Evaluation of different driving styles during conditionally automated highway driving

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Abstract

Discomfort and well-being of the driver and/or the passengers during automated driving as well as their acceptance and trust in the automation system are important criteria considering the usage of automated driving vehicles. Thereby, the driving behaviour of the automated vehicle plays an important role. For this contribution, we implemented three driving styles, which differ only regarding the tactical driving behaviour on the manoeuvre level. Trajectory planning and control was identical. One driving style contained only lane following on the right lane without lane changes. The other two driving styles varied according to their lane change decision behaviour. To evaluate the aforementioned criteria of the driving styles, a driving study (N=31) was conducted in real traffic on a highway with a test vehicle in which vehicle guidance was performed by an automation system. The results reveal that the well-being of the drivers is not influenced by the driving style. On the contrary, trust and acceptance are influenced by the driving style. Overall, 97% of the participants would prefer a driving style including lane change manoeuvres. However, 61% had the highest feeling of safety while driving without lane changes.

Introduction

Besides technical and legal questions, human-computer interaction is considered essential for the development of automated driving functions on all levels of automation which have been defined in the taxonomy for automated driving systems published by the Society of Automative Engineers (SAE, 2016), e.g. in Saffarian et al. (2012). So far, work in this domain mainly focused on concepts for the interaction between driver and automation (e.g. Albert et al., 2015; Flemisch, 2003; Flemisch et al., 2014; Hoc, 2000; Schreiber et al., 2009), control transitions and take-over requests (eg. Feldhütter et al., 2018; Gold, 2016; Gold et al., 2013; Petermann-Stock et al., 2013; Zeeb et al., 2015), or the design of human machine interfaces (e.g. Albert et al., 2015; Franz et al., 2012; Othersen, 2016). Furthermore, the way the vehicle behaves and its so called "driving style" is considered to have an important influence on trust, acceptance, and the experience of automated driving (Bellem et al., 2016; Elbanhawi et al., 2015; Festner et al., 2017; Oliveira et al., 2019). Following Griesche et al. (2016), the driving style is described by a set of parameters on the tactical and operational vehicle guidance layers, defined by Matthaei (2015).

In D. de Waard, A. Toffetti, L. Pietrantoni, T. Franke, J-F. Petiot, C. Dumas, A. Botzer, L. Onnasch, I. Milleville, and F. Mars (2020). Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2019 Annual Conference. ISSN 2333-4959 (online). Available from http://hfes-europe.org

However, there is no common knowledge about the precise configuration of the parameters that differentiate various driving styles. Most of the previous studies, comparing different driving styles during automated driving, focused on dynamic metrics such as velocity, longitudinal and lateral acceleration, jerk, and the duration of a lane change (Bellem et al., 2018; Festner et al., 2016; Hartwich et al., 2018; Lange et al. 2014). Regarding the accepted point in time at which the lane change should be initiated, research from a human factors perspective is sparse. Rossner and Bullinger (2019) compared three highly-automated driving styles during highway driving varying different factors. One of those factors, the inition time of the lane change manoeuvres, included the tactical lane change decision. Results show that people prefer a more comfortable driving style which is defined with a following distance to the leading vehicle of 2.9*s*, a maximum acceleration of 1.5m/s^2, a maximum deceleration of -2m/s^2, a duration of the lane change to the left of 9*s* and to the right of 8.5*s* and the distance to a leading vehicle with overtaking initiation of 130*m*. Nevertheless, by also varying these other factors, no conclusion can be made that the factor considering the initiation time of the lane change manoeuvres had the key influence on the perceived safety and comfort.

All the previous mentioned studies have in common that they were all conducted under simulated settings (Bellem et al., 2018; Rossner & Bullinger, 2019) or on test tracks (Festner et al., 2016; Festner et al., 2017; Hartwich et al., 2018; Lange et al., 2014) leaving aside important influences of real-world scenarios.

The aim of this study was to overcome these limitations and to investigate different driving styles differing on the tactical vehicle guidance in real-world highway driving. Main focus and, thus, an exploratory research question was if the driving style has an influence on the aforementioned metrics perceived comfort, personal well-being, trust, and acceptance. Moreover, it should be examined what the preferred driving style is considering well-being and safety.

Method

Test setup and equipment

The driving study took place on the three-lane German highway A9 between the highway exits Lenting and Holledau. The test vehicle was an Audi A7, year of construction 2010. A prototypical level 3 (SAE, 2016) automation system was implemented in the test vehicle which completely performed the lateral and longitudinal vehicle guidance. However, the test vehicle only drove on the right and middle lane of the highway due to safety reasons.

