Transportation Research Part F: Psychology and Behaviour 105 (2024) 206–221

Contents lists available at ScienceDirect

Transportation Research Part F: Psychology and Behaviour

journal homepage: www.elsevier.com/locate/trf

User evaluation of comfortable deceleration profiles for highly automated driving: Findings from a test track study

Stefanie Horn [a,c,*], Patrick Rossner [d], Ruth Madigan [c], Hans-Joachim Bieg [b], Claus Marberger [b], Philipp Alt [a], Hanna Otto [a], Michael Schulz [a], Andreas Schultz [a], Erdi Kenar [a], Angelika C. Bullinger [d], Natasha Merat [c]

[a] *Robert Bosch GmbH, Cross-Domain Computing Solutions, Abstatt, Germany*
[b] *Robert Bosch GmbH, Corporate Research, Renningen, Germany*
[c] *Institute for Transport Studies, University of Leeds, Leeds, United Kingdom*
[d] *Ergonomics and Innovation, Chemnitz University of Technology, Chemnitz, Germany*

ARTICLE INFO

Keywords:
Highly Automated Vehicles
Driving Comfort
Driving Style
Human-Like Driving
Deceleration Profiles
Non-Driving Related Activities

ABSTRACT

As automated vehicles advance and become more widespread, it is increasingly important to ensure optimal driving comfort for passengers. Recent research has focused on developing driving styles for automated vehicles that are perceived to be most comfortable. However, there is still little understanding of whether, and how, possible driving styles need to be adjusted for specific traffic scenarios. In this study, 36 participants experienced three different deceleration profiles (a linear deceleration profile 'One-Step', and two versions of stepwise deceleration profiles 'Two-Step V1 and V2') across different driving scenarios (deceleration before curves, approaching a speed-limit sign, and a stop sign). Deceleration profiles were rated by participants and the impact of non-driving related activities on driving comfort was investigated. Results showed a positive rating for all deceleration profiles in terms of comfort. For decelerations to a standstill at a Stop Sign, participants seemed to prefer the One-Step approach, in which there is a continuous, and constant deceleration. However, participants described the Two-Step V1 as a gentle and calmer approach and ranked it more frequently as a personal favourite than the One-Step profile or the Two-Step V2 profile. The visual distraction of the passenger through a non-driving activity had no impact on passenger comfort or profile preferences for the scenarios tested within this study. Nonetheless, participants reported perceiving a lower intensity of longitudinal vehicle movements when visually distracted during the drive. The results of the study provide insights into the design and implementation of comfortable deceleration profiles.

1. Introduction

Highly automated driving (SAE Level 4; SAE, 2021) can have far-reaching advantages but also comes with new challenges. One key challenge is to ensure comfort for the passenger, even when engaging in non-driving related activities such as smartphones and tablets (Diels & Thompson, 2018). Despite significant technological developments and years of research, there are still concerns that an unnatural driving style of Highly Automated Vehicles (HAVs) could cause discomfort (Elbanhawi, Simic, & Jazar, 2015; Deligianni

* Corresponding author at: Robert Bosch GmbH, Cross-Domain Computing Solutions, Abstatt, Germany.
E-mail addresses: stefanie.horn@de.bosch.com, tsseh@leeds.ac.uk (S. Horn).

https://doi.org/10.1016/j.trf.2024.05.025
Received 17 November 2023; Received in revised form 25 April 2024; Accepted 29 May 2024
Available online 16 July 2024
1369-8478/

et al., 2017). This unnaturalness may arise from the fact that HAVs' movement patterns are likely to differ from human manual driving patterns because HAVs determine their kinematics through sensor perception and make decisions based on optimised logic, norms, and technical constraints (ISO, 2020). Human-like driving, on the other hand, is a habitual way of driving which involves practising and repeating manoeuvres. It evolves from personal experiences and is shaped by individual speed preferences, thresholds for overtaking, distances to obstacles, and attitudes towards traffic regulations, which are "expected to be influenced by attitudes and beliefs relating to driving as well as more general needs and values" (Elander, West & French, 1993, p. 279). An HAV driving style may not align with passengers' preferences (Peng et al., 2022). Therefore, it may be beneficial to study and incorporate human-like driving patterns into HAVs' driving style, to enhance passenger driving comfort and match passengers' preferences (Scherer et al., 2016; Natarajan, Akash, & Misu, 2022).

Driving comfort is defined as a "state which is achieved by the removal or absence of uneasiness and distress" (Bellem et al., 2016, p. 45). Various factors can influence comfort, including vertical, longitudinal, and lateral motion forces such as acceleration and jerk (Bae, Moon & Seo, 2020; Bellem et al., 2016; Yusof et al., 2016). Acceleration represents the rate of change of velocity with respect to time, while jerk is the rate at which the vehicle's acceleration changes over time. These forces cause movements of the passenger's head and body and can influence the perception of comfort and well-being, particularly when the passenger is engaged in a non-driving related activity (NDRA) such as reading (Burkhard et al., 2018). Very high jerk can be similar to the experience of a 'kick'-movement (de Winkel et al., 2023). The focus of this paper will be on deceleration manoeuvres, which have a large influence on these body movements, and are important to control vehicle speed, the distance to obstacles, and to reduce the risk of traffic accidents. Improving the driving style of a vehicle by reducing the forces acting on the passengers' bodies is a common approach to enhance passenger comfort (Elbanhawi, Simic, & Jazar, 2015). Dettmann et al. (2021) and Bellem et al. (2018) advise that this can be achieved through smooth acceleration and jerk values. Suitable values for acceleration and jerk for driving comfort have been analysed in previous studies (Scherer et al., 2016; Yusof et al., 2016; Bellem et al., 2018; Peng et al., 2022). These studies consistently show a preference for lower over higher values for acceleration and jerk, as they reduce the forces acting on the passengers' bodies. However, different studies suggest different values for comfortable longitudinal declaration and jerk values. Well-perceived values for peak longitudinal decelerations range from -0.5 m/s^2 (Hajiseyedjavadi et al., 2022) to -1.3 m/s^2 (Ekman et al., 2016; Yusof et al., 2016). These values were obtained from Wizard-of-Oz experiments using manually driven vehicles or from motion-based driving simulator studies. Scherer et al. (2016) investigated driving comfort values in a test track study with a real HAV, using different deceleration values for declarations from 30 to 0 kph before stop signs. They recommend that HAVs should not use a deceleration value below -1.0 m/s^2 to enhance comfort. Despite the important relationship between jerk and human motion perception (Gianna, Heimbrand & Gretsy, 1996), to our knowledge, no specific analysis of comfortable jerk values for HAVs has been conducted yet. An investigation by Bellem et al., (2016,2017) showed that jerk has an even stronger impact on driving comfort than acceleration, leading to a recommendation of smooth initial action (corresponds to a smooth initial jerk) at the beginning of decelerations. Müller et al. (2013) examined the thresholds of human 'just notable differences' (JND) for vehicle motions and identified an average threshold value of 0.53 m/s^3 for jerk. This JND threshold could serve as a basis for further investigations into comfortable jerk values for HAVs.

Apart from identifying comfortably experienced peak values for acceleration and jerk, it is crucial to understand how the deceleration profile can be designed to make it as natural and human-like as possible. The deceleration profile refers to the pattern of decreasing velocity over time and can take on various shapes. Bellem et al. (2018) proposed different deceleration profiles for decelerations of an HAV driving behind a truck in a moving-simulator-based study. The results implied that passengers did not like a deceleration profile involving a rapid jerk applied over a longer period right at the onset of the deceleration (in this study, it was 2 s). This suggests that the initial jerk should be rather smooth. Scherer et al. (2016) proposed a deceleration profile which was derived from human-like driving from manual drives in a driving simulator. This profile gradually reduced speed by breaking down the deceleration process into phases. This could be helpful to reduce jerk and, consequently, forces acting on the passenger's body. The research findings by Scherer et al. (2016) indicated that participants considered the onset of the deceleration profiles derived by human manual drives as too soon, associated with a lower deceleration peak of -0.81 m/s^2, and generally found it less pleasant compared to a faster linear deceleration approach that utilized a higher deceleration peak of -1.35 m/s^2. However, it remained unclear whether the negative ratings were related to the design and shape of the deceleration profile, or the peak deceleration itself.

