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Comfort and Safety in Conditional Automated Driving in Dependence on Personal Driving Behavior

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ABSTRACT When changing from active driving to conditional automated driving (CAD), the question arises whether users still prefer their own driving behavior while being a passenger. The aim of this paper is to analyze driving behavior preferences in CAD based on the perception of comfort and safety, taking the personal driving behavior into account. Furthermore, it is investigated if users are able to manually demonstrate their desired driving behavior for CAD. Data on the personal, desired and experienced automated driving behavior of 42 participants from a real-world study was used to investigate both research questions for car-following (CF) and decelerating to a lead vehicle (DL) situations. In a first step, the personal and desired driving behavior is compared with the automated driving behavior based on selected parameters. Subsequently, the relationship between behavior differences and the assessed situation comfort and safety is analyzed. The results show a dependency between differences of personal and automated driving behavior and subjective ratings for comfort and safety. Furthermore, results suggest that participants prefer a driving behavior similar to or more defensive than their own for CAD. Our findings also show that participants were able to demonstrate their desired comfort driving behavior in CF and DL situations.

INDEX TERMS Automated driving, driving style, driving behavior, car-following, comfort perception, safety perception.

I. INTRODUCTION

AUTOMATED driving is one of the leading trends for the future of mobility with the aim of increasing comfort and road safety, optimizing traffic flow and enabling users to spend their time with non-driving related activities. As a guideline for the step-wise introduction of automated driving functions, SAE International developed a six-stage framework for classifying different levels of automation [1]. Whereas the responsibility of the entire dynamic driving task (DDT) is taken by the driver in Level 0, the DDT is fully taken over by the automated system in Level 5, eliminating the need of a driver. The safety of passengers in critical driving situations has been continuously enhanced in recent decades with the introduction of active driver assistance systems up to Level 2 [2]. Despite the simultaneous control of longitudinal and lateral vehicle guidance by Level 2 systems, the driver is still responsible for system monitoring.

On the way to fully automated driving, Level 3 (L3) represents a milestone, being the first level in which the driver is no longer obligated to constantly monitor the system performing the DDT. Conditional automated driving (CAD) is another term being used to describe driving in L3. However, the Operational Design Domain in L3 is still limited and the

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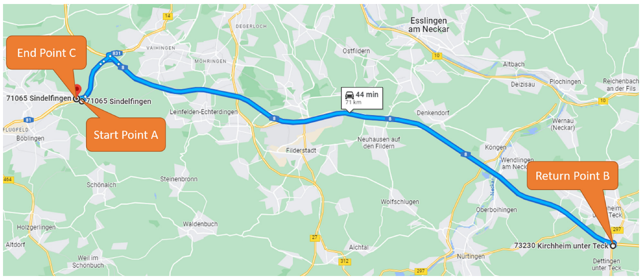


FIGURE 1. Study reference route from [20] for recording personal driving behavior PDB (Section A-B), desired driving behavior DDB (Section B-C) and automated driving behavior ADB (Section A-(B)-C). Maps Data: Google, © 2023 GeoBasis-DE/BKG (©2009) [21].

driver needs to be able to take back control if requested by the system.

With CAD, the role of the active driver is changing to that of a passenger [3], [4]. Consequently, the question arises of how people want to be driven in their new passive role. To answer this question, a common approach by previous studies is to let users experience and compare different driving styles, predominantly by the usage of driving simulators [5], [6], [7], [8]. The presented driving behaviors are mostly predefined as defensive and aggressive or a prerecording of the user's personal driving behavior [9], [10], [11]. The preferred behavior for automated driving is often determined by ratings for comfort and safety.

However, the number of studies investigating preferences for automated driving behavior is not yet sufficient to understand how users want to be driven in an automated vehicle (AV), especially with regard to their personal driving behavior. In addition, multiple scenarios and maneuvers have been investigated in urban and rural environments [5], [6], [7], [11], [12], [13], [14], whereas lane change maneuvers have been the primary focus on motorways [8], [10], [15], [16], [17]. Although steady-state car-following and decelerating to a lead vehicle are both driving situations with a high frequency [18] and considered as highly comfort relevant [3], [19], they have been rarely examined so far.

Therefore, the aim of this study is to analyze the influence of personal driving behavior on the perception of comfort and safety in CAD for steady-state car-following and decelerating to a lead vehicle on motorways as the introduction of further L3 systems is most likely for this road type. In addition, it is investigated whether a desired driving behavior for CAD can be manually demonstrated by the user.

For this analysis, vehicle data of surrounding objects and vehicle kinematics from the two-part real-world driving study with 42 participants conducted in [20] are used. The aim of the study was to analyze preferences in CAD based on the perception of comfort and safety, taking the participants' personal driving style into account. The study is conducted on a given German motorway section of around 71 km, shown in Fig. 1.

In the first part, participants drove manually from starting point A to C via B. In section A-B, the personal driving behavior (PDB) is recorded. To minimize the influence of the study setup on the personal driving behavior, participants did not receive any instructions regarding their driving behavior. For section B-C, participants were instructed to manually demonstrate their desired driving behavior (DDB) for CAD, showing how they want to be driven by a L3 system.

In the second part, participants were driven in an AV on the complete route (section A-(B)-C). During the drive, participants were free to evaluate the AV's driving behavior in any situation with regard to comfort and safety. Both ratings were given on a seven-point Likert scale from -3 (very uncomfortable/unsafe) to 3 (very comfortable/safe). Participants sat in the passenger seat and were driven by L2 ADAS functions, presented as L3 system with a safety driver, monitoring the system.

Based on the analysis of participants' verbal feedback about the reason for their rating, 99 different driving situation categories were derived that describe what the participants rated. In this paper, the following three categories are analyzed:

1) steady-state car-following
2) decelerating to a lead vehicle (intensity)
3) decelerating to a lead vehicle (timing)

In *steady-state car-following* situations, participants rated the distance to the lead vehicle within the same lane. In *decelerating to a lead vehicle* situations, participants were either rating whether the deceleration intensity (2) was too strong, too weak or just right or whether the timing at which the AV started to decelerate (3) was too late, too early or just right.

It is examined whether user-like driving behavior is also preferred in CAD by comparing PDB with ADB. Furthermore, it is investigated whether desired-like driving behavior in CAD actually represents the desired behavior by comparing DDB with ADB. By determining the preferred driving behavior, important implications for the design of future conditional automated driving systems can be derived.