The participants were seated on the driver seat and were accompanied by two experimenters. One always sat on the passenger seat and was acting as a safety driver. This task was supported via a monitor containing information about the automation system, a second interior mirror, driving school mirrors as well as driving school pedals to be able to intervene in vehicle guidance in risky driving situations (referring to Cramer et al., 2018). This experimenter was able to adapt the driving function, for instance the target velocity or abort/initiate lane changes, only in exceptional cases if it was necessary. The second experimenter was seated in the back row and was responsible for the questionnaires, functional variations, and providing the participants with instructions.

The participants received visual information about the activation status, the current manoeuvre, and surrounding obstacles in front of the vehicle in the instrument cluster display. Data recording included vehicle data, internal data of the automation system, audio recordings, front camera, as well as driver observation camera.

Driving styles

Three driving styles were implemented in the test vehicle. The functional realization on the operational layer of the automation system (according to Matthaei (2015)) was equal for all driving styles. The trajectory planning was based on the approach of Werling et al. (2010) including adaptions by Heil et al. (2016). The decisions on the tactical layer of the automation system (according to Matthaei (2015)), in this case executing lane changes, were different for the driving styles. Considering the first driving style, the vehicle was not performing any lane changes, and thus was only driving in the right lane of the highway. The other two driving styles performed lane changes. Their execution was implemented considering different aspects according to Ulbrich and Maurer (2015). The aspects of dynamic traffic were implemented based on a fuzzy logic (cf. Du and Swamy (2019) for basic principles about fuzzy logic). For the two driving styles with lane changes, the shape parameters of the membership function for the deceleration of the rear vehicle (cf. Ulbrich & Maurer, 2015) are varied: 0.6 and 0.9m/s^2 (dynamic driving style), or 0.38 and 0.63m/s^2 (cautious driving style). Moreover, the time gap for the rear vehicle (cf. Ulbrich & Maurer, 2015) differed between the cautious (2.0*s*) and the dynamic (0.5*s*) driving style. These parameters were selected with developers of the automated driving function. However, the two driving styles with lane changes were called *cautious* and *dynamic* to distinguish them, both represented defensive driving behaviour. This can further be seen in Figure 1, 2, and 3, which represent the timely distributions of the lateral and longitudinal accelerations as well as the velocity for each driving style. The amount of performed lane changes depending on the driving style is presented in Table 1. Lane change aborts occurred quite often. One main reason was the limited rear sensor range (approximately 150*m*).

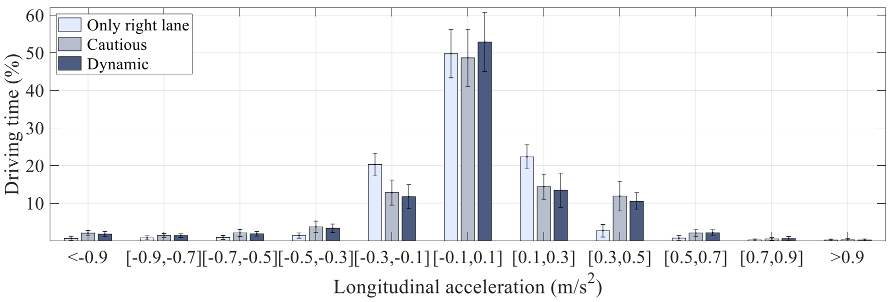

Figure 1. Distribution (mean and standard deviation) of the longitudinal acceleration over the driving time for the three driving styles.

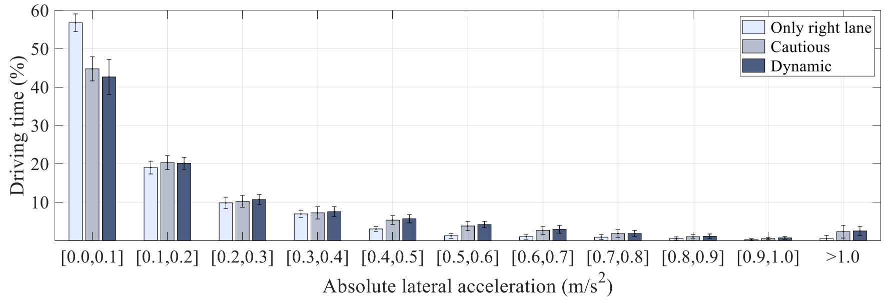

Figure 2. Distribution (mean and standard deviation) of the absolute lateral acceleration over the driving time for the three driving styles.

