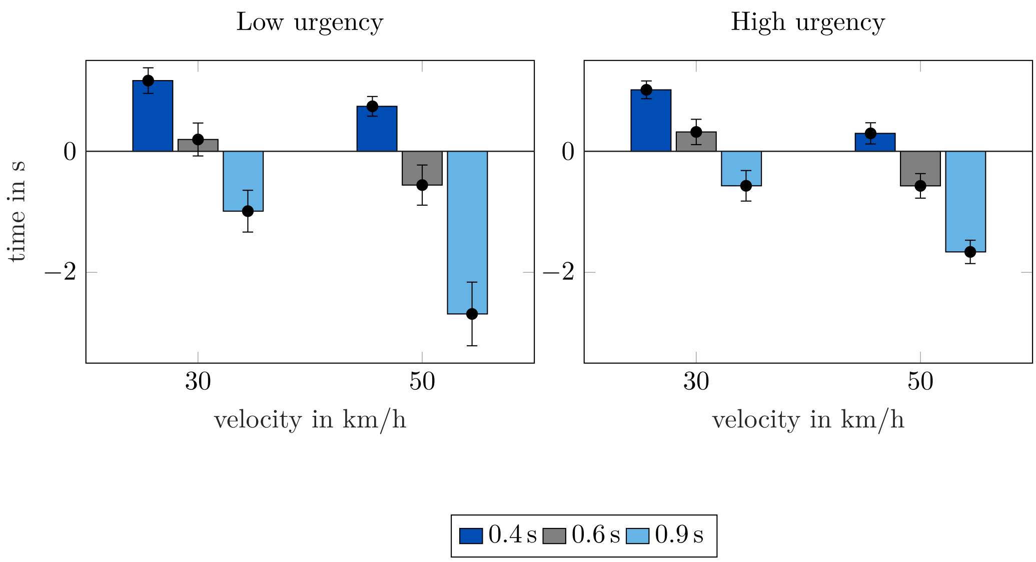


Figure 6.9: Means and errors of objective *predictability* ratings (time difference between expected time to change lanes and the actual lane change).

In subjective and objective measure the smallest start condition is the best predictable. Thus, hypothesis H1.1 can be confirmed. In the subjective measure especially, at 50 km h^{-1} and high urgency an earlier lane change is expected. The results of the objective measure are not that clear. Those results show that at high urgency and at higher velocity a much earlier lane change is expected than at slow velocities, what confirms the subjective measure. Thus, hypothesis H2.1 is accepted. At low urgency the start of the lane change is expected earlier. Thus, hypotheses H3.1 is accepted based on the subjective measure.

Independent variable	F	p	η_p^2
Velocity	$F(1,38) = 8.84$	$< .001$	.67
Urgency	$F(1,38) = 1.149$	.291	.029
$t_{r,AV,LA}$	$F(2,37) = 74.744$	$< .001$	.802
Velocity * urgency	$F(1,38) = 0.32$	.574	.01
Velocity * $t_{r,AV,LA}$	$F(2,37) = 5.180$	.010	.219
Urgency * $t_{r,AV,LA}$	$F(2,37) = 5.851$	.010	.219
Velocity * urgency * $t_{r,AV,LA}$	$F(2,37) = 2.05$	.144	.10

Table 6.6: Results of the ANOVA (2 (velocity) x 2 (urgency) x 3 (start $t_{r,AV,LA}$)) of the objective *predictability* measure.

6.3.2.2 Cooperation

The participants' ratings of their own *cooperation* of every manoeuvre is illustrated in Figure 6.10. A three-way ANOVA for repeated measure design is conducted for the subjective

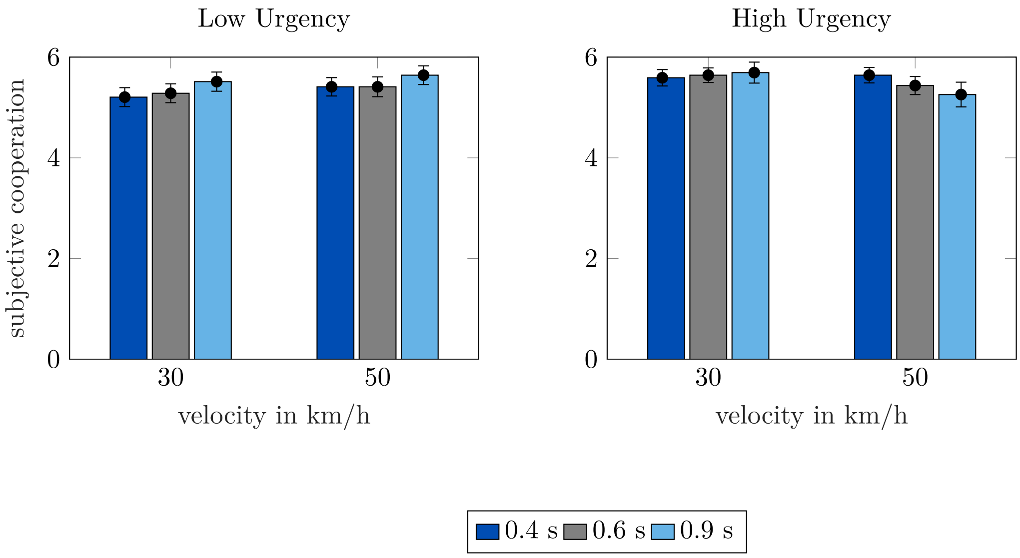


Figure 6.10: Means and errors of subjective *cooperative* ratings from [1 'not cooperative' to 7 'very cooperative'].

measurement of the *cooperation* with no significant results (cf. Table 6.7). However, the analysis clarifies that the participants were rating themselves as very cooperative (M = 5.48, SE = 0.19).

6.3.2.3 Acceptance

The evaluated *acceptance* of the AV's driving style to change lanes from interacting human drivers' perspective is illustrated in Figure 6.11. A three-way MANOVA for repeated measure

Independent variable	F	p	η_p^2
Velocity	$F(1,38) = .069$	.794	.02
Urgency	$F(1,38) = 2.46$	.125	.061
$t_{r,AV,LA}$	$F(2,37) = .301$	$< .742$	.016
Velocity * urgency	$F(1,38) = 4.03$	.052	.10
Velocity * $t_{r,AV,LA}$	$F(2,37) = 1.09$	.347	.06
Urgency * $t_{r,AV,LA}$ (Greenhouse-Geisser)	$F(1.542, 58.592) = 4.04$	.052	.10
Velocity * urgency * $t_{r,AV,LA}$	$F(2,37) = .57$	.570	.03

Table 6.7: Results of the ANOVA (2 (velocity) x 2 (urgency) x 3 (start $t_{r,AV,LA}$)) of the subjective rating of the participants' own *cooperation*.

design is conducted (Table 6.8). The main effects velocity and start show significant results. The main effect urgency has marginally significant influence. At the univariate measure

Independent variable	F	p	η_p^2
Velocity	$F(2,37) = 17.48$	$< .001$	.49
Urgency	$F(2,37) = 3.16$	.054	.15
$t_{r,AV,LA}$	$F(4,35) = 19.61$	$< .001$	.69
Velocity * urgency	$F(2,37) = 19.61$	$< .001$	.34
Velocity * $t_{r,AV,LA}$	$F(4,35) = 3.60$	.015	.291
Urgency * $t_{r,AV,LA}$	$F(4,35) = 0.64$	.638	.068
Velocity * urgency * $t_{r,AV,LA}$	$F(4,35) = 3.20$	.024	.27

Table 6.8: Results of the MANOVA (2 (velocity) x 2 (urgency) x 3 (start $t_{r,AV,LA}$)) of the subjective *acceptance* scales satisfying and usefulness.

after Bonferroni-correction ($\alpha/2$), all main factors have significant influence on both scales: velocity (satisfying: $F(1,38) = 7.98$, $p = .001$, $\eta_p^2 = .27$, usefulness: $F(1,38) = 10.29$, $p < .001$, $\eta_p^2 = .44$), urgency (satisfying: $F(1,38) = 3.64$, $p = .023$, $\eta_p^2 = .128$, usefulness: $F(1,38) = 6.25$, $p = .017$, $\eta_p^2 = .141$) and start (satisfying Greenhouse-Geisser: $F(1.84, 64.89) = 21.61$, $p < .001$, $\eta_p^2 = .413$, usefulness: $F(2,37) = 31.85$, $p < .001$, $\eta_p^2 = .63$). Using a post-hoc analysis with a repeated Bonferroni-correction ($\alpha/2$) shows significant results between the factor stages of the start condition: between 0.4 s and 0.9 s (satisfying: $\Delta M_{0.4,0.9} = 0.819$, SE = 0.136, $p < .001$; usefulness $\Delta M_{0.4,0.9} = 0.701$, SE = 0.087, $p < .001$) and between 0.6 s and 0.9 s (satisfying: $\Delta M_{0.6,0.9} = .564$, SE = 0.108, $p < .001$; usefulness $\Delta M_{0.6,0.9} = 0.471$, SE = 0.083, $p < .001$). The difference between 0.4 s and 0.6 s on the scale satisfying is also significant ($\Delta M_{0.4,0.6} = 0.255$, SE = 0.097, $p = .004$). But the differences on the usefulness scale do not lead to significant findings ($\Delta M_{0.4,0.6} = 0.255$, SE = 0.097, $p = .037$).

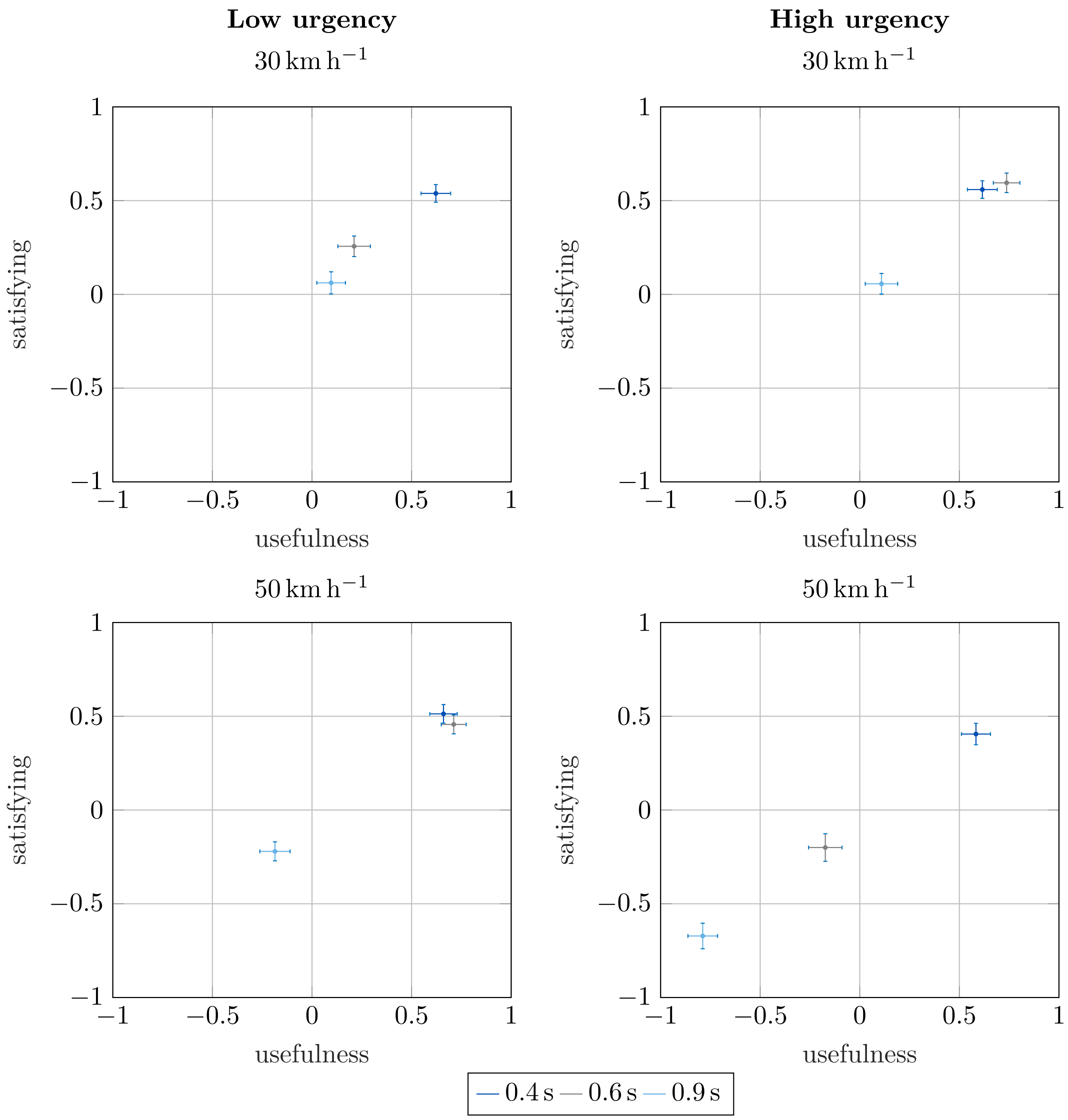


Figure 6.11: Means and errors of the two scales *usefulness* and *satisfying* measured to evaluate acceptance from [-2 to 2].

The significant ordinal interaction between velocity, start, and urgency points out that especially at a velocity of $50\,\mathrm{km\,h^{-1}}$, the start condition of 0.9 s is not accepted. This effect is larger at high urgency of the manoeuvre. At high urgency the start condition of 0.6 s at $30\,\mathrm{km\,h^{-1}}$ is still accepted. But the evaluations decreases at $50\,\mathrm{km\,h^{-1}}$. However, at low urgency the start condition of 0.6 s is better accepted. The start condition of 0.4 s is highly accepted under all study conditions, what confirms hypothesis H1.5. Especially, under high urgency the acceptance is decreasing for a larger time headway as start condition. This confirms hypothesis H3.5. Since, a start condition of 0.6 s at small velocities is better accepted than at fast velocities. Hypothesis H2.5 is also accepted.

Cronbach's α validates the quality of the questionnaire in the used setting. The scale satisfying has a high degree on reliability (Cronbach's $\alpha = .93$), since the items are highly correlating with each other $r > .71$. The scale usefulness has a slightly smaller reliability (Cronbach's $\alpha = .82$). On this scale, except the item activating ($r \leq -.09$), all other items are highly correlating ($r > .69$). Thus, the item activating influences the intern consistency of the scale negatively. Consequently, the reliability of the scale usefulness increases if the item activating is neglected (Cronbach's $\alpha = .91$). In order to analyse the structure of the questionnaire an exploratory factorial analysis is performed. The Bartlett-Test ($\chi^2(36) = 3831.63$, $p < .001$) as well as the Kaiser-Meyer-Olkin Measure of Sampling Adequacy (KMO = .94), suggest that the scales can be used for a factorial analysis with two factors. However, all items, except the item activating are loading on one factor ($r > .82$). Also in a study of Zoellick et al. (2019), assessing the acceptance of passengers of a automated shuttle, the item-scale showed a high reliability except the item activating. As the item is also hard to relate to the assessment of driving style of interacting human drivers, the item is neglected in future studies. Without this item, the two-factor structure of the acceptance scale (Van Der Laan et al., 1997) could not be replicated, which also failed in the previous mentioned study of Zoellick et al. (2019) and in studies of Hartwich et al. (2018) and Beggiato et al. (2015). Thus, there are also arguments to use one scale in order to analyse the raised acceptance only.

6.3.2.4 Criticality

Criticality ratings are illustrated in Figure 6.12. A three-way ANOVA for repeated measure design is conducted (Table 6.9). All main effects are significant: velocity, urgency, and start condition. Using a post-hoc analysis with a repeated Bonferroni-correction (α) shows significant results between the factor stages of the start condition: between 0.4 s and 0.9 s ($\Delta\mathrm{M}_{0.4,0.9} = -0.724$, SE $= 0.236$, $p = 0.012$) and between 0.6 s and 0.9 s ($\Delta\mathrm{M}_{0.6,0.9} = -0.481$, SE $= 0.161$, $p = .015$). The difference between 0.4 s and 0.6 s is not significant ($\Delta\mathrm{M}_{0.4,0.6} = -0.244$, SE $= 0.190$, $p = .620$).

The dis-ordinal interaction between the factors velocity and urgency, considering Bonferroni-

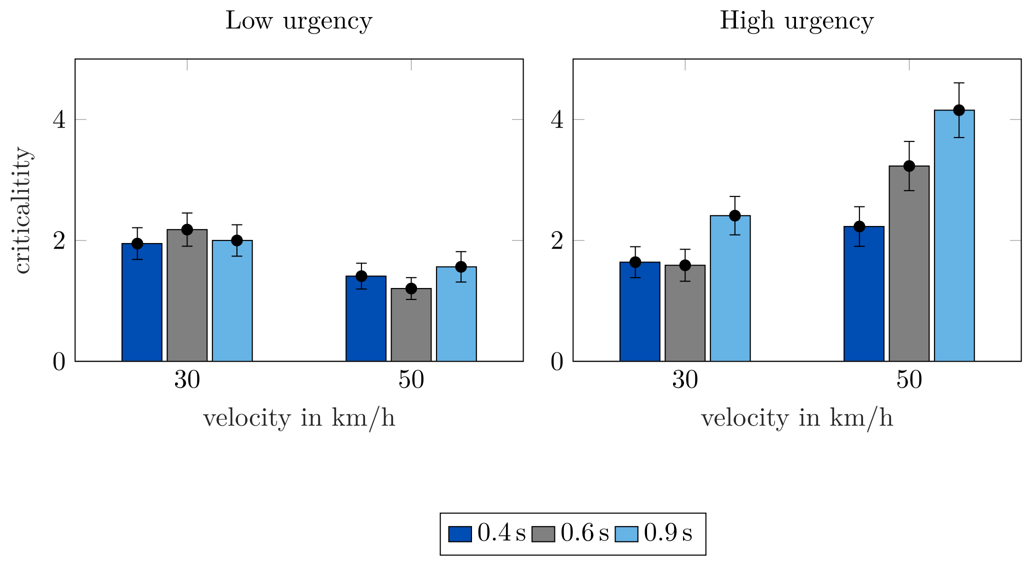


Figure 6.12: Means and errors of *criticality* ratings from [0 to 10].

Independent variable	F	p	η_p^2
Velocity	$F(1, 38) = 13.34$	.001	.27
Urgency	$F(1, 38) = 29.51$	$< .001$	.44
$t_{r,AV,LA}$ (Greenhouse-Geisser)	$F(1.67, 63.46) = 6.94$	.003	.15
Velocity * urgency	$F(2, 37) = 49.58$	< 001	.57
Velocity * $t_{r,AV,LA}$	$F(2, 37) = 2.93$	.066	.14
Urgency * $t_{r,AV,LA}$ (Greenhouse-Geisser)	$F(1.62, 61.60) = 19.02$	.002	.18
Velocity * urgency * $t_{r,AV,LA}$	$F(2, 37) = 2.41$	.104	.12

Table 6.9: Results of the ANOVA (2 (velocity) x 2 (urgency) x 3 (start $t_{r,AV,LA}$)) of the subjective *criticality*.

correction ($\alpha/2$), shows that at high urgency target velocities of $30\,\mathrm{km\,h^{-1}}$ are rated significantly less critical than at $50\,\mathrm{km\,h^{-1}}$ ($\Delta\mathrm{M}_{30,50} = -1.325$, SE $= 0.190$, $p < .001$). At low urgency the opposite effect is shown ($\Delta\mathrm{M}_{30,50} = 0.650$, SE $= 0.140$, $p < .001$). The difference between high and low urgency is only significant at $50\,\mathrm{km\,h^{-1}}$ ($\Delta\mathrm{M}_{\mathrm{LowU,HighU}} = -1.812$, SE $= 0.211$, $p < .001$) and not at $30\,\mathrm{km\,h^{-1}}$ ($\Delta\mathrm{M}_{\mathrm{LowU,HighU}} = 0.162$, SE $= 0.202$, $p < .427$).

A significant ordinal interaction clarifies that participants asses smaller time headway as less critical, especially hat $50\,\mathrm{km\,h^{-1}}$. Post-hoc simple effects analyses with Bonferroni-correction ($\alpha/2$) show significant differences at $50\,\mathrm{km\,h^{-1}}$ between 0.4 s and 0.9 s ($\Delta M_{0.4,\,0.9} = -1.346$, SE $= 0.289$, $p < .001$) as well as 0.6 s and 0.9 s ($\Delta M_{0.6,\,0.9} = -0.872$, SE $= 0.299$, $p = .018$). The difference between 0.4 s and 0.6 s ($\Delta M_{0.4,\,0.6} = -0.474$, SE $= 0.250$, $p = .196$) is not significant. At $30\,\mathrm{km\,h^{-1}}$ is no difference between the factor levels significant: 0.4 s and 0.6 s ($\Delta M_{0.4,\,0.6} = -0.090$, SE $= 0.224$, $p = 1$), 0.4 s and 0.9 s ($\Delta M_{0.4,\,0.9} = -0.410$, SE $= 0.248$, $p = .318$) and between 0.6 s and 0.9 s ($\Delta M_{0.6,\,0.9} = -0.321$, SE $= 0.202$, $p = .365$). The difference between the velocities with Bonferroni-correction ($\alpha/2$) is not significant for the start conditions 0.4 s ($\Delta M_{30,\,50} = -0.026$, SE $= 0.173$, $p = .196$) and 0.6 s ($\Delta M_{30,\,50} = -0.333$, SE $= 0.172$, $p = .060$). Only the difference between the velocities at the start condition 0.9 s ($\Delta M_{30,\,50} = -0.654$, SE $= 0.208$, $p = .003$) is significant.

The start condition 0.4 s is rated less critical than 0.9 s, especially at $50\,\mathrm{km\,h^{-1}}$ and high urgency. Thus, hypothesis H1.2 is neglected. At low urgency AV's driving styles at higher velocity are rated with lower criticality, but at high urgency the opposite effect is found. AV's driving styles at $50\,\mathrm{km\,h^{-1}}$ are rated with higher criticality as expected before conducting the study. Therefore, hypothesis H2.2 cannot be accepted. AV's driving styles at high urgency are rated at $50\,\mathrm{km\,h^{-1}}$ as more significant more critical, while at $30\,\mathrm{km\,h^{-1}}$ no significant difference is found. Thus, hypothesis H3.2 is accepted based on the results at $50\,\mathrm{km\,h^{-1}}$ only.

6.3.2.5 Delay

The subjective *delay* measure is illustrated in Figure 6.13. A three-way ANOVA for repeated measure design is conducted (Table 6.10). All main effects are significant: velocity, urgency and start condition. Using a post-hoc analysis with Bonferroni-correction ($\alpha/2$) shows significant results between the factor stages of the start condition: 0.4 s and 0.6 s ($\Delta\mathrm{M}_{0.4,0.6} = -0.269$, SE $= .100$, $p = .032$), between 0.6 s and 0.9 s ($\Delta\mathrm{M}_{0.6,0.9} = -0.622$, SE $= 0.116$, $p < .001$) and between 0.4 s and 0.9 s ($\Delta\mathrm{M}_{0.4,0.9} = -.891$, SE $= 0.119$, $p < .001$).

The significant interaction between velocity, urgency, and start condition, can be interpreted by taking a look at Figure 6.13. At high urgency participants rate the start condition 0.6 s at $30\,\mathrm{km\,h^{-1}}$ less delaying than at $50\,\mathrm{km\,h^{-1}}$. At $30\,\mathrm{km\,h^{-1}}$ 0.6 s is rated even less delaying

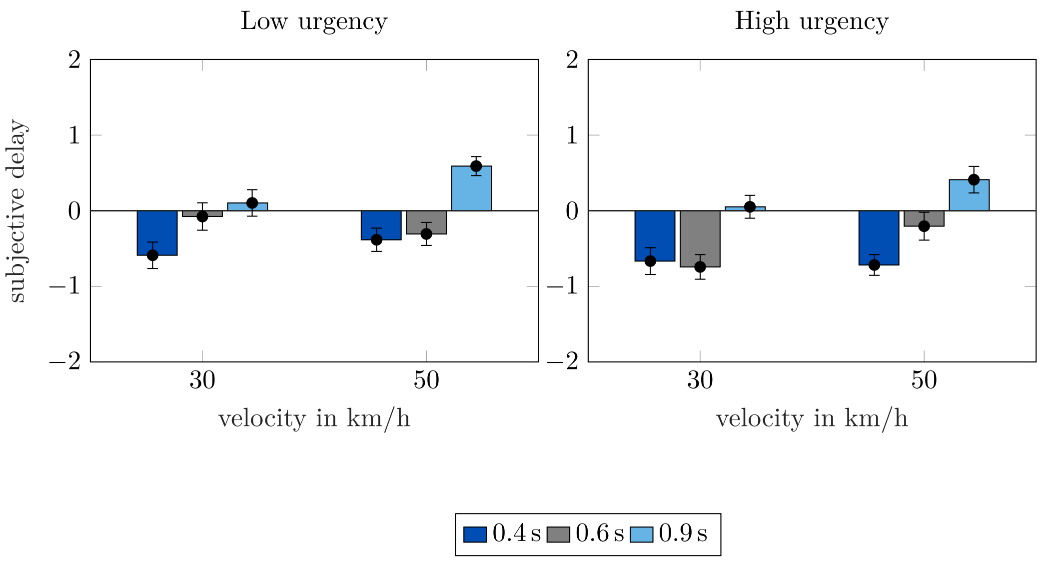


Figure 6.13: Means and errors rating of the surveyed *delay* from [-2 'time-saving' to 2 'delaying'].

Independent variable	F	p	η_p^2
Velocity	$F(1,38) = 5.58$	.023	.13
Urgency	$F(1,38) = 5.53$	.024	.13
$t_{r,AV,LA}$	$F(2,37) = 27.42$	$< .001$	.60
Velocity * urgency	$F(1,38) = 0.54$	.467	.01
Velocity * $t_{r,AV,LA}$	$F(2,37) = 1.51$	.233	.08
Urgency * $t_{r,AV,LA}$	$F(2,37) = 0.33$	.724	.02
Velocity * urgency * $t_{r,AV,LA}$	$F(2,37) = 3.91$	.029	.18

Table 6.10: Results of the ANOVA (2 (velocity) x 2 (urgency) x 3 (start $t_{r,AV,LA}$)) of the subjective *delay*.

than 0.4 s. For all other variations the 0.4 s is rated least and 0.9 s is rated most delaying. At low urgency the start condition 0.6 s is rated in the opposite direction than at high urgency, target velocities of 50 km h^{-1} are rated less delaying than at 30 km h^{-1}.

The objective *delay* measure is illustrated in Figure 6.14. A three-way ANOVA for repeated

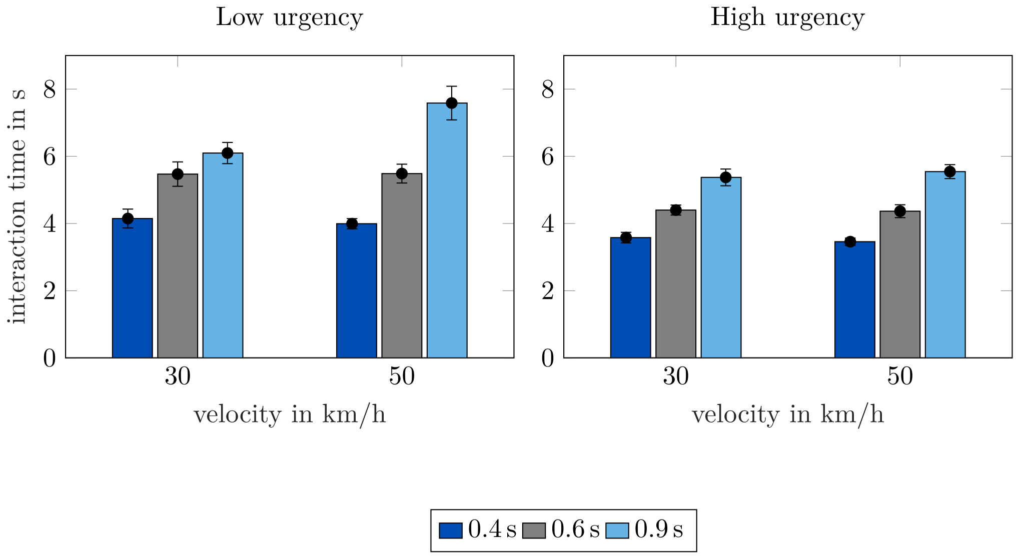


Figure 6.14: Means and errors of the objective measured *interaction time* (time difference between the actual lane change and the time the AV and the participant's vehicle are at same height.)

measure design is conducted (Table 6.11). The analysis shows significant results for the main

Independent variable	F	p	η_p^2
Velocity	$F(1,35) = 0.79$	.381	.02
Urgency	$F(1,35) = 23.22$	$< .001$	.40
$t_{r,AV,LA}$ (Greenhouse-Geisser)	$F(1.583, 53.821) = 78.52$	$< .001$	.69
Velocity * urgency	$F(1,35) = 2.86$	.100	.08
Velocity * $t_{r,AV,LA}$	$F(2,34) = 4.89$	.014	.22
Urgency * $t_{r,AV,LA}$ (Greenhouse-Geisser)	$F(1.896, 66.359) = 5.46$	.007	.14
Velocity * urgency * $t_{r,AV,LA}$	$F(2,34) = 3.71$	.035	.18

Table 6.11: Results of the ANOVA (2 (velocity) x 2 (urgency) x 3 (start $t_{r,AV,LA}$)) of the *interaction time.*

effects urgency and the start condition. The influence of velocity is not significant. Using a post-hoc analysis with Bonferroni-correction ($\alpha/2$) shows significant results between the factor stages of the start condition: between 0.4 s and 0.6 s ($\Delta M_{0.4,0.6} = -1.191$, SE = .133, $p < .001$), between 0.6 s and 0.9 s ($\Delta M_{0.6,0.9} = -1.229$, SE = 0.204, $p < .001$) and between 0.4 s and 0.9 s ($\Delta M_{0.4,0.9} = -2.417$, SE = 0.229, $p < .001$).

The significant interaction between velocity, urgency, and start condition can be interpreted by taking a look at Figure 6.14. Smaller time headway as start condition lead to an earlier start of the lane change. In difference to the subjective measure, in which one exception occurred at the objective measure at all variations. Thus, hypothesis H1.3 can be confirmed based on the objective and subjective measure. The start of the AV's lane change at high urgency takes less time than at low urgency, similar to the subjective measure, what leads to accept hypothesis H3.3. Since, the main factor velocity is not significant in the objective measure and shows different direction at the subjective measure, hypothesis H2.3 is neglected.

6.3.2.6 Disturbance

The results of the subjective *disturbance* measure are illustrated in Figure 6.15. A three-

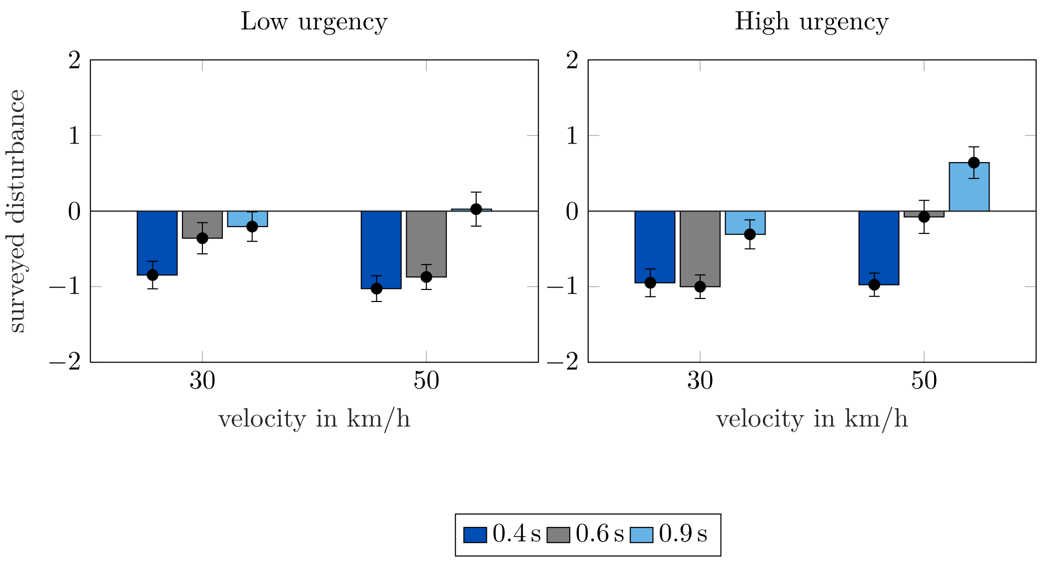


Figure 6.15: Means and errors of the surveyed *disturbance* with the items not disturbing and disturbing from [-2 to 2].

way ANOVA for repeated measure design is conducted (Table 6.12). The analysis shows significant results for the main effects velocity and the start condition. The influence of urgency is not significant. Using a post-hoc analysis with Bonferroni-correction ($\alpha/2$) shows significant results between the factor stages of the start condition: between 0.4 s and 0.6 s ($\Delta M_{0.4,0.6} = -0.372$, SE = 0.100, $p = .002$), between 0.6 s and 0.9 s ($\Delta M_{0.6,0.9} = -0.615$, SE = 0.127, $p < .001$) and between 0.4 s and 0.9 s ($\Delta M_{0.4,0.9} = -0.937$, SE = 0.142, $p < .001$). Moreover, the analysis demonstrates a significant interaction between velocity, urgency, and start condition. This interaction is analysed descriptive by interpreting Figure 6.15. At $30\,\mathrm{km\,h^{-1}}$ the start condition 0.6 s is rated even less disturbing than the start condition 0.4 s. For all other variations the start condition 0.4 s is rated least and the start condition 0.9 s is rated most disturbing. Therefore, hypothesis H1.3 is accepted. At $50\,\mathrm{km\,h^{-1}}$ the

Independent variable	F	p	η_p^2
Velocity	$F(1,38) = 6.41$	.016	.14
Urgency	$F(1,38) = .84$	.365	.02
$t_{r,AV,LA}$	$F(2,37) = 23.69$	$< .001$	.56
Velocity * urgency	$F(1,38) = 14.88$	$< .001$	.56
Velocity * $t_{r,AV,LA}$	$F(2,37) = 3.96$	.028	.18
Urgency * $t_{r,AV,LA}$	$F(2,37) = 0.69$	.507	.04
Velocity * urgency * $t_{r,AV,LA}$	$F(2,37) = 3.44$	.043	.16

Table 6.12: Results of the ANOVA (2 (velocity) x 2 (urgency) x 3 (start $t_{r,AV,LA}$)) of the surveyed *disturbance* .

start condition 0.4 s is even marginally less disturbing than at 30 km h^{-1}. At the other start conditions 0.6 s and 0.9 s, the AV's driving styles are rated in different direction. AV's driving styles at 30 km h^{-1} are rated less disturbing than at 50 km h^{-1}. This occurs primarily because those start conditions are rated worse at high urgency. AV's driving styles at high urgency and 50 km h^{-1} are less accepted, confirmed by the significant interaction of the factors velocity and urgency. Thus, hypothesises H2.3 and H3.3 are partly accepted.

6.3.3 Part II: Exploratory investigation

6.3.3.1 Time headway

The time headway between the AV and the lag vehicle of the adjusted gap at the start of the AV's lane change is displayed in Figure 6.16. A three factorial ANOVA for repeated measure design (urgency x velocity x braking) (Table 6.13) shows, that the time headway $t_{r,AV,LA}$ differs significantly for the main effect velocity. The main effects urgency and braking are not significant. The ordinal significant interaction between urgency and velocity shows that

Independent variable	$F(1,37)$	p	η_p^2
Velocity	3.85	.057	.10
Urgency	36.63	$< .001$	.50
Braking	1.02	.319	.03
Velocity * urgency	5.27	.028	.16
Velocity * braking	0.01	.941	$< .01$
Urgency * braking	5.16	.029	.122
Velocity * urgency * braking	3.66	.064	.09

Table 6.13: Results of the ANOVA (2 (urgency) x 2 (velocity) x 2 (braking)) of the time headway between the AV and the lag vehicle of the adjusted gap $t_{r,AV,LA}$.

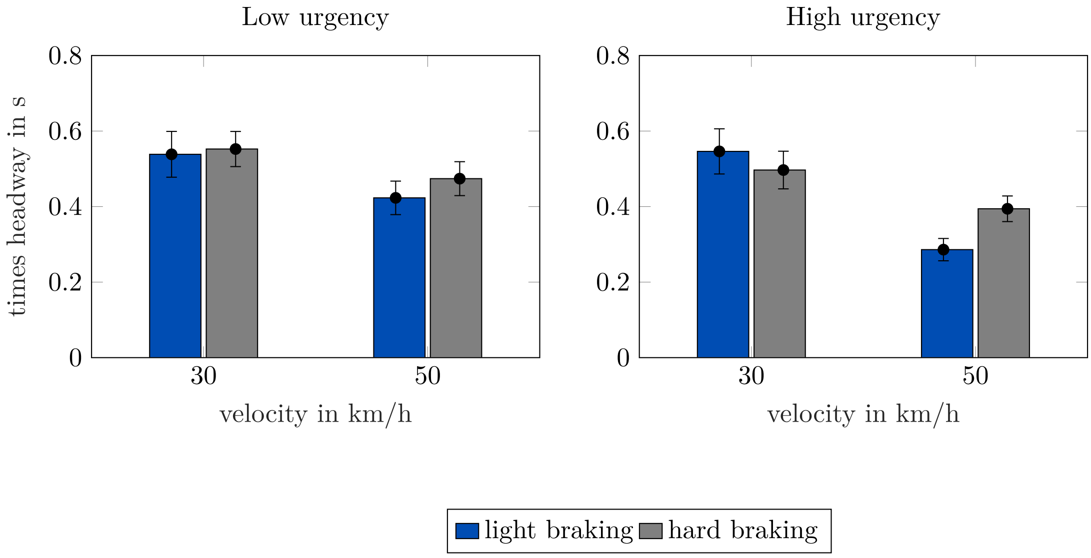


Figure 6.16: Means and errors of the time headway between the AV and the lag vehicle of the adjusted gap $t_{r,AV,LA}$ at the time the participants started the AV's lane change.

the difference between $30\,\mathrm{km\,h^{-1}}$ and $50\,\mathrm{km\,h^{-1}}$ is higher at high urgency ($\Delta M_{30,50} = .118$, $SE = 0.034$, $p < .001$) of the lane change than at low urgency ($\Delta M_{30,50} = 0.097$, $SE = 0.025$, $p < .001$). The ordinal significant interaction between velocity and braking, considering Bonferroni-correction ($\alpha/2$), indicates that at $30\,\mathrm{km\,h^{-1}}$ the AV's driving styles with hard (hB) or light (lB) braking to the adjusted gap have no influence on the preferred time headway at the start of the AV's lane change $t_{r,AV,LA}$ ($\Delta M_{lB,hB} = -0.018$, $SE = 0.046$, $p = .702$). In contrast, at $50\,\mathrm{km\,h^{-1}}$, AV's driving styles with hard braking resulted in a significant higher realized time headway at the start of the AV's lane change $t_{r,AV,LA}$ than AV's driving styles with light braking ($\Delta M_{lB,hB} = -0.080$, $SE = 0.026$, $p = .004$).

6.3.3.2 Delay

The time span between the AV and the lag vehicle of the adjusted gap were at same height and the start of the lane change is illustrated in Figure 6.17. A three-way ANOVA for repeated measure design is conducted (Table 6.14). The ANOVA shows significant results in all main effects: velocity, urgency and braking. At $50\,\mathrm{km\,h^{-1}}$ the lane change is released significantly earlier than at $30\,\mathrm{km\,h^{-1}}$. Moreover, at high urgency the lane change is released significantly earlier than at low urgency and at hard braking the lane change is started significantly earlier than at light braking.

