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Comfort in Automated Driving:
Analysis of Driving Style Preference in Automated Driving

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Summary

Over the last years, driving automation has increasingly moved into focus in human factors research. A large body of research focusses on situations in which the human driver needs to regain control. However, little research has so far been conducted on how SAE level 3+ automated driving should be designed with focus on occupant comfort.

This thesis aims at identifying a comfortable driving style for automated vehicles. As a basis, it was necessary to pinpoint driving metrics, which vary between driving styles and can be manipulated in order to design a comfortable driving style. Hence, Study 1 was conducted, in which drivers (N = 24) manually drove on a highway or on urban and rural roads with certain driving styles. Results show relevant metrics (i.e., lateral and longitudinal acceleration, lateral and longitudinal jerk, quickness, and headway distance in seconds) and that these metrics vary across maneuvers and thus, a maneuver-specific analysis is recommended. As these metrics are derived from manual data, it remained unclear after Study 1, in which range the metric values should vary for comfortable automated driving.

Therefore, as a second step, the main metrics were varied and the subsequent combinations implemented in an automated vehicle as well as in a dynamic simulator with two different configurations. The combinations were then subject to ratings by 72 participants. Results show that the metrics and values found in Study 1, are able to elicit a range of comfort ratings in automated driving. It was also found, that acceleration is a key variable in experiencing comfort. However, it is not the sole predictor. Additionally, as higher levels of automated driving with larger velocities are still bound to considerable constraints for on-road testing, the second study was also used to validate a dynamic driving simulator to allow comfort during automated driving to be studied. In comparison to ratings on a test track, the dynamic simulator setting with longitudinal orientation is able to show both relative and absolute validity of comfort ratings.

In the third and final step, different approaches to automated maneuvers were rated by participants (N = 72) regarding the comfort they experienced. A lane change, an acceleration, and a deceleration maneuver were chosen as test maneuvers. The lateral or longitudinal acceleration was varied in each of these maneuvers. Results, again, show comfort ratings are maneuver specific. On one hand, symmetrical and early-onset lane change maneuvers and symmetrical acceleration maneuvers were preferred. However, symmetrical deceleration maneuvers and deceleration maneuvers with a slower acceleration decrease evoke the highest comfort ratings. These ratings made it possible to offer guidelines for the design of automated driving styles.

Furthermore, dependence on a number of personality traits was analyzed. Results suggest the general preference for certain driving styles to be unaffected by personality. However, it seems,

participants with certain personality types are less particular about their preference for certain driving styles.

Summed up, comfortable automated driving is – under the investigated circumstances – characterized by maneuvers with sufficient headway distance and smooth applications of small acceleration and small jerk. These should, even so, still provide sufficient motion feedback. Surrounding traffic seems to play an important role through urgency and should be considered for on-road implementation. Differences in personality did not seem to play a crucial role.

Zusammenfassung

Automatisiertes Fahren ist in den letzten Jahren zunehmend in den Fokus von Human Factors Forschung gerückt. Bisher wurde jedoch wenig Forschung betrieben, die sich mit dem Thema eines komfortablen Fahrstils für Fahrzeuge mit SAE Level 3+ beschäftigt.

Ziel dieser Arbeit ist es, einen komfortablen Fahrstil für automatisierte Fahrzeuge zu beschreiben. Im ersten Schritt war es hierzu notwendig, diejenigen Metriken zu identifizieren, die zwischen verschiedenen manuellen Fahrstilen variieren und so manipuliert werden können, dass ein komfortabler Fahrstil entsteht. Hierzu fuhren Probanden (N = 24) in Studie 1 manuell mit jeweils bestimmten Fahrstilen auf der Bundesautobahn oder auch auf Überland- bzw. innerstädtischen Strecken. Die Ergebnisse zeigen, dass je nach Manöver unterschiedliche Metriken relevant sind. Entsprechend wird eine manöverspezifische Analyse empfohlen. Die zentralen Metriken sind laterale und longitudinale Beschleunigung, lateraler und longitudinaler Ruck, Quickness und der Zeitabstand zum Vorausfahrenden. Da diese Metriken auf Fahrdaten aus manueller Fahrt beruhen, bleibt nach Studie 1 offen, welche Ausprägungen oder Wertebereiche zu komfortablem automatisierten Fahren führen.

Aus diesem Grund, wurden die zentralen Metriken im zweiten Schritt variiert und die jeweiligen Kombinationen in einem automatisierten Fahrzeug sowie in einem dynamischen Simulator mit zwei Orientierungen implementiert. Diese Kombinationen wurden von 72 Probanden bewertet. Die Ergebnisse zeigen, dass Metriken und Wertebereiche aus Studie 1 in der Lage sind, eine Spanne an Komfortbewertungen für automatisiertes Fahren aufzuspannen. Es zeigt sich hierbei zudem, dass Beschleunigung eine Schlüsselrolle im Komforterleben spielt, zeitgleich aber auch nicht der einzige Prädiktor für Komforterleben ist. Zusätzlich diente Studie 2 zur Validierung eines dynamischen Fahrsimulators im Hinblick auf Untersuchungen zum Komfortempfinden beim automatisierten Fahren. Da momentan Realfahrtstudien mit SAE Level 3+ Fahrzeugen besonders in höheren Geschwindigkeitsbereichen noch mit sehr großen Hindernissen und Aufwänden verbunden sind, bietet

sich ein dynamischer Simulator als vielversprechende Methode an. Verglichen mit Komfortbewertungen auf einer Teststrecke, zeigt der untersuchte, longitudinal orientierte dynamische Simulator sowohl relative als auch absolute Validität.

Im dritten Schritt wurden verschiedene Ansätze zur Parametrierung automatisierter Manöver von Probanden (N = 72) bezüglich wahrgenommenen Komforts bewertet. Insgesamt wurden der Längs- und Querbeschleunigungsverlauf in Spurwechsel-, Beschleunigungs- und Verzögerungsmanövern variiert. Insgesamt führen symmetrische Manöver zu guten Komfortbewertungen. Wieder zeigt sich jedoch auch, dass die Ergebnisse manöverspezifisch betrachtet werden sollten. Während Spurwechsel mit früherem stärkerem Beschleunigungsverlauf ebenfalls gute Bewertungen erzielen, führen Verzögerungsmanöver mit späteren stärkeren Beschleunigungswerten eher zu höheren Komfortbewertungen. Diese Bewertungen erlauben Rückschlüsse und weißen Implikationen für die Gestaltung automatisierter Fahrstile auf.

Zudem wurde der Einfluss verschiedener Persönlichkeitsaspekte in Studie 3 untersucht. Diese scheinen die allgemeine Präferenz für komfortable Manöverausprägungen nicht zu beeinflussen. Bestimmte Persönlichkeitsmerkmale scheinen jedoch dazu zu führen, dass diese Präferenzen nicht so stark ausgeprägt sind.

Zusammengefasst ist komfortables automatisiertes Fahren, wie es in dieser Arbeit untersucht wurde, durch Manöver charakterisiert, die ausreichenden Längsabstand sowie harmonische Manöververläufe mit kleinen Beschleunigungs- und Ruckwerten aufweisen. Diese Manöver bieten jedoch trotzdem noch ausreichend Rückmeldung über die Bewegung. Der umgebende Verkehr scheint aufgrund von entstehender Dringlichkeit eine wichtige Rolle zu spielen und sollte bei der Implementierung beachtet werden. Persönlichkeitsunterschiede scheinen keine Schlüsselrolle zu spielen.

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Index of Abbreviations

BTL model	Bradley Terry Luce model (Bradley & Terry, 1952; Luce, 2012)
DBI	Driving Behaviour Inventory
DBQ	Driving Behaviour Questionnaire
DSQ	Driving Style Questionnaire
FMS	Fast Motion Sickness Scale
NHTSA	National Highway Traffic Safety Administration
JND	Just Noticeable Difference
LOC	Locus of Control
MDSI	Multidimensional Driving Style Inventory
SAE	Society of Automotive Engineers
SSS	Sensation Seeking Scale
TAS	Thrill and Adventure Seeking
TTMD	Time To Minimum Distance

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1 Introduction and background

Automated driving is currently one of the most important and popular automobile topics. Vehicle automation is changing the way we drive and experience driving. It is predicted to have a beneficial impact on many aspects of driving, such as traffic flow, comfort, allocation of time resources, and – very importantly – safety. As safety has a special relevance, many studies in the field of automated driving to date have focused on safety aspects, e.g. takeover quality or time (e.g. Radlmayr, Gold, Lorenz, Farid, & Bengler, 2014; Zeeb, Buchner, & Schrauf, 2015). These studies supply valuable insights for automation levels, in which the human driver is still needed as a fallback.

Little focus has so far been placed on the aspect of comfort in automated vehicles (see Hartwich, 2017). This, however, seems crucial to investigate. Uncomfortable solutions, much like untrusted ones, will have a detrimental influence on system usage (Jamson, 2006; Lee & Moray, 1992; Lee & See, 2004; Muir, 1994; Siebert, Oehl, Höger, & Pfister, 2013). If automated systems are not engaged, the predicted benefits cannot emerge. To ensure drivers experience a comfortable ride in automated systems, this thesis focusses on identifying and describing comfortable automated driving.

To address comfortable automated driving, three studies were conducted. The first study focuses on identifying comfort related driving metrics and their characteristics derived from manual driving. The second study focuses on transferring these insights into automated vehicles and on method validation. The final study incorporates all findings and evaluates different approaches to design comfortable automated driving.

Before these central studies of this thesis are presented, an introduction into important underlying concepts will be given. First, an overview over vehicle automation is given in Chapter 1.1. Hereby and in the thesis in general, the focus lies on passenger cars. An interview follows in Chapter 1.2, which was conducted with an expert group that has experience in on-road higher level automated driving. Following the interview, it is necessary to define comfort and give an overview over relevant literature. As another fundamental factor, the basics of motion perception will be discussed subsequently in Chapter 1.4. The interpersonal perspective will then be taken into account by reviewing the influence of personality on driving in Chapter 1.5. This leads to the distinction multiple driving styles, which are described in Chapter 1.6. The following part of this thesis begins with the research objective of this thesis in Chapter 1.7, which leads to the conducted studies in Chapters 2 through 4. Finally, an overall discussion and conclusion are given in Chapter 5.

1.1 Automating vehicles and traffic

The term automation refers to “technology that actively selects data, transforms information, makes decisions, or controls processes” (Lee & See, 2004, p. 50). Manufacturers, politicians, as well as the general public hope to reduce traffic accidents and fatal injuries, environmental pollution, load of infrastructure in metropolitan areas, and traffic congestion by automating traffic. Above that, automated traffic is expected to increase traffic efficiency, safety, and comfort. Automated driving may also have side effects on drivers, society, and our understanding of driving experience. As Bainbridge (1983), Parasuraman, Sheridan, and Wickens (2000), as well as Walker, Stanton, and Young (2001) point out, automation does not necessarily reduce drivers’ workload, but changes the task the driver has to perform.

Automation of traffic further gives rise to a plethora of questions (see e.g., Gasser, 2013). These concern legal issues, such as liability, societal questions, such as the need for special driver’s education, ethical issues, or human-machine-interaction issues. The latter are comprised of questions regarding trust, situation awareness, mental models, take-over readiness, and also of joy of driving and comfort. So far, most research has been conducted concerning take-over behavior, situation awareness, and mental models (see e.g., Beggiato & Krems, 2013; Endsley, 1996; Merat, Jamson, Lai, & Carsten, 2012; Radlmayr et al., 2014; Zeeb et al., 2015).

Across different fields of research and addressed questions, a common framework to classify automation levels is essential. Various frameworks of levels of automation have been described. For one, Parasuraman et al. (2000) outline a 10-level scale that classifies automation based on how much control and information the driver retains. Their scale ranges from humans having full control and the automation offering no assistance (level 1) to the automation deciding and acting on its own while disregarding the human operator (level 10). While this classification can be broadly applied to all kinds of human computer interaction, different organizations have defined taxonomies specifically for the driving context. Most commonly cited are SAE International (SAE International, 2014), NHTSA (National Highway Traffic Safety Administration, 2013) and Bundesanstalt für Straßenwesen (Gasser et al., 2012; Gasser, 2013). With publishing the Federal Automated Vehicles Policy (National Highway Traffic Safety Administration, 2016) the NHTSA has adopted SAE’s taxonomy making the SAE taxonomy the leading taxonomy. The SAE taxonomy offers not only a detailed description of each level, but also describes respective automated systems and provides definitions of related terms. An overview of SAE’s taxonomy is given in Table 1.

Table 1

Overview of automation levels per SAE International's J3016 (2014).

Level	0 No automation	1 Driver assistance	2 Partial automation	3 Conditional automation	4 High automation	5 Full automation
Monitoring	Driver monitors the driving environment			Automated driving system monitors the driving environment		
Execution steering and acceleration	Human driver	Human driver and automated system	Automated system	Automated system	Automated system	Automated system
Fallback	Human driver	Human driver	Human driver	Human driver	Automated system	Automated system
Driving modes	-	Some	Some	Some	Some	All

In general, there is a responsibility shift in all taxonomies between levels two and three. Whereas the driver must monitor the systems' actions continuously in level two, this is not necessary in levels three and upwards. This thesis aims at improving driving comfort for automated driving systems on SAE automation levels 3 and higher.

The studies reported in this thesis were conducted on different automation levels depending on their objective. Study 1 was conducted as a manual driving study at level 0. Study 2 was conducted on level 3, whereas Study 3 was conducted on level 4. As it was always clear in the last two studies that the automation performs all aspects of driving including e.g., lane changes, it was not possible for participants to distinguish from experience whether the system operated on levels three, four, or five, because participants experienced neither a take-over situation nor limits of system capability. To date only few people have experienced automated driving on SAE levels three and higher in on-road traffic. In order to gain access to this valuable information and wealth of experience before conducting studies, an interview was conducted with seven of these experts in the following chapter.

1.2 Experts' perspective on comfortable automated driving style

In the summer of 2013 a team of researchers from Daimler AG succeeded in enabling an automated vehicle to drive the Bertha Benz Memorial Route from Mannheim to Pforzheim in Germany by itself (Ziegler et al., 2014). These researchers have gained valuable insights on how it feels to be a passenger in an automated vehicle in real traffic. To get a first impression of when automated driving is experienced as comfortable and what influences experiencing a comfortable automated driving style, an interview was conducted as a part of this thesis in 2013 with seven of the experts. The goal of this interview was to obtain first-hand information on how automated driving is experienced and where crucial points regarding experiencing comfort may lie. The interviews were recorded and transcribed. The answers were then grouped and analyzed in a descriptive manner per topic or question.

In detail, participants were asked to describe different driving styles they had experienced in manual or automated driving and what characterizes these. Participants were then asked to state which driving style they prefer for automated driving and which aspects play the most important role. The interview consisted of written demographic questions and 13 predefined verbal questions (see Appendix A – Interview for the translated English version and the German original questions).

To correctly interpret the answers, it is important to bear in mind the characteristics of the sample. All participants both developed automated driving and had gained practical experience with automated driving. The minimum practical experience with SAE level three driving was approx. 25 km, whereas the maximum was between 3,000 and 4,000 km. On a 7-point scale on affinity towards technology six out of seven participants marked the highest possible affinity towards technology. These values may possibly also indicate exalted trust in technology in contrast to the general public. Furthermore, the interviewees were all developers of the system they were interviewed on. They had an accurate mental model and knew about the system's strengths and weaknesses. All interviewees were men between the age of 30 and 42 years of age. Their manual driving experience ranged between 8 and 30 hours per week (M = 12.93 hrs., SD = 7.73 hrs.), whereas they held their drivers license for an average of 19 years (SD = 4.51 yrs.).

When asked about driving styles in general, participants mentioned four in total: ambitious, dynamic, jerky-restless, and comfortable. Ambitious driving style was mentioned only once and was described as similar to a sporty or dynamic driving style but without breaking speed limits and with as little lateral acceleration as possible. Both the ambitious and the dynamic driving style share cutting corners and using the whole width of the street, i.e. following the racing line. Dynamic driving was additionally characterized by not necessarily adhering to speed limits, increased lateral acceleration in curves, and by high fuel consumption. Both driving styles were mentioned either in describing participants' own driving style or by describing the driving style of other human drivers. The jerky-restless driving style was characterized as not being anticipatory, resulting in frequent switches between acceleration and brake pedal, driving with too little headway, jerky steering, being too fast in curves, steering too late upon entering a curve, driving too far to the right or left of the lane or swerving in the lane, irrational behavior, and reminding participants of a student driver having his/her first lesson. All participants expressed that this student driver driving style would be the worst-case driving style for automated vehicles. Likewise, all participants agreed on a comfortable driving style being the preferred style for automated vehicles. Comfortable driving was characterized by anticipatory and consistent driving, more headway distance, more distance to a vehicle which is being overtaken before cutting back in, less overtaking in general, little change in lateral or longitudinal acceleration, defensive and smooth driving, which is allowed to take more time.

Acceleration behavior was mentioned as being a very important factor in automated driving by all participants. A jerk-free, consistent way of driving was asked for. Other important aspects were anticipatory driving, foreseeable driving behavior, headway distance, velocity in relation to the speed limit and to others while overtaking, as well as feedback.

On a different notion, the experts were asked whether they experienced being driven by another driver or an automated vehicle differently. This was done to get an impression of how easily results of existing research on passengers in manually driven cars can be transferred to automated vehicles.

All interviewees stated that driving as a passive driver in an automated vehicle feels somehow different than being a passenger in another human drivers' car. For one it was said that, the fact alone of sitting in the driver's seat, leads to a feeling of being responsible and perceiving a loss of control in an automated car. Whereas, they feel less responsible as a passenger to a human driver. All interviewees stated that they draw information about whether the driver is in control of the situation and vehicle by observing his/her behavior. Most participants stated that it is easier to presume what a human driver can handle, because oneself can be used as reference. System limits and detection quality of an automated system cannot be estimated as easily. This issue is also brought up in research on trust (see Chapter 1.5.2).

In summary, experts, who had experienced automated driving, preferred a comfortable driving style in automated vehicles. They wished for anticipatory and comprehensible behavior. This is in line with Lee and See's (2004) theory on trust, in which the predictability of a system is theorized to have a large effect on trust in automation. Concerning measurable driving style, small acceleration and jerk as well as adhering to the speed limit and keeping sufficient headway distance were wished for. Most participants accepted arriving later at their destination if aforementioned criteria are met.

The results of this interview, alongside insights found in literature and described in the next section, are used as a starting point and a reference for the investigations conducted throughout this thesis.

1.3 Driving comfort

Comfort is an essential aspect of the driving experience and is one of the major goals in automated driving. This is apparent not only in the interview described in Chapter 1.2, but also in studies. For example, Tischler (2013) asked 491 participants in which situations they enjoyed driving the most. In total, 83 % of the participants mentioned situations with high driving comfort. As experienced comfort influences trust in and acceptance of an automated system (Siebert et al., 2013) and both trust and acceptance are a vital component for the usage of automation and purchasing decisions (Engeln & Vratil, 2008; Lee & Moray, 1992; Lee & See, 2004; Muir, 1987; Parasuraman & Riley, 1997), it is advisable to ensure comfort or the developed automated system will not be used and fails to deliver the intended benefits (Jamson, 2006; Regan, Stevens, & Horberry, 2014). In addition, Hartung, Mergl, and Bubb (2005) argue that vehicles are increasingly distinguished by the comfort they provide.

Although – or maybe because – comfort is such an everyday term no sufficing definition can be found. The existing models and definitions of comfort as a general concept tend to contradict each other. For example, whereas some see comfort on one end of a spectrum and discomfort on the other (e.g., Vergara & Page, 2000), Zhang, Helander, and Drury (1996) define comfort and discomfort as relatively independent constructs which can occur simultaneously. They see discomfort as something evoked by biomechanical circumstances, whereas comfort is associated with well-being and relaxation. For Zhang et al. (1996) the presence of discomfort does not necessarily rule out comfort and the absence of discomfort does not necessarily imply comfort.

The International Organization for Standardization (1997, p.9) defines comfort in ISO 5805 as a "complex subjective entity depending upon the effective summation of all the physical factors present in the induced environment, as well as upon individual sensitivity to those factors and their summation, and such psychological factors as expectation." This ISO norm points out that the perception of comfort is influenced both externally, e.g. physical influences from the environment, and also internally, e.g. sensitivity and psychological factors. The summation of these factors ultimately result in experiencing comfort, thus making the experience subjective and individual. Slater (1985) defines comfort as "a pleasant state of physiological, psychological, and physical harmony between a human being and the environment." (p. 4). This definition also incorporates both internal and external factors. Especially when taking loss of control into account, which may be experienced in higher automated driving, the psychological aspect of experiencing comfort seems to gain influence (see also Elbanhawi, Simic, & Jazar, 2015). For Summala (2007) the concept of comfort is closely linked to the feeling of control and safety. He sees comfort as a pleasant mood or emotion without strong activation or arousal. In his Multiple Comfort Zone Model, Summala (2005, 2007) proposes that four driving-related factors influence feeling comfortable: safety margins, the vehicle-road system, rule following, and travel progress and expectation. The first factor, safety margins, describes both sufficient time and space margins to the surroundings. This factor shows a link to driving style. The factor vehicle-road system is mainly concerned with vibrations, thermal, and visual issues, e.g., glare. For the factor rule following, Summala (2007) assumes, e.g., not being concerned with being fined to be influential on experienced comfort. The last factor, travel progress as expected, is assumed to cause discomfort when, e.g., the driver has to drive slower than he/she had expected due to traffic congestion. Progressing faster or as expected, contributes to experiencing comfort. Summala (2007) assumes that if the factors are held within a certain range or above a certain threshold, a comfortable state is maintained and no corrective longitudinal or lateral control actions will be undertaken by the driver.

Ellinghaus and Schlag (2001) provide work in a field closely related to comfort in automated vehicles: passenger comfort. They see passenger comfort as a result of a variety of influences. Among these are ergonomic influences, vibrations, how safe the vehicle is perceived, but also trust in the driver and the congruency with expected movements. Expectations also play a crucial role in Krist's (1994) model of comfort. She hypothesizes that experienced comfort or discomfort is the result of a constant comparison between expectancies and reality. Further, she assumes that only the discrepancies and the unresolved issues reach conscious perception. As, according to Krist (1994) existing discrepancies imply discomfort, comfort exists only without discrepancies between expectation and reality, which do not reach conscious perception. This may be the reason why participants seem to find it easier to state their degree of discomfort than their degree of comfort. Hence, studies such as by Hartwich, Beggiato, Dettmann, and Krems (2015) have focused on assessing discomfort instead of comfort.

Throughout the different definitions of comfort, three aspects are commonly shared (de Looze, Kuijt-Evers, & van Dieën, 2003). Firstly, comfort is always subjectively perceived and may vary between people under the same circumstances. Secondly, comfort can be affected by various kinds of influence, i.e., internal and external influences. Thirdly, experiencing comfort is always a reaction.

In literature, the most common terms used to describe experiencing comfort during driving are ride comfort and driving comfort. Ride comfort is a term usually used from an engineering point of view, e.g. work on chassis. Although Heißing and Ersoy (2011, p. 421) broadly define ride comfort as "the overall comfort and well-being of the vehicle's occupants during vehicle travel", ride comfort is usually seen as not only dependent on acceleration, jerk (i.e. the derivative of acceleration), or headway distance, but also on road surface conditions, the suspension system, the precision and promptness of the vehicle response to a driver's commands, and side slip angle (Fenton & Chu, 1977; Hernandez & Kuo, 2003; Mitschke & Wallentowitz, 2004; Wu, Liu, & Pan, 2009).

In contrast, the term driving comfort is used inconsistently. It can include aesthetic components such as interior design or directly perceivable characteristics from a passenger's point of view, such as accelerations, jerks, headway distance, and interior noise levels (Probst, Krafczyk, Büchele, & Brandt, 1982; Summala, 2007; Wei & Rizzoni, 2004).

In this thesis, the term more common in human factors research, automated 'driving comfort' will be used. The influence of various factors, such as vibrations or aesthetic elements is acknowledged. Focus, however, will lie on factors which can be directly controlled and manipulated through driving style.

Another related concept is driving pleasure. Driving pleasure is a pleasure deriving from the interaction between driver and vehicle during the active piloting of the vehicle (Tischler, 2013). As this thesis focusses on automated driving, many important factors for driving pleasure, such as e.g. delay between pressing the acceleration pedal and the vehicle's response, cease to be applicable.

Engeln and Vratil (2008) further make a clear distinction between comfort and pleasure in general. They define comfort as the avoidance of uncomfortable actions or stimuli. They assume comfort and the number or intensity of negative stimuli to have a linear relationship. The less negative stimuli, the more comfort is experienced. In contrast, they see pleasure as intrinsic motivated actions and perception of stimuli. This relationship is described similar to the relationship of arousal and performance described by the Yerkes-Dodson law (Yerkes & Dodson, 1908). An individual ideal level has to be found. Engeln and Vratil (2008) differentiate between comfort and pleasure in that way that pleasure can only be perceived when actively engaging in an action. Comfort, on the other hand, can also be experienced without active engagement.

One of the main problems of comfort in research, apart from the lack of a commonly shared definition, is the methodological issue of measuring experienced comfort. There have been attempts at measuring comfort via physiological measures (Engeln & Vratil, 2008; Uenishi, Tanaka, Yoshida, Tsutsumi, & Miyamoto, 2002) or indirectly by measuring discomfort (Seidl, 2000; Hartwich et al., 2015). Most research, however, relies on questionnaire data and verbal feedback. Even so, no acknowledged, standardized questionnaire exists. An adequate and satisfactory objective and/or subjective instrument has yet to be found. According to Engeln and Vratil (2008) a residual variance remains even when using objective measures.

In sum, even though contradicting models of comfort and the role of discomfort exist, comfort seems to be an individual experience evoked and influenced through both internal and external factors. In the specific case of automated vehicles, driving comfort can be understood as not only the absence of uneasiness and anxiety, which might arise from both internal and external factors, e.g. loss of control in automated driving, but also as a feeling of well-being and an attribution of positive valence towards how a maneuver is driven by the automated vehicle (see Bellem, Thiel, Schrauf, & Krems, 2018). For the purpose of this thesis an implementable understanding of experiencing comfort via driving style has to be found. Thus, this thesis tries to find a suitable approximation of human experience of comfort in highly and fully automated vehicles.

1.4 Physiological basics of motion perception

As pointed out by numerous definitions of comfort (e.g., Slater, 1985) physiology plays an essential role in experiencing comfort. In order to analyze comfortable driving, the physiological basics of perception leading to a comfortable experience must be considered.

Decker (2008) presents an overview over human perception and driving metrics. He matches the vestibular, visual, auditory, sensorimotor, and haptic sensory channels to different driving metrics, such as orientation and position in the environment, velocity, acceleration, or steering wheel angle. In some cases, more than one sensory channel can perceive a certain metric, e.g. both the vestibular and the sensorimotor channel can perceive acceleration. In other cases, more than one sensory channel is necessary to correctly interpret input. This can be the case when walking forwards, while one's head is turned to the side. Visual and vestibular information suggest a sideways movement as the sensory organs are located in the turned head. Only when taking additional, i.e. sensorimotor, cues into account, is it possible to correctly interpret the direction of the body (Zenner, 2010).

Even though perception is triggered by objective and measurable cues, it cannot be quantified in a general manner. For one, human perception varies interpersonally and intrapersonally – depending e.g. on sleepiness or distraction – and may change due to adaption (Zenner, 2010). Further, the increase of different stimuli may lead to differences in perceiving said increases (Stevens, 1962).

In driving, the visual channel is reported to be the most important sensory channel (MacAdam, 2003; Reymond, Kemeny, Droulez, & Berthoz, 2001; Vollrath & Krems, 2010). Vestibular perception is ranked as the second most important input (see MacAdam, 2003), but is expected to increase in importance in highly and fully automated driving as visual focus and attention may be averted from the driving relevant areas of interest. Both visual and vestibular perception will be described with special relevance to automated driving in the following section. The perception of other less dominant cues, such as haptic cues, e.g. the perception of pressure resulting from being pressed into a seat upon acceleration, will be mentioned but play a minor role in this thesis.