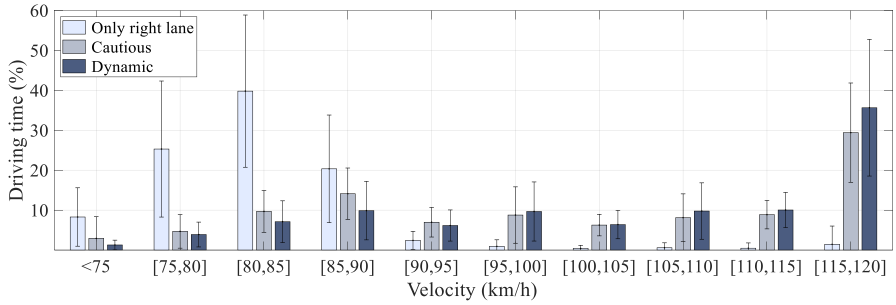

Figure 3. Velocity distribution (mean and standard deviation) over the driving time for the three driving styles.

Table 1. Amount (mean (M) and standard deviation (SD)) of lane changes (LC) and lane change aborts depending on the driving style.

	Cautious			*Dynamic*		
	M	*SD*	*LC abort*	*M*	*SD*	*LC abort*
Lane change left	3.33	1.65	48.98%	5.13	2.11	35.83%
Lane change abort left	3.20	2.44		2.87	1.59	
Lane change right	2.60	1.48	39.53%	4.77	1.94	30.58%
Lane change abort right	1.70	1.37		2.10	1.37	

Study design

The driving study was conducted in German. At the beginning of the study, the participants received a verbal briefing on how to handle the test vehicle and what to expect during the driving study. Following, the participants drove manually on the highway and activated the automation system. The sequence of the driving study is presented in Figure 4.

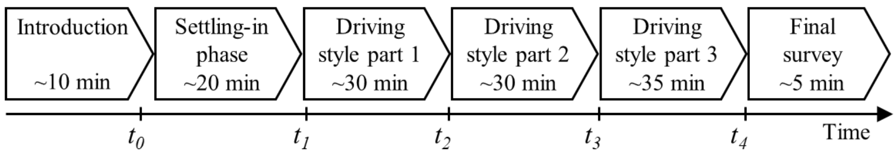

Figure 4. Sequence of driving study.

During the settling-in phase, for approximately the first 7 minutes, the automation system conducted no lane changes and started with these afterwards. Subsequently, the participants experienced the three driving styles in a randomized order. However, part 1 and 2 were a bit shorter as part 3 due to the fact that the turnaround at the highway exit was earlier. During the driving parts, the participants' task was to speak all their thoughts out loud (think-aloud method, Ericsson & Simon, 1980) about the driving behaviour of the automation system. The evaluation of the participants' comments is not part of this paper. At the end of every driving part, the participants answered a questionnaire about, for instance, trust and acceptance (cf. section results). Summing up, a short overall questionnaire was conducted.

Processing and evaluation of the data

The rating scales of the questionnaires were assumed as interval scaled variables because the answer scales were equidistant (Döring & Bortz, 2016). Furthermore, normal distribution of the data was expected if $N>30$ (Bortz & Schuster, 2010; Field, 2012). For data evaluation, a repeated measures analysis of variance (ANOVA) with following post-hoc analysis using Bonferroni correction was conducted for the dimensions well-being, comfort, trust, and acceptance. The data was corrected, if Mauchly's test for sphericity showed significance (Greenhouse-Geisser or Hunyh-Feldt correction ($\varepsilon > 0.75$)).

Sample

N=32 participants were available for this driving study, whereby one had to be excluded from data evaluation due to bad performance of the automation system induced by bad weather. The sample (N=31) had a mean age of 36.1 years (SD=11.9, MIN=22, MAX =65) and was a variation of professional background and gender (22.6% technical female, 25.8% technical male, 25.8% non-technical female, and 25.8% non-technical male). The median mileage per year was 15,001-20,000 *km* and the mean mileage per week was 265*km* (SD=203*km*) with on average 41% highway driving. 74% of the participants used adaptive cruise control, 77% lane keeping assistance, and 48% partially automated driving systems (e.g. traffic jam assistance) before.