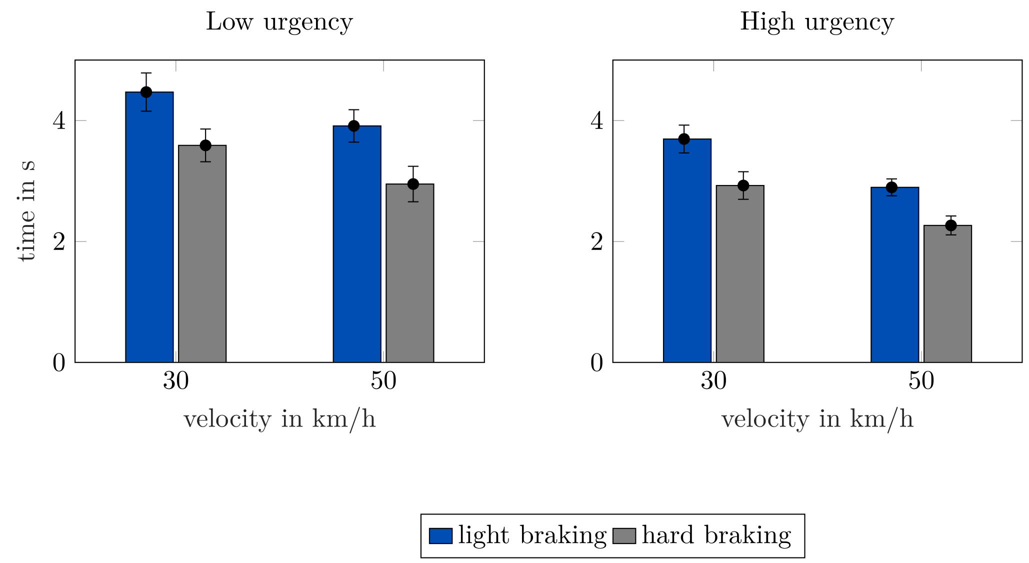


Figure 6.17: Means and errors of the times span between the AV and the lag vehicle of the adjusted gap was at same height and the start of the lane change.

Independent variable	$F(1,37)$	p	η_p^2
Velocity	14.92	$< .001$	.29
Urgency	39.19	$< .001$	.51
Braking	62.49	$< .001$	.63
Velocity * urgency	0.40	.533	.01
Velocity * braking	1.96	.170	.050
Urgency * braking	0.34	.855	$< .01$
Velocity * urgency * braking	0.34	.563	$< .01$

Table 6.14: Results of the ANOVA (2 (urgency) x 2 (velocity) x 2 (braking)) of the times span between the AV and the lag vehicle of the adjusted gap was at same height and the start of the lane change.

6.3.3.3 Participants' driving styles

Descriptive description

The reaction of the participants, Figure 6.18a, illustrate that the time headway between the automated and the lag (participant's vehicle) vehicle was increasing up to a time headway of 2 s. The participants seem to decelerate approx. between 2 s and 3 s after the AV and the lag vehicle was at same height and thereafter seem to decelerate and reduce the velocity very moderately, as illustrated in Figure 6.18b and 6.18c. The time headway shows a degressive profile with a maximum of approx. 2 s between the AV and the lag vehicle of the adjusted gap at all scenario variations and variations of the AV's driving style.

Cooperation

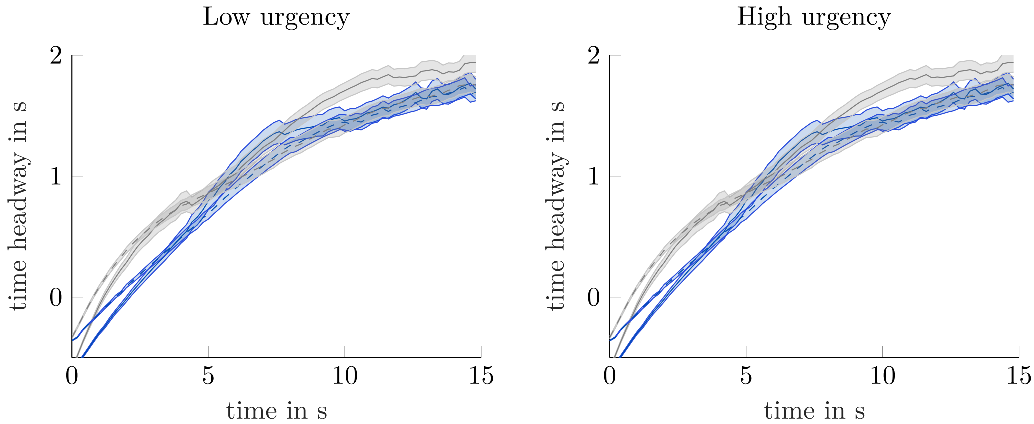
Similar to the first part, also in the second part of study, participants estimated their own driving style as very cooperative (M = 5.48, SE = 0.19), as illustrated in Figure 6.19. A three-factorial ANOVA for repeated measure design is conducted (Table 6.14). The analysis

Independent variable	$F(1,37)$	p	η_p^2
Velocity	5.80	.021	.13
Urgency	3.97	.053	.10
Braking	0.50	.482	.01
Velocity * urgency	0.50	.482	.01
Velocity * braking	0.73	.398	.019
Urgency * braking	0.94	.338	.02
Velocity * urgency * braking	< 0.01	$> .999$	$< .01$

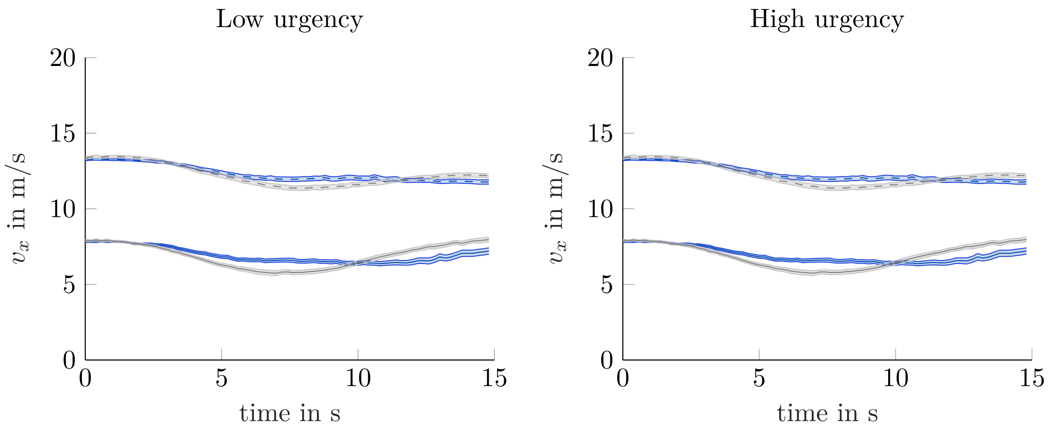
Table 6.15: Results of the ANOVA (2 (urgency) x 2 (velocity) x 2 (braking)) of the surveyed *cooperation*.

shows a significant main effect for the factor velocity. But still the mean difference between the cooperation at difference velocities can be classified as low, showing a slightly higher cooperativeness at faster velocity ($\Delta M_{30,50} = -0.218$, SE = 0.091).

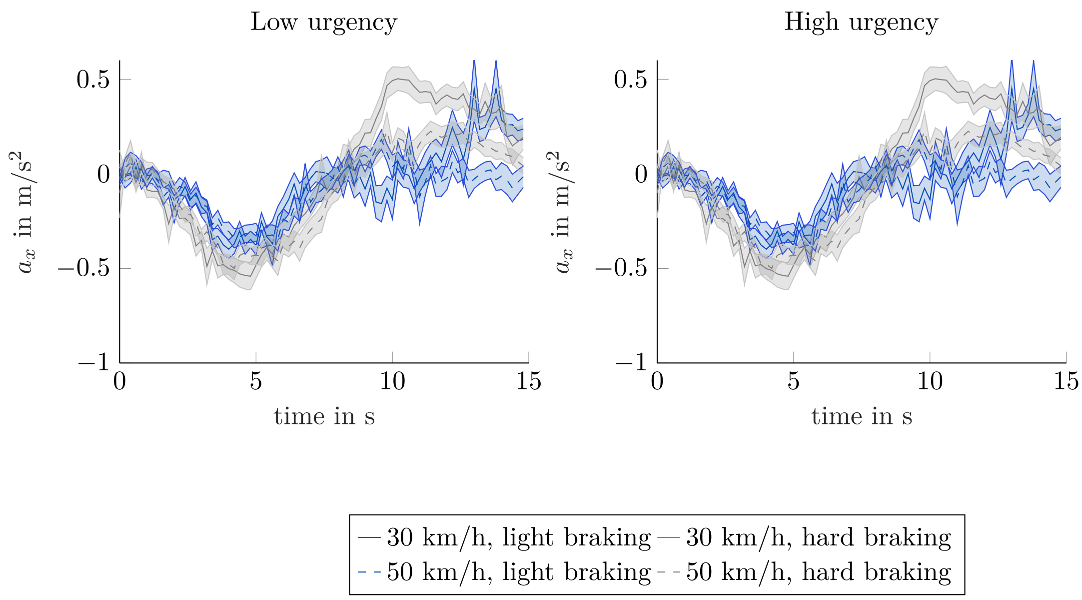
The objective cooperativeness is illustrated in Figure 6.19. A three-factorial ANOVA for repeated measure design is conducted (Table 6.16). The main effect urgency is significant. At high urgency participants react more cooperative than at low urgency.



(a) Means and errors (pale area) of the time headway between the AV and the lag vehicle of the adjusted gap (particpant's vehicle).



(b) Means and errors (pale area) of the velocity in longitudinal direction $\mathrm{v_x}$ of the lag vehicle of the adjusted gap.



(c) Means and errors (pale area) of the acceleration in longitudinal direction a_x of the lag vehicle of the adjusted gap.

Figure 6.18: Participants' reaction due to the lane changing AV. At time equal to zero the AV and the lag vehicle of the adjusted gap are at the same height.

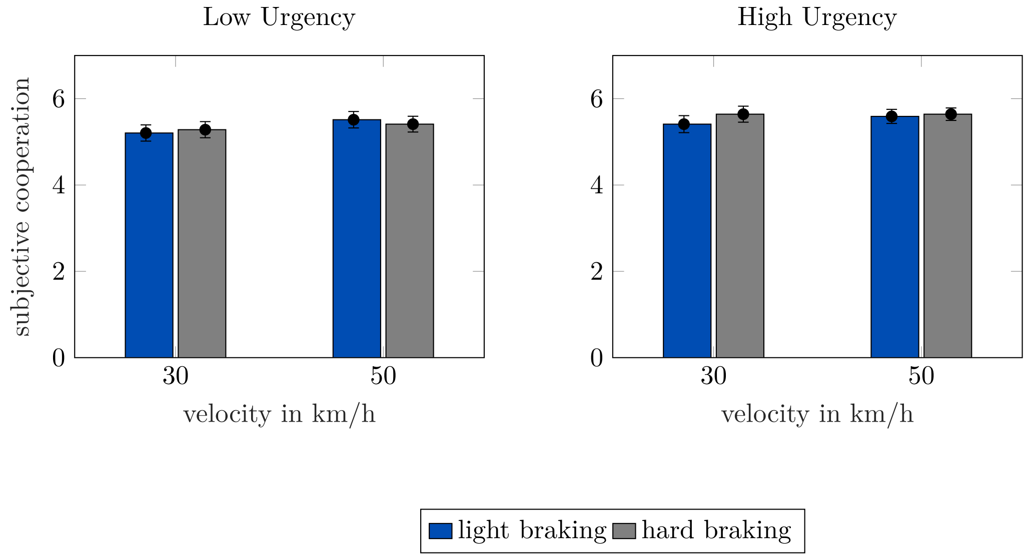


Figure 6.19: Means and errors of the surveyed *cooperation*.

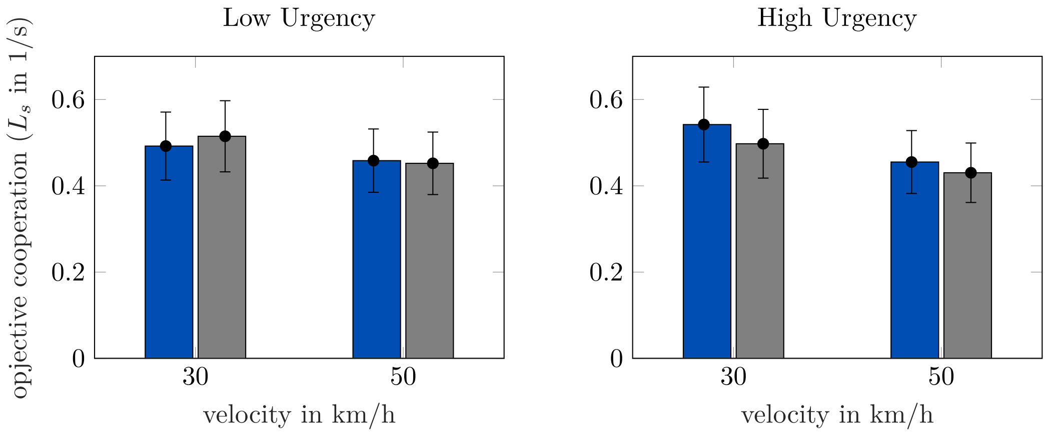


Figure 6.20: Means and errors of the objective *cooperation*.

6.3.4 Participants' comments

After the first part of the study 20 of 39 participants expected at high urgency an earlier lane change, with a smaller time headway between the AV and the lag vehicle of the adjusted gap, than at low urgency. 16 participants expected the AV to change lanes earlier at $50\,\mathrm{km\,h^{-1}}$ and 9 participants at $30\,\mathrm{km\,h^{-1}}$.

In the second part of the study, 18 participants referred the time they started the AV's lane change to the distance between the lag vehicle of the adjusted gap and the AV. 19 participants referred the time they started the AV's lane change to the distance between the AV and the lead vehicle of the adjusted gap as important criteria. 24 participants requested a better communication of the lane change, e.g. with a lateral displacement of the AV before the lane change or with an earlier set of the turn signal. Moreover, four participants stated that the AV should change lanes with shorter duration and six participants stated the AV

Independent variable	$F(1,39)$	p	η_p^2
Velocity	0.44	.726	.04
Urgency	40.00	$<.001$	.77
Braking	1.40	.261	.11
Velocity * urgency	1.44	.247	.11
Velocity * braking	2.30	.094	.17
Urgency * braking	1.19	.327	.11
Velocity * urgency * braking	1.48	.237	.11

Table 6.16: Results of the ANOVA (2 (urgency) x 2 (velocity) x 2 (braking)) of the objective *cooperation* $\max(\mathrm{L_s})$.

was following the lead vehicle of the adjusted gap too close during and after the lane change. Six participants wanted the AV to change lanes even earlier than they started the lane change of the AV on their own.

6.4 Discussion and conclusion

The present study investigates start conditions of AV's lane changes in a dense mixed-traffic scenario. The study focuses on a lane change to the right into a gap in front of the AV and was evaluated from the perspective of the lag vehicle of the adjusted gap (cf. section 4.2.1). The following section describes the behaviour patterns that should be considered for the design of an AV's driving style by the key questions introduced in section 4.1.2, due to step *Start the lane change* of the procedure to design an AV's driving style from interacting human drivers' perspective (cf. section 4.1.1).

Which time headway should the AV adhere to the lag vehicle of the adjusted gap before the AV's lane change should be started out of interacting human drivers' perspective?

Since, interacting human drivers expect a cost-reducing and efficient AV's lane change as evaluated in the pre- and post test (cf. section 6.3.1), results of this study suggest that start conditions for the AV's lane changes should not be implemented too conservative. It seems that the expectations of the AV's driving style are dominated by human driving style. Interacting human drivers expect small time headway to other human drivers to start their own lane change in order to force their way on the target lane (cf. section 3.2.2). This supports the findings of Beggiato and Krems (2013): the mental model of a system is paramount for its assessment.

The subjective *predictability* measure confirms the assumption, that a time headway of 0.4 s is most predictable, especially at 50 km h^{-1} and high urgency (cf. section 6.3.2.1). However, even the starting condition with a time headway of 0.4 s is rated as too late. At high urgency and at 50 km h^{-1} the start condition 0.6 s is rated objective most predictable over all evaluated scenarios, what leads to the conclusion that the optimum distance lies between those two time headway in terms of *predictability* of the AV's driving style or that the participants needed time for the information processing process (cf. section 2.1.1), until they pressed the button.

The measurements of the surveyed *acceptance*, *delay*, and *disturbance* (cf. Figure 6.11, Figure 6.13, and Figure 6.15, respectively) are drawing a similar picture. The starting condition 0.4 s is subjectively most accepted, rated as least delaying and as least disturbing. Nevertheless, all three scales show nearly no difference for the starting conditions 0.4 s and 0.6 s at low urgency and 50 km h^{-1}. A comparison of the objective *delay* (cf. section 6.3.2.5) with the surveyed *acceptance* (cf. section 6.3.2.3) leads to the conclusion that the accepted time span depends, similar to the surveyed *predictability* (cf. section 6.3.2.1), on the scenario. At high urgency and 30 km h^{-1}, the starting condition of 0.6 s is similarly accepted than the starting condition of 0.4 s. This does not apply at high urgency and 50 km h^{-1}. Here, the smaller start condition 0.4 s is significantly more accepted. At low urgency and at 30 km h^{-1} an opposite effect is found: the starting condition 0.4 s is rated with significant higher *acceptance* as the starting condition 0.6 s. At low urgency and 50 km h^{-1} almost no difference is found.

The results demonstrate that start conditions with smaller time headway are not rated with higher *criticality* than more conservative start conditions. Even the opposite effect could be shown: in scenarios with road work on the AV's lane (high urgency), start conditions with a larger time headway are rated more critical than smaller ones yet only at high urgency and 50 km h^{-1} (cf. Figure 6.12). This effect is amplified in scenarios in which the AV did not start the lane change due to diminished cooperation of the participants and hence the security driver of the AV had to perform a manual lane change or emergency stop at the lane end (cf. Table 6.2). That the objective for interacting human drivers as less critical assessed starting condition of 0.9 s for an AV's lane change is surveyed as more critical could be justified in the multiple comfort zone model of Summala (2005). This model is based on experience and must be learned (Lewis-Evans et al., 2010). As mentioned above the expectations on the AV's driving style at lane changes could be orientated at human drivers' driving style. The argumentation for the subjective *criticality* ratings could take the same line and lets one suggest that participants perceive the starting condition of 0.9 s as unusual, what caused the unpleasant feeling (cf. Summala (2005)).

Those findings are strengthened in the second part of the study, in which participants adjusted small time headway as starting conditions. In the exploratory part of the study participants' adjusted time headway between approx. 0.3 s and 0.55 s (cf. Figure 6.16). Participants expected even smaller time headway at high urgency and 50 km h^{-1} as evaluated in the first part of the study (cf. Figure 6.16) and reduced velocity only slightly, to enable the AV to change lanes (cf. Figure 6.18). Based on the results of the present study and the results of Lütteken et al. (2016) it can be assumed that the necessary cooperation to enable the AV's lane change was a decisive factor.

Which impact does the urgency of the lane change, the velocity of the adjusted gap and the AV's deceleration to communicate the lane change have?

The scenario influences the participants ratings. Thus, it can be confirmed that the context influences the processing of the information, as described by Baumann et al. (2006) in a situational model. In the following the influence of different urgencies of the situations, velocities of the adjusted gap and the AV's deceleration to communicate the lane change is discussed in more detail.

Different urgency of the lane change is operationalized in the scenario by variation of the length of the AV's starting lane. The variation with the shorter starting lane was referred in the studies instruction due to road work. In the second part of the present study, it is shown that participants react in scenarios with higher urgency with significantly more cooperation (cf. Table 6.16). Therefore, the present results are reproducing the findings of Stoll et al. (2018), Benmimoun et al. (2004), and Ehmanns (2001, 2002). Moreover, the present study implies that in scenarios with a closer lane end, the vehicle that wants to change lanes should expect less from the cooperating vehicles of the adjusted gap and start its lane change significant earlier (cf. section 6.3.3.1). Overall, cooperation is expected from all actors: aiming to work on a quick solution. All scales raised show that especially at $50\,\mathrm{km\,h^{-1}}$ the influence of high urgency in cases the lane change is started too late has a highly negative influence on the participants ratings. It is to be expected that this influence is larger at even higher velocities.

The velocity influences the assessment of the AV's driving style only at low urgency: AV's driving styles at $30\,\mathrm{km\,h^{-1}}$ are rated more critical than at $50\,\mathrm{km\,h^{-1}}$. Consequently, at low urgency the participants adjusted a larger time headway $t_{r,AV,LA}$ as starting condition at $30\,\mathrm{km\,h^{-1}}$ than at $50\,\mathrm{km\,h^{-1}}$ in the second part of the study. This confirms the findings of Tscharn et al. (2018), in which the same time headway in car-following is rated more critical for slower velocities. In other driving simulator studies this effect is not found (Lewis-Evans et al., 2010; Siebert et al., 2014, 2017). Studies in real traffic are convicting that velocity influences the time headway in car-following in real traffic. It could be shown that in cases with faster velocities, the increase of the time headway decreases (Brackstone et al., 2009; Bubb et al., 2015). However, in cases the vehicle that wants to change lanes approaches a lane end at the starting lane (high urgency), the time span the vehicle needs to reach the lane end, estimated by interacting human drivers, seems to dominate the scenario, as explained above: AV's driving styles at $50\,\mathrm{km\,h^{-1}}$ are rated with higher *criticality* than at $30\,\mathrm{km\,h^{-1}}$.

Consequently participants allow smaller time headway as start condition at high urgency to defuse the situation on the AV's starting lane (cf. Figure 6.16).

At $50\,\mathrm{km\,h^{-1}}$ and with an AV's driving style with hard braking to the adjusted gap, in order to communicate the AV's intention to change lanes, participants started the lane change of the AV significant earlier (cf. section 6.3.3.2), than with an AV's driving style with light braking. Moreover, the participants realized a significantly larger time headway between the AV and the lag vehicle of the adjusted gap at the start of the AV's lane change at an AV's driving style with hard braking, than with an AV's driving style with light braking (cf. section 6.3.3.1). This confirms the results of the first study: AV's driving styles with hard braking result in a significantly faster understanding of the AV's intention to change lanes (cf. section 5.3.1.1) and to significantly higher cooperation (cf. section 5.3.1.2) of interacting human drivers.

7 Driving study III - Execute the lane change

Philipp Hartl assisted in designing and conducting of the driving study as part of his Master's thesis (Hartl, 2020). For this Doctoral thesis, the data was evaluated separately.

In the previous study (cf. chapter 6), it was clearly evident that interacting human drivers expect the AV's start of the lane change with small distances to the lead and lag vehicle of the adjusted gap in order to design a predictable, acceptable and not to forget a subjective evaluated uncritical AV's driving style. Thus, in this study the lane change is started with the smallest evaluated time headway of 0.4 s between the AV and the lag vehicle of the adjusted gap. To meet road traffic regulations as fast as possible (cf. section 3.2) the newly lining-up vehicles have to pull apart like an accordion after the AV's start of the lane change. To investigate whether distances can be restored from the perspective of interacting human drivers this study investigates different AV's driving styles at the execution of the lane change in a within-subject design on a test track with N = 37 participants, in order to answer the research question, pertaining *Execute the lane change*, formulated in section 4.1.2: Whether, at what time or to which extent should the AV increase the distance to the lead vehicle of the adjusted gap from the perspective of interacting human drivers? To gain standardized scenarios, all lane change manoeuvrers are executed automatically (cf. section 4.2.2) in a similar scenario on the test ground (cf. section 4.2.1). The study is divided into two parts. In a first part participants evaluate different AV's target time headway to the lead vehicle of the adjusted gap. Moreover, different AV's driving styles to adjust the target time headway, one with light braking of the AV and one with light deceleration using only the drag torque, are evaluated. In addition AV's driving styles with long and short lane change duration are assessed. In a second part the difference between AV's driving styles that increase the target time headway with the start of the lane change, after the lane change or not at all and influences of the perspective (whether the participant is driving the lead or lag vehicle of the adjusted gap) are estimated.

7.1 Hypotheses and exploratory questions

Interacting human drivers state to prefer an efficient AV's driving style at lane changes (cf. section 6.3.1). Efficiency in terms of the overall traffic is assumed as avoidance of active braking (Bengler and Zimmer, 2002). This implies most likely a deceleration of following vehicles and could effect the subjective rating negatively, cause traffic congestion, or even accidents. Thus, the following hypothesis is formulated:

- AV's driving styles in which the time headway to the lead vehicle of the adjusted gap is increased during the lane change with light braking lead to a lower *predictability* (H1.1) of the AV's intention, lower *acceptance* (H1.2), higher *criticality* (H1.3) and *workload* (H1.4) of interacting human drivers, compared to AV's driving styles in which the adjusted gap is increased with weak deceleration using the drag toque only.

As more the AV increases the time headway to the lead vehicle of the adjusted gap, as more the driver of the lag vehicle of the adjusted gap has to decelerate. Therefore the following hypothesis is examined:

- AV's driving styles with a recovery of the time headway to the lead vehicle of the adjusted gap of 1.5 s lead to a lower *predictability* (H2.1) of the AV's intention, lower *acceptance* (H2.2), higher *criticality* (H2.3) and *workload* (H2.4) of interacting human drivers, compared to AV's driving styles with a recovery to a time headway to the lead vehicle of the adjusted gap of 1 s only.

To date ADSs do not change lanes in dense traffic on public roads and the human driver's mental models (cf. section 2.1.1.2) of driving styles in lane change scenarios are dominated by human drivers (cf. section 3.2.2). But, still can shorter lane change duration lead to temporarily smaller distances between the AV and the lag vehicle of the adjusted gap, in comparison to long lane change durations. Thus, the following hypothesis is formulated:

- AV's driving styles with lane change durations comparable to human drivers increase the *predictability* (H3.1) of the AV's intention, increase the *acceptance* (H3.2) and the *criticality* (H3.3), and decrease the *workload* (H3.4) of interacting human drivers, in comparison to AV's driving styles with longer lane change durations.

Small following distances are one of the main reasons for traffic accidents (Gründl, 2005), the requirements according to traffic road regulations are usually undercut on the target lane (cf. section 3.2.1). Since, following distances required of road traffic regulations are mainly based on response times of human drivers, the AV could drive with smaller following distances. For AVs time headway to the front vehicle between 0.4 s and 0.5 s can be safe (Friedrich, 2015), what could increase road capacity and minimizes the necessary reaction of the human driver of the lag vehicle of the adjusted gap to re-establish safe distances to its new front vehicle. Nevertheless, a driving style with too small following distances is rated as aggressive and reckless (Ellinghaus, 1986). Similar to a long lane change duration, an increase of the time headway to the lead vehicle of the adjusted gap that is started after the AV's lane change gives the human driver of the lag vehicle of the adjusted gap a longer time budget to react and re-establish safe distances to its new front vehicle until both vehicles are intersecting on the target lane, as the increase is started with the start of the AV's lane change. But, as mentioned above, the human drivers' mental models in lane change scenarios are dominated by human drivers. If human drivers change lanes in such small adjusted gaps they mostly increase the distance to the lead vehicle of the adjusted gap directly after the start of the lane change (cf. section 3.2.2). Thus, the following hypothesis is formulated:

- AV's driving styles in which the increase of the target time headway to the lead vehicle of the adjusted gap is started with the start of the lane change lead to a different *predictability* (H4.1) of the AV's intention, different *criticality* (H4.2), *acceptance* (H4.3), and *workload* (H4.4) of interacting human drivers, in comparison to AV's driving styles in which the increase of the target time headway to the lead vehicle of the adjusted gap is started after the end of the AV's lane change or AV's driving styles in which the target time headway to the lead vehicle of the adjusted gap is increased only marginal.

Since, a shorter distance to the lead vehicle of the adjusted gap, results in a larger distances to the lag vehicle of the adjusted gap, it is assumed that the AV's driving style is rated differently from the perspective of the lead or lag vehicle. Thus, the following hypothesis is formulated:

- Human drivers of the lead vehicle of the adjusted gap rate the AV's driving styles with different *predictability* (H5.1) of the AV's intention, different *criticality* (H5.2), *acceptance* (H5.3), and *workload* (H5.4), compared to human drivers of the lag vehicle of the adjusted gap.

In addition, the gaze behaviour of the participants and therefore their Area of Interests (AOI) over the whole lane change manoeuvre is evaluated. On one hand to evaluate if there are differences in the gaze behaviour over different strategies to change lanes and to analyse the participants' general gaze strategy. The following exploratory questions are formulated.

- How is the *gaze behaviour* of interacting human drivers during interaction with a lane changing AV in a lane change scenario (Q1.1)? Does the *gaze behaviour* change if the AV adjusts a different target time headway (Q1.2), changes lanes with different durations (Q1.3) or adjusts different rates of deceleration to reach the target time headway (Q1.4)?

Hypothesises (H1 -H3) and the exploratory questions (*Q1*) are evaluated in a first and hypothesises (H4 - H5) in a second part of the study.

7.2 Method

7.2.1 Test scenario

The study took place in August 2019 and was executed on the test-ground described in section 4.2.1. The set-up on the test ground is illustrated in Figure 7.1a. The participants drove either the lead or lag vehicle of the adjusted gap. The driver of the lead vehicle was instructed to drive with $50\,\mathrm{km\,h^{-1}}$. Like in the previous study (cf. chapter 6), the driver of the lag vehicle was asked to follow the lead vehicle with a time headway of approx. $1\,\mathrm{s}$. In order to keep the required target time headway to the lead vehicle of the adjusted gap, the participants had a customized marker at the windscreen, as illustrated in Figure 7.1b. The AV was humanly accelerated to target velocity of $65\,\mathrm{km\,h^{-1}}$. Then the automated driving function was activated. The AV was overtaking the lag vehicle of the adjusted gap and aimed to get a target time headway of $t_{\mathrm{t,LE,AV}} = 0.4\,\mathrm{s}$ to the lead vehicle of the adjusted gap. In case the time headway to the lag vehicle was larger than $t_{\mathrm{r,AV,LA}} > 0.4\,\mathrm{s}$ the AV started to change lanes in different variations. The driving function was deactivated at the end of the straight. This was approx. $25\,\mathrm{s}$ after the start of the lane change.

(a) Set-up.

(b) Marker: pink paper strip at the wind-shield

Figure 7.1: Participating vehicles on the test ground.

7.2.2 Procedure and study design

Possible interested volunteers answered an online questionnaire. Participants were selected gender balanced. The overall duration of the study was approx. 90 minutes per participant and was structured in a pre-test and instructions, a first study part (within-subjects design), a second study part (within-subjects design), and a post-test as followed:

Pre-test and instructions: At first participants answered an online questionnaire, in order to describe the sample, given in Appendix C.2.1. At the test ground, they were informed about the content and their tasks during the study, as shown in Appendix C.1. The participants were instructed to react to the AV's intention to change lanes the same way as they would cooperate in real traffic and that the scenario ends at the end of the straight of the test track and not already when the AV completed the lane change. Driving the lead vehicle the participants were asked to observe the AV over the vehicle's mirrors.

Part I: The AV performed eight manoeuvrers with a combination of parameters listed in section 7.2.3.1. The participants were driving the lag vehicle of the adjusted gap. After every manoeuvrer, the participants completed a questionnaire with the subjective measures summarized in section 7.2.4.1, via a guided interview over telephone by an experimenter driving the lead vehicle of the adjusted gap.

Part II: The AV performed six manoeuvrers with a combination of parameters listed in section 7.2.3.2. The participants were driving either the lead or lag vehicle of the adjusted gap in randomized order. After three manoeuvrers the participants changed vehicles. After every manoeuvrer the participants filled in the same questionnaire as in the first part, via a guided interview over telephone by an experimenter driving either the lead or lag vehicle of the adjusted gap.

Post-test: Debriefing and answering of a post-test questionnaire.

7.2.3 Independent variables

This section summarizes the independent variables of the first and second part of the study, representing different variations of the AV's driving style to change lanes.

7.2.3.1 Part I

The independent variables and their operationalization of the first part of the study are illustrated in Table 7.1. The target time headway, its adjustment and the lane change duration was varied. To create the impressions that the adjustment of the target time headway at the factor level weak deceleration was reached always with drag torque only, due to control deviations, the brake lights were additionally deactivated with the start of the lane change to give also at control deviations the participants the impression that front the vehicle is decelerating using the drag torque, only. To differentiate between light deceleration and light braking additionally to the deceleration strength with the deactivation of the brake lights is valid, since the detection of a braking front vehicle is mainly dominated by the brake lights and not by the change of the front vehicle's motions (Bengler and Zimmer, 2002). So that very light and short braking interventions were not visible to the participants in the lag vehicles of the adjusted gap over direct communication via eHMI (cf. 2.2.1).

Independent variables	Variations	Operationalization
Target time headway	$t_{\text{t,LE,AV}} = 1\,\text{s}$ (short) $t_{\text{t,LE,AV}} = 1.5\,\text{s}$ (long)	time headway between lead vehicle and AV at the end of the manoeuvres
Adjustment	light deceleration light braking	amount of deceleration to reach $t_{\text{t,LE,AV}}$
Lane change duration	$\text{M}(t_{\text{LCD}}) = 4.4\,\text{s}$ (short) $\text{M}(t_{\text{LCD}}) = 11.8\,\text{s}$ (long)	time span to get from starting to target lane

Table 7.1: Operationalization of independent variables of study part I (2x2x2 within-subject design)

Figure 7.2a illustrates the adjustment of the target time headway $t_{\text{t,LE,AV}}$ between the AV and lead vehicle of the adjusted gap during and after the lane change. At the start of the lane change the AV had a mean time headway of $\text{M}(\min(t_{\text{t,LE,AV}})) = 0.40\,\text{s}$ with a standard error of $\text{SE}(\min(t_{\text{t,LE,AV}})) = 0.04\,\text{s}$ to the lead vehicle of the adjusted gap. In case the time headway between the AV and the lag vehicle of the adjusted gap was larger than $t_{\text{r,AV,LA}} > 0.4\,\text{s}$ the AV started to change lanes and increased the target time headway to the lead vehicle of the adjusted gap in different variations.

If the AV brakes to increase the target time headway to the lead vehicle of the adjusted gap in both conditions the time headway overshot. If the target time headway was $t_{\text{t,LE,AV}} = 1\,\text{s}$ and the AV decelerates weakly the mean maximum time headway was $\text{M}(\max(t_{\text{t,LE,AV}})) = 1.09\,\text{s}$ with a standard error of $\text{SE}(\max(t_{\text{t,LE,AV}})) = 0.01\,\text{s}$. At light braking the mean maximum time headway was $\text{M}(\max(t_{\text{t,LE,AV}})) = 1.72\,\text{s}$ with a standard error of $\text{SE}(\max(t_{\text{t,LE,AV}})) = 0.04\,\text{s}$. At target time headway of $t_{\text{t,LE,AV}} = 1.5\,\text{s}$ and the AV was weakly decelerating the mean maximum time headway was $\text{M}(\max(t_{\text{t,LE,AV}})) = 1.62\,\text{s}$ with a standard error of $\text{SE}(\max(t_{\text{t,LE,AV}})) = 0.01\,\text{s}$. At light braking the mean of the maximum was $\text{M}(\max(t_{\text{t,LE,AV}})) = 2.16\,\text{s}$ with a standard error of $\text{SE}(\max(t_{\text{t,LE,AV}})) = 0.04\,\text{s}$. In case of the AV is lightly braking to adjust the target time headway, the target time headway was overshooting for more than half a second. If the target time headway is adjusted with the target time headway not only the slope of the graph is steeper, but also the maximum time headway is larger. Thus, it is not possible to strictly separate between those two factors. Since, the maximum time headway at light braking and a target time headway of $t_{\text{t,LE,AV}} = 1\,\text{s}$ is comparable to the condition were the time headway is adjusted with weak deceleration at a target time headway of $t_{\text{t,LE,AV}} = 1.5\,\text{s}$ in case the maximum time headway has a significant influence on the dependent measure a significant interaction between the factors target time headway and its adjustment is expected.

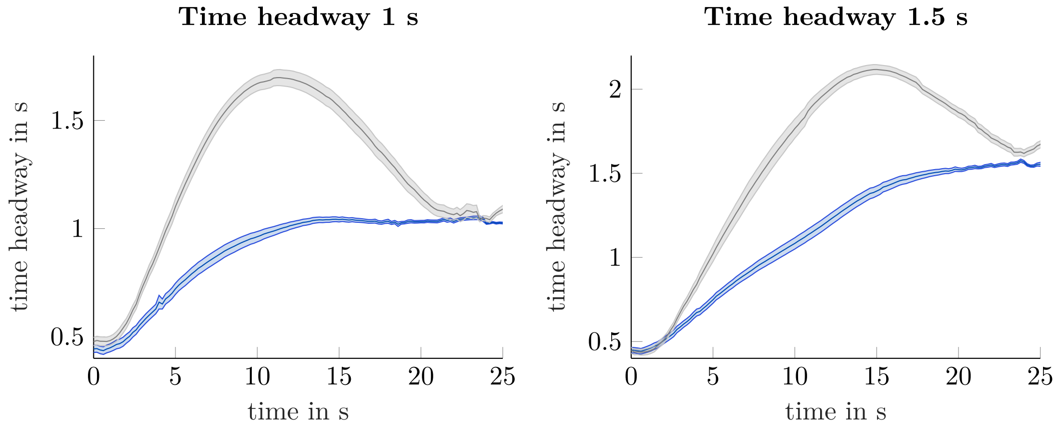
Figure 7.2b illustrates the velocity in longitudinal direction of the AV during and after the lane change. In case of target time headway of $t_{\mathrm{t,LE,AV}} = 1\,\mathrm{m\,s^{-1}}$ and the AV was weakly decelerating to adjust it, the mean of the minimum velocity was $\mathrm{M}(\min(v_x)) = 11.90\,\mathrm{m\,s^{-1}}$ with a standard error of $\mathrm{SE}(\min(v_x)) = 0.07\,\mathrm{m\,s^{-1}}$. At light braking the mean of the minimum velocity was $\mathrm{M}(\min(v_x)) = 10.27\,\mathrm{m\,s^{-1}}$ with a standard error of $\mathrm{SE}(\min(v_x)) = 0.09\,\mathrm{m\,s^{-1}}$. At target time headway of $t_{\mathrm{t,LE,AV}} = 1.5\,\mathrm{m\,s^{-1}}$ and the AV was weakly decelerating to adjust it, the mean of the minimum velocity was $\mathrm{M}(\min(v_x)) = 11.79\,\mathrm{m\,s^{-1}}$ with a standard error of $\mathrm{SE}(\min(v_x)) = 0.07\,\mathrm{m\,s^{-1}}$. At light braking the mean of the minimum velocity was $\mathrm{M}(\min(v_x)) = 10.05\,\mathrm{m\,s^{-1}}$ with a standard error of $\mathrm{SE}(\min(v_x)) = 0.16\,\mathrm{m\,s^{-1}}$.

Figure 7.2c illustrates the AV's acceleration in longitudinal direction during and after the lane change. In case of target time headway of $t_{\mathrm{t,LE,AV}} = 1\,\mathrm{s}$ and the AV was weakly decelerating to adjust it, the mean of the minimum acceleration was $\mathrm{M}(\min(a_x)) = -1.08\,\mathrm{m\,s^{-2}}$ with a standard error of $\mathrm{SE}(\min(a_x)) = 0.12\,\mathrm{m\,s^{-2}}$. At light braking the mean of the minimum acceleration was $\mathrm{M}(\min(a_x)) = -1.80\,\mathrm{m\,s^{-2}}$ with a standard error of $\mathrm{SE}(\min(a_x)) = 0.12\,\mathrm{m\,s^{-2}}$. At target time headway of $t_{\mathrm{t,LE,AV}} = 1.5\,\mathrm{m\,s^{-2}}$ and the AV was weakly decelerating to adjust it, the mean minimum acceleration was $\mathrm{M}(\min(a_x)) = -1.05\,\mathrm{m\,s^{-2}}$ with a standard error of $\mathrm{SE}(\min(a_x)) = 0.10\,\mathrm{m\,s^{-2}}$. At light braking the mean of the minimum acceleration was $\mathrm{M}(\min(a_x)) = -1.85\,\mathrm{m\,s^{-2}}$ with a standard error of $\mathrm{SE}(\min(a_x)) = 0.12\,\mathrm{m\,s^{-2}}$.