The paper is organized as follows: Section II gives an overview about previous research. Based on this, the hypothesis for this paper are derived in Section III. Section IV describes how each driving situation is defined and extracted from the driving data. Section V describes the method for analyzing user preferences in conditional automated driving. The results are presented in Section VI, followed by the discussion in Section VII. The paper ends with a conclusion in Section VIII.

II. RELATED WORK

Previous literature presents a large variety of methods and parameters that can be used to describe and compare different driving behaviors [22]. Often, the term driving style is used as well in this context. In some literature, driving style is described as consistent and stable over a longer period of time, whereas driving behavior is seen as situation-dependent [23], [24], [25]. However, a clear separation of the two concepts is difficult due to the different understandings and large definitional overlaps across various literature.

A common feature of both concepts is that both can be described by objective parameters such as vehicle kinematics and/or their relations to surrounding traffic environment. The parameters are represented by, e.g., sections of time series data [3], [26], [27], [28], statistical characteristics [7], [16], [18], [29], [30], [31] or a dimensionless combination of different parameter types [9], [20], [32], [33]. To distinguish between different driving behaviors, manual or data driven classification is often performed on the basis of value ranges or data patterns. A description on a subjective level by terms such as "aggressive" or "defensive" is also possible for both concepts [22], [24]. For the purpose of this paper, the term driving behavior is used as it is considered more appropriate with regard to individual driving situations.

In the following literature review on preferences in automated driving, however, the term chosen in the source is used. For a better comparison of results on how people want to be driven, the studies are clustered based on the analyzed driving situations. The studies reviewed in the following sections regarding preferences for automated driving are all conducted in driving simulators except for [8], [13], both conducting a real-world study.

A. LANE CHANGE BEHAVIOR

Preferences for automated lane changes on motorways also regarding the participant's personal driving style are analyzed in [9], [10]. Whereas the results of [10] show that participants prefer their own style, the results of [9] suggest that participants prefer a more dynamic style compared to their own. In [8], [15], [16], participants prefer a defensive and less dynamic style when choosing from different predefined driving styles. In addition, [17] recommend early rather than late lateral motion feedback.

B. DECELERATION BEHAVIOR WHILE APPROACHING A LEAD VEHICLE

In [8], participants preferred an earlier and softer deceleration when decelerating to a lead vehicle independently of the distraction degree by non-driving related tasks (NDRT). Similar results regarding preferences in longitudinal dynamics are seen in [17]. Here, two variants with either a low and constant deceleration or a reduced longitudinal jerk were preferred over typical human behavior with strong initial deceleration found in [34] and [35].

Reference [36] analyzed the perception of time-to-collision (TTC) in manual and automated (L2) driving when approaching a slower lead vehicle. In both cases, participants underestimated the TTC, meaning that they expected a collision to occur earlier than it actually would. However, the underestimation was lower for automated driving. The results of [37] showed that take-over requests in critical and dynamic deceleration maneuvers while approaching a lead vehicle can lead users to decelerate even more than necessary or to change lanes while taking back control. This, in turn, increases the risk of rear-end collisions with following and overtaking vehicles.

C. DISTANCING BEHAVIOR IN STEADY-STATE CAR-FOLLOWING

Reference [38] investigated the subjective comfort of different time headways depending on speed and visibility for car-following in automated driving in urban and rural environment as well as on highways. For the majority of time headway intervals, results show that the same time headway is perceived as less comfortable at lower than at higher speeds. These results are in contrast to [39], where no dependency of preferred time headways on speed was found for manual and assisted driving (Level 1). A continuous increase in risk, discomfort and effort perception for a decreasing time headway from 2 s to 0.5 s is seen in [40].

References [41], [42], [43] analyze human car-following behavior based on real-world driving data from large-scale studies to create a reference for the design and development of automated driving systems. Under the assumption that users will prefer their own driving behavior in automated driving, many research papers focus on learning human-like car-following for AVs [44], [45], [46], [47]. The results found in [48] indicate that users prefer a steady-state car-following behavior that is similar to or more defensive than their own.

Higher rates of AVs in the future and their ability to communicate with both each other and the environment will influence the distancing behavior between vehicles as well. With the goal of traffic flow optimization for increasing fuel efficiency, platooning will enable vehicles to also maintain closer distances between each other while still ensuring safety [49], [50], [51].

D. DRIVING BEHAVIOR ACROSS INDIVIDUAL DRIVING SITUATIONS

Preferences for automated driving are also analyzed on the basis of an overall behavior across individual driving situations over the complete duration of an automated drive. Reference [7] analyzed preferences in fully automated driving for defensive and aggressive driver types in an automated drive with 12 different scenarios including four hazard situations. The results showed that defensive drivers preferred a driving style that is similar to their own, promoting their trust, acceptance and subjective evaluation such as comfort and safety while also reducing their take-over frequency. A similar trend was seen for aggressive drivers although without significance. The influence of different automated driving styles on user preferences in intersection scenarios was also investigated by [6], analyzing participants' dissatisfaction with the automated driving style based on the frequency and magnitude of accelerator and brake pedal activations. Whereas the conservative automated driving style increased the frequency and magnitude of the accelerator pedal actuation, the aggressive automated driving style increased the frequency and magnitude of the brake pedal actuation.

Possible advantages of a situation-adaptive automated driving style compared to a constant automated driving style are shown in [5]. Here, the change in trust by adapting the automated driving style to the participants' preference in intersection scenarios is investigated. Four styles ranging from very defensive to very aggressive were presented that were changed by participants according to their preferences or a predefined logic.

Reference [20] analyzed driving style preferences for CAD on motorways. The results show that participants with a very defensive to moderate driving style rated the AV's driving style, being similar to their own, as more comfortable but equally safe compared to participants with a moderate to very aggressive driving style.

References [3], [12], and [52] come to different conclusions when investigating the influence of age on the experience of automated driving styles for different driving situations on rural roads and motorways. In all studies, participants experience their own and up to two predefined automated driving styles. Reference [3] found that both groups of younger and older participants preferred the style of a younger driver, being more dynamic. On the other hand, a defensive style was preferred by younger and older drivers in [52]. Young drivers even rejected their own driving style the most in terms of safety and comfort. Results of [12] show that older drivers prefer their own style, which is characterized by a comparatively more defensive and calmer driving behavior.