Another limitation of HAV driving comfort studies so far is the insufficient investigation of passengers' engagement in NDRAs. Passengers of HAVs are allowed to divert their attention to other activities like reading or working (SAE International, 2021). However, visually distracted passengers are more susceptible to centripetal accelerations and tilt their heads less consistently compared to attentive passengers who are looking ahead (Burkhard et al., 2018). This phenomenon is a result of the unawareness of the upcoming vehicle manoeuvres when passengers' visual attention is diverted from the road ahead and may apply to longitudinal accelerations as well. Festner (2019, p. 141) also found that visually distracted passengers perceive excessive automated vehicle movements as less comfortable than attentive passengers. Increased or excessive vehicle dynamics can occur in situations in driving where the movements of the vehicle, such as acceleration, deceleration, or steering actions, are too intense or abrupt.

Consequently, Festner (2019) recommends an adaptation of the HAV driving style dependent on the passengers' activities. This leads to the question of whether human-like movement patterns are appropriate for inattentive passengers. It is important to note that human-like driving behaviour is not optimized for passengers who are visually distracted. However, professional chauffeurs are trained to transport passengers who may engage in NDRAs such as working on a laptop. The driving style of trained chauffeurs may differ from that of untrained manual drivers, and as mentioned by Festner (2019), their style of driving may provide valuable insights for the development of driving styles for HAVs. To the best of our knowledge, there have been no studies conducted so far that adapt driving behaviours from trained chauffeurs to study automated driving styles.

1.1. Current study

The present study builds on previous research findings and guidelines regarding comfortable acceleration values, jerk values, and their combination in deceleration profiles in highly automated driving. While some studies have investigated deceleration approaches for HAVs, there is a need for more detailed real-world investigations to determine which acceleration and jerk values, as well as deceleration profiles, are perceived as comfortable in highly automated driving, based on the passengers' state (e.g., visually distracted by an NDRA or attentive and watching the road ahead).

In this study, participants experienced two human-like deceleration profiles derived from driving data from a trained chauffeur, as well as one deceleration profile derived from state-of-the-art Advanced Driver Assistance Systems (ADAS). We addressed one main research question (Q1) along with two interconnected sub-questions (Q2, Q3) based on the quantitative data gathered during the study:

(Q1) Are the three deceleration profiles rated differently in terms of driving comfort?
(Q2) Do different deceleration scenarios influence the perceived driving comfort of the three deceleration profiles?
(Q3) Does the visual distraction of the passengers by an NDRA influence the perceived driving comfort of the three deceleration profiles?

In addition to these research questions, we addressed one more question based on qualitative interview data:

(Q4) Which Deceleration Profile was most preferred by the participants, and why?

2. Methods

2.1. Participants

A total of 36 participants (14 female, 22 male) took part in the study. The participants' ages ranged from 19 to 63 years (M = 42.33 years, SD = 14.5). Two data sets (2 male) had to be partially excluded from the evaluation due to missing data in some experimental conditions. Participants were recruited by an independent market research institute (ipi, Institute for Product and Market Research GmbH). They gave consent to participate in the study and were compensated for their involvement. The study received ethical approval from the Ethics Committee of the RUMBA project consortium (protocol name Bosch2022a, date of approval 9th May 2022).

For this study, only participants who had a valid driver's licence, were between 19 and 65 years old, had no professional driving experience (e.g., driving instructors, chauffeurs, or truck drivers), and were not employees of the automotive industry, were recruited.

A sensitivity to motion sickness could affect perceived driving comfort during the test drives. Therefore, all participants completed a preliminary survey asking how quickly they generally experience motion sickness symptoms as passengers, while reading a book or playing on their phones on curved roads or in stop-and-go traffic (see Fig. 1). It is noteworthy that 15 participants reported experiencing motion sickness symptoms after just 1 to 5 min on curved roads, and 11 participants experienced motion sickness after 15 min in

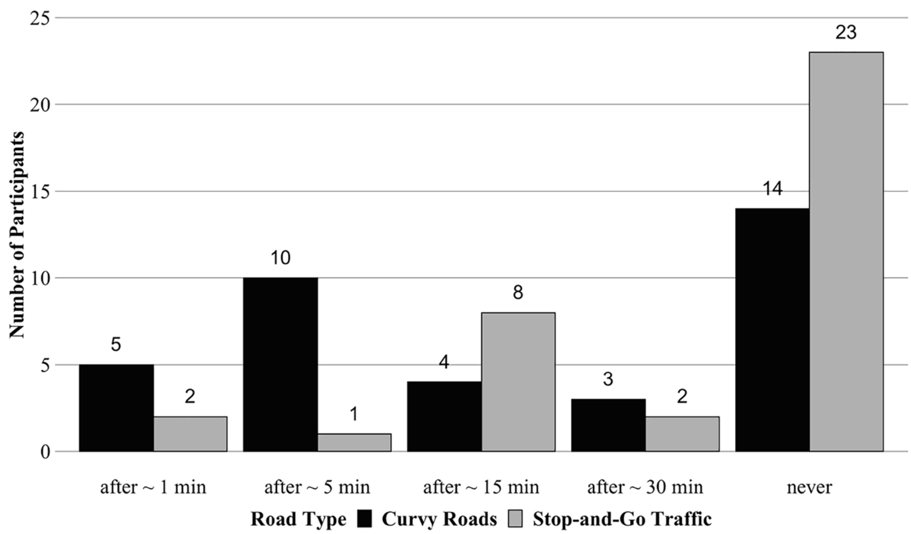

Fig. 1. Self-assessed sensitivity to motion sickness of participants at various time intervals during different driving conditions. Black bars correspond to curved roads and grey bars to stop-and-go traffic.

Fig. 2. The vehicle used for this study. It was equipped with an automated driving system.

stop-and-go traffic. No participants were excluded due to their sensitivity to motion sickness. However, study results will be interpreted in the context of these reports.

Participants also rated their interest in technology and cars on a 7-point scale (1 – "I find technology/cars boring" to 7 – "Technology/cars excite me"), with averages indicating that participants had a moderate to high interest in these variables (technology: M = 5.47, SD = 1.32; cars: M = 5.14, SD = 1.44). A majority (22 out of 36) preferred being passengers than drivers, others preferred being drivers due to a desire for control and dissatisfaction with others' driving. When asked about their use of driving assistance systems like cruise control, speed limiters, and lane-keeping assistants; cruise control was the most used (frequently to occasionally by 26 participants). Other systems were less known or rarely used, suggesting that participants had limited experience with semi-automated vehicles. The moderate to high affinity for technology and cars doesn't quite match the very limited use of ADAS systems while driving. Therefore, the affinity probably does not relate to the use of ADAS, but rather to other concepts of driving.

2.2. Apparatus

The experiment took place on a closed test track located in Bad Sobernheim, Germany (operated by TRIWO Automotive Testing GmbH). The track consists of one loop, with a length of approximately 3.10 km. One driving loop lasted approximately 4 min, and it took participants about 1 h to complete the study, including post-drive interviews. The vehicle used for this study was a VW Golf 7 Variant (see Fig. 2) equipped with an automated system designed to control both longitudinal and lateral operations of the vehicle, achieving Level 4 autonomy (SAE, 2021). To achieve high reproducibility of the vehicle's movements, a vehicle-in-the-loop system was used. This means that the system behaviour was not based on the real road layout (e.g., lane markings), but rather on a previously recorded GPS route. Participants were seated in the driver's seat of the vehicle, with a safety driver always present in the co-driver's seat to intervene in an emergency. In addition, the experimenter was seated in the back seat to be able to ask for the participants' feedback immediately after they experienced the scenarios relevant to the studies. The dashboard's HMI interface displayed driving-related information such as travelling speed, current set speed, detected traffic signs, curves, and upcoming manoeuvres. No other agent vehicle or vulnerable road user was present on the test track.