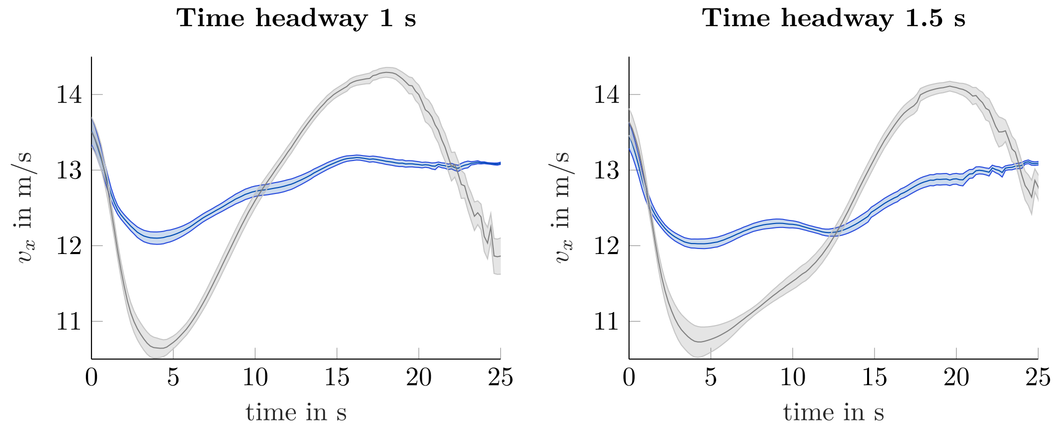
The lateral displacement during and after the lane change is illustrated in Figure 7.3a. The short lane change duration took in mean $\mathrm{M}(t_{\mathrm{LCD}}) = 4.43\,\mathrm{s}$ with a standard error of $\mathrm{SE}(t_{\mathrm{LCD}}) = 0.09\,\mathrm{s}$ and the long lane change duration took in mean $\mathrm{M}(t_{\mathrm{LCD}}) = 11.78\,\mathrm{s}$ with a standard error of $\mathrm{SE}(t_{\mathrm{LCD}}) = 0.12\,\mathrm{s}$. The participants were advised not to rate the overshoot on the target lane existent for the short lane change duration.

The lateral velocity during and after the lane change is illustrated in Figure 7.3b. In case of a long lane change duration, the mean of the minimum velocity $\mathrm{M}(\min(v_y)) = -0.62\,\mathrm{m\,s^{-1}}$ and the standard error was $\mathrm{SE}(\min(v_y)) = 0.01\,\mathrm{m\,s^{-1}}$. At a short lane change duration the mean minimum velocity was $\mathrm{M}(\min(v_y)) = -1.53\,\mathrm{m\,s^{-1}}$ with a standard error of $\mathrm{SE}(\min(v_y)) = 0.02\,\mathrm{m\,s^{-1}}$.

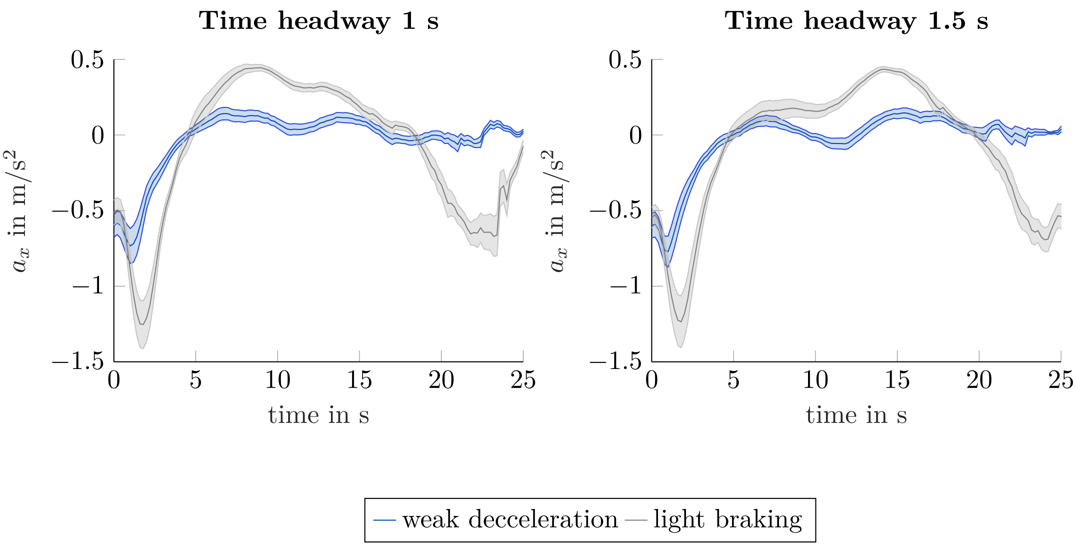
The lateral acceleration during and after the lane change is illustrated in Figure 7.3c. In case of a long lane change duration, the mean of the minimum acceleration was $\mathrm{M}(\min(a_y)) = -0.21\,\mathrm{m\,s^{-2}}$ with a standard error of $\mathrm{SE}(\min(a_y)) < 0.01\,\mathrm{m\,s^{-2}}$ and the mean maximum acceleration was $\mathrm{M}(\max(a_y)) = 0.14\,\mathrm{m\,s^{-2}}$ with a standard error of $\mathrm{SE}(\max(a_y)) < 0.01\,\mathrm{m\,s^{-2}}$. At a short lane change duration the mean minimum acceleration was $\mathrm{M}(\min(a_y)) = -0.88\,\mathrm{m\,s^{-2}}$ with a standard error of $\mathrm{SE}(\min(a_y)) = 0.03\,\mathrm{m\,s^{-2}}$ and mean maximum acceleration was $\mathrm{M}(\max(a_y)) = 0.66\,\mathrm{m\,s^{-2}}$ with a standard error of $\mathrm{SE}(\max(a_y) = 0.02\,\mathrm{m\,s^{-2}}$.



(a) time headway between AV and lead vehicle.

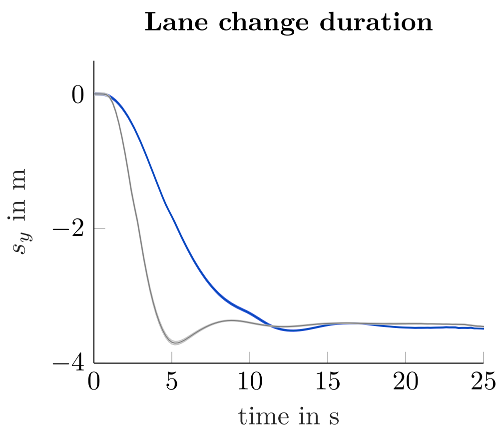


(b) AV's velocity in longitudinal direction.

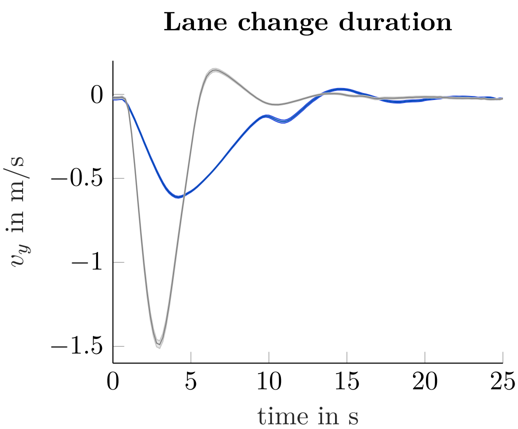


(c) AV's acceleration in longitudinal direction

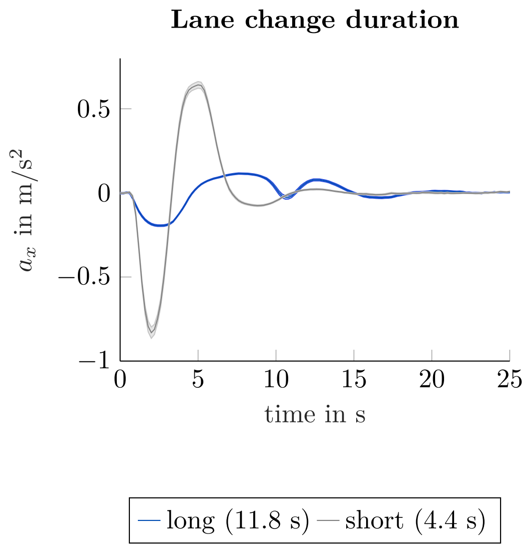
Figure 7.2: Means (centre line) and errors (pale area) in Frenet coordinates over time. At time equal to zero the AV starts to change lanes.



(a) AV's lateral displacement during and after the lane change.



(b) AV's velocity in lataeral direction.



(c) AV's acceleration in lateral direction

Figure 7.3: Means (centre line) and errors (pale area) of the respective sizes. At time equal to zero the AV starts to change lanes. The participants were advised not to rate the overshoot existent for the short lane change duration

7.2.3.2 Part II

The independent variables and their operationalization of the second part of the study are illustrated in Table 7.2. At the start of the lane change the AV had a time headway of $\mathrm{M}(\min(t_{\mathrm{t,LE,AV}})) = 0.39\,\mathrm{s}$ with a standard error of $\mathrm{SE}(\min(t_{\mathrm{t,LE,AV}})) = 0.02\,\mathrm{s}$ to the lead vehicle of the adjusted gap. If the time headway to the lag vehicle was larger than $t_{\mathrm{r,AV,LA}} \geq 0.4\,\mathrm{s}$ the AV started to change lanes and increased the target time headway to the lead vehicle in different variations. Either the time headway is increased marginal to $t_{\mathrm{t,LE,AV}} = 0.5\,\mathrm{s}$ or to $t_{\mathrm{t,LE,AV}} = 1\,\mathrm{s}$ with the start of the lane change (with LC) or after the AV reached the target lane (after LC).

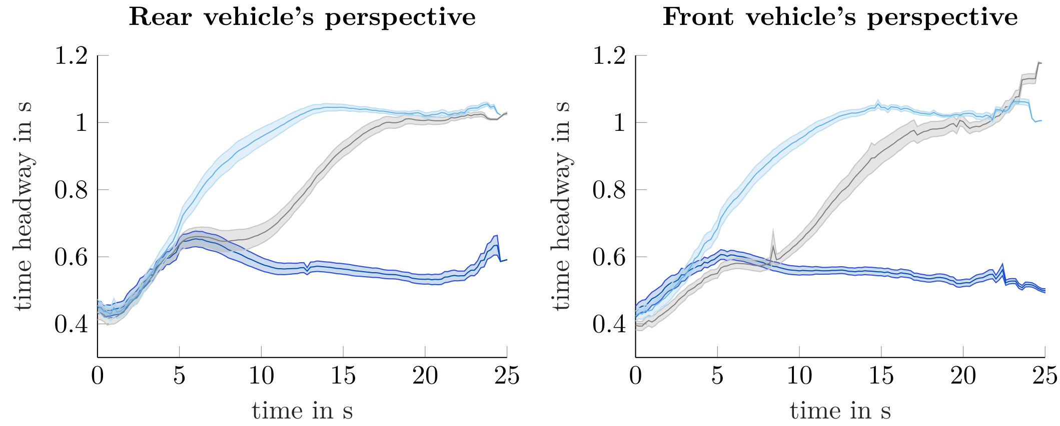
Independent variables	Variations	Operationalization
Perspective	lag vehicle lead vehicle	participants are driving the lag or lead vehicle
Adjustment	$t_{\mathrm{t,LE,AV}} = 0.5\,\mathrm{s}$ (marginal) $t_{\mathrm{t,LE,AV}} = 1\,\mathrm{s}$ (with LC) $t_{\mathrm{t,LE,AV}} = 1\,\mathrm{s}$ (after LC)	adjustment and size of target time headway between AV and lead vehicle

Table 7.2: Operationalization of independent variables of study part II (2x3 within-subject design).

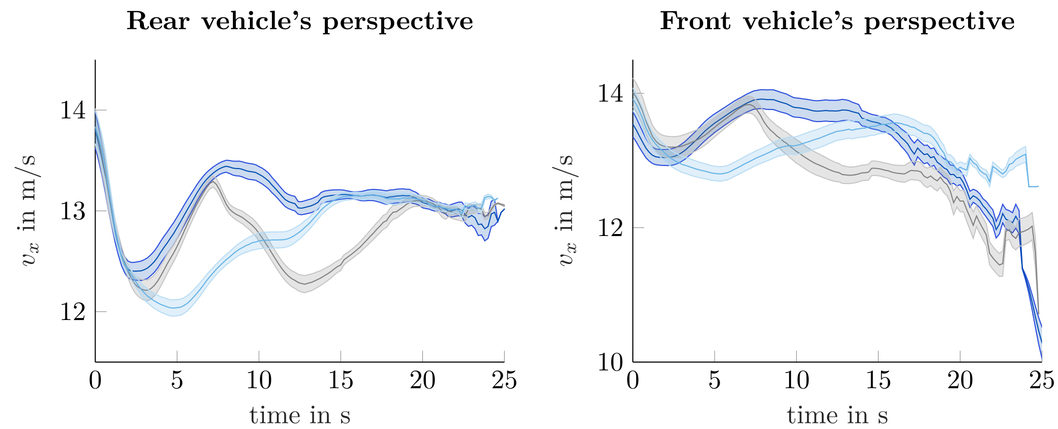
The course of the target time headway $t_{\mathrm{t,LE,AV}}$ during and after the lane change is illustrated in Figure 7.4a. At the factor level 'marginal', the mean maximum time headway was $\mathrm{M}(\max(t_{\mathrm{t,LE,AV}})) = 0.66\,\mathrm{s}$ with a standard error of $\mathrm{SE}(\max(t_{\mathrm{t,LE,AV}})) = 0.02\,\mathrm{s}$. At the factor level 'with LC' the mean maximum time headway was $\mathrm{M}(\max(t_{\mathrm{t,LE,AV}})) = 1.06\,\mathrm{s}$ with a standard error of $\mathrm{SE}(\max(t_{\mathrm{t,LE,AV}})) = 0.02\,\mathrm{s}$. This is comparable to the factor level 'after LC' with a mean maximum time headway $\mathrm{M}(\max(t_{\mathrm{t,LE,AV}})) = 1.07\,\mathrm{s}$ and a standard error of $\mathrm{SE}(\max(t_{\mathrm{t,LE,AV}})) = 0.02\,\mathrm{s}$.

The AV's velocity v_x and acceleration a_x in longitudinal direction during and after the lane change is illustrated in Figure 7.4b and 7.4c, respectively. The AV was applied to increase the target distance with weak deceleration, comparable to the first part of the study with deactivation of the brake lights with the start of the lane change. In case the participants were driving the lead vehicle of the adjusted gap they decreased the velocity early due to the upcoming lane end on the test track, which caused a decrease of the AV's velocity.

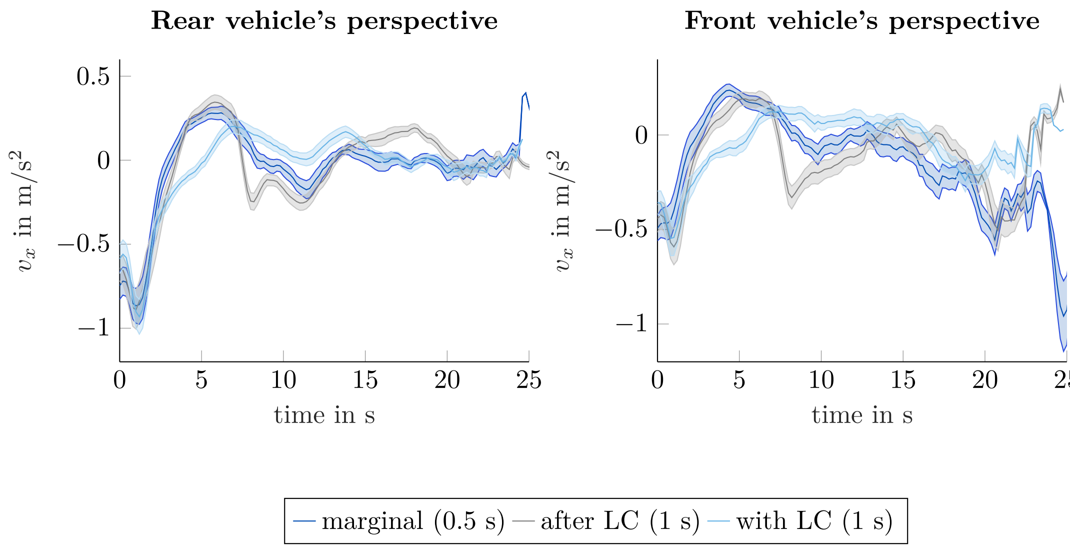
The AV's lateral displacement $\mathrm{s_y}$, velocity $\mathrm{v_y}$ and acceleration a_y were applied similar to the variant with a long lane change duration in the first part of the study. The mean lane change duration, which is evaluated from the start of the lane change manoeuvre until the



(a) time headway between AV and lead vehicle.



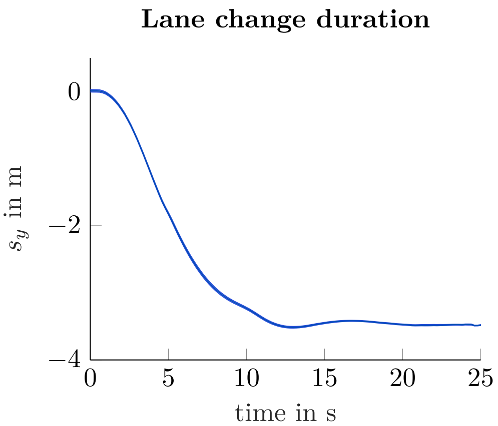
(b) AV's velocity in longitudinal direction.



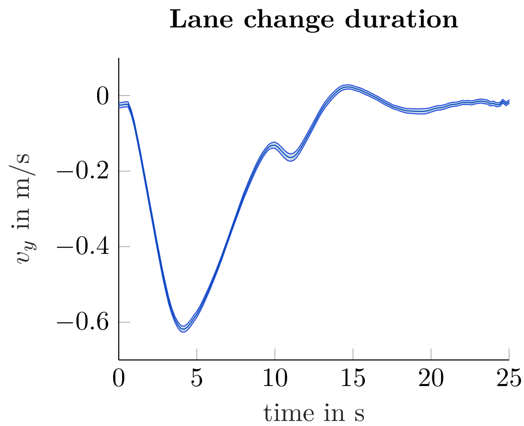
(c) AV's acceleration in longitudinal direction

Figure 7.4: Means (centre line) and errors (pale area) in Frenet coordinates over time. At time equal to zero the AV starts to change lanes.

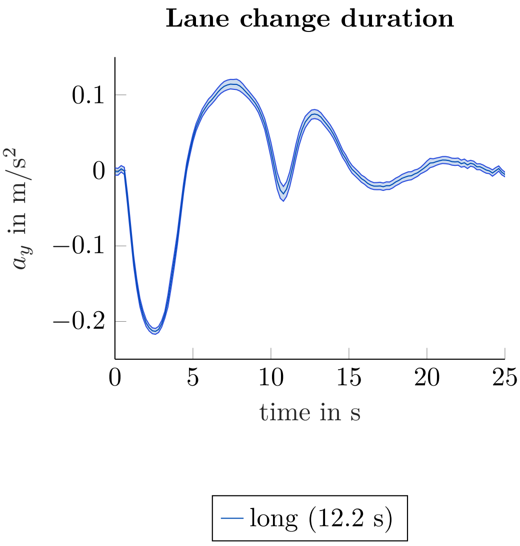
AV reached the target lane ($s_y > 3.5$m), was slightly longer $\mathrm{M}(t_{\mathrm{LCD}}) = 12.18\,\mathrm{m\,s^{-1}}$ with a standard error of $\mathrm{SE}(t_{\mathrm{LCD}}) = 0.31\,\mathrm{m\,s^{-1}}$. The course of s_y, v_y and a_y are illustrated in Figures 7.5a, 7.5b and 7.5c, respectively.



(a) AV's lateral displacement.



(b) AV's velocity in lataeral direction.



(c) AV's acceleration in lateral direction

Figure 7.5: Means (centre line) and errors (pale area) of the lane change duration. At time equal to zero the AV starts to change lanes

7.2.4 Dependent variables

The metrics were attached to the armatures of the lag and lead vehicle of the adjusted gap as visualized in Figure 7.6. The subjective metrics summarized below are used in part one and two of the study as given in the Appendix C.2.

(a) Lag vehicle: Questionaires and eye-tracking system.

(b) Lead vehicle: Questionaires only.

Figure 7.6: Insight of the vehicle building the adjusted gap. For both vehicles driving data via sensors of the AV are recorded.

7.2.4.1 Part I and II

Criticality. Measured in the argumentation of section 6.2.4.2 using the similar subjective measure. In study part I in order to evaluate objective *criticality* the time headway between the AV and the lag vehicle of the adjusted gap over time and the minimum and maximum from the point both vehicles are intersecting on the target lane are analysed.

Predictability. Measured in the argumentation of section 5.2.4.1 using a similar subjective measure according to the predictability of AV's driving style only. To assess to which degree the AV's driving style was in accordance with the participants' expectations, participants were asked after each manoeuvre when they would have expected the AV to change lanes. A seven-point rating scale was used, ranging from 1 ('not at all') to 7 ('absolutely').

Acceptance. Measured in the argumentation of section 6.2.4.2 using the similar subjective measure, whereby the item *activating* of the scale usefulness was not used for reasons see the argumentation in section 6.3.2.3.

Workload. An increasing *workload* can relate with negative emotions and stress or could lead to a reduced performance in the primary driving task (definition cf. 2.1) (Bubb et al., 2015). To measure subjective *workload* the rating scale Mental Effort (Zijlstra, 1993) is used, which was identified in a comparable driving scenario in order to evaluate the *workload* of lane changing elderly drivers (de Waard et al., 2009) as valid and reliable instrument. The scale is unidimensional from 0 ('absolute absence') to 220 ('maximum').

Gaze behaviour. In the first part of the study an eye-tracking system is used in order to record the participants' AOIs. Therefore the head-mounted SMI Eye Tracking Glasses of the company SensoMotoric Instruments, as illustrated in Figure 7.6a, with the evaluation software BeGaze 3.5 is used.

7.2.4.2 Post-test

After the study participants were asked about their impression of the timing of the start of the lane change from -3 ('earlier'), over 0 ('exactly as expected'), to 3 ('later'). Moreover, a standardized interview is conducted, concerning if the AV could drive in real traffic with the participants' best rated AV's driving style, if the participants recognized differences between the variations and their preferred lane change duration.

7.2.5 Sample

The study was performed with N = 37 participants (15 female). The distribution to the age group is shown in Table 7.3. They were on average age 38.2 years old (SD = 13.5) and had

	under 17	18-24	25-44	45-65	over 65
male	0 (0)	1 (4)	10 (12)	11 (2)	0 (1)
female	0 (0)	5 (4)	7 (12)	3 (2)	0 (0)

Table 7.3: Age distribution of the sample (compared with rated valid drivers license for the vehicle classes (B, B96, BE, BF17, BEF17) based on 37 participants).

in average a driver license for 20.1 (SD = 13.3) years. Moreover, 29 of the participants had a technical and eight had a non technical profession. 25 participants were working for the AUDI AG. Their median driven mileage per week was 150 km. The participants were driving 37 % on highways, 29 % on country roads and 14.4 % in cities with less than 100 000 inhabitants as well as 19.6 % in cities with more than 100 000 inhabitants. 28 of the participants had experience with Adaptive Cruise Control and 26 with Lane Assist. Participants stated to use those systems in everyday life as given in Table 7.4. 27 participants never participated

	never	seldom	occasionally	often	always
Adaptive Cruise Control (N = 28)	-	10.7 %	17.9 %	42.9 %	28.6 %
Lane Assist (N = 26)	7.7 %	19.2 %	30.8 %	15.4 %	26.9 %

Table 7.4: Relative frequency of usage of Adaptive Cruise Control and Lane Assist.

in test drives of Level 2 and 3 AVs (definition cf. section 2.2), 3 participated every half year and 7 participated less than every half a year. The participants rated themselves comparable to the samples used in the studies described in chapter 5 and 6, as pro-social drivers Harris et al. (2014) with an average of M = 4.81 (SD = 0.54).

7.2.6 Data preparation and statistical analysis

To replace missing information in the collected data due to recording male function during the study an Expectation Maximization analysis is used (Little and Rubin, 2019, p.187-188). The premise for the method is, that MCAR-test according to Little does not lead to significant findings, which implies that the missing values accrue randomly. For every objective measurement of one participant, in which no data could be recorded, data is neglected and 9 of 288 of every objective measures were replaced by Expectation Maximization analysis.

The surveyed evaluations via rating scale are equidistant and therefore, are assumed as interval scaled variables (Döring and Bortz, 2016, p.244-245). Moreover, normal distribution of the data is assumed, because of sample sizes N > 30 (Bortz and Schuster, 2010, p.87). In case of more than two factor stages of a independent variable Mauchly's test for sphericity is performed and if its violated, the Greenhouse-Geisser corrected values are reported. In the statistical analysis values for univariate and multivariate tests (Pillai's trace) are reported and a statistical significance level of $\alpha = .05$ is applied if not stated otherwise.

7.3 Results

7.3.1 Part I

7.3.1.1 Predictability

The surveyed *predictability* is illustrated in Figure 7.7. A three-way ANOVA for repeated measure design is conducted (Table 7.5). The adjustment of the target time headway is significant with a large effect size and therefore hypothesises H1.1 is accepted. The lane change duration also has a significant influence with a small effect size and therefore also hypothesis H3.1 can be confirmed, but the lane change duration seems to have a small influence on *predictability*. The target time headway has no significant influence with a high p-value and therefore hypothesis H2.1 must be rejected.

7.3.1.2 Acceptance

The surveyed *acceptance*, consisting of the scales satisfying and usefulness described in section 7.2.4.1 is provided in Figure 7.8. A three-way MANOVA for repeated measure design is conducted (Table 7.6). It appears that the adjustment of the target time headway is rated

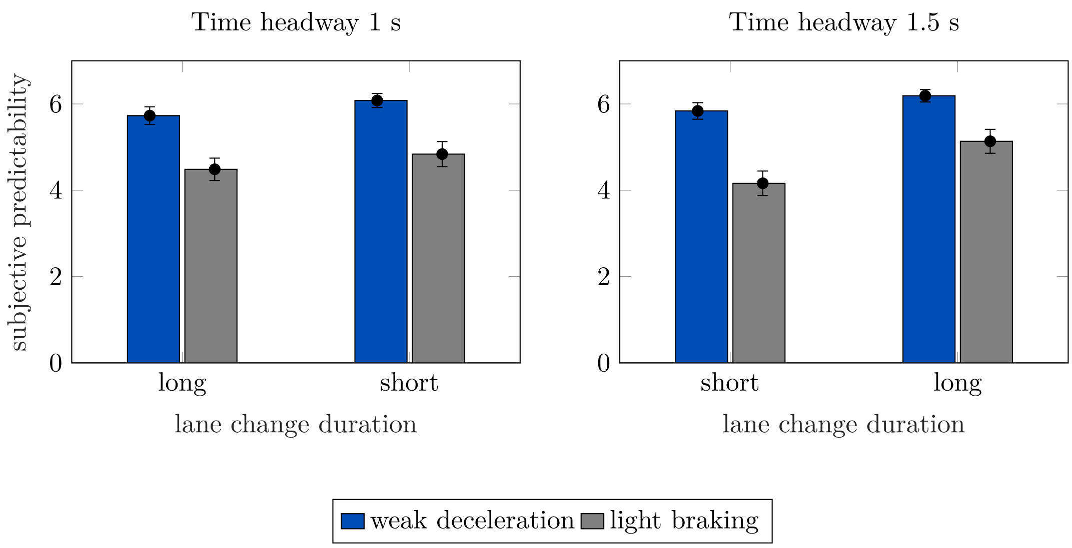


Figure 7.7: Means and errors of subjective *predictability* ratings from 1 to 7.

Independent variable	$F(1,36)$	p	η_p^2
$t_{\text{t,LE,AV}}$	0.13	.725	$< .01$
t_{LCD}	8.93	.005	.03
Adjustment	34.25	$< .001$	.18
$t_{\text{t,LE,AV}}$ * t_{LCD}	1.06	.311	$< .01$
$t_{\text{t,LE,AV}}$ * adjustment	0.37	.549	$< .01$
Adjustment * t_{LCD}	1.25	.270	$< .01$
$t_{\text{t,LE,AV}}$ * adjustment * t_{LCD}	1.77	.192	$< .01$

Table 7.5: Results of the ANOVA (2 (lane change duration t_{LCD}) x 2 (adjustment of target time headway) x 2 (target time headway $t_{\text{t,LE,AV}}$)) for the surveyed *predictability*.

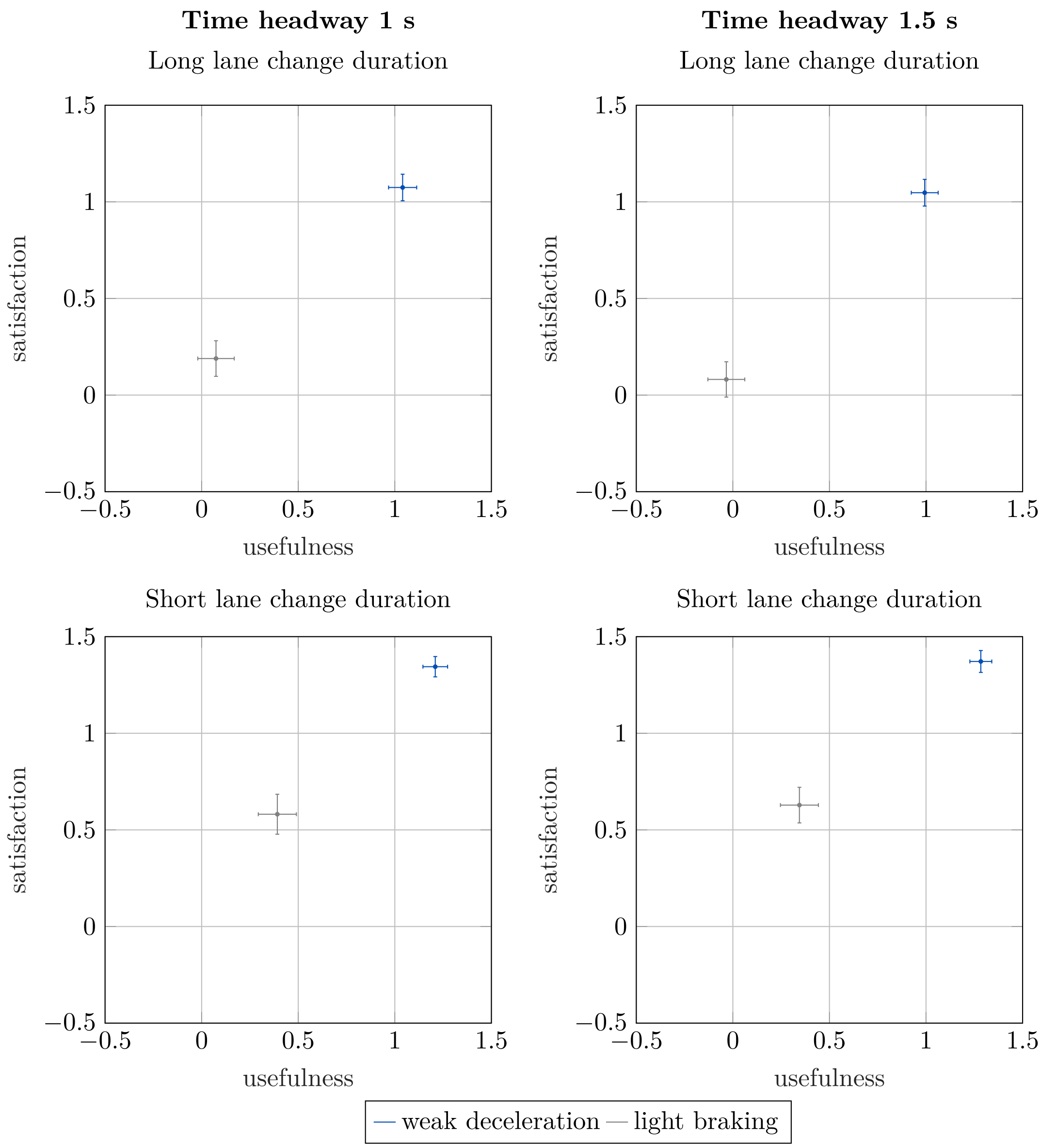


Figure 7.8: Means and errors of subjective *acceptance* ratings from -2 to 2.

significantly different with largest effect size. AV's driving styles in which the adjustment of the target time headway is reached with weak deceleration only, are rated with higher *acceptance*. Nevertheless, AV's driving styles in which the adjustment of the target time headway is made with light braking are still in the positive area of the scale. The difference between long and short lane change duration are also significant: short lane change durations are rated with higher *acceptance* than long lane change durations. The factor target time headway makes no significant difference with very high p-value.

Independent variable	$F(2,35)$	p	η_p^2
$t_{\mathrm{t,LE,AV}}$	0.11	.900	$< .01$
t_{LCD}	7.80	.002	.31
Adjustment	18.21	$< .001$	.51
$t_{\mathrm{t,LE,AV}}$ * t_{LCD}	0.18	.84	.01
$t_{\mathrm{t,LE,AV}}$ * adjustment	0.37	.70	.02
Adjustment * t_{LCD}	0.70	.50	.04
$t_{\mathrm{t,LE,AV}}$ * adjustment * t_{LCD}	0.80	.46	0.04

Table 7.6: Results of the MANOVA (2 (lane change duration t_{LCD}) x 2 (adjustment of target time headway) x 2 (target time headway $t_{\mathrm{t,LE,AV}}$)) for the surveyed *acceptance* over the scales satisfying and usefulness.

Those findings are confirmed by the ANOVA for repeated measure design of both scales with Bonferroni adjustment ($\alpha = \alpha/2$). The influence of the adjustment of the target time headway has a significant influence: satisfying ($F(1,36) = 37.46$, $p < .001$, $\eta_p^2 = .18$); usefulness ($F(1,36) = 32.60$, $p < .001$, $\eta_p^2 = 0.16$). Also the influence of the lane change duration is significant: satisfying ($F(1,36) = 5.80$, $p = 0.021$, $\eta_p^2 = .02$); usefulness ($F(1,36) = 11.20$, $p < .001$, $\eta_p^2 = .04$). The influence of the target time headway is not significant: satisfying ($F(1,36) = 0.15$, $p = 0.70$, $\eta_p^2 < .01$); usefulness ($F(1,36) = .03$, $p = .873$, $\eta_p^2 < .01$). There are no significant interactions.
The adjustment of the target time headway is significant with a large effect size and therefore hypothesises H1.2 is accepted. The significant main effect lane change duration shows a large effect size. Therefore, also hypothesis H3.2 can be confirmed. The target time headway has no significant influence with a high p-value. Thus, hypothesis H2.2 must be rejected.

In order to validate the quality of the used questionnaire the Cronbach's α for both scales is calculated. Both scales are highly reliable (usefulness: Cronbach's $\alpha = .94$, satisfaction: Cronbach's $\alpha = .94$), which can be traced back too a high inter-item-correlation (usefulness: $r > .83$, satisfaction: $r > .85$),

7.3.1.3 Criticality

The surveyed *criticality* as described in section 7.2.4.1 is provided in Figure 7.9. Mean values of all manoeuvres are mostly rated in the area of harmless only AV's driving styles with light braking are partly rated with unpleasant or higher. To avoid property and personal damage during the study, the AV's driving style should not be rated as dangerous or uncontrollable (correspond to a scale value seven and higher). This is reached mainly. Eight of 148 manoeuvres with light braking are rated with value seven or higher (always variations with light braking). A three-way ANOVA for repeated measure design (Table 7.5) shows a

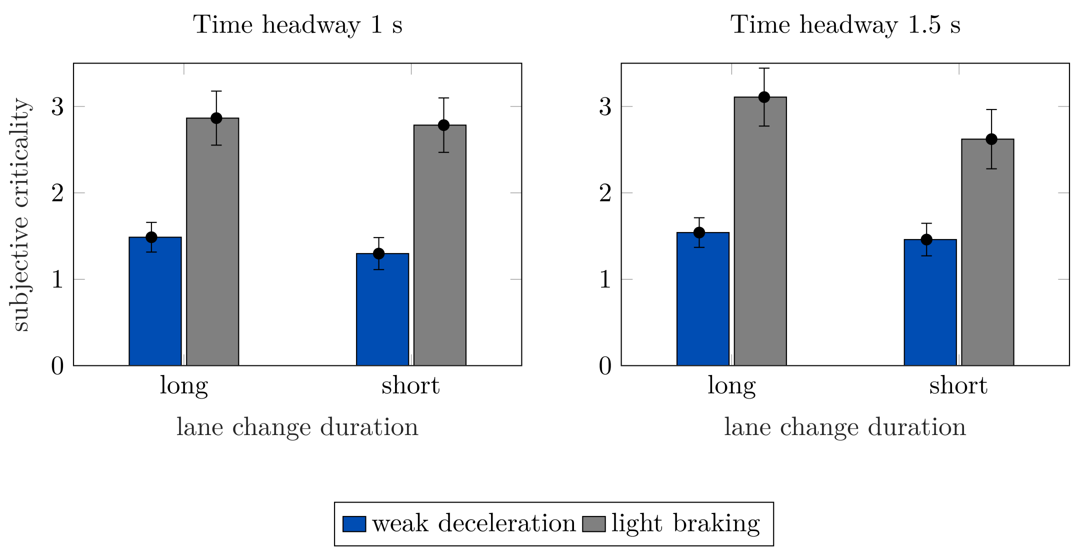


Figure 7.9: Means and errors of subjective *criticality* ratings from 0 to 10.

significant lower *criticality* for AV's driving styles in which the adjustment of the target time headway is made with weak deceleration only than with light braking. The main effects lane change duration and time headway are not significant.

Independent variable	$F(1, 36)$	p	η_p^2
$t_{\mathrm{t,LE,AV}}$	0.45	.508	$< .01$
t_{LCD}	1.23	.275	$< .01$
Adjustment	30.55	$< .001$	.16
$t_{\mathrm{t,LE,AV}}$ * t_{LCD}	0.41	.526	$< .01$
$t_{\mathrm{t,LE,AV}}$ * adjustment	0.10	.757	$< .01$
Adjustment * t_{LCD}	0.31	.583	$< .01$
$t_{\mathrm{t,LE,AV}}$ * adjustment * t_{LCD}	0.95	.335	$< .01$

Table 7.7: Results of the ANOVA (2 (lane change duration t_{LCD}) x 2 (adjustment of target time headway) x 2 (target time headway $t_{\mathrm{t,LE,AV}}$)) for the surveyed *criticality* ratings.

Figure 7.10 illustrates, that the time headway between the AV and lag vehicle of the adjusted gap at the factor level light braking, in order to adjust the target time headway shortly after the start of the lane change, remains the same or even decreases for a brief interval. Thereafter, the participants seem to overcompensate, which results in a strong increase of the time headway afterwards. At the factor level weak deceleration after a constant or even decreasing period, the time headway shows an almost constant increase up to approx. the time headway required by German road regulation for car-following (cf. section 3.2) of 1.5 s. This results in two characteristic points of the graph's course for different variation of the AV's driving style, analysed in the following: minimum time headway after the intersection of both vehicles on the target lane and the maximum time headway.