1.4.1 Visual perception of motion

Three main types of motion can be perceived visually (Goldstein, 2008). The first type is seeing an object moving through a stationary background without moving one's eyes. The second type is following a moving object through a stationary background by focusing on the object. The third type is moving though the stationary environment. Naturally, a combination is also possible, e.g. watching a moving object while oneself is moving.

Goldstein (2008) describes two explanations for the visual perception of motion: the physiological approach – the reafference principle – and the behavioral approach of the optical array. The reafference principle was first described by von Holst and Mittelstaedt (1950). It assumes that three kinds of signals are necessary to perceive motion. These are a motoric signal, which is sent to the muscles moving the eye balls, a so called efferent copy, which is a copy of the motoric signal, and an afferent signal, which is given when a retinal image moves and stimulates the receptors. If either the efferent copy or the afferent signal is stronger than the other, motion is perceived.

The optical array is based on Gibson's work on the perception of motion. According to him, humans and many animals can not only see light, but also patterns and changes of pattern (Gibson, 1958, 1968; Goldstein, 2008; Lee, 1980). These patterns make up the optical array. Movement is detected by changes in the optical array. Here, a distinction is made between ego movement – or locomotion – and the movement of objects in the visual array. An object moving through the static environment changes the perspectives of the array's texture. The object is registered as covering and uncovering parts of the static background. In locomotion, the whole optic array moves in a flow pattern, whereas the point towards which the movement is directed – the focus of expansion – remains motionless. A contracting optical flow signalizes backward motion, whereas an expanding optical flow signalizes forward motion. The extent of the optical flow, i.e. how fast the objects move, allows an identification of how far away they are. This explains why objects closer to the observer seem to be moving much faster than objects close to the horizon when looking out of the window of a fast car or train. The speed of optical flow also allows the observer to approximate his or her own speed.

In addition, the optic flow field can also be used to not only perceive the distance to an object, but also to determine a time to collision (Lee, 1976).

In automated driving, not only the movement of the environment relative to the driver is an important factor. Further, visual motion cues can also be obtained from steering wheel motions. The movement of the steering wheel according to automated movements can support initial trust building but may be rendered unnecessary after sufficient trust has been built. Thus, moving the steering wheel during automated driving may be a trust related factor and may indirectly influence experienced comfort.

1.4.2 Vestibular perception of motion

Situations exist in which visual perception alone is insufficient. In highly and fully automated driving, it can further be hypothesized that visual attention will not be directed at driving related tasks. In these cases, vestibular perception of motion is important to perceive motion and subsequently experience comfort. Even on its own, the vestibular sensory channel has been shown to be critical for driving (see Reymond et al., 2001).

Responsible for sensing vestibular motion cues is the vestibular organ located in the inner ear (Zenner, 2010). The vestibular organ in each ear consists of two otolith organs or maculae and three semicircular canals. The different specialized capacities of maculae and semicircular canals reflect in the difference in their anatomical structure. The maculae are specialized in translatory motion detection. This corresponds to the perception of longitudinal or lateral acceleration. The semicircular canals, on the other hand, are specialized in angular acceleration. This corresponds to perceiving the yaw, roll, and pitch of a vehicle while driving. The three semicircular canals are arranged thus one canal is aligned with one direction or dimension. A specific activation pattern results for each combination of angular acceleration.

Kingma (2005) analyzed thresholds for perceiving motion through the vestibular system by accelerating participants on a sled in either longitudinal or lateral direction. Visual, auditory, and proprioceptive cues were eliminated or masked by darkness, headphones and a constantly vibrating seat. The threshold for longitudinal acceleration was found to be at 0.085 m/s^2. The corresponding threshold in lateral direction was found at 0.065 m/s^2. The longitudinal velocity threshold lies at 0.135 m/s and the lateral velocity threshold at 0.104 m/s. Müller, Hajek, Radic-Weissenfeld, and Bengler (2013) identified average just notable differences (JNDs) at 0.09 m/s^2 for acceleration and 0.53 m/s^3 for jerk. Gianna, Heimbrand, and Gresty (1996) found thresholds depending on the gradient of acceleration. In stepwise acceleration with a correct response rate of 67 % the threshold lay at 0.48 m/s^2. When using ramps of 0.028 m/s^3 and 0.079 m/s^3 respectively, thresholds are found at 0.12 m/s^2 and 0.19 m/s^2. When using a parabolic increase of .0152 m/s^4 the threshold lies at 0.167 m/s^2. This implicates that not only the acceleration itself but also the way it changes is relevant to the perception of motion (see also Soyka, Robuffo Giordano, Beykirch, & Bülthoff, 2011). The JNDs as well as insights into the course of acceleration changes will be taken into account in the design of maneuvers throughout this thesis.

In general, a smooth integration of visual and vestibular cues seems to be important because a visual-vestibular conflict can lead to uneasiness and motion sickness (Lackner, 2009; Reason, 1978; Sivak & Schoettle, 2015).

1.4.3 Further sensory channels relevant for motion perception

As mentioned above, motion can also be perceived through proprioceptors or haptic cues. Proprioceptors are receptors within muscles and joints, which allow the brain to interpret information from the vestibular system in context (Zenner, 2010). Haptic cues are, e.g., the pressure when being pressed into the seat upon strong accelerations. Another possible motion cue is the movement of hair or feeling air flow on skin. These factors, as aforementioned pressure, usually imply strong forces, such as strong acceleration. Because this thesis focusses on comfort, such factors will not be analyzed further.

The auditory channel does not allow the direct perception of motion, but noise or sound are also known to influence driving experience (Huang, Griffin, & Morioka, 2009; Wu et al., 2009). Increased sound levels have a detrimental influence on comfort (Engelbrecht, 2013; Wu et al., 2009). Sound or noise can be elicited from the engine or from the movement itself. However, loud noises are, again, only expected in a dynamic driving style and will not be regarded in this thesis

In sum, vestibular and visual motion perception are central to experiencing comfortable automated driving. Both will receive special attention in the design and implementation of trajectories throughout this thesis.

1.5 Personality and driving

After an introduction into the biological basis of perceiving comfort related influences on the human body, this chapter will focus on the influences of personality on driving and preference for certain driving behavior.

Iversen (2004) shows in her study how drivers' attitudes are a relatively good predictor of their driving behavior and that both attitudes and behavior are comparatively stable over time. Likewise Lajunen, Corry, Summala, and Hartley (1998) state in their definition of driving style, that the way a person drives is also influenced by their personality. Multiple studies have been conducted to identify which facets of personality influence which aspects of driving. Out of these, this thesis will focus on the personality traits sensation seeking, trust in automated systems, and locus of control, because either their significance for automated driving has been acknowledged in literature (e.g., Lee & See, 2004; Muir, 1987; Rudin-Brown & Parker, 2004) or because of their influence on manual driving and thus potential to influence experiencing automated driving (e.g., Jonah, 1997; Rundmo & Iversen, 2004). In the following, it will be described how these traits influence manual driving and why they seem promising as an influence on experiencing comfortable automated driving.

1.5.1 Sensation seeking

Sensation seeking is "a trait defined by the seeking of varied, novel, complex, and intense sensations and experiences, and the willingness to take physical, social, legal, and financial risks for the sake of such experience." (Zuckerman, 1994, p. 27). Zuckerman (1971) further divides the concept into four subscales: thrill and adventure seeking, experience seeking, disinhibition, and boredom susceptibility. A summary of 40 studies reveals a positive relationship between sensation seeking and risky driving (Jonah, 1997). In addition, Jonah (1997) points out, that the subscale Thrill and Adventure Seeking shows the strongest relationship to risky driving. Rimmö and Åberg (1999) found that sensation seeking is associated with traffic violations, but not so much with mistakes, inattention or errors. The authors suspect that the relationship between sensation seeking and accidents is mediated by violation frequencies. In addition to increased traffic violations, such as speeding and ignorance of traffic rules, a relationship between sensation seeking and risk perception and thus risky behavior was observed by Rundmo and Iversen (2004). This, in turn, is reported to lead to more damage and injuries (Rundmo & Iversen, 2004). All in all, sensation seeking seems to have an influence on human driving.

As highly and fully automated driving are novel and often thrilling for novices, sensation seeking – or specifically Thrill and Adventure Seeking – seem promising in this context. It is imaginable that persons with distinctly stronger thrill and adventure seeking may be more open to highly or fully automated driving and may thus accept a wider variety of behaviors as comfortable driving or may even expect a driving style with stronger accelerations.

1.5.2 Trust in automated systems

Multiple studies have identified trust as a key variable in the usage of automation (e.g., Hergeth, 2016; Hoff & Bashir, 2015; Lee & See, 2004; Muir, 1987; Pop, Shrewsbury, & Durso, 2015). Because trust is a common concept and widely spoken of in everyday life, multiple models and definitions of trust exist (for an overview see Lee & See, 2004). However, most definitions and models seem to have three points in common (Hoff & Bashir, 2015; Muir, 1987): Firstly, trust is given by a someone, who trusts, to a trustee. One has trust in something or someone. Secondly, trust is always directed at possible future events. It always corresponds to an expectation of something or a confidence in someone which is connected to a risk. Thirdly, trust may be bound to one or multiple characteristics of its object. One may, for example, trust in someone else's judgement and honesty, but not in their loyalty. Hoff and Bashir (2015) combine the last two points and add that the trustee must always have an incentive to perform. In case of automation this may be based on the intended functionality of the system.

Even though the definitions of trust mostly share the mentioned points, Muir (1987) criticizes their failure to incorporate the multidimensional nature of trust, which she sees suggested by the plethora of definitions. Barber (1987) tries to incorporate the multidimensionality in his definition of trust. For him the basis of trust is dependent on the existence of norms or standards. These can be, for example, of social, technical, or moral nature. Further, he assumes trust can mean two things, which are different in their character and yet can at the same time be intertwined: For one, trust is the expectation that a person or system will competently perform a task in question. Apart from this, trust concerns fiduciary obligations. Here the expectation lies in the assumption that the trusted person or system will perform the task even when it is opposing his/her/its own interests, placing others' interests before their own. In short, Barber (1987) sees two aspects of trust: competently performing a task and performing said task even if it may be opposing to the trustee's interests.

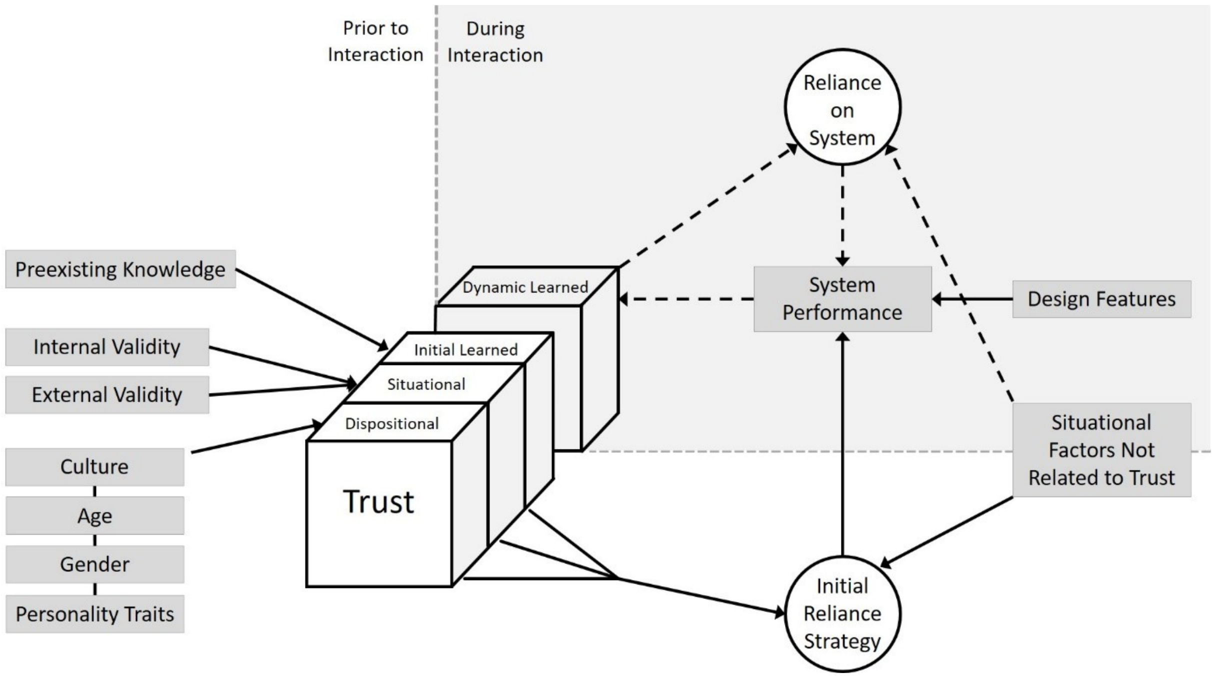


Figure 1. Model of factors influencing trust in automation by Hoff and Bashir (2015). Adapted from "Trust in automation", by K. Hoff and M. Bashir, 2015, *Human Factors*, 57(3), p. 427 with author's permission.

As the definitions vary, so do the theories of underlying factors. The most commonly named underlying factors are predictability, dependability or reliability, faith, competence, responsibility, familiarity, understandability, robustness, and feedback or explanation of intention (Muir & Moray, 1996; Parasuraman & Riley, 1997; Rempel, Holmes, & Zanna, 1985; Jian, Bisantz, & Drury, 2000;

Stanton & Young, 2000). Lee and Moray (1992) condensed these factors into three groups: performance, process, and purpose. Dependability, robustness, competence, and reliability describe a well performing system. Being able to understand underlying mechanisms and the intention of the system are grouped using the term process of automated systems. And finally, the purpose of automated systems describes the designer's intended purpose or competence of the automated system.

After a comprehensive review of literature on trust in automated systems, Hoff and Bashir (2015) propose a layered model of trust. According to this model depicted in Figure 1, trust consists of the layers dispositional, situational, and initial learned trust even before the first interaction with an automated system. The initially learned trust is determined by previously existing knowledge or experience with other systems. Situational trust varies depending on the internal variability of the operator or driver, e.g. expertise, mood, or attentional capacity, and the external variability, e.g. system complexity, task difficulty, or perceived risk. Finally, dispositional trust is said to be influenced by culture, age, gender, and other personality traits. During an interaction, a dynamically learned facet is added. This facet is influenced by the current system performance, which itself is influenced by various factors. Research on these factors has thus far not been conclusive. This model infers that trust can on one hand be influenced by the quality of the system and system interaction, but on the other hand unvarying aspects also persist. The distinction between preexisting and dynamically learned trust can be found in literature describing that trust can be built and adapted through interaction (Muir & Moray, 1996). According to Lee and See (2004) both cognition and emotion are essential for building trust, but emphasis lies on emotion or so called gut feeling. Once trust is built, it is not necessarily stable, but prone to changes depending on experiences (Hoff & Bashir, 2015; Lee & See, 2004). According to Lee and See (2004) not only the system failure as such influences trust in the system, but more importantly the system's predictability.

All in all, trust is an important factor when it comes to the usage of automated systems. It may lead to a differing behavior in activating SAE level three+ automated systems and may further influence how easily comfort is experienced. Therefore, it is interesting to analyze whether varying levels of trust towards automation also influence experienced comfort in automated driving. A person with high trust in automated systems may be more open as to what he/she experiences as comfortable.

1.5.3 Locus of control

Locus of control (LOC) is the third personality trait which will be examined in this thesis. LOC describes whether a person perceives an event to be due to own preceding behavior or due to external influence. The former describes an internal locus of control, whereas the latter describes an external locus of control. The concept has first been described by Rotter (1966) in his theory on social learning. He describes LOC as an important puzzle piece in the description of personality. Further, he postulates that learning through reinforcement is influenced depending on whether people perceive the event to be a result of their own action or the result of external forces. According to Rotter (1966) people, who have an external locus of control are less likely to see a connection between their behavior and following events and are thus less likely to adapt their expectancies for future reinforcement than people with an internal locus of control.

Whereas initial research on locus of control has been conducted on social learning, the concept was later applied and adapted to specific topics such as driving. Research on the influence of LOC on manual driving has, however, been inconclusive. Some studies show relationships between LOC and driving related factors, such as accident involvement, seat belt use, or traffic violations (Hoyt, 1973; Montag & Comrey, 1987; Özkan & Lajunen, 2005). Others find inconclusive or no relationships (Arthur & Doverspike, 1992; Iversen & Rundmo, 2002).

Regardless of its unclear role in manual driving, LOC may play a decisive role in automated driving. Here, it is not of interest to group driving behavior due to internal or external LOC, but to assess whether being driven by an automated vehicle is perceived differently depending on LOC. A clear distinction is made, because control really is external. It is possible that persons with a more external LOC are used to not feeling in control and may be more at ease than people with internal LOC, who may feel a strong loss of control and thus be more skeptical of an automated vehicle's actions. Rudin-Brown and Parker (2004) found participants scoring high on internal LOC retain more direct involvement in driving with an adaptive/active cruise control system. Thus, they were also quicker in overriding the system in system failure situations. Jenssen (2010) found that persons scoring high on external LOC are more likely to trust the functionality of in-vehicle devices. This may perhaps also be extended to higher level automated vehicles. This permits the notion, that passive drivers with an external LOC accept a larger variety of driving behaviors as comfortable, whereas passive drivers with an internal LOC may be more critical.

On a related note concerning driving velocity, Horswill and McKenna (1999) found participants to feel more comfortable with higher speeds when instructed to imagine being the driver, i.e. in control, in comparison to when being instructed to imagine being the passenger, i.e. control being external. These results lead to the idea that persons might prefer lower speeds when being passive drivers in automated vehicles than when actively driving themselves. This, in turn, shows that control is an important factor in the experience of automated driving.

After this review of literature, the three introduced aspects of personality, sensation seeking, trust, and locus of control, seem promising for to influencing experiencing automated driving. Their potential influence will play a role especially in the final study of this thesis.

1.6 Driving style

Next to the general physiological basics of motion perception and the influence of individual personality, another interpersonal influence may play a role in experiencing comfortable automated driving style: one's own driving style.

It is still discussed whether driving style can be seen as a facet of personality, as it is internalized and research shows it to be stable over time (see Murphey, Milton, & Kiliaris, 2009; Sagberg, Selpi, Bianchi Piccinini, & Engström, 2015; Tricot, Sonnerat, & Popieul, 2002). Even though phenotypical driving styles are dependent on multiple factors, such as traffic congestion, drivers show a preference for a certain driving style (MacAdam, Bareket, Fancher, & Ervin, 1998).

A driver in manual driving is used to the vehicle behaving according to his or her own driving style. This makes it reasonable, that comfort ratings of automated driving will be made by contrasting the automated driving style to one's own. Further, Ellinghaus and Schlag (2001) report that passengers in a manually driven vehicle base their rating of comfort mainly on the driver's driving style. This is a reason to assume a similar relationship in automated driving (Elbanhawi et al., 2015; Verberne, Ham, & Midden, 2015). Thus, it appears crucial to identify the essential components of an automated driving style, which provide passengers with comfort and ease. The concept of driving style, its assessment, and first insights related to automated driving will be described below.

1.6.1 Definition of driving style

Definitions and classifications of driving style vary throughout literature (see Sagberg et al., 2015). There have been multiple approaches to a definition. The definition by Elander, West, and French (1993) is one of the most commonly cited definitions. The authors describe manual driving style as a person's habitual way of driving. They further assume that this established habit, in turn, is influenced by general and driving specific attitudes and beliefs. Lajunen et al. (1998) also view driving style as something which is internalized and influenced by a person's character, their perception of their own driving abilities, and their driving experience.

There are more definitions to be found in literature. However, most definitions share three aspects (see also Sagberg et al., 2015). The first aspect is that driving style is relatively stable and habitual or internalized. Secondly, driving styles differ between drivers. And finally, driving style can be influenced by internal and external constraints, motives, or choices and thus can also be consciously altered. Different research shows the importance of external constraints in the analysis of driving style. A driver may show different driving styles depending on the current environment, e.g. traffic congestion level, road type, or weather (Ericsson, 2000; Murphey et al., 2009; Sagberg et al., 2015; Tricot et al., 2002). Hence, Sagberg et al. (2015, p. 1251) define driving style as a "habitual way of driving, which is characteristic for a driver or a group of drivers". This habitual way explicitly may include both internal and external influences.

Not only approaches to a definition of driving style vary, but also the presumed underlying factors or components. According to Elander et al. (1993) the existence of different driving styles results from two causes: (1) a different approach to what is a good or a bad driving style in combination with the appraisal of one's driving skill level and (2) differing attitudes towards driving. Among others, these attitudes also consider how likely the driver believes to be involved in an accident. In a similar way, Groot, Centeno Ricote, and Winter (2012) define the willingness to take risks and the amount of confidence in one's own abilities to be the main components of driving style. These aspects are reported to be mainly responsible for different driving styles in younger and older drivers. MacAdam et al. (1998) ascribe the existence of different driving styles to a person's level of aggressiveness, which manifests in readiness to overtake, be overtaken, or to follow. A link to sensation seeking can be presumed. The willingness to take risks or engagement in risky behavior seem to be a shared factor in all models.

Apart from driving style, the concept of driving behavior can be found in literature. Whereas Sagberg et al. (2015) propose, driving styles are subcategories of driving behavior, it can also be argued that driving behavior is a manifestation of driving style. This is supported by, e.g., Elander et al. (1993), Møller and Haustein (2013), Taubman-Ben-Ari (2006), and Tricot et al. (2002), who use the occurrence of behaviors as a method to characterize driving styles and assign driving style trait-like qualities. This, in turn, may explain the relationship between self-reported driving style and both driving behavior and personality traits (Taubman-Ben-Ari, Mikulincer, & Gillath, 2004). An example of the relationship between driving style and behavior can be found in the Multidimensional Driving Style Inventory (MDSI) by Taubman-Ben-Ari et al. (2004). Here, angry driving style, e.g., manifests itself in behaviors such as swearing at other drivers or honking one's horn at others. According to Dogan, Steg, and Delhomme (2011) behavior is further regulated dependent on environmental restraints as well as the driver's goals and motives. Thus, driving behavior can be seen as situational, whereas driving style can be seen as persistent and trait-like.

In this thesis driving style is seen as a relatively stable personal way of driving, which is influenced by internal factors, such as goals, and external factors, such as traffic congestion or weather.

1.6.2 Assessing driving style

In the past, multiple approaches to assess driving style have been made. Driving styles were differentiated and analyzed via questionnaires or by measuring objective driving data.

The most common questionnaire-based assessments of driving style are the Driving Style Questionnaire (DSQ; French, West, Elander, & Wilding, 1993; West, French, Kemp, & Elander, 1993), the Driving Style Questionnaire by Ishibashi, Okuwa, Doi, and Akamatsu (2007), the Driving Behaviour Questionnaire (DBQ; Reason, Manstead, Stradling, Baxter, & Campbell, 1990), the Driving Behaviour Inventory (DBI; Gulian, Matthews, Glendon, Davies, & Debney, 1989), and the Multidimensional Driving Style Inventory (MDSI; Taubman-Ben-Ari et al., 2004). Most questionnaires focus on items concerning attitude towards driving, e.g. whether a person feels stressed by driving, emotional states during driving, e.g. whether a driver tends to get angry with others while driving, and behavior during driving, e.g. whether speed limits are ignored. The MDSI by Taubman-Ben-Ari et al. (2004) has often been cited and used for studies. Although its replication in other languages and cultural backgrounds is debated (see Poó, Taubman-Ben-Ari, Ledesma, & Díaz-Lázaro, 2013) it is seen as one of the important self-reported questionnaires on driving style. The reason is that the MDSI incorporates findings of other questionnaires, such as the DSQ, DBQ, and DBI. Within the MDSI, items concerning different driving behaviors and attitudes towards driving are clustered into facets of driving style, namely into: angry, risky, high velocity, anxious, dissociative, distress-reduction, patient, and careful driving style.

According to Winner, Hakuli, and Wolf (2012) a person's driving style should be measured objectively and seen as a personality trait, which is mainly influenced by other aspects of personality and driving experience. In their review of literature Winner et al. (2012) found a consensus on the method of measuring driving styles through objective data: Driving styles are mainly differentiated through speed, longitudinal acceleration, and headway distance. Furthermore, a classification of driving style based on objective data is enabled. Winner et al. (2012) found that driving styles are usually classified as comfort-oriented, safety-oriented, or fast and dynamic (e.g., Langari & Won, 2005; Murphey et al., 2009; Vlieger, Keukeleere, & Kretzschmar, 2000). A comfort-oriented driving style is defined as a driving style with seldom and small acceleration values (Dovgan, Tusar, Javorski, & Filipic, 2012). Rodríguez González, Wilby, Vinagre Díaz, and Sánchez Ávila (2014), e.g., differentiate between smooth and aggressive driving styles by lateral and longitudinal acceleration and speed. Vlieger et al. (2000) have observed longitudinal acceleration values of approx. 0.50 m/s^2 for calm driving and in contrast approx. 1 m/s^2 for aggressive driving in city traffic.

Tricot et al. (2002) give an overview over research on driving style based on driving data conducted or funded by car manufacturers and suppliers. They also found the distinction into three driving styles: economical, medium, and sporting driving. The driving styles were assigned by analyzing the common metrics of acceleration and speed, but also accelerator and brake pedal position, the steering wheel angle, and engine speed. Doshi and Trivedi (2010) approach the assessment of driving style by using the standard deviation of longitudinal and lateral acceleration and jerk, as well as headway distance. They reject the approach of additionally measuring brake and throttle data as they say it is already implied. Further, they describe brake and throttle data to be dependent on the test vehicle, while acceleration data is relatively vehicle independent. Doshi and Trivedi (2010; see also Murphey et al., 2009) assume that driving styles can be differentiated using the jerk profile. They categorize drivers into aggressive drivers with higher jerk profiles and non-aggressive drivers with lower jerk profiles. In their study, they are able to show relatively stable jerk profiles for individual drivers. This allows the suggestion that the jerk profile is also a consistent measure of a driver's driving style. Murphey et al. (2009) similarly classify a driver's driving style by matching jerk profiles and traffic density level.

In sum, it seems both subjective and objective assessments or classifications of driving style are viable and have their strong suits and weaknesses. Of course, when driving in an automated vehicle, a person's own driving style can only be assessed through self-report. The recommendation for objective classification of driving style, which can be derived from existing literature on manual driving, focusses on speed, acceleration, jerk, and headway distance.

1.6.3 Driving style in context of driving automation and comfort

It is not only important to view driving style with regard to which metrics can be manipulated for improved comfort in automated driving. It may also help understand human's wishes and expectations. Jamson (2006) found that drivers who enjoy speeding were less likely to use intelligent speed adaption driver assistance systems. This may suggest that a more aggressive manual driver may differ in his expectations towards an automated driving style from less aggressive drivers. This assumption is explicitly addressed in the final study reported in Chapter 4.

Furthermore, drivers, who deem themselves as dynamic drivers, can be expected to test system limits from the beginning on, whereas drivers, who see themselves as more comfortable drivers, on the other hand, can be expected to take over before system limits are reached (Winner et al., 2012). This may point towards a relationship between driving style and willingness to take risks or trust in automation.

Evans (1996) further found that the way a driver chooses to perform a maneuver, i.e. the driver's driving style, is more important to experiencing a feeling of safety than the driver's driving skill. An emphasis on safety can also be found in the Multiple Comfort Zone Model by Summala (2005, 2007). Especially the first factor, namely safety margins, show a link to driving style. According to the model, a driving style would be experienced as comfortable if, among the other aspects, a certain personal threshold concerning time and distance headway is not surpassed. Thus, a close relationship between a feeling of safety and the acceptance of a driving style is presumed to apply for comfort in automated driving. Elbanhawi et al. (2015) propose, both experienced safety but also familiarity to be the two aspects of highly automated driving styles which show a relevance to the comfort experienced in automated driving (see also Verberne et al., 2015).