Results

Well-Being

The well-being of the participants during the study was evaluated by the short version A of the German multidimensional state survey (MDBF, Steyer, et al., 1997). This short form has 12 items on a five-point rating scale from 1 ("not at all") to 5 ("very"), corresponding to the three bipolar dimensions *good-bad mood*, *awake-tired*, and *calm-nervous*. For every subscale, the values of the respective items were summed up leading to a value per subscale between 4 and 20, whereby a high value indicates a good mood, awakeness, and calmness and a low value a bad mood, tiredness, and nervousness. The participants were asked to rate their current well-being five times: in the beginning, after the settling-in phase, and after each driving style. No differences were found between the various times of measurement for either the dimension *good-bad mood* (F(2.46)=1.34, p=.268, f=.21), *awake-tired* (F(2.89)=2.45, p=.071, f=.29), or *calm-nervous* (F(2.92)=1.32, p=.273, f=.21). All three subscales reached mean values between 15.8 and 18.5 out of a maximum of 20. Thus, the overall well-being of the participants during the experiment can be described as in a good, awake, and calm mood. The values for the mean (*M*) and standard deviation (*SD*) for all times of measurement and subscales can be found in Table 2.

Table 2. Participants' mean ratings for the three dimensions of the MDBF

	Beginning		*Settling-in phase*		*Only right lane*		*Cautious*		*Dynamic*	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Good-bad mood	18.45	1.23	18.00	1.77	17.94	1.91	17.58	2.36	17.94	1.90
Awake-tired	16.81	2.07	17.00	1.79	15.84	3.01	16.35	2.67	16.65	2.48
Calm-nervous	16.39	2.62	16.48	2.11	17.35	2.76	16.55	2.80	17.00	2.07

Comfort

To survey driving comfort, the subscales *discomfort* and *comfort* of the questionnaire to measure driving comfort and enjoyment developed by Engelbrecht (2013) were used. Hereby, the rating scale was adapted to seven anchors from 1 (“does absolutely not apply”) to 7 (“does absolutely apply”). The participants were asked to rate the previous car ride after each driving condition. The sample of the subscale *comfort* was reduced due to a mistake in the questionnaire for the first participants. The ANOVA revealed no differences for the perceived *discomfort* (F(1.52)=1.61, p=.214, f=.23) and *comfort* (F(1.35)=3.42, p=.063, f=.14) between the three different driving styles. Overall, the experienced discomfort during the automated car ride was rated low (mean values around 2) and the comfort high (mean values around 5.50). The values for the mean (*M*) and standard deviation (*SD*) for each driving style and subscale can be found in Table 3.

Table 3. Participants' mean ratings for their perceived comfort and discomfort for the three driving styles (scale: 1≙"does absolutely not apply" - 7≙"does absolutely apply").

	Only right lane		*Cautious*		*Dynamic*	
	M	*SD*	*M*	*SD*	*M*	*SD*
Comfort (N = 23)	5.85	1.14	5.21	1.20	5.73	0.84
Discomfort	1.78	0.99	2.07	1.90	1.77	0.79

Trust

To assess the trust in the automation the questionnaire of Körber (2018) was used which is divided into six subscales with a range from 1 (“strongly disagree”) to 5 (“strongly agree”). To determine the general trust in automation, the subscale *Propensity to Trust* was surveyed once before the study. In order to get the respective trust in the automation system of each driving style, the participants were asked to rate the corresponding items of the subscales *Reliability/Competence, Understanding/Predictability*, and *Trust in Automation* after each driving condition.

The evaluation of the *Propensity of Trust* scale showed a mean value of the sample of 3.56 (SD=.53). The applied ANOVA indicated significant differences between the driving styles for the three subscales *Reliability/Competence* (F(1.67)=3.42, p=.049, f=.34), *Understanding/Predictability* (F(1.92)=10.90, p<.001, f=.60), and *Trust in Automation* (F(1.65)=5.43, p=.001, f=.43). The following post hoc pairwise comparisons did not reveal any significant difference for the dimension *Reliability/Competence* (p>.05). Considering the subscale *Understanding/ Predictability*, results of the post hoc analysis showed that the participants ranked the driving style only using the right lane with higher understanding and predictability in comparison to the dynamic ($M_{1\text{-}3}$=0.36, p=.019) as well as the cautious driving style ($M_{1\text{-}2}$=0.61, p=.001). Furthermore, the participants showed less trust in automation during the cautious driving style compared to the driving style only using the right lane ($M_{1\text{-}2}$=.44, p=.044), and the dynamic driving style ($M_{2\text{-}3}$=-0.32, p=.047). The results are represented in Figure 5. and Table 4.