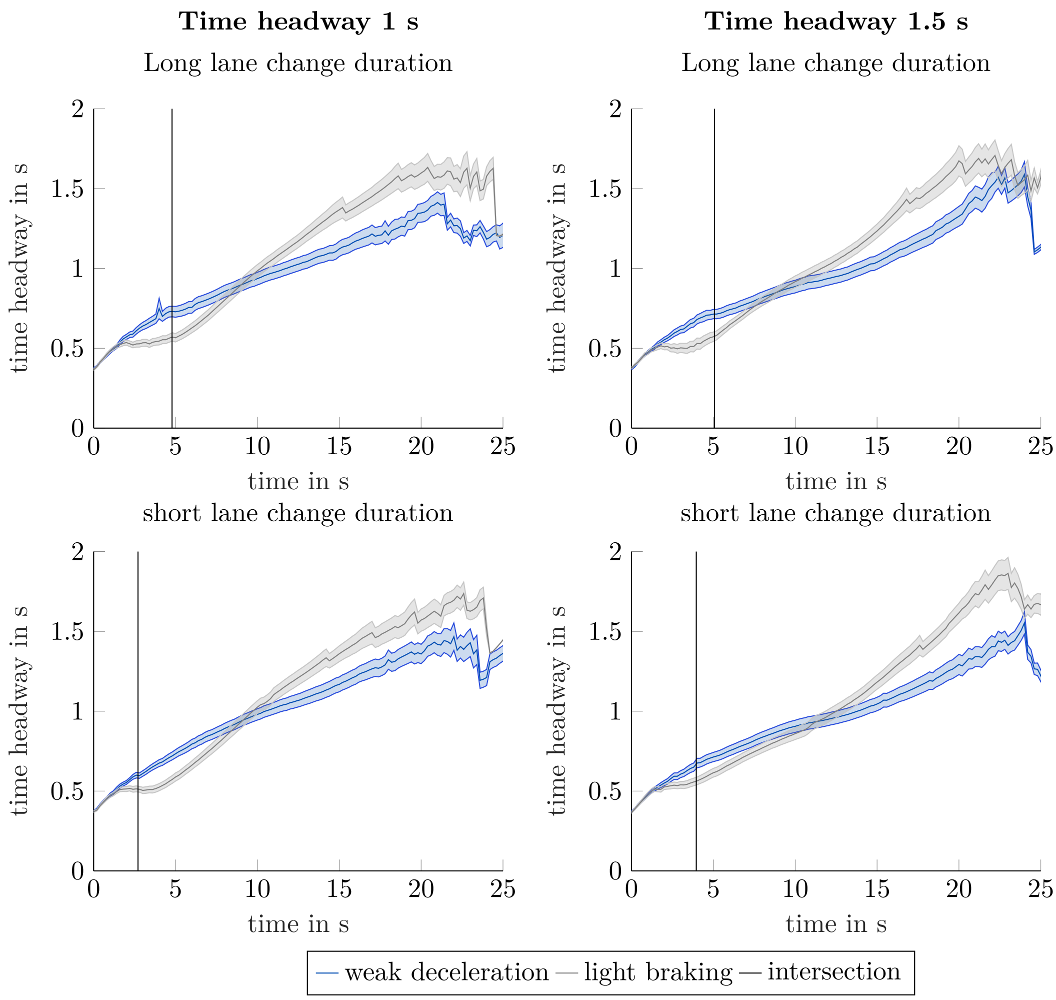


Figure 7.10: time headway between the AV and lag vehicle over time for the different variations. The AV starts the lane change at time = 0. The black line (intersection) represent the mean time span from the start of the lane change to the point the AV's right side and the lag vehicle's left side y-position in Frenet coordinates are intersecting on the target lane.

Only if the AV and the lag vehicle are intersecting on the target lane a collision of both traffic participants is possible. The minimum time headway between the AV and lag vehicle of the adjusted gap from this time stamp is provided in Figure 7.11. A three-factorial ANOVA for repeated measure design (Table 7.8) shows that the adjustment of target time headway is significant in the same way as for the surveyed *criticality*. AV's drivings styles with light braking lead to significant lower minimum time headway and therefore to higher *criticality* of the scenario. In contrast to the subjective measure also AV's driving styles with a long lane change duration lead to greater minimum time headway and therefore, also to a decreasing *criticality*.

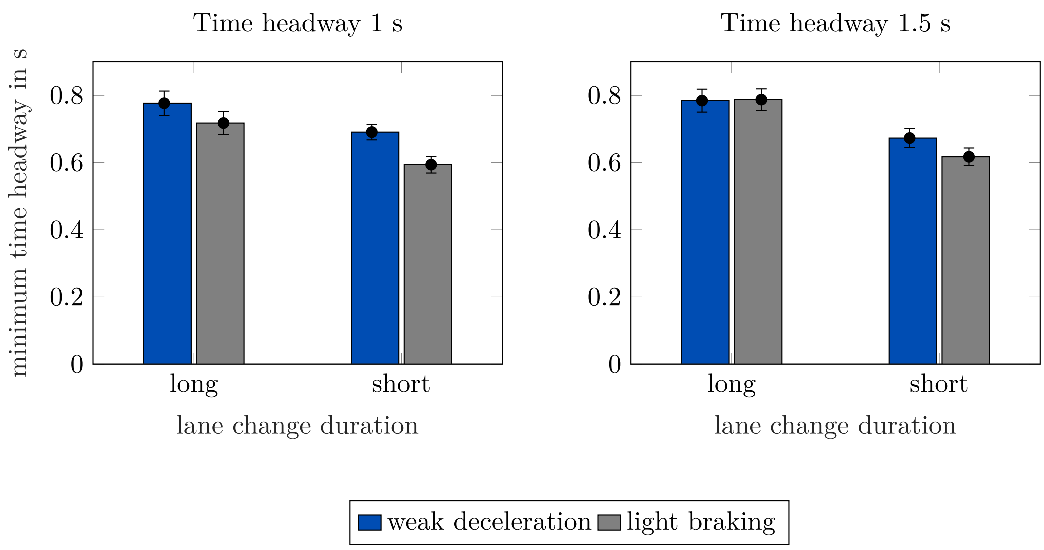


Figure 7.11: Means and errors of minimum time headway between the AV and lag vehicle after the AV's right side and the lag vehicle's left side y-position in Frenet coordinates are intersecting.

Independent variable	$F(1, 36)$	p	η_p^2
$t_{\mathrm{t,LE,AV}}$	1.74	.110	$< .01$
t_{LCD}	70.25	$< .001$	.10
Adjustment	10.89	.001	.02
$t_{\mathrm{t,LE,AV}}$ * t_{LCD}	1.27	.266	$< .01$
$t_{\mathrm{t,LE,AV}}$ * adjustment	3.87	.057	$< .01$
Adjustment * t_{LCD}	3.08	.087	$< .01$
$t_{\mathrm{t,LE,AV}}$ * adjustment * t_{LCD}	0.05	.815	$< .01$

Table 7.8: Results of the ANOVA (2 (lane change duration t_{LCD}) x 2 (adjustment of target time headway) x 2 (target time headway $t_{\mathrm{t,LE,AV}}$)) of minimum time headway between the AV and lag vehicle after the AV's right side and the lag vehicle's left side y-position in Frenet coordinates are intersecting.

The adjustment of the target time headway is significant in the subjective and objective measure and therefore hypothesis H1.4 is accepted. The significant main effect lane change duration, is only significant in the objective measure of the minimum time headway between the AV and the lag vehicle after the AV's right side and the lag vehicle's left side y-position in Frenet coordinates are intersecting. Because the results illustrate that a short lane change duration leads only to a more critical scenario for a brief interval shortly after the start of the lane change, the hypothesis H3.4 is partly accepted. The target time headway has no significant influence with a high p-value and therefore hypothesis H2.4 must be rejected.

7.3.1.4 Workload

The surveyed *workload* as described in section 7.2.4.1 is provided in Figure 7.12. A three-

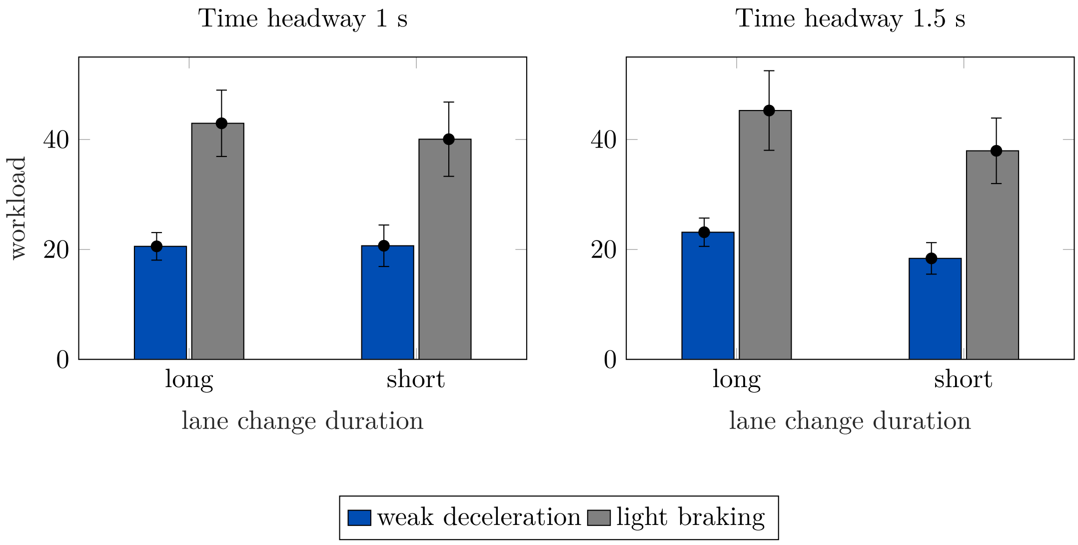


Figure 7.12: Means and errors of subjective workload ratings from 0 to 220.

way ANOVA for repeated measure design (Table 7.9) shows a significant lower *criticality* for AV's driving styles in which the adjustment of the target time headway is made with weak deceleration than with light braking and therefore hypothesis H1.5 is accepted. Different lane change durations result in no significant difference. Thus, hypothesis H3.4 is not accepted. The target time headway has no significant influence with a high p-value. As a result, hypothesis H2.4 must also be rejected.

7.3.1.5 Gaze behaviour

The participants' AOIs are only successfully recorded for N = 14 participants, due to calibration failures over the duration of the study. In order to analyse exploratory question (Q1.1), the percentage of the proportion of the AOI is illustrated in Figure 7.13. The proportion of AOI's are comparable for all different variation of the AV's driving style. At the time point

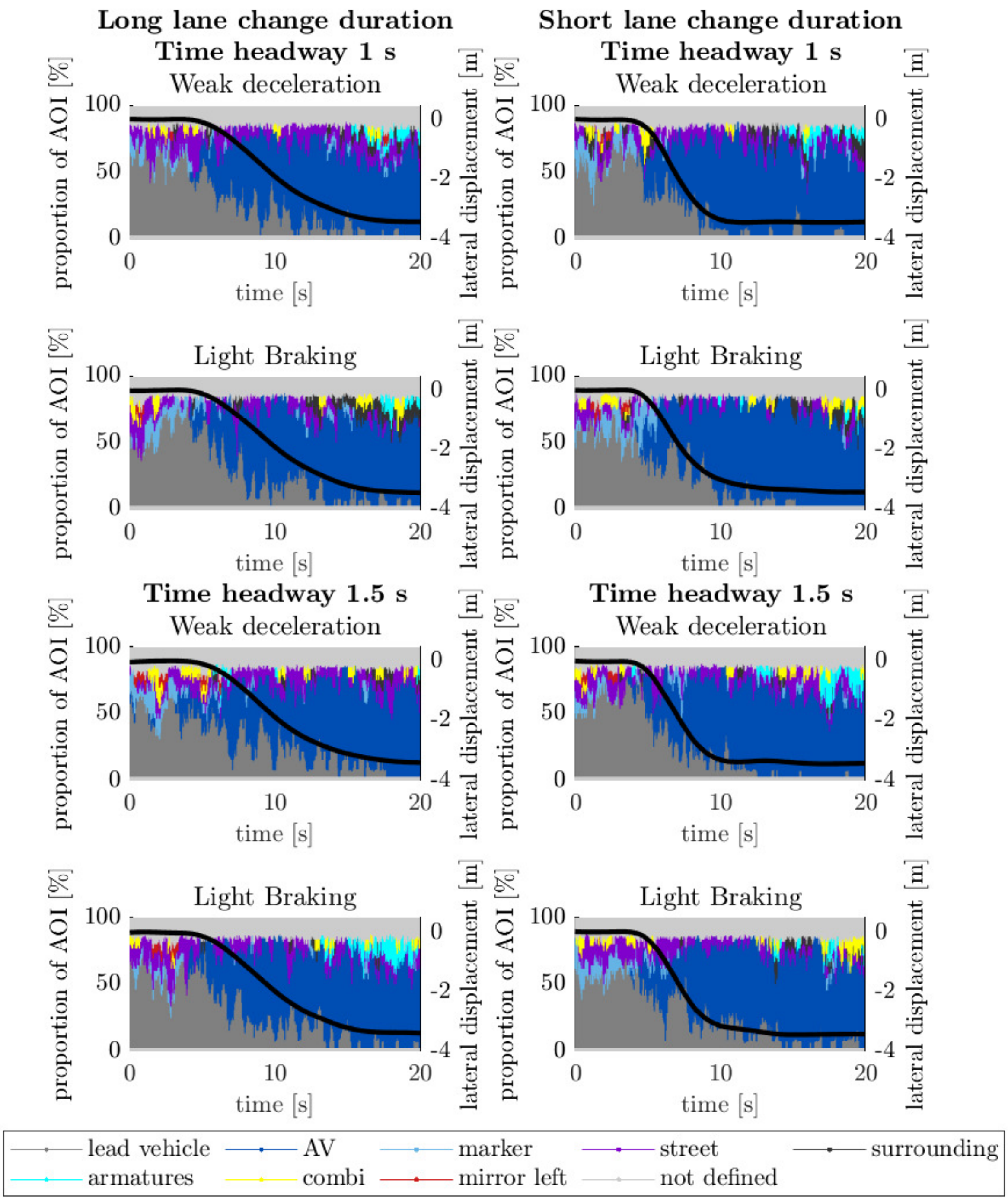


Figure 7.13: Proportion of the AOI from the time equal to zero the AV and lag(participant's) vehicle was at the same height. The black thick lane represents the AV's lateral displacement during the lane change.

Independent variable	$F(1,36)$	p	η_p^2
$t_{\mathrm{t,LE,AV}}$	$< .01$	.970	$< .01$
t_{LCD}	3.52	.069	$< .01$
Adjustment	14.19	$< .001$	.10
$t_{\mathrm{t,LE,AV}}$ * t_{LCD}	1.68	.203	$< .01$
$t_{\mathrm{t,LE,AV}}$ * adjustment	.01	.906	$< .01$
Adjustment * t_{LCD}	1.06	.310	$< .01$
$t_{\mathrm{t,LE,AV}}$ * adjustment * t_{LCD}	$< .01$	.973	$< .01$

Table 7.9: Results of the ANOVA (2 (lane change duration t_{LCD}) x 2 (adjustment of target time headway) x 2 (target time headway $t_{\mathrm{t,LE,AV}}$)) of the surveyed workload ratings.

at which the AV and the lag vehicle are at same height, the participants are mainly focusing the ‘lead vehicle’. Also a percentage of the AOIs is at the ‘street’, ‘combi’, or ‘marker’ at the windscreen, an orientation to meet the study instructions to keep a time headway of 1 s to the lead vehicle. Before the start of the AV’s lane change only a small proportion of the participants’ AOIs is at the future cut-in vehicle (‘AV’) or the ‘left mirror’. Only with the start of the lane change participants focus their sharp seeing part of the eye to the ‘AV’ with a considerably percentage.

Figure 7.14 illustrates also that the AOI changes increase in this part of the manoeuvres. Those changes, as illustrated in the individual AOIs for all successfully recorded participants in the appendix (cf. Figure A.1 - A.14 in the appendix), are mainly between the ‘lead vehicle’ and the ‘AV’. Some are also between the ‘street’ and the ‘AV’ in those cases the participants were fixating points on the street before the lead vehicle instead of the vehicle itself.

During the lane change the focus shifts from the ‘lead vehicle’ to the ‘AV’ and little by little to the new vehicle in front of the participants driving the lag vehicle. After the AV has changed lanes the relative AOI changes are decreasing at roughly the same level as at the start of the lane change. From this point, also AOIs to the ‘surrounding’, ‘combi’ or ‘armatures’ of the lag vehicle, and at the location of the questionnaires, are increasing. The AOI ‘not defined’ represents time stamps at which no AOI could be labelled. Possible reasons are saccades between AOI’s fixation or inaccuracies of the eye tracking system.

Over the whole manoeuvres the participants changed their AOIs in mean between 17 and 20 times, as illustrated in Figure 7.15. Those are slightly higher for long than for short lane change durations. There is no notable change in the gaze behaviour, by comparing Figure 7.13 and Figure 7.14, in case the AV has different target time headway (Q1.2) or adjusts

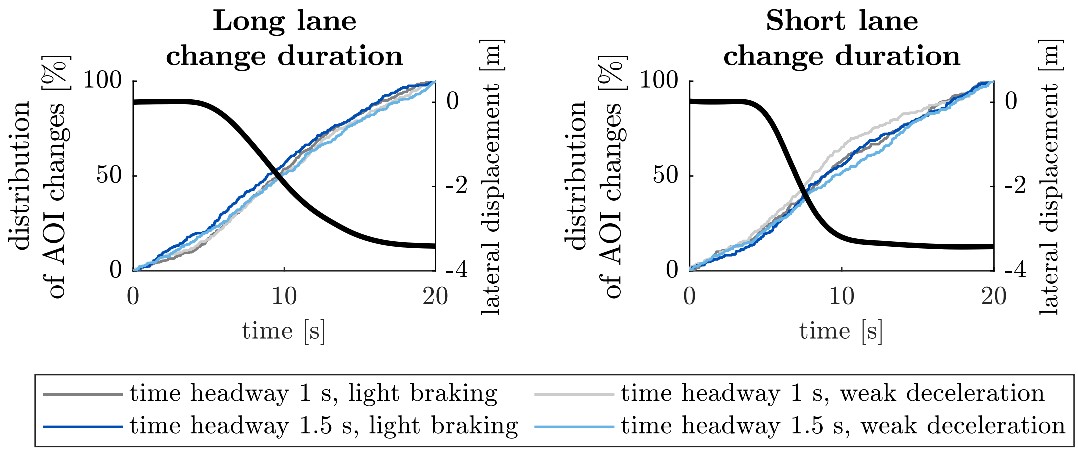


Figure 7.14: Distribution of AOI changes over different variations of the AV's driving style. At time equal to zero the AV and lag (participant's) vehicle was at the same height. The black thick line represents the AV's lateral displacement during the lane change.

those differently (Q1.4). The total AOI changes seem to be slightly higher at long than at short lane change duration (Q1.3).

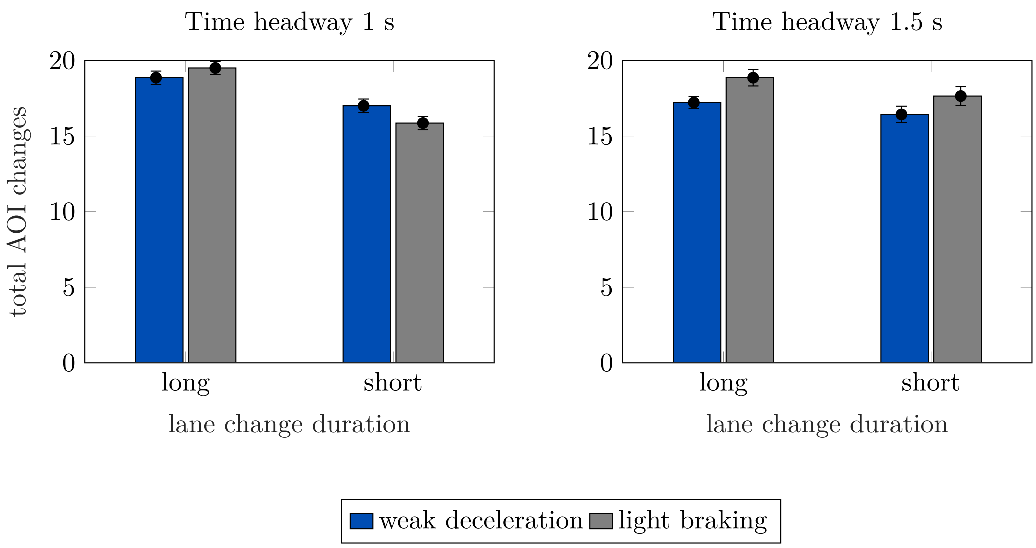


Figure 7.15: Means and errors of total AOI changes at different variations of the AV's driving style.

7.3.2 Part II

In the second part of the study participants were also changing the perspective. The participants drove for three manoeuvres in a row either the lag or lead vehicle of the adjusted gap and changed then to the vehicle not yet driven. In order to evaluate differences between both perspectives, subjective ratings could be used only.

7.3.2.1 Predictability

The surveyed *predictability* is illustrated in Figure 7.16. A two-way ANOVA for repeated measure design is conducted (Table 7.10). The results show that both main effects adjustment

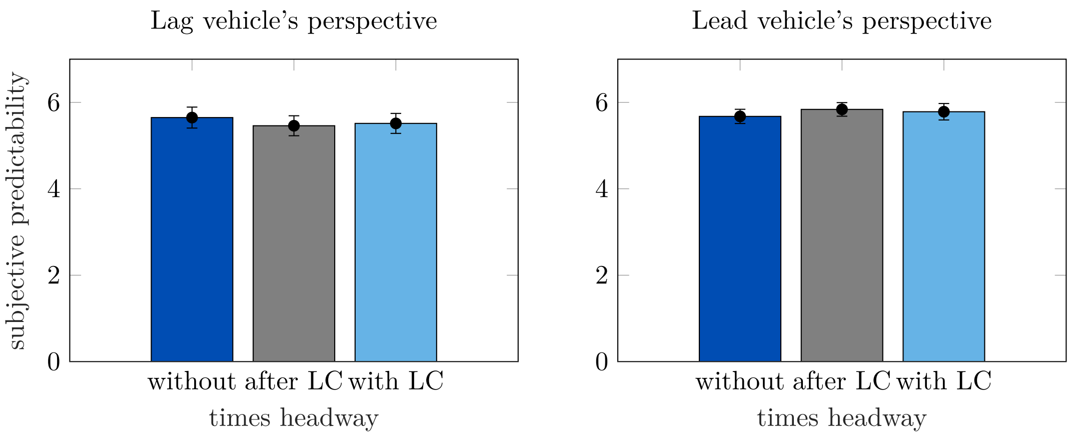


Figure 7.16: Means and errors of subjective *predictability* ratings.

and perspective have no significant influence on the *predictability* ratings. Especially the *p*-value for the main factor adjustment is very high, which suggest that there is really no difference between all three presented variations. Thus, hypothesis (H4.1) and (H5.1) are neglected.

Independent variable	F	p	η_p^2
Perspective	$F(1,36) = 2.34$	.134	$< .01$
Adjustment	$F(2,72) < 0.01$	.996	$< .01$
Perspective * adjustment	$F(2,72) = 0.49$	.615	$< .01$

Table 7.10: Results of the ANOVA (2 (perspective) x 3 (adjustment)) for the surveyed *predictability*.

7.3.2.2 Acceptance

The surveyed *acceptance*, consisting of the scales satisfying and usefulness described in section 7.2.4.1 is provided in Figure 7.17. A two-way MANOVA for repeated measure design is conducted (Table 7.11). Results show that both main effects adjustment and perspective

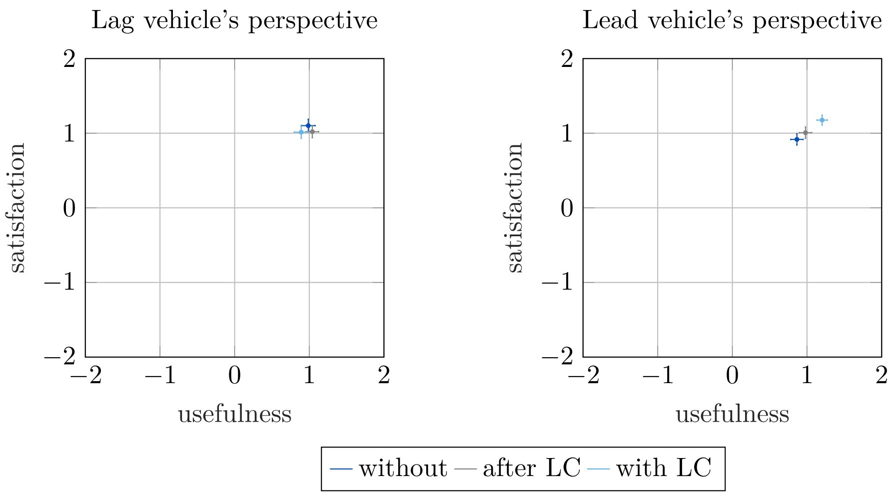


Figure 7.17: Means and errors of subjective *acceptance* ratings.

have no significant influence on the *acceptance* ratings. This is also true for the univariate analysis of the scales usefulness and satisfying. Hypothesis (H4.2) and (H5.2) are neglected.

Independent variable	F	p	η_p^2
Perspective	$F(1, 36) = 0.44$	.647	.025
Adjustment	$F(2, 72) = 0.74$	.568	.040
Perspective * adjustment	$F(2, 72) = 1.52$	.199	.08

Table 7.11: Results of the MANOVA (2 (perspective) x 3 (adjustment)) for the surveyed *acceptance* over the scales satisfying and usefulness.

In order to validate the quality of the used questionnaire the Cronbach's α for both scales is calculated. Both scales are highly reliable (usefulness: Cronbach's α = .93, satisfaction: Cronbach's α = .96), which can be traced back to a high inter-item-correlation (usefulness: $r > .85$, satisfaction: $r > .91$),

7.3.2.3 Criticality

The surveyed *criticality* is illustrated in Figure 7.18. A two-way ANOVA for repeated measure design is conducted (Table 7.12). Results show that both main effects adjustment and

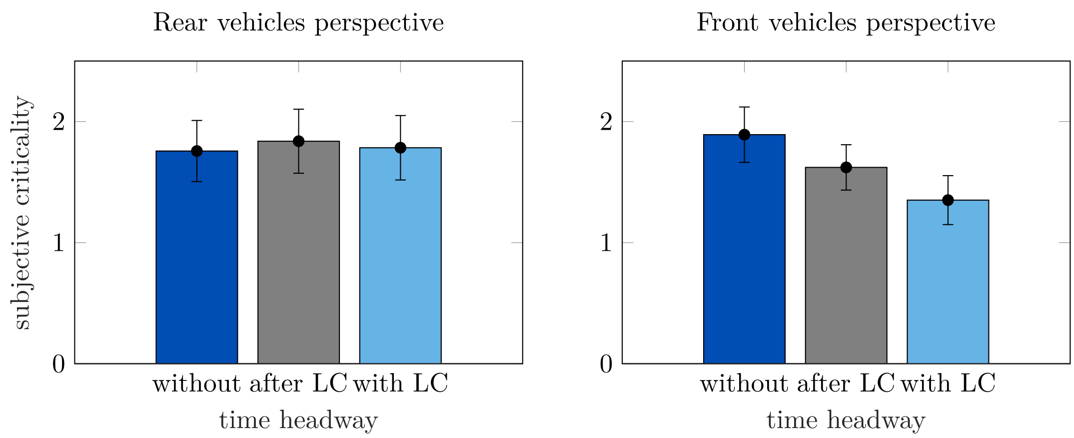


Figure 7.18: Means and errors of subjective *criticality* ratings.

perspective have no significant influence on the *criticality* ratings. Hypothesis (H4.3) and (H5.3) are neglected.

Independent variable	F	p	η_p^2
Perspective	$F(1, 36) = 0.84$	.365	$< .01$
Adjustment	$F(1.864, 67.109) = .96$	.381	$< .01$
Perspective * adjustment	$F(1.769, 63.680) = 1.12$	.324	$< .01$

Table 7.12: Results of the ANOVA (2 (perspective) x 3 (adjustment)) for the surveyed *criticality*.

7.3.2.4 Workload

The surveyed *workload* is illustrated in Figure 7.19. A two-way ANOVA for repeated measure design is conducted (Table 7.13). Results show that both main effects adjustment and perspective have no significant influence on the *workload* ratings. Hypothesis H4.4 and H5.4 are neglected.

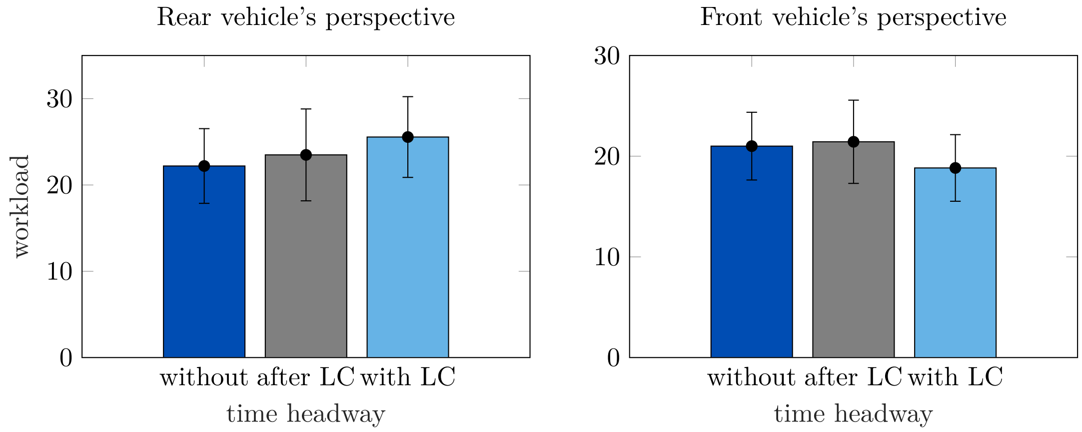


Figure 7.19: Means and errors of subjective *workload* ratings.

Independent variable	F	p	η_p^2
Perspective	$F(1, 36) = 0.98$	.329	$< .01$
Adjustment	$F(1.669, 60.068) = 0.02$	.960	$< .01$
Perspective * adjustment	$F(1.575, 56.685) = 0.48$	.574	$< .01$

Table 7.13: Results of the ANOVA (2 (perspective) x 3 (adjustment)) for the surveyed *workload*.

7.3.3 Participants' comments

The participants' comments for each manoeuvre in both parts of the study are clustered. The *acceptance* ratings of each cluster is illustrated in Figure 7.20. Most of the manoeuvres (333) are not commented. In case the participants decide to comment manoeuvres the *acceptance* ratings in mean are decreasing. The rating the AV 'slowed me down' is rated with the lowest *acceptance* rates 64 times. Moreover, the participants stated comments due to the lane change duration. Thus, 39 comments rated the slow lane change duration as too slow ('LC too slow'). Only 11 comments rated the fast lane change duration as too fast ('LC too fast'). Also participants commented 12 times that the AV's positions at the starting lane before the start of the lane change was too close to the lead vehicle of the adjusted gap ('position too far forward') and 14 times was too close to the lag vehicle of the adjusted gap ('position too far backward'). The *acceptance* rating of those comments suggest it is better to avoid that the AV gets too close to the lag vehicle than to the lead vehicle of the adjusted gap.

Even though the condition under which the AV started the lane change was kept constant over all manoeuvres according the comments, participants experienced those differently. Comments concerning the start of the lane change were: the AV 'waited too long', 'hesitant' or 'waited too short'. Since, those comments refer to the timely behaviour that was not controlled as starting condition of the lane change, the time span between the AV and lag

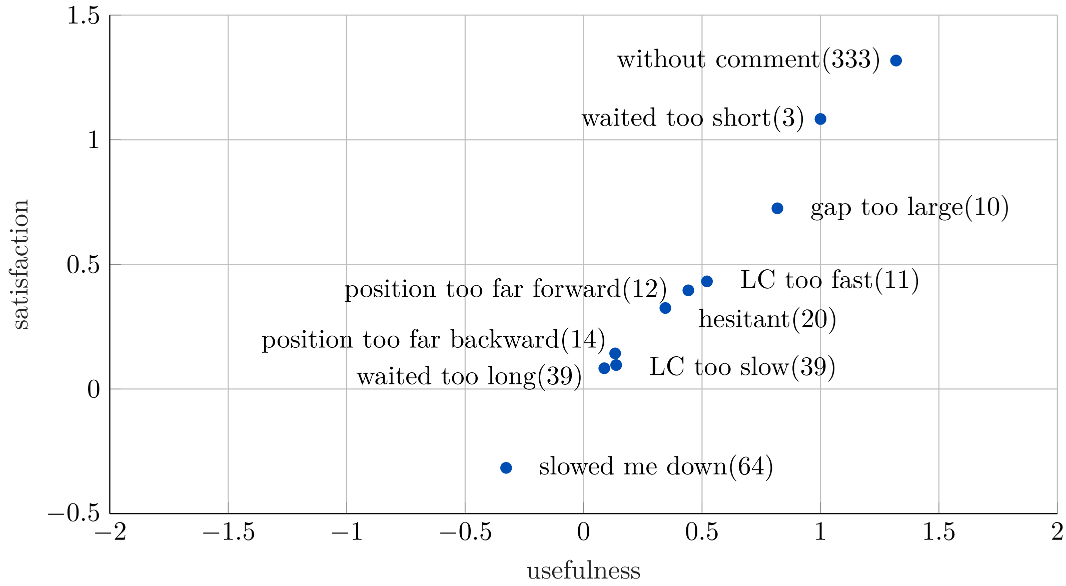


Figure 7.20: Acceptance ratings and error of manoeuvres with different clusters of participants' comments over the scales satisfaction and usefulness for both parts of the study [from -2 to 2].

vehicle was at same height and the start of the lane change is illustrated in Figure 7.21. The

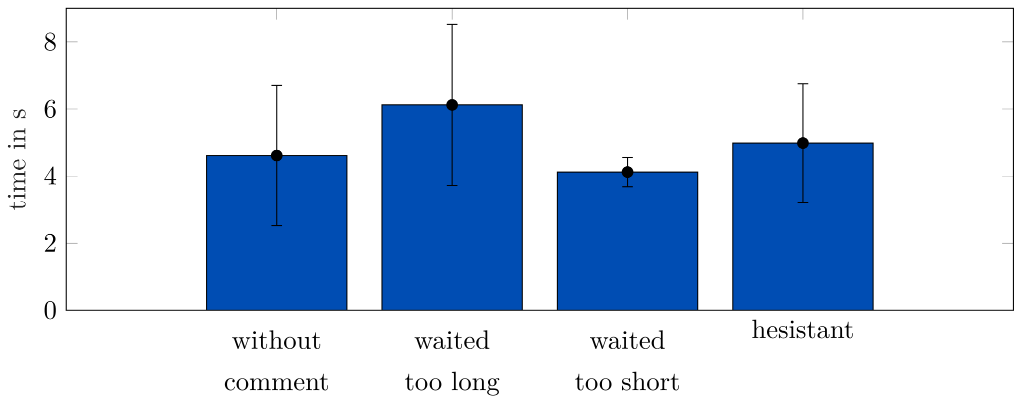


Figure 7.21: Mean and standard deviation of the interaction time the AV was at same height as the lag vehicle and the start of the lane change.

Figure shows that at manoeuvres 'without comment' the mean interaction time is M = 4.61 s with a standard deviation of SD = 2.09 s. 20 manoeuvres are commented with 'hesitant'. Those show a comparable mean time span M = 4.98 s and a standard deviation SD = 1.77 s. Since all of those manoeuvres were with short lane change duration, suggest that those comments were strongly related to lane change duration. Manoeuvres (39) commented with the AV 'waited too long' to start to change lanes show a considerably longer mean time span of M = 6.12 s with a standard deviation of SD = 2.4 s. Even a few manoeuvres (3) where commented with the AV 'waited too short' to start with the lane change (M = 4.12 s, SD = 0.44 s). Figure 7.22 shows the frequency of the interaction times where the AV 'waited too long'. Interaction times from 2.5 s are too long, but most of them are lying above the mean interaction time of all manoeuvres 'without comment'.

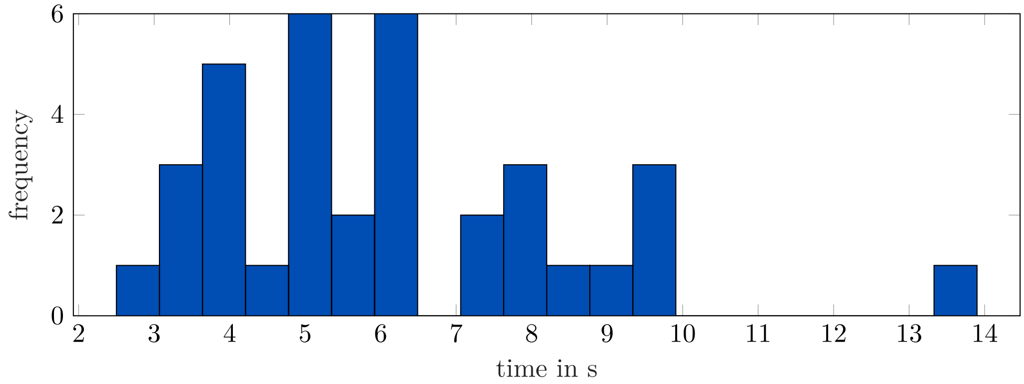


Figure 7.22: Frequency of different interaction time spans that were rated with the AV 'waited too long'.

7.3.4 Post-test

The participants answered the post-test described in section 7.2.4.2. They participants expect the start of the lane change in mean M = −0.14 a bit earlier with a standard error of SE = 0.08. With 29 of 37 participants a standardized final interview is conducted. 27 participants state that the AV could drive in real dense traffic scenario with the AV's driving style they rated best. 28 participants state that they recognized differences between the different variations of the AV's driving styles. Moreover, 22.2 % of the participants state to prefer the long and 59.2 % the short lane change duration. The remaining 18.6 % have no preference.

7.4 Discussion and conclusion

The present study evaluates different possibilities to design the AV's driving style at the execution of the lane change in a dense mixed-traffic scenario. The study focuses on a lane change to the right into a gap in front of the AV and was evaluated from the perspective of the lead and lag vehicle of the adjusted gap (cf. section 4.2.1). The following section describes the behaviour patterns that should be considered and those that don't have a significant influence to the evaluations of interacting human drivers by means of the key questions introduced in section 4.1.2, due to the step *Execute the lane change* of the procedure to design an AV's driving style from interacting human drivers' perspective (cf. section 4.1.1).

Does it make a difference how large the distance to the lead vehicle of the adjusted gap is expanded and at what time?

Comparable to human drivers should the AV start to change lanes into small adjusted gaps, whereby it is not possible to keep safety distances required by road traffic regulations (cf. section 3.2). However, this study gives reason to believe, based on the first and second study part, that the AV could start to increase its time headway to the lead vehicle of the adjusted gap already with the start of the lane change, comparable to human driving style at lane changes (cf. section 3.2.2).

The first part of the study shows no significant influence of the target time headway on the subjective measurements of the *predictability* (p = .725), *acceptance* (p = .900), *workload* (p = .970) or subjective (p = .508) or objective (p = .110) *criticality*, (cf. Table 7.5, 7.6, 7.9, 7.7, 7.8, respectively). Moreover, no significant interactions with the factor level target time headway are shown. The high p-values give reason to believe that the participants recognized no difference between the variations. In the second part of the study, the moment the relaxation starts ('with LC' or 'after LC') or to increase the target time headway only 'marginal' does also not influence the subjective *predictability* (p = .996), *acceptance* (p = .568), *criticality* (p = .381) and *workload* (p = .960) of interacting human drivers significantly, with also very high p-values (cf. Table 7.10, 7.11, 7.12, 7.13, respectively). There is also no significant interaction between the factor level perspective and the factor level adjustment of the target time headway. Thus, it seems also to be suitable for the drivers of the lead vehicle of the adjusted gap, if the AV does increase the time headway only 'marginal' during and after the lane change.

Thus, the AV can start to increase the distance during the lane change in order to increase its response times to the lead vehicle of the adjusted gap as early as possible. Or the AV cannot increase the distance to target vehicle at all and therefore follow with a short time headway, in order to increase the road capacity. Even though a target time headway of 0.5 s might be safe for AVs (Friedrich, 2015). The result should not be interpreted in a way that close following distances do not influence the ratings. It is likely that tailgating is not accepted for longer distances, which could not be investigated. Every manoeuvre had a maximum duration of approx. 25 s, from the point the AV started to change lanes (cf. Figure 7.4). Depending on the time to execute the lane change (M = 12.2 s) (cf. Figure 7.5) itself, the close following distance was only maintained for a few seconds after the AV changed lane. Moreover, the driver of the lead vehicle is exposed to danger with such small following distances and such a driving style is not permitted, according to German road regulations (cf. section 3.2).