E. RESEARCH GAP

As the level of automation increases with conditional automated driving, the need to investigate user preferences increases as well. In this context, driving behavior preferences for *steady-state car-following* and *decelerating to a lead vehicle* on motorways are of special interest, given the anticipated increase in automated systems of L3 or higher on this road type. Despite their large overall proportion of driving situations on motorways [18] and their high relevance for comfort in automated driving [3], [19], both have been rarely examined so far. Furthermore, the user's personal driving behavior has been mostly neglected when analyzing these two. Therefore, the present study analyzes user preferences in terms of comfort and safety in conditional automated driving for *steady-state car-following* and *decelerating to a lead vehicle* on motorways, taking the personal driving behavior into account.

III. DERIVATION OF HYPOTHESES

Previous studies have shown that behavior preferences for automated driving can depend on users' own driving behavior [11], [13]. As it was already found in [20] (data basis for this paper) that differences between the overall personal and automated driving style show a significant correlation with comfort, it is expected that this dependency can be found in individual driving situations as well. Although a correlation was only found for comfort in [20], we hypothesize the following:

H1: The comfort and safety ratings depend on the behavior differences between PDB and ADB in *steady-state car-following* and *decelerating to a lead vehicle* situations.

When analyzing user preferences for automated driving, the changed role of the driver has to be considered as well. As the DDT and monitoring responsibility is transferred to the automated vehicle, the possibilities for intervention by the driver are reduced and can be further delayed by NDRTs [4], [8], [53]. Combined with a limited predictability of the AV's trajectory [54], the preference for a more defensive behavior might increase. Although this hypothesis could not be confirmed in [20] with regard to overall driving style preferences, it is expected to apply for driving behavior in individual driving situations. We therefore hypothesize the following:

H2: Participants prefer a more defensive driving behavior than their own for conditional automated driving in *steady-state car-following* and *decelerating to a lead vehicle* situations.

In order to identify user preferences for automated driving, a common approach by previous studies is to let users experience and compare different driving styles. However, participants were only able to choose from their own or predefined automated driving styles. Although participants were asked to demonstrate their desired driving style for automated driving in [20], the demonstrated driving style was only compared to the participants' personal driving style. It has not been analyzed if participants preferred an automated driving style resembling their demonstrated desired driving style for CAD. Assuming that participants were able to demonstrate their desired driving behavior, we hypothesize the following:

H3: When comparing DDB and ADB, DDB-like automated driving is among the preferred behaviors in *steady-state car-following* and *decelerating to a lead vehicle* situations with regard to comfort and safety.

IV. DATA PREPROCESSING

In order to extract the driving situations *steady-state car following* and *decelerating to a lead vehicle* from the recorded driving data, boundaries for both situations have to be defined. Furthermore, the parameters used for comparing the driving behavior in each situation are determined. In general, data collected in roadworks as well as curves on motorway feeder roads, on- and off-ramps are excluded to ensure comparability of driving behavior in similar driving environments. It is presumed that roadworks, in particular, alter the participants' driving and assessment behavior. Narrow lanes and a reduced lateral distance to other objects pose an additional risk that is different from the conditions experienced outside of these areas. The same is applied for data recorded outside the given reference route, such as when participants took a wrong exit.

A. STEADY-STATE CAR-FOLLOWING

For analyzing *steady-state car-following*, the time gap is used. It is defined as

$$t_{gap} = \frac{d}{v}, v > 0. \tag{1}$$

The parameter d describes the longitudinal distance between the front bumper of the test vehicle and the rear bumper of the lead vehicle, whereas v corresponds to the longitudinal velocity of the test vehicle.

For extracting *steady-state car following* situations from the participants' manual drive, the following five conditions are set. Firstly, time gaps are only considered for speeds greater than 60 km/h to exclude data collected in traffic jams. Time gaps at velocities exceeding 140 km/h are also not taken into account, as the AV's maximum driving speed is limited to 130 km/h. As a result, the distancing behavior is analyzed within a velocity range that is typically observed on motorways [55]. Furthermore, *steady-state car-following* situations are only considered as steady-state, if the absolute relative velocity between the test and lead vehicle is below 2 m/s. Fourthly, lead vehicles outside the test vehicle's stopping distance are are not regarded as such as the distance between both vehicles is seen as a random result of the traffic situation and not as a consciously chosen distance by the participants. In this paper, the stopping distance d_s is based on the kinematics equation and consists of two components, the reaction distance d_r before the participants start to brake and the braking distance d_{br}, see Eq. (2).

$$d_s = d_{br} + d_r = \frac{1}{2}\frac{(v_{init} - v_{end})^2}{|a_d|} + v_{init}t_r. \tag{2}$$

The initial velocity is described by v_{init} and the end velocity by $v_{end} = 0$. For the participants, an average deceleration to standstill of $a_d = -5$ m/s^2 and a human reaction time of $t_r = 1$ s is assumed. The deceleration value is set between comfort braking below 2 m/s^2 [56], [57] and strong emergency braking around 8 m/s^2 and higher [58], [59]. The human reaction time depends on the driver's state of attention and driving situation as well as its criticality and varies approximately between 0.6 s and 2 s [60], [61], [62], [63]. The chosen reaction time value represents a more attentive driver as it can be assumed that participants are more attentive during a study. Finally, all conditions mentioned above need to be fulfilled for at least 5 s.

Following the described extraction conditions for PDB and DDB, several individual *steady-state car-following* situations are obtained, each with varying duration. To minimize the influence of time gap variation during longer car-following, each extracted situation is segmented into 5 s-sections, which are treated as separate situations. The minimum time gap of a 5 s-section is used as comparison parameter to compare driving behavior. For ADB, the minimum time gap is taken from the 5 s-timeframe before the rating moment.

B. DECELERATING TO A LEAD VEHICLE

To extract *decelerating to a lead vehicle* situations from the driving data, the start and end of a deceleration have to be defined. The method is explained in the following using an exemplary deceleration profile shown in Fig. 2.