1.6.4 Summary of driving style

All in all, driving style is most commonly defined as a habitual way of driving, which differs between drivers and is influenced by internal and external factors. Most research identifies three driving styles: comfort-oriented, normal, and dynamic or aggressive. These styles are most commonly differentiated by analyzing longitudinal and lateral acceleration, jerk, velocity, overtaking behavior, and headway distance. Questionnaires commonly group drivers regarding behaviors, e.g. violations, driver states, e.g. calmness, and attitude towards driving, e.g. patient driving style.

Lange, Maas, Albert, Siedersberger, and Bengler (2014) have found that comfortable automated driving does not have to be significantly less dynamic than manually driven comfortable driving. Thus, insights obtained through studies with manual driving can be a good indicator for what may be experienced as comfortable in automated driving.

1.7 Research objective

Based on insights and addressing assumptions from aforementioned current research, this thesis aims at characterizing a driving style for automated vehicles, which will be experienced as comfortable by the majority of participants.

To approach this research goal, three studies were conducted. Study 1 was conducted in a highway and an urban and rural setting. This study aimed at three goals: (1) identifying the most common maneuvers, (2) identifying driving style differentiating metrics in manual driving, and (3) gaining insight into the characteristics of these metrics. Study 2 is based on these findings. Two maneuvers were presented in six variations, which were derived from the first study's results. Participants experienced the maneuvers either in a vehicle on a test track, a dynamic simulator aligned transversely to a supporting rail system, or in a dynamic simulator aligned lengthwise to the supporting rail system. The goals of this study were (1) to validate that metric's characteristics classified as comfortable in manual driving are also experienced as comfortable in automated driving, (2) to identify whether one metric dominates, and (3) to validate whether the dynamic simulator could validly present the maneuvers. In Study 3, three maneuvers were examined regarding which driving style is experienced as most comfortable in automated driving. To ensure addressing the majority of people, the influence of personality traits and self-reported driving style on preferences were taken into account.

The three studies are presented in the following chapters. Each chapter consists of a published paper or a manuscript submitted for publication (see Table 2), an additional analysis where necessary, and a section to conclude the insights and put them into context.

Table 2

Overview over published papers and submitted manuscripts as well as the chapters based on these texts.

	Article	Chapters including article text
I	Bellem, H., Schönenberg, T., Krems, J. F., & Schrauf, M. (2016). Objective metrics of comfort: developing a driving style for highly automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour, 41*, 45–54. https://doi.org/10.1016/j.trf.2016.05.005	2.1, 2.2, 2.3, 2.4
II	Bellem, H., Klüver, M., Schrauf, M., Schöner, H.-P., Hecht, H., & Krems, J. F. (2017). Can we study autonomous driving comfort in moving-base driving simulators? a validation study. *Human Factors, 59*(3), 442-456. https://doi.org/10.1177/0018720816682647	3.1, 3.2, 3.3, 3.4
III	Bellem, H., Thiel, B., Schrauf, M., & Krems, J. F. (2018). Comfort in automated driving: an analysis of preferences for different automated driving styles and their dependence on personality traits. *Transportation Research Part F: Traffic Psychology and Behaviour, 55*, 90-100. https://doi.org/10.1016/j.trf.2018.02.036	4.1, 4.2, 4.3, 4.4

2 Study 1: Objective metrics of comfort

As described above, definitions of driving style and likewise ways of assessing driving style vary. In order to identify which metrics are essential in determining a comfortable driving style in automated driving, metrics determining a comfortable manual driving style were identified as a first step. The idea behind the following study was to narrow down possible influences to the essential maneuvers and metrics.

Study 1 was published in 2016 as "Objective metrics of comfort: Developing a driving style for highly automated vehicles" (see reference Bellem, Schönenberg, Krems, & Schrauf, 2016). The study is segmented into two parts. The first part is a study conducted on rural and urban roads, whereas the second part is a study conducted on a highway. These parts are referenced in the publication as study I and study II. Chapter 2.5 is appended to the published paper to put the study into context of this thesis.

2.1 Introduction

Throughout the last years, a major topic in automotive industry has been automated driving. Together with the central question of when the technology will be ready to be widely introduced, research has focused on topics such as attentiveness issues, situation awareness, engagement in secondary tasks, distraction, and driver monitoring. We believe all of these topics to be important but want to address a more fundamental challenge: How does a highly automated vehicle need to drive in order to meet a – now passive – driver's expectations?

When being a passenger in a human-driven vehicle our feeling of comfort is primarily based on the driver's driving style (Ellinghaus & Schlag, 2001). We believe that the same applies when being a passenger in an automated vehicle. Thus, we find it crucial to identify the essential components of an automated driving style which give passengers a maximum amount of comfort and ease. Throughout literature there is no uniform definition of comfort. Thus, in this paper comfort is understood as a state which is achieved by the removal or absence of uneasiness and distress.

Elander et al. (1993) define the concept of driving style as a habitual way of driving, which includes a person's preference of velocity, their individual conditions for overtaking, preferred headway distance and how strictly they abide traffic laws. Other studies also explicitly mention the importance of acceleration behavior, which is a natural result of different preferences for velocity changes, in differentiating driving styles (see e.g., Müller et al., 2013; Reiser, Zellbeck, Härtle, & Klaiß, 2008). Many studies have divided the concept of driving style into three styles: comfortable, dynamic, and everyday driving (Langari & Won, 2005; Murphey et al., 2009; Vlieger et al., 2000). This implies that the perceived comfort should be maximal for comfortable driving and minimal in dynamic driving. Lange et al. (2014) have found that automated driving does not have to be less dynamic than manual driving to be perceived as comfortable. Thus, results based on manual data should be a good indicator of which automated driving style may be perceived as comfortable.

As automated driving needs to offer a high level of comfort, the aim of our research is to identify maneuver specific objective metrics which are able to classify driving as comfortable, dynamic, or everyday driving and can be used to parametrize automated driving in an optimal way.

There have been multiple studies in the past addressing the issue measuring and assessing manual driving styles. Many studies are based on questionnaire data (Møller & Haustein, 2013; Reason et al., 1990; Taubman-Ben-Ari et al., 2004). Others have used objective data but have exclusively focused on speed and/or acceleration (e.g., Doshi & Trivedi, 2010; Vlieger et al., 2000). Moreover, further studies have used multiple metrics but relied on algorithms which summarized data of road types without regard for the individual maneuvers driven (Ericsson, 2000). In our research, however, automated driving makes it necessary to obtain objective data, which can be used to parameterize an automated system. Additionally, it is essential to split a trip into different maneuvers in order to achieve a feeling of comfort not only on the whole but for every second along the way.

This paper describes two studies. The first study was conducted on rural, suburban and urban roads with a maximum speed of 100 km/h (62 mph). The second study was conducted on a highway with a maximum speed of 120 km/h (75 mph).

For maneuver-specific analysis we chose maneuvers, which are common in both the urban and rural as well as the highway setting. For this cause, we counted the frequency of maneuvers stated in literature (see i.e. Manstetten, 2014; Toledo, Musicant, & Lotan, 2008; Wu, Yeh, & Chen, 2014) in 1008 km of real roads. This resulted in four main maneuvers:

1. Decelerating to a moving target (approx. 16 % of maneuvers)
   The ego vehicle decelerates from a steady velocity upon closing in on another vehicle, which is driving at a non-varying lower speed.

2. Accelerating from non-zero speed (approx. 18 % of all maneuvers)

   The ego vehicle accelerates from a non-zero speed to a goal speed without a leading vehicle.

3. *Lane change* (approx. 20 % of all maneuvers)

   The ego vehicle changes lanes. This can be to overtake another vehicle or for navigational purposes.

4. Following at a non-varying speed (approx. 27 % of all maneuvers)

   The ego vehicle follows another vehicle. Both vehicles maintain a steady velocity.

For each maneuver, a variety of data were obtained. As the vestibular system plays a key role in not only the development of nausea or motion sickness (Reason, 1978) but also in the perception of driving in general (Lange et al., 2014; Müller et al., 2013), we have focused on metrics which can not only be manipulated in an automated system but can also be perceived by the vestibular system. Humans' vestibular system is not able to perceive speed itself, but perceives changes in speed – acceleration. Strong acceleration on its own can lead to an impaired feeling of comfort or even nausea. However, humans are even more sensitive to rapid changes in acceleration – jerks – than to acceleration itself (Gianna et al., 1996; Probst et al., 1982). In the reported studies, we have recorded both acceleration and jerk. *Mean acceleration* is able to analyze the maneuver as a whole or in larger segments. Analyzing the first derivative of acceleration – *jerk* – allows specific points in an acceleration to be easily identified in the maneuver where acceleration changes rapidly. We propose multiple peaks of jerk occur throughout the longitudinal maneuvers (see *Figure 2.* Exemplary *acceleration*.Figure 2). Thus, we have decided to not only look at the maximum jerk within each maneuver, but to analyze two jerks in the maneuver *acceleration from non-zero speed* and two or four jerks respectively in the maneuver *deceleration to a moving target*. The first jerk within the acceleration maneuver is the *maximum absolute jerk recorded upon pressing the gas pedal*, while the second jerk represents the *maximum absolute jerk upon releasing the gas pedal*. *Deceleration to moving target* can be split into two or four jerk-relevant subsections. This depends on whether brakes are applied or not. Here, the first jerk is the *maximum absolute jerk upon release of the gas pedal*, the second and third jerk describe the *maximum absolute jerks upon pressing* and *upon releasing the brakes*. These jerks can only be observed when brakes are used. Finally, the fourth jerk describes the *jerk upon pressing the gas pedal* again.

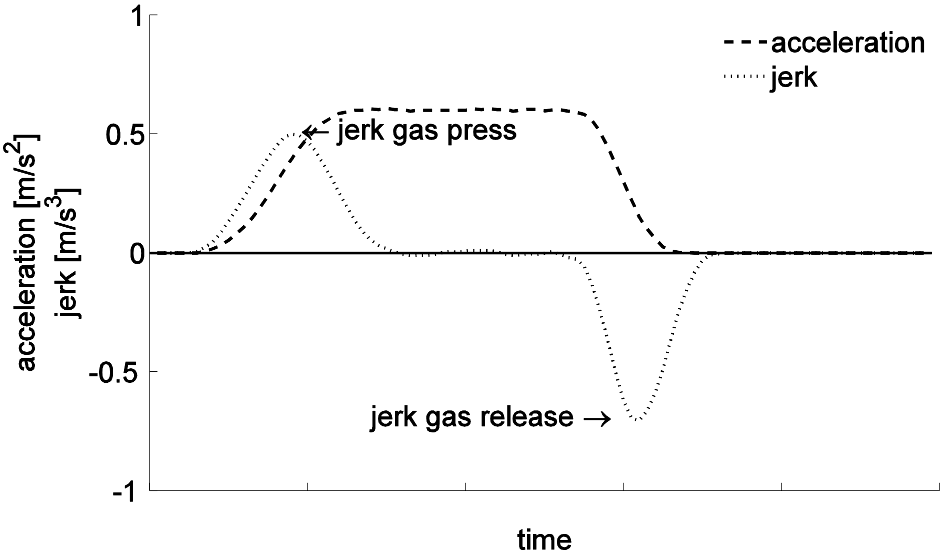


Figure 2. Exemplary *acceleration*. The development of acceleration and jerk are depicted over the course of a maneuver.

Acceleration from non-zero speed is characterized by longitudinal acceleration and jerk. The first maximum of jerk corresponds to *jerk upon pressing gas pedal*, whereas the second absolute maximum corresponds to *jerk upon release of the gas pedal*.

In addition to the widely used metrics of acceleration and jerk the metric *quickness* will be analyzed throughout the studies. *Quickness* describes the swiftness with which a maneuver takes place, thus being able to describe characteristics of the maneuver as a whole. The metric is used as a performance measure in the assessment of flying qualities of aircrafts and especially helicopters (Padfield, 2007). In our studies, we have adapted the measure to automobile conditions. *Longitudinal quickness q_{long}* is defined as $q_{long} = \bar{a} / \Delta v$ by the m*ean longitudinal acceleration* $\bar{a}$ and the *change in longitudinal velocity* Δv. *Lateral quickness q_{lat}* was recorded for *lane change* and is defined as $q_{lat} = v_{lat} / d_{lat}$ by *lateral velocity v_{lat}* and *lateral offset d_{lat}*. A high quickness value describes a lane change which happens rapidly (see Figure 3).

In the maneuver deceleration to a moving target we additionally recorded minimum headway distance in seconds. Headway distance in seconds and standard lane deviation were recorded for the maneuver following.

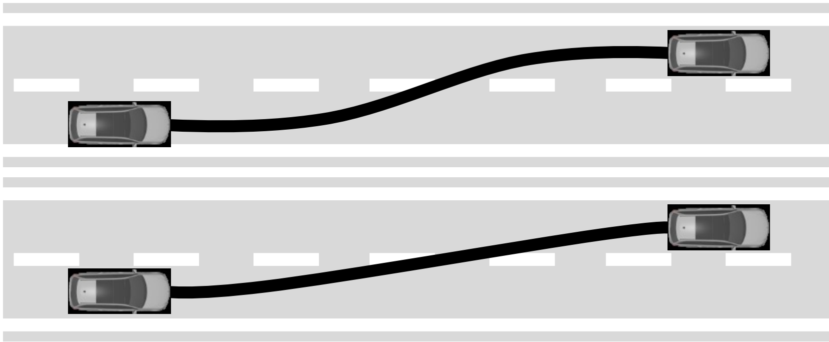


Figure 3. Illustration of quickness. A lane change to the left is shown with high quickness (top) and low quickness (bottom).

In summary, longitudinal acceleration, two or four longitudinal jerks, longitudinal quickness, and minimum headway distance in seconds were recorded for the maneuver decelerating to a moving target. For the maneuver acceleration from non-zero speed longitudinal acceleration, two longitudinal jerks, and longitudinal quickness were recorded. For the maneuver lane change we recorded lateral acceleration, lateral jerk, and lateral quickness. And finally, headway distance in seconds and standard lane deviation were recorded tor the maneuver following.

Because longitudinal changes in lane changes are strongly influenced by surrounding traffic only lane changes with speed changes smaller than 10 % of initial speed were used. This reduces the influence of longitudinal movement on the perception of lateral metrics (Mitschke & Wallentowitz, 2004).

The two studies and their results will be described separately. The general discussion includes insights and a comparative discussion of both studies.

2.2 Part 1: Study I on rural and urban roads

In the first study, we tested the following hypothesis within a rural and urban environment: Metrics exist within each maneuver, which are able to distinguish between the three driving styles dynamic, comfortable, and everyday driving.

More specifically we hypothesized for maneuver decelerating to a moving target that longitudinal acceleration, jerks upon releasing the gas pedal, pressing of the brake, releasing the brake, and pressing of the gas pedal, as well as longitudinal quickness and headway distance to be able to differentiate the driving styles. We assumed a negative relationship between acceleration, jerk, and quickness on one side and comfort on the other. However, we assumed a positive relationship between headway distance and perceived comfort. For the maneuver accelerating from non-zero speed we hypothesized the metrics longitudinal acceleration, jerk upon pressing the gas pedal and jerk upon releasing the gas pedal, as well as longitudinal quickness to be of importance. Our hypothesis concerning the relationships between comfort and the metrics of the acceleration maneuver were similar to the hypotheses concerning the deceleration maneuver. In respect to the lane change maneuver we hypothesized both lateral acceleration maxima, the resulting jerks and lateral quickness to be the metrics capable of differentiating between driving styles. Again, we assumed lower accelerations and jerks as well as a lower quickness to correspond with a higher level of perceived comfort. For the fourth maneuver – following at a non-varying speed – we hypothesized headway distance to be positively correlated with comfortable driving whereas a higher standard lane deviation was assumed to be positively related to dynamic driving.

To test our hypotheses participants were asked to manually drive a round course and to imitate the three different driving styles. These consisted of normal everyday driving, driving as participants perceived as comfortable, and driving as participants perceived as dynamic. The instructions were randomized in order.

2.2.1 Material and method

(1) Participants

A total of twelve participants (11 male, 1 female) were recruited for this study. Their age ranged from 25 to 56 years (M = 38.17 yrs.; SD = 9.47 yrs.). Participants were recruited employees of Daimler AG. Driving experience was assessed through the number of years participants had held their driver’s license so far (M = 20.08 yrs.; SD = 9.33 yrs.) and through their mileage in the last 12 months (M = 16.917 km / approx. 10.500 mi; SD = 11.912 km / approx. 7.400 mi). The mean mileage is slightly above the German average (see TopTarif, 2013).

This study was conducted on a round course of 16 km (10 miles). The round course included different types of roads: narrow and curvy roads without center line markings, roads through neighborhoods where participants had to give way to traffic from the right, urban scenarios with traffic lights, roundabouts, rural roads, as well as a highway-like section. Speed limits ranged from 30 km/h up to 100 km/h (19 – 62 mph).

(2) Design

In this study a single factor within subject design was used. Participants were instructed to drive along the round course four times: once to get accustomed to the vehicle and to become familiar with the round course. Three further rounds were driven to record data. This ensured that all participants encountered all parts of the track in each condition. The three rounds for testing were instructed as comfortable, dynamic, or everyday trips in a randomized order. The instructions were given using a standardized sentence: "In the following road section we ask you to drive in a fashion that corresponds to your idea of dynamic driving." (Translated from German original). The instruction was changed to "comfortable driving" or "everyday driving" as necessary. The distinction was made in accordance with previous driving style studies (see Introduction).

Throughout the test runs participants were asked to rate maneuvers immediately after they were completed, respecting the current instruction to drive dynamically, comfortably or as they would drive in everyday life on a 5-point scale. Here, 5 represented having driven the last maneuver exactly how it was instructed, whereas 1 represented not having driven the last maneuver as instructed at all. This data was to help identify and explain outliers.

Participants were not allowed to activate assistance systems such as adaptive cruise control or active lane keeping. This ensured the recorded data came from manual and not partially automated driving.

(3) Material

The recorded measures were obtained through the vehicle's CAN bus and through an additional hardware system iTraceF200, which was installed into the trunk of the car. This allowed for highly accurate acceleration data. Additionally, a windshield-mounted camera facing in driving direction was installed to be able to clearly identify maneuvers during data analysis. Manual triggers were set for every maneuver throughout the trips to facilitate maneuver based analysis.

2.2.2 Results

In order to identify the metrics capable of distinguishing between the three driving styles comfortable, dynamic and everyday driving all metrics of each maneuver were analyzed using Analysis of Variance and Bonferroni-corrected post hoc tests (see Table 3).

As a first step, it was necessary to exclude the maneuver deceleration to a moving target from analysis because not enough data could be obtained.

Table 3

Metrics able to distinguish between driving styles per maneuver on rural and urban roads.

		overall effect		everyday - comfortable		everyday - dynamic		comfortable - dynamic	
		F	*p*	*t*	*p*	*t*	*p*	*t*	*p*
accelerating from non-zero speed	acceleration	48.49	<.001***	5.06	.001**	-5.30	<.001***	-9.34	<.001***
	jerk pressing gas pedal	17.64	<.001***	3.90	.010**	-2.69	.009**	-5.67	<.001***
	jerk releasing gas pedal	34.87	<.001***	-4.29	.315	5.46	<.001***	6.48	<.001***
	quickness	26.71	<.001***	3.40	.028*	-4.25	<.001***	-6.61	<.001***
lane change	acceleration	19.77	<.001***	4.35	.009**	-3.02	.002**	-5.81	<.001***
	Jerk	10.53	<.001***	2.94	.046*	-2.03	.071	-4.60	<.001***
	quickness	14.32	<.001***	2.46	.071	-2.95	.005**	-5.59	<.001***
following	headway distance in seconds	31.47	<.001***	-2.51	.012*	5.07	<.001***	8.72	<.001***
	standard lane deviation	3.10	.049*	0.65	1.000	-1.67	.313	-2.57	.052

Note. * p < .05 , ** p < .01, *** p < .001.

The maneuver acceleration from non-zero speed was performed in mean from 8.70 m/s (*SD* = 5.37 m/s) to 16.63 m/s (*SD* = 6.54 m/s) in the everyday driving condition, from 8.61 m/s (*SD* = 3.68 m/s) to 15.27 m/s (*SD* = 4.35 m/s) in the comfort condition, and from 11.31 m/s (*SD* = 5.26 m/s) to 21.37 m/s (*SD* = 7.10 m/s) in the dynamic condition. Analysis shows significant effects for mean acceleration (ω^2 = 0.37), jerk upon pressing the gas pedal (ω^2 = 0.17), jerk upon releasing the gas pedal (ω^2 = 0.29), as well as for longitudinal quickness (ω^2 = 0.24). Mean longitudinal acceleration, jerk upon pressing the gas pedal, and longitudinal quickness show significant effects in post hoc testing between all three driving styles. Jerk upon releasing the gas pedal shows significant differences between everyday and dynamic driving as well as between comfortable and dynamic driving.

Lane changes were experienced at mean velocity of 15.11 m/s (*SD* = 5.81 m/s) in everyday driving, 13.25 m/s (*SD* = 2.85 m/s) in comfortable, and 14.55 m/s (*SD* = 4.52 m/s) in dynamic driving. An ANOVA examining the data of the lane change maneuver shows a significant result for mean lateral acceleration (ω^2 = 0.27). Post-hoc analysis shows a significant difference between all driving styles. Maximum jerk also shows a significant overall difference (ω^2 = 0.16), and shows significant post-hoc effects for comfortable and everyday driving. Likewise, lateral quickness shows a significant difference (ω^2 = 0.21). Post-hoc analysis shows significant differences between everyday and dynamic driving as well as between comfortable and dynamic driving.

The maneuver following at non-varying speed was experienced at a mean velocity of 14.04 m/s (*SD* = 5.60 m/s) in the everyday driving condition, at a mean velocity of 13.09 m/s (*SD* = 4.38 m/s) in the comfort condition, and at a mean velocity of 14.37 m/s (*SD* = 5.00 m/s) in the dynamic condition. Analysis shows the metric headway distance in seconds was able to distinguish between the three driving styles (ω^2 = 0.37). Post-hoc analysis shows significant differences between comfortable and dynamic driving as well as between everyday and dynamic driving and everyday and comfortable driving. The metric standard lane deviation shows a significant overall effect (ω^2 = 0.03), but fails to show significant effects in post-hoc analysis.

2.2.3 Discussion

The aim of the first study was to identify objective metrics which are able to show the difference between the three driving styles comfortable, dynamic and everyday driving. For each of the maneuvers analyzed, easy to obtain metrics were identified.

For the maneuver acceleration from non-zero speed longitudinal acceleration, jerk upon pressing the gas pedal, jerk upon releasing the gas pedal, and longitudinal quickness were all hypothesized to be discriminating metrics. All of the four proposed metrics are able to distinguish between all driving styles with exception of jerk upon releasing the gas pedal. This metric did not show a difference between comfortable and everyday driving. This might indicate that everyday driving and comfortable driving are closer than everyday and dynamic driving. In contrast to everyday and comfortable driving, participants tended to accelerate past the goal velocity in the dynamic scenario and use the vehicle's drag in order to reach goal velocity. Thus, the jerk upon releasing the gas pedal has a larger effect within the maneuver.

In the data for *lane change* significant differences were found between all driving styles for *lateral acceleration*. The metric *jerk* shows differences only between comfortable and everyday driving as well as between comfortable and dynamic driving. *Lateral quickness* on the other hand, shows significant differences between dynamic and everyday driving as well as between dynamic and comfortable driving. This might imply that in terms of jerk everyday driving has a tendency towards dynamic rather than comfortable driving, while it shows a tendency towards comfortable driving in terms of quickness. Drivers might tend to make longer lane changes with a perceivable feeling for the change in lateral acceleration within the *lane change*.

The only proposed metric which was not able to discriminate between any driving styles is *standard lane deviation* in the maneuver *following*. Whereas *headway distance in seconds* is different in dynamic driving in comparison to the other two driving styles, *standard lane deviation* seems to be unaffected by the driving style change. This could have two reasons: For one, *standard lane deviation* could be an irrelevant metric. On the other hand, exactly the opposite could be true. S*tandard lane deviation* could be such a fundamental and basic metric for feeling comfortable or even safe that the driving styles share the same characteristics for this metric.

This study not only supports the assumption that not only speed and acceleration are important parameters (see Doshi & Trivedi, 2010; Vlieger et al., 2000), further, the study also shows the necessity to use a maneuver-based approach instead of overall means of metrics over whole trips (see Ericsson, 2000).

In conclusion, it was possible to identify metrics for each maneuver, which are able to distinguish the three driving styles as hypothesized. Hence, as a next step, it is necessary to extend the scope and move from an urban and rural environment to the highway scenario which involves higher velocities.

2.3 Part 2: Study II on highway

The second study was conducted under highway conditions. The two major reasons for explicitly looking at highway conditions are, firstly, highly automated systems are first developed for highways before their functionality will be adapted to urban surroundings. And secondly, higher velocities lead to a different perception of certain physical parameters (Mitschke & Wallentowitz, 2004; Siebert, Oehl, & Pfister, 2014). For example, the perception of lateral acceleration as well as the perception of headway distance change with increasing velocity. However, one cannot assume the same kind of relationship with velocity for all metrics. As research in the field of psychophysics has shown, an increase in the strength of a stimulus does not necessarily lead to an exactly proportional increase in the perception of said stimulus (see Goldstein, 2008).

Studies (see Ammon, 2013; Mitschke & Wallentowitz, 2004) show, the slower one drives, the higher measurements of lateral acceleration can be observed. In contrast, mean acceleration values decrease with higher speeds. Humans are more sensitive to lateral acceleration when driving at higher speeds (Mitschke & Wallentowitz, 2004).

Another main difference to study I lies in the setting itself. Whereas highway scenarios involve higher velocities than urban and rural surroundings, they are less complex. Traffic on highways follows the same direction, while traffic going the other way is strictly separated. There are no intersections or crossings and thus neither yield or stop signs nor traffic lights exist. Also, the behavior of fellow road users is more predictable. This is also due to the fact that no pedestrians or cyclists use or cross highways. In general, the number of possible maneuvers is smaller for the highway scenario than for an urban or country road situation.

Again, we assume that the metrics recorded for each maneuver are able to differentiate between driving styles. In Study II the metrics from study I are used. However, adjustments to the maneuver *lane change* had to be made. As no lane changes for navigational purposes are necessary in study II and overtaking is only allowed on the left in Germany, we have decided to analyze lane changes to the right and to the left separately in the highway scenario. Additionally, we introduce two measurement times for *lateral acceleration* as well as three time periods for *lateral jerk* measurement for the maneuver *lane change* for more detailed insights. An exemplary lane change is displayed in Figure 4. The two lateral acceleration metrics *lateral acceleration 1* and *2* are the two maximum absolute accelerations found throughout the maneuver. These two maxima segment the maneuver into three phases: onset, lane switch, and end. Within these sections the maximum absolute lateral jerk is identified. *Jerk onset* is the maximum absolute lateral jerk recorded before the first maximum absolute lateral acceleration. *Jerk lane switch* is the maximum absolute lateral jerk between the first and second maximum absolute lateral acceleration. Whereas, *jerk end* is the maximum absolute lateral jerk after the second maximum absolute acceleration.

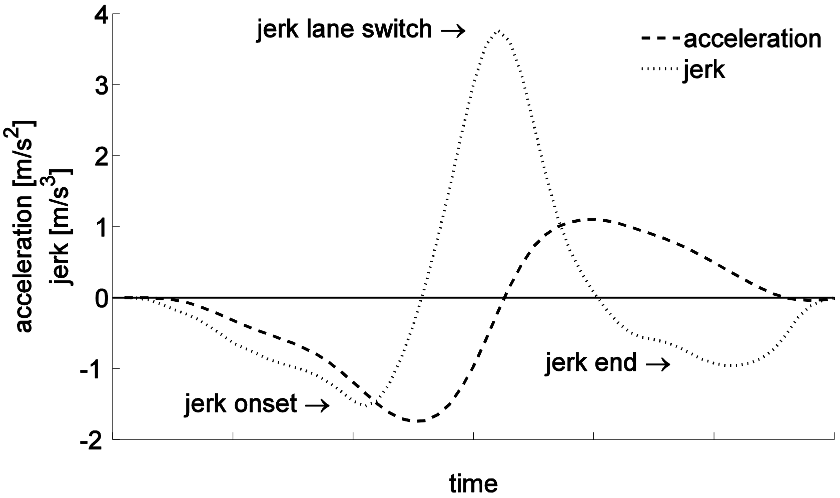


Figure 4. Exemplary lane change to the left characterized by *lateral acceleration* and *lateral jerk*. The different maxima in jerk are marked using arrows.