2.3. Independent variables

2.3.1. Deceleration profiles: derivation and description

In this study, we manipulated the deceleration profile of the vehicle to understand its effect on passenger comfort. To ensure consistency, the vehicle's maximum speed as well as average speed (time to complete one lap), lateral acceleration, and lane position

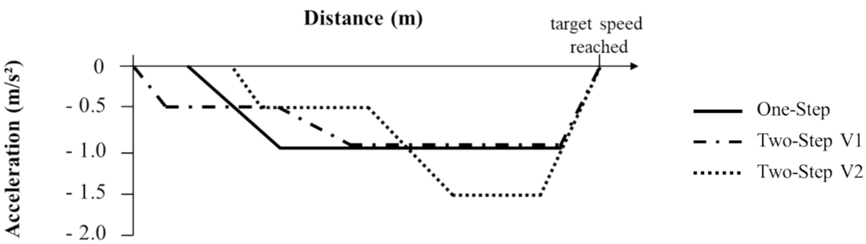

Fig. 3. Three Deceleration Profiles tested in this study are illustrated. The continuous line represents the One-Step profile, the dash-dotted line shows the Two-Step V1 profile, and the dotted line illustrates the Two-Step V2 profile. The three Deceleration Profiles have different deceleration onset points but reach the target speed at the same point.

Table 1
Key parameters for characterising the longitudinal decelerations of the One-Step Profile.

Parameter	Description	One-Step Profile
$a_{x,min}$	maximum deceleration value in m/s2 (rate of change of longitudinal speed along x-axis)	-1.0 m/s^2
j_x	jerk in m/s3 (rate of change of the longitudinal acceleration along x-axis)	-0.6 m/s^3

were maintained at the same level across all trials. One trial corresponded to one lap of the test track. We implemented three different deceleration profiles, namely the One-Step, Two-Step Version 1 (V1), and Two-Step Version 2 (V2) profiles, as illustrated in Fig. 3. These profiles were developed using current state-of-the-art practices (Bellem et al., 2018), and driving data obtained from a chauffeur before the commencement of this study.

2.3.1.1. One-step deceleration profile. Table 1 provides an overview of the key parameters used to implement the **One-Step Profile**. This profile represents a symmetrical deceleration design commonly found in recent ADAS applications and was used in a similar form by Bellem et al. (2018). This One-Step profile features a symmetrical-looking shape (see Fig. 3) and is characterized by a maximum deceleration value of $a_{x,min} = -1.0$ m/s^2 and an input jerk of $j_x = -0.6$ m/s^3.

2.3.1.2. Two-step deceleration profiles. The Two-Step approaches V1 and V2 were derived from chauffeur-like driving behaviour. To gather data for these profiles, driving data was collected from a professional chauffeur driving the study's test track. Information on GPS, speed, acceleration, jerk, accelerator and braking pedal activation was captured and recorded. Analysis of decelerations over a 1.5 h −drive indicated that the chauffeur gradually released the pressure on the accelerator pedal, allowing the car to coast for a brief period (approximately 2 s on average), before gradually applying the braking pedal. This process effectively divides the deceleration into two steps: a first input jerk, which corresponds to releasing the accelerator pedal, and a second input jerk, which corresponds to the application of the braking pedal. The first input jerk was brief (on average about 1 sec, observed jerk values: -0.9 to -1.5 m/s^3) and corresponded to releasing the accelerator pedal, followed by a plateau where acceleration remained constant for 2 s before a second input jerk (observed jerk values: -0.3 to -0.6 m/s^3) which corresponded to the application of the braking pedal.

The profile identified from the chauffeur's driving data does not correspond to the human-like deceleration profile presented in a study by Bellem et al. (2018), which was derived from manual driving data. However, this chauffeur's approach supports the suggestions made by Bellem et al. (2018) regarding the reduction of jerk at the beginning of a deceleration action. This reduction in initial forces acting on the passengers' body at the onset of the deceleration, potentially reduces the forces referred to as a 'kick'-head movement by de Winkel et al. (2023). Table 2 provides an overview of the key parameters used to design the Two-Step profiles.

The Variant **Two-Step V1** achieves a maximum deceleration value of $a_{x,min} = -1$ m/s^2, analogous to the One-Step profile. This occurs via a short input jerk of $j_{x,1} = -1$ m/s^3 and a second smoother jerk of $j_{x,2} = -0.3$ m/s^3. The plateau between steps one, $j_{x,1}$, and two, $j_{x,2}$, reaches an acceleration of $a_{x,min,1} = -0.5$ m/s^2 and is 2 s long.

Deceleration Profile **Two-Step V2** achieves a maximum deceleration value of -1.5 m/s^2. This occurs via an input jerk of $j_{x,1} = -1$ m/s^3 and a second jerk of $j_{x,2} = -0.6$ m/s^3. The plateau between steps one, $a_{x,min,1} = -0.5$ m/s^2, and two $a_{x,min,2} = -1.5$ m/s^2, reaches an acceleration of $a_{x,min,1} = -0.5$ m/s^2 and is also 2 s long.

The Two-Step V2 differs only in the second input jerk (see second phase of acceleration decrease in Fig. 3) and the maximum acceleration value from V1. Variant V2 was included to learn whether a Two-Step variant using a higher deceleration peak value is perceived as more comfortable compared to the One-Step variant (One Step $a_{x,min} = -1.0$ m/s^2 and Two-Step V2 $a_{x,min,2} = -1.5$ m/s^2).

Each of the three deceleration profiles results in different deceleration distances (in meters) from the deceleration onset until the target speed is reached (see label on the x-axis in Fig. 3), influenced also by the extent of speed reduction. As a result, they commence from distinct points and converge at the same point where the target speed is reached (see Fig. 3). This approach ensures maximum comparability among the three profile variants within these physical limits.

In addition to the three Deceleration Profiles, participants were exposed to another driving behaviour within a separate drive. This behaviour involved varying deceleration onsets and deceleration values and was presented in a randomized order alongside the other three Deceleration Profiles. This driving behaviour was included for separate testing purposes and is not the focus of this paper.

Table 2
Key parameters for characterising the longitudinal decelerations of the Two-Step Profiles.

Parameter	Description	Two-Step V1	Two-Step V2
$a_{x,min,1}$	first maximum deceleration plateau in m/s^2 describing the first Step of the Two-Step profiles	-0.5 m/s^2	-0.5 m/s^2
$a_{x,min,2}$	second maximum deceleration plateau in m/s^2 describing the second Step of the Two-Step profiles	-1.0 m/s^2	-1.5 m/s^2
$j_{x,1}$	first jerk in m/s^3 applied to build up the first plateau of the Two-Step profiles	-1.0 m/s^3	-1.0 m/s^3
$j_{x,2}$	second jerk in m/s^3 applied to build up the second plateau of the Two-Step profiles	-0.3 m/s^3	-0.6 m/s^3

2.3.2. Deceleration scenarios

To evaluate the deceleration profiles, participants were asked to rate the decelerations in four different driving scenarios (see Fig. 4):

- Scenario 1: Deceleration from 70 kph to 50 kph in front of a Curve (left bend, wide radius of about 100 m). The vehicle reached the target speed halfway between the curve entrance and the curve apex.
- Scenario 2: Deceleration from 65 kph to 35 kph in front of a Curve (left bend, narrow radius of about 25 m). The vehicle reached the target speed halfway between the curve entrance and the curve apex.
- Scenario 3: Deceleration from 70 kph to 50 kph in front of a 50 kph Speed Limit Sign. The vehicle reached the target speed when approaching the Speed Limit Sign.
- Scenario 4: Deceleration in front of a Stop Sign from 40 kph to 0 kph. The vehicle reached the target speed 2 m ahead of the Stop Sign.

2.3.3. Non-driving related activity

To evaluate the impact of NDRA engagement on the users' experience of the deceleration profiles, participants were requested to engage in the Surrogate Reference Task (SuRT; ISO, 2015), using the "SuRT-Mobile" app 2015, developed by the DLR Institute of Transportation Systems. The SuRT task was presented on a smartphone screen and entailed a visual-manual activity (see Fig. 5). Participants were required to identify and click on the side (right or left) where a target circle, larger than all other circles displayed, was located. For this task, they were instructed to hold the smartphone in their dominant hand in a natural position. Participants were instructed by the experimenter to "play the game as well as possible and to try to reach a higher score compared to their previous attempt". The participants' performance in this task was not recorded. Instructions were only given to ensure that participants focused on the task and moved their visual attention away from the road ahead.