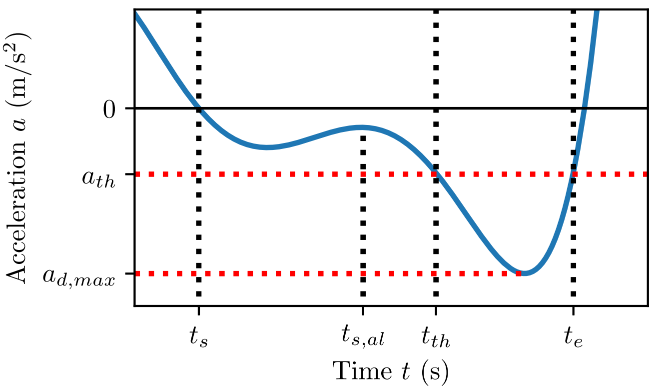


FIGURE 2. Exemplary vehicle data of a deceleration profile including all time stamps based on the extraction method for *decelerating to a lead vehicle* situations.

In a first step, only decelerations stronger or equal to the threshold of $a_{th} = -0.2$ m/s^2 with a duration of at least 0.5 s are considered. The time at which a deceleration exceeds a_{th} is denoted by t_{th}. Starting from t_{th}, the start and end of the deceleration is determined. The start t_s is defined as the time at which the acceleration signal has its first zero crossing before t_{th}. If no zero crossing is found within a timeframe of 3 s before t_{th}, an alternative start time $t_{s,al}$ is used. The point in time $t_{s,al}$ is defined as the time at which the acceleration signal has its weakest deceleration value within a 3 s-timeframe prior to t_{th}. The end t_e is defined as the time at which the deceleration intensity falls below $a_{th} = -0.2$ m/s^2. In addition, the parameter time-to-collision (TTC) is taken into account for the extraction process. The TTC is defined as

$$ttc = \frac{d}{v_r}, v_r > 0, \tag{3}$$

where v_r denotes the relative longitudinal velocity to the lead vehicle at $t_s/t_{s,al}$. Decelerations with a negative TTC or a TTC above 60 s are not considered. This is based on the assumption that, in both cases, the deceleration was not a response to a lead vehicle. Extracted deceleration situations with a total length of less than one second are not considered as well for the same reason.

As participants named the deceleration intensity or timing in *decelerating to a lead vehicle* situations as reason for their rating, different comparison parameters are chosen accordingly for each reason. For ratings relating to the deceleration intensity, the maximum deceleration $a_{d,max}$ is chosen as comparison parameter to compare driving behavior. To compare the timing of a deceleration, the time-to-collision ttc at the deceleration start t_s is chosen.

As the TTC is more sensitive at lower relative velocities due to its asymptotic profile around zero, the behavior comparison for deceleration timing is split into two relative velocity ranges. Rated deceleration timings for ADB with $v_r \leq 5$ km/h ($ttc_{v_{r,lo}}$) are only compared to extracted deceleration timings in PDB and DDB within the same relative velocity range. Accordingly, the same applies to rated deceleration timings for ADB with $v_r > 5$ km/h ($ttc_{v_{r,hi}}$).

V. ANALYSIS OF DRIVING BEHAVIOR DIFFERENCES

In the previous section, comparison parameters were selected for each driving situation category that quantify and represent the driving behavior. For *steady-state car-following* (CF), the time gap t_{gap} was chosen. For the deceleration intensity when *decelerating to a lead vehicle* ($\mathrm{DL_{Int}}$), the maximum deceleration intensity $a_{d,max}$ was chosen. For the deceleration timing when *decelerating to a lead vehicle* ($\mathrm{DL_{Ti}}$), the time-to-collision $ttc_{v_{r,lo/hi}}$ at the deceleration start for two different relative velocity ranges was chosen.

In order to compare ADB with PDB as well as ADB with DDB within the extracted driving situations described in Section IV, the following method is proposed. Selected process steps in the method description are marked with capital letters to reference the according sections in Fig. 3, showing a schematic representation of the method, using *steady-state car-following* driving behavior as an example.

Based on the comparison parameters p_{cp} chosen in the previous section, the difference between personal and automated as well as desired and automated driving behavior is generally described by

$$\Delta DB^{P/D} = p_{cp}^{PDB/DDB} - p_{cp}^{ADB}. \tag{4}$$

For each participant, the behavior difference is calculated between all extracted manual driving situations (PDB/DDB) and all rated driving situations (ADB) during the automated drive (see **A** in Fig. 3) within their respective categories CF, $\mathrm{DL_{Int}}$ and $\mathrm{DL_{Ti}}$.

As comfort and safety ratings are analyzed in dependency to the calculated behavior differences, the rating of a single situation during automated driving (see **C** in Fig. 3) is assigned to all behavior differences (see **B** in Fig. 3) that are calculated with the respective rated situation. The resulting pairs of behavior differences and ratings are referred to as data points (see **D** in Fig. 3) in the remainder of the paper.

For hypothesis H1, the Kendall rank correlation coefficient is calculated between all driving behavior differences ΔDB^{P} and ratings of comfort and safety (see **E** in Fig. 3) in each driving situation category. Furthermore, the correlation is also calculated for the absolute behavior differences $|\Delta DB^{P}|$ to isolate the influence of the direction in which the ADB differs from PDB. H1 is accepted for each rating criteria showing a significant correlation with either the behavior differences ΔDB^{P} or the absolute behavior differences $|\Delta DB^{P}|$.

In a next step, behavior differences are further categorized into three groups. Based on (4), positive differences represent a more aggressive ($\mathrm{ADB_{magg}^{PDB}}$, $\mathrm{ADB_{magg}^{DDB}}$) and negative differences a more defensive ($\mathrm{ADB_{mdef}^{PDB}}$, $\mathrm{ADB_{mdef}^{DDB}}$) driving behavior of the AV compared to the PDB and DDB, respectively. Difference values that are near zero represent driving behavior that is comparable to the PDB ($\mathrm{ADB_{eq}^{PDB}}$) and DDB ($\mathrm{ADB_{eq}^{DDB}}$), respectively.

To define similar to equal driving behavior, a symmetrical similarity threshold is introduced (see **E** in Fig. 3). For *steady-state car-following*, a symmetrical similarity threshold of $\Delta t_{gap,th} = \pm 0.2$ s is chosen. The similarity threshold $\Delta a_{d,max,th} = \pm 0.25$ m/s^2 for the deceleration intensity is based on human perception thresholds taken from [64]. With regard to the deceleration timing, similarity thresholds of $\Delta ttc_{v_{r,lo},th} = \pm 6$ s and $\Delta ttc_{v_{r,hi},th} = \pm 2$ s are set for their respective relative velocity ranges.