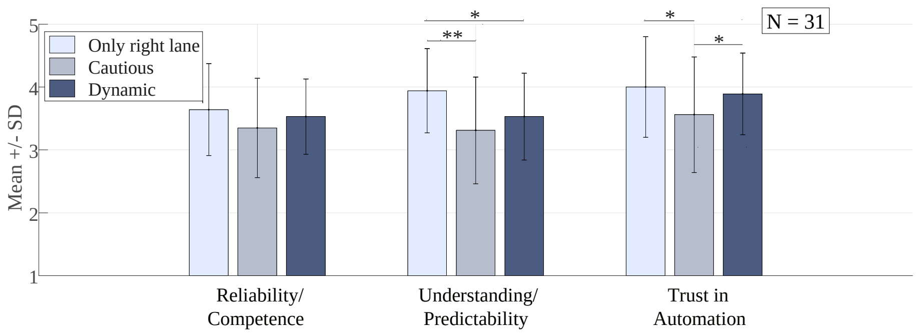

*Figure 5. Participants' mean ratings for three dimensions of the questionnaire of Körber (2018) for the three driving styles (scale: 1≙"strongly disagree" - 5≙"strongly agree"; *p<.05, **p<.01).*

Table 4. Participants' mean ratings for three dimensions of the questionnaire of Körber (2018) for the three driving styles.

	Only right lane		*Cautious*		*Dynamic*	
	M	*SD*	*M*	*SD*	*M*	*SD*
Reliability/Competence	3.64	0.73	3.35	0.79	3.53	0.60
Understanding/Predictability	3.94	0.67	3.31	0.85	3.53	0.69
Trust in Automation	4.00	0.80	3.56	0.92	3.89	0.65

Acceptance

The acceptance of the driving style was evaluated by the questionnaire of Van der Laan et al. (1997) in the German version (Kondzior, n.d.). This questionnaire has nine items on a five-point rating scale from -2 to 2 in which the mean value of five items results in the *usefulness* scale (y-axis) and the mean value of the other four items in the *satisfying* scale (x-axis). The ANOVA revealed a significant difference between the driving styles for both the *usefulness* (F(1.84)=5.03, p=.012, f=.41) and *satisfying* scale (F(1.95)=3.28, p=.046, f=.33). Subsequently post hoc analysis showed a significant higher usefulness for the dynamic driving style compared to the driving style only using the right lane ($M_{1\text{-}3}$=-.42, *p*=.009). No other post hoc pairwise comparison showed a significant effect (*p*>.05). The scores with positive mean values point out that all driving styles were seen as useful and satisfying (Figure 6). The values for the mean (*M*) and standard deviation (*SD*) for each driving style and the two subscales can be found in Table 5.

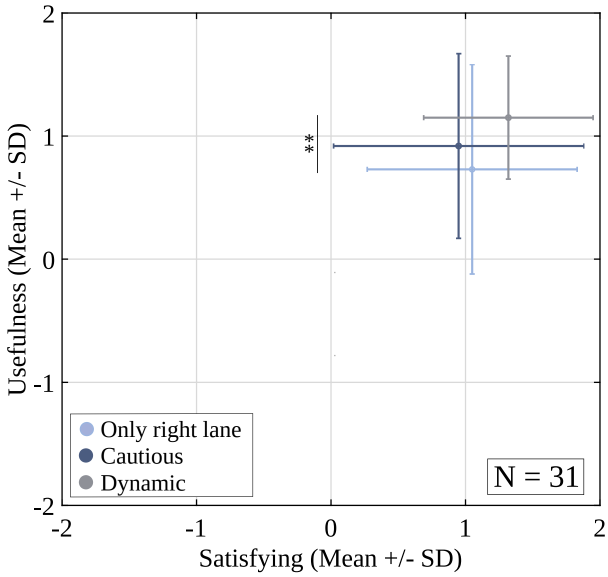

*Figure 6. Evaluation of acceptance of the three driving styles (scale: five-point semantic differential; **p<.01)*

Table 5. Participants' mean ratings for the two dimensions usefulness and satisfying of the acceptance questionnaire of van der Laan (1997) for the three driving styles (scale: five-point semantic differential)

	Only right lane		*Cautious*		*Dynamic*	
	M	*SD*	*M*	*SD*	*M*	*SD*
Usefulness	0.73	0.85	0.92	0.75	1.15	0.50
Satisfying	1.05	0.78	0.95	0.93	1.32	0.63

Prioritisation

After the participants had experienced all three driving styles, they were asked to choose one of them considering the following statements:

- During which car ride did you feel the best *well-being*?
- During which car ride did you feel the *safest*?
- Which car ride’s driving style would you prefer for an automated vehicle driving on the highway?