Are braking interventions permitted to increase the target time headway?

Even if the AV should start the lane change with small time headway to the lead vehicle of the adjusted gap and the increase of the time headway can be started immediately with the start of the lane change, this should still be done slowly. The study shows that in order to increase the target time headway usage of the vehicle's brakes should be avoided, as far as possible.

AV's driving styles with light braking are rated consistent significantly worse than AV's driving styles, in which the target time headway is adjusted with weak deceleration only. AV's driving styles with light braking are in mean rated as 'harmless' to the border of 'unpleasant' (cf. Figure 7.9). Nevertheless, eight manoeuvres with light braking are rated with 'dangerous' or higher. AV's driving styles with weak deceleration are rated in mean as 'harmless' but to the border of 'nothing noticed'. The clearest significant drop in rating shows the *acceptance* scale (cf. Table 7.6), in case the AV adjusts target time headway with light braking. Also that 30 % of the participants' comments (cf. Figure 7.20) were stated due to the AV's driving style with light braking and those manoeuvres caused the only drop in the negative area of the *acceptance* scale shows convincingly that such behaviour should be avoided.

The bad ratings could also have been caused by the AV's driving style at the factor level with light braking. At this factor level the time headway overshot above the desired one, which resulted in an increase of the velocity to adjust the desired time headway after the light braking (cf. Figure 7.2a and Figure 7.2b). However, Bengler and Zimmer (2002) made experiments at comparable deceleration intensities to the present first part of the study at the AV's driving style with light braking (cf. Figure 7.2a) and showed that the perception of the deceleration of lead vehicles of the human driver is mainly dominated by the brake light. Moreover, the participants had the chance to comment the reasons for the ratings on the manoeuvre, wherein the participants did not relate the bad ratings to the AV's driving style with a deceleration and acceleration behaviour caused by the overshoot but to the AV's deceleration and therefore the light braking, only (cf. Figure 7.20). Thus, it is likely that the bad rating are caused by the brake light activation of the AV or the light braking itself and not by the AV's driving style, which was characterized by the overshoot.

Do interacting human drivers prefer long or short lane change durations?

Participants prefers the shorter evaluated variation of the lane change duration. The short lane change duration is lying at the lower limit of the passenger's comfort (cf. section 3.3). Because, in AV's driving styles with short lane change durations the AV's starting lane is freed faster than with long lane change durations, such a driving style could influence the traffic flow on the AV's starting lane positively.

The lane change duration has significant influence on the *predictability* of the AV's driving style (cf. Table 7.5) with a large effect size. AV's driving styles with short lane change duration are rated significantly more predicable than AV's driving styles with long lane change duration. A possible cause is that the long lane change durations presented in this study are very seldom (Kreisel, 2016) and short lane change durations are comparable to the driving style of human drivers (cf. section 3.2.2) that lie in mean between 2.5 s - 6.28 s (cf. Table 3.4). The objective *criticality* measure of the minimum time headway between the AV and the lag vehicle of the adjusted gap from the point both vehicle are intersecting on the target lane is significant lower with an AV's driving style with short than with long lane change duration (cf. Figure 7.10 and Table 7.8). A long lane change duration decreases the *acceptance* ratings significantly with a high effect size (cf. Table 7.6) and increases in the *workload* tend to be significant (cf. Table 7.9). A possible interpretation is that human drivers accept only the predicted behaviour. Another answer could be delivered by the analyses of the *gaze behaviour*. The analyses of the AOI changes shows a steeper slope of the distribution of AOI changes (cf . Figure 7.14) over the lane change, what causes in mean a higher absolute number of AOI changes at AV's driving styles with long than with short lane change durations. Since, the analyses of the *gaze behaviour* is done, due to recording errors, with 14 participants only, the validity of this argument is limited.

8 Implications, discussion, limitations and future work

Chapter 3 analyses the discrepancy between human driving style and road traffic regulation in car-following and lane change scenarios (cf. section 3.2). Based on the summarized human driving styles in car-following, it has to be expected that AVs also have to execute mandatory lane changes into small adjusted gaps. In order to design an AV's driving style for a lane change in dense mixed-traffic a communication model between AVs and human drivers is derived in this thesis (cf. section 4.1.1). The communication model is used to define a procedure to design an AV's driving style, that maximizes the chance that interacting human drivers cooperate enough that the lane change can be executed. The procedure to design an AV's driving style in cooperative mandatory lane change scenarios (cf. section 3.1) contains five steps: 1. analyse, 2. communicate 3. interpret, 4. start, 5. execute (cf. section 4.1.1). Thus, the AV has to analyse the scenario, communicate the own intention to change lanes, interpret if interacting human drivers react cooperatively and to start and execute the lane change in case of cooperative or select a new adjusted gap in case of uncooperative interacting human drivers.

Based on the communication model (cf. section 4.1.1) systematic studies are carried out and an AV's driving style in lane change scenarios is derived, which, according to the participant's assessment, can be used on public roads (cf. section 7.3.4). The results are subject to restrictions and should be tested in real traffic but also in other and more complex scenarios (cf. section 3.1). In the following, every step of the procedure to design an AV's driving style from interacting human drivers' perspective is discussed and suggestions for future work are given. Moreover, implications for the design of an AV's driving style in lane change scenarios, three each of the research questions formulated respectively for the steps communicate, start, and execute (cf. section 4.1.2), based on the driving studies presented in chapter 5, 6, and 7 are summarized and discussed.

8.1 Analyse the scenario

The first step of the procedure to design an AV's driving style in a dense traffic mandatory lane change is simplified in context of this work. The first step includes the selection of the most suitable adjusted gap and the recognition that in specific scenarios a direct lane change without the cooperation of human drivers even into the most suitable adjusted gap is not possible. An algorithm is proposed in Potzy et al. (2019c). However, it is not tested for functionality under real conditions, such as in a real vehicle or traffic scenario, and thus represents an approach for further work.

To realize a realistic initial scenario on the test ground, comparable to dense traffic, two vehicles build the adjusted gap on the target lane and a simplified automation is implemented to enable the AV to change lanes into the adjusted gap (cf. section 4.2). An experiment represents an extraordinary situation for the participant and they are usually particularly concentrated. Due to the standardized repetition a high internal validity is achieved. A higher external validity is achieved on the test ground than in the driving simulator (Lietz et al., 2008). But, the external validity of the findings on the test ground is still limited. Human drivers' distance behaviour in traffic, e.g. depends on the velocity and the environment (Brackstone et al., 2009; Knospe et al., 2002). Furthermore, similar scenarios (cf. Figure 4.4) are considered in the course of this work, which the participants repeatedly experienced in permuted sequence with different variations of the AV's driving style the urgency of the AV's lane change or the target velocity. In the context of this thesis only velocities of the lead vehicle of the adjusted gap of $30\,\mathrm{km\,h^{-1}}$ and $50\,\mathrm{km\,h^{-1}}$ are investigated, due to limitation of the test track length. To transfer the results to the highway the evaluation of higher velocities and more complex scenarios, e.g. with more vehicles, is required.

To reach a comparable initial scenario at the target lane to dense traffic (cf. section 3.2.2), the time headway from the lag to the lead vehicle of the adjusted gap of $1\,\mathrm{s}$ is realized in the first study (cf. section 5.2.1) using the Adaptive Cruise Control of the lag vehicle. Since the deactivation of the Adaptive Cruise Control requires the active deactivation over the Adaptive Cruise Control lever or usage of the throttle or brake pedals, the distance is realized in the further studies (cf. section 6.2.1 and section 7.2.1) by sticking markers into the windscreen (cf. Figure 7.1b), which participants could use for orientation to realize the required distance. This is done in order to allow a natural reaction due to the intention to change lanes of the AV. That the participants used the marker to keep the distances is confirmed by the gaze analysis (cf. section 7.3.1.5). However, some participants stated that they found the markers in their field of vision disturbing and exhausting. An alternative would be to visualize the correct distance in the instrument cluster or in the head-up display, e.g. as implemented in driving simulators using an Enhanced Reality Strip (Frey, 2008). The human driver of the lead vehicle of the adjusted gap is driving with Cruise Control to hold the target velocity and to gain a standardized initial scenario. Only when the participants drove the lead vehicle of the adjusted gap in the second part of the third study (cf. chapter 7) they are asked to keep the recommended velocity manually.

Notwithstanding that the studies took place on a test ground, recording errors of the AV on the test track could not be avoided. The missing data is replaced by an Expectation Maximization analysis (cf. section 5.2.6, 6.2.6, and 7.2.6). Since, only a small fraction of the data is missing, the application of the Expectation Maximization analysis algorithm provides an adequate way to estimate the missing data and leads to a systematic underestimation of the standard error (Lüdtke et al., 2007).

A sample with limited representativeness to the population of drivers is tested. The studies are carried out in collaboration with the AUDI AG on a AUDI test track in Neuburg (cf. Figure 4.5). Due to the close company relations within the project and the resulting possibilities for recruitment at all studies, participants are recruited by a general call for participation and therefore a self-selection sample is tested (Döring and Bortz, 2016). As a result, the participants may be particularly motivated or interested in participating in studies and/ or ADAS or ADS (defined in section 2.2). In addition, a high proportion of the subjects in the first, second and third study are employees of the AUDI AG (cf. section 5.2.5, section 6.2.5, and section 7.2.5), who could tend to have a greater knowledge and interests in new developments of their-own company and therefore in AVs. Thus, the overall assessment of the AV's driving style could be more positive than with a population-representative sample. The second experiment is even conducted with an expert sample and thus exclusively with participants with previous knowledge in the development of ADAS and/ or ADS. This may affect the generalization of the results, since all participants had a profound knowledge of ADS and most of them had already experienced it themselves (cf. section 6.2.5). In addition, gender and age effects are shown in the choice of distances during car-following (Ohta, 1993; Taieb-Maimon and Shinar, 2001). It is also possible that the assessment of the AV's driving style is influenced by these variables, but is not balanced in the sample of the first and second study (cf. section 5.2.5 and section 6.2.5) and only partly in the third study (cf. section 7.2.5). Furthermore, the recruitment of the participants took place around the headquarters of the AUDI AG in Ingolstadt. Since both the legal requirements and the social norms depend on the respective country or culture (Antov et al., 2012), this could also have an influence on the evaluation of the AV's driving style.

8.2 Communicate the lane change

Position in clearly visible area! Figure 7.20 shows that manoeuvrers, in which the AV is not in the visual range of the human drivers driving the lag vehicle of the adjusted gap, are rated worse, descriptively. As the visual range of a driver is influenced by the vehicle geometry (Hudelmaier, 2003; Woyna, 2014), it is better if the AV is positioned too far forward (at the lead vehicle of the adjusted gap) than too far backward (at the lag vehicle of the adjusted gap).

Set the turn signal! Setting the turn signal is crucial to announce a lane change to interacting road users. This supports the findings of Kelsch et al. (2015) and confirms that the exchange of information via suitable interfaces is necessary (cf. section 4.1). The results are in a line with the findings of Ehmanns (Ehmanns, 2002, p.76), who teaches that human drivers react earlier to a cut-in vehicle communicating it's intention with a set turn signal, than if the turn signal is not set. The time when the AV and the lag vehicle of the adjusted gap are at the same height is a good choice to activate the turn signal in the evaluated scenario (cf. Figure 5.19). The importance to activate the turn signal emphasizes the benefit of direct communication (cf. section 4.1) and could be an indication to establish further eHMIs on the AV to support communication with human drivers also in further scenarios, such as e.g. to coordinate the right of way at a bottleneck (Rettenmaier et al., 2019, 2020).

Use the AV's driving style! It is shown that the AV's driving style can also be used as dHMI (cf. section 2.2.1) for the communication of the AV's intension (cf. section 4.1). Hard braking to the adjusted gap is detected faster than light braking (cf. chapter 5). If the AV's turn signal is not set to communicate the AV's intention to change lanes, a lateral offset in advance of the AV's lane change does results in an increase of interacting human drivers' cooperative behaviour and improves the acceptance of the AV's driving style. But no effect is shown, if the turn signal is used to communicate the AV's intention to change lanes (cf. chapter 5). Because, not to activate the turn signal to communicate the lane change is not an option for an AV, a lateral offset in advance of a lane change can be dispensed. Thus, the results of Kauffmann et al. (2018b), that an lateral offset leads to better rating of the AV's driving style, could not be fully replicated. However, these results are not obtained in a study with real vehicles on the test track, but in the driving simulator. On the basis of the results, changes in longitudinal dynamics are to be classified as more communicative than changes in lateral dynamics. It is open to the extent that the results are transferable to accelerations, e.g. on an on-ramp of a highway.

8.3 Interpret cooperative behaviour

As a further step of the introduced communication model it is necessary to identify cooperative or non-cooperative behaviour of interacting human drivers. This is not considered in the context of this thesis and represents a starting point for subsequent work. In the second and third study (cf. chapter 6 and 7), the participants were instructed to behave exactly as they would if they are cooperating in real traffic (cf. instructions in the appendix B.1 and C.1). This may have led to a deviation of the participants' driving style in comparison to real traffic (Bubb et al., 2015, p.613).

Furthermore, in all studies the participants rated themselves on the prosocial scale of the Prosocial and Aggressive Driving Inventory (Harris et al., 2014) as prosocial drivers (cf. section 5.2.5, section 6.2.5, and section 7.2.5), which points to a very cooperative participant collective in all three studies.

8.4 Start the lane change

Start with small distances to interacting human drivers! Start changing lanes with small distances to the lag vehicle of the adjusted gap (0.3 s - 0.6 s). It is shown that a time headway of 0.4 s and 0.6 s between the AV and the lag vehicle of the adjusted gap are perceived as most predictable by interacting human drivers and are more accepted compared to a time headway of 0.9 s (cf. section 6.3.2). At higher velocity of the adjusted gap and with higher urgency of the lane change (due to lane narrowing), the accepted and predictable time headway shift towards 0.4 s. If interacting human drivers start the AV's lane change themselves out of the lag vehicle of the adjusted gap even smaller time headway between 0.3 s and 0.55 s, with an overall mean of 0.46 s, are realized (cf. section 6.3.3 and Figure 6.16). Compliance with safety distances is not decisive. This means, that the distances the AV should realize to interacting human drivers are in a similar size range as human drivers start the lane change themselves (cf. Table 3.3). The fact that the AV's driving style is designed to be as human drivers like as possible in order to increase its acceptance is known and proven in the field of human-robot interaction under the term anthropomorphism (Fong et al., 2003). Lütteken et al. (2016) teaches that the costs are an essential factor for cooperation, since in cases in which lower cooperation is expected human drivers cooperate more frequently. Thus, an AV's driving style that requires smaller time headway and therefore less deceleration of the lag vehicle of the adjusted gap should cause that human drivers cooperate more often. However, on the test track no other than the directly involved vehicles needed to be expected. This could have let to an underestimation of distances, because of a low perceived risk of an accident (Fuller et al., 2008; Wilde, 1982). Moreover, during the series of studies at the start of the lane change the AV is driving at least the same or a higher velocity than the lag vehicle of the adjusted gap and adjusts its velocity to the velocity of the lead vehicle of the adjusted gap during the scenario. As a results, the AV's velocity was mostly higher or equal compared to the velocity of the lag vehicle of the adjusted gap during the evaluated scenarios. Thus, the time to collisions between the AV and lag vehicle of the adjusted gap was mostly infinite and thus could not be evaluated. Even, if the time to collision is mostly used for objective evaluation of the scenario's criticality (Saffarzadeh et al., 2013; Minderhoud and Bovy, 2001). Considering response times of the human driver (cf. section 2.1.1), the small time headway (cf. Figure 7.11) at the start of the lane change brings interacting human drivers still into a critical scenario, e.g. the lead vehicle needs to brake suddenly in real traffic scenario. Nevertheless, it needs to be mentioned that the participants, driving the lag vehicle of the adjusted gap, compensated the small time headway to the AV at the start of the AV's lane change and increased the distance to the AV to diffuse the scenario, while the AV was changing lane (cf. Figure 7.10).

Don't wait too long! The start of the lane signalizes interacting human drivers that their cooperation is correctly interpreted by the AV, in form of a dHMI. Time headways between the AV and the lag vehicle of the adjusted gap are not sufficient to describe the start of the lane change; there is a maximum interaction time from which the lane change should occur, even though the time headway between the AV and the lag vehicle of the adjusted gap of 0.4 s, evaluated best in the first part of the second study (cf. chapter 6), has not yet been realized. Figure 7.20 shows that lane changes, in which the AV 'waited too long' to change lanes, are not accepted by interacting road users. These lane changes are realized in mean after an interaction time (time span after the AV and the lag vehicle of the adjusted gap was at same height to the start of the lane change) of 6.1 s. Interaction times of more than 2.5 s can be considered to be too long, but most of them lie noticeably above the mean of 4.6 s of all manoeuvres without comment (cf. Figure 7.22). If the lane change is executed too early has little effect on the acceptance of interacting human drivers (cf. Figure 7.21). The second part of the second study (cf. chapter 6) recorded interaction times between 2.3 s and 4.5 s until the participants started the AV's lane change themselves out of the lag vehicle of the adjusted gap. Ehmanns (Ehmanns, 2002, p.76) reports that interacting human drivers react due to a clear communicated request for a lane change by using the turn signal within a reaction time of approx. 2 s. A time span between 2 s and 3 s is confirmed by the descriptive analysation of the participant's driving style in the second part of the second driving study (cf. section 6.3.3.3) and the time span the participants needed to understand the AV's intention to change lanes, if the turn signal is set (cf. section 5.9). Tanida and Pöppel (2006) state that cooperative action should happen on the 'anticipative control' timescale, which they determine to be around 2 s. Combining this fact with the start of the cooperation of human drivers and interaction times that were rated with the AV 'waited too long' to change lanes, it is assumed that the AV should start it's lane change with smaller time headway to the lag vehicle of adjusted gap than 0.4 s, after a maximum interaction time between 4 s and 5 s. Thereby, the AV should rather start too early than too late.

Dependencies on the scenario and the AV's driving style! The time headway as starting condition of the AV's lane change and the maximum interaction time depends on the scenario and the AV's driving style; in case of higher urgency, velocity and dynamics to communicate the intention to change lanes, the lane change is expected with smaller time headway between the AV and the lag vehicle of the adjusted gap (cf. Figure 6.16) and with shorter interaction times (cf. Figure 6.17).

8.5 Execute the lane change

Increase following distance! Since, the AV has to start its lane change with small distances to the human drivers building the adjusted gap, as explained above, the AV has to increase the target time headway to the lead vehicle of the adjusted gap during the lane change to meet road traffic regulations, as soon as possible (cf. section 3.2). The human drivers ratings, due to the AV's driving style, are almost similar at a different target time headway. Whether the target time headway is increased during or shortly after the lane change or not at all has small influence (cf. section 7.3.2). Also whether the human drivers are driving the lead or lag vehicle of the adjusted gap has small influence. The assumption that the AV could follow the front vehicle with small following distances is restricted, because those are kept too short (cf. discussion in section 7.4) and bring human drivers of front vehicles in a dangerous situation (cf. section 3.2). If the AV increases its own time headway to the lead vehicle of the adjusted gap during the lane change to 1.5 s, at the end of the approx. 650 m long straight of the test track (cf. section 4.2.1), distances between the lead and lag vehicle of the adjusted gap are re-established. That would allow to start the AV's lane change according to traffic road regulation on German highways (cf. section 3.2). This is achieved without a significant decrease of interacting human drivers ratings of the AV's driving style. The fact that interacting human drivers expect the AV to start its lane change with small time headway to their vehicles, with small interaction times, and the fact that interacting human drivers increase their target time headway to the AV themselves very quickly after the AV started its lane change (cf. Figure 7.10), underlines the importance of stable communication (cf. section 4.1) and reduces the necessity of an absolute energy analysis of the participating actors. This is another hint that additional information, e.g. visualisation that the AV needs a larger adjusted cap to start its lane change, to interacting human drivers of the AV's inner states over another eHMI, additionally to the communication of the intention change lanes by the turn signal, could increase the willingness of interacting human drivers to cooperate even before the AV starts to change lanes.

Avoid unnecessary braking interventions! The restoration of the distance to the lead vehicle of the adjusted gap should be done slowly, using only the AV's drag torque. Active braking of the AV should be avoided, as this has a negative effect on all collected data (cf. section 7.3.1). Even, if the mean minimum deceleration in the variation with light braking was only $\mathrm{M}(\min(a_x)) = -1.80\,\mathrm{m\,s^{-2}}$ (cf. section 7.2.3.1). However, this effect could have also been caused by the AV's driving style at the factor level with light braking. At this factor level the time headway overshot above the desired one, which resulted in an increase of the velocity to adjust the desired time headway after the light braking (cf. Figure 7.2a and Figure 7.2b). It can be assumed that this fact particularly influences the evaluation of the AV's driving style in scenarios the AV needs to change lanes into faster traffic, for example on a highway access. Also, such scenarios are not evaluated in this thesis, it can be suspected that the AV needs a strategy to synchronize its velocity to the velocity of the adjusted gap, under consideration of dynamical restrictions from AV's passenger's perspective (cf. section 3.3), as far as possible before it starts to change lanes. A possible algorithm is proposed in Potzy et al. (2019c).

Realize human-like lane change durations! The lane change durations of the AV's driving style should be designed at the lower limit of the passengers' comfort (cf. section 3.3), comparable to human driving style at lane changes (cf. section 3.2.2) and not with longer lane change durations and therefore with lower lateral dynamics (cf. chapter 7).

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List of Figures

List of Tables

Acronyms

ADAS	Advanced Driver Assistant System
ADS	Automated Driving System
aHMI	automation Human-Machine-Interface
AOI	Area of Interest
ANOVA	Univariate Analysis of Variance
approx.	approximately
AV	automated vehicle
dHMI	dynamic Human-Machine-Interface
eHMI	external Human-Machine-Interface
DGPS	Differential Global Positioning System
e.g.	for example
HMI	Human-Machine-Interface
iHMI	infotainment Human-Machine-Interface
LC	lane change
MANOVA	Multivariate Analysis of Variance
vHMI	vehicle Human-Machine-Interface
V2V	vehicle to vehicle
V2X	vehicle to infrastructure

Appendix

A Appendix for study I

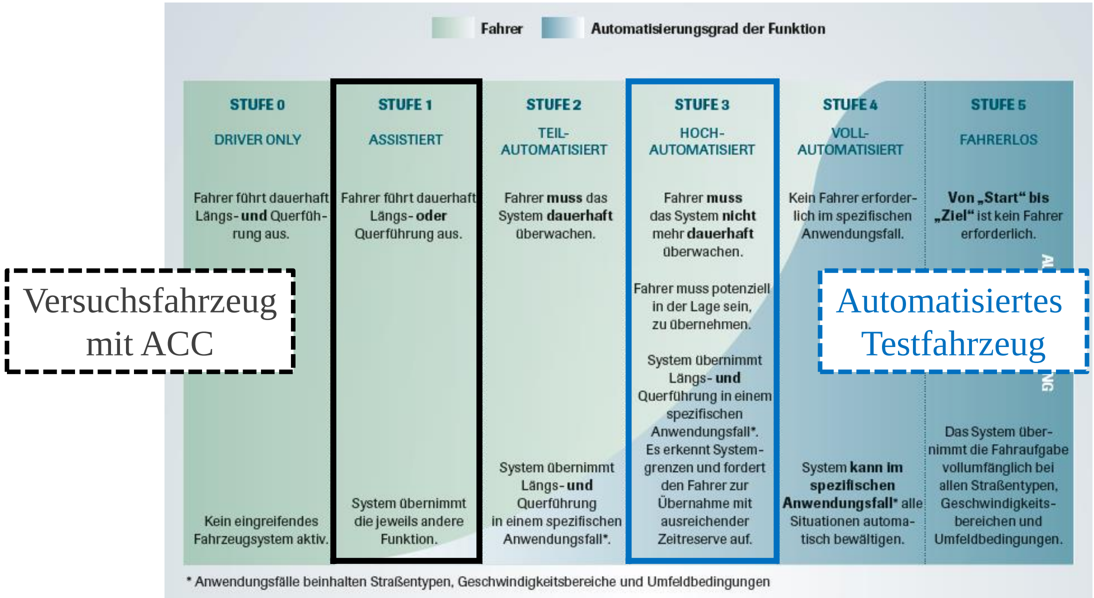
A.1 Participant's instructions

Außenwahrnehmung automatisierten Fahrverhaltens

HERZLICH WILLKOMMEN ZUR VERSUCHSEINWEISUNG

Automatisierungsstufen des automatisierten Fahrens

nach dem Verband der Automobilindustrie (VDA, 2015)



→ Zentrales Thema: Interaktion von Fahrzeugen mit unterschiedlichen Automatisierungsgraden

Gegenstand der Probandenstudie

Situation: Mischverkehr

Vor allem in dichtem Verkehr:

Viel Interaktion

Kernfragen:

- Wie werden automatisierte Fahrfunktionen von interagierenden Verkehrsteilnehmern wahrgenommen?
- Wie können automatisierte Fahrzeuge optimal mit menschlichen Fahrern interagieren?

Forschungsfragen

Bisher

- Betrachtung der Innenwahrnehmung automatisierten Fahrens
- Betrachtung der Interaktion von Mensch und eigenem automatisierten Auto

Wenig über

- die Außenwahrnehmung der automatisierten Fahrzeuge
- die Interaktion von Menschen und anderen automatisierten Autos

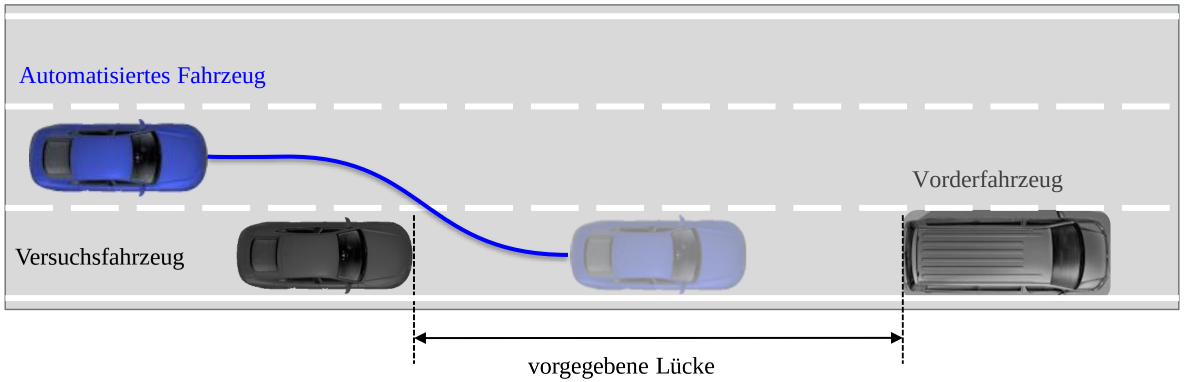
Fahrsituation

Der Einfädelvorgang

= Fahrstreifenwechsel in eine Lücke auf der Nachbarspur
(z.B. Einscheren nach dem Überholen; Reißverschlussverfahren vor einer Fahrbahnverengung)

→Vor allem in dichtem Verkehr: Kooperation nötig, um Einfädeln zu ermöglichen

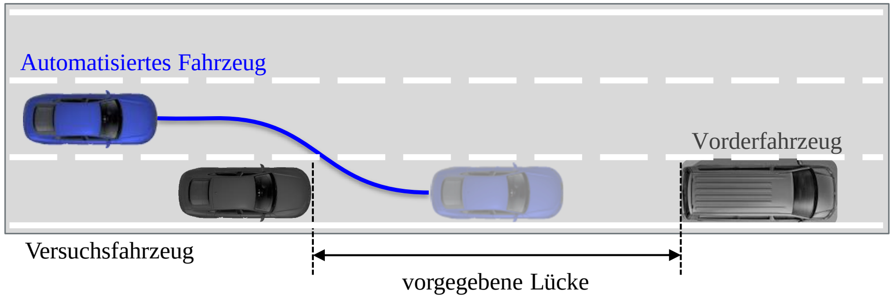
→Deshalb ist es wichtig, das Einfädeln anzukündigen



Ziel der Studie

→ Zielfrage:

Wie kann ein automatisiertes Fahrzeug den Einfädelwunsch optimal ankündigen bzw. das Einfädeln optimal durchführen?



→ Ihre Aufgaben:

- Bewerten Sie verschiedene Einfädelmanöver
- Evaluieren Sie unterschiedliche Methoden zur Ankündigung eines Einfädelwunsches
- Sagen Sie uns, wie automatisierte Fahrzeuge in Zukunft fahren sollen

Ablauf der Studie

Einstiegs-fragebogen
(10 min)

Eingewöhnungsfahrt,
Ausprobieren des ACC, eigenes Einfädeln

Studie Teil 1:
Bewerten von 24 verschiedenen Einfädelstrategien
(45 min)

kurze Erklärung

Studie Teil 2:
Einstellen der präferierten Strategie
(15 min)

Abschluss-fragebogen
(10 min)

Vorgehen der Studie zur Evaluation der Einfädelstrategien

- Sie folgen dem Vorderfahrzeug mit aktivem ACC bei ca. 30 bzw. ca. 50 km/h
- Das automatisierte Fahrzeug wird versuchen, sich einzufädeln
- Sie reagieren so, wie Sie es unter normalen Verkehrsbedingungen machen würden
- Sie drücken auf den Taster, sobald Sie sich sicher sind, dass sich das Auto einfädeln möchte
- Anschließend bewerten Sie Situation mit kurzen Fragen

Einführung Kurzfragebögen während der Fahrt

- Die Fragen werden Ihnen nach jedem Fahrmanöver gestellt und direkt beantwortet
- Bitte dabei ca. 10 km/h fahren oder stehenbleiben
- Die meisten Fragen werden anhand von Ratingskalen bewertet

- Ihre persönliche Meinung ist gefragt
- Ihre Angaben werden pseudonymisiert
- Es gibt keine falschen oder richtigen Antworten

Offene Fragen?

Jetzt kann es losgehen!
Viel Spaß!

A.2 Questionnaires

A.2.1 Sample

Teil A: Erfahrung mit Fahrerassistenzsystemen

ACC (Adaptive Cruise Control / Abstandsregeltempomat)					
A1. Sind Sie bereits (privat oder dienstlich) mit einem Abstandsregeltempomat (ACC) gefahren?	☐ Ja		☐ Nein		
A2. Wenn Sie mit einem Fahrzeug fahren, welches mit ACC ausgestattet ist, wie häufig schalten Sie dieses auf der Autobahn ein?	nie	selten	gele-gent-lich	oft	immer
	☐	☐	☐	☐	☐
A3. Wie viele Jahre sind Sie insgesamt mit Fahrzeugen gefahren, die mit einem ACC ausgestattet waren?	ca. _______________ Jahre				

Weitere Fahrerassistenzsysteme					
A4. Sind Sie bereits (privat oder dienstlich) mit einem <u>aktiven Spurhalteassistenten</u> (z. B. Audi Active Lane Assist) gefahren?	☐ Ja		☐ Nein		
A5. Wenn Sie mit einem Fahrzeug fahren, welches mit einem aktiven Spurhalteassistenten ausgestattet ist, wie häufig schalten Sie dieses auf der Autobahn ein?	nie	selten	gele-gent-lich	oft	immer
	☐	☐	☐	☐	☐
A6. Sind Sie bereits (privat oder dienstlich) mit einem teilautomatisierten System (z. B. Stauassistent) gefahren?	☐ Ja		☐ Nein		

A7. Wenn Sie mit einembFahrzeug fahren, welches mit einem teilautomatisierten System ausgestattet ist, wie häufig schalten Sie dieses auf der Autobahn ein (sofern die Voraussetzungen dafür erfüllt sind, z. B. Stau)?	nie	selten	gele-gent-lich	oft	immer
	☐	☐	☐	☐	☐
A8. Sind Sie bereits (privat oder dienstlich) mit einem <u>Tempomaten</u> gefahren?	☐ Ja		☐ Nein		
A9. Wenn Sie mit einem Fahrzeug fahren, welches mit einem <u>Tempomaten</u> ausgestattet ist, wie häufig schalten Sie diesen auf der Autobahn ein?	nie	selten	gele-gent-lich	oft	immer
	☐	☐	☐	☐	☐

Teil B: Ihre Fahrgewohnheiten

B1. Wie lange besitzen Sie bereits Ihren Führerschein der Klasse B?	ca. ________________ Jahre	
B2. Legen Sie Ihren Arbeitsweg oder sonstige Strecken (privat oder dienstlich) regelmäßig mit dem Auto zurück?	☐ Ja	☐ Nein
B3. Wie hoch ist Ihre durchschnittliche wöchentliche Kilometerleistung durch den Arbeitsweg und sonstige Fahrten?	ca. ________________ Kilometer	
B4. Wie hoch ist Ihre jährliche Kilometerleistung (inkl. Urlaubsfahrten, etc.) insgesamt? *Geben Sie bitte den Bereich an.*	bis 5.000 km	☐
	5.001 – 10.000 km	☐
	10.001 – 15.000 km	☐
	15.001 – 20.000 km	☐
	20.001 – 25.000 km	☐

	25.001 – 30.000 km	☐
	30.001 – 35.000 km	☐
	35.001 – 40.000 km	☐
	über 40.000 km	☐
B5. Wie verteilen sich Ihre Fahrten mit dem Auto (in km) auf folgende Straßentypen (gesamt 100%)? *Falls Sie einen Straßentypen nicht nutzen, tragen Sie bitte Null ein.*	Stadt (%)	
	Land-/Bundesstraße (%)	
	Autobahn (%)	

Teil C: Ihre Einstellung zum automatisierten Fahren

C1. Man kann verschiedene Meinungen zum automatisierten Fahren haben. Daher hätten wir gerne Ihre Reaktionen auf die folgenden Aussagen.

Bitte sagen Sie uns, ob Sie der jeweiligen Aussage zustimmen oder nicht.

		Ich neige dazu, zu widersprechen	Ich stimme eher zu	Kann ich nicht beantworte n
a	Automatisiertes Fahren kann mich in monotonen oder stressigen Fahrsituationen entlasten.	☐	☐	☐
b	Automatisiertes Fahren kann schwere Unfälle verhindern.	☐	☐	☐
c	Ich glaube nicht, dass es jemals zuverlässig funktionieren wird.	☐	☐	☐
d	Wenn das Auto selber fährt, kann ich andere Dinge tun.	☐	☐	☐
e	Automatisiertes Fahren macht mir Angst.	☐	☐	☐

Teil D: Fragen zu Ihrer Person

D1. Markieren Sie die Position zwischen den Wortpaaren, die Ihrem Fahrstil am besten entspricht.

Überlegen Sie nicht, sondern antworten Sie ehrlich und aus dem Bauch heraus. Es gibt keine richtigen und falschen Antworten. Machen Sie in jeder Zeile ein Kreuz.

Im Vergleich zu anderen Autofahrern fahre ich überwiegend…

a	schnell	☐	☐	☐	☐	☐	langsam
b	ängstlich	☐	☐	☐	☐	☐	mutig
c	offensiv	☐	☐	☐	☐	☐	defensiv
d	vorsichtig	☐	☐	☐	☐	☐	risikobereit
e	sportlich	☐	☐	☐	☐	☐	gemütlich

D2. Bitte benutzen Sie die unten angegebene Skala, um anzugeben, wie oft Sie das jeweilige Fahrverhalten zeigen.

Überlegen Sie nicht, sondern antworten Sie ehrlich und aus dem Bauch heraus. Es gibt keine richtigen und falschen Antworten. Machen Sie in jeder Zeile ein Kreuz.

		Nie	**Fast nie**	**Manch-mal**	**Relativ oft**	**Sehr oft**	**Immer**
a	Beim Abbiegen besonders aufmerksam sein	☐	☐	☐	☐	☐	☐
b	Ausreichend langsam bremsen, um die Fahrer hinter mir zu warnen	☐	☐	☐	☐	☐	☐
c	Beim Spurwechsel durch Spiegel-, und Schulterblick tote Winkel überprüfen	☐	☐	☐	☐	☐	☐
d	Beim Folgen anderer Fahrzeuge einen Sicherheitsabstand einhalten (mehr als halber Tacho in m)	☐	☐	☐	☐	☐	☐
e	Die Geschwindigkeit verringern, um mich schlechten Witterungsbedingungen anzupassen	☐	☐	☐	☐	☐	☐

f	Anderen Fahrern Vorfahrt gewähren, wenn sie Vorfahrt haben	☐	☐	☐	☐	☐	☐
g	Beim Fahren auf den umliegenden Verkehr und die Straße achten	☐	☐	☐	☐	☐	☐
h	Die Geschwindigkeit verringern, um mich schlechten Straßenverhältnissen anzupassen	☐	☐	☐	☐	☐	☐
		Nie	**Fast nie**	**Manch-mal**	**Relativ oft**	**Sehr oft**	**Immer**
i	Richtungsanzeigen (Blinker) benutzen, um anderen Fahrern meine Abbiegeabsicht mitzuteilen	☐	☐	☐	☐	☐	☐
j	In einem Baustellenbereich abbremsen	☐	☐	☐	☐	☐	☐
k	In der Nähe von Fußgängern besonders vorsichtig fahren	☐	☐	☐	☐	☐	☐
l	Beim Heranfahren an Kreuzungen besonders aufmerksam sein	☐	☐	☐	☐	☐	☐
m	In der Nähe von Fahrradfahrern besonders vorsichtig fahren	☐	☐	☐	☐	☐	☐
n	Vorsichtiger fahren, um Menschen oder Fahrzeugen am Straßenrand Platz zu machen (z.B. langsamer fahren, auf die andere Seite fahren)	☐	☐	☐	☐	☐	☐
o	An einem Stoppschild vollständig zum Stillstand kommen	☐	☐	☐	☐	☐	☐
p	Verkehrszeichen befolgen	☐	☐	☐	☐	☐	☐
q	Vorhandene Geschwindigkeitsbegrenzungen in Schulbereichen befolgen	☐	☐	☐	☐	☐	☐

Teil E: Demographie

E1. Ihr Alter: *Geben Sie bitte den Bereich an, in dem sich Ihr Alter befindet.*	<31 ☐	31-40 ☐	>40 ☐
E2. Ihr Geschlecht:	☐ weiblich ☐ männlich		
E3. Welchen beruflichen Hintergrund (z. B. Ausbildung oder Studium) haben Sie?	☐ technischer Hintergrund ☐ nicht-technischer Hintergrund		
E4. Sind Sie Mitarbeiter der AUDI AG?	☐ ja ☐ nein		

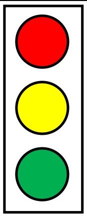
Ihr Teilnehmer-Code, bitte ausfüllen:		
E5. Die ersten zwei Buchstaben des Vornamens Ihrer Mutter Beispiel: Inge → In	**E6. An welchem Tag im Monat hat <u>Ihre Mutter</u> Geburtstag?** Beispiel: 25.01.1952 → 25	**E7. Die ersten zwei Buchstaben des Vornamens <u>Ihres Vaters</u>** Beispiel: Heinrich → He

Vielen Dank, dass Sie sich die Zeit genommen haben, den Fragebogen zu beantworten!

☐ Ich bin damit einverstanden, dass meine Kontaktdaten zum Zwecke der Terminvereinbarung erhoben, verarbeitet und genutzt werden. Des Weiteren bin ich damit einverstanden, dass meine Daten im Fragebogen zum Zwecke der Auswertung für die Probandenstudie erhoben, verarbeitet und genutzt werden. Diese werden nicht in Verbindung mit Ihren Kontaktdaten gebracht und separat gespeichert. Nach erfolgreicher Studiendurchführung werden die angegebenen Daten gelöscht.