The resulting behavior groups (see **F** in Fig. 3) are used for hypothesis H2 within each driving situation category. To verify H2, a Mann-Whitney-U test is used to compare the comfort and safety ratings of the participants between the groups $\mathrm{ADB_{mdef}^{PDB}}$ and $\mathrm{ADB_{eq}^{PDB}}$ as well as $\mathrm{ADB_{eq}^{PDB}}$ and $\mathrm{ADB_{magg}^{PDB}}$. A comparison between two groups is only performed if each group contains a minimum number of five participants and ten ratings. Furthermore, the behavior differences ΔDB^{P} or the absolute behavior differences $|\Delta DB^{P}|$ need to show a significant correlation with the corresponding rating criteria. A correction based on the Bonferroni-Holm method is utilized for all group comparisons.

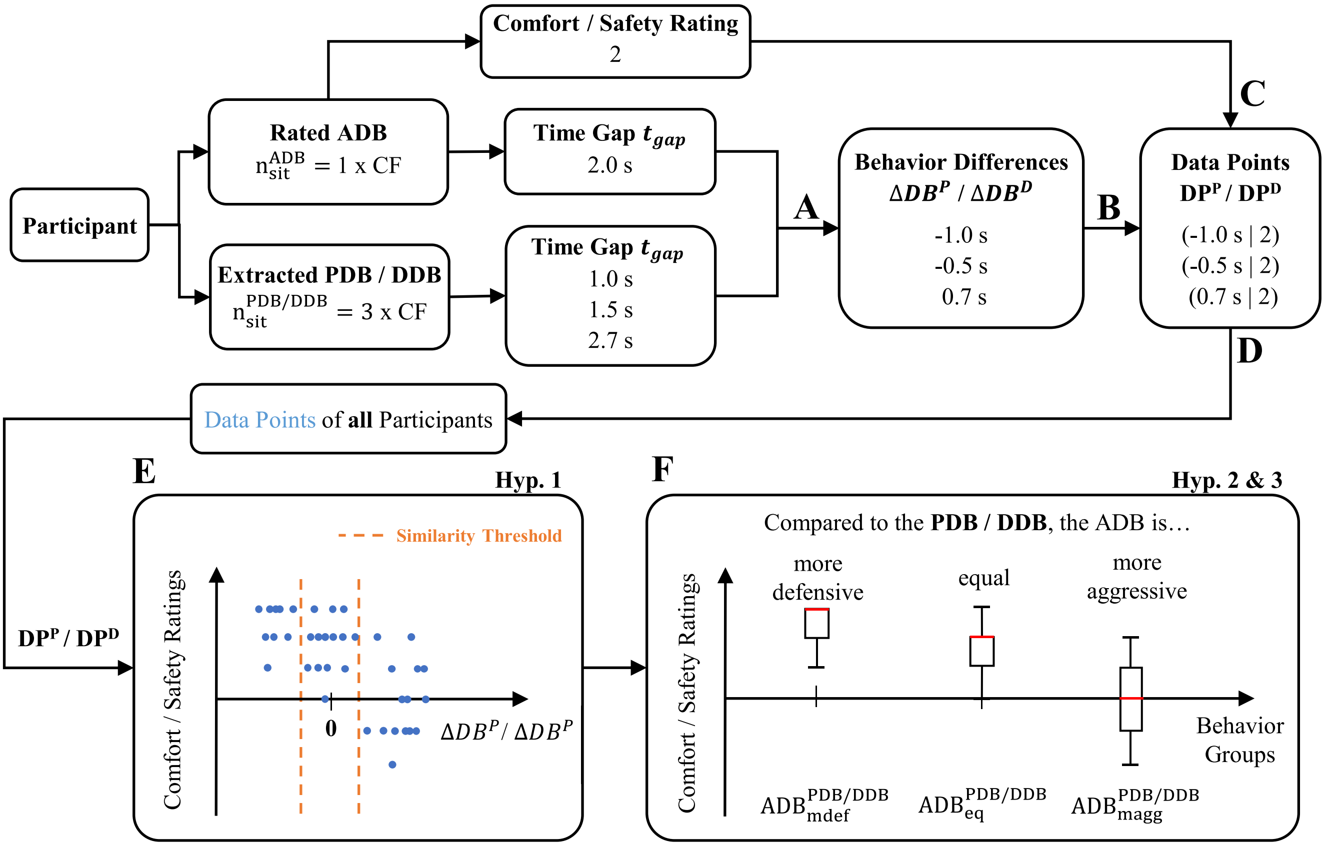
Hypothesis H3 is verified in a similar way as H2. As a prerequisite, the behavior differences ΔDB^{D} or the absolute behavior differences $|\Delta DB^{D}|$ and ratings need to show a significant correlation (see **E** in Fig. 3). To compare comfort and safety ratings of the participants between the groups $\mathrm{ADB_{mdef}^{DDB}}$ and $\mathrm{ADB_{eq}^{DDB}}$ as well as $\mathrm{ADB_{eq}^{DDB}}$ and $\mathrm{ADB_{magg}^{DDB}}$ (see **F** in Fig. 3), a Mann-Whitney-U test is used. Just as for H2, a comparison between two groups is only performed if each group contains a minimum number of five participants and ten ratings. Furthermore, the Bonferroni-Holm method is also utilized for all group comparisons.

H3 is accepted in two cases. Case 1: Ratings in group $\mathrm{ADB_{eq}^{DDB}}$ are significantly higher than in both other groups $\mathrm{ADB_{magg}^{DDB}}$ and $\mathrm{ADB_{mdef}^{DDB}}$. Case 2: Ratings in group $\mathrm{ADB_{eq}^{DDB}}$ are significantly higher compared to one of both other groups while showing no difference in ratings with the respective other group (see **F** in Fig. 3).