Eye movement data from the participants were collected to analyse engagement in the NDRA. For this purpose, an infrared camera (1.2 MP resolution) with active infrared illumination was placed on the dashboard behind the steering wheel. Images were recorded

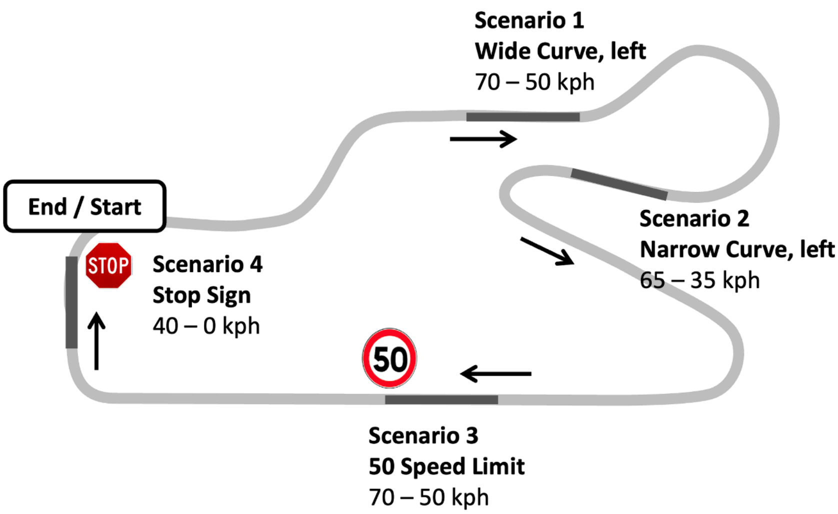

Fig. 4. The 3.10 km test track loop. Deceleration Scenarios 1–4 are depicted in the illustration, with the dark grey colour highlighting the areas where the decelerations occurred. The drives ended at the stop sign and started immediately after it.

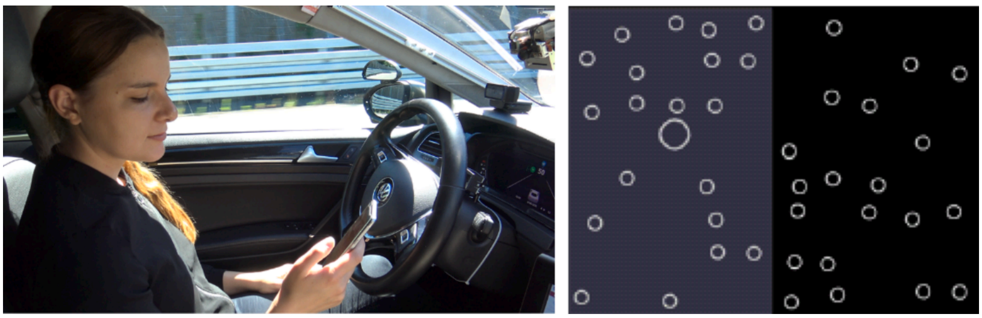

Fig. 5. A passenger in the test vehicle holding the smartphone while engaging in a NDRA, specifically the SuRT, which is displayed on the right side. The smartphone was positioned in the passenger's dominant hand.

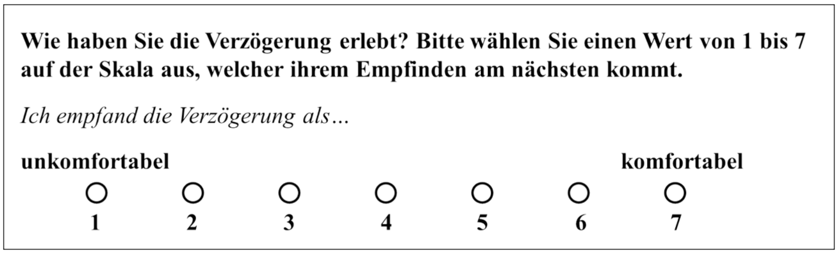

Fig. 6. The original comfort scale used in this study is in German language.

throughout the experiment at a rate of 48 Hz. Processing of the images and computation of glance statistics occurred off-line following the procedures described in Bieg et al. (2020) and Victor et al. (2005). The percentage of road centre gazes (PRC) was computed from gaze pitch and heading angles within a region of $\pm 20^\circ$ eccentricity (here, 0° denotes a glance ahead towards the road). This proportion was computed while participants were driving (velocity > 10 km/h) for each condition and is used to determine if participants diverted their visual attention to the NDRA by looking down at the smartphone or maintained their focus on the road by looking ahead.

2.4. Dependent variables

2.4.1. Post-scenario rating

After each deceleration scenario, right after the vehicle reached the target speed, the participants were asked to evaluate the deceleration manoeuvre based on perceived comfort using a 7-point Likert scale (see Fig. 6). For instance, immediately after the deceleration process in front of the curve was completed, the experimenter asked the participant “How did you perceive the deceleration? Please choose a value on the scale from 1 to 7 that best represents your experience.” And instructed them to provide a verbal rating using the scale provided: 1) “I experienced the deceleration as … 1 – uncomfortable to 7 – comfortable”. The scale shown in Fig. 6 was positioned at the middle console of the vehicle, enabling the participants to access questions at any time.

2.4.2. Post-drive evaluations

The drives were divided into two categories: Block A and Block B, as further detailed in Section 2.5. In Block A, participants had the opportunity to observe the drive ahead, while in Block B, participants were directed to participate in the SuRT task. Once participants completed each drive, a brief semi-structured interview was carried out, aiming to uncover impressions of deceleration profiles and personal preferences. The interview following the drives in Block A included the following open-ended questions:

- How did you perceive the decelerations during the recent automated drive?
- In comparison to the previous drive, how was your overall driving experience?
- Did you perceive any differences between the current drive and the previous one?

After experiencing drives within Block B while engaged in an NDRA, participants were asked two more questions in addition to the ones mentioned above:

- How did you feel while being driven and playing the game on the smartphone?
- Were you able to freely engage in playing the game?

After responding to the interview questions, participants were requested to rank the Deceleration Profiles. If they were unable to decide, participants had the option to assign multiple Deceleration Profiles to the same rank:

- Please rank the Deceleration Profiles, starting with your favourite and moving downward.
- Which variant would you personally prefer and why?

2.5. Design and procedure

This experiment utilized a within-subject design (see study procedure depicted in Fig. 7). The Deceleration Scenario (four scenarios shown in Fig. 4), the Deceleration Profile (three variants shown in Fig. 3), and the Passenger State (two states: attentive and looking ahead vs. visually distracted by an NDRA) were chosen as within-subject factors. All participants experienced each Deceleration Profile twice across all deceleration scenarios, once in an attentive state and once in a visually distracted state (see Fig. 7, Block A and B), resulting in six experimental drives on the test track in total (one drive lasted about 5 Minutes).

Before the experiment, participants were required to provide their consent and complete a pre-experimental questionnaire that included demographic questions. Upon arrival, they were provided with information about the procedure. Before the experimental trials began, participants underwent two practice drives on the test track to allow familiarisation with the vehicle and the environment. During the first practice drive, participants were seated in the co-driver’s seat, and the safety driver manually drove the vehicle for one

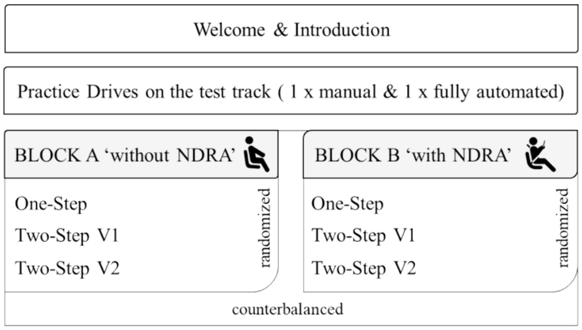

Fig. 7. Schematic representation of the study procedure. Blocks were presented in a counterbalanced order. Variations of the deceleration profiles were presented randomized.

loop on the test track. The experimenter used this opportunity to explain the Deceleration Scenarios, and participants were asked to provide an initial rating and familiarize themselves with the comfort rating scale (see Fig. 6). For the second practice drive, the participants were in the driver's seat and experienced a fully automated drive on the track. Each loop on the track began directly after the stop sign and ended with the vehicle coming to a standstill in front of the stop sign.