For the factor well-being, nearly half of the participants (48.39%) preferred the dynamic driving style. Only four participants (12.90%) chose the driving style that was only using the right lane, and 12 (38.71%) the cautious driving style. In contrast, 19 participants (61.29%) indicated that they felt the safest during the driving style only using the right lane and only seven (22.58%) during the cautious driving style, and five (16.13%) during the dynamic driving style. For their overall prioritisation, 96.8% of the participants favoured a driving style including lane change manoeuvres (dynamic: 54.84%, cautious: 41.94%) and only one participant (3.23%) would prefer a driving style only using the right lane (Figure 7).

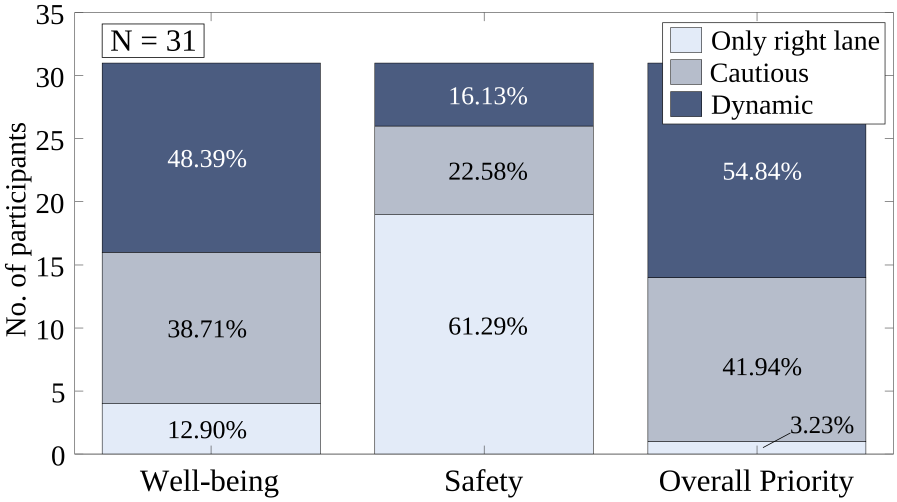

Figure 7. Distribution of the preferred driving style considering well-being, safety, and an overall priority.

Conclusion and Discussion

Three different driving styles for conditionally automated highway driving with varying lane change behaviour were evaluated. Overall, over 60% of the participants felt the safest during the driving style only using the right lane of the highway as well as rated this driving style as the most predictable and understandable. An explanation for this result is that the absence of lane changes leads to the higher predictability and feeling of safety. Moreover, the lower velocity could also have influenced the feeling of safety (Figure 3). In contrast to this, the driving style only using the right lane was considered as less useful than the dynamic driving style. The overall priority clearly showed that the majority preferred a driving style including lane changes as only one driver voted for the driving style only using the right lane. However, the driving style did not influence the well-being of the participants. This metric was always evaluated after the test drive when the vehicle was parked and, thus, might have influenced the real well-being while driving. Evaluating the latter metric while driving should be considered. During the cautious driving style, the participants reported less trust in automation than during the dynamic driving style. A presumable reason for that could be the higher number of aborted lane changes during the cautious driving style. Overall, even if there are differences between the three driving styles, the participants always perceived high well-being and comfort as well as high trust and acceptance. Furthermore, results indicate that the dynamic driving style is overall preferred, even though ratings in trust and safety were higher during a driving style only using one lane of the highway.

As it is always important to have a look at real-world scenarios, this also has its limitations when it comes to the standardisation of the conditions. On a real highway among other vehicles, the behaviour of other drivers, the traffic, and the weather is not controllable as it is in simulated settings or on test tracks. Considering this, the study took place at the same times during the day to ensure similar traffic and it was avoided to drive when it was raining, but in real-world settings, some variances are not preventable. The study was voluntary, so most of the participants were interested in automated driving and not too anxious or sceptical about it. Consequently, this could have influenced the ratings.

Much more research is necessary in this field to design a driving style for automated highway driving. One aspect for instance could be the influence of the motivation of the car ride or non-driving related tasks. Both aspects could have an important impact on the perception of different driving styles during automated driving.

Acknowledgments

We would like to extend a big "thank you" to our colleagues, in particular Neha Lal, Sebastian Bayerl, Alexander Freier, and Frieder Gottmann for their assistance with the test vehicle software or supporting as a safety driver.

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