VI. RESULTS

In total, the distance to a lead vehicle was rated 109 times by 29 of 42 participants during *steady-state car following* situations. 68 out of these 109 driving situations were rated outside of roadworks at velocities between 60 km/h and 140 km/h. The deceleration intensity in *decelerating to a lead vehicle* situations was rated 37 times, whereas the deceleration timing was rated 35 times. Excluding ratings that were given during roadworks or outside the predefined reference route, 21 of 37 and 22 of 35 ratings remain in their respective category. As described in Section IV, the analysis of deceleration timing is split into two relative velocity ranges. Out of 22 ratings, 9 were given at a relative velocity of $v_r \leq 5$ km/h whereby 13 were given at $v_r > 5$ km/h.

The results of the driving behavior comparison between PDB and ADB as well as DDB and ADB are summarized in Table 1, 2 and 3. In Table 1, the number of data points is given by N_{DP}, the number of ratings by N_R and the number of extracted driving situations of participants' manual drive



Note: Schematic representation

Note: Schematic representation

FIGURE 3. Schematic method representation for analyzing the influence of driving behavior differences between personal and automated as well as desired and automated driving behavior on the perception of comfort and safety in CAD. For visualizing the behavior difference calculation, exemplary time gap values in *steady-state car-following* (CF) situations are used.

in section A-B (PDB) and section B-C (DDB), respectively, by N_{DS}. The number of participants rating a specific driving situation category is given by N_P.

A. COMPARING PERSONAL WITH AUTOMATED DRIVING BEHAVIOR

The comfort ratings show a significant correlation with behavior differences regarding the time gap Δt_{gap}^P in *steady-state car-following* situations and deceleration timing at higher relative velocities $\Delta ttc_{v_{r,hi}}^P$ in *decelerating to a lead vehicle* situations. No significant correlation is found between comfort ratings and behavior differences regarding the deceleration timing at lower relative velocities $\Delta ttc_{v_{r,lo}}^P$ and the deceleration intensity $\Delta a_{d,max}^P$ in *decelerating to a lead vehicle* situations. The safety ratings show a significant correlation with behavior differences regarding the time gap Δt_{gap}^P, the deceleration intensity $\Delta a_{d,max}^P$ and the deceleration timing at higher relative velocities $\Delta ttc_{v_{r,hi}}^P$. No significant correlation is found between safety ratings and behavior differences regarding the deceleration timing at lower relative velocities $\Delta ttc_{v_{r,lo}}^P$. Except for comfort and $|\Delta t_{gap}^P|$ as well as safety and $|\Delta a_{d,max}^P|$, each rating criteria showing a significant correlation with the behavior differences also shows a significant correlation with the absolute behavior differences. For the latter, the correlation coefficients show a reversed sign.

The comparison of comfort and safety ratings is only performed between the categorized driving behavior differences groups fulfilling the analysis requirements defined in Section V. The results of the group comparison are summarized in Table 2. The shown p-values are corrected with the Bonferroni–Holm method.

For the time gap in *steady-state car-following* situations, a more defensive and a more aggressive ADB is rated significantly less comfortable compared to a PDB-like ADB. However, the difference in ratings between a more defensive and PDB-like ADB is considered small. For the time gap in *steady-state car-following* situations, a more defensive ADB is perceived as significantly safer and a more aggressive ADB is perceived as significantly less safe compared to a PDB-like ADB. For the deceleration intensity in *decelerating to a lead vehicle* situations, no significant difference with regard to safety is found between a more defensive and a PDB-like ADB. On the other hand, a more aggressive ADB is perceived as significantly less safe compared to a PDB-like ADB.

TABLE 1. Correlation analysis of driving behavior differences between personal and automated driving behavior (ΔDB^P) as well as desired and automated driving behavior (ΔDB^D) with both comfort and safety ratings.

Compared Behavior	Driving Situation	Behavior Differences ΔDB	Quantity of Data N_P	N_{DS}	N_R	N_{DP}	Comfort τ	Comfort p	Safety τ	Safety p
PDB vs. ADB	CF	Δt^{P}_{gap}	25	1669	68	4576	−0.08	<0.001***	−0.31	<0.001***
		$\lvert\Delta t^{P}_{gap}\rvert$					−0.02	0.135	0.08	<0.001***
	DL$_{\text{Int}}$	$\Delta a^{P}_{d,max}$	14	170	21	273	−0.02	0.731	−0.14	0.004**
		$\lvert\Delta a^{P}_{d,max}\rvert$					−0.02	0.595	−0.07	0.130
	DL$_{\text{Ti}}$	$\Delta ttc^{P}_{v_{r,lo}}$	8	44	9	52	0.00	0.980	−0.04	0.683
		$\lvert\Delta ttc^{P}_{v_{r,lo}}\rvert$					0.02	0.823	−0.02	0.861
		$\Delta ttc^{P}_{v_{r,hi}}$	10	74	13	101	0.20	0.010*	0.19	0.019*
		$\lvert\Delta ttc^{P}_{v_{r,hi}}\rvert$					−0.18	0.018*	−0.27	<0.001***
DDB vs. ADB	CF	Δt^{D}_{gap}	25	1654	68	4214	−0.10	<0.001***	−0.33	<0.001***
		$\lvert\Delta t^{D}_{gap}\rvert$					−0.03	0.006**	0.03	0.015*
	DL$_{\text{Int}}$	$\Delta a^{D}_{d,max}$	14	189	21	317	−0.25	<0.001***	−0.01	0.767
		$\lvert\Delta a^{D}_{d,max}\rvert$					−0.21	<0.001***	0.02	0.690
	DL$_{\text{Ti}}$	$\Delta ttc^{D}_{v_{r,lo}}$	8	53	9	69	−0.07	0.443	−0.06	0.529
		$\lvert\Delta ttc^{D}_{v_{r,lo}}\rvert$					0.03	0.754	0.14	0.141
		$\Delta ttc^{D}_{v_{r,hi}}$	10	67	13	81	0.03	0.773	−0.01	0.946
		$\lvert\Delta ttc^{D}_{v_{r,hi}}\rvert$					0.14	0.103	0.12	0.165

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

TABLE 2. Comparison of the mean ratings between the resulting behavior groups (see F in Fig. 3) representing an automated driving behavior ADB that is more defensive, equal or more aggressive compared to the participants' personal driving behavior PDB.