A.2.2 Study part I

Fragebogen zur Studie Teil 1 – Nach jeder Fahrsituation

	1. Bewertung		
a	Wie empfanden Sie die gerade erlebte Fahrsituation?	☐ eher negativ ☐ neutral ☐ eher positiv	

	2. Einschätzung der gerade erlebten Situation *Die folgenden Aussagen beziehen sich auf das gerade erlebte Fahrmanöver.*							
		Trifft absolut nicht zu **1**	**Trifft nicht zu** **2**	**Trifft eher nicht zu** **3**	**Teil/ teils** **4**	**Trifft eher zu** **5**	**Trifft zu** **6**	**Trifft absolut zu** **7**
a	**Erwartetes Fahrverhalten:** Das Fahrzeug auf dem Nachbarfahrstreifen hat sich so verhalten, wie Sie es erwartet haben	☐	☐	☐	☐	☐	☐	☐
b	**Eindeutige Einfädelabsicht:** Das Fahrzeug auf dem Nachbarfahrstreifen hat seine Einfädelabsicht eindeutig angezeigt	☐	☐	☐	☐	☐	☐	☐
c	**Sinnvolles Fahrverhalten:** Das Verhalten des Fahrzeugs auf dem Nachbarfahrstreifen war sinnvoll	☐	☐	☐	☐	☐	☐	☐
d	**Zufriedenheit:** Sie waren mit dem Verhalten des Fahrzeugs auf dem Nachbarfahrstreifen zufrieden	☐	☐	☐	☐	☐	☐	☐
e	**Eigene Kooperation:** Ein Beobachter würde Ihr Verhalten während des Einfädelvorgangs als kooperativ beurteilen	☐	☐	☐	☐	☐	☐	☐

3. Wahrnehmung der gerade erlebten Situation			
a	Haben Sie vom Fahrzeug auf dem Nachbarfahrstreifen eine Mitteilung der Manöverabsicht wahrgenommen?	Nein ☐	☐ Ja
b	Wenn ja: welche?		

A.2.3 Study part II

Fragebogen zur Studie Teil 2 – Präferierte Einfädelstrategie des automatisierten Fahrzeugs

Einschätzung Einfädelstrategie bei ca. 50 km/h
Die folgenden Aussagen beziehen sich auf Einfädelmanöver NACH LINKS (Proband 1-20) bzw. RECHTS (Proband 21-40)

1. Querversatz								
a	Würden Sie sich für eine Einfädelstrategie mit oder ohne Querversatz entscheiden?	☐ Mit			☐ Ohne			
		Gar nicht wichtig 1	2	3	4	5	6	**Absolut wichtig** 7
b	Ist Ihnen das wichtig?	☐	☐	☐	☐	☐	☐	☐
c	Wie beurteilen Sie die Stärke des Querversatzes?	☐ Zu schwach		☐ Genau richtig			☐ Zu stark	
c-	Würden Sie eine andere Stärke des Querversatzes bevorzugen?	☐ Nein ☐ Ja, ich denke der Querversatz war zu schwach und ich wünsche mir einen etwas stärkeren ☐ Ja, ich denke der Querversatz war zu schwach und ich wünsche mir einen viel stärkeren ☐ Ja, ich denke der Querversatz war zu stark und ich wünsche mir einen etwas schwächeren ☐ Ja, ich denke der Querversatz war zu stark und ich wünsche mir einen viel schwächeren ☐ Kann ich nicht sagen						
d	Würden Sie einen Querversatz in die andere Richtung bevorzugen?	☐ Nein		☐ Ja			☐ Kann ich nicht sagen	
e	Würden Sie sich den Querversatz zu einem anderen Zeitpunkt wünschen?	☐ Nein		☐ Ja			☐ Kann ich nicht sagen	
f	Wenn ja, zu welchem Zeitpunkt? (z.B. früher oder später?)							

g	Würden sich Ihre Einschätzungen bei einem Einfädelmanöver in die andere Richtung verändern?	☐ Nein	☐ Ja	☐ Kann ich nicht sagen
h	Wenn ja, wie?			
i	Würden sich Ihre Einschätzungen bei einem Einfädelmanöver mit anderer Geschwindigkeit verändern?	☐ Nein	☐ Ja	☐ Kann ich nicht sagen
j	Wenn ja, wie? (z.B. bei deutlich höherer oder niedriger Geschwindigkeit?)			
k	Haben Sie noch weitere Anmerkungen zum Querversatz? Bitte notieren Sie diese hier.			

	2. Verzögerung								
a	Würden Sie sich für eine Einfädelstrategie mit starker oder schwacher Verzögerung entscheiden?	☐ Schwache Verzögerung				☐ Starke Verzögerung			
		Gar nicht wichtig **1**	**2**	**3**	**4**	**5**	**6**	**Absolut wichtig** **7**
b	Ist Ihnen das wichtig?	☐	☐	☐	☐	☐	☐	☐
c	Wie empfanden Sie **die von Ihnen ausgewählte** Verzögerung?	☐ Zu schwach		☐ Genau richtig			☐ Zu stark	
d	Würden Sie sich eine noch stärkere oder schwächere Verzögerung wünschen?	☐ Nein ☐ Ja, ich habe die schwache Verzögerung gewählt und wünsche mir eine noch schwächere ☐ Ja, ich habe die schwache Verzögerung gewählt und wünsche mir eine etwas stärkere ☐ Ja, ich habe die starke Verzögerung gewählt und wünsche mir eine noch stärkere						

		☐ Ja, ich habe die starke Verzögerung gewählt und wünsche mir eine etwas schwächere ☐ Kann ich nicht sagen		
e	Würden sich Ihre Einschätzungen bei einem Einfädelmanöver in die andere Richtung verändern?	☐ Nein	☐ Ja	☐ Kann ich nicht sagen
f	Wenn ja, wie?			
g	Würden sich Ihre Einschätzungen bei einem Einfädelmanöver mit anderer Geschwindigkeit verändern?	☐ Nein	☐ Ja	☐ Kann ich nicht sagen
h	Wenn ja, wie? (z.B. bei deutlich höherer oder niedriger Geschwindigkeit?)			
i	Haben Sie noch weitere Anmerkungen zur Verzögerung? Bitte notieren Sie diese hier.			

3. Abstand									
a	Würden Sie sich für eine Einfädelstrategie mit kleinem oder großem Abstand entscheiden?	☐ kleiner Abstand				☐ großer Abstand			
		Gar nicht wichtig **1**	**2**	**3**	**4**	**5**	**6**	**Absolut wichtig** **7**	
b	Ist Ihnen das wichtig?	☐	☐	☐	☐	☐	☐	☐	
c	Wie empfanden Sie **den von Ihnen ausgewählten** Abstand?	☐ Zu klein		☐ Genau richtig		☐ Zu groß			
d	Würden Sie sich einen noch kleineren oder größeren Abstand wünschen?	☐ Nein							

		☐ Ja, ich habe den kleinen Abstand gewählt und wünsche mir einen noch kleineren ☐ Ja, ich habe den kleinen Abstand gewählt und wünsche mir einen etwas größeren ☐ Ja, ich habe den großen Abstand gewählt und wünsche mir einen noch größeren ☐ Ja, ich habe den großen Abstand gewählt und wünsche mir einen etwas kleineren ☐ Kann ich nicht sagen		
e	Würden sich Ihre Einschätzungen bei einem Einfädelmanöver in die andere Richtung verändern?	☐ Nein	☐ Ja	☐ Kann ich nicht sagen
f	Wenn ja, wie?			
g	Würden sich Ihre Einschätzungen bei einem Einfädelmanöver mit anderer Geschwindigkeit verändern?	☐ Nein	☐ Ja	☐ Kann ich nicht sagen
h	Wenn ja, wie? (z.B. bei deutlich höherer oder niedriger Geschwindigkeit?)			
i	Haben Sie noch weitere Anmerkungen zum Abstand? Bitte notieren Sie diese hier.			

4. Blinkzeitpunkt								
a Haben Sie sich eher für einen frühen oder für einen späten Blinkzeitpunkt entschieden?	☐ Früh			☐ Spät		☐ Kann ich nicht sagen		
	Gar nicht wichtig **1**	**2**	**3**	**4**	**5**	**6**	**Absolut wichtig** **7**	

b	Ist Ihnen das wichtig?	☐	☐	☐	☐	☐	☐	☐
c	Wie empfanden Sie den von Ihnen ausgewählten Blinkzeitpunkt?	☐ Zu früh		☐ Genau richtig		☐ Zu spät		
d	Würden Sie sich einen noch früheren bzw. späteren Blinkzeitpunkt wünschen?	☐ Nein ☐ Ja, ich habe einen frühen Blinkzeitpunkt gewählt und wünsche mir einen noch früheren ☐ Ja, ich habe einen frühen Blinkzeitpunkt gewählt und wünsche mir einen späteren ☐ Ja, ich habe einen späten Blinkzeitpunkt gewählt und wünsche mir einen noch späteren ☐ Ja, ich habe einen späten Blinkzeitpunkt gewählt und wünsche mir einen früheren ☐ Kann ich nicht sagen						
e	Würden sich Ihre Einschätzungen bei einem Einfädelmanöver in die andere Richtung verändern?	☐ Nein		☐ Ja		☐ Kann ich nicht sagen		
f	Wenn ja, wie?							
g	Würden sich Ihre Einschätzungen bei einem Einfädelmanöver mit anderer Geschwindigkeit verändern?	☐ Nein		☐ Ja		☐ Kann ich nicht sagen		
h	Wenn ja, wie? (z.B. bei deutlich höherer oder niedriger Geschwindigkeit?)							
i	Haben Sie noch weitere Anmerkungen zum Blinker? Bitte notieren Sie diese hier.							

5. Gesamtstrategie

a	Entsprechen die ausgewählten Parameter Ihrer präferierten Einfädelstrategie?	☐ Nein	☐ Ja
b	Bitte begründen Sie Ihre Antwort.		
c	Haben Sie noch Anmerkungen? Bitte notieren Sie diese hier.		

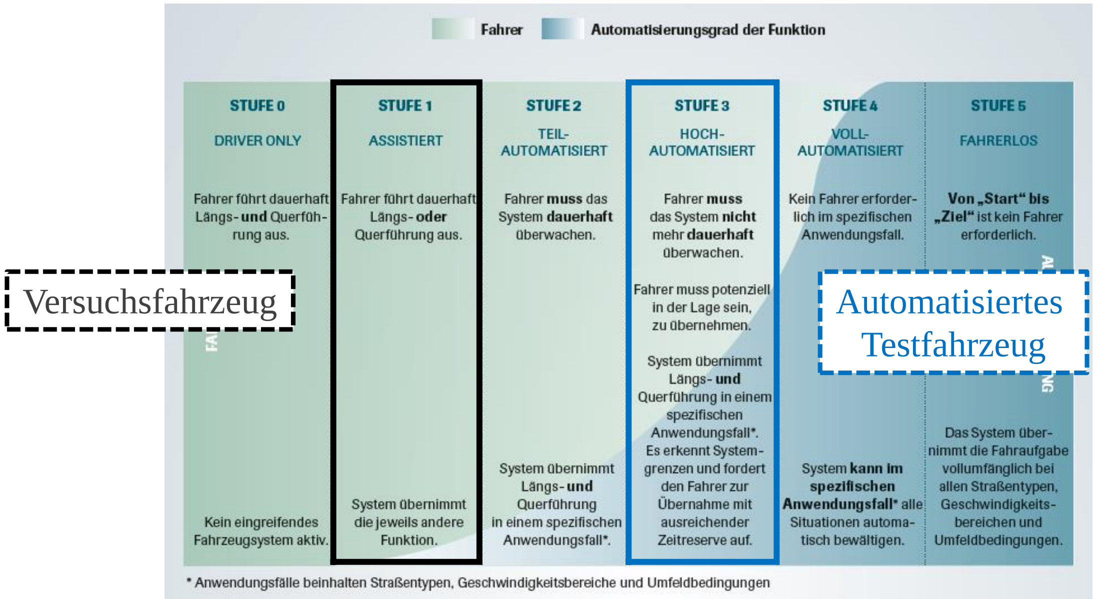
B Appendix for study II

B.1 Participant's instructions

Außenwahrnehmung des automatisierten Einfädelvorgangs

Automatisierungsstufen des automatisierten Fahrens

nach dem Verband der Automobilindustrie (VDA, 2015)



→ Zentrales Thema: Interaktion von Fahrzeugen mit unterschiedlichen Automatisierungsgraden

Gegenstand der Probandenstudie

Situation: Mischverkehr

Vor allem in dichtem Verkehr:

Viel Interaktion

Kernfragen:

- Wie werden automatisierte Fahrfunktionen von interagierenden Verkehrsteilnehmern wahrgenommen?
- Wie können automatisierte Fahrzeuge optimal mit menschlichen Fahrern interagieren?

Forschungsfragen

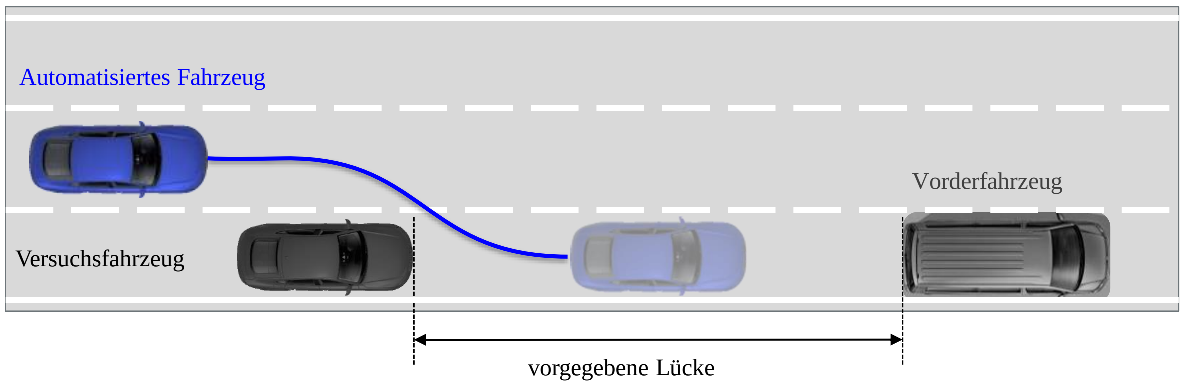
Bisher

- Betrachtung der Innenwahrnehmung automatisierten Fahrens
- Betrachtung der Interaktion von Mensch und eigenem automatisierten Fahrzeug

Wenig über

- die Außenwahrnehmung der automatisierten Fahrzeuge
- die Interaktion von Menschen und anderen automatisierten Fahrzeugen

Fahrsituation



Ablauf der Studie

Einstiegs-fragebogen
(10 min)

Eingewöhnungsfahrt

Halten des Abstandes mittels Marker

Studie Teil 1:
Bewerten von 12 verschiedenen Einfädelstrategien
(40 Minuten)

kurze Erklärung

Studie Teil 2:
Einstellen des Einfädelzeitpunkts
(20 min)

Abschluss-fragebogen
(10 min)

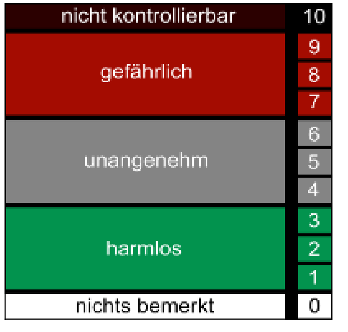
Vorgehen der Studie zur Evaluation der Einfädelstrategien

- Sie folgen dem Vorderfahrzeug bei ca. 30 bzw. ca. 50 km/h
- Das automatisierte Fahrzeug wird versuchen, sich einzufädeln
- Sie reagieren so, wie Sie es unter normalen Verkehrsbedingungen machen würden
- Sie drücken auf den Taster, sobald Sie erwarten würden, dass das automatisierte Fahrzeug einfädelt
- Das automatisierte Fahrzeug fädelt vor Ihnen ein

Einführung Kurzfragebögen während der Fahrt

- Die Fragen werden Ihnen nach jedem Fahrmanöver gestellt und direkt beantwortet
- Bitte dabei stehenbleiben
- Die meisten Fragen werden anhand von Ratingskalen bewertet

<table>
<tr><td rowspan="3">a</td><td colspan="4">Erwarteter Einfädelzeitpunkt
Der Wechselzeitpunkt des automatisierten Fahrzeugs war so, wie Sie es erwartet hatten.</td><td colspan="5">☐ ja ☐ nein</td></tr>
<tr><td colspan="9">Wann hätten Sie ein Einfädeln des automatisierten Fahrzeugs erwartet?</td></tr>
<tr><td>Früher</td><td>-3</td><td>-2</td><td>-1</td><td>0</td><td>1</td><td>2</td><td>3</td><td>Später</td></tr>
<tr><td>b</td><td colspan="9">Situation
Wie kritisch empfanden Sie die gerade erlebte Fahrsituation?</td></tr>
<tr><td rowspan="2">c</td><td colspan="9">Eigenes Fahrverhalten
Wie würde ein Beobachter Ihr Fahrverhalten in der eben erlebten Situation beurteilen?</td></tr>
<tr><td>nicht kooperativ</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>sehr kooperativ</td></tr>
</table>



d	**Verhalten des automatisierten Fahrzeugs** Bitte bewerten Sie das gerade erlebte Verhalten des automatisierten Fahrzeugs.						
	störend	☐	☐	☐	☐	☐	nicht störend
	verzögernd	☐	☐	☐	☐	☐	zeitsparend
	Nützlich	☐	☐	☐	☐	☐	Nutzlos
	Angenehm	☐	☐	☐	☐	☐	Unangenehm
	Schlecht	☐	☐	☐	☐	☐	Gut
	Nett	☐	☐	☐	☐	☐	Nervig
	Effizient	☐	☐	☐	☐	☐	Unnötig
	Ärgerlich	☐	☐	☐	☐	☐	Erfreulich
	Hilfreich	☐	☐	☐	☐	☐	Wertlos
	Nicht wünschenswert	☐	☐	☐	☐	☐	Wünschenswert
	Aktivierend	☐	☐	☐	☐	☐	Einschläfernd

- Ihre persönliche Meinung ist gefragt
- Ihre Angaben werden pseudoaonymisiert
- Es gibt keine falschen oder richtigen Antworten

Offene Fragen?

Jetzt kann es losgehen!
Viel Spaß!

B.2 Questionnaires

B.2.1 Sample

Teil A: Ihre Erfahrungen in der Nutzung und Entwicklung von Fahrerassistenzsystemen

ACC (Adaptive Cruise Control / Abstandsregeltempomat)					
A1. Sind Sie bereits (privat oder dienstlich) mit einem Abstandsregeltempomat (ACC)gefahren?	☐ Ja		☐ Nein		
A2. Wenn Sie mit einem Fahrzeug fahren, welches mit ACC ausgestattet ist, wie häufig schalten Sie dieses auf der Autobahn ein?	nie	selten	gele-gent-lich	oft	imme r
	☐	☐	☐	☐	☐
A3. Wie viele Jahre sind Sie insgesamt mit Fahrzeugen gefahren, die mit einem ACC ausgestattet waren?	ca. ______________ Jahre				

Nutzung automatisierter Funktionen					
A4. Sind Sie bereits (privat oder dienstlich) mit einem aktiven Spurhalteassistenten (z. B. Audi Active Lane Assist) gefahren?	☐ Ja		☐ Nein		
A5. Wenn Sie mit einem Fahrzeug fahren, welches mit einem <u>aktiven Spurhalteassistenten</u> ausgestattet ist, wie häufig schalten Sie dieses auf der Autobahn ein?	nie	selten	gele-gent-lich	oft	imme r
	☐	☐	☐	☐	☐
A6. Sind Sie bereits (privat oder dienstlich) mit einer Kombination aus aktivem Spurhalteassistent und ACC (teilautomatisiertes System, z. B. Stauassistent) gefahren?	☐ Ja		☐ Nein		

A7. Wenn Sie mit einem Fahrzeug fahren, welches mit einem <u>teilautomatisierten System</u> ausgestattet ist, wie häufig schalten Sie dieses auf der Autobahn ein (sofern die Voraussetzungen dafür erfüllt sind, z. B. Stau)?	nie	selten	gele-gent-lich	oft	imme r
	☐	☐	☐	☐	☐

A8.	**Haben Sie bereits an Testfahrten mit einem teil- oder hochautomatisierten System teilgenommen?**	☐ Ja		☐ Nein		
A9.	**Wie häufig nehmen Sie im Schnitt an Testfahrten mit einem teil- oder hochautomatisierten System teil?**	Seltener als einmal pro Halbjahr	Einmal pro Halb-jahr	Alle 2-3 Monate	Einmal im Monat	Öfter als einmal im Monat
		☐	☐	☐	☐	☐

	Entwicklung automatisierter Funktionen	
A10.	**Sind Sie bereits in der Entwicklung und/oder Forschung automatisierter Fahrfunktionen tätig gewesen?**	☐ Ja ☐ Nein
A10-a.	**Wie viele Jahre waren bzw. sind Sie in der Forschung und/oder Entwicklung automatisierter Fahrfunktionen tätig?**	_______________ Jahre
A10-b.	**Welchen Schwerpunkt hatte(n) Ihre Tätigkeit(en) im Bereich der Forschung/Entwicklung automatisierter Fahrfunktionen? Mehrfachauswahl möglich.**	☐ Fahrende Funktionen ☐ Parkende Funktionen ☐ Mensch-Maschine-Schnittstelle ☐ Konzeptentwicklung ☐ Systemarchitektur ☐ Wahrnehmung ☐ Verhaltensgenerierung ☐ Andere

Teil B: Ihre Fahrgewohnheiten

B1. **Wie lange besitzen Sie bereits Ihren Führerschein der Klasse B?**	ca. __________________ Jahre	
B2. **Legen Sie Ihren Arbeitsweg oder sonstige Strecken (privat oder dienstlich) regelmäßig mit dem Auto zurück?**	☐ Ja	☐ Nein
B3. **Wie hoch ist Ihre durchschnittliche wöchentliche Kilometerleistung durch den Arbeitsweg und sonstige Fahrten?**	ca. __________________ Kilometer	
B4. **Wie hoch ist Ihre jährliche Kilometerleistung (inkl. Urlaubsfahrten, etc.) insgesamt?** *Geben Sie bitte den Bereich an.*	bis 5.000 km	☐
	5.001 – 10.000 km	☐
	10.001 – 15.000 km	☐
	15.001 – 20.000 km	☐
	20.001 – 25.000 km	☐
	25.001 – 30.000 km	☐
	30.001 – 35.000 km	☐
	35.001 – 40.000 km	☐
	über 40.000 km	☐
B5. **Wie verteilen sich Ihre Fahrten mit dem Auto (in km) auf folgende Straßentypen (gesamt 100%)?** *Falls Sie einen Straßentypen nicht nutzen, tragen Sie bitte Null ein.*	Stadt (%)	
	Land-/Bundesstraße (%)	
	Autobahn (%)	

Teil C: Ihre Einstellung zum automatisierten Fahren

C1.	**Man kann verschiedene Meinungen zum automatisierten Fahren haben. Daher hätten wir gerne Ihre Reaktionen auf die folgenden Aussagen.** *Bitte sagen Sie uns, ob Sie der jeweiligen Aussage zustimmen oder nicht.*			
		Ich neige dazu, zu widersprechen	Ich stimme eher zu	Kann ich nicht beantworten
a	Automatisiertes Fahren kann mich in monotonen oder stressigen Fahrsituationen entlasten.	☐	☐	☐
b	Automatisiertes Fahren kann schwere Unfälle verhindern.	☐	☐	☐
c	Ich glaube nicht, dass es jemals zuverlässig funktionieren wird.	☐	☐	☐
d	Wenn das Auto selber fährt, kann ich andere Dinge tun.	☐	☐	☐
e	Automatisiertes Fahren macht mir Angst.	☐	☐	☐

Teil D: Fragen zu Ihrer Person

D1. Markieren Sie die Position zwischen den Wortpaaren, die Ihrem Fahrstil am besten entspricht.

Überlegen Sie nicht, sondern antworten Sie ehrlich und aus dem Bauch heraus. Es gibt keine richtigen und falschen Antworten. Machen Sie in jeder Zeile ein Kreuz.

Im Vergleich zu anderen Autofahrern fahre ich überwiegend…

a	Schnell	☐	☐	☐	☐	☐	langsam
b	Ängstlich	☐	☐	☐	☐	☐	mutig
c	Offensiv	☐	☐	☐	☐	☐	defensiv
d	Vorsichtig	☐	☐	☐	☐	☐	risikobereit
e	Sportlich	☐	☐	☐	☐	☐	gemütlich

D2. Bitte benutzen Sie die unten angegebene Skala, um anzugeben, wie oft Sie das jeweilige Fahrverhalten zeigen.

Überlegen Sie nicht, sondern antworten Sie ehrlich und aus dem Bauch heraus. Es gibt keine richtigen und falschen Antworten. Machen Sie in jeder Zeile ein Kreuz.

		Nie	**Fast nie**	**Manch -mal**	**Relativ oft**	**Sehr oft**	**Immer**
a	Beim Abbiegen besonders aufmerksam sein	☐	☐	☐	☐	☐	☐
b	Ausreichend langsam bremsen, um die Fahrer hinter mir zu warnen	☐	☐	☐	☐	☐	☐
c	Beim Spurwechsel durch Spiegel-, und Schulterblick tote Winkel überprüfen	☐	☐	☐	☐	☐	☐
d	Beim Folgen anderer Fahrzeuge einen Sicherheitsabstand einhalten (mehr als halber Tacho in m)	☐	☐	☐	☐	☐	☐
e	Die Geschwindigkeit verringern, um mich schlechten Witterungsbedingungen anzupassen	☐	☐	☐	☐	☐	☐

f	Anderen Fahrern Vorfahrt gewähren, wenn sie Vorfahrt haben	☐	☐	☐	☐	☐	☐
g	Beim Fahren auf den umliegenden Verkehr und die Straße achten	☐	☐	☐	☐	☐	☐
		Nie	**Fast nie**	**Manch-mal**	**Relativ oft**	**Sehr oft**	**Immer**
h	Die Geschwindigkeit verringern, um mich schlechten Straßenverhältnissen anzupassen	☐	☐	☐	☐	☐	☐
i	Richtungsanzeigen (Blinker) benutzen, um anderen Fahrern meine Abbiegeabsicht mitzuteilen	☐	☐	☐	☐	☐	☐
j	In einem Baustellenbereich abbremsen	☐	☐	☐	☐	☐	☐
k	In der Nähe von Fußgängern besonders vorsichtig fahren	☐	☐	☐	☐	☐	☐
l	Beim Heranfahren an Kreuzungen besonders aufmerksam sein	☐	☐	☐	☐	☐	☐
m	In der Nähe von Fahrradfahrern besonders vorsichtig fahren	☐	☐	☐	☐	☐	☐
n	Vorsichtiger fahren, um Menschen oder Fahrzeugen am Straßenrand Platz zu machen (z.B. langsamer fahren, auf die andere Seite fahren)	☐	☐	☐	☐	☐	☐
o	An einem Stoppschild vollständig zum Stillstand kommen	☐	☐	☐	☐	☐	☐
p	Verkehrszeichen befolgen	☐	☐	☐	☐	☐	☐
q	Vorhandene Geschwindigkeitsbegrenzungen in Schulbereichen befolgen	☐	☐	☐	☐	☐	☐

D3. Bitte benutzen Sie die unten angegebene Skala, um anzugeben, wie stark Sie den Aussagen zustimmen. *Überlegen Sie nicht, sondern antworten Sie ehrlich und aus dem Bauch heraus. Es gibt keine richtigen und falschen Antworten. Machen Sie in jeder Zeile ein Kreuz.*						
		stimme überhaupt nicht zu	**stimme eher nicht zu**	**teils-teils**	**stimme eher zu**	**Stimme sehr zu**
a	Ich übernehme gern Verantwortung.	☐	☐	☐	☐	☐
b	Es hat sich für mich als gut erwiesen, selbst Entscheidungen zu treffen, anstatt mich auf das Schicksal zu verlassen.	☐	☐	☐	☐	☐
c	Bei Problemen und Widerständen finde ich in der Regel Mittel und Wege, um mich durchzusetzen.	☐	☐	☐	☐	☐
d	Erfolg ist oft weniger von Leistung, sondern vielmehr von Glück abhängig.	☐	☐	☐	☐	☐
e	Ich habe häufig das Gefühl, dass ich wenig Einfluss darauf habe, was mit mir geschieht.	☐	☐	☐	☐	☐
f	Bei wichtigen Entscheidungen orientiere ich mich oft an dem Verhalten von anderen.	☐	☐	☐	☐	☐

Teil E: Demographie

E1. Bitte geben Sie Ihr Alter an:	_______________ Jahre	
E2. Ihr Geschlecht:	☐ weiblich ☐ männlich	
E3. Welchen beruflichen Hintergrund (z. B. Ausbildung oder Studium) haben Sie?	☐ technischer Hintergrund ☐ nicht-technischer Hintergrund	
E4. Sind Sie Mitarbeiter der AUDI AG?	☐ ja ☐ nein	
Ihr Teilnehmer-Code, bitte ausfüllen:		
E5. Die ersten zwei Buchstaben des Vornamens <u>Ihrer Mutter</u> Beispiel: Inge → In	**E6. An welchem Tag im Monat hat <u>Ihre Mutter</u> Geburtstag?** Beispiel: 25.01.1952 → 25	**E7. Die ersten zwei Buchstaben des Vornamens <u>Ihres Vaters</u>** Beispiel: Heinrich → He

Vielen Dank, dass Sie sich die Zeit genommen haben, den Fragebogen zu beantworten!

B.2.2 Pre-Test

Pretest-Fragebogen
Fahrversuch zur „Wahrnehmung des automatisierten Einfädelns"

1. Ihr Teilnehmer-Code		
Die ersten zwei Buchstaben des Vornamens Ihrer Mutter Beispiel: Inge → In	**An welchem Tag im Monat hat Ihre Mutter Geburtstag?** Beispiel: 25.01.1952 → 25	**Die ersten zwei Buchstaben des Vornamens Ihres Vaters** Beispiel: Heinrich → He

2. Erwartungshaltung an automatisierte Fahrzeuge

Man kann verschiedene Meinungen zum automatisierten Fahren bzw. zu automatisierten Fahrzeugen haben. Daher hätten wir gerne Ihre Reaktionen auf die folgenden Aussagen.
Bitte sagen Sie uns, ob Sie die jeweiligen Aussagen für zutreffend erachten oder nicht.

		Trifft absolut nicht zu 1	Trifft nicht zu 2	Trifft eher nicht zu 3	Teil/ teils 4	Trifft eher zu 5	Trifft zu 6	Trifft absolut zu 7
a	Automatisierte Fahrzeuge werden nur auf Sonderstrecken (d.h. auf Strecken, auf welchen nur automatisierte Fahrzeuge zugelassen sind) fahren.	☐	☐	☐	☐	☐	☐	☐
b	Automatisierte Fahrzeuge und menschliche Fahrer können im Straßenverkehr problemlos interagieren.	☐	☐	☐	☐	☐	☐	☐
c	Automatisierte Fahrzeuge sollten gekennzeichnet werden.	☐	☐	☐	☐	☐	☐	☐
d	Automatisierte Fahrzeuge können in der Interaktion mit manuellen Fahrern *hilfreiche* Interaktionspartner sein.	☐	☐	☐	☐	☐	☐	☐
e	Automatisierte Fahrzeuge können ihre Fahrstrategie so gestalten, dass eine *zeitsparende* Interaktion zwischen manuellem und automatisiertem Fahrzeug möglich ist.	☐	☐	☐	☐	☐	☐	☐

		Trifft absolut nicht zu 1	Trifft nicht zu 2	Trifft eher nicht zu 3	Teil/ teils 4	Trifft eher zu 5	Trifft zu 6	Trifft absolut zu 7
f	Automatisierte Fahrzeuge können Ihre Fahrstrategie so gestalten, dass eine *nutzbringende* Interaktion zwischen menschlichem Fahrer und automatisiertem Fahrzeug möglich ist.	☐	☐	☐	☐	☐	☐	☐

3. Erwartungshaltung an den Einfädelvorgang								
Bitte geben Sie an, inwiefern die jeweiligen Aussagen zum Fahrverhalten eines automatisierten Fahrzeugs Ihrer Meinung nach zutreffen.								
		Trifft absolut nicht zu 1	**Trifft nicht zu 2**	**Trifft eher nicht zu 3**	**Teil/ teils 4**	**Trifft eher zu 5**	**Trifft zu 6**	**Trifft absolut zu 7**
Das automatisierte Fahrzeug sollte den **Zeitpunkt des Einfädelns** so wählen, dass...								
Sicherheit	...gesetzliche Sicherheitsabstände zu mir nicht unterschritten werden, ich hierfür aber stärker verzögern muss.	☐	☐	☐	☐	☐	☐	☐
Effizienz	...es bei kleinem Abstand zu mir einfädelt, um den Verkehrsfluss nicht aufzuhalten, dabei allerdings gesetzliche Sicherheitsabstände zu mir unterschritten werden könnten.	☐	☐	☐	☐	☐	☐	☐
Kosten	...es vermeidet, dass ich meine Geschwindigkeit zu stark reduzieren muss, um es einfädeln zu lassen, dabei allerdings gesetzliche Sicherheitsabstände unterschritten werden könnten.	☐	☐	☐	☐	☐	☐	☐

		Trifft absolut nicht zu 1	Trifft nicht zu 2	Trifft eher nicht zu 3	Teil/ teils 4	Trifft eher zu 5	Trifft zu 6	Trifft absolut zu 7
Während das automatisierte Fahrzeug einfädelt, sollte es…								
Kosten	…in jedem Fall vermeiden, dass ich meine Geschwindigkeit weiter reduzieren muss, auch wenn dabei gesetzliche Sicherheitsabstände unterschritten werden könnten.	☐	☐	☐	☐	☐	☐	☐
Sicherheit	…den gesetzlichen Sicherheitsabstand zum Vorderfahrzeug einhalten, auch wenn ich dadurch meine Geschwindigkeit weiter reduzieren muss.	☐	☐	☐	☐	☐	☐	☐
Effizienz	…möglichst geringe Abstände zu mir und dem Vorderfahrzeug wählen, um ein zügiges Manöver zu gewährleisten, auch wenn dabei Sicherheitsabstände unterschritten werden könnten.	☐	☐	☐	☐	☐	☐	☐

		Trifft absolut nicht zu 1	Trifft nicht zu 2	Trifft eher nicht zu 3	Teil/ teils 4	Trifft eher zu 5	Trifft zu 6	Trifft absolut zu 7
Beim **Abschluss** des Einfädelns sollte das automatisierte Fahrzeug…								
Sicherheit	…den Sicherheitsabstand zum Vorderfahrzeug sofort wiederherstellen, falls er zu gering sein sollte, auch wenn ich dadurch stärker verzögern muss.	☐	☐	☐	☐	☐	☐	☐

Kosten	...langsam den notwendigen Abstand zum Vorderfahrzeug herstellen, sodass ich meine Geschwindigkeit weniger stark reduzieren muss.	☐	☐	☐	☐	☐	☐	☐
Effizienz	...langsam den notwendigen Abstand zum Vorderfahrzeug herstellen, sodass ich und folgende Fahrzeuge weniger stark verzögern müssen.	☐	☐	☐	☐	☐	☐	☐

B.2.3 Study part I

Fragebogen zur Studie Teil 1 – Nach jeder Fahrsituation

<table>
<tr><td colspan="3">Situation: ________________________ Taster betätigt? ☐ ja ☐ nein |
Grund:__________________________</td></tr>
<tr><td colspan="3">Situation erfolgreich? Nein, Grund:</td></tr>
<tr><td rowspan="2">a</td><td>Erwarteter Einfädelzeitpunkt
Der Wechselzeitpunkt des automatisierten Fahrzeugs war so, wie Sie es erwartet hatten.</td><td>☐ ja ☐ nein</td></tr>
<tr><td colspan="2">Wann hätten Sie ein Einfädeln des automatisierten Fahrzeugs erwartet?
genau richtig
Früher ☐ ☐ ☐ ☐ ☐ ☐ ☐ Später</td></tr>
<tr><td rowspan="2">b</td><td>Situation
Wie kritisch empfanden Sie die gerade erlebte Fahrsituation?</td><td></td></tr>
<tr><td>Anmerkungen.
Falls > harmlos: Wieso?</td><td></td></tr>
<tr><td>c</td><td colspan="2">Eigenes Fahrverhalten
Wie würde ein Beobachter Ihr Fahrverhalten in der eben erlebten Situation beurteilen?
nicht kooperativ ☐ ☐ ☐ ☐ ☐ ☐ ☐ sehr kooperativ</td></tr>
</table>

d	**Verhalten des automatisierten Fahrzeugs** Bitte bewerten Sie das gerade erlebte Verhalten des automatisierten Fahrzeugs.						
	störend	☐	☐	☐	☐	☐	nicht störend
	aufhaltend	☐	☐	☐	☐	☐	zeitsparend
	Nützlich	☐	☐	☐	☐	☐	Nutzlos
	Angenehm	☐	☐	☐	☐	☐	Unangenehm
	Schlecht	☐	☐	☐	☐	☐	Gut
	Nett	☐	☐	☐	☐	☐	Nervig
	Effizient	☐	☐	☐	☐	☐	Unnötig
	Ärgerlich	☐	☐	☐	☐	☐	Erfreulich
	Hilfreich	☐	☐	☐	☐	☐	Wertlos
	Nicht wünschenswert	☐	☐	☐	☐	☐	Wünschenswert
	Aktivierend	☐	☐	☐	☐	☐	Einschläfernd

B.2.4 Study part II

Fragebogen zur Studie Teil 2 – Nach jeder Fahrsituation

Situation: ________________________ Anzahl Fehlversuche: ________________________	
War der Einfädelvorgang passend? Wenn nein, was hat nicht gepasst?	
FV 1 - Grund:	FV 2 – Grund:
FV 3 – Grund:	FV 4 - Grund:
Eigenes Fahrverhalten Wie würde ein Beobachter Ihr Fahrverhalten in der eben erlebten Situation beurteilen? nicht kooperativ ☐ ☐ ☐ ☐ ☐ ☐ ☐ sehr kooperativ	
Anmerkungen	

Fragebogen zur Studie Teil 2 – Am Ende des Studienteils

I1	Sie haben in diesem Versuchsteil Situationen erlebt, in denen das automatisierte Fahrzeug dringlicher einscheren musste, und Situationen in denen es mehr Zeit hatte, den Fahrstreifen zu wechseln. Hat sich dies auf den Zeitpunkt, zu dem das automatisierte Fahrzeug einfädeln sollte, ausgewirkt? Wenn ja, inwiefern?
	☐ ja ☐ nein
I2	Hat sich die Dringlichkeit des Fahrstreifenwechsels auf Ihr **eigenes Fahrverhalten** ausgewirkt? Wenn ja, inwiefern?
	☐ ja ☐ nein

m	Was kann an der Gestaltung des Fahrstreifenwechsels noch verbessert werden?

B.2.5 Post-Test

Posttest-Fragebogen

Fahrversuch zur „Wahrnehmung des automatisierten Einfädelvorgangs“

1. Erwartungshaltung an automatisierte Fahrzeuge								
Man kann verschiedene Meinungen zum automatisierten Fahren bzw. zu automatisierten Fahrzeugen haben. Daher hätten wir gerne Ihre Reaktionen auf die folgenden Aussagen. *Bitte sagen Sie uns, ob Sie die jeweiligen Aussagen für zutreffend erachten oder nicht.*								
		Trifft absolut nicht zu 1	**Trifft nicht zu** 2	**Trifft eher nicht zu** 3	**Teil/ teils** 4	**Trifft eher zu** 5	**Trifft zu** 6	**Trifft absolut zu** 7
a	Automatisierte Fahrzeuge werden nur auf Sonderstrecken (d.h. auf Strecken, auf welchen nur automatisierte Fahrzeuge zugelassen sind) fahren.	☐	☐	☐	☐	☐	☐	☐
b	Automatisierte Fahrzeuge und menschliche Fahrer können im Straßenverkehr problemlos interagieren.	☐	☐	☐	☐	☐	☐	☐
c	Automatisierte Fahrzeuge sollten gekennzeichnet werden.	☐	☐	☐	☐	☐	☐	☐
d	Automatisierte Fahrzeuge können in der Interaktion mit manuellen Fahrern *hilfreiche* Interaktionspartner sein.	☐	☐	☐	☐	☐	☐	☐
e	Automatisierte Fahrzeuge können ihre Fahrstrategie so gestalten, dass eine *zeitsparende* Interaktion zwischen manuellem und automatisiertem Fahrzeug möglich ist.	☐	☐	☐	☐	☐	☐	☐
f	Automatisierte Fahrzeuge können Ihre Fahrstrategie so gestalten, dass eine *nutzbringende* Interaktion zwischen menschlichem	☐	☐	☐	☐	☐	☐	☐

	Fahrer und automatisiertem Fahrzeug möglich ist.							