The experimental trials were carried out in a counterbalanced order of two Blocks, as shown in Fig. 7. In Block A, the participants experienced the loop three times, experiencing a different Deceleration Profile each time, while looking ahead and watching the driving environment. After each deceleration was finished, the experimenter immediately prompted the participants to verbally rate their comfort level using the scale provided. At the end of each round, the vehicle came to a stop at the stop sign, and participants answered post-drive questions. After the second deceleration variant was experienced, participants were also asked to rank the variants they experienced after each loop. The same procedure was followed in Block B, but participants were asked to perform the NDRA on the smartphone while driving.

3. Results

The IBM software SPSS Statistics (Version 21.0.1.0 (171)) was used to analyse the data. For the NDRA engagement (section 3.1) and the post-scenario comfort analysis (section 3.2), repeated-measures ANOVAs were conducted. F-values were reported, with degrees of freedom (dfs) presented in parentheses. The format shows the Hypothesis df first (the number of subfactors of the variable minus one) and the Error df second (the product of the number of subjects minus one and the total number of measurements per subject minus one). A significance level of 0.05 and the effect size partial eta squared ($\eta_p{}^2$) were used to interpret the results. The p-values for all post hoc tests were adjusted using the Bonferroni-Holm method (Holm, 1979). An effect size of $\eta_p{}^2 = 0.01$ represents a small effect, while a value of $\eta_p{}^2 = 0.06$ signifies a medium effect, and a value of $\eta_p{}^2 = 0.14$ indicates a large effect. For the analysis of the post-drive profile rankings (section 3.3), the Wilcoxon-signed rank test was conducted to interpret the participants' feedback. A rank-biserial correlation (r) was used as an effect size measure (calculated by dividing the Z-score obtained from the test by the square root of the total number of observations, n = 34). For interpreting the magnitude of r, Cohen's benchmarks for small (0.1), medium (0.3), and large (0.5) effect sizes were used for interpretation.

The order of the experimental trials (which have been randomized) and blocks (which have been counterbalanced), the participant's age and gender showed no statistically significant effects on the participants' feedback and are therefore not reported. Moreover, no link between motion sickness sensitivity, affinity for technology/cars, preferences for being driven as a co-driver, experience with driver assistant systems, and perceived driving comfort and rankings could be found for the sample of this study.

3.1. NDRA engagement checking

NDRA engagement required participants to divert their attention from the road to the smartphone. To verify that attention was indeed diverted, we monitored the Percentage of fixations towards the Road Centre (PRC) using eye-tracking throughout the drives. While the presence of the steering wheel or participants' arms occasionally obstructed the eye-tracker, resulting in a loss of data, we still achieved over 90 % data availability on average. However, technical limitations required the exclusion of eye-tracking data from 8 participants, leaving us with data from n = 28 participants for analysis. Fig. 8 illustrates the PRC values across different conditions.

A two-way repeated-measures ANOVA was performed to investigate the effects of Passenger State (with vs. without NDRA engagement) and Deceleration Profile (One-Step, Two-Step V1, Two-Step V2) on the PRC. Mauchly's test indicated a violation of the sphericity assumption for the Passenger State effect, therefore the Greenhouse-Geisser correction was applied. The corrected ANOVA revealed a highly significant main effect for Passenger State ($F(1.00, 27.00) = 681.750$, $p < 0.001$***, $\eta_p{}^2 = 0.967$), indicating that passengers glanced away from the roadway more frequently when engaged with the NDRA ($M_{Block2} = 0.07$, $SE = 0.02$) than when they were looking straight ahead ($M_{Block1} = 0.72$, $SE = 0.01$). In contrast, there was no significant effect for Deceleration Profile on PRC ($F(2,54) = 0.604$, $p = 0.551$, $\eta_p{}^2 = 0.026$), and no significant interaction effect ($F(2,54) = 0.527$, $p = 0.594$, $\eta_p{}^2 = 0.022$).

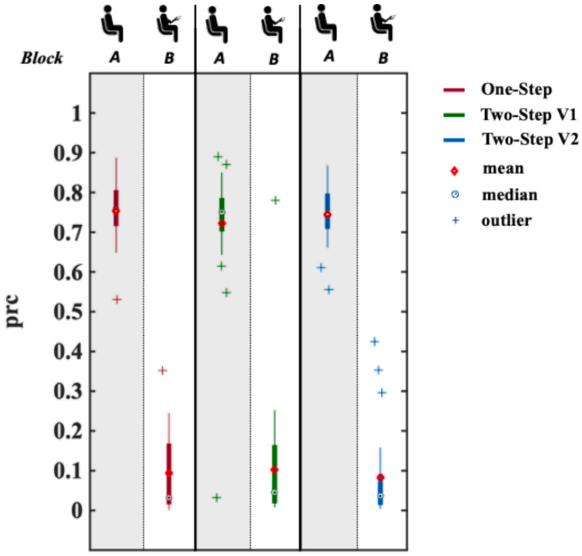

Fig. 8. Boxplots representing the percentage of road centre gazes (PRC, n = 28) distributions across the drives with different Deceleration Profiles for Block A (without NDRA engagement) and Block B (with NDRA engagement). The whiskers extend from the edge of the box to the farthest observation within a certain length (known as the adjacent value).

3.2. Post-scenario comfort ratings

The post-scenario comfort ratings were analysed using a three-way repeated-measures ANOVA with the within-subject factors Deceleration Profile (One-Step, Two-Step V1, Two-Step V2), Deceleration Scenario (Curve 1, Curve 2, 50 Speed Limit Sign, Stop Sign), and Passenger State (with vs. without NDRA engagement). Data from two participants was excluded from this analysis due to missing information from single experimental trials, leading to post-scenario feedback from n = 34 participants.

Overall, participants rated all three Deceleration Profiles positively in terms of comfort with mean ratings above 6.0 for all Deceleration Scenarios, respectively (ratings on a scale of 1-uncomfortable to 7-comfortable, see Fig. 9). Data points identified as outliers in the boxplots stem from different participants, suggesting that they are meaningful responses, and thus, they were not excluded from the tests.

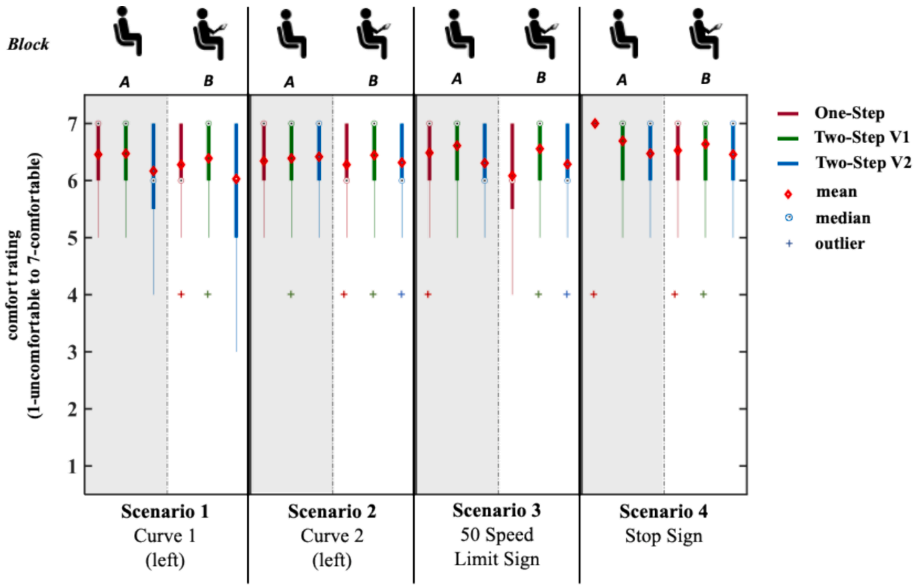

Fig. 9. Boxplots representing Comfort ratings (n = 34) across Deceleration Scenarios 1 to 4, for Block A (without NDRA) and Block B (with NDRA) and each Deceleration Profile. The whiskers extend from the edge of the box to the farthest observation within a certain length (known as the adjacent value).