Rating Criteria	Driving Situation	Behavior Differences ΔDB	Ratings $\text{ADB}^{\text{PDB}}_{\text{mdef}}$	Ratings $\text{ADB}^{\text{PDB}}_{\text{eq}}$	Ratings $\text{ADB}^{\text{PDB}}_{\text{magg}}$	$\text{ADB}^{\text{PDB}}_{\text{mdef}}$ vs. $\text{ADB}^{\text{PDB}}_{\text{eq}}$		$\text{ADB}^{\text{PDB}}_{\text{eq}}$ vs. $\text{ADB}^{\text{PDB}}_{\text{magg}}$	
			M (SD)	M (SD)	M (SD)	U	p	U	p
Comfort	CF	Δt^{P}_{gap}	2.02 (1.46)	2.06 (1.26)	1.75 (1.43)	808 357	0.030*	739 930	<0.001***
Safety	CF	Δt^{P}_{gap}	2.67 (0.81)	2.16 (1.28)	1.45 (1.65)	648 127	<0.001***	820 177	<0.001***
	DL$_{\text{Int}}$	$\Delta a^{P}_{d,max}$	2.57 (0.88)	2.70 (0.70)	2.26 (1.07)	909	0.515	6686	<0.001***

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

TABLE 3. Comparison of the mean ratings between the resulting behavior groups (see F in Fig. 3) representing an automated driving behavior ADB that is more defensive, equal or more aggressive compared to the participants' demonstrated desired driving behavior DDB.

Rating Criteria	Driving Situation	Behavior Differences ΔDB	Ratings $\text{ADB}^{\text{DDB}}_{\text{mdef}}$	Ratings $\text{ADB}^{\text{DDB}}_{\text{eq}}$	Ratings $\text{ADB}^{\text{DDB}}_{\text{magg}}$	$\text{ADB}^{\text{DDB}}_{\text{mdef}}$ vs. $\text{ADB}^{\text{DDB}}_{\text{eq}}$		$\text{ADB}^{\text{DDB}}_{\text{eq}}$ vs. $\text{ADB}^{\text{DDB}}_{\text{magg}}$	
			M (SD)	M (SD)	M (SD)	U	p	U	p
Comfort	CF	Δt^{D}_{gap}	1.95 (1.54)	2.21 (1.14)	1.79 (1.45)	629 629	0.271	657 325	<0.001***
	DL$_{\text{Int}}$	$\Delta a^{D}_{d,max}$	2.05 (1.17)	2.25 (0.99)	1.13 (1.33)	581	0.546	9314	<0.001***
Safety	CF	Δt^{D}_{gap}	2.72 (0.75)	2.20 (1.22)	1.53 (1.64)	468 299	<0.001***	696 759	<0.001***

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

B. COMPARING DESIRED WITH AUTOMATED DRIVING BEHAVIOR

The comfort ratings show a significant correlation with behavior differences regarding the time gap Δt^{D}_{gap} in *steady-state car-following* situations and the deceleration intensity $\Delta a^{D}_{d,max}$ in *decelerating to a lead vehicle* situations. No significant correlation is found between comfort ratings and the deceleration timing behavior differences $\Delta ttc^{D}_{v_{r,lo/hi}}$ in

TABLE 4. Summary of all hypothesis for comfort (C) and safety (S).

Driving Situation	Comparison Parameter	H1		H2		H3	
		C	S	C	S	C	S
CF	t_{gap}	✓	✓	✗	✓	✓	✗
DL_{Int}	$a_{d,max}$	✗	✓	-	✗	✓	-
DL_{Ti}	$ttc_{v_{r,lo}}$	✗	✗	-	-	-	-
	$ttc_{v_{r,hi}}$	✓	✓	-	-	-	-

both relative velocity ranges in *decelerating to a lead vehicle* situations. The safety ratings show a significant correlation with the time gap behavior differences Δt^D_{gap}. No significant correlation is found between safety ratings and behavior differences regarding the deceleration intensity $\Delta a^D_{d,max}$ and the deceleration timing $\Delta ttc^D_{v_{r,lo/hi}}$ in both relative velocity ranges. Each rating criteria showing a significant correlation with the behavior differences also shows a significant correlation with the absolute behavior differences. For safety and $|\Delta t^D_{gap}|$, the correlation coefficient shows a reversed sign.

The comparison of comfort and safety ratings is only performed between the categorized driving behavior differences groups fulfilling the analysis requirements defined in Section V. The results of the group comparison are summarized in Table 3. The shown *p*-values are corrected with the Bonferroni–Holm method.

For the time gap in *steady-state car-following* situations, no significant difference is found between a more defensive ADB and an DDB-like ADB with regard to comfort. In contrast, a more aggressive ADB is rated significantly less comfortable compared to DDB-like ADB. For the deceleration intensity in *decelerating to a lead vehicle* situations, no significant difference is found between a more defensive ADB and a DDB-like ADB with regard to comfort. In contrast, a more aggressive ADB is rated as significantly less comfortable compared to a DDB-like ADB. For the time gap in *steady-state car-following* situations, a more defensive driving ADB is perceived as significantly safer and a more aggressive ADB is perceived as significantly less safe compared to a DDB-like ADB.

VII. DISCUSSION

This study was conducted to analyze the dependency of the perception of comfort and safety in conditional automated driving on personal driving behavior for *steady-state car-following* and *decelerating to a lead vehicle* situations. In addition, it was investigated whether a desired driving behavior for conditional automated driving can be manually demonstrated by a user for both situations. A final summary of all hypothesis results is given in Table 4.

It was assumed in hypothesis H1 that comfort and safety ratings depend on the behavior differences between personal and automated driving behavior in *steady-state car-following* and *decelerating to a lead vehicle* situations. Altogether, hypothesis H1 can be confirmed for the time gap in *steady-state car-following* situations with regard to both comfort and safety as well as the deceleration intensity with regard to safety and the deceleration timing at higher relative velocities with regard to comfort and safety in *decelerating to a lead vehicle* situations. For the deceleration intensity as well as the deceleration timing at higher relative velocities, however, it has to be considered that the correlation is mainly driven by positive ratings with the values two and three.

These results extend the findings of [7], where a significant interaction effect between the AV's driving style and personal driving style on driver's trust, acceptance, and takeover behavior was found. This indicates that taking the personal driving behavior into account for the system design of automated systems in Level 3 or higher could help to fulfill the users' expectations.