2.3.1 Material and method

(1) Participants

Data were obtained from twelve participants (2 female, 10 male). Age ranged from 25 years to 60 years (*M* = 35.25 yrs.; *SD* = 12.77). Similar to the participants from the first study, driving experience ranged from 8 years to 42 years of holding a driving permission (*M* = 16.54 yrs.; *SD* = 11.38 yrs.). Annual mileage within the last year lies between 500 km (310 mi) and 35 000 km (21 750 mi; *M* = 14 401.17 km / approx. 8 950 mi; *SD* = 11 378.40 km / approx. 7 050 mi), which is close to the German average (see TopTarif, 2013).

(2) Design

As in study I, a single factor within subject design was used. Every participant drove a 90 km (56 miles) return trip on highway A 81 with medium to light traffic. The trip was split up into eight sections of 10 km (6.2 miles) each, resulting in four sections per direction. The first section was used to accustom participants to the vehicle and experimental setup. Three sections followed which consisted of an everyday driving section, a comfortable section, and a dynamic section in randomized order. On the return trip only the first three sections were used for data assessment. Again, the driving styles assigned to the sections were randomized in order.

Analogous to study I, participants were asked to rate how well they had been able to implement the respective driving style instruction on a 5-point scale ranging from “not at all” to “exactly so”. Again, these ratings were used to identify outliers.

Additionally, participants were not allowed to use any assistance systems such as cruise control or adaptive cruise control in study II either.

(3) Material

The same measuring set up was used as in study I. Most data were supplied through the vehicle's CAN bus. This was supplemented by data from an iTraceF200. The front view was recorded using a wind shield mounted camera.

2.3.2 Results

In order to analyze whether the recorded metrics are able to differentiate between driving styles ANOVAs and Bonferroni-corrected post-hoc tests were used on the data of each maneuver (see Table 4).

On average, participants decelerated from 31.31 m/s (SD = 2.86 m/s) to 26.09 m/s (SD = 3.63 m/s) in the everyday driving condition of *decelerating behind a moving target*. In the comfort condition, they decelerated from 29.67 m/s (SD = 2.40 m/s) to 25.20 m/s (SD = 3.24 m/s) and from 32.56 m/s (SD = 1.62 m/s) to 27.23 m/s (SD = 3.17 m/s) in the dynamic condition. As in study I the metrics recorded for the maneuver *decelerating behind a moving target* are *mean acceleration*, various jerks and *quickness*. Both *mean acceleration* (ω^2 = 0.12) and *quickness* (ω^2 = 0.11) show significant differences between dynamic and comfortable driving. For those maneuvers in which participants used the vehicle's brakes *jerk upon releasing the brakes* shows an overall significant effect (ω^2 = 0.06), but fails to show an effect in post-hoc analysis. The remaining jerks do not show a significant effect ($0.01 \leq \omega^2 \leq 0.10$). The metric *minimum headway distance in seconds* (ω^2 = 0.06) is also able to show significant differences. Like *mean acceleration* and *quickness minimum headway distance in seconds* only shows a significant effect in the comparison of dynamic and comfortable driving.

In the maneuver *acceleration from non-zero speed* participants accelerated in mean from 24.96 m/s (SD = 3.12 m/s) to 32.54 m/s (SD = 2.61 m/s) in the everyday driving condition, from 23.98 m/s (SD = 3.27 m/s) to 31.07 m/s (SD = 1.10 m/s) in the comfort condition, and from 25.20 m/s (SD = 3.55 m/s) to 32.85 m/s (SD = 1.17 m/s) in the dynamic condition. For this maneuver data from the metrics *mean acceleration, jerk upon pressing the gas pedal*, *jerk upon releasing the gas pedal*, and *quickness* was analyzed. *Jerk upon pressing the gas pedal* does not show a significant difference between the three driving styles (ω^2 = 0.06). The three metrics *mean longitudinal acceleration* (ω^2 = 0.28), *jerk upon releasing the gas pedal* (ω^2 = 0.12), and *quickness* (ω^2 = 0.18) show significant differences between driving styles. On post-hoc level data for *mean acceleration* also show significant differences between comfortable and everyday driving as well as between comfortable and dynamic driving. Analysis of the metric *jerk upon releasing the gas pedal* only shows a significant effect between comfortable and everyday driving. Post-hoc analysis for *quickness* shows significant differences between comfortable and everyday driving as well as between comfortable and dynamic driving.

Table 4

Metrics able to distinguish between driving styles per maneuver on a highway.

		overall effect		everyday - comfortable		everyday - dynamic		comfortable - dynamic	
		F	*p*	*t*	*p*	*t*	*p*	*t*	*p*
decelerating behind a moving target	acceleration	7.00	.002**	-1.88	.066	1.71	.092	3.81	.001**
	jerk releasing gas pedal	0.07	.934	-	-	-	-	-	-
	jerk pressing brake pedal	2.18	.134	-	-	-	-	-	-
	jerk releasing brake pedal	3.33	.046*	2.15	.130	0.06	.957	-2.77	.054
	jerk pressing gas pedal	1.42	.247	-	-	-	-	-	-
	quickness	7.48	.001**	2.08	.264	-1.62	.180	-4.06	.001**
	minimum headway distance in seconds	3.88	.025*	-1.69	.420	1.03	.799	2.77	.020*
accelerating from non-zero speed	acceleration	13.30	<.001***	3.46	.004**	-1.89	.150	-5.35	<.001***
	jerk pressing gas pedal	3.09	.053	-	-	-	-	-	-
	jerk releasing gas pedal	5.33	.007**	-3.48	.006**	-0.86	1.000	2.73	.057
	quickness	9.25	<.001***	3.11	.027*	-1.61	.250	-4.32	<.001***

(continued)		overall effect		everyday - comfortable		everyday - dynamic		comfortable - dynamic	
		F	*p*	*t*	*p*	*t*	*p*	*t*	*p*
lane change to the left	acceleration 1	2.28	.118	-	-	-	-	-	-
	acceleration 2	3.25	.051	-	-	-	-	-	-
	jerk onset	0.14	.869	-	-	-	-	-	-
	jerk lane switch	6.85	.003**	1.22	1.000	-2.56	.029*	-3.14	.003**
	jerk end	5.25	.010*	2.29	.153	-1.19	.591	-3.22	.008**
	quickness	3.97	.028*	1.45	.595	-1.44	.351	-2.93	.024*
lane change to the right	acceleration 1	5.77	.008**	2.35	1.000	-2.05	.088	-2.74	.013*
	acceleration 2	4.78	.017*	0.80	1.000	-2.06	.087	-2.49	.035*
	jerk onset	4.19	.026*	1.56	1.000	-1.74	.187	-2.39	.038*
	jerk lane switch	6.17	.006**	2.05	.815	-1.93	.120	-3.05	.008**
	jerk end	3.82	.035*	0.96	1.00	-1.79	.166	2.22	.062
	quickness	4.91	.015*	2.68	.745	-1.57	.265	-2.72	.016*
following	headway distance in seconds	7.77	.001**	-1.64	.270	2.80	.024*	4.07	.001**
	standard lane deviation	1.00	.374	-	-	-	-	-	-

Note. * p < .05 , ** p < .01, *** p < .001.

The maneuver *lane change* was analyzed separately depending on the direction of the lane change. Regarding *lane changes to the left* the average speed was 30.63 m/s (*SD* = 2.61 m/s) in the everyday driving condition, 27.09 m/s (*SD* = 3.22 m/s) in the comfort condition, and 30.56 m/s (*SD* = 4.32 m/s) in the dynamic condition. For *lane change to the right* the average speed was 32.51 m/s (*SD* = 3.34 m/s) in the everyday driving condition, 28.85 m/s (*SD* = 3.64 m/s) in the comfort condition, and 33.23 m/s (*SD* = 1.84 m/s) in the dynamic condition. For both *lane change to the left* and *to the right mean lateral acceleration 1* and *2*, as well as *jerks onset*, *lane switch*, and *end*, and *quickness* were analyzed. None of the two acceleration measures are able to show significant differences for *lane change to the left* (acceleration 1: ω^2 = - 0.34; acceleration 2: ω^2 = 0.10). For *lane change to the right*, however, significant differences can be found for both *mean lateral acceleration 1* (ω^2 = 0.24) and *mean lateral acceleration 2* (ω^2 = 0.20). Post-hoc analysis shows these effects are due to the significant difference between dynamic and comfortable driving. For the maneuver *lane change to the left jerk lane switch* (ω^2 = 0.24) and *jerk end* (ω^2 = 0.18) show significant differences between the three driving styles. *Jerk lane switch* shows significant differences both between dynamic and everyday driving, as well as between dynamic and comfortable driving. However, a significant difference can only be found between comfortable and dynamic driving for *jerk end*. In the variation to the right all three jerk metrics show significant differences between driving styles ($0.16 \leq \omega^2 \leq 0.26$). Both *jerk onset* and *jerk lane switch* show a significant difference between dynamic and comfortable driving. No significant differences can be found after a Bonferroni-corrected post-hoc analysis for metric *jerk end*. For the maneuver variation *lane change to the left quickness* shows significant differences between the driving styles (ω^2 = 0.08). Upon post-hoc analysis significant differences are found only between comfortable and dynamic driving. The same results show for lane change to the right (ω^2 = 0.23).

The maneuver *following* was driven at a mean velocity of 27.82 m/s (*SD* = 4.86 m/s) in the everyday driving condition, 25.29 m/s (*SD* = 4.03 m/s) in the comfort condition, and at an average velocity of 27.85 m/s (*SD* = 4.07 m/s) in the dynamic condition. As in study I, the metric *headway distance in seconds* is able to distinguish between the driving styles for the maneuver *following* (ω^2 = 0.13). Upon closer analysis, only the differences between everyday and dynamic driving as well as between comfortable and dynamic driving show a significant difference in post-hoc testing. Again, *lane keeping* shows no significant differences between driving styles (ω^2 = 0.03).

2.3.3 Discussion

In study II, as assumed, metrics, which were able to discriminate between the three driving styles, could be recorded for all maneuvers. Comfortable and dynamic deceleration behind a moving target can be distinguished by *longitudinal acceleration*, *longitudinal quickness* and *minimum headway distance in seconds*. Interestingly, *jerk* does not play a role in this distinction. This can be due to the interaction with high velocity. As Mitschke and Wallentowitz (2004) state, accepted acceleration decreases with increasing speed. Naturally the change of acceleration – jerk – cannot be expected to be high then either. The velocities in each study compared between the different driving styles seem homogenous with slight tendencies of slower driving in the comfort condition for e.g. lane changes to the left.

Similarly, only *jerk upon releasing the gas pedal* is able to distinguish – and this only – between comfortable and everyday driving in the maneuver of *acceleration from a non-zero speed*. Compared to study I this suggests that jerks are prone to an interaction with velocity and tend to be smaller and more alike for larger velocities. Yet, this is not surprising because accelerations and thus jerks are smaller at higher speeds (Mitschke & Wallentowitz, 2004). Despite this, *longitudinal acceleration* and *quickness* are, nonetheless, able to distinguish between driving styles.

Of the two metrics recorded for the maneuver *following lane keeping* shows no differences between driving styles. Regardless, *headway distance in seconds* is able to discriminate between dynamic and comfortable as well as between dynamic and everyday driving. This is in line with study I. Thus, we propose *lane keeping* should be investigated further in order to ascertain whether it constitutes a fundamental safety metric or can be discarded as irrelevant.

The metrics of maneuver *lane change to the right* could all, except for *jerk end,* separate between comfortable and dynamic driving. Whereas *lane change to the left* paints a different picture. Within this maneuver type, both acceleration metrics fail to distinguish between driving styles along with *jerk onset*. This needs to be seen in the light that lane changes to the left were only made for overtaking purposes. Overtaking a vehicle makes it necessary to identify an appropriate gap on the left lane and slide into it. Consequently, overtaking always conveys a sense of urgency. These circumstances and results from lane change to the left suggest that the maxim of driving in a certain driving style may have been substituted as a primary goal by managing to find a gap and initiate the lane change itself at the right point in the right manner. As soon as this task has been completed *jerk lane switch* and *jerk end* distinguished between driving styles again. At this point the primary goal would have been re-substituted by fulfilling the instruction of driving with a certain driving style. The resetting of the primary goal may be due to a perceived possible safety risk which is always prioritized over comfort. *Quickness*, being a metric characterizing the lane change as a whole, is able to tell dynamic from comfortable driving. The difference in results between *lane change to the left* and *lane change to the right* shows the necessity to analyze the two varieties of lane changes separately. Additionally, investigating the combination with a greater variation in longitudinal measures might prove to be interesting.

2.4 Conclusion of Study 1

All in all, it can be concluded that the same driving style discriminating metrics can be found in both studies with only a few minor exceptions. For the maneuver *acceleration from non-zero speed* the small exemption is *jerk upon pressing the gas pedal* in study II. This can be due to the in average higher velocity in the highway study (approx. 15 m/s or 54 km/h) and thereby resulting in higher sensitivity to acceleration and acceleration changes. Regarding lane changes the only exemption – even after dividing the lane change maneuver into two direction related maneuvers in the highway condition –has to be made for *jerk end* in *lane change to the right*. Again, this difference between the two studies can be put down to the distinctly higher average velocity in the highway study and thus a lower tolerance for lateral acceleration and consequently jerk. Otherwise the same metrics discriminate between driving styles for lane changes to the right on highways and lane changes in a rural environment. *Lane change to the left*, however, only shows differences between the driving styles in *quickness* and *jerks lane switch* and *jerk end*. This uniqueness compared to *lane change to the right* and the *lane change in rural and urban environment* shows the necessity to split up the lane changes in the highway environment regarding their direction, purpose, and urgency. The maneuver *following* shows the same relative results in study I as in study II. In short, results indicate the same metrics are relevant in both environments. Moreover, results are backed by being mainly in accordance with the just noticeable differences reported by Müller et al. (2013) as well as Kingma (2005).

It has to be kept in mind that our data relies on participants' subjective ideas of driving styles and manual implementation of these. This leaves room for future research to identify possible interindividual differences.

A different point which should receive further attention regardless of the environment is the frequency of maneuvers. Due to the non-controllable surrounding conditions in an on-road study we were not able to investigate whether the overall frequency and/or prerequisite conditions to perform a certain maneuver vary between driving styles. A direct link is seen by Bar-Gera and Shinar (2005) between the tendency to initiate a lane change for overtaking and driving style metrics as well as surrounding conditions. The same was assumed by Elander et al. (1993).

In conclusion, we have found three main results. As a first result, upon comparison of the two studies described in this chapter, it becomes evident that it is necessary to segment a trip into individual maneuvers in order to assess and subsequently create a comfortable ride. Secondly, we were able to show performance metrics which differentiate between the three driving styles. And finally, we were able to show that these metrics, with small allowances, are applicable in both a rural-urban environment and under highway conditions.

2.5 Results in context

The results support assumptions of behavioral adaptation in driving context. This adaptation takes place due to both external influences, such as congestion level, and internal influences, such as drivers' motives and goals (Dogan et al., 2011; Summala, 1997). In Study 1, drivers were able to manipulate their driving thus, that different driving styles could be observed. In addition, the importance of acceleration – both in form of maximum values and seen over the duration of the maneuver as quickness – and jerk were also supported. However, data lead to the notion of not only observing jerk in single points in time, but studying the progression throughout a maneuver. Additionally, data indicates the influence of external factors, such as speed of vehicles in the target lane. Environmental influences will thus be controlled as much as possible in the following studies.

An important finding for further research is the result that driving style should be analyzed segmented by maneuvers and not as a whole. This makes research easier, but also shows that comfort has to be provided every minute of the way, thus putting more pressure on the implementation.

3 Study 2: Can we study autonomous driving in moving-base driving simulators?

As a next step, it was necessary to further investigate the findings of the Study 1 with automated instead of manual implementation. A study was conducted to validate the range of values suggested by the first study in automated driving. Additionally, the aim was to ascertain whether a dominant metric exists and to learn whether a driving simulator could be used for this specific examination of comfort in automated vehicles.

The following chapters 3.1 through 3.4 were published as "Can we study autonomous driving comfort in moving-base driving simulators? A validation study" in 2017 (see reference Bellem et al., 2017). In addition, further analysis is reported in Chapter 3.5. The overall results are put in context in Chapter 3.6.

3.1 Introduction

In the last decade, autonomous cars have become a rapidly evolving technology, which is on current agendas of a plethora of universities, car manufacturers, and other technology and software corporations. The trend of autonomous driving does not only revolutionize the automobile industry, but it fundamentally changes the driving task itself. The SAE International (2014) defines six stages of driving automation ranging from level 0 (no automation) to level 5 (full automation). As the automation level rises, the driving task changes considerably. Whereas the human driver is in full command at level 0 and has to perform all tasks associated with driving, more and more aspects of the driving task are automated in the intermediate levels, changing the human's task from active driving to monitoring the automation and ultimately even removing this responsibility as well.

As automation increases, the question of how drivers prefer to be driven becomes more and more important. For instance, at first glance, travelling in the center of a lane might be a reasonable lane-keeping behavior from a technical point of view. From a psychological perspective, however, driving in the center of a lane is not necessarily the trajectory a driver would prefer, especially when driving in bends or when turning maneuvers are being considered, in which curves are usually cut on the inner side in order to keep lateral accelerations relatively low (e.g., Boer, 1996; Siegler, Reymond, Kemeny, & Berthoz, 2011). Recent surveys revealed that passengers are very hesitant in their acceptance of automated transport systems (MacSween-George, 2003; Schoettle & Sivak, 2014).

Therefore, it is even more important to investigate comfort experienced in highly or fully automated driving.

The concept of comfort is complex. A common scientific definition has yet to be established. According to de Looze et al. (2003) all definitions of comfort to date share three aspects: (1) comfort is subjective and may vary between persons, (2) experiencing comfort is always a reaction, and (3) comfort can be influenced by internal factors, e.g. sensitivity, as well as external factors, e.g. physical influences. One mayor point in the discussion on comfort as a construct, is whether it should be seen as a dimension with comfort on one end and discomfort on the other (e.g., Vergara & Page, 2000) or whether discomfort is something, which is evoked by biomechanical circumstances, and can coexist with comfort, which is associated with well-being (Zhang et al., 1996). This controversy contributes to the existing difficulties in ascertaining a widely acknowledged method of assessment.

Ellinghaus and Schlag (2001) as well as Krist (1994) specifically point at the role of drivers' expectation in experiencing comfort. According to them, expectancies of maneuvers and actually experienced maneuvers are constantly compared, eliciting a feeling of comfort if expectancies are met. Deviations between expected and actual driving behavior might not only increase symptoms of motion sickness (Reason, 1978; Sivak & Schoettle, 2015), but might considerably threaten user acceptance and user comfort. Sivak and Schoettle (2015) have further found that loss of control and the inability to foresee vehicle actions are identified as major points when rating riding comfort as a passenger. This link between expectancies and actual experience has influenced the described study as becomes apparent in the Method section. With the intention of making a first step towards identifying preferred automated driving, this study compares different variations of an automated lane change maneuver, as well as an automated deceleration maneuver behind a slower lead vehicle, regarding experienced driving comfort. These two maneuvers were chosen because they are not only among the most common maneuvers in highway settings (see Bellem et al., 2016), where higher levels of automation will be introduced first, but also because they represent a longitudinal maneuver or a lateral maneuver and both involve another traffic member.

In order to study driving comfort in automated vehicles, driving simulators not only provide a safe and cost-efficient alternative to technically demanding and cost-intensive on-road studies, but they also enable developers to test prototype systems. However, valuable insights obtained from a driving simulator are only of particular use when they can be transferred to the real world. In literature, the distinction between physical validity and behavioral validity was established in order to assess the validity of driving simulators (e.g., Blana, 1996; Mullen, Charlton, Devlin, & Bedard, 2011). Physical validity refers to the extent to which a driving simulator is capable of reproducing physical reality. For instance, a simulator demonstrates physical validity, if physical components such as layout, dynamic characteristics, or visual displays correspond to on-road driving. Behavioral validity on the other hand, refers to the behavioral correspondence between driving behavior in the simulator and on real roads. Thus, it describes to what extent the behavior, performance, and experience of drivers in a simulator match those on a real road.

Blaauw (1982) subdivided behavioral validity into absolute validity and relative validity. Absolute validity is established when dependent variables such as driving parameters, psychophysiological measures, or subjective evaluations take on the same numerical values in a driving simulator as in a real setting. Relative validity is given when differences of the dependent variable between conditions are of the same order, direction, and magnitude (Blaauw, 1982; Godley, Triggs, & Fildes, 2002; Mullen et al., 2011; Wang et al., 2010). For most research questions, establishing relative validity is sufficient (Reed & Green, 1999; Törnros, 1998). Absolute validity, however, is required when determining absolute numerical values, such as general take-over request times, or when intervention thresholds of an advanced driver assistance system need to be identified (Gemou, 2013).

The reservation must be made, however, that behavioral validity of a driving simulator is always limited to a specifically defined research question or driving task (Allen, Mitchell, Stein, & Hogue, 1991; Godley et al., 2002; Mullen et al., 2011; Nilsson, 1993) and that due to the many different architectures, algorithms and parameterizations of driving simulators employed in driving simulator research (Fischer, Eriksson, & Oeltze, 2012; Greenberg & Blommer, 2011; Nilsson, 1993), generalizations across studies and simulators concerning the effect of motion cueing can only be made with caution.

In order to lay the basis for studying driving comfort in autonomous vehicles using driving simulators, we determined the behavioral validity of two simulator configurations of a high-fidelity hexapod moving-base simulator on a linear rail system. The simulator configurations differed in the vehicle being placed in the hexapod dome either in parallel to the rail system (MBS_long) or in transverse (MBS_lat; see Method section for details).

Even though physical and behavioral validity are often assumed or found to be positively related (e.g., Ba, Zhang, & Salvendy, 2014; Blana, 1996; Klüver, Herrigel, Heinrich, Schöner, & Hecht, 2016; Lee et al., 2013; but see Grabe, Pretto, Giordano, & Bülthoff, 2010; Reed & Green, 1999) there is growing evidence that not a scaling factor of 100%, but subunity scaling factors of around 50% to 70% are preferred in slalom task driving (Berthoz et al., 2013; Pretto, Nusseck, Teufel, & Bülthoff, 2009) or in lane change maneuvers (Greenberg, Artz, & Cathey, 2003). However, the aforementioned studies did not compare simulators results with results from an on-road study, but were based on ratings of perceived realism or driving performance data. In this study, we compared two scaling parameter sets, differing regarding their scaling factors of longitudinal and lateral acceleration, to a test track setting. In the first parameter set (MBS_Lat), lateral acceleration is simulated in the exact same manner as it was recorded in the test-track study (a scaling factor of 100%), whereas longitudinal acceleration was scaled down to 17%. In the second parameter set (MBS_Long), lateral acceleration was scaled down to 50% and longitudinal acceleration to 60%. Thus, the MBS_Lat has higher physical validity in lane change maneuvers, whereas the MBS_Long has higher physical validity in deceleration maneuvers (for detailed description of the simulator configurations see Method section). This is the first study, which validated two scaling parameter sets against on-road data. Furthermore, our study is the first which validated passive driving rather than active driving.

The purpose of this study is to lay the foundation for studying driving comfort in autonomous vehicles using an advanced moving-base driving simulator. In this study, we (a) evaluate whether the moving-base driving simulator is generally capable to adequately study experienced driving comfort in autonomous vehicles by comparing results from the simulator with results from a test-track study, (b) compare two different motion scaling parameter sets, and (c) compare six different variations of each a lateral and a longitudinal automated maneuver regarding experienced driving comfort, allowing to draw inferences on the underlying parameters. Results concerning the validity of the driving simulator will influence the setting of future studies, whereas insights from comfort ratings will be used to further improve automated driving towards a comfortable driving experience for passive drivers.

3.2 Method

3.2.1 Participants

A total of 52 men and 20 women (mean age across groups 41.03 yrs., SD = 11.38 yrs., range 21 yrs. – 61 yrs.; Data per setting is reported in Table 5) participated in this experiment. Both, employees and non-employees of the Daimler AG took part in this study and were distributed evenly across groups. All participants held a valid driver's license, had normal or corrected-to-normal vision, were naïve to the purpose of the experiment, and had little or no previous simulator experience. Data were collected anonymously. Informed consent was obtained after the task had been explained. Participants were free to terminate participation in the experiment at any time without any consequences. Participants received 30 € for their participation. All experimental procedures were conducted in accordance with the ethical guidelines of the Declaration of Helsinki.

Table 5

Demographic data per setting of groups and ANOVA or Pearson's chi² results comparing the groups.

	Test Track		Simulator						
			Longitudinal		Lateral				
	(N= 28)		(N = 22)		(N = 22)				
	M	*SD*	*M*	*SD*	*M*	*SD*	*df*	*F*	*p*
Age in yrs.	41.32	10.51	39.05	12.82	42.50	11.16	2,69	0.56	.576
	Male	Female	Male	Female	Male	Female	df	Chi^2	p
Sex	20	8	16	6	16	6	2	0.01	.992
Experience level 2 automation at least weekly	4		3		3		2	0.01	.997
No experience with driving automation	11		10		6		2	1.61	.446

3.2.2 Design

We chose two classes of common maneuvers for this study including a lane change to the left (producing large lateral acceleration forces), and a deceleration maneuver as a reaction to a slower vehicle driving ahead (producing longitudinal acceleration forces). These maneuvers were chosen because they represent two of the most common maneuvers shown in highway scenarios (see Bellem et al., 2016). Because highly and fully automated driving will first be introduced on highways, this criterion is of special relevance to the choice of maneuvers. In addition, these two maneuvers provide insight into a primarily lateral and a primarily longitudinal maneuver.

A 3 x 6 factorial design was chosen for each of the two maneuvers. The first factor Environment is a between-subjects factor describing the setting with the levels Test-Track, MBS_Lat, and MBS_Long. The second factor Scenario is a within-subjects factor, encompassing six differently parameterized variations of a deceleration maneuver and six different variations of a lane change maneuver (see Figure 5).

Of the 72 participants in total, 28 participants experienced the on-road setting, 22 participants experienced the MBS_Lat setting, and another 22 participants experienced the MBS_Long configuration of the moving-base simulator. For each of the two maneuvers, the six scenarios were comprised of different combinations of three parameters which were found in earlier studies to be classified by participants as comfortable driving (Bellem et al., 2016). Mean values and their standard deviations from the study by Bellem et al. (2016) are the basis for the parameters of the study reported here. The parameters are described in more detail in Apparatus and Stimuli and are further illustrated in Figure 7. Due to physical and technical constraints, a fully factorial design of the parameters could not be established. Combinations were thus chosen such, that they were feasible and comparable, e.g. not requiring a significantly longer track, but also in such a way that they could still be expected to be rated differently, based on just noticeable differences (see Müller et al., 2013), and still be representative of the original data they were based on. Hence, the variations were designed to be experienced as comfortable but not equally comfortable.

The experiment was divided into two blocks, in which either lane change maneuvers or deceleration maneuvers were driven. To prevent order effects, the order of the two blocks was counterbalanced, and the order of scenarios within the blocks was randomized across participants (see Figure 5).

3.2.3 Apparatus and stimuli

(1) Environments

Test-Track Study. The test-track study took place on a 280 m long test track with two lanes, closed off to public traffic. The ego-vehicle, a Mercedes Benz CLS (C218), drove autonomously and was equipped with a soft- and hardware system enabling the vehicle to drive according to the predefined scenarios without any intervention of the participant. In order to synchronize the behavior of the ego- and target vehicle in the deceleration scenario, the target vehicle was controlled through a high-precision GPS tracking system and several soft- and hardware components.

