Measuring Passengers' Comfort and Perceived Safety in Automated Driving: Good Practices, Challenges, and Opportunities

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Abstract

Passenger comfort and perceived safety, as two psychological states, are crucial for user acceptance of automated driving. The accurate measurement of these passenger states contributes to human-centred designs for automated vehicles and developing predictive models for providing personalised settings. However, practical challenges and best practices are rarely discussed in the literature. This workshop aims to address this gap by creating a forum to synthesise current practices and explore novel, effective measurement approaches. The session includes expert talks on subjective, objective, and model-based measurement methodologies, and interactive breakout sessions. Participants will critically evaluate existing methodologies and design future multi-modal strategies, including incorporating artificial intelligence (AI). The workshop will produce numerous outcomes, including the collaborative development of a research outlook and a methodological paper for knowledge sharing.

CCS Concepts

• **Human-centered computing → HCI design and evaluation methods**; **HCI theory, concepts and models**.

Keywords

Comfort, Perceived safety, Automated vehicles, Measurement

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1 Introduction

Enhancing user experiences is crucial for the public acceptance of automated vehicles (AVs). Research has investigated passengers' psychological states, including comfort and perceived safety, to inform AV design and develop predictive models [3, 4, 6–8, 10, 13].

Comfort in automated driving is a state of "subjective feelings of ease and pleasantness", influenced by "users' expectations, their communication with AVs, and the varying environmental and traffic conditions" [13, p. 191]. Perceived safety is described as "feeling relaxed, safe and comfortable" [8, p. 179]. These concepts are closely linked, with research combining them, like "feeling safe/natural/comfortable", to evaluate an overall pleasant experience with automated driving [5]. [6] suggest that feeling safe and relaxation contribute to a positive experience, which ultimately enhances acceptance.

However, the subjective nature of these states presents challenges in their measurement. While a wide range of physical, psychological, and physiological methods exists, their application is inconsistent, and effective combinations are not well-explored. Moreover, the context of automated driving, such as limited cabin space, engagement in non-driving-related activities (NDRAs), and changing external environment, adds further complexities.

1.1 Subjective evaluation

Self-reported data, through single or multi-item scales, are common for subjective evaluation. Participants indicate their level of agreement or disagreement with one or multiple statements.

Single-item questions are practical and often used. For example, research has used a five-point Likert scale ranging from 1 (very comfortable) to 5 (very uncomfortable) [20] and an 11-point scale ranging from 0 (completely uncomfortable) to 10 (completely comfortable) [12]. [6] used a 100-point scale to measure discomfort during an automated ride; participants pressed a button on the handset to indicate their discomfort level on a scale ranging from 0 (comfortable) to 100 (uncomfortable). Similarly, [8] asked drivers to rate their perceived safety by pressing a sensor on the steering wheel, which provides visual feedback on an LED bar. Such pressure was mapped to a scale ranging from 1 to 10. However, single-item scales risk oversimplifying these complex states. Moreover, the variation in scale length (e.g., 5, 11, and 100) and labelling (e.g., very low versus completely uncomfortable) hinders the comparability of results across studies.

Multi-item scales offer more depth and allow examination of sub-constructs of comfort and perceived safety. [6] used a 32-item questionnaire to assess four dimensions of comfort, including convenience, joy, and lack of convenience and joy. [11] identified three items - feeling safe, relaxed, and anxious – to characterise perceived safety in partially automated driving. However, commonly accepted and validated scales for both states in the AV context are lacking. Second, their length makes them impractical for capturing the dynamic nature of these states in real-time during a drive.

1.2 Objective evaluation

Physiological metrics are used for real-time, non-intrusive monitoring of occupants during an automated ride. Research has shown that in uncomfortable situations, such as an AV approaching an intersection, heart rate decreases while pupil diameter increases and eye blink rate decreases [1]. [16] found skin conductance responses (SCRs) to be sensitive to discomfort in the changing driving environment. Motion sickness has been correlated with electrodermal activity, skin temperature, and heart rate, e.g., [17, 19]. Research has also linked perceived safety to metrics, such as electrodermal activity, heart rate variability, and pupil dilation [8, 15].

However, physiological measures also have limitations. Their use relies on the assumed correlation with various cognitive and emotional states, including stress, cognitive load, emotional arousal, and fatigue. Moreover, these signals are susceptible to artefacts caused by body movement, vehicle motion, and interactions with in-vehicle systems [2, 9], leading to potential inaccuracies. Individual variations also challenge the generalisation of physiological inferences [19].

1.3 Behavioural inferences

Users' behaviour is sometimes used to infer psychological states. For example, [14] suggested that passengers' willingness to engage in NDRAs might indicate comfort. Braking during the use of partial automation could suggest lower perceived safety [8]. However, the relationship between these behaviours and specific psychological states is not yet clearly established.