The lack of dependency of safety on behavior differences with regard to the deceleration timing at low relative velocities might be explained by the sensitivity of the TTC comparison parameter to changes in a low relative velocity range that can lead to large differences for similar situations. Another reason could be the low amount of data, making it hard to identify a possible trend. The lack of dependency of comfort on behavior differences with regard to the deceleration intensity might be explained by looking at comfort ratings of different *decelerating to a lead vehicle* situations during the automated drive. It was observed that higher deceleration values not always lead to lower comfort ratings and vice versa. The participants' preference for a specific driving behavior may therefore depend on the surrounding context, meaning that no general trend can be derived.

In hypothesis H2, it was assumed that participants prefer a more defensive driving behavior than their own for conditional automated driving in *steady-state car-following* and *decelerating to a lead vehicle* situations. For H2, only the time gap in *steady-state car-following* with regard to comfort and safety as well as deceleration intensity in *decelerating to a lead vehicle* with regard to safety were considered, fulfilling the analysis requirements defined in Section V.

For the time gap in *steady-state car-following* situations, H2 was confirmed with regard to safety but rejected with regard to comfort. Both a more defensive and personal-like automated driving behavior were rated as similarly comfortable. Although larger time gaps with respect to participants' personal driving behavior are preferred in terms of safety, they could be perceived as unnecessary regarding comfort. For instance, increasing the time gap also increases the frequency of cut-in vehicles, which might be perceived as disturbing by a participant as it discontinues the driving experience. A more defensive driving behavior does therefore not necessarily lead to higher comfort ratings.

In contrast to a more defensive driving behavior in *steady-state car-following* situations, a more aggressive driving behavior was both perceived as significantly less comfortable and safe compared to a personal-like automated driving behavior. Shorter time gaps compared to participants' time gaps in personal driving could be perceived as a higher willingness of the AV to take risks than participants are willing to take themselves. Furthermore, the driving flow might be discontinued with relative shorter time gaps as the AV has to react more often to velocity changes of the lead vehicle.

For the deceleration intensity in *decelerating to a lead vehicle* situations, H2 is rejected with regard to safety. Both a more defensive and personal-like automated driving behavior were rated as similarly safe. As the level of safety is already close to saturation for personal-like automated driving behavior, it is possible that it can not be further increased by an even more defensive behavior with comparatively lower deceleration intensities.

A more aggressive behavior compared to participants' personal driving behavior for deceleration intensity was rated as significantly less safe. Stronger decelerations than personal-like decelerations might be interpreted by participants as the result of an incorrect situation assessment of the AV, leading to a rejection of a more aggressive behavior. These results are in line with previous findings of [17]. Here, a relative comparison of three deceleration variants showed that deceleration profiles with predominantly low and constant deceleration as well as deceleration profiles with reduced longitudinal jerk are preferred over typical human behavior with strong initial deceleration.

Hypothesis H3 assumed that a conditional automated driving behavior closely resembling the participants' demonstrated desired driving behavior is among the preferred behaviors in *steady-state car-following* and *decelerating to a lead vehicle* situations with regard to comfort and safety. For H3, only the time gap in *steady-state car-following* with regard to comfort and safety as well as the deceleration intensity in *decelerating to a lead vehicle* with regard to comfort were considered, fulfilling the analysis requirements defined in Section V.

For the time gap in *steady-state car-following* situations, H3 was confirmed with regard to comfort but rejected with regard to safety. For safety, a more defensive behavior than desired-like automated driving behavior is preferred. This might be explained by the results in H2, showing that a more defensive behavior is also preferred compared to the participants' own behavior, indicating that the demand for safety increases with the changed driver role. As participants stay in their active role when demonstrating their desired driving behavior for CAD, it can be assumed that participants are not aware of the possible changes in safety perception when changing their driver role.

With regard to comfort in *steady-state car-following* situations, the ratings show a similar distribution over behavior differences between both personal and automated as well as desired and automated driving behavior. It can therefore be assumed that the demonstrated desired driving behavior reflects the personal driving behavior. This thesis is supported by previous results in [23], where the data for the present paper was collected. Here, the comparison of the participants' personal and demonstrated desired overall driving style showed no significant difference.

For the deceleration intensity in *decelerating to a lead vehicle* situations, H3 can be confirmed with regard to comfort. This result is supported by the feedback of many participants, who stated that they focused on decelerating more gently when trying to demonstrate their desired driving behavior for conditional automated driving.

For the results found in this paper, the following limitations have to be considered. A first limitation is seen in the different traffic conditions for each participant due to real-world driving data resulting in high external validity which is consequently accompanied by lower internal validity. Another limitation is seen in the limited amount of collected data. Although personal and desired driving behavior data was collected each on a motorway section of approximately 36 km, rerunning the study over a longer period of time could help to reduce the variance in both behaviors. Further reruns of the study could also help to reduce the influence of first-exposure contact on the perception of comfort and safety [8]. This could also help to balance the different number of ratings between participants, that is caused by the participants' freedom to choose which situation they want rate.

VIII. CONCLUSION

In this paper, data of a real-world driving study was analyzed to investigate how an automated driving behavior that differs from a participant's own driving behavior influences the perception of comfort and safety in conditional automated driving (CAD) for *steady-state car-following* and *decelerating to a lead vehicle*.

The results indicate that a personal-like automated driving behavior is consistent with the user's comfort driving preference for CAD, but not necessarily with their safety driving preference. Here, depending on the driving situation, a more defensive automated driving behavior compared to the user's personal driving behavior can contribute significantly to an increased feeling of safety for the user. In contrast, an automated driving behavior that is more aggressive than the user's personal driving behavior is generally perceived as significantly less comfortable and safe. The challenge of future L3 system design will therefore be to find a situation-specific driving behavior optimum that lies between a driving behavior that is similar to or more defensive than the user's personal driving behavior.

In addition, a new approach to identify driving behavior preferences for CAD was introduced. In this approach, participants were given the opportunity to manually demonstrate their desired driving behavior for CAD and to analyze whether this behavior is preferred when experienced during automated driving. As the demonstrated desired driving behavior is among the preferred behaviors for CAD, this new approach could extend established development methods. Instead of letting users chose between predesigned driving behaviors, users could be enabled to directly demonstrate their preferred automated driving behavior for specific situations.

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