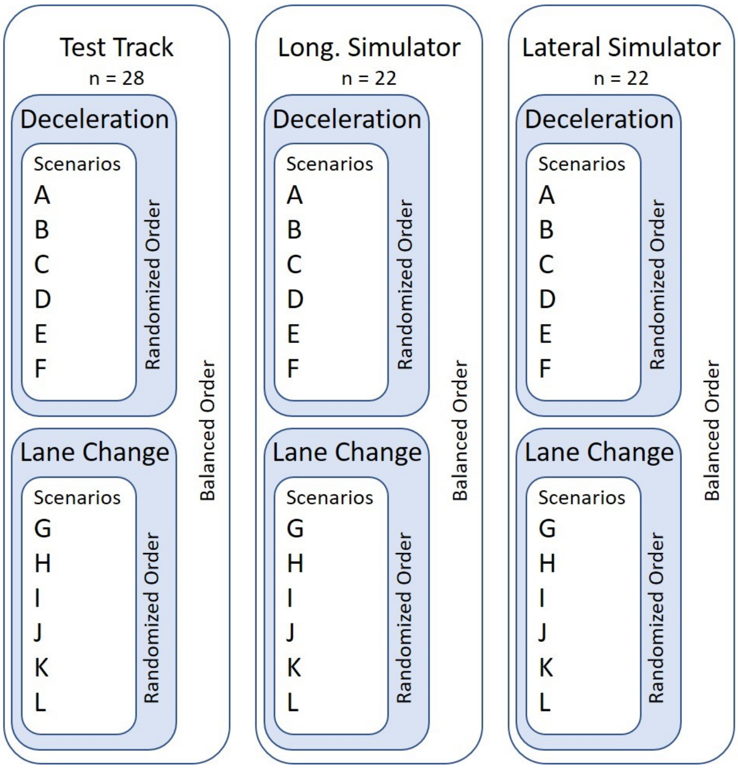


*Figure 5***.** Illustration of the study design. The between-factor Environment encompasses two within maneuvers with six within scenarios each per environment.

Driving Simulator (MBS_Lat and MBS_Long). The high-fidelity moving-base simulator is based on a 12.5-meter-long linear rail system. A hexapod, which moves along this linear rail via air bearings, comprises six linear actuators and carries a spherical dome with a height of 4.5 m and an inner diameter of 7.5 m. In this dome, a full-scale vehicle mock-up can be either positioned parallel or transversely to the linear rail. Hence, depending on the orientation of the mock-up, the motion space of the linear rail can be used to simulate either lateral (MBS_Lat) or longitudinal motion (MBS_Long). Orthogonally to the linear rail, the moving-base simulator has a motion space of ±1 meter. The motion cueing system of the MBS_Lat was parameterized with a lateral scaling factor of 100% and a longitudinal scaling factor of around 17%. In the MBS_Long setting, 60% of the longitudinal accelerations and 50% of the lateral accelerations were simulated by the motion system. In order to reproduce the scenarios from the test-track study, the measured accelerations in the test-track study were directly transmitted to the motion system. Consequently, no vehicle dynamics model was interposed to simulate the scenarios. However, due to the limited workspace, a classical washout algorithm was used, which attenuates low frequency accelerations.

An eight-channel projection system inside the dome created a 360° horizontal field of view with a resolution of 2048 x 1536 pixels for each projector. Additionally, two LCD displays with a resolution of 800 x 600 pixels were mounted on the side mirrors in order to simulate mirror images. An illustration of the MBS_Lat and MBS_Long is given in Figure 6. A more detailed description of the moving-base simulator can be found in Zeeb (2010).

The simulation environment was a replica of the test track environment. The scenarios were presented as completely automated and needed no input from the driver. Both steering wheel and pedals were monitored, however, in order to record driver input if it occurred.

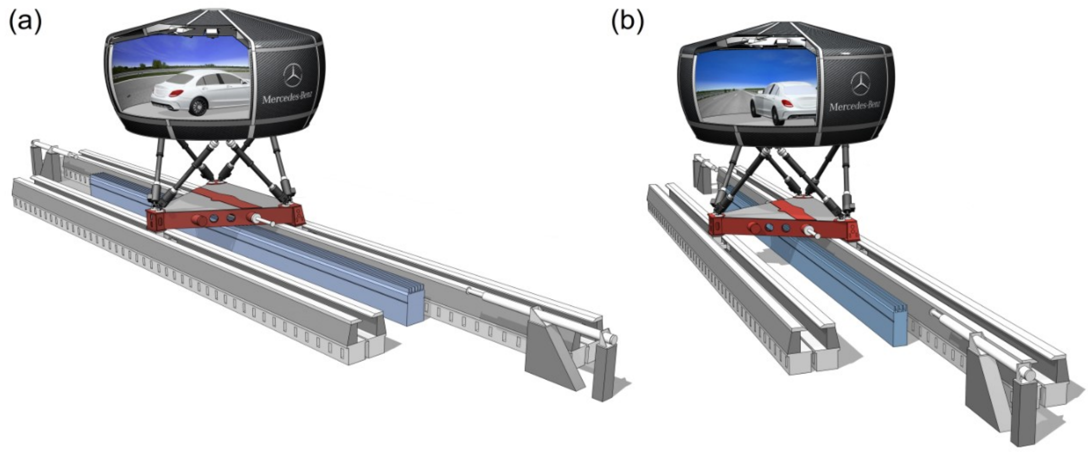


*Figure 6***.** Illustration of the advanced moving-base simulator at the Daimler AG. As can be seen in (a), the full-scale mock-up is positioned transversely to the linear axis so that the linear axis can be fully used to simulate lateral motion cues (MBS_Lat). In (b), the mock-up is positioned parallel to the linear axis (MBS_Long) in order to use the linear axis for the simulation of longitudinal motion cues.

(2) Scenarios

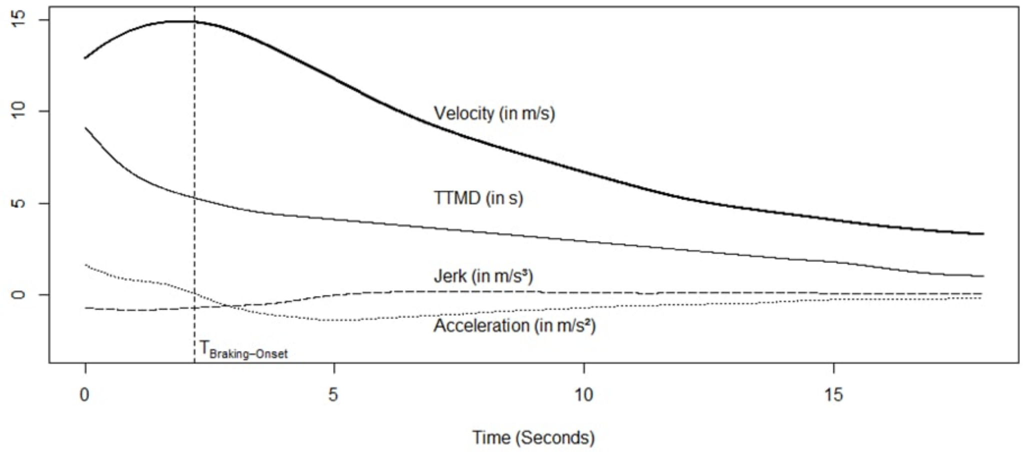
Deceleration. The deceleration maneuvers started with the ego-vehicle accelerating to 50 km/h and the target vehicle synchronously accelerating to 10 km/h. While approaching the target vehicle, the ego-vehicle initiated a deceleration maneuver with the given parameterization.

The deceleration scenarios were generated by combining values of jerk upon application of brakes (Jerk), gradient of time-to-minimum-distance ($TTMD_{grad}$) and time-to-minimum-distance at the onset of the maneuver ($TTMD_{init}$). The onset of the maneuver was defined as the moment when the acceleration pedal was released. Jerk is defined as the derivate of acceleration (or 2nd derivate of velocity) upon application of brakes. Time-to-minimum-distance is defined similarly to time-to-collision (TTC). However, instead of taking collision as a reference TTMD refers to the point of minimum headway distance in seconds, which is constant throughout all variations. $TTMD_{grad}$ is defined as the change rate of TTMD throughout the deceleration. A higher $TTMD_{grad}$ may be experienced as a faster adaptation to the head vehicle's speed. $TTMD_{init}$ is defined as the TTMD at maneuver onset. A smaller $TTMD_{init}$ may be experienced as a deceleration which begins closer to the obstacle than with a larger $TTMD_{init}$. These three parameters had been shown to be relevant for perceived driving comfort in an on-road study (see Bellem et al., 2016). The absolute values of the different metrics are either the mean of metrics classified as comfortable in Bellem et al. (2016) or correspond to the standard deviation around these mean values. Parameters are illustrated in Figure 7.

Lane Change. At the beginning of each lane change maneuver, the ego-vehicle accelerated to 50 km/h in the right lane. After approximately 2.5 seconds of maintaining the desired velocity, an automated lane change to the left according to the given parameters was performed in order to avoid a stationary vehicle, which was positioned in the right lane. During the lane change maneuver, the steering wheel moved in accordance with the vehicle's lateral movement.

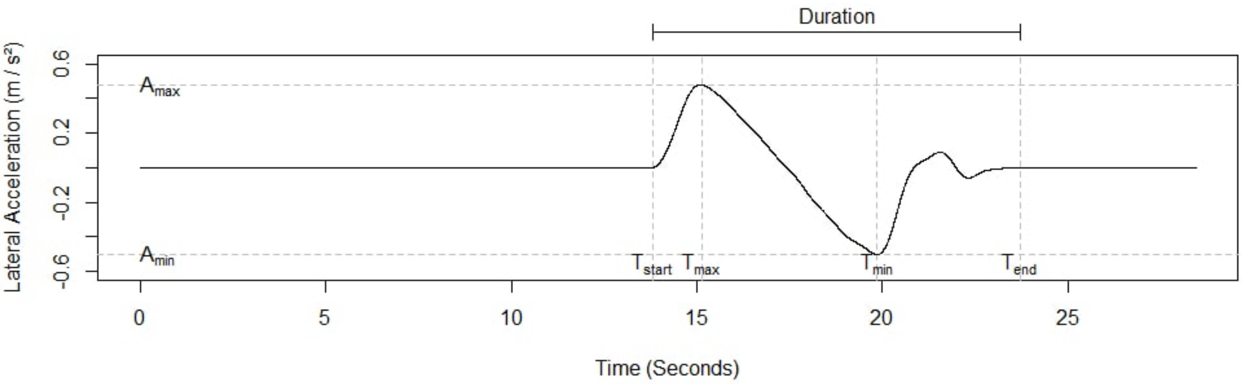
The scenarios were generated by combining the acceleration maximum (A_{max}), the ratio between acceleration minimum and maximum (Gamma), and the relative point in the maneuver at which the acceleration maximum occurs (Alpha). Whereas acceleration is a widely used metric (see Winner et al., 2012), Alpha and Gamma are rather novel. They are an approach to capturing the course of the lane change. Alpha describes how symmetrical the build-up of acceleration is with respect to maneuver duration. A small Alpha represents a lane change which is performed with an early maximum of lateral acceleration and may thus be experienced as a lane change with earlier distinctly perceivable onset. Gamma, on the other hand, expresses how symmetrical the maneuver is with regard to the magnitude of lateral acceleration. A Gamma of 1 represents a lane change during which both lateral acceleration maximum to the left and to the right have identical strength. The smaller Gamma the stronger the acceleration to the left (A_{max} in Figure 7) compared to the acceleration to the right (A_{min} in Figure 7). This may be experienced as jerkier to the left than to the right because a larger acceleration maximum has to be build up in less time when compared to a Gamma of 1 with the same Alpha. As in the deceleration maneuver, the absolute values of the parameters are based on mean and standard deviation values classified as comfortable in a previous study (see Bellem et al., 2016). Lane change onset was held constant to allow results to be based on the varied characteristics of the lane change and not on mere rating of risk.

(a) Deceleration Maneuver



Parameter	Description	Scenarios A	B	C	D	E	F
Jerk	Jerk at $T_{BrakingOnset}$ in m/s³	-1.67	-1.10	-0.53	-0.53	-1.67	-0.53
$TTMD_{grad}$	Gradient or slope of the time-to-minimum distance after $T_{BrakingOnset}$	-0.71	-0.48	-0.26	-0.26	-0.26	-0.71
$TTMD_{init}$	Time-to-minimum distance at $T_{BrakingOnset}$ in seconds	5.47	3.66	1.86	5.47	1.86	1.86

(b) Lane Change Maneuver



Parameter	Description	Scenarios G	H	I	J	K	L
A_{max}	Maximum of acceleration in m/s²	2.68	1.76	0.43	2.50	1.70	0.48
Gamma	Ratio between acceleration minimum and maximum ($\|A_{min}\| / A_{max}$)	1.21	1.09	1.01	0.93	1.13	1.05
Alpha	Relative time point of A_{max} in seconds (T_{max} / Duration of Maneuver)	0.44	0.32	0.32	0.20	0.44	0.20

*Figure 7***.** Illustration of the parameters for both the lane change maneuver and the deceleration maneuver for comfortable driving. In (a), the deceleration maneuver D is illustrated. In (b), the lane change maneuver L is shown. Additionally, the assignment of parameter combinations to the scenarios is given.

3.2.4 Procedure

At the beginning of the experiment, participants filled in a questionnaire to obtain both standard demographic information and subjective ratings of their experience with driving simulation, automated driving, and various driver assistance systems. Subsequently, participants were made familiar with the experimental procedure. They were instructed to provide a comfort rating for each scenario, indicating the extent to which the experienced scenario corresponded to their preference for comfortable automated driving. The rating was given on a scale from one to seven, with one meaning "not at all", and seven meaning "exactly this way". Participants also had the opportunity to comment on the maneuvers with regard to comfortable automated driving.

In general, the experimenter made the participants aware that they should base their judgments on the lane change or deceleration maneuver alone and not, for example, on the basis of the acceleration at the beginning of each scenario. Thus, the rating was intended to capture the comfort of the subject rather than evaluate the presence or quality of the simulation in case of the simulator studies. The inter-trial interval lasted approximately 60 seconds for the lane change maneuvers and 150 seconds for the deceleration maneuvers.

Each of the two blocks began with a training scenario to familiarize participants with the procedure (Scenarios B and H as middle variation). After each scenario, the participant took over the ego-vehicle in order to drive it back to its initial starting position in the test-track study, whereas in the simulator studies the simulation was reloaded with a new scenario.

3.3 Results

For each of the two maneuvers, we performed two separate repeated measures ANOVAs using the afex-package in R (R Core Team, 2013; Singmann et al., 2014) to contrast each simulator with the test-track study. Environment (levels: Test-Track vs. MBS_Lat or Test-Track vs. MBS_Long) was treated as a between-subjects factor, and Scenario as a within-subjects factor. Comfort ratings were squared to correct for their negatively skewed distribution. A visual inspection of the skewness-corrected ratings revealed no obvious deviations from normality and subsequent Box's M Tests indicated no violation of homoscedasticity for each model. Since the assumption of sphericity was violated, we used the Greenhouse-Geisser correction for the degrees of freedom. Results are given in Table 6. In order to further illustrate the results, we plotted the means in Figure 8.

Matching of the verbal comments showed, in scenarios with higher comfort ratings it was mentioned more often that the scenario had been experienced as smooth and/or anticipatory. Further analysis of the comments will be omitted here but can be obtained from the authors.

Table 6

Results from the repeated-measures ANOVAs concerning comfort rating.

		MBS_Long				MBS_Lat			
Maneuver	Factor	df_1,df_2	F	p	η^2	df_1,df_2	F	p	η^2
Deceleration	Environment	1, 48	0.66	.42	.01	1, 48	4.07	.05*	.08
	Scenario	3.73, 179.21	54.84	<.0001***	.53	4.21, 202.08	47.62	<.0001***	.50
	Environment* Scenario	3.73, 179.21	1.39	.24	.03	4.21, 202.08	2.36	.05*	.05
Lane Change	Environment	1,48	1.93	.17	.04	1, 48	8.52	.005**	.15
	Scenario	3.33, 159,91	43.22	<.0001***	.47	3.54, 169.76	64.22	<.0001***	.57
	Environment* Scenario	3.33, 159.91	1.73	.16	.03	3.54, 169.76	9.70	<.0001***	.17

Note. ***p ≤ .001, **p ≤ .01, *p ≤ .05.

In statistical terms, absolute validity is supported by the absence of significant main and interaction effects. Relative validity is given when no interaction between Environment and Scenario can be found. Hence, the non-significant interaction and main effects of the MBS_Long reported in Table 6 support that relative validity and absolute validity can be concluded for the MBS_Long. The MBS_Lat however, was not found to have relative validity. Whereas in the lane change maneuver the interaction effect is particularly large and relative validity has to be clearly rejected, in the deceleration maneuver it is a matter of argument whether an effect size of 0.05 and a statistical significance of 0.05 are of practical relevance, especially when considering Bonferroni-corrected significance levels of 0.0125.

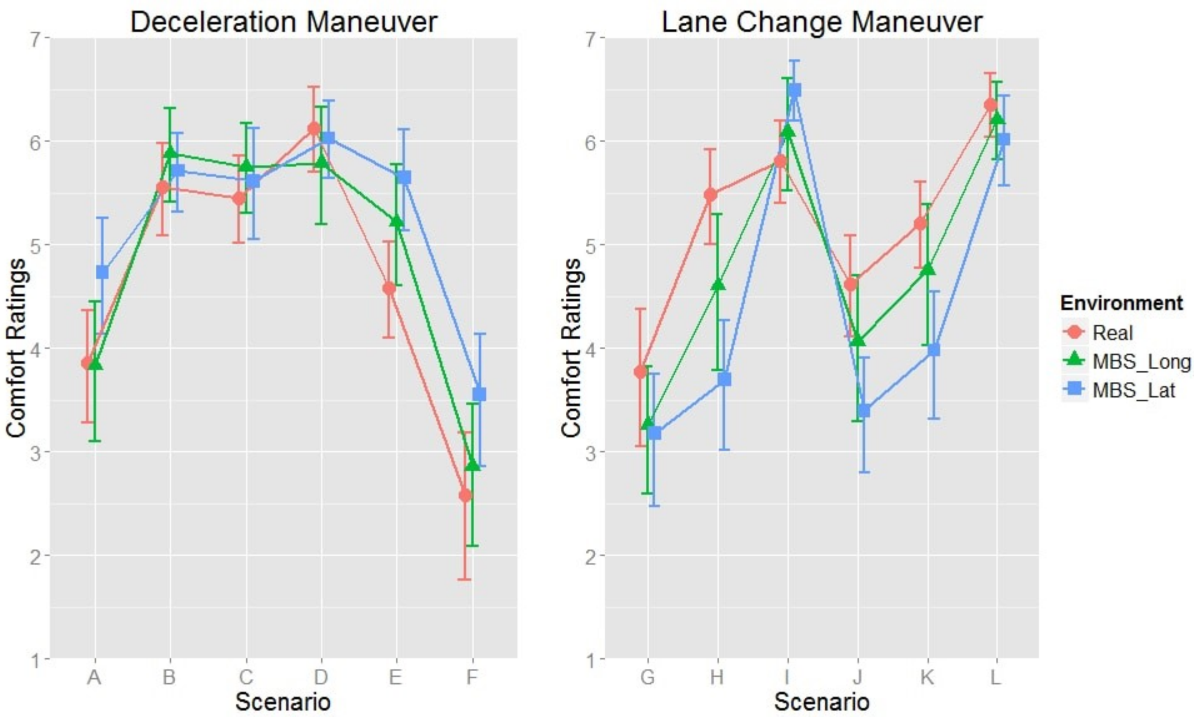


Figure 8. Illustration of the comfort ratings. Squared comfort ratings were averaged across environments and scenarios, and subsequently transformed back to their original scaling. Error bars indicate 95% confidence intervals.

To further examine which maneuver parameters might be at the basis of these differences, we performed a multilevel regression analysis using the lme4-package in R (Bates, Maechler, Bolker, & Walker, 2014) with repeated measures on the first level, and participants on the second level. As the dependent variable, the comfort rating was used. For each of the six parameters describing the deceleration and lane change maneuvers, we built a separate model and added the maneuver parameter and its square to the model as first level predictors to allow for a curvilinear relationship. At the second level, we added Environment as a dummy-coded variable to the model, with the test-track environment being set as the reference level. Additionally, a cross-level interaction between Environment and the maneuver parameters was entered. Again, comfort ratings were squared to meet the assumption of normally distributed residuals. Subsequently, comfort ratings and maneuver parameters were subjected to a z-transformation before model-fitting to prevent biased parameter estimation due to multicollinearity produced by the high correlation between the linear and curvilinear term of the maneuver parameter. For each model, a visual inspection of the residual plots revealed no obvious deviations from normality or homoscedasticity. To determine the variance explained by the parameters, we calculated R^2 for each model according to the algorithm suggested by Xu (2003). To illustrate the results, we simulated expected values based on the multilevel regression models as proposed by King, Tomz, and Wittenberg (2000). Results and illustrations of the multilevel analyses are given in Figure 9 and Figure 10.

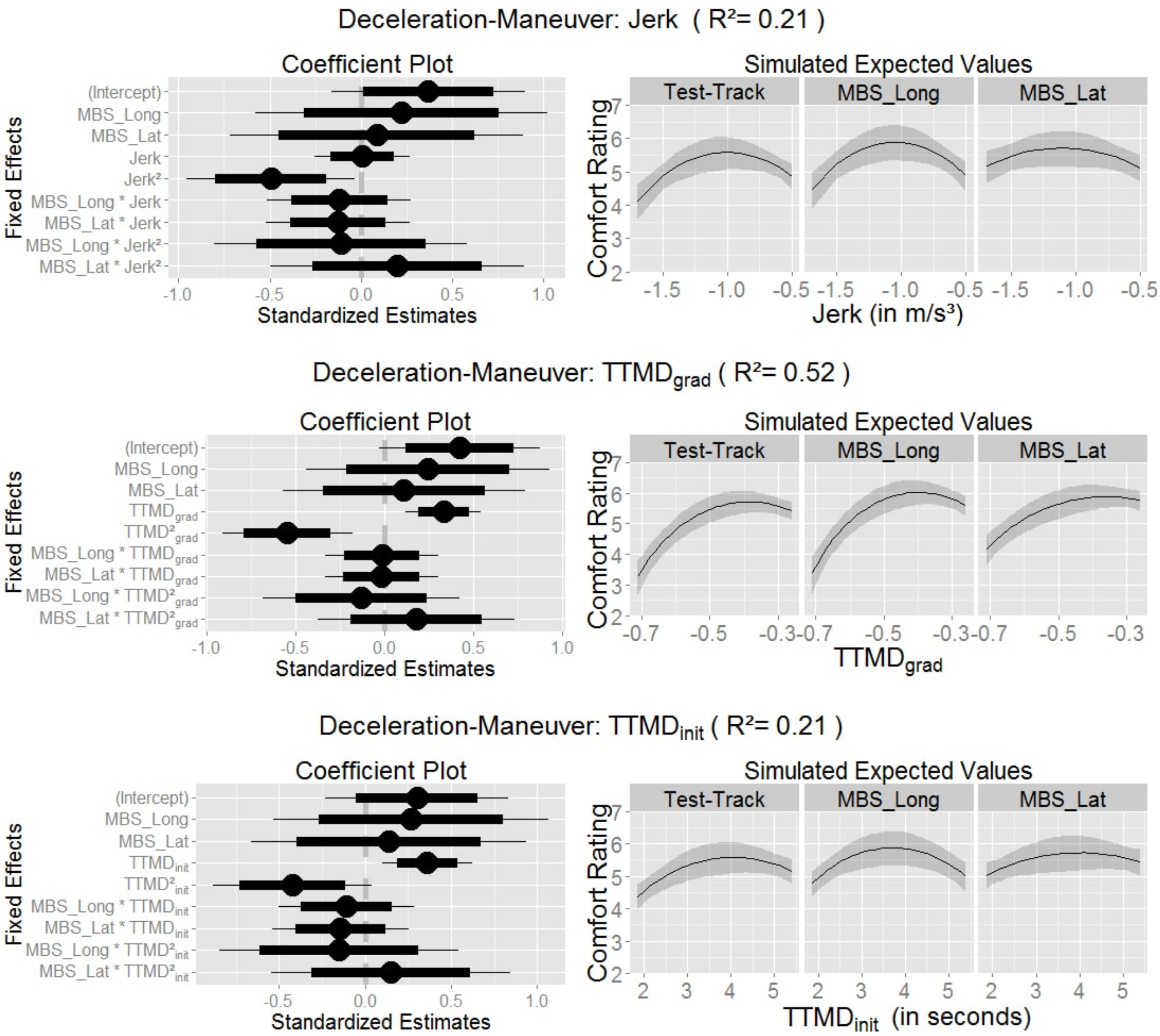


Figure 9. Results of the multilevel analyses of the deceleration maneuver. In the left column, standardized regression coefficients are illustrated in a coefficient plot. The thick error bars indicate the 95% confidence interval and the thin error bars indicate the 99.9% confidence interval. A fixed effect is significant on the alpha-level of 0.05 (0.001) when zero is outside of its thicker (thinner) confidence interval. In the right column, simulated expected values are plotted for each environment. Note that comfort ratings were transformed back to their original scaling. Error bands indicate the 95% confidence interval. R^2 was calculated using the algorithm proposed by Xu (2003).

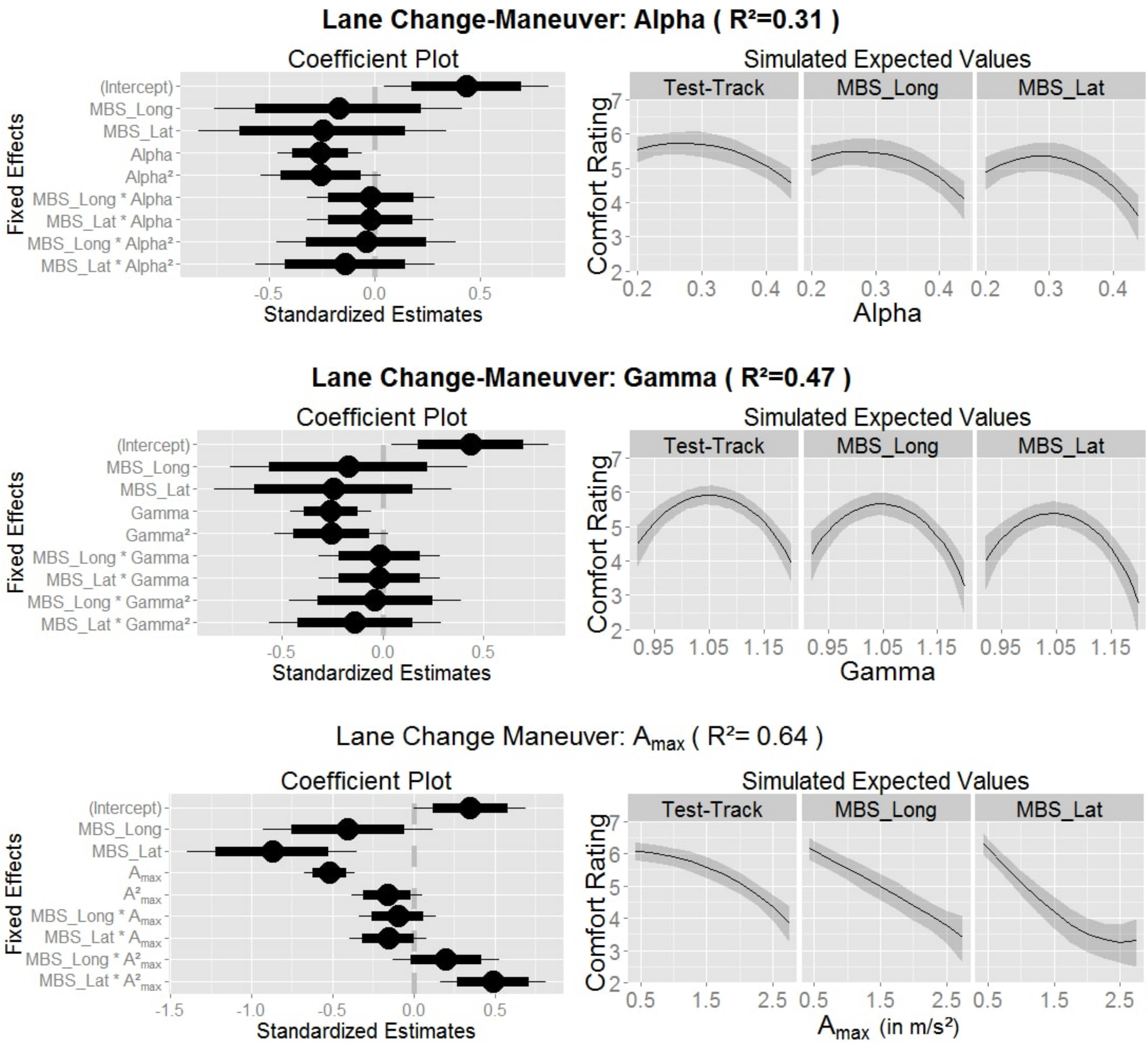


Figure 10. Results of the multilevel analyses of the lane change maneuver. In the left column, standardized regression coefficients are illustrated in a coefficient plot. The thick error bars indicate the 95% confidence interval and the thin error bars indicate the 99.9% confidence interval. A fixed effect is significant on the alpha-level of 0.05 (0.001) when zero is outside of its thicker (thinner) confidence interval. In the right column, simulated expected values are plotted for each environment. Note that comfort ratings were transformed back to their original scaling. Error bands indicate the 95% confidence interval. R^2 was calculated using the algorithm proposed by Xu (2003).