A three-way repeated-measures ANOVA test showed a significant main effect of the Deceleration Scenario ($F(3,99) = 7.041$, $p < 0.001$***, $\eta_p^2 = 0.176$). Post-hoc Bonferroni tests showed significantly higher Passenger Comfort ratings for Scenario 4 (Stop Sign, M = 6.613, SE = 0.071) in comparison to Scenario 1 (Curve 1: M = 6.304, SE = 0.091, p = 0.003), Scenario 2 (Curve 2: M = 6.368, SE = 0.077, p < 0.001), and Scenario 3 (50 Speed Limit: M = 6.382, SE = 0.090, p = 0.047). There was no significant effect of the Deceleration Profile ($F(2,66) = 3.064$, $p = 0.053$, $\eta_p^2 = 0.085$), nor was there an effect of Passenger State (Greenhouse-Geisser correction applied: $F(1.00,33.00) = 4.110$, $p = 0.051$, $\eta_p^2 = 0.111$). The interactions between factors Passenger State and Deceleration Profile ($F(2,66) = 1.12$, $p = 0.331$, $\eta_p^2 = 0.03$), Passenger State and Deceleration Scenario ($F(3,99) = 0.04$, $p = 0.75$, $\eta_p^2 = 0.01$), Deceleration Profile and Deceleration Scenario ($F(6,198) = 1.66$, $p = 0.013$, $\eta_p^2 = 0.05$), and Passenger State x Deceleration Profile x Deceleration Scenario ($F(6,198) = 9.72$, $p = 0.628$, $\eta_p^2 = 0.02$) were all non-significant.

3.3. Post-drive ranking

Participants were instructed to rank the profiles after experiencing the second deceleration variant within each Block. They were allowed to assign multiple profiles to a single rank. For instance, one participant chose to rank both the One-Step and Two-Step V1 variants as their top choice on rank 1, and Two-Step V2 on rank 2. The results of this ranking are depicted in Fig. 10. Across each Block, the majority of participants consistently ranked Two-Step V1 as their first choice, in comparison to One-Step and Two-Step V2. This trend is more prominent in Block A where the participants didn’t engage in the NDRA.

The goal of the statistical analysis was to determine which Deceleration Profile was most preferred by the participants for the drives without NDRA (Block A) and the drives with NDRA (Block B), respectively. Data from two participants was excluded from this analysis due to missing information from single experimental trials, leading to post-drive rankings from n = 34 participants. We analysed the frequency with which each Deceleration Profile was assigned to the top rank 1. Therefore, we conducted two separate Wilcoxon-Signed-Ranks tests, one for Block A and one for Block B.

Within Block A, participants assigned profile Two-Step V1 significantly more often on rank 1 than Two-Step V2 (Z = 2.540, n = 34, p = 0.011, r = 0.435), indicating a moderate to strong preference for Two-Step V1. There was no significant difference between the One-Step and Two-Step V1 (Z = 1.084, n = 34, p = 0.28, r = 0.186) and no difference between One-Step and Two-Step V2 (Z = 1.900, n = 34, p = 0.057, r = 0.326).

The analysis for Block B showed that participants assigned Two-Step V1 more often on rank 1 than Two-Step V2 (Z = 2.144, n = 34, p = 0.032, r = 0.368). No statistical differences in rankings were found between One-Step and Two-Step V1 (Z = 0.573, n = 34, p = 0.567, r = 0.098) or between One-Step and Two-Step V2 (Z = 1.895, n = 34, p = 0.058, r = 0.325).

3.4. Qualitative feedback

The objective of the interview was to gain a deeper understanding of the participant’s *perception of the three Deceleration Profiles,* and their *reasons for favouring a particular profile* across Block A and B. Furthermore, the interview aimed to explore any perceived *differences between the drives with and without NDRA engagement*. Participants had the freedom to provide as much feedback as they wanted, and some participants were able to share more detailed impressions than others. The experimenter carefully transcribed the insights obtained from the interviews conducted during the study. The transcript was independently analysed by two researchers, who

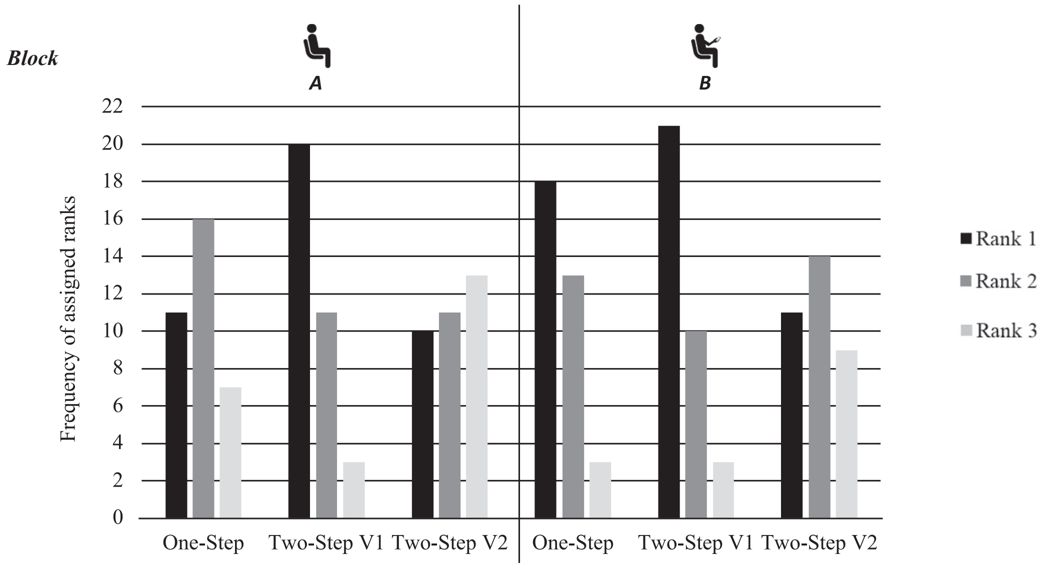

Fig. 10. Ranking of the Deceleration Profiles (n = 34) with the possibility to assign the same rank to multiple profiles.

categorized it according to the relevant topics and questions. Subsequently, categories were established to group the participants' terms used in their responses. These categories were adopted from an experts' comfort workshop by Peng et al., (2024), who derived categories based on frequently used definitions of comfort. They were additionally reviewed and discussed by the two researchers to ensure coherence and reliability.

The following categories were identified for the terms used by the participants to describe their experience of the drives within **Block A**:

1. Perception of the *Physical Comfort* and *Physical Discomfort* during the drive includes terms describing the physical perception of the vehicle's movements, and the naturalness (for definition see Introduction, p.1 of this manuscript) of the driving style.
2. *Comparison* of the *Kinematic Behaviour* of the vehicle across the different drives,
3. Perception of the feeling of *Ease and Unease* includes terms such as comfortable, calm, and relaxed for ease and their counterparts for unease.
4. Perception of the feeling of *Pleasantness* or the *Lack of Pleasantness* includes terms linked to happiness and positive effects for pleasantness, and the counterparts for the lack of pleasantness.
5. Perception of the feeling of *Safety* or the *Lack of Safety* includes terms linked to feeling safe and secure or their counterparts for the lack of safety.

A summary of the terms used by the participants within these categories is presented in Table 3. Blue-marked category names reflect a positive valence of the terms in that category, and light, red-marked category names reflect negatively associated terms within the category. In general, it can be noticed that the terms used are predominantly linked to positively valenced categories. Nonetheless, some differences can be observed in the terms participants chose to describe their experiences of the three Deceleration Profiles. Participants used a larger variety of terms to describe their feelings around *Physical Comfort* after the drives with the One-Step and Two-Step V1 Profile, in comparison to the drives with the Two-Step V2 profile. While participants felt that the vehicle dynamics of the drive with One-Step and Two-Step V1 were 'appropriate', or 'well balanced/slow', the opposite was mentioned for Two-Step V2, which was described as 'sporty' and 'jerky' (see category *Physical Discomfort*). The terms, 'sporty', 'jerky', and 'unnatural' were also brought up to express their experience of the One-Step Profile, but not as frequently as for Two-Step V2. However, overall, all three Deceleration Profiles were considered as 'smooth' and 'natural' by participants. The *Deceleration Onset* of the three Deceleration Profiles was assessed differently: The onset of the Two-Step V2 deceleration was more often evaluated as 'too late' in comparison to the One-Step version, while the onset of Two-Step V1 was referred to as 'well-chosen' and 'earlier' than One-Step and Two-Step V2. Generally, participants perceived the Two-Step V2 as 'more dynamic'[1] than One-Step and Two-Step V1. A few also described One-Step as 'more dynamic' than Two-Step V1. When looking at the terms used to express their feelings around the category *Ease*, fewer terms can be found for the Two-Step V2 profile than for One-Step and Two-Step V1. Participants mentioned the feeling of being 'relaxed' across all drives, however, 'comfort' was mentioned explicitly for One-Step and Two-Step V1, and the term 'calm' only for Two-Step V1. Terms around the feeling of *Pleasantness* were used for all three Deceleration Profiles, whereby the number of mentions was noticeably higher for Two-Step V1, lower for One-Step and lowest for Two-Step V2. All the terms mentioned around the perceived feeling of *Safety* were positive terms for One-Step and Two-Step V1. These include the terms 'safe', 'anticipatory', 'less risky', 'in good hands' or 'well-considered'. The term 'responsive', which can be interpreted as positive, was only mentioned for Two-Step V2, and the participant who mentioned it explained that "I prefer this driving style because I feel that the vehicle is doing something and reacts.". Apart from that, some participants described Two-Step V2 with the term 'risky' and referred to it as 'unsafe'.