2. Erwartungshaltung an den Einfädelvorgang								
Bitte geben Sie an, inwiefern die jeweiligen Aussagen zum Fahrverhalten eines automatisierten Fahrzeugs Ihrer Meinung nach zutreffen.								
		Trifft absolut nicht zu 1	**Trifft nicht zu 2**	**Trifft eher nicht zu 3**	**Teil/ teils 4**	**Trifft eher zu 5**	**Trifft zu 6**	**Trifft absolut zu 7**
Das automatisierte Fahrzeug sollte den **Zeitpunkt des Einfädelns** so wählen, dass…								
Sicherheit	…gesetzliche Sicherheitsabstände zu mir nicht unterschritten werden, ich hierfür aber stärker verzögern muss.	☐	☐	☐	☐	☐	☐	☐
Effizienz	…es mit kleinem Abstand zu mir einfädelt, um den Verkehrsfluss nicht aufzuhalten, dabei allerdings gesetzliche Sicherheitsabstände zu mir unterschritten werden könnten.	☐	☐	☐	☐	☐	☐	☐
Kosten	…es vermeidet, dass ich meine Geschwindigkeit zu stark reduzieren muss, um es einfädeln zu lassen, dabei allerdings gesetzliche Sicherheitsabstände unterschritten werden könnten.	☐	☐	☐	☐	☐	☐	☐

		Trifft absolut nicht zu 1	Trifft nicht zu 2	Trifft eher nicht zu 3	Teil/ teils 4	Trifft eher zu 5	Trifft zu 6	Trifft absolut zu 7
Während das automatisierte Fahrzeug einfädelt, sollte es…								
Kosten	…in jedem Fall vermeiden, dass ich meine Geschwindigkeit weiter reduzieren muss, auch wenn dabei gesetzliche Sicherheitsabstände unterschritten werden könnten.	☐	☐	☐	☐	☐	☐	☐
Sicherheit	…den gesetzlichen Sicherheitsabstand zum Vorderfahrzeug einhalten, auch wenn ich dadurch meine Geschwindigkeit noch weiter reduzieren muss.	☐	☐	☐	☐	☐	☐	☐
Effizienz	…möglichst geringe Abstände zu mir und dem Vorderfahrzeug wählen, auch wenn dabei Sicherheitsabstände unterschritten werden könnten.	☐	☐	☐	☐	☐	☐	☐

		Trifft absolut nicht zu 1	**Trifft nicht zu 2**	**Trifft eher nicht zu 3**	**Teil/ teils 4**	**Trifft eher zu 5**	**Trifft zu 6**	**Trifft absolut zu 7**
Beim **Abschluss** des Einfädelns sollte das automatisierte Fahrzeug...								
Sicherheit	...den Sicherheitsabstand zum Vorderfahrzeug sofort wiederherstellen, falls er zu gering sein sollte, auch wenn ich dadurch stärker verzögern muss.	☐	☐	☐	☐	☐	☐	☐
Kosten	...langsam den notwendigen Abstand zum Vorderfahrzeug herstellen, sodass ich meine Geschwindigkeit weniger stark reduzieren muss.	☐	☐	☐	☐	☐	☐	☐
Effizienz	...langsam den notwendigen Abstand zum Vorderfahrzeug herstellen, sodass ich und folgende Fahrzeuge weniger stark verzögern müssen.	☐	☐	☐	☐	☐	☐	☐

3. Situationsabhängige Gestaltung des automatisierten Einfädelvorgangs	
Bitte geben Sie an, in welcher Situation das automatisierte Fahrzeug das beschriebene Fahrverhalten zeigen sollte. Mehrfachantworten möglich.	
Kosten - Den *Zeitpunkt* des Einfädelns so wählen, dass ich möglichst wenig verzögern muss. - *Während* des Einfädelns den Abstand zum Vorderfahrzeug so wählen, dass ich nicht zusätzlich verzögern muss, auch wenn dabei das automatisierte Fahrzeug den Sicherheitsabstand zum Vorderfahrzeug unterschreitet.	☐ im zähfließenden Verkehr bei ca. 30 km/h ☐ auf der Autobahn bei geringer Geschwindigkeit von ca. 50 km/h ☐ auf der Autobahn bei hoher Geschwindigkeit von ca. 130 km/h ☐ in folgenden Situationen: ____________________ ☐ in keiner Situation
Sicherheit beider Fzg. Sicherheitsabstände stets einhalten, sowohl zu mir, als auch zum Vorderfahrzeug, auch wenn dies bedeutet, dass ich insgesamt stärker verzögern muss.	☐ im zähfließenden Verkehr bei ca. 30 km/h ☐ auf der Autobahn bei geringer Geschwindigkeit von ca. 50 km/h ☐ auf der Autobahn bei hoher Geschwindigkeit von ca. 130 km/h ☐ in folgenden Situationen: ____________________ ☐ in keiner Situation
Sicherheit manuelles Fzg. - Sicherheitsabstände zu mir stets einhalten. - *Während* des Einfädelns vermeiden, dass ich zusätzlich ausgebremst werde, auch wenn dadurch Sicherheitsabstände zum Vorderfahrzeug u.U. nicht eingehalten werden.	☐ im zähfließenden Verkehr bei ca. 30 km/h ☐ auf der Autobahn bei geringer Geschwindigkeit von ca. 50 km/h ☐ auf der Autobahn bei hoher Geschwindigkeit von ca. 130 km/h ☐ in folgenden Situationen: ____________________
Effizienz - Den *Zeitpunkt* des Einfädelns bei geringem Abstand zu mir wählen, um den Verkehrsfluss nicht aufzuhalten, auch wenn dabei der Sicherheitsabstand zu mir unterschritten werden könnte. - *Während* des Einfädelns den Abstand zum Vorderfahrzeug und zu mir möglichst gering wählen, um ein schnelles Einfädeln zu gewährleisten, auch wenn dabei die Sicherheitsabstände zu mir und dem Vorderfahrzeug unterschritten werden könnten.	☐ im zähfließenden Verkehr bei ca. 30 km/h ☐ auf der Autobahn bei geringer Geschwindigkeit von ca. 50 km/h ☐ auf der Autobahn bei hoher Geschwindigkeit von ca. 130 km/h ☐ in folgenden Situationen: ____________________ ☐ in keiner Situation

	4. **Weitere Vorschläge**
a	Haben Sie noch weitere Anmerkungen, was bei der Wahl des Einfädelzeitpunktes des automatisierten Fahrzeugs zu beachten wäre? Bitte geben Sie auch an, ob dies abhängt von der Geschwindigkeit der Fahrzeuge, der Dringlichkeit der Situation oder der Stärke, mit der das automatisierte Fahrzeug seinen Einfädelwunsch mitteilt.
b	Haben Sie weitere Vorschläge, wie die Durchführung eines automatisierten Einfädelvorgangs sinnvoll wäre?

	5. **Anmerkungen**
a	Haben Sie noch Anmerkungen zu dem Fahrversuch, den Fragebögen oder allgemeine Anmerkungen?

C Appendix for study III

C.1 Participant's instructions

Bewertung eines automatisierten Fahrstreifenwechsels

HERZLICH WILLKOMMEN ZUR VERSUCHSEINWEISUNG

Gegenstand der Probandenstudie

Situation: Mischverkehr

Vor allem in dichtem Verkehr:

Viel Interaktion

Automatisierter Fahrstreifenwechsel notwendig

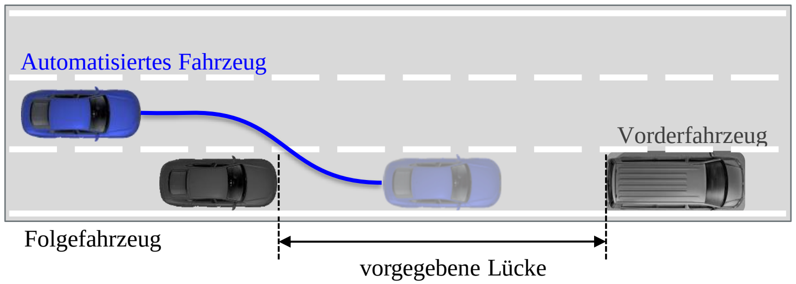
Kernfrage:

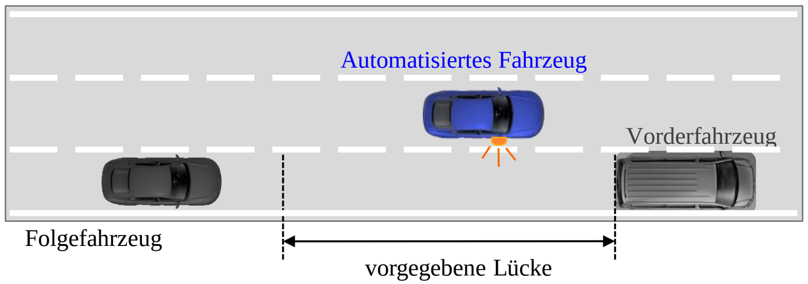
- Wie soll sich ein automatisiertes Fahrzeug verhalten?

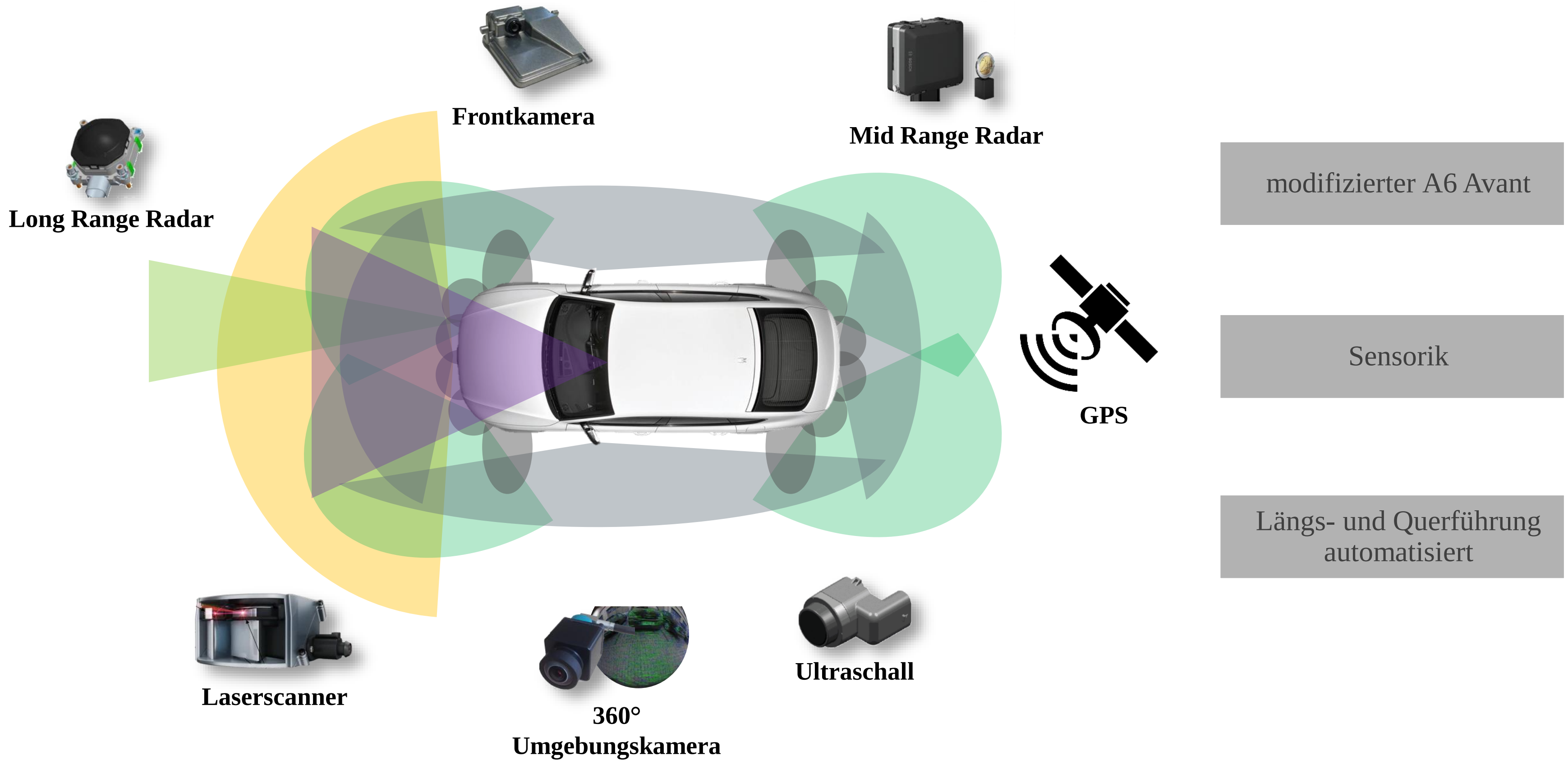
Szenario

Sie fahren nach der Arbeit auf der A9 Richtung München. Durch ein erhöhtes Verkehrsaufkommen am Autobahnkreuz Holledau kommt es zu zähfließendem Verkehr. Zahlreiche Fahrzeuge möchten von der Autobahn abfahren und ordnen sich auf der rechten Spur ein. Weitere Fahrzeuge versuchen von der linken auf die rechte Spur zu wechseln. Sie fahren bereits auf der rechten Spur und möchten **ein** Fahrzeug vor Ihnen einscheren lassen. Es handelt sich dabei um ein autonomes Fahrzeug. Das Fahrzeug hat durch Blinken angezeigt, dass es einfädeln möchte und eine ausreichende Lückengröße abgewartet. Die Frage ist nun, wie es den Fahrstreifenwechsel **durchführen und abschließen** soll?

Um diese Frage zu beantworten stellen wir die beschriebene Situation mithilfe von 3 Fahrzeugen nach. Wir führen verschiedene Varianten des Einfädelvorgangs durch und sie bewerten, wie gut die jeweilige Variante ist.






Frontkamera
Mid Range Radar
Long Range Radar
modifizierter A6 Avant
Sensorik
GPS
Längs- und Querführung automatisiert
Laserscanner
360° Umgebungskamera
Ultraschall

Ablauf der Studie

Eingewöhnungsfahrt

Studie Teil 1:
Bewerten von 8 verschiedenen Einfädelstrategien
(30 min)

Studie Teil 2:
Bewerten von 3 verschiedenen Einfädelstrategien
(10 min)

Fahrzeugwechsel

Studie Teil 2:
Bewerten von 3 verschiedenen Einfädelstrategien
(10 min)

Abschlussfragebogen
(10 min)

6

Vorgehen

- Vorderfahrzeug in konstantem Abstand bei ca. 50 km/h folgen
- automatisierte Fahrzeug versucht sich einzufädeln
- Sie reagieren so, wie Sie es **im alltäglichen Verkehr** machen würden
- Das automatisierte Fahrzeug wartet bis der Abstand zu Ihnen groß genug ist
- Das automatisierte Fahrzeug fädelt vor Ihnen ein
- **Ihre Meinung zum gezeigten Fahrverhalten**

Offene Fragen?

Jetzt kann es losgehen!

Viel Spaß!

C.2 Questionnaires

C.2.1 Sample

Teil A: Erfahrung mit Fahrerassistenzsystemen

ACC (Adaptive Cruise Control / Abstandsregeltempomat)						
A1	**Sind Sie bereits (privat oder dienstlich) mit einem Abstandsregeltempomat (ACC) gefahren?**	☐ Ja ☐ Nein				
A2	**Verfügt eines Ihrer derzeitig genutzten Fahrzeuge (privat oder dienstlich) über ein ACC?**	☐ Ja ☐ Nein				
A3	**Wie viele Jahre sind Sie insgesamt mit Fahrzeugen gefahren, die mit einem ACC ausgestattet waren?**	ca. _______________ Jahre				
A4	**Wenn Sie mit einem Fahrzeug fahren, welches mit ACC ausgestattet ist, wie häufig schalten Sie dieses auf der Autobahn ein?**	nie	selten	gele-gent-lich	oft	imme r
		☐	☐	☐	☐	☐

Spurhalteassistenten (z.B. Audi Active Lane Assist)						
A5	**Sind Sie bereits (privat oder dienstlich) mit einem aktiven Spurhalteassistenten (z. B. Audi Active Lane Assist) gefahren?**	☐ Ja ☐ Nein				
A6	**Verfügt eines Ihrer derzeitig genutzten Fahrzeuge (privat oder dienstlich) über einen aktiven Spurhalteassistenten?**	☐ Ja ☐ Nein				
A7	**Wie viele Jahre sind Sie insgesamt mit Fahrzeugen gefahren, die mit einem aktiven Spurhalteassistenten ausgestattet waren?**	ca. _______________ Jahre				
A8	**Wenn Sie mit einem Fahrzeug fahren, welches mit einem aktiven Spurhalteassistenten ausgestattet ist, wie**	nie	selten	gele-gent-lich	oft	imme r

häufig schalten Sie diesen auf der Autobahn ein?	☐	☐	☐	☐	☐

Nutzung automatisierter Funktionen					
A9. Sind Sie bereits (privat oder dienstlich) mit einer Kombination aus aktivem Spurhalteassistent und ACC (teilautomatisiertes System, z. B. Stauassistent) gefahren?	☐ Ja		☐ Nein		
A10. Wenn Sie mit einem Fahrzeug fahren, welches mit einem <u>teilautomatisierten System</u> ausgestattet ist, wie häufig schalten Sie dieses auf der Autobahn ein (sofern die Voraussetzungen dafür erfüllt sind, z. B. Stau)?	nie	selten	gele-gent-lich	oft	imme r
	☐	☐	☐	☐	☐
A11. Haben Sie bereits an Testfahrten mit einem <u>teil- oder</u> <u>hochautomatisierten System</u> teilgenommen?	☐ Ja		☐ Nein		
A12. Wie häufig nehmen Sie im Schnitt an Testfahrten mit einem <u>teil- oder hochautomatisierten System</u> teil?	Selte ner als einm al pro Halb jahr	Einm al pro Halb-jahr	Alle 2-3 Monat e	Einm al im Mona t	Öfter als einma l im Mona t
	☐	☐	☐	☐	☐

Teil B: Ihre Fahrgewohnheiten

B1.	**Wie lange besitzen Sie bereits Ihren Führerschein der Klasse B?**	ca. __________________ Jahre	
B2.	**Wie hoch ist in etwa Ihre jährliche Fahrleistung? (Durchschnitt der letzten 5 Jahre)**	ca. __________________ km	
B3.	**Wie verteilen sich Ihre Fahrten mit dem Auto auf folgende Straßentypen (gesamt 100%)?** *Falls Sie einen Straßentypen nicht nutzen, tragen Sie bitte Null ein.*	Straße in Großstadt (mehr als 100.000 Einwohner)(%)	________ %
		Straße in Stadt / Kleinstadt(%)	________ %
		Land-/Bundesstraße (%)	________ %
		Autobahn (%)	________ %
B4.	**Müssen Sie zum Fahren eine Sehhilfe tragen?** *In der Studie wird ein System zur Blickdatenerfassung verwendet, hierfür müssen wir wissen ob Sie zum Fahren eine Sehhilfe benötigen.*	☐ Ja	☐ Nein

Teil C: Ihr Interesse und Einstellung zum automatisierten Fahren

C.	**Man kann verschiedene Meinungen zum automatisierten Fahren haben. Daher hätten wir gerne Ihre Ansicht zu folgenden Aussagen.** *Bitte sagen Sie uns, ob Sie der jeweiligen Aussage zustimmen oder nicht.*			
		Ich neige dazu, zu widersprechen	Ich stimme eher zu	Kann ich nicht beantworten
a	Automatisiertes Fahren kann mich in monotonen oder stressigen Fahrsituationen entlasten.	☐	☐	☐
b	Wenn das Auto selber fährt, kann ich andere Dinge tun.	☐	☐	☐
c	Automatisiertes Fahren kann schwere Unfälle verhindern.	☐	☐	☐
d	Automatisiertes Fahren macht mir Angst.	☐	☐	☐
e	Ich glaube nicht, dass es jemals zuverlässig funktionieren wird.	☐	☐	☐

Teil D: Ihr Fahrverhalten

D. Bitte benutzen Sie die unten angegebene Skala, um anzugeben, wie oft Sie das jeweilige Fahrverhalten zeigen. *Überlegen Sie nicht, sondern antworten Sie ehrlich und aus dem Bauch heraus. Es gibt keine richtigen und falschen Antworten. Machen Sie in jeder Zeile ein Kreuz.*							
		Nie	**Fast nie**	**Manch -mal**	**Relativ oft**	**Sehr oft**	**Immer**
a	Beim Abbiegen besonders aufmerksam sein	☐	☐	☐	☐	☐	☐
b	Ausreichend langsam bremsen, um die Fahrer hinter mir zu warnen	☐	☐	☐	☐	☐	☐
c	Beim Spurwechsel durch Spiegel-, und Schulterblick tote Winkel überprüfen	☐	☐	☐	☐	☐	☐
d	Beim Folgen anderer Fahrzeuge einen Sicherheitsabstand einhalten (mehr als halber Tacho in m)	☐	☐	☐	☐	☐	☐
e	Die Geschwindigkeit verringern, um mich schlechten Witterungsbedingungen anzupassen	☐	☐	☐	☐	☐	☐
f	Anderen Fahrern Vorfahrt gewähren, wenn sie Vorfahrt haben	☐	☐	☐	☐	☐	☐
g	Beim Fahren auf den umliegenden Verkehr und die Straße achten	☐	☐	☐	☐	☐	☐
h	Die Geschwindigkeit verringern, um mich schlechten Straßenverhältnissen anzupassen	☐	☐	☐	☐	☐	☐
i	Richtungsanzeigen (Blinker) benutzen, um anderen Fahrern meine Abbiegeabsicht mitzuteilen	☐	☐	☐	☐	☐	☐

j	In einem Baustellenbereich abbremsen	☐	☐	☐	☐	☐	☐
k	In der Nähe von Fußgängern besonders vorsichtig fahren	☐	☐	☐	☐	☐	☐
l	Beim Heranfahren an Kreuzungen besonders aufmerksam sein	☐	☐	☐	☐	☐	☐
m	In der Nähe von Fahrradfahrern besonders vorsichtig fahren	☐	☐	☐	☐	☐	☐
n	Vorsichtiger fahren, um Menschen oder Fahrzeugen am Straßenrand Platz zu machen (z.B. langsamer fahren, auf die andere Seite fahren)	☐	☐	☐	☐	☐	☐
o	An einem Stoppschild vollständig zum Stillstand kommen	☐	☐	☐	☐	☐	☐
p	Verkehrszeichen befolgen	☐	☐	☐	☐	☐	☐
q	Vorhandene Geschwindigkeitsbegrenzungen in Schulbereichen befolgen	☐	☐	☐	☐	☐	☐

Teil E: Demographie

<table>
<tr><td rowspan="4" colspan="2">E1. Ihr Alter:</td><td colspan="2">☐ bis 24 Jahre</td></tr>
<tr><td colspan="2">☐ 25 - 44 Jahre</td></tr>
<tr><td colspan="2">☐ 45 - 65 Jahre</td></tr>
<tr><td colspan="2">☐ über 65 Jahre</td></tr>
<tr><td colspan="2">E2. Welchen beruflichen Hintergrund (z.B. Beruf oder Ausbildung) haben Sie?</td><td>☐ technisch</td><td>☐ nicht-technisch</td></tr>
<tr><td colspan="2">E3. Sind Sie Mitarbeiter der AUDI AG?</td><td>☐ ja</td><td>☐ nein</td></tr>
<tr><td colspan="4">Ihr Teilnehmer-Code, bitte ausfüllen:
Der Teilnehmercode dient dazu Ihre Daten im Versuch zu pseudonymisieren, damit können die Daten nur noch durch den Code auf ihre Person zurückgeführt werden.</td></tr>
<tr><td>E4. Die ersten zwei Buchstaben des Vornamens <u>Ihrer Mutter</u>

Beispiel:
Inge → In</td><td>E5. Den Geburtsmonat <u>Ihrer Mutter</u> in Zahlen

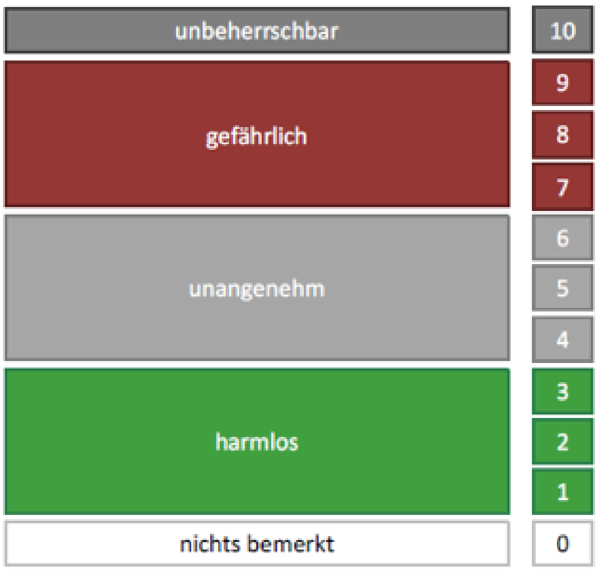
Beispiel:
05.01.1952 → 01</td><td>E6. Die ersten zwei Buchstaben des Vornamens <u>Ihres Vaters</u>

Beispiel:
Heinrich → He</td><td>E7. Den Geburtsmonat <u>Ihres Vaters</u> in Zahlen

Beispiel:
07.05.1958 → 05</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
</table>

C.2.2 Study part I and II

a	Hat sich das Fahrzeug so verhalten, wie Sie es erwartet haben?	1	2	3	4	5	6	7
Anmerkung:								
b	Wie kritisch empfanden Sie die gerade erlebte Fahrsituation?							
Anmerkung:								



c	**Eigene Reaktion:** Markieren Sie mit einem Kreuz, wie beansprucht Sie sich durch die Fahraufgabe in dieser Situation gefühlt haben.

Skala	Beschreibung
220	
	ausserordentlich anstrengend
200	
	sehr stark anstrengend
180	
160	
	stark anstrengend
140	
120	ziemlich anstrengend
100	
80	
	einigermassen anstrengend
60	
40	etwas anstrengend
20	kaum anstrengend
0	

Anmerkung:

d	**Verhalten des automatisierten Fahrzeugs** Bitte bewerten Sie das gerade erlebte Verhalten des automatisierten Fahrzeugs.

nützlich	☐	☐	☐	☐	☐	nutzlos
angenehm	☐	☐	☐	☐	☐	unangenehm
schlecht	☐	☐	☐	☐	☐	gut
nett	☐	☐	☐	☐	☐	nervig
effizient	☐	☐	☐	☐	☐	unnötig
ärgerlich	☐	☐	☐	☐	☐	erfreulich
hilfreich	☐	☐	☐	☐	☐	wertlos
nicht wünschenswert	☐	☐	☐	☐	☐	wünschenswert

C.3 AOI's for each participant

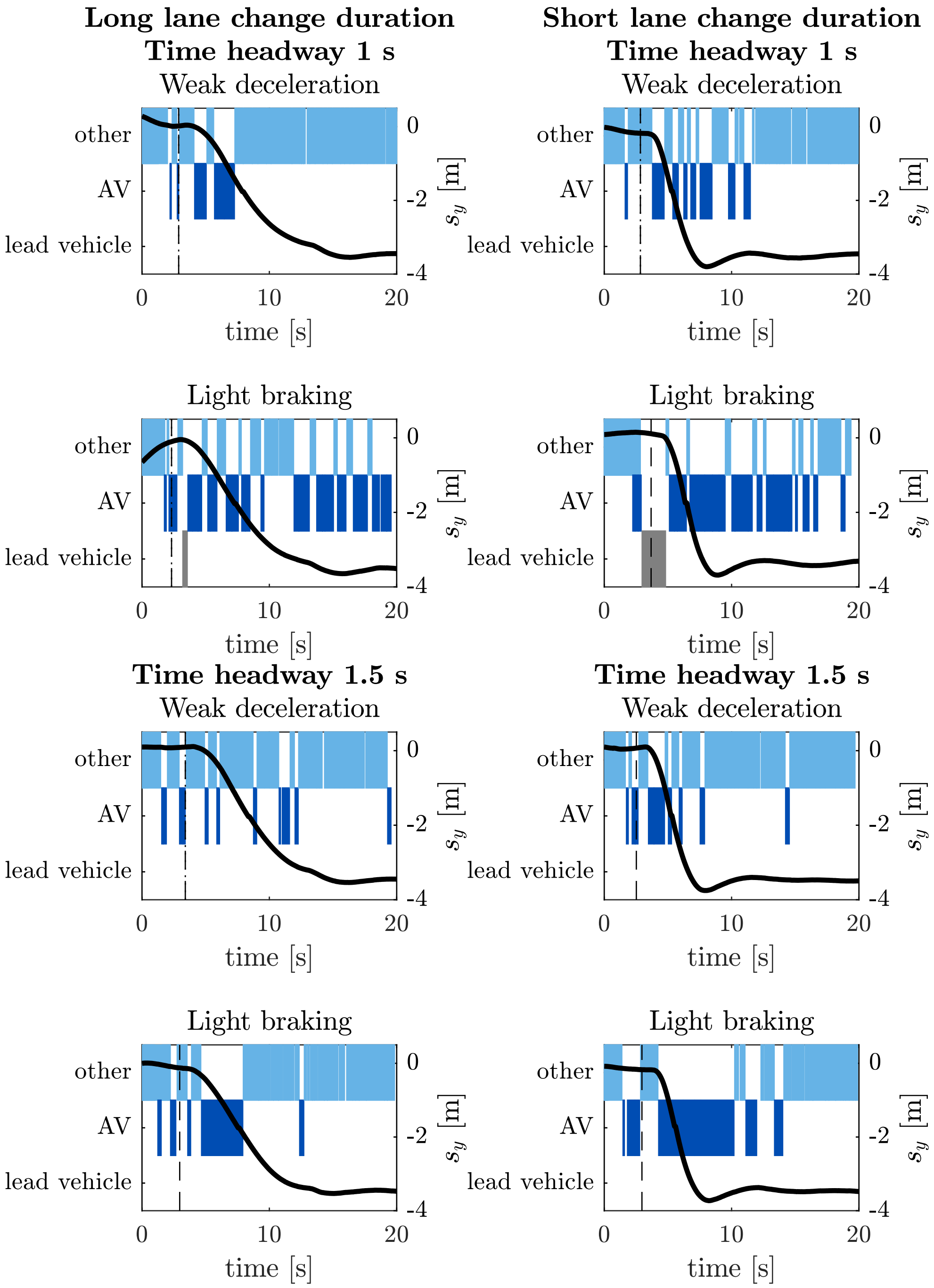


Figure A.1: Proband 1.

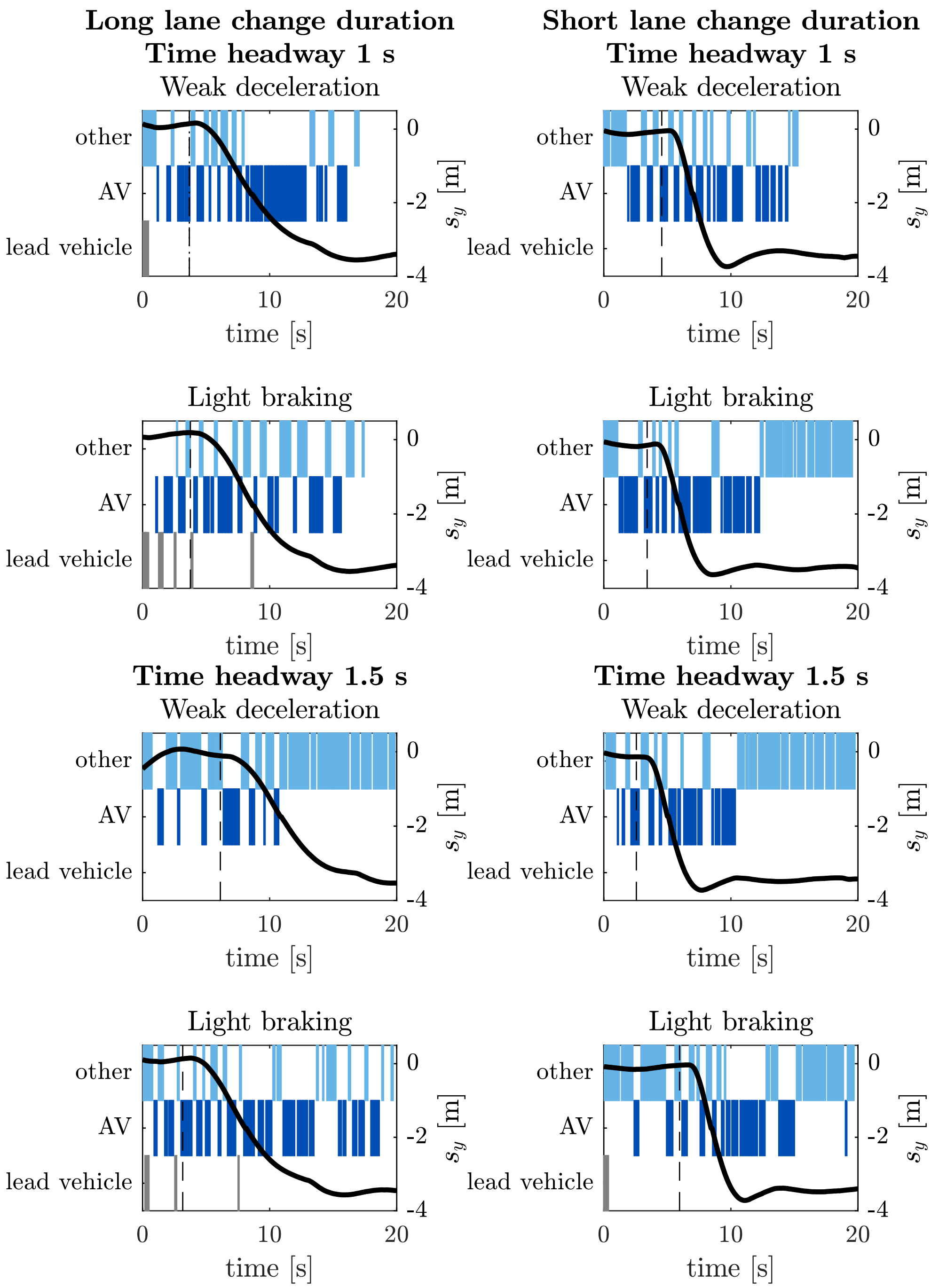


Figure A.2: Proband 3.

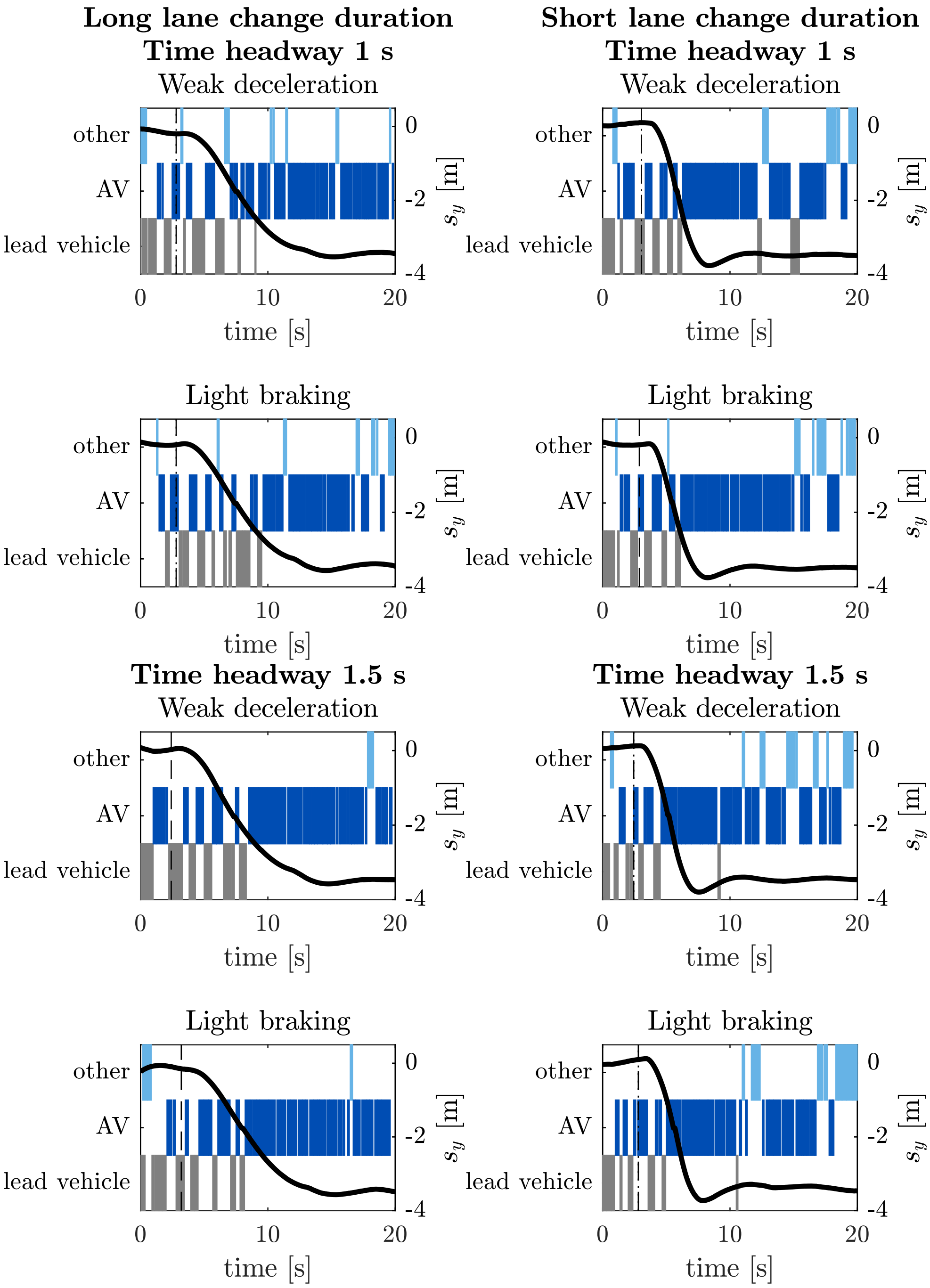


Figure A.3: Proband 4.