3.4 Discussion

For both lane change and deceleration maneuvers, results support relative and absolute validity for the MBS_Long. In the MBS_Lat configuration, however, relative validity for the lane change maneuver cannot be supported. Also, data only hints at a weak relative validity for the deceleration maneuver. Consequently, only the moving base simulator configured with lateral and longitudinal scaling factors of 50% and 60% (MBS_Long) seems to be a valid research tool to examine driving comfort in automated lane change and deceleration maneuvers. In contrast, the lateral configuration (MBS_Lat) seems inadequate for studying driving comfort, especially for lane change maneuvers. Furthermore, we found not only that the relative comfort ratings among the lane change conditions did not correspond to those of the test track environment, but driving comfort was generally rated lower in the MBS_Lat, compared to the test track environment.

Because the MBS_Long configuration optimally exploits the available motion space to simulate longitudinal motion cues, it is not surprising that this configuration is superior, compared to the MBS_Lat configuration in the deceleration maneuver. However, it is surprising that in this study the MBS_Long seems to be superior to the MBS_Lat configuration, which is optimized for simulating these lateral cues, in the lane change maneuver, even though a lane change requires an adequate simulation of lateral motion. In the following section several explanations for these counterintuitive findings are discussed.

As can be seen from the multilevel analyses, the effect in the MBS_Lat of the linear and curvilinear component of the maximal acceleration A_{max} on driving comfort was significantly different from those in the test-track study, whereas in all other parameters the MBS_Lat produced identical results. At the same time, A_{max} was found to be the best predictor of driving comfort, as it explained most of the variance. This finding indicates, that the source of the poor validity of the MBS_Lat may be traced back to an erroneous simulation of maximal lateral acceleration cues. From the simulated expected values illustrated in Figure 10, we see that already a little increase in lateral acceleration in the MBS_Lat led to a severe decrease in comfort ratings, compared to a rather mild decrease in the test-track study. Thus, A_{max} seemed to be also responsible for driving comfort being rated significantly lower in the MBS_Lat, compared to the test track environment. When considering the scaling factors for lateral accelerations in the two simulator configurations, it is evident that simulating only 50% (MBS_Long) of the lateral acceleration, produced more valid comfort ratings than a physically valid 100% scaling factor (MBS_Lat). This counterintuitive result was also found in previous studies. Pretto et al. (2009) varied four scaling factors (0.5, 0.75, 1.0, 1.25) for lateral acceleration in a slalom driving task, and concluded a scaling factor of 60% as being the perceived optimal motion gain. Greenberg et al. (2003) varied three scaling factors (0, 0.25, 0.5, 0.7) in a lane change task, and concluded that lateral motion scale factors of around 50% are sufficient to produce naturalistic driving performance. Probably one of the most comprehensive motion cueing studies was carried out by Berthoz et al. (2013). Across three advanced moving-base driving simulators, they examined the effect of lateral motion scaling on the perceived realism and driving performance in a slalom driving task. They concluded a factor between 0.4 and 0.75 as being the optimal motion gain for lateral acceleration. As potential explanations, they noted that the preference for subunity motion scaling might be attributable to constraints of the vehicle dynamics models. However, our findings contradict this notion, because no vehicle model was interposed in this study. Rather, measured accelerations from the test-track study were directly transmitted to the motion system.

A plausible and promising explanation was proposed by Berthoz et al. (2013). They suggested that motion cueing has to be scaled down in order to match an underestimated speed in virtual environments. Thus, the basis of this effect might be found rather in the physical validity of the display system than in the motion system (Correia Grácio, Bos, van Paassen, & Mulder, 2014). Indeed, many studies found that speed and distance were underestimated in virtual environments (e.g., Banton, Stefanucci, Durgin, Fass, & Proffitt, 2005; Fischer et al., 2012; Harris, Jenkin, & Zikovitz, 2000; Knapp & Loomis, 2004).

Even though an underestimation of speed is known for decades in driving simulator research, the theoretical basis still remains unknown. Considering that the aforementioned studies relied on visual systems with monoscopic cues, there is growing empirical evidence that providing stereoscopic cues enhances the visual-vestibular integration (Butler, Campos, Bülthoff, & Smith, 2011) and might reduce the visual-vestibular mismatch, which is often assumed to evoke simulator sickness (Reason, 1978). Furthermore, it was found that stereoscopic cues considerably improved heading judgements (van den Berg & Brenner, 1994), increased perceptions of ego speed and self-displacement (Palmisano, 2002), and decreased vection onsets and increased vection duration (Palmisano, 1996 but see Ijsselsteijn, Ridder, Freeman, Avons, & Bouwhuis, 2001). As a consequence, introducing stereoscopic cues to fixed-base simulators might enhance their physical validity at first sight, but they would most likely decrease the behavioral validity due to a higher visual-vestibular mismatch. This might explain, why a stereoscopic display in an otherwise identical fixed-base driving simulator was barely found to improve driving performance, compared to a monoscopic display (Forster, Paradies, & Bee).

Nevertheless, this hypothesis remains speculative and it will be the task of future research to determine whether the preference for subunity scaling factors might dissolve when providing stereoscopic visual cues.

Leaving the theoretical basis aside, our data supports that the preference for subunity scaling factors seems to be not only limited to active driving tasks, but also to passive driving tasks. Furthermore, we could demonstrate for the first time that a moving-base simulator can be utilized to study perceived comfort in autonomous vehicles, given the motion cueing algorithm is adequately parameterized. However, we want to point out that it is difficult to generalize findings across several research questions and different architectures of driving simulators. Considering that a growing body of traffic psychology research relies on driving simulators, it is crucial that driving simulators are subject to constant validation. Furthermore, as Godley et al. (2002) noted, the accumulated evidence that different driving simulators were found to be useful research tools for a variety of driving tasks adds weight to the validity of driving simulator research.

In addition to the findings on simulator validity, it was possible to identify in which way the characteristics of the maneuvers influence comfort ratings. Results point in the direction of acceleration being the strongest influence on comfort. As expected, less acceleration is perceived as favorable. Participants' verbal comments regarding the smoothness of scenarios and anticipatory qualities in combination with the found importance of $TTMD_{grad}$ also suggests the course of the maneuver plays an important role in experiencing comfort.

3.4.1 Potential limitations

We have performed many statistical tests which increased the risk of Type I errors. However, we believe that corrections for the alpha level (e.g., Bonferroni-correction) would have been too conservative, especially when considering that the simulators were not tested against being valid, but tested against not being valid. In addition, we point out that using a within subjects design would have provided the method of choice but was not feasible due to the large logistical challenge and reasonableness towards participants. It can further be discussed, whether a multi-dimensional measure of comfort may have been a stronger measure. However, participants in pretests have shown difficulty rating comfort on a multi-dimensional scale. This is also reflected in the comments participants gave after each variation, which mainly reduced comfort to smoothness and anticipation.

A further possible limitation addresses the method used to assess driving comfort. Also due to the fact that no common understanding exists on the precise definition of comfort, finding a valid tool for assessment has proven to be difficult. In retrospect, we suspect that the unidimensional 7-point scale used may not have been the optimal choice. There have been different approaches to objectively measure driving comfort, such as via physiological measures (e.g., Engeln & Vratil, 2008) or indirectly by measuring discomfort (e.g., Hartwich et al., 2015). However, a residual variance remains even when using objective measures (Engeln & Vratil, 2008). We are also aware that other aspects, such as feeling safe, may have influenced the ratings as they are closely linked or in some theories a part of comfort (see Summala, 2007). However, we also believe that comfort is not obtainable if a person is not feeling safe. A valid and widely supported questionnaire or assessment method has yet to be established.

Especially in simulators motion sickness can be an important influence on data. Because participants in this study reported mainly no or only seldom little discomfort regarding motion sickness we did not control our results for symptoms of simulator and motion sickness. Also because trials were randomized, we believe that a systematic bias of motion or simulator sickness is unlikely. At last, our analysis and discussion might be characterized as having a post-hoc character. However, we want to point at the explorative nature of this study which is due to the novelty of studying perceived comfort of autonomous vehicles in driving simulators.

3.4.2 Conclusion

We found that participants preferred downscaled motion cues to physically correct motion cues which can be plausibly attributed by an underestimation of speed in virtual environments. It would be interesting for further research to test whether providing stereoscopic cues would enhance speed perception and thus resolve the preference for subunity scaling factors. In summary, we were able to demonstrate relative and absolute behavioral validity for the MBS_Long for both lane change and deceleration maneuvers within the range of parameterization which is relevant for driving comfort in autonomous cars. For the MBS_Lat in the given configuration (100% scaling factor for lateral motion cues, 17% scaling factor for longitudinal motion cues) however, we could conclude only weak relative validity for the deceleration maneuver and no relative validity for the lane change maneuver. A scaling factor of 50% to 60% appears to be the key factor for behavioral validity of the driving manoeuvers under consideration in this study, which can be provided by the MBS_Long configuration consistently for both lateral and longitudinal motion cues.

Regarding experiencing comfort, maximum acceleration as well as how parameters change over the course of a maneuver seem to be key influences.

3.5 Additional analysis

In addition to the published findings, this study made it possible to analyze the metrics and corresponding values based on Study 1. As a first step, an ANOVA was conducted over the scenarios per environment to test whether the scenarios lead to different ratings. A significant effect was found for each maneuver in all settings (see Table 7).

Table 7

Analysis of rating variance for the different scenarios of Study 2.

Maneuver	Environment	df	F	p	ω^2
Lane Change	Test track	5, 162	16.77	< .001	0.32
	Simulator lateral	5, 126	29.88	< .001	0.52
	Simulator longitudinal[1]	5, 57.96	19.26[1]	< .001	-
Deceleration	Test track	5, 162	31.51	< .001	0.48
	Simulator lateral	5, 126	13.42	< .001	0.32
	Simulator longitudinal	5, 126	19.14	< .001	0.41

Note. [1] Welch's F, due to violation of variance homogeneity.

Post hoc tests were performed per maneuver using a Bonferroni-Holm correction. As expected, the scenarios with weakest acceleration and also the variations with the smallest gradient in Time to Minimum Distance achieved the highest ratings (for a full analysis see Appendix B – Post hoc tests simulator and testing ground). Even though analysis reported in Study 2 found maximum acceleration to be the best predictor of driving comfort, as it explained most of the variance, it was found that the ratings of the variations are not solely dependent on maximum acceleration. According to Kingma (2005), just noticeable difference (JND) in lateral acceleration lies at 0.06 m/s^2 in laboratory settings. This implies that variations with acceleration values which differ by more than the mentioned JND should lead to significantly different ratings of comfort, if experiencing comfort solely relies on the perception of acceleration. Ratings, however, show that scenarios with acceleration differences, which are greater than 0.06 m/s^2, do not necessarily differ significantly, e.g. scenarios H and J (1.76 m/s^2 and 2.60 m/s^2). Thus, it may be assumed that acceleration is not the sole determinant of comfort.

Also, the identification of differences may have been inhibited by the scale used. A scale from 1 to 7 seemed practical at the time of study design, because a scale with 7 steps can still be handled in an auditory presentation by participants. However, the 7-point scale does not seem to be sensitive enough to portrait small differences and preferences. This will be considered in Study 3 by using a direct comparison approach.

As a second step in the additional analysis, it was examined whether the implemented automated maneuvers based on comfortable manual driving results from Study 1 are also experienced as comfortable. Comfort was rated on a 7-point scale between *exactly this way* (7) and *not at all* (1) leaving the middle at 4. Mean ratings are shown in Table 8.

This made it possible to identify whether the scenarios were experienced as significantly less favorable than the middle category. One sample t-tests were used with a Bonferroni-corrected significance value of .008. In the lane change maneuver on the test track no scenario scored significantly less than the middle category. In the simulator environments scenario G showed a significant effect in both longitudinal, $t(21) = -3.39$, $p = .003$; and lateral simulator environment, $t(21) = -3.70$, $p = .001$. Concerning the deceleration on the test track, scenario F shows a mean value significantly lower than 4, $t(27) = -7.04$, $p < .001$. The same effect can be found in the longitudinal simulator environment, $t(21) = -4.82$, $p < .001$; but not in the lateral simulator environment, $t(21) = -2.40$, $p = .026$, when using the Bonferroni-corrected criterion of .008.

This implies that in lane changes the scenario with the strongest lateral acceleration in combination with the largest alpha or latest point of acceleration maximum is not experienced as favorable. In general, it seems the rating of lane changes is strongly dependent on maximum acceleration. This may imply that lane changes with smaller accelerations and earlier perceivable onsets are preferred over lane changes with strong and later accelerations. In the deceleration maneuver, the scenario with the shortest TTMD and smallest jerk onset is disapproved of in all environments. This may imply that participants wish for an early reaction of the automated vehicle.

Table 8

Mean comfort ratings of different maneuver scenarios per environment in Study 2 on a scale from 1 to 7.

Environment	deceleration scenario					
	A	B	C	D	E	F
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*
Test Track	3.61 (1.40)	5.39 (1.34)	5.32 (1.22)	6.00 (1.25)	4.39 (1.34)	2.21 (1.34)
Simulator Longitudinal	3.50 (1.60)	5.77 (1.15)	5.64 (1.18)	5.55 (1.71)	5.00 (1.54)	2.45 (1.50)
Simulator Lateral	4.55 (1.34)	5.64 (0.95)	5.41 (1.53)	5.95 (0.95)	5.50 (1.30)	3.27 (1.42)
	lane change scenario					
	G	H	I	J	K	L
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*
Test Track	3.39 (1.69)	5.32 (1.33)	5.68 (1.25)	4.42 (1.35)	5.07 (1.18)	6.29 (0.94)
Simulator Longitudinal	2.91 (1.51)	4.18 (1.97)	5.91 (1.51)	3.36 (1.76)	4.45 (1.71)	6.14 (0.94)
Simulator Lateral	2.82 (1.50)	3.36 (1.56)	6.45 (0.74)	3.09 (1.44)	3.73 (1.42)	5.91 (1.15)

In general, the data obtained in manual driving seems to be an adequate basis for research on automated driving.

3.6 Summary of insights from Study 2

Study 2 was conducted to validate data found in Study 1 in an automated context and to evaluate whether a dynamic driving simulator is a valid tool for further investigations of comfort in automated vehicles. For the first aim, scenarios were derived from the values found in Study 1 and rated by participants. In order to evaluate the simulator environments, validity and motion scaling parameters were examined. It was shown that the values found in Study 1 influence comfort experience in automated vehicles and elicit different ratings when varied. It has to be noted, that even though quickness was reported as an important metric in Study 1, it was not manipulated in Study 2.

This was because the length of the maneuver variations and lateral offset were held constant to ensure comparability by eliminating the influence of duration and headway distance.

Concerning the manipulated metrics, it was found that maximum acceleration seems to be an important criterion but not the sole criterion for experiencing comfort. Furthermore, upon comparison of the data from two simulator settings and the test track data, it becomes evident that the longitudinal simulator setting with scaling factors of 50 % and 60 % seems to be a valid alternative to on-road testing regarding comfort ratings of automated driving. This is an important finding because the simulator offers an easy to manipulate, replicable environment.

Yet, open questions remain. Studies 1 and 2 have shown the importance of acceleration, but also the importance of the course of acceleration, i.e., jerks, alpha and gamma. However, it remains unanswered how the course of acceleration should be designed for comfort oriented automated driving. Further, so far participants' personalities and manual driving style have not been considered. Existing literature indicates that personality traits could have an influence on experiencing comfort in automated driving (see i.e., Lee & See, 2004; Muir, 1987; Rudin-Brown & Parker, 2004; for more details see Chapter 1.5). Both the course of acceleration and the influence of personality will be addressed in Study 3.

4 Study 3: Preferences in automated driving and their dependence on personality traits

In this chapter, a final evaluation of differently parameterized maneuvers will be described. Maneuvers are implemented, based on the restraints of comfortable parameterization identified in the previous chapters. The following text has been published under the title "Comfort in automated driving: An analysis of preferences for different automated driving styles and their dependence on personality traits" in Transportation Research Part F (see reference Bellem et al., 2018). As before, an additional analysis is appended.

4.1 Introduction

Automated driving is currently one of the main trends in the automotive industry. As technical realization of highly automated driving or automation on SAE level 3 (SAE International, 2014) draws closer, attention is now being shifted from the sheer feasibility to the question of how an acceptable driving style and thus comfort can be implemented.

So far, no widely shared and agreed-upon definition of comfort has been established in the scientific community. For one, it is still debated whether comfort and discomfort should be seen as opposite poles of one construct or whether they can coexist (see Vergara & Page, 2000; Zhang et al., 1996; for a review on comfort in driving assistance see Engeln & Vratil, 2008). Comfort is commonly associated with a feeling of well-being and an attribution of positive valence towards the eliciting entity and, depending on the view on comfort, associated with the absence of discomfort and uneasiness. Summala (2007) also points out that comfort is pleasant and is not experienced in the face of high arousal. Even though no definition of comfort is agreed upon, de Looze et al. (2003) identified commonly shared aspects of the majority of definitions of comfort: 1) comfort is subjective, 2) comfort is influenced by internal and external factors, and 3) comfort is experienced as a reaction to something. Regarding highly automated driving, the relationship between expected and actual driving, as well as experiencing loss of control, provide further promising influencing factors on comfort (Elbanhawi et al., 2015; Krist, 1994; Krüger, Neukum, & Schuller, 1999). Furthermore relevant to highly automated driving, a close relationship is seen between comfort and trust, as well as acceptance of automated vehicles (Siebert et al., 2013). Both trust and acceptance are vital to the usage of a system (Muir, 1987; Parasuraman & Riley, 1997), thus comfort may be seen as a barrier to technology adoption. This makes an evaluation of driving style preferences in automated driving important.

Apart from the question of how comfort can be defined, driving comfort has – so far – been mainly investigated in the context of manual driving. Only little research exists on passenger comfort (see Ellinghaus & Schlag, 2001). Key results found by Ellinghaus and Schlag (2001), which may be transferred to being driven in an automated vehicle, address the feeling of control, possible reasons for motion sickness and factors influencing experiencing comfort. Concerning the latter, Ellinghaus and Schlag (2001) found that a passenger's experienced comfort relies strongly on the driver's driving style and, among others, on factors such as the vehicle's safety equipment, safety systems and seats. Evaluating the comfort of passengers in automated vehicles, however, is yet a novel field. Out of the mentioned options, manipulating driving style seems to be the most promising option for substantially influencing experienced driver comfort in highly or fully automated vehicles. Both the passive safety systems of the vehicles and the seats are not very likely to change substantially due to a higher automation level.

Manual driving styles are described by a person's habitual way of driving (French et al., 1993). Among others, this includes the preference for speed, acceleration profiles, individual conditions for overtaking, preferred headway distance, and abiding traffic laws. In the past years, driving styles have received scientific attention (for an overview see Sagberg et al., 2015). This research has however, been largely focused on manual driving and crash risk (see e.g., French et al., 1993) or topics such as fuel efficiency (see e.g., Murphey et al., 2009). Based on these findings and on findings by Ellinghaus and Schlag (2001), it seems important to take a closer look at the relationship between driving style and experiencing comfort in a context of automated vehicles. Due to the existing relationship between user, comfort, acceptance, trust, and likeliness of usage (Jamson, 2006; Siebert et al., 2013; Winner et al., 2012), it is important to identify a most comfortable driving style. The many anticipated advantages of SAE level 3+ driving automation, such as fewer traffic accidents and less traffic congestion, depend on the extent of system usage. Thus, the success of automated driving also depends on the systems' automated driving style.

From a technology-driven perspective, an endless number of automated driving styles present themselves. For example, it is possible to mimic an average human driving style, to match the automated driving style to the passive driver's own driving style, or to implement an artificially constructed driving style. Out of the plethora of possibilities, it is important to identify the underlying factors determining a comfortable automated driving style. For this purpose, a simulator study was conducted. The aim was to evaluate differently implemented automated maneuvers regarding experienced comfort. To ensure findings result in a comfortable experience for as many people as possible, it was also analyzed whether the found preferences are personality dependent.

As highly and fully automated driving will first be possible on highways, focus lay on the most frequent maneuvers on highways. The most common lateral maneuver is the lane change. In addition, this maneuver is still rather novel in automation context. Concerning longitudinal maneuvers, focus lay on acceleration as well as on deceleration. Here, deceleration is performed in relation to another vehicle driving ahead. This was done, not only because of the maneuvers commonness, but also because it takes the restraints arising from surrounding traffic into account.

In this study, three variations of each of the three maneuvers are compared. On the basis that familiar circumstances elicit less distress and may make a person feel more comfortable (see Elbanhawi et al., 2015), we have chosen to base the variations in this study on recorded data of manual driving (Bellem et al., 2016). Because jerk has been shown to elicit a stronger influence on experiencing comfort than acceleration itself (Gianna et al., 1996) and further based on findings in previous studies (Bellem et al., 2017), our focus lay on the manipulation of lateral or longitudinal jerk. The maneuvers and their variations will be described more thoroughly in Chapter 4.2.3 Maneuvers.

As stated above, it is also a goal of this paper to assess whether preferences for automated driving styles depend on the driver's personality. In manual driving, it is assumed that as a person's own driving style is internalized and not only influenced by experience but also by the driver's personality (Lajunen et al., 1998). This has been suspected for automated driving as well (see Stanton & Young, 2000). This assumption has, however, not been investigated. These results can provide implications for the design of highly automated driving systems.

Alongside self-reported driving style, trust in automation, locus of control, sensation seeking, and willingness to take risks were used to investigate personality dependency of comfort. Trust in automated systems presents itself as a potential influence, because control is handed over to the vehicle completely in highly automated driving. In general, trust is seen as a very important factor for reliance on automated systems as well as their dis- or misuse and use (Lee & Moray, 1992; Lee & See, 2004; Muir, 1994). Likewise, locus of control – an important driver characteristic (Beggiato & Krems, 2013; Holland, Geraghty, & Shah, 2010; Stanton & Young, 2000) – might be an influencing factor. It is possible, that drivers with a high external locus of control might be more comfortable with not being in control and are thus less critical about automated driving styles.

Another personality trait, which has often been associated with driving style, is sensation seeking (see e.g., Jonah, 1997; Taubman-Ben-Ari et al., 2004; Zuckerman & Neeb, 1980). Sensation seeking is, for instance, found to correlate positively with reckless driving (Jonah, 1997). Thus, a high sensation seeking score might stand in relationship with the preference for more dynamic automated driving. Because sensation seeking incorporates taking the necessary risks as well as the need for new, intense and varying sensations and experiences (Zuckerman, 2010), it seems necessary to additionally regard willingness to take risks as an own factor in this study.

In short, the major objectives of this study were (a) to identify which of the proposed acceleration profiles is experienced as most comfortable for each maneuver and (b) to assess whether ratings of comfort made in this study are dependent on the assessed personality traits.

For both the lane change (H1) and the acceleration maneuver (H2), we hypothesize the maneuver variation with the smallest jerk, i.e. the acceleration-symmetrical maneuver, to be experienced as most comfortable (see Gianna et al., 1996). Regarding deceleration behind a leading vehicle, the influence of the leading vehicle has to be taken into account as well. In his work on tau (or time to collision), Lee (1976) describes the typical closing in behavior of manual drivers as a high deceleration which decreases strongly in the beginning of the maneuver and subsides to a small decrease of deceleration towards the end. We assume this to have a stronger influence on preference in the deceleration maneuver than mere minimum jerk (H3).

Concerning personality traits and manual driving style, we hypothesize, the traits described above to be influential. In detail, we assume that participants scoring high in high velocity driving, angry or risky driving style are influenced less in their preferences by stronger accelerations or jerks (H4a/b/c) than participants scoring low on these subscales. Hence, their preference values should not differ as much between alternatives as those of low scorers.

Additionally, we assume participants who score high on careful driving to prefer the variation, which shows an early reaction of the vehicle, i.e. with an early maximum jerk, over the variation with the late jerk maximum (H4d). Furthermore, we assume participants with a low trust in automated systems (H5) – like participants with a high internal locus of control (H6) – prefer the variation that shows a strong jerk early on to the variation with the strong jerk at the end. While on the contrary, a preference for the late variation is expected for participants who score high in thrill and adventure seeking, i.e. sensation seeking, (H7) as well as for participants scoring high on the willingness to take risks (H8). These hypotheses are based on the assumption that drivers want to be driven as they drive themselves.

4.2 Method

4.2.1 Participants

In total, 72 participants (34 female, 38 male) took part in the study. Participants' age ranged from 21 to 66 years (*M* = 41.79 yrs., *SD* = 10.28 yrs.). Upon being asked to rate their opinion on autonomous driving as “skeptical / negative opinion”, “neutral”, or “favorable / positive opinion”, the majority of participants (73.61 %) state they look favorably on automated driving. Only 5.56 % state to have a negative opinion on automated driving. All participants had experienced a moving-base driving simulator before. Only 9.72 % of the participants had no experience with advanced driving assistance systems (ADAS), whereas 51.39 % used cruise control or a more advanced ADAS more often than once a week. Participants were offered 30 € (approx. 33 $) compensation for participation.

No participants had to be excluded from analysis entirely. Three ratings had to be excluded from deceleration analysis and two ratings were excluded from acceleration analysis. In both cases, they were excluded due to errors in the simulation. This error occurred during the last maneuver, which means that the ratings of the previous two maneuvers were not affected.

4.2.2 Simulator

The study was conducted in a high-fidelity moving base simulator illustrated in Figure 11. The simulator consists of a dome, in which a full-scale mock up is surrounded by a 360° field of view. The dome rests on a hexapod system, which itself is mounted on a 12.5 m linear rail system.

A highway scenario was simulated throughout the study. Each maneuver started on the right lane of a two-lane highway. The on-coming traffic lane was separated with a central guardrail. There was no accompanying traffic apart from a truck driving ahead of the ego vehicle in the deceleration maneuver.

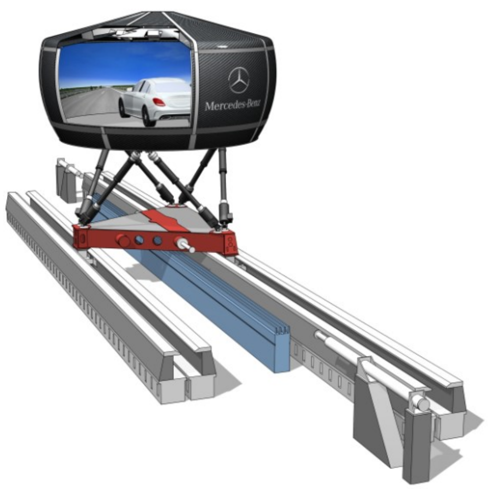


*Figure 11***.** Illustration of the moving-base simulator.