When engaging in NDRA during the drive within **Block B**, 17 out of 34 participants explicitly mentioned being mentally distracted by playing the game and perceiving the vehicle movements only subliminally. Six participants stated that the curved parts of the drive felt somewhat disturbing when engaging in the smartphone game. Three different individuals highlighted that they were unable to play the game unhindered across all three drives because they felt rather unsafe and wanted to look ahead and observe the vehicle's behaviour.

In addition to the categories assigned for the terms mentioned in Block A, within Block B the category "NDRA engagement" referred to the ability to actively engage in the NDRA during the drive.

It was assessed through two questions included in the interview after the drives in Block B (see section 2.4.2). The participants' terms are summarised in Table 4. Upon initial examination, it becomes apparent that participants used a smaller number of terms to describe their experience of *Physical Comfort* than in Block A.

Once again, all three Deceleration Profiles were consistently associated with terms like 'smooth' and 'natural'. While 'appropriate dynamics' were mentioned for the One-Step and Two-Step V1 profiles, they were not mentioned for the Two-Step V2 profile. Additionally, a 'constant braking pattern' was only noted for the One-Step profile, aligning with the terminology used in Block A. During the NDRA engagement, participants did not mention terms such as 'slow' or 'slow speed', and they seemed unable to evaluate the deceleration onset or offset. Similar to Block A, participants expressed terms related to *Physical Discomfort* such as 'too sporty', 'jerky', 'unnatural', and 'too strong deceleration', particularly after the drives with Two-Step V2 and One-Step profiles. Another term that emerged solely after drives with NDRA engagement was 'too strong lateral forces'. One participant who mentioned this explained,

[1] Participants described in the interviews in the German language a profile as "dynamischer" (more dynamic). They linked the description "dynamischer" with a driving style perceived as active, leading to a heightened sense of movement (e.g., quicker changes in speed and direction) and potentially less comfort. In German, the "weniger dynamisch" (less dynamic) driving style was described as gentler, with slower changes in speed and direction. Participants experienced this as a calmer and more stable ride, leading to a higher sense of comfort.

Table 3
Categorisation of the terms describing the participants' qualitative perception of the three Deceleration Profiles, encompassing drives in Block A when driven with no NDRA engagement. Numbers next to each term represent the number of times each term was mentioned by participants (n = 34). Participants had the freedom to provide as much feedback as they wanted. Repetitions of terms from a single participant are excluded from the word count.

Category of terms	One-Step Profile [a]	Two-Step V1 Profile [b]	Two-Step V2 Profile [c]
Physical Comfort	appropriate dynamics (3)	appropriate dynamics (4)	
	well-balanced between sporty and too slow (2)	slow speed (2)	
	constant braking (6)		
	smooth (4)	smooth (10)	smooth (3)
	natural (2)	natural (5)	natural (3)
		deceleration onset well-chosen (3)	deceleration onset well-chosen (1)
Physical Discomfort	sporty (1)		sporty (11)
	jerky (1)		jerky (5)
	unnatural (3)		
			too strong deceleration (5)
	onset too late (4)		onset too late (9)
	onset too early (1)		
Comparison of Kinematic Behaviour	more dynamic than [b](4), and [c](3)	less dynamic than [a](6), [c](14)	more dynamic than [a], [b](12)
	less dynamic than [c] (12)		
		braking distance longer than [a], [c](2)	
Ease	relaxed (8)	relaxed (9)	relaxed (3)
	comfortable (6)	comfortable (10)	
		calm (6)	
Pleasantness	pleasant (10)	pleasant (18)	pleasant (8)
Perceived Safety	safe (2)	safe (4)	
	anticipatory (4)	anticipatory (2)	
	in good hands (1)		
		disciplined & well-considered (2)	
			responsive (2)
Lack of perceived Safety			unsafe (3)
			risky (3)

Table 4
Categorisation of the terms describing the participants' qualitative perception of the three Deceleration Profiles, encompassing drives in Block B when driven with NDRA engagement. Numbers next to each term represent the number of times each term was mentioned by participants (n = 34). Participants had the freedom to provide as much feedback as they wanted. Repetitions of terms from a single participant are excluded from the word count.

Category of terms	One-Step Profile [a]	Two-Step V1 Profile [b]	Two-Step V2 Profile [c]
Physical Comfort	appropriate dynamics (2)	appropriate dynamics (3)	
	constant braking (4)		
	smooth (7)	smooth (14)	smooth (6)
	natural (2)	natural (5)	natural (5)
Physical Discomfort	sporty (2)		sporty (5)
	jerky (3)		jerky (4)
	unnatural (2)		unnatural (1)
	too strong deceleration (5)	too strong deceleration (1)	too strong deceleration (7)
			onset too late (2)
	too strong lateral forces (5)	too strong lateral forces (5)	too strong lateral forces (4)
Comparison of Kinematic Behaviour	[a] more dynamic than [b](10)	[b] less dynamic than [c](13)	[c] more dynamic than [a](7)
	[a] more dynamic than [c](3)	[b] more dynamic than [a](1)	
			no difference between [a] & [c] (2)
		no difference between [b] & [c] (1)	
	no difference between [a] & [b] (6)		
		no difference between [a] & [b] & [c] (4)	
Ease	relaxed (6)	relaxed (5)	relaxed (5)
	comfortable (8)	comfortable (8)	comfortable (5)
		calm (1)	
Unease	tense (1)	tense (1)	tense (1)
Pleasantness	pleasant (12)	pleasant (16)	pleasant (8)
		satisfying (3)	satisfying (1)
Perceived Safety	safe (6)	safe (5)	safe (6)
		anticipatory (1)	responsive (1)
Lack of perceived Safety	not safe (2)	not safe (3)	not safe (2)
NDRA engagement	unfamiliar situation (5)	unfamiliar situation (6)	unfamiliar situation (4)
	able to play the game unhindered (30)	able to play the game unhindered (31)	able to play the game unhindered (30)
Lack of NDRA engagement	sometimes looked ahead to stay informed (4)	sometimes looked ahead to stay informed (2)	sometimes looked ahead to stay informed (5)

“During the drive, I only sensed the curves, prompting me to look up and observe the car’s behaviour.”. When *Comparing the Dynamics* of the three Deceleration Profiles, participants occasionally experienced difficulties distinguishing between the drives. Eleven participants explicitly stated that they felt no difference between at least two out of three driving behaviours experienced. One individual among these eleven mentioned, “I devoted 95 % of my attention to the game, leaving me with limited awareness of the decelerations.”. Others were able to make comparisons and predominantly perceived Two-Step V2 as more dynamic than One-Step and Two-Step V1. That notion that the One-Step profile was perceived as more dynamic than Two-Step V1 was mentioned more frequently than Two-Step V1 being perceived as more dynamic than One-Step. However, during the drives in Block B, participants mentioned feeling ‘tense’, leading to the addition of the category *Lack of Ease*. This category was specific to Block B and not observed in Block A. Regarding terms related to the category *Perceived Safety*, participants mentioned fewer terms in Block B. Participants who expressed feeling ‘unable to engage in the NDRA unhindered’ indicated that they felt ‘unsafe’ during those drives, which contributed to the category *Lack of Perceived Safety*. When asked about their experience of engaging in the Smartphone game during the drive, participants indicated that it felt ‘unfamiliar’ to be seated in the driver’s seat while shifting their attention to the game. Overall, the majority of participants stated that they were ‘able to play the game’ during the drive without hesitance. However, a few participants mentioned that they wanted to ‘occasionally look up/ ahead’ and observe the vehicle’s movements to stay informed. The PRC values in Fig. 8 (see section 3.1) showed that there were some outliers within the drives with NDRA engagement, which reflect the data of the participants who stated that they occasionally looked up.