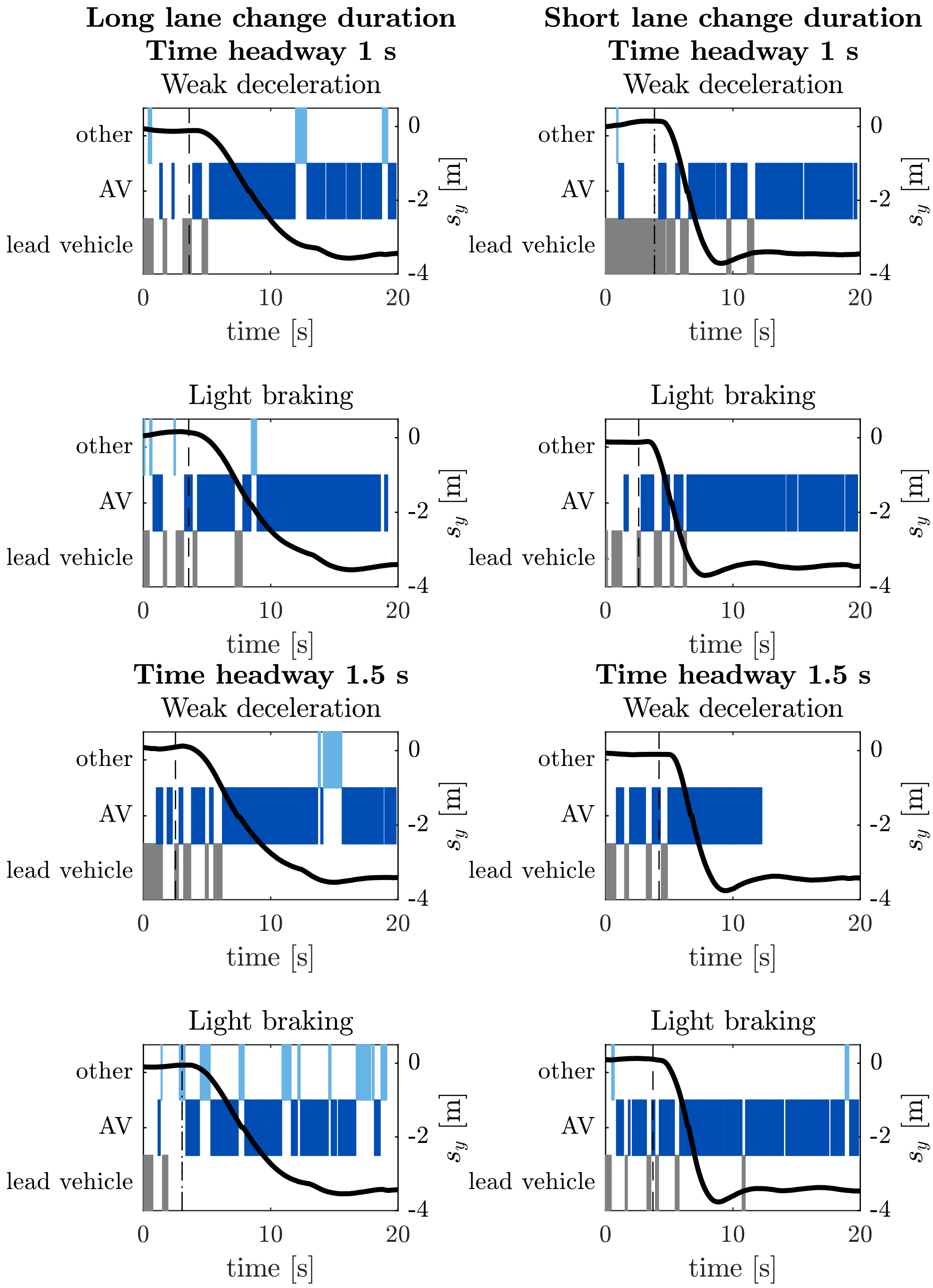


Figure A.4: Proband 5.

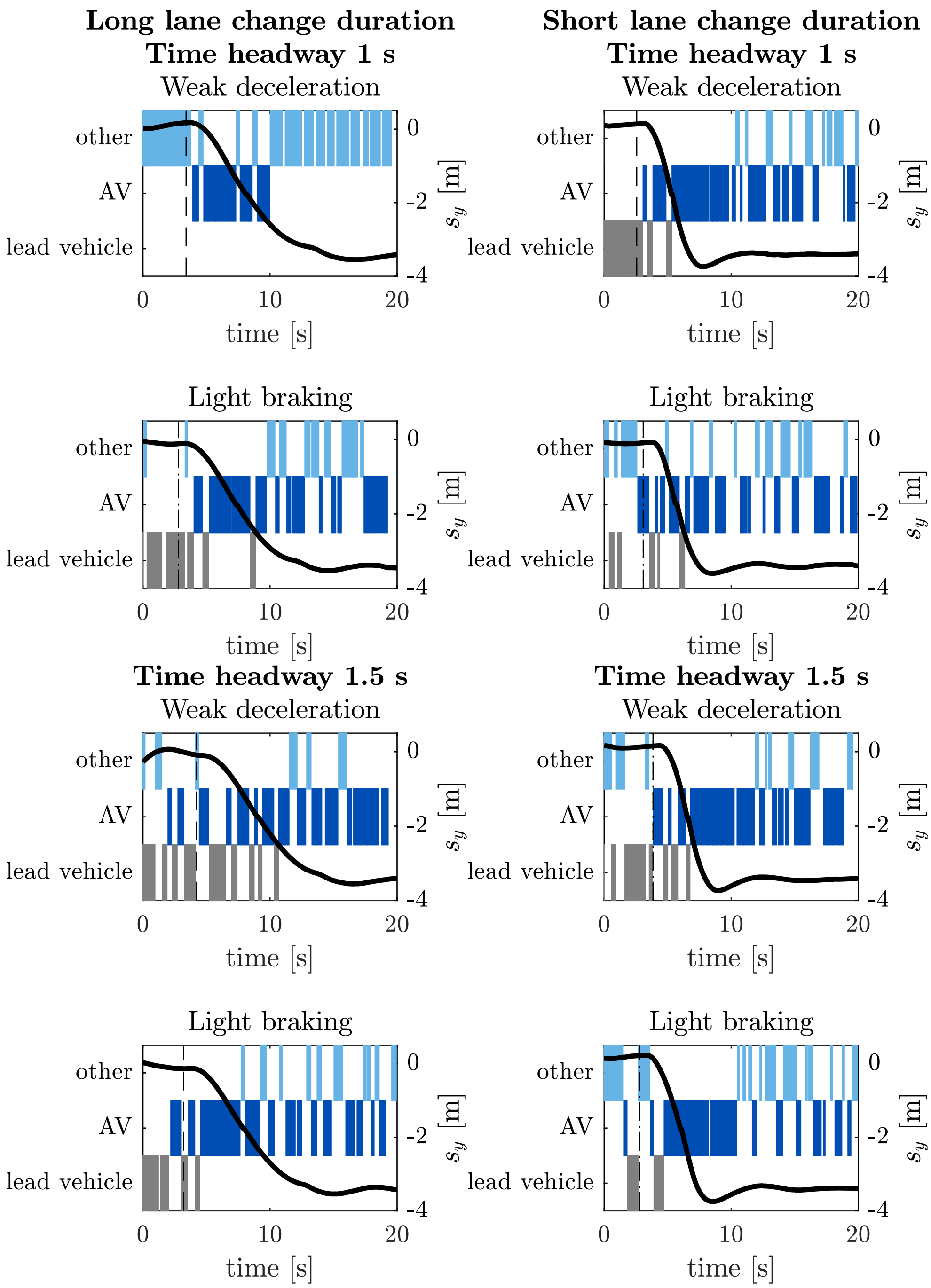


Figure A.5: Proband 6.

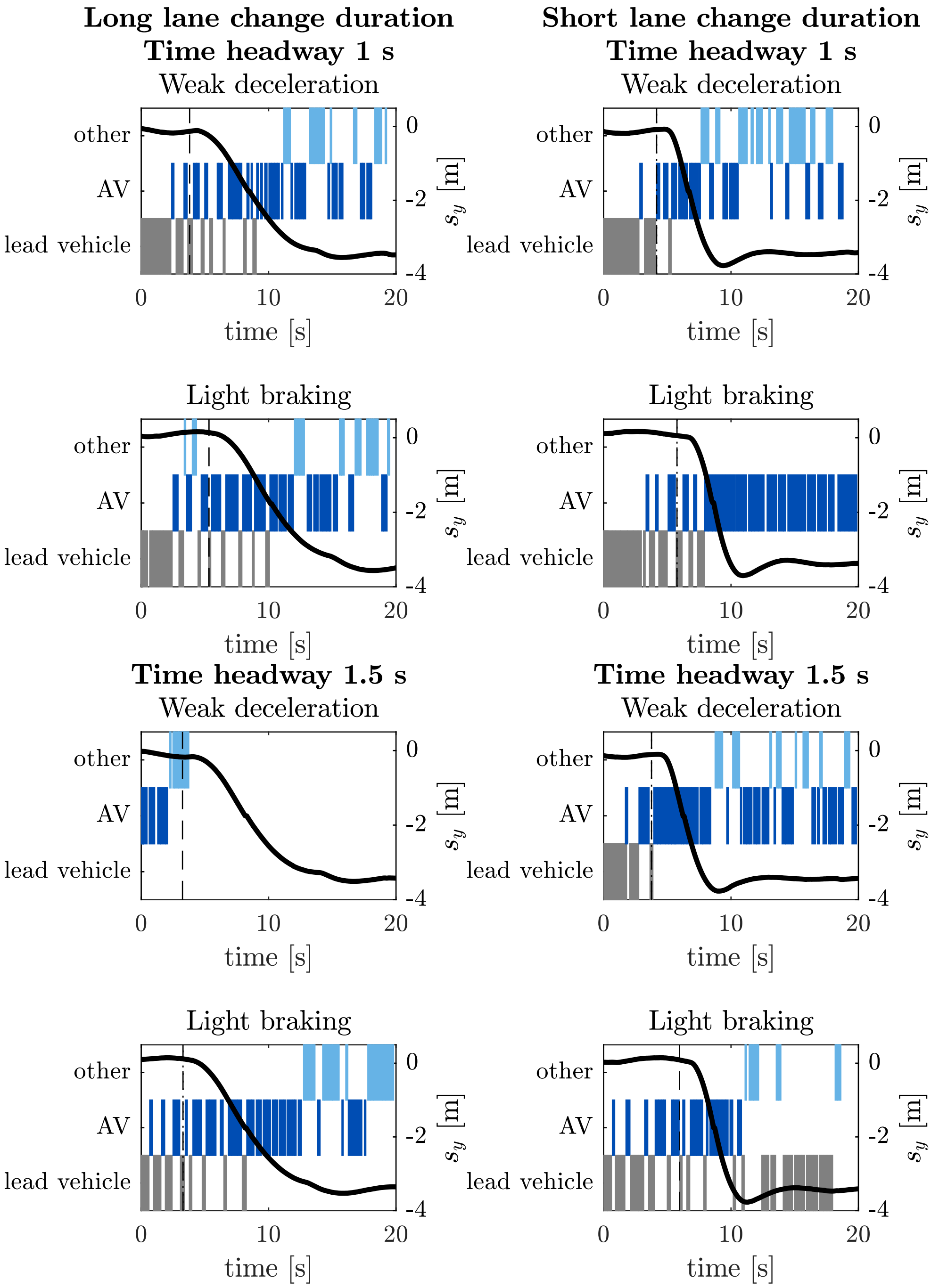


Figure A.6: Proband 9.

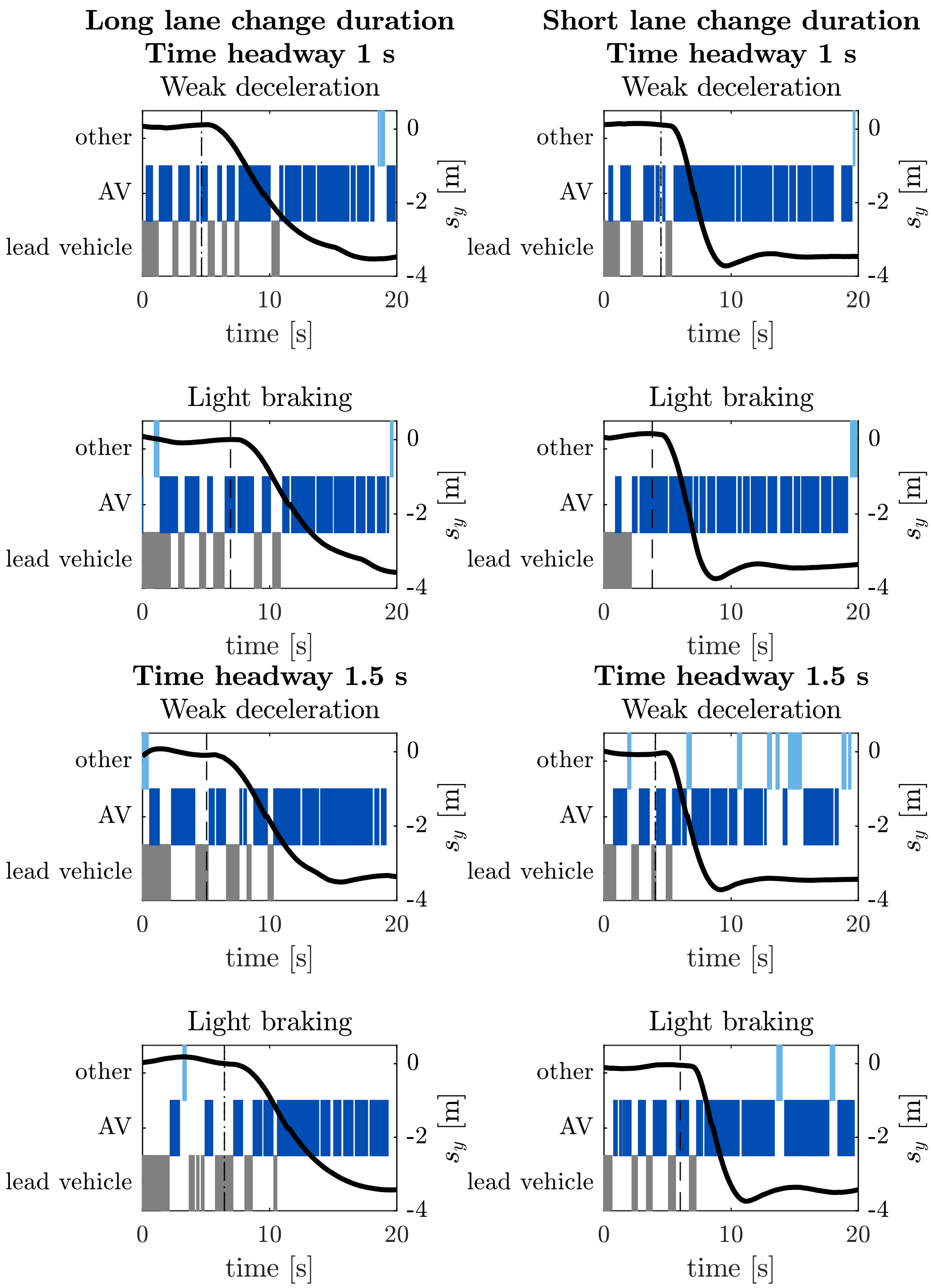


Figure A.7: Proband 16.

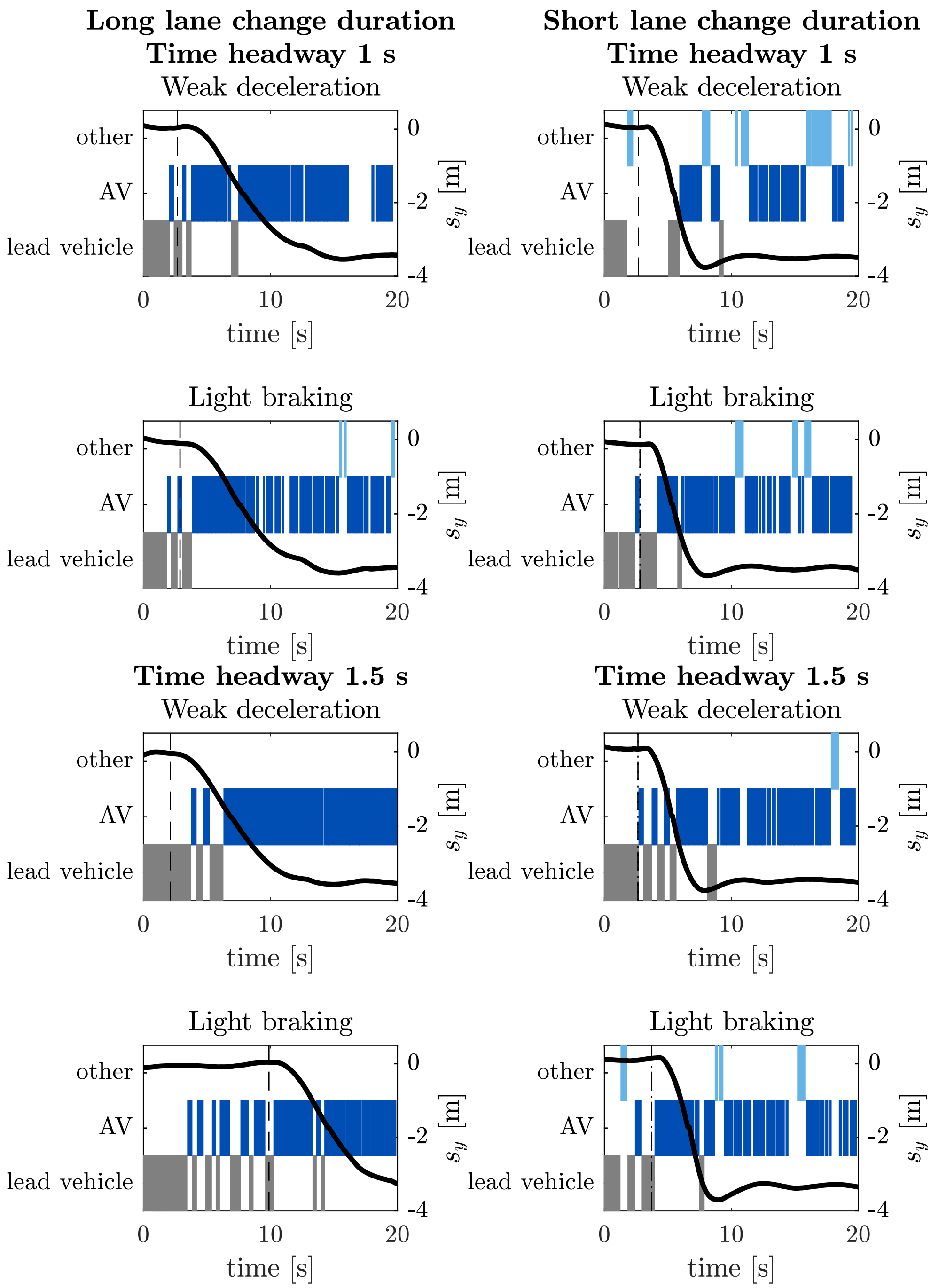


Figure A.8: Proband 21.

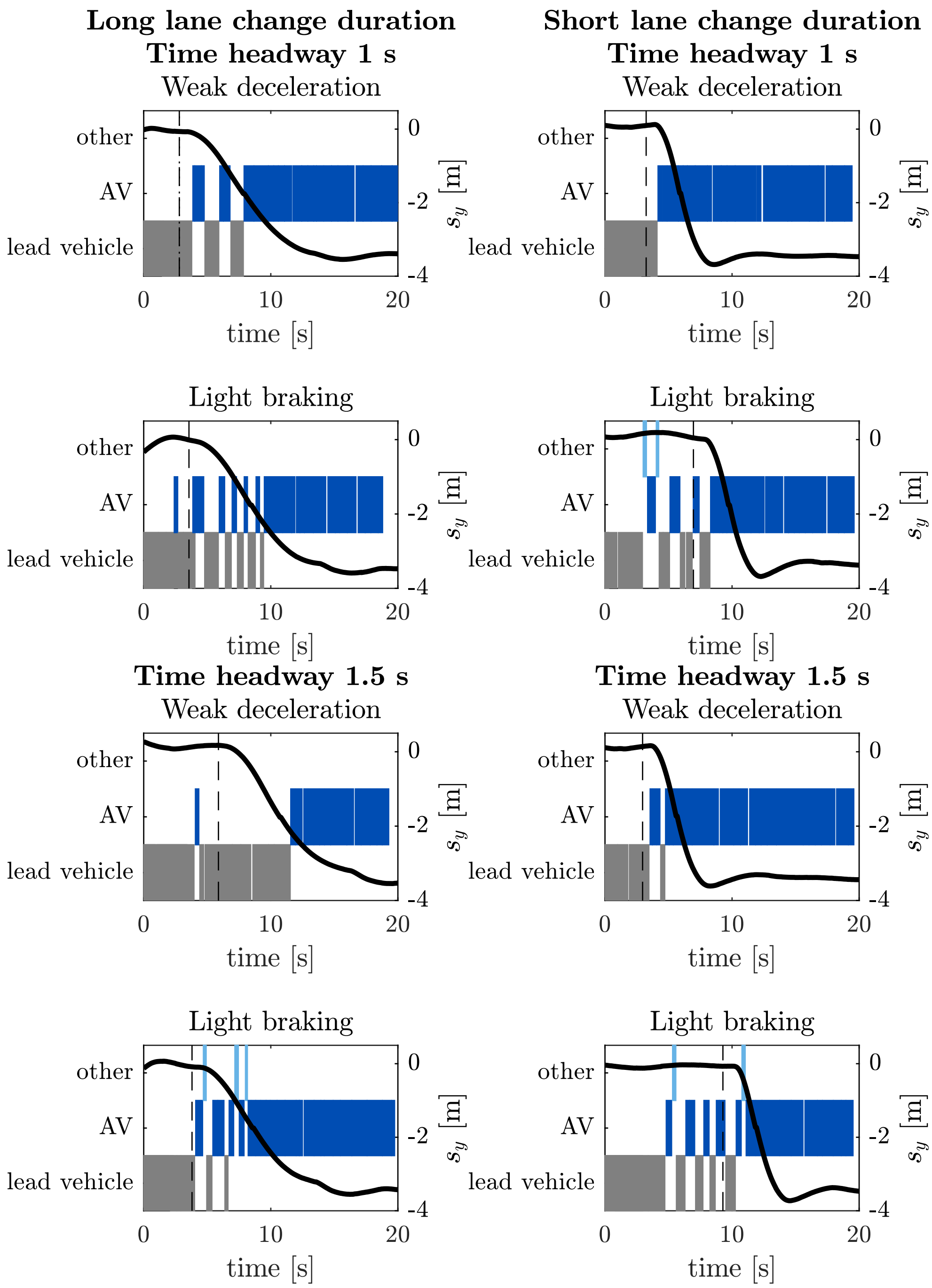


Figure A.9: Proband 22.

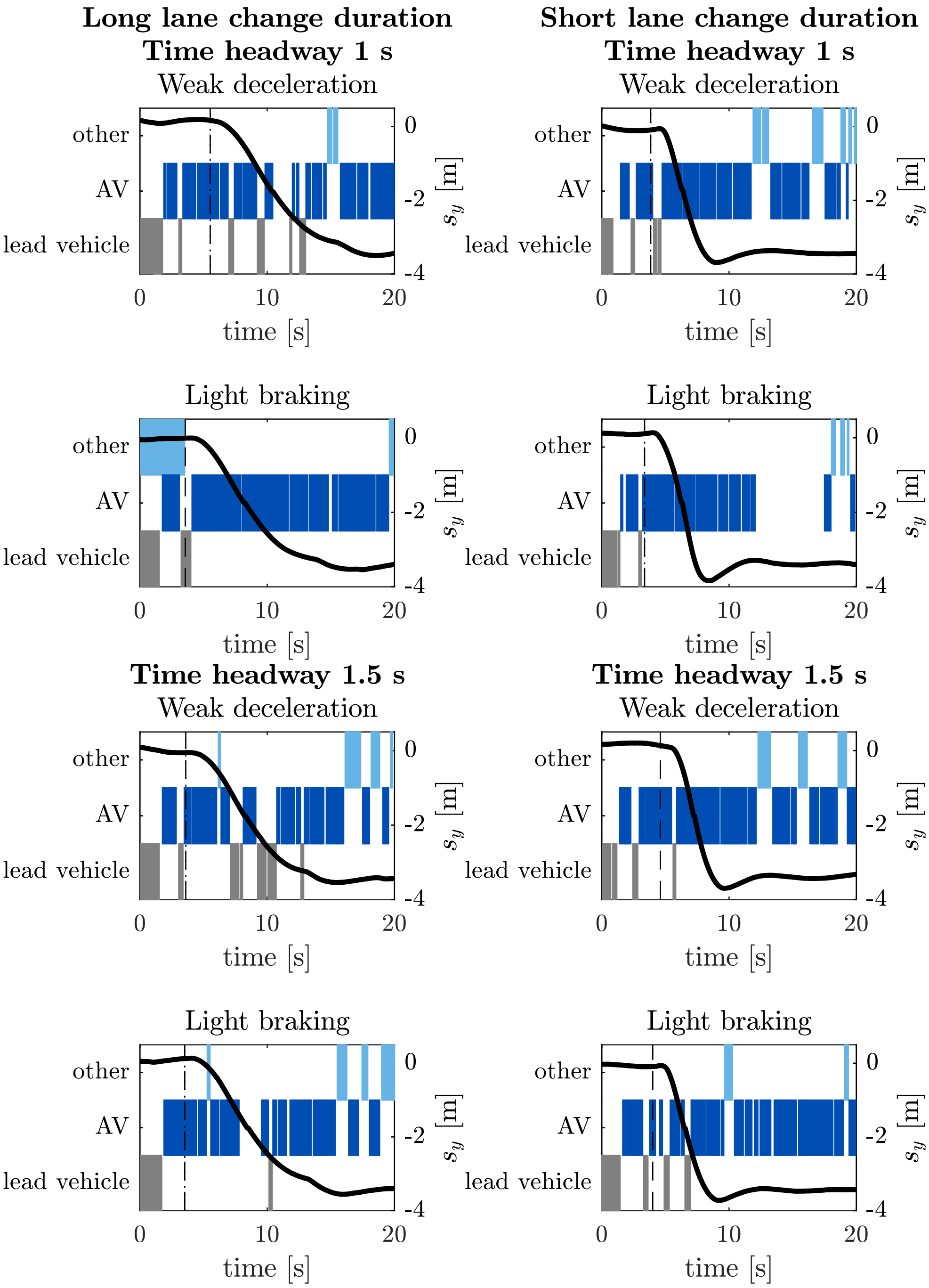


Figure A.10: Proband 23.

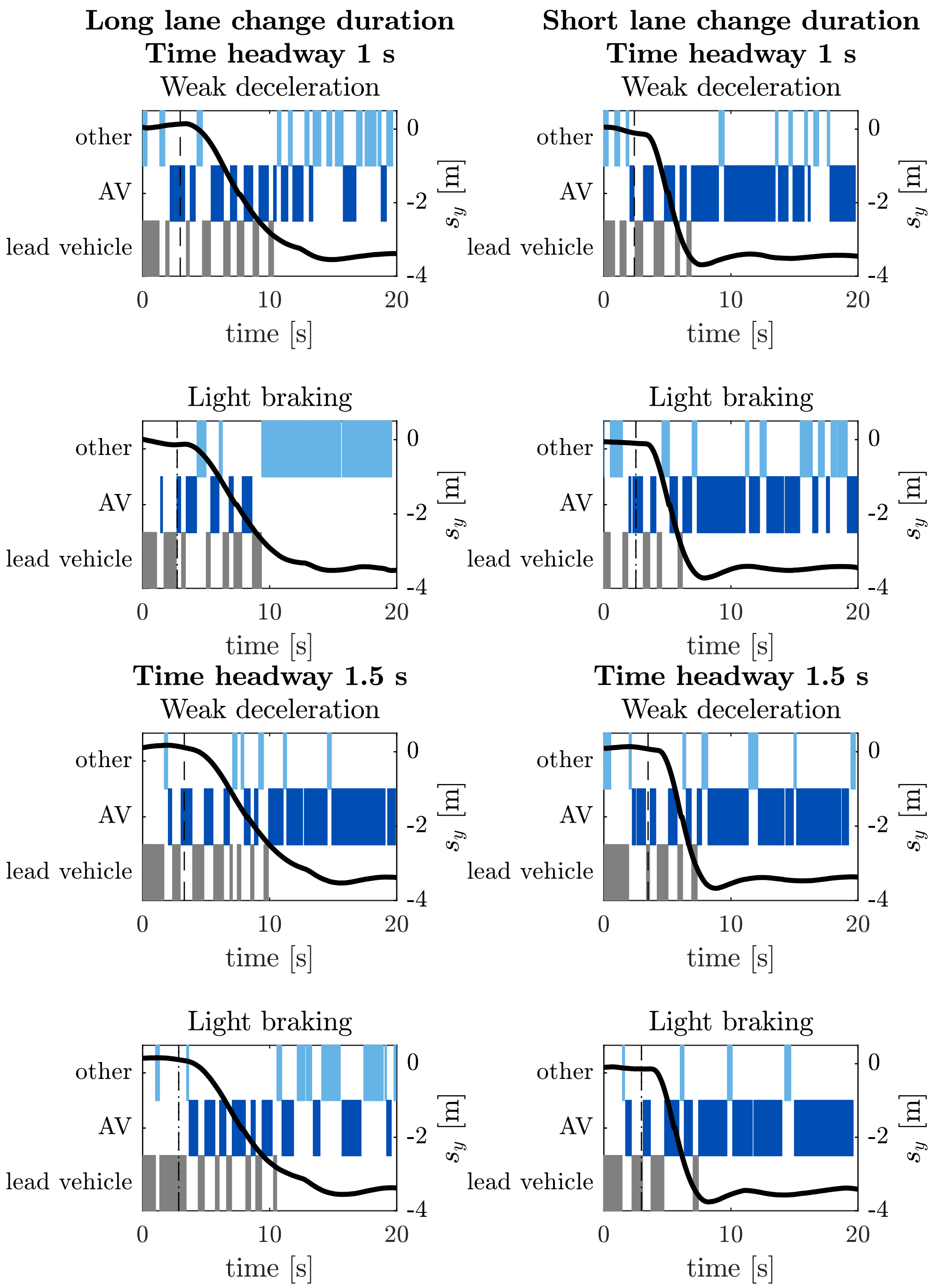


Figure A.11: Proband 25.

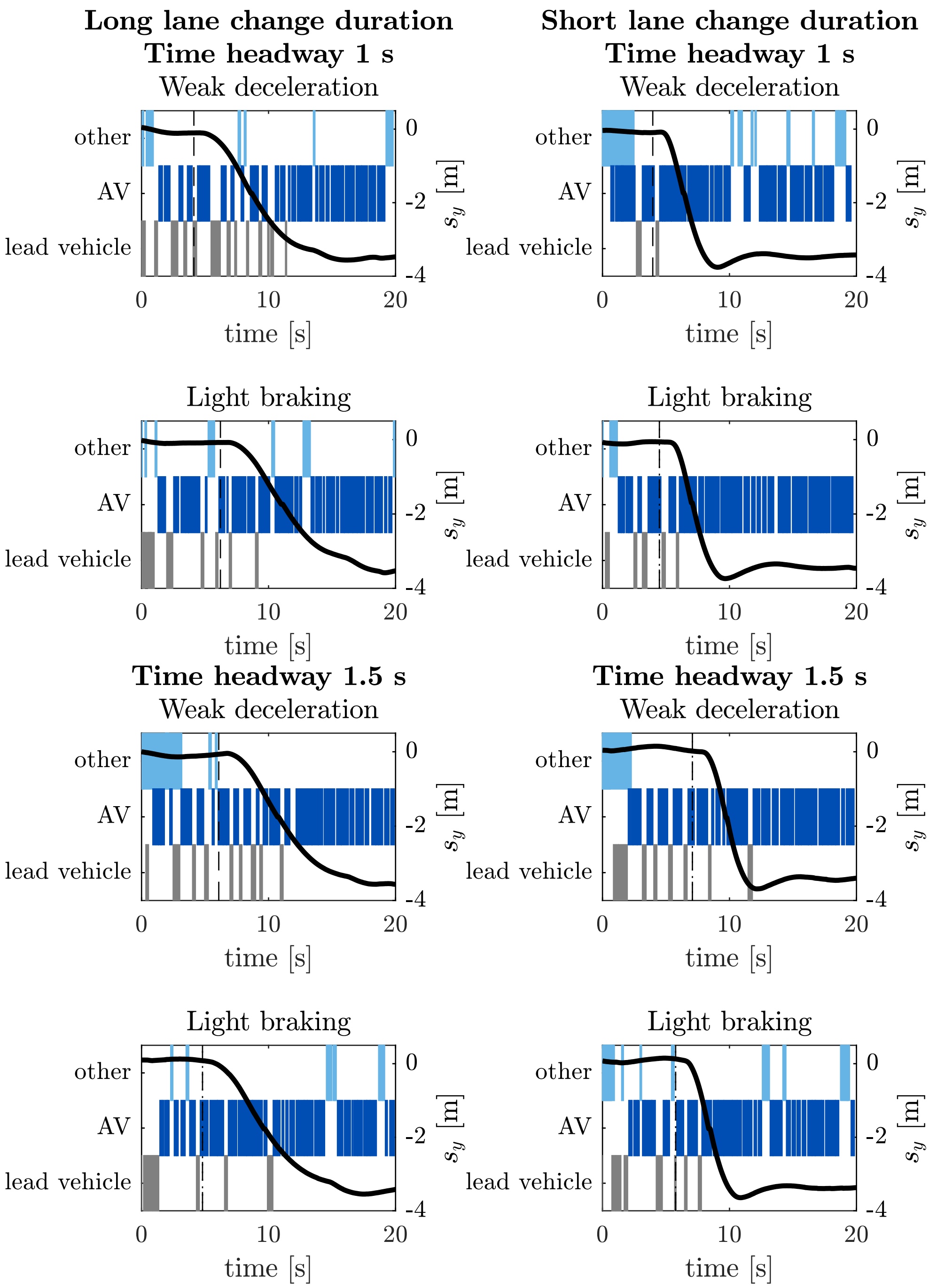


Figure A.12: Proband 29.

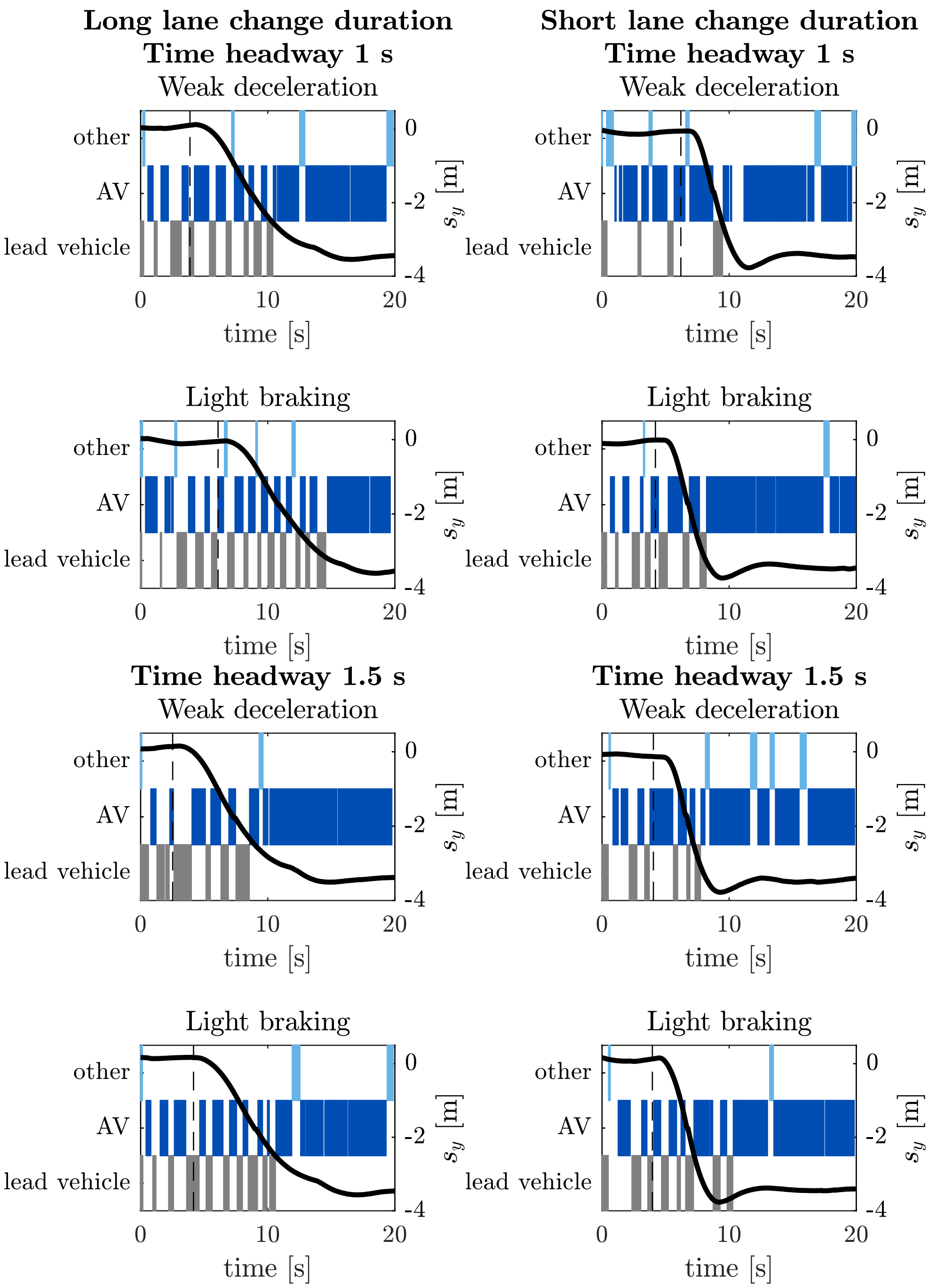


Figure A.13: Proband 34.

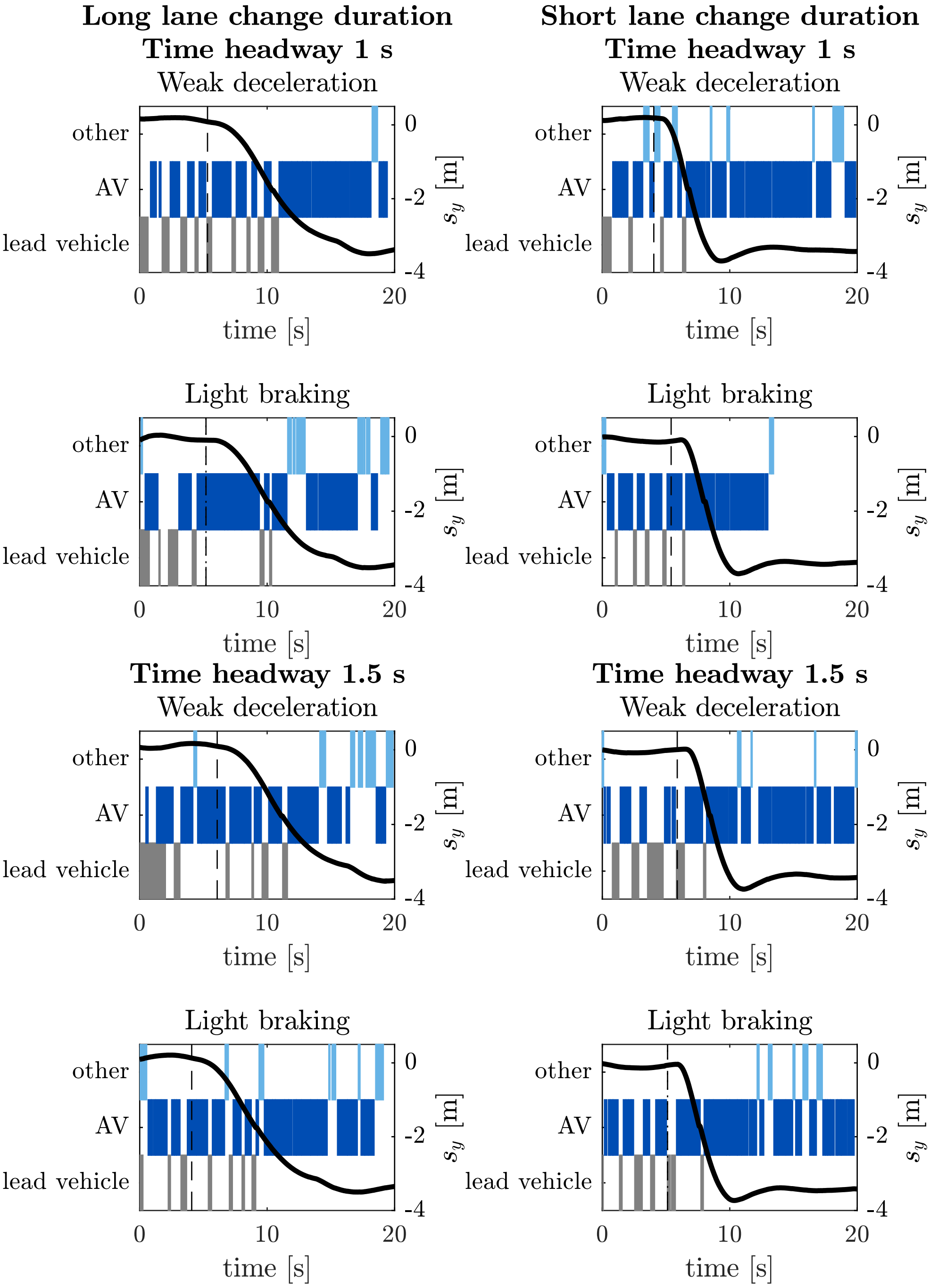


Figure A.14: Proband 36.