4.2.3 Maneuvers

Participants experienced a fully automated lane change to the left, acceleration, and deceleration behind a slower truck. Three different variations of each maneuver were presented. The variations are based on previous studies on manual and highly automated driving (Bellem et al., 2016; Bellem et al., 2017). To assure participants were able to experience differences between the maneuver variations, the variations were cross-checked against just noticeable differences reported by Müller et al. (2013).

The lane change maneuver was performed at a speed of 100 km/h (approx. 62 mph). The lane change was made necessary due to the right lane merging onto the left lane. This was additionally made visible using traffic signs at 400m, 200 m, and 100 m (approx. 437 yds., 218 yds., and 109 yds.) ahead of the merging point. In each variety, the vehicle initiated the lane change at 200 m from the merging point. All variations of the lane change maneuver were completed after eight seconds.

The lane change to the left was characterized by the relative magnitudes of the first and second lateral acceleration maximum and by how early on the first acceleration maximum occurred in the lane change maneuver (see Figure 12). Thus, lateral jerk and the symmetry of the lane change maneuver were subsequently manipulated. Figure 13 illustrates how the three alternatives vary regarding their trajectory and symmetry.

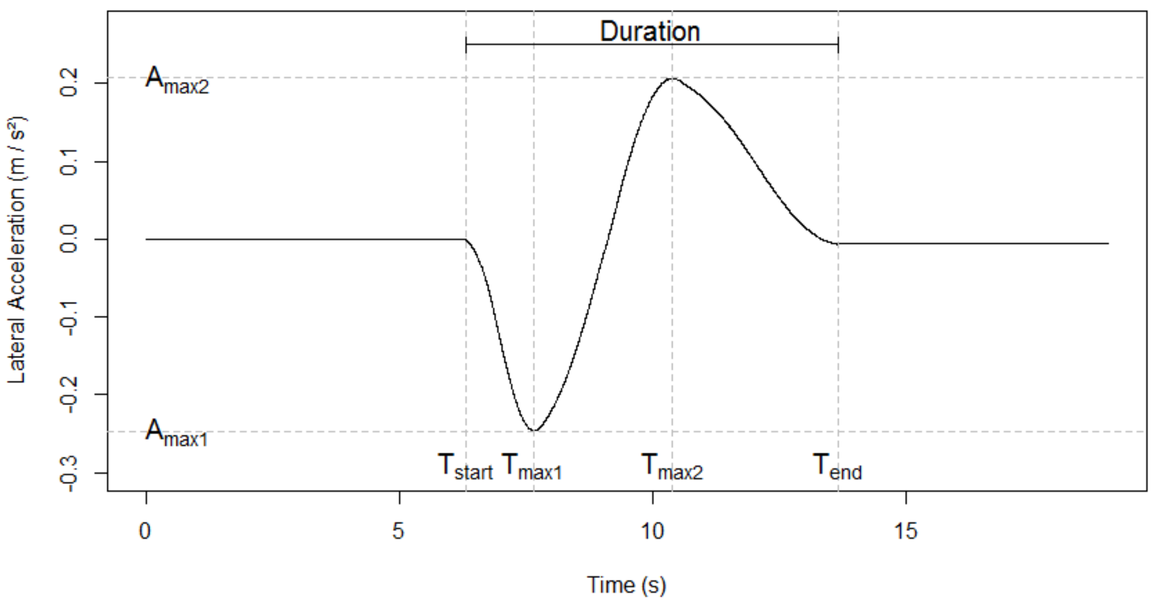


Figure 12. An exemplary lane change to the left is illustrated. The start (T_{start}) and end of the maneuver (T_{end}) as well as the maxima of lateral acceleration (T_{max1} and T_{max2}) are marked.

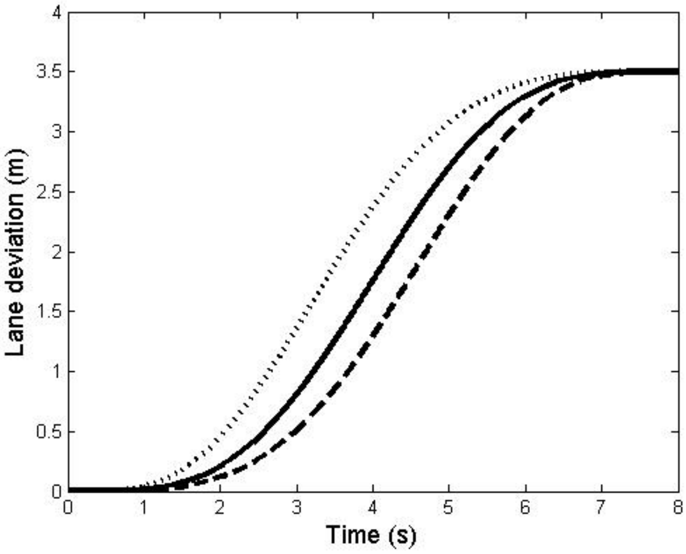


Figure 13. The trajectories of the three lane changes are illustrated. The middle graph shows a symmetrical lane change, whereas the left and right graphs show alternatives with an earlier or later lateral acceleration maximum.

As in the other maneuvers, the acceleration maneuver began with an immediate speed of 100 km/h (approx. 62 mph). After 10 seconds, a sign, marking the new speed limit of 120 km/h (approx. 75 mph), was reached. This triggered the acceleration.

The acceleration variations were characterized through the jerks occurring in the first and last phase of the acceleration. The jerks were thus manipulated that one symmetrical and two skewed accelerations were described (see Figure 14). All variations show the same maximum acceleration of 0.6 m/s2. Moreover, the duration of the maneuvers was held at 11 seconds for all deceleration variations.

In the deceleration scenario participants also started at 100 km/h (approx. 62 mph). A truck was driving at 80 km/h (approx. 50 mph) ahead. After ten seconds, participants' vehicle started decelerating. The deceleration was completed after eleven seconds, resulting in a time headway of two seconds.

The deceleration maneuver could have been described analogous to the acceleration, but we have chosen a different approach. In his work on tau or on how humans approach stationary obstacles or obstacles moving at a fixed speed, Lee (1976) observed that deceleration is strongest in the beginning and decreases almost asymptotically. Assuming that – due to familiarity – drivers want to be driven the way they drive themselves (Elbanhawi et al., 2015), one variation follows this supposed natural behavior (see continuous line in Figure 15). A second variation follows the approach used in the acceleration maneuver (see the dashed variation in Figure 15). The third variation shows similarities to the second variation. However, jerk is held smaller by choosing a near logarithmic acceleration course (see dotted line in Figure 15) instead of a plateau and linear acceleration and thus also contrasting to the tau approach. In order to keep variations comparable, not only the duration of the maneuver but also the initial jerk was identical.

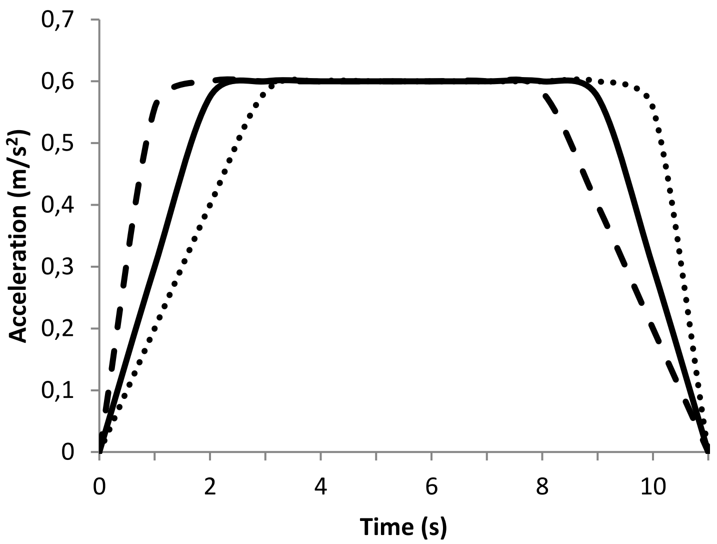


Figure 14. Three exemplary accelerations are illustrated. Maximum acceleration remains the same, whereas skewness varies. The continuous line describes the symmetrical acceleration.

4.2.4 Design and procedure

A 3x3 within-subjects design was applied. The first factor is represented by the maneuvers lane change, acceleration and deceleration. As a second factor, all maneuvers were presented in three varieties. Each participant experienced all maneuvers in each variety.

After filling in a pre-drive questionnaire, participants experienced a highly automated (SAE level 3+) highway trip of 60 s to get used to the setting. The three maneuvers followed in balanced order. All variations of one maneuver were presented en bloc. The three variations were arranged in three pairs for pairwise comparison. This resulted in three pairs of variations and participants thus experiencing each maneuver six times. Both the order of the three pairs and which variety would be presented first in each pair were randomized. After each individual variation pair, participants stated which of the two varieties presented in a direct pair-comparison they preferred over an intercom system. When participants had experienced and rated the total nine pairs, they were asked to fill in a follow-up questionnaire. The procedure is visualized in Figure 16.

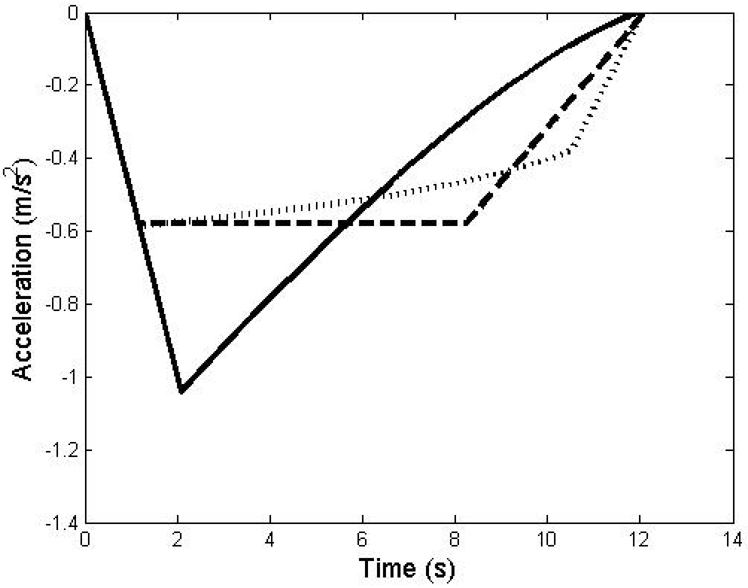


Figure 15. Three decelerations behind a vehicle are illustrated. Whereas the dashed line represents the variation analogous to the acceleration approach, the dotted line shows a smoother variation and the continuous line illustrates the tau-based variation.

4.2.5 Questionnaires

Both before and after the simulator ride, participants were asked to fill in questionnaires. The pre-drive questionnaire consisted of basic demographic questions and questions on experience with assistance systems and driving simulators. Further, participants were asked to rate their attitude toward risk on a 7-point one-item scale, rate their wellbeing or rather their current level of sickness using the Fast Motion Sickness Scale (FMS; Keshavarz & Hecht, 2011), state their general attitude towards autonomous driving, and complete the Multidimensional Driving Style Inventory (MDSI; Taubman-Ben-Ari et al., 2004) in order to assess self-reported driving style. The MDSI consists of 44 items, which are clustered into eight subscales. The items inquire whether certain behaviors are shown during manual driving, e.g. misjudging the speed of other vehicles.

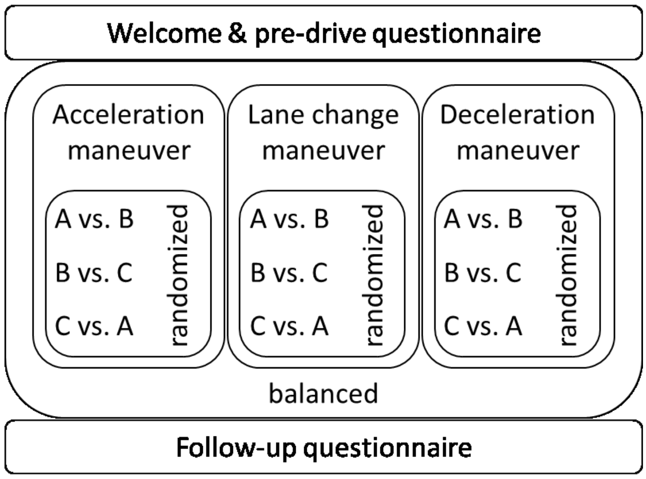


Figure 16. Illustration of the study procedure. Maneuvers were presented en bloc in a balanced order. Variations of the maneuvers, visualized here as A, B, and C, were presented in pairs. Both the order of the pairs and the order within the pairs were randomized.

The post-drive questionnaire included a follow-up question on wellbeing (FMS), the Thrill and Adventure Seeking subscale of the Sensation Seeking Scale V (subscale TAS in SSS V; Zuckerman, Eysenck, & Eysenck, 1978), a questionnaire on Locus of Control (Rotter, 1966), and Trust in Automated Systems (Jian et al., 2000). The FMS was asked to be able to identify participants, whose ratings may have been influenced by simulator sickness. The subscale Thrill and Adventure Seeking of the Sensation Seeking Scale V was used because this subscale has shown to have the strongest relationship to risky driving (Jonah, 1997). This subscale consists of 10 items and was presented in the German translation by Beauducel, Strobel, and Brocke (2003). Further, the questionnaire on locus of control by Rotter (1966) was presented with a focus on general locus of control and not solely focused on locus of control in driving. This was done, because – as per definition – the human driver hands all control to the vehicle in highly automated driving. Thus, a more general approach seemed more promising. Finally, the questionnaire on trust in automated systems by Jian et al. (2000) is a 12-item questionnaire proposing to measure the trust between a human and an automated system. The pre-drive and post-drive questionnaire were filled in separately due to organizational reasons.

All in all, the data obtained from participants consisted of demographic data, data on experience with simulators and driving assistance systems, willingness to take risks, well-being or motion sickness, attitude towards automated driving, self-reported driving style (MDSI), thrill and adventure seeking (SSS-V subscale TAS), locus of control, trust in automated systems, and preferred variations in the paired-comparisons.

4.3 Results

4.3.1 Data analysis method

Main effects of the paired comparisons were analyzed using the BTL model (Bradley & Terry, 1952; Luce, 2012) with the package eba (ver. 1.7-1; Wickelmaier & Schmid, 2004) in R. The BTL model allows analysis of paired-comparison data regarding whether a difference, i.e. a main effect, can be found. It is then further possible to analyze preference order using utility scale values and whether these preference ratings differ (for more information on the utilization of the BTL model in research on preferences see Oberfeld, Hecht, Allendorf, & Wickelmaier, 2009). Utility scale values are coefficients, which allow concluding an order of preference. This technique was chosen to be able to represent results of a paired comparison on an absolute scale by utilizing maximum likelihood approximation. The goodness-of-fit test reveals that the model fits the data well in the lane change maneuver, $G^2(1) = 0.68$, $p = .409$; the acceleration maneuver, $G^2(1) = 0.26$, $p = .611$; and the deceleration maneuver $G^2(1) = 0.92$, $p = .337$.

4.3.2 Data analysis results

A significant main effect can be found for all three maneuvers, lane change: $\chi2(2) = 40.27$, $p < .001$; acceleration $\chi2(2) = 48.14$, $p < .001$; deceleration: $\chi2(2) = 81.46$, $p < .001$. For further analysis, a sum to unity normalization was applied. This maintains the ratio between utility scale values, while normalizing values in a way, that they add up to 1, facilitating an interpretation. Figure 17 depicts the utility scale values of the three variations per maneuver and their respective 95 % confidence intervals. These were used as a basis for interpreting variation differences. In the lane change maneuver, the variation with a later maximum lateral acceleration has a mean utility scale value of 0.14, which is two to three times and significantly lower than the utility scale values for the symmetrical variation and the variation with the early lateral maximum. The latter show mean utility scale values of 0.36 and 0.50. For the deceleration maneuver the tau variation has a significantly lower utility scale value of .07 compared to the contrasting jerk reduced variation and the classic variation analogous to the acceleration approach with utility scale values of 0.42 and 0.51. The acceleration maneuver is the only maneuver in which none of the 95 % confidence intervals overlaps. The symmetrical variation shows the highest utility scale value with a value of 0.59 followed by the variation with skewness to the left with a utility scale value of 0.27 and finally the variation with skewness to the right with a utility scale value of 0.13.

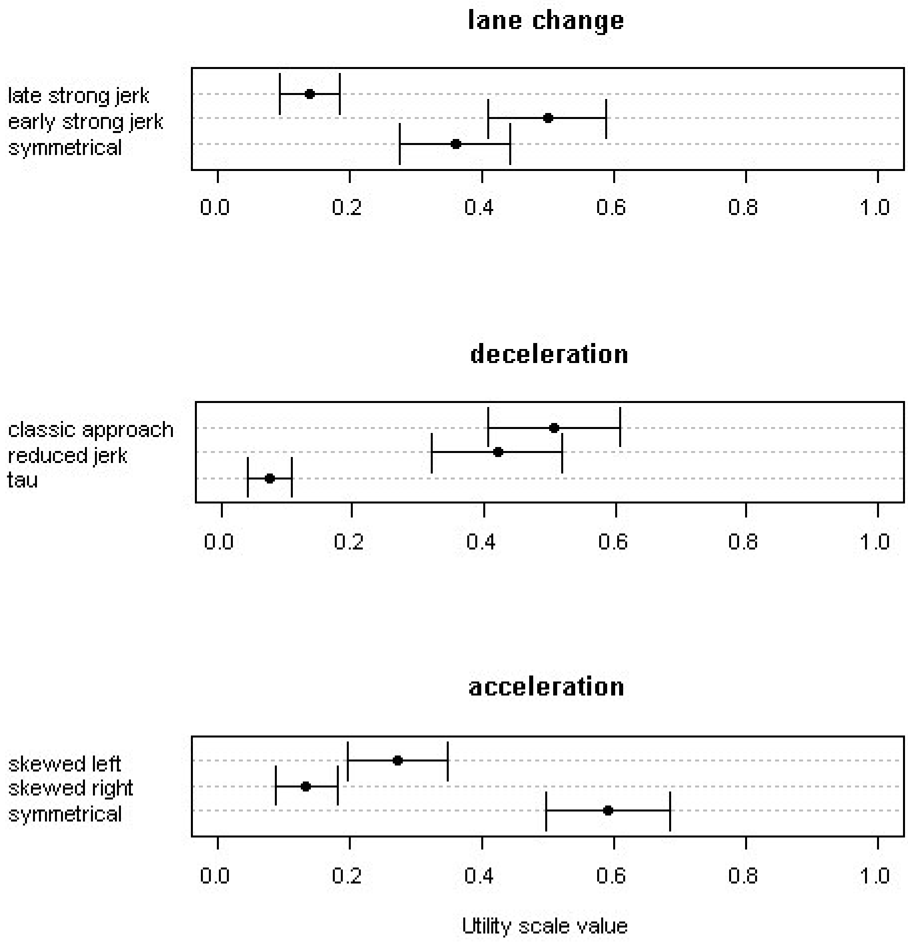


Figure 17. The utility scale values for each variation are depicted per maneuver along with their respective 95 % confidence intervals. Values were standardized per maneuver to a sum of one, while preserving the ratio between the utility scale values of each variation.

Before results regarding personality were analyzed in depth, internal consistency was checked for all scales or subscales (see Table 9). Because internal consistency across participants is not met for the scales dissociative, distress-reduction, patient, and careful driving style of the MDSI, no analysis will be done using these scales. Results from the scales anxious, angry, and high velocity driving style have to be interpreted with caution due to questionable internal consistency.

The following analysis compares preference ratings dependent on personality traits using a between-group comparison. The cut point of the groups was set at the 25th and 75th percentile of each scale or subscale respectively. These groups of high and low scores were then compared to each other.

Table 9

Values of internal consistency for the respective questionnaires.

Scale		*M* (*SD*)	Kurtosis	Skewness	Internal consistency (Cronbach's α)
MDSI					
	risky driving style	1.88 (0.77)	4.50	1.17	.735
	anxious driving style	1.79 (0.54)	2.42	0.53	.655
	high velocity driving style	2.38 (0.73)	2.30	0.46	.627
	angry driving style	2.03 (0.69)	2.62	0.51	.618
	dissociative driving style	1.66 (0.42)	3.30	0.70	.568
	distress-reduction driving style	2.63 (0.73)	2.59	0.20	.538
	patient driving style	4.47 (0.76)	2.72	0.06	.264
	careful driving style	4.70 (0.51)	2.41	0.22	.150
Trust in Automated Systems		5.65 (0.78)	4.02	-1.06	.844
Locus of Control		11.15 (3.36)	2.58	0.27	.659
Sensation Seeking					
	Thrill and Adventure Seeking	6.15 (2.65)	2.58	-0.38	.757

No significant group differences can be found regarding anxious or angry driving style (for an overview of main effects see Table 10). The preferences in the risky driving style group comparison show a significant effect in the acceleration maneuver. This effect is based on the preference for the variation with an early acceleration maximum being distinctly lower in the group of participants with low risky driving style. Concerning high velocity driving style significant effects are found for both lane change and acceleration. In the lane change maneuver, no significant differences were found on variation-level. Albeit, it can be observed that utility scale values for all variations are closer together for participants with lower scores on high velocity driving than for their counterparts. In acceleration, the confidence intervals of the variation skewed to the right do not overlap with the other two variations for participants scoring low on high velocity driving style. This is unlike the utility scale values shown by their high scoring counterparts, which are the same for both skewed variations and which even have slightly overlapping confidence intervals with the symmetrical variation.

Table 10

Main effects of the 25 and 75 percentile comparisons or male and female comparison.

Scale	Lane change		Deceleration		Acceleration	
	$G^2(2)$	*p*	$G^2(2)$	*p*	$G^2(2)$	*p*
MDSI						
risky driving style	0.65	.722	3.03	.220	6.34	.042*
anxious driving style	1.99	.370	0.75	.686	0.40	.820
high velocity driving	7.04	.030*	2.45	.293	7.48	.024*
angry driving style	1.70	.427	1.69	.430	5.23	.073
Trust in Automated Systems	4.11	.128	0.08	.960	0.13	.937
Locus of Control	1.20	.549	2.60	.273	1.45	.483
Sensation Seeking						
TAS	5.61	.060	4.62	.099	0.31	.857
1-item risk	1.37	.503	1.57	.456	2.91	.234
Age	0.80	.670	0.99	.610	4.44	.109
Sex	1.04	.594	0.35	.840	1.51	.469

Note. Significant effects: * $p < .050$.

No significant group effects were found for Trust in Automated Systems, Locus of Control, Thrill and Adventure Seeking, the One Item Risk Scale, as well as for participants' gender and age.

4.4 Discussion

This study was conducted to identify which of the tested acceleration profiles elicits the most comfortable experience. In turn, results can support implementation of user-centered automated lane changes, accelerations and decelerations behind steadily moving vehicles. In general, it was possible to identify driving styles, which are experienced as more comfortable than others are.

In the lane change maneuver (H1), the symmetrical variation and the variation with strong initial lateral jerk are preferred over the variation with a weaker initial lateral jerk. A tendency also becomes visible to prefer the variation with the stronger initial lateral jerk to the symmetrical variation. This tendency contradicts our assumptions. It is additionally surprising, because criticality is reduced to a minimum through no fellow traffic or hard boundaries and an early lane change onset. This might indicate that passive drivers prefer the safest possible lane change alternative disregarding whether actual risk is immanent or not. However, the results of the deceleration maneuver seem to contradict this theory. Here, the variation with the most deceleration in the first part of the maneuver is rejected (H3). Another explanation could be that drivers prefer an early perceivable action of the vehicle towards the situation (see Lange et al., 2014), but not necessarily a very strong initial action.

In both the acceleration (H2) and the deceleration maneuver (H3), results point toward a jerk minimizing approach. In the deceleration maneuver, it becomes evident that the variation based upon the tau approach with the most deceleration in the first part of the maneuver should not be used in implementing an automated driving style. This is surprising, as this behavior was reported as natural behavior in literature (Lee, 1976; Spurr, 1969). This is an indication that drivers do not necessarily want automated vehicles to drive as humans do. Data from the acceleration maneuver, however, fully met our initial assumptions (H2). The symmetrical acceleration and thus variation with the smallest overall jerk was preferred. The variation with a slower acceleration increase in the beginning of the maneuver was rated as second best, whereas the variation with a strong jerk in the beginning was rated as least favorable variation. This might be because a slower acceleration increase might seem more controlled, whereas a stronger acceleration increase might seem unnecessarily strong.

In general, it seems impossible to separate urgency and perceived accident risk from driving comfort. Further, it seems that the perception of even the smallest risk elicits a preference for early perceivable actions of the automated vehicle. Another study would be necessary to investigate this notion. In this case, a continuous rating may be useful (see Cleij et al., 2015; Hartwich et al., 2015).

Concerning participants' personalities, differences in preference were only found for the self-assessment of driving style. Whereas angry driving style (H4b) and careful driving style (H4d) did not yield results, risky (H4c) and high velocity (H4a) driving style showed effects in the acceleration and/or the lane change maneuver. However, the main preference stayed the same, disregarding the assessed personality traits. On the other hand, what could be observed, was that participants scoring low on risky driving style tended to prefer the early onset acceleration even less than participants scoring high on risky driving style did. From an outside perspective, an early perceivable action would suggest, the car has everything under control and no risk is imminent. However, as stated above, the acceleration maneuver poses no threat whatsoever. This could lead to the assumption, that a strong early acceleration increase could have surprised low risk drivers and increased perceived risk, because a strong acceleration may be perceived as riskier than a weaker acceleration. Additionally, this behavior might also be very different from their own and may thus not be experienced as particularly comfortable. The tendency to favor the early onset acceleration less also points in direction of our hypothesis (H4c). This assumed, that participants with a higher score on risky driving style are influenced less in their rating by the manipulation than participants scoring low on risky driving style.

Differences in preferences were also found for participants who score high versus low in high velocity driving (H4a). In the acceleration maneuver, high velocity drivers' preferences are almost identical for the early and late variation and do not significantly differ from the symmetrical variation. This is in line with our assumption that high velocity drivers accept a wider variety of acceleration behaviors (H4a). In contrast, a tendency of preferences lying closer together is found for participants scoring low on high velocity driving in the lane change maneuver (H4a). High scorers, however, clearly prefer the variation with an early strong jerk. This might indicate high scorers being not quite as sensitive about stronger or weaker jerks but preferring immediate motion feedback (see Lange et al., 2014).

Apart from self-reported driving style, other personality traits do not seem to have an influence on preferences for automated driving styles (H5-8). Hence, this points towards a general, trait-independent preference.

4.4.1 Limitations

This paper has taken a first step towards analyzing comfort provoked by automated driving. However, this study has been conducted in a simulator. The transferability of the results mentioned above should be validated in an on-road setting.

The fact that no effect could be found for trust in automated systems could be because the differences in preference are negligible when it comes to being a passive driver, as the other personality related results suggest. Furthermore, it is possible that not trust is the key component but the accuracy of the mental model. Kircher, Larsson, and Hultgren (2014) report that participants often took over control in situations they thought the system could not handle before system limits were reached, i.e. without testing whether the system could handle the situation and whether they could trust it more. This could imply that in this study trust did not play a major role, because no system limits were reached and the situation was never risky. Conducting an on-road study may also help mitigate this possible limitation.

Moreover, participants largely looked favorably on automated driving. While results may represent the group of people willing to use automated driving once it is available, it is unclear whether they are also fully representative of the overall population.

4.4.2 Conclusion

As a conclusion, it was possible to identify driving styles that are perceived as comfortable for automated driving. These are characterized by low jerks and by eliciting a feeling of safety through early actions in situations in which a criticality might arise and a softer onset in uncritical situations. The preferred driving style does not necessarily correspond to how a human driver would drive the vehicle manually. These conclusions could be drawn independent of both personality factors and self-reported driving style.

4.5 Additional analysis

As in the previous study, further analysis was conducted. In addition to questioning participants which variation they preferred, they were also asked directly how large the experienced difference in comfort was in the categories of small, medium, or large. By asking participants to rate the extent of how different the variations are, it is possible to obtain direct information on how strongly variations differ even if they elicit a similarly comfortable experience. An overview is given in Figure 18.