4. Discussion

The objective of this study was to examine the impact of different Deceleration Profiles for automated driving on passengers’ evaluations of driving comfort. Building upon guidelines from prior research and pilot studies, three deceleration profiles were identified for inclusion: a One-Step, a Two-Step Version 1 (V1), and a Two-Step Version 2 (V2) deceleration profile. Two of these profiles showed similarities in jerk (input jerk of One-Step and Two-Step V2) and two of them similarities in the maximum deceleration peak value (One-Step and Two-Step V1, see Fig. 3). In addition, we examined the impact of NDRA engagement on passengers’ comfort levels while experiencing each of these profiles across different scenarios.

All three Deceleration Profiles were rated positively in terms of passenger comfort, and ratings were quite similar across the Deceleration Scenarios on the approach to two curves, a speed limit sign, and a stop sign. Interview results provided further insights into participants’ experiences of the three deceleration profiles. The terms employed by participants to convey their perceptions were consistently associated with categories related to driving comfort (Peng et al., 2024). It is noteworthy that although the comfort ratings for the three profiles were quite similar, terms around Physical Discomfort were only mentioned after drives with One-Step and Two-Step V2 within Block A (no NDRA engagement). These two profiles had a similar input jerk, which was higher than the Two-Step V1 input jerk. Terms linked to the Lack of Safety were solely brought up after drives with the Two-Step V2 profile. Overall, fewer positive words were used to describe the experience of Two-Step V2 compared to the other two profiles. Thus, it would appear that when passengers were not engaged in an NDRA, the jerk and maximum deceleration peak value experienced during the Two-Step V2 and One-Step profiles were experienced as causing more physical discomfort, and a greater lack of safety than the Two-Step V1 deceleration profile. However, interestingly, the study revealed that comfort was rated significantly higher for the deceleration in front of the Stop Sign in comparison to the deceleration in front of Curves 1/2 and the 50 Speed Limit Sign. It is important to note that the Stop Sign was the only scenario in which the AV came to a full standstill, whereas in all other scenarios, the AV just reduced its speed to a pre-defined target speed. During the interview, some participants mentioned a preference for a quicker and more responsive deceleration, like the One-Step profile, at the Stop Sign, allowing them to continue the drive as swiftly as possible, especially when there is no other traffic participant at the intersection, as was the case in the experiment. Since the One-Step profile reduces speed in a single step, it may have appeared more ’responsive’ when compared to the Two-Step profiles, which spread the deceleration across two steps. This leads us to believe that comfort preferences in terms of deceleration may vary depending on the situation. It also supports the findings of Delmas et al. (2022), who suggest that driving conditions should be considered to understand the factors relevant for optimising comfort.

While other studies (e.g., Festner, 2019) have shown an impact of NDRA engagement on passenger comfort, there were no significant effects in the current study. The interview results provide some interesting insights as to why this was the case. Participants reported that they became so distracted by the NDRA that distinguishing between the three deceleration profiles became difficult. Moreover, they indicated a decreased awareness of lateral vehicle movements when visually distracted by the NDRA, in contrast to their experience when being not distracted by an NDRA. A diminished perception of longitudinal vehicle movements and a more pronounced perception of lateral vehicle movements considered disturbing have already been reported by Festner (2019). This insight sheds light on why the comfort ratings, the rankings and post-Block B drive interviews showed less differentiation between the three profiles compared to those conducted after Block A drives, suggesting that manufacturers should prioritise refining lateral accelerations as well to enhance comfort.

Overall, the qualitative analysis of the interviews provided valuable insights beyond what was captured through quantitative ratings alone. This in-depth exploration enabled us to understand nuanced aspects of passengers’ perceptions, leading to more informed design recommendations.

To further interpret the findings, we explored if the participants’ characteristics (age and gender) and preferences (interest in technology and cars, preference for driving, use of ADAS), influenced their perceived driving comfort and ratings of the deceleration profiles. However, we found no link between these characteristics and participant feedback. This absence of a link, both in the quantitative and qualitative responses, suggests that preferences for driving profiles and comfort are highly individual. This highlights the potential benefit of customizing driving styles to suit individual preferences. Interestingly, even participants susceptible to motion sickness did not report differing experiences based on the vehicle deceleration pattern. Tomzig et al. (2023) found that a deceleration style similar to the Two-Step Versions applied in this study could even help to reduce motion sickness symptoms. Future research should systematically investigate how different driving parameters such as acceleration and jerk, and different driving profiles can impact or improve motion sickness symptoms and passengers' feelings of comfort.

4.1. Limitations

One of the limitations of the current study was that a ceiling effect emerged for all comfort questions, making it difficult to interpret the differences in comfort ratings. In general, it can be assumed that the Deceleration Profiles tested are all perceived and accepted as quite comfortable. However, the combination of quantitative ratings and qualitative interview results provides additional insights which allow us to understand which elements of a deceleration profile might contribute to the level of comfort experienced. Another potential limitation was the presence of a safety co-driver in the co-driver's seat. This may have influenced the participants' driving experience and therefore, their feelings of comfort. However, since the automated driving system controlled the vehicle movements, and the safety driver did not intervene in the driving task, potential impacts were likely minimal.

Finally, the chosen NDRA, the SuRT game, was perceived as an easy task and had only the purpose of distracting the passengers visually. Nevertheless, it appeared that passengers struggled to perceive longitudinal movements while actively participating in the NDRA. Another less cognitively demanding task might have led to different comfort perceptions by passengers. It would be relevant for subsequent studies to analyse passengers' comfort experiences with different types of NDRA.

4.2 Conclusions and future research

This study is one of the first investigations of different deceleration profile approaches for automated driving across different traffic scenarios using a real HAV and provides guidelines for the design of comfortably perceived deceleration profiles. Our results suggest that the traffic situation can influence passenger driving comfort during highly automated driving, particularly in the case of no engagement in other tasks. Although all three deceleration profiles can be recommended as leading to a positive level of driving comfort, the combination of both quantitative ratings and qualitative interviews provides useful insights for maximizing comfort. It could be beneficial to implement a profile which uses a lower peak deceleration of -1.0 m/s^2 and reflects the driving behaviour of the Two-Step V1 profile. This profile was ranked slightly better than the other profiles for drives with and without NDRA. In addition, unlike the other profiles, participants did not mention any terms relating to Physical Discomfort or Lack of Safety when discussing the Two-Step V1 profile. Future research should consider further external circumstances, road designs, road furniture, traffic interactions with other road users and different NDRAs as they might have additional impacts on passenger comfort (Rossner and Bullinger, 2020; Hajiseyedjavadi et al., 2022; Delmas et al., 2022). It is recommended to use a mixture of quantitative and qualitative investigations to provide the most detailed recommendations.

CRediT authorship contribution statement

Stefanie Horn: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Patrick Rossner:** Writing - review, Methodology, Conceptualization. **Ruth Madigan:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Hans-Joachim Bieg:** Writing – review & editing, Resources, Methodology, Data curation, Conceptualization. **Claus Marberger:** Writing – review & editing, Methodology, Conceptualization. **Philipp Alt:** Writing – review & editing, Resources, Methodology. **Hanna Otto:** Validation, Methodology, Conceptualization. **Michael Schulz:** Resources, Project administration, Methodology. **Andreas Schultz:** Writing – review & editing, Resources. **Erdi Kenar:** Resources. **Angelika C. Bullinger:** Supervision, Validation. **Natasha Merat:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

The authors of this study wish to thank Adelina Heinz and Konstantin Felbel from the Ergonomics and Innovation research group at TU Chemnitz for their invaluable contributions to the study. The study was conducted within the project RUMBA (www.projekt-rumba.de, accessed on 4th October 2023) which is funded by the German Federal Ministry of Economic Affairs and Climate Action (funding number: 19A20007K). The Hi-Drive project (Grant agreement 101006664) funded by the European Union's Horizon 2020 research and innovation programme also supported the study, as it sponsors the co-authors Dr. Ruth Madigan and Prof. Natasha Merat from the University of Leeds.

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