Chi^2 tests were performed to analyze differences in the ratings. Significant effects were found in the deceleration, $\chi^2(4) = 18.67$, $p < .001$; as well as the lane change maneuver, $\chi^2(4) = 11.62$, $p = .020$; but not in the acceleration maneuver, $\chi^2(4) = 3.12$, $p = .539$. As a second step, it was analyzed using standardized residuals, whether the distribution of rating the difference between variations as small, medium, or large was equally distributed within all comparisons per maneuver. In the deceleration maneuver, significant effects are found for the frequency of rating the difference between the jerk reduced deceleration and the classic approach deceleration as small ($z = 2.45$, $p < .050$) or large ($z = -2.28$, p < .050) compared to an equal distribution of "small", "medium", and "large" ratings per comparison. Results imply that the difference between these two variations was rated significantly more often as small and significantly less often as large. The contrast of the jerk reduced deceleration to the tau approach was perceived similarly strong as the contrast between the classic approach and the tau deceleration. This mirrors the fact that the tau variation is experienced as a different approach. A closer look at the standardized residuals in the lane change maneuver reveals, that only the rating of the difference between the early and the late maximum lateral acceleration as large stands out significantly ($z = 2.287$, $p < .050$). Thus, analysis supports the assumption that the difference between these two variations is experienced more strongly. This is not surprising, as the symmetrical variation can be seen as a variation in between the other two. As also suspected, no significant effect was found for the acceleration maneuver, $\chi^2(4) = 3.12$, $p = .539$. This indicates a homogenous rating over all comparisons and rating increments.

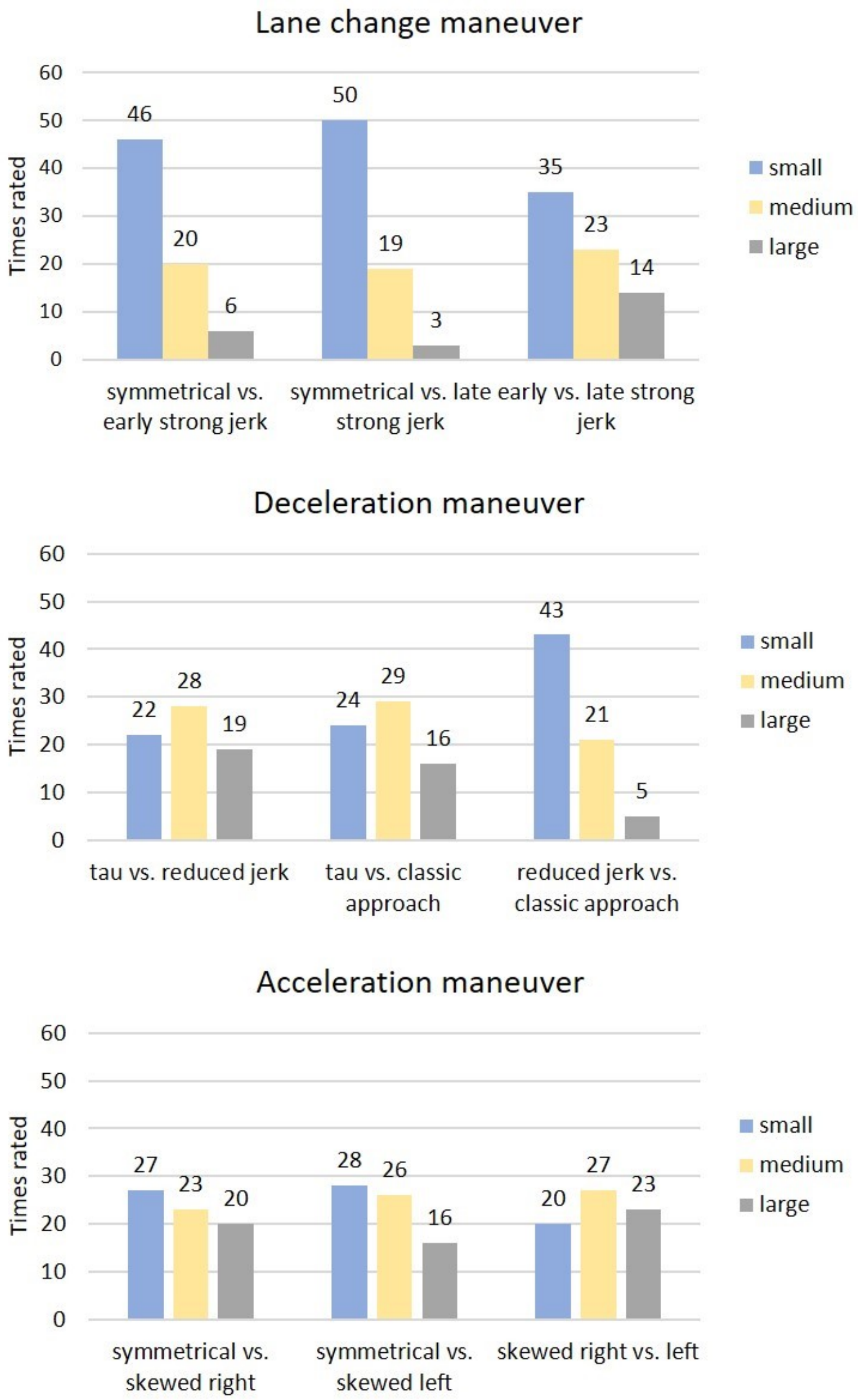


Figure 18. Ratings of how large the difference between variations was experienced.

In sum, only the distribution of ratings in deceleration reduced jerk vs. classic approach and lane change early vs. late strong jerk differ from the other distributions in said maneuvers. The differences between the variations were either in line with the variation design or assumptions. Also, no comparisons were rated as either only small or only large. This may indicate that the used metric characteristics were chosen from within a plausible scope.

4.6 Summary of insights from Study 3

Study 3 was able to show (1) preferred automated driving styles regarding comfort for the tested maneuvers and (2) that the ratings seem to be independent of personality when it comes to overall preferences but not necessarily regarding how particular participants were about the variations. The overall preference for symmetrical lane changes and those with a stronger initial jerk, symmetrical acceleration maneuvers, and jerk reduced or classic approach deceleration maneuvers was not affected by self-reported manual driving style, thrill and adventure seeking, willingness to take risks, trust, nor by locus of control. Thus, it seems feasible to design one automated driving style in order to provide comfort in automated driving.

5 Summary & conclusion

The aim of this thesis was to identify and describe the characteristics of comfortable automated driving. Hence, three studies were conducted. Study 1 consisted of manually driven trips under the instruction, in turn, to drive comfortably, dynamic or as always. Trips were set in both a highway setting and a rural and urban setting. This study was conducted to identify driving style discriminating metrics and determine their thresholds for comfortable driving. Study 2 focused on whether the same thresholds can be assumed in automated driving, which metric has the greatest influence on experiencing comfort in automated driving, and whether a driving simulator is a valid tool for investigating driver comfort in automated vehicles. The third study incorporated findings from the two previous studies. Using these findings, three variations of the three central maneuvers deceleration, acceleration and lane change were designed. The variations of each maneuver were experienced in a driving simulator and rated in pairs. Resulting preference rankings were analyzed regarding personality traits and self-reported manual driving style. The results, limitations, and implications of the three studies are discussed below and summarized by a general conclusion.

5.1 Summary of results

As a first result of Study 1, data showed the necessity to analyze driving styles by maneuver instead of, e.g., trip wise. Depending on the maneuver, the main metrics found in the manually driven study are acceleration, jerk, and quickness – each in longitudinal or respective lateral direction – as well as headway distance. The comparison of results from highway condition and urban and rural condition show that the same basic metrics are responsible for characterizing a driving style as comfortable in both environments. Only the specific metrics' values are velocity-dependent and thus differ between the environments.

Yet, two questions arise. The first question addresses the issue of lane keeping. Lane keeping did not vary between the three driving styles. However, it is mentioned as an important factor in the interview conducted prior to the study (see Chapter 1.2). This implies, either lane keeping is not relevant in objective data or there are necessary and sufficient conditions for comfortable driving. As dynamic driving does not need to be wholly uncomfortable or even risky, a certain quality of lane keeping may pose to be necessary for safe and acceptable driving in general.

The second question, which arose, is concerned with the role of urgency. This question has special relevance for lane change maneuvers. When performing a lane change with fellow traffic, it is more important to avoid an accident than to maintain a most comfortable trajectory. At the same time, waiting until a most comfortable lane change is possible may take considerable time and thus rival the goal of arriving at one's destination in a reasonable time. The study was not able to resolve conclusively to which extent traffic congestion – and thus gap size – influences experiencing comfort. The role of traffic conditions and the question of necessary and sufficient requirements for comfortable automated driving both allow for further research.

The first study was conducted under on-road traffic conditions. Thus, results can be viewed as externally valid. However, they are not replicable and conditions were different for every participant or even for every maneuver within one participant's trip. As discussed above, traffic conditions are an influential issue. In addition, data were collected from manual driving. It can be hypothesized that comfort is experienced differently, when the participant is being driven by an automated vehicle in comparison to driving him-/herself (see Elbanhawi et al., 2015). Consequently, the next study was conducted using replicable, automated maneuvers under the same environmental influences for all participants.

In the second study, a lateral and a longitudinal maneuver – lane change and deceleration behind a slower vehicle – were used to (1) compare a longitudinal and a lateral simulator setting to a test track setting, (2) identify whether values found in Study 1 can be transferred to automated driving, and (3) analyze whether a dominant metric exists. Relative and absolute validity were found for the longitudinal simulator setting. This means, that comfort ratings of maneuvers presented in the longitudinal setting simulator with linear motion scaling factors of approximately 50-60 % are comparable both relative and absolute to comfort ratings of the same maneuvers on a test track. More importantly, it could be shown that the metrics and values found in the initial study are capable of creating a comfortable automated driving experience. Furthermore, a dominant metric was identified. Maximum acceleration was found to be the best, but not sole, predictor of comfort ratings. This is in line with the common focus on acceleration in literature (see Chapter 1.3). The consensus in literature and the described study is that acceleration should be kept low. Taking this into account acceleration was held low in the final study described in Chapter 4.

A methodological insight from the second study is the necessity to change the rating system. In the Study 2, participants were asked to rate their comfort experience on a 7-point scale. This method may have been too imprecise or insensitive to fully depict differences in comfort experience. Therefore, paired comparisons were used in Study 3.

In the final study, variations of a lane change, a deceleration behind a slower vehicle and an acceleration maneuver were rated regarding experienced comfort in a moving-base driving simulator.

As assumed from the results of the preceding study, not only maximum acceleration leads to a variation in comfort rating. The manipulation of the course of acceleration and jerk leads to distinct preference differences. Results generally point in the direction of preference for smooth, jerk-minimized variations. However, in lane changes a high comfort rating can also be found for the variation with an early perceivable onset. This is interesting because an earlier perceivable onset is the result of a stronger acceleration increase and stronger jerk at the beginning of the maneuver. In the deceleration maneuver, however, the variation with the strongest onset is distinctly favored least. An explanation for this incongruity may be provided by the influence of motion feedback and urgency. An early motion feedback during a lane change may give the passive driver the impression of control and less time in between lanes. Whereas motion feedback seems favorable in lane changes, a strong early deceleration in a situation, which may not call for such a strong reaction, might surprise the passive driver. As found in the on-road study based on manual driving data, lane changes to the left, i.e. away from obstacles such as slower vehicles or an ending lane, are performed different from lane changes back onto the original lane with only slower vehicles in the rear. This is assumed to be due to perceived urgency. It may be possible that urgency is perceived in the lane change maneuver in Study 3, whereas it is not perceived in the deceleration maneuver. Another possibility is the expectancy participants have towards system behavior. Behaving as expected is an important aspect when it comes to trust and experiencing comfort (Krist, 1994; Muir, 1994; Tischler, 2013). A lane change with early stronger acceleration may be within the range of expected behaviors. The tau-approach deceleration, on the other hand, may present itself as unexpectedly strong in the beginning. Interestingly, this also implies that passive drivers may not expect automated vehicles to drive as a human driver would. The behavior best resembling human deceleration (see Lee, 1976) was favored least by the participants.

In addition to the analysis of metrics and values, personality was considered in Study 3. In general, the assessed personality constructs do not seem to have a significant influence on comfort ratings. A small influence on comfort ratings was found for self-reported high-velocity and risky driving style. Notwithstanding, the influence is not strong enough to change the overall preference order of the experienced variations. Only the proximity of the ratings is influenced. This implies that experiencing comfort in automated driving is mainly independent of the measured personality traits. This is interesting for both trust in automation and locus of control. As trust and LOC influence behavior (Kircher et al., 2014; Lee & See, 2004; Rudin-Brown & Parker, 2004) one may expect the constructs to influence the perception of behavior as well. Hoff and Bashir (2015) report that trust plays a smaller role when participants cannot directly compare automated to manual performance. Further, in the case of LOC a general assessment was used to find a relationship between participants with a generally internal or external LOC. It may be possible that assessing LOC in this manner was too broad to detect a relationship. Assessing driving-specific LOC may yield different results.

5.2 Implications

5.2.1 Scientific implications

This thesis was able to show the complexity of the construct of comfort. In Chapter 1.3 an approach toward a definition is made. However, it shows that comfort can be evoked by such a plentitude of factors, that a working definition seems reasonable when looking at specific influences. Because this thesis focusses on the comfort elicited through driving style, factors such as seating or interior design, which may influence the overall experience of comfort (see Ellinghaus & Schlag, 2001), have been excluded. As experienced comfort has a large subjective component (see Chapter 1.3), it is thus difficult to define and even more difficult to assess.

As discussed in Chapter 1.3, there have been different approaches to the measurement of comfort. This thesis has focused on subjective ratings, because objective ratings rather assess discomfort, e.g. Hartwich et al. (2015), and thus have deficits in assessing different levels of comfort, if all varieties are per se comfortable. After Study 2 and Study 3 of this thesis, it can be argued that verbally assessed direct comparisons of variations are a promising method. In Study 2 a Likert scale approach was chosen. However, when all variations are expected to be comfortable, a skewed distribution seems to be likely and impedes analysis. This was also the case in Study 2. Therefore, a direct comparison was used in Study 3. This facilitates analysis via maximum likelihood approximation and BTL models. However, this method focuses on overall ratings and comparisons. Whereas the method is easy to use and provides a good overall impression, it is not possible to investigate which facets have the largest impact on the rating, unless these facets are systematically varied in the design. In Study 3 the facets were regarded in the design in such a way, that the three variations of each maneuver were based on a variation of the course of acceleration, i.e. jerk. There is still, however, a lack of an instrument, which allows for multifaceted testing. This in turn, would allow for more precise addressing of all comfort influencing aspects. First steps would be to identify the main aspects, e.g. psychological, physiological, and physical factors (compare Chapter 1.3), to design items for the respective aspects, and to determine whether the aspects should be weighed individually for every participant. Due to its subjective nature, it is possible that different persons weigh certain factors differently and thus reach a different comfort rating. It remains debatable whether this instrument would be independent of context and thus widely applicable or rather specialized.

5.2.2 Practical implications

This thesis has two major practical implications. Firstly, a recommendation for a comfortable automated driving style can be given. So far, literature has mainly focused on keeping acceleration as low as possible (e.g., af Wåhlberg, 2006). This thesis has additionally contributed that the course of acceleration is another influential factor, which should not be neglected. Even though the same maximum acceleration was used within each type of maneuver, the variations in Study 3 were experienced differently. Whereas a symmetrical approach yielded good ratings in all maneuvers, early or late onsets of the acceleration maximum were experienced as differently favorable depending on the maneuver. This stresses that in addition to acceleration thresholds, the maneuver-specific characteristic should be considered by system developers to increase experienced comfort.

As second major practical implication, results of this thesis imply that it is not necessary to implement different automated driving styles for passengers with different personality traits. This has the great benefit, that preferences do not need to be detected and only one automated driving style needs to be designed. Results show a tendency that participants with certain personality traits may be more open to classify a wider variety of driving as comfortable than other participants.

In general, this thesis has contributed to the field by systematically investigating maneuvers while improving the method and by providing first answers to the question of how comfort can be elicited through driving style.

5.3 Limitations

Apart from these implications, this thesis has also opened two questions, which could impact the design of comfortable automated driving. One is concerned with on-road validation and combination of the studied maneuvers, whereas the other is concerned with the interaction with non-driving related tasks. This study has analyzed driving style under test-track and simulator settings. As shown in Study 2, the results obtained in the simulator study can be seen as valid. However, this can only be said for how the accelerations are experienced. In Study 1 it is also acknowledged that the direction of lane changes seems to have an impact. Mediated by urgency, it is possible that thresholds for comfortable driving are adapted to congestion as well as to overall traffic and environment characteristics (see Mitschke & Wallentowitz, 2004; Summala, 1997). So far, results lack an on-road validation. This should be rectified as soon as the means are ready and are allowed to be used in traffic by participants. This would also allow for taking a look at the interaction of the different maneuvers. In this thesis lane changes were analyzed under the premise of no longitudinal acceleration. In on-road traffic, lane changes can be combined with longitudinal acceleration, e.g. when overtaking. This thesis did not investigate whether this combination has an influence on experiencing comfort.

One of the benefits of level 3+ automated driving is that drivers will be able to engage in other tasks. This engagement evokes the question of motion sickness (e.g., Sivak & Schoettle, 2015). Today, some passengers experience motion sickness as passengers but not as drivers. Level 3+ automated driving will allow all drivers to become passengers, even if just temporarily. It would thus be important to validate the comfort ratings under the condition of simultaneous engagement in non-driving related tasks. On one hand, it could be expected that participants are more sensitive due to the risk of motion sickness. On the other hand, it could be that participants are less sensitive, because their focus is turned away from the driving style to a different task at hand.

A further influencing factor is sensor range. Depending on the maneuver 10 – 19 % of the participants of Study 3 explicitly wished the maneuvers to start earlier. To-date, this is not possible due to sensor range limits. The results indicate that a more anticipatory automated driving with even smaller accelerations and jerks would increase comfort. The wish for anticipatory driving is also explicitly expressed by the experts in the interview in Chapter 1.2. Regarding this criticism, it must be kept in mind that Study 3 was conducted in an environment without surrounding traffic and constraints arising thereof. The experience may be different in regular traffic. However, the maneuver lengths were derived from data from the manually driven study and by using full sensor range of sensors in cars available at that time. Maneuvers were adapted to real circumstances and may thus seem unnecessary quick in a controlled testing environment. Nonetheless, increased sensor range, especially in combination with real-life traffic, allows for further research.

Another aspect, which has not been addressed in this thesis is comfort regarding take-over situations. This thesis has focused on comfort through driving style. The design of take-over situations will presumably influence take-over comfort in an ergonomic way. In SAE Level 3 systems the vehicle will be in control of the driving task, the driver is, however, still the fallback in case of system limits etc. This topic is also closely linked to the issue of sensor range. A larger sensor range would provide longer take-over times and thus could lead to higher acceptance ratings in take-over situations.

5.4 Conclusion

To sum up findings from all studies, comfortable automated driving is characterized by maneuvers with sufficient headway distance and smooth courses of small acceleration and small jerk, which still provide sufficient motion feedback. Surrounding traffic seems to play an important role through urgency and should be taken into account for on-road implementation. Differences in personality did not seem to play a crucial role. All in all, this thesis has shown the possibility to describe and develop a comfortable automated driving style. This may allow all the benefits of SAE level 3+ automated driving to be reached, while at the same time experiencing a comfortable ride.

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Appendix

Appendix A – Interview

1) How many hours have you been driven autonomously? How many as safety driver and how many as passenger?
2) How long have you been working on autonomous driving?
3) Do you have experience with partially automated driving? If so, which systems? How many hours approximately? Since when have you been using the system?
4) How would you describe your own driving style? How would you characterize a [driving style mentioned by participant] driving style?
5) When being a passenger in someone's car, what aspect of their driving bothers you most often? (Help: Try to think of the last time you were a passenger in someone's car)
6) How would you describe the driving style of the fully automated system you have been working on?
7) What do you like about its driving style?
8) What do you dislike about its driving style?
9) Try to imagine buying a fully automated car in a couple of years. What driving style should that car have? What would have to be different to the current version?
10) What is most important for you regarding automated driving style?
11) Do you think it would make a difference whether you are riding in a car with a human driver or in an automated car? How? Why?
12) Do you think a fully automated system should behave like or different to a human driver? How? Why?
13) Please try to answer the following question in one or two sentences: What is your general opinion on "fully automated driving"?

Demographic information

Age: _____ years

Sex: o male o female

Driving experience: _______ h / week

Driver's license for __________ years

Please mark the position between “Cars are boring” and “Cars fascinate me” which reflects your opinion best.

Cars are boring			Neither nor			Cars fascinate me
O	O	O	O	O	O	O

Please mark your affinity towards technology on the scale below ranging from “I try to avoid technology” to “Technology fascinates me”.

I try to avoid technology			Neither nor			Technology fascinates me
O	O	O	O	O	O	O

German Original

1) Praktische Erfahrung mit autonomem Fahren: Wie viele Stunden sind Sie bereits autonom gefahren (Fahrer/Beifahrer)?
2) Wie lange beschäftigen Sie sich bereits mit dem Thema?
3) Haben Sie Erfahrungen mit (teil-)automatisiertem Fahren? Wenn ja, welche Systeme? Wie viele Stunden Erfahrung? bzw. : Seit wann? Wie viele Stunden pro Woche?
4) Wie würden Sie Ihren eigenen Fahrstil einschätzen? Was ist für Sie …?
5) Wenn Sie daran denken, wie Sie als Beifahrer bei Ihrem Partner oder einem Bekannten/ Verwandten mitfahren, welchen Aspekt des Fahrstils bemängeln / würden Sie gerne ändern? Und wie (in welche Richtung, wie im Vergleich zu eigenem Fahrstil)? (Hilfe: Wann letztes Mal mit wem mitgefahren: Wie war das…)
6) Wie ordnen Sie den Fahrstil der AF ein?
7) Was gefällt Ihnen gut am AF-Fahrstil?
8) Was gefällt Ihnen nicht? Was darf auf keinen Fall passieren?
9) Stellen Sie sich vor, Sie kaufen sich in ein paar Jahren ein komplett autonom fahrendes Fahrzeug, welchen Fahrstil soll dieses Fahrzeug haben (falls AF-Erfahrung, dann im Vergleich zu aktuellem AF)?
10) Was ist Ihnen am Fahrstil des AF besonders wichtig?

11) Denken Sie, es macht einen Unterschied, ob Sie von einem Fahrzeug oder von einem Menschen gefahren werden? In wie fern? / Warum?
12) Inwiefern soll/muss sich das autonome Fahrzeug anders verhalten als ein menschlicher Fahrer?

13) (Nur ganz kurz) Wie stehen Sie dem Thema „autonomes Fahren“ generell gegenüber?

Demographische Angaben

Alter: _____ Jahre

Geschlecht: o männlich o weiblich

Fahrerfahrung: _______ h / Woche

Fahrerlaubnis seit __________ Jahren

Bitte geben Sie auf der Skala von „Ich finde Autos langweilig“ bis „Autos begeistern mich“ Ihre Affinität zu Autos im Allgemeinen an.

Ich finde Autos langweilig			Weder noch			Autos begeistern mich
O	O	O	O	O	O	O

Bitte geben Sie auf der Skala von „Ich meide Technik, wenn möglich“ bis „Technik begeistert mich“ Ihre Affinität zu Technik im Allgemeinen an.

Ich meide Technik, wenn möglich			Weder noch			Technik begeistert mich
O	O	O	O	O	O	O

Appendix B – Post hoc tests simulator and testing ground

Table 11

Post hoc test for the lane change maneuver in the test track environment.

scenario	G	H	I	J	K
H	< .001***				
I	< .001***	.617			
J	.028*	.070	.005**		
K	< .001***	.617	.339	.339	
L	< .001***	.045*	.339	< .001***	.006**

Note. Bonferroni-Holm correction was used, * $p < .05$, ** $p < .01$, *** $p < .001$

Table 12

Post hoc test for the deceleration maneuver in the test track environment.

scenario	A	B	C	D	E
B	< .001***				
C	< .001***	.839			
D	< .001***	.173	.167		
E	.108	.030*	.046*	< .001***	
F	< .001***	< .001***	< .001***	< .001***	< .001***

Note. Bonferroni-Holm correction was used, * $p < .05$, ** $p < .01$, *** $p < .001$

Table 13

Post hoc test for the lane change maneuver in the lateral simulator environment.

scenario	G	H	I	J	K
H	.890				
I	< .001***	< .001***			
J	1.000	1.000	< .001***		
K	.180	1.000	< .001***	.690	
L	< .001***	< .001***	.890	< .001***	< .001***

Note. Bonferroni-Holm correction was used, * $p < .05$, ** $p < .01$, *** $p < .001$

Table 14

Post hoc test for the deceleration maneuver in the lateral simulator environment.

scenario	A	B	C	D	E
B	.046*				
C	.180	1.000			
D	.004**	1.000	.937		
E	.111	1.000	1.000	1.000	
F	.012*	< .001***	< .001***	< .001***	< .001***

Note. Bonferroni-Holm correction was used, * $p < .05$, ** $p < .01$, *** $p < .001$

Table 15

Post hoc test for the lane change maneuver in the longitudinal simulator environment.

scenario	G	H	I	J	K
H	.056				
I	< .001***	.004**			
J	.556	.904	< .001***		
K	.014*	1.000	.021*	.556	
L	< .001***	< .001***	1.000	< .001***	.006**

Note. Bonferroni-Holm correction was used, * $p < .05$, ** $p < .01$, *** $p < .001$

Table 16

Post hoc test for the deceleration maneuver in the longitudinal simulator environment.

scenario	A	B	C	D	E
B	< .001***				
C	< .001***	1.000			
D	< .001***	1.000	1.000		
E	.007**	.492	.757	.873	
F	.135	< .001***	< .001***	< .001***	< .001***

Note. Bonferroni-Holm correction was used, * $p < .05$, ** $p < .01$, *** $p < .001$

Academic CV and publications

Name	Hanna Bellem
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Place of birth	Herrenberg

Education

05/2013 – 06/2018	Doctorate student, Technische Universität Chemnitz
10/2010 – 04/2013	Student M.Sc. Psychology, Technische Universität Chemnitz
01/2012 – 05/2012	Erasmus semester, Risk Psychology, Environment and Safety, NTNU Trondheim, Norway
10/2007 – 07/2010	Student B.Sc. Psychology, Technische Universität Chemnitz
09/1998 – 06/2007	Allgemeine Hochschulreife, Goldberg-Gymnasium Sindelfingen

Professional experience and theses

Starting 10/2017	Development engineer, Robert Bosch GmbH, Abstatt
07/2016 – 09/2017	Research Specialist, BMW AG, München
05/2013 – 06/2016	Doctorate student, Research and Development, Daimler AG, Sindelfingen
06/2012 – 12/2012	Master's thesis, "An on-road study of system awareness, acceptance, and trust of a simulated Workload Adaptive Cruise Control", Technische Universität Chemnitz, in cooperation with BMW Group Forschung und Technik GmbH, München
08/2009 – 10/2009	Internship, L-Lab, Hella KGaA Hueck & Co and Universität Paderborn, Paderborn
06/2010 – 12/2012	Student assistant, Lehrstuhl für Allgemeine Psychologie I und Arbeitspsychologie, Technische Universität Chemnitz
03/2010 – 07/2010	Bachelor's thesis, „Die CTT als geeignetes Maß zur Erfassung von Ablenkung im automobilen Kontext", Lehrstuhl für Allgemeine Psychologie I und Arbeitspsychologie, Technische Universität Chemnitz

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Eidesstattliche Erklärung

Hiermit erkläre ich, Hanna Bellem, dass ich die vorliegende Arbeit selbstständig verfasst, nicht anderweitig zu Prüfungszwecken vorgelegt und keine anderen als die angegebenen Hilfsmittel verwendet habe. Sämtliche wissentlich verwendeten Textausschnitte, Zitate oder Inhalte anderer Verfasser wurden ausdrücklich als solche gekennzeichnet.

Hanna Bellem

Stuttgart, den 08.06.2018