1.4 Overall remarks

Accurate measurement of comfort and perceived safety is essential for creating design guidelines [7] and developing predictive models for personalised AV experiences [10]. However, the practical challenges of these measurement techniques are often not explicitly discussed in the literature, while reflections on the pros and cons of different approaches could better inform future studies. More importantly, the effective combination of different methods to achieve accurate, real-time measurement of passenger states remains underexplored.

The emerging artificial intelligence (AI) and large language models (LLMs) offer potential for better understanding users and their intent [18]; however, the application of these tools to enhance passenger state measurement in the automated driving context has not been sufficiently investigated.

Taken together, a synthesis of current measurement approaches and an exploration of new mixed methods are needed to establish more generalisable measurements for these psychological states in automated driving. This assists researchers in the AutoUI community to better explore subjective experiences, which will ultimately contribute to improved AV designs and the development of more accurate predictive models.

2 Workshop goals

To address the lack of shared knowledge on effectively measuring passenger psychological states, this workshop will facilitate discussions on the practicalities of measuring passenger comfort and perceived safety in automated driving. We aim to synthesise current practices and collaboratively explore novel, effective, and reliable approaches. Specifically, we aim to:

(1) Evaluate methodologies: Share and critically evaluate existing measurement approaches, creating a community knowledge repository on their practical application.
(2) Identify future directions: Collaboratively brainstorm novel and combined measurement strategies, including AI and LLMs, for effective real-time assessment in automated driving.

To support these goals, we will bring together a multidisciplinary group of researchers and practitioners, featuring insights from invited experts. All interested participants are welcome.

3 Organisation

3.1 Pre-workshop

Dissemination activities, such as promoting the workshop on social media, will be made to attract interested participants.

3.2 Tentative schedule for the workshop

The workshop is expected to last about 2.5 to 3 hours. Three organisers (CP, PB, and YY) will moderate discussions and guide tasks. We expect approximately 15 participants.

(1) Welcome and introduction (10 min)

- Introduction of organisers and speakers.
- Introduction of the workshop's goals, activities, and schedule.
- Dividing the audience into two breakout groups.

(2) Workshop session 1: Setting the scene (80 min, incl. 10 min break)

- Organisers' introduction (10 min):
  Concise presentation providing definitions of comfort and perceived safety, a brief overview of current measurement approaches, and introducing the problem of lacking shared best practices and challenges of existing methods.
- Expert talks (60 min):
  Three speakers will discuss:

(a) Advantages and limitations of subjective measurement methods;
(b) Advantages and practical challenges of using objective data (e.g., physiological and behavioural), such as signal processing, artefact removal, and individual variations;
(c) Attempts and experiences of applying mathematical and AI-based models for passenger state measurements.
Speakers are encouraged to share their experiences in combining methods

(3) Workshop session 2: Discussions (40 min)

- Task 1: Critical assessment of the present (20 min)
  Each group discusses measurement categories (e.g., subjective, objective). Based on the talks and their experience, participants will identify: a) Challenges of each method. b) Effective solutions that have worked for them.
  This will be written down on post-it notes and arranged on a shared whiteboard.
- Task 2: Discovering future methodologies (20 min)
  Each group works on the following task: Develop a multimodal approach to continuously measure comfort and perceived safety in automated driving. This includes discussions on how to effectively combine subjective, objective, and behavioural data, and the role of AI/LLMs in data collection or real-time inference.

(4) Workshop session 3: Reflections (25 min)

- Each moderator summarises the output from each group. (20 min)
- Closing words (5 min)

4 Expected outcome

The primary outcome will be a shared, community-driven understanding of state-of-the-art in comfort and perceived safety measurement, moving beyond published literature to include practical experiences. This synthesis of current methodologies, challenges, and potential best practices will provide participants with a clearer methodological landscape, assisting researchers in the AutoUI community in selecting suitable methods. Second, this workshop will collaboratively define a research agenda and produce a methodological paper for public dissemination. This paper will outline key areas for future work, focusing on more robust, multi-modal measurement approaches and leveraging AI. Finally, by bringing together diverse experts and researchers, the workshop will build a strong professional network, fostering future collaborations to solve these critical measurement challenges.

5 Speakers

- Prof Riender Happee received the Ph.D. degree from Delft University of Technology, The Netherlands in 1992. He investigated road safety and introduced biomechanical human models for impact and comfort at TNO Automotive (1992-2007). Currently, he investigates human interaction with automated vehicles, focusing on safety, motion comfort and acceptance at the Delft University of Technology, where he is a Full Professor.
- Prof Marieke Martens is a full professor 'Automated Vehicles and Human Interaction' at Eindhoven University of Technology (TU/e). Since 1996, she has been working as a research in the area of human factors and traffic behavior at TNO. Marieke is primarily interested in research related to human behavior and automated driving, an innovation that is primarily technology driven and has far from reached the desired level of readiness to be safely introduced on a large scale on public roads for the general public.
- Dr. Kumar Akash is a Principal Scientist at Honda Research Institute USA, leading the Human and Social Science group in San Jose, California. His academic background includes a Ph.D. and M.S. in Mechanical Engineering from Purdue University and a B.Tech. from IIT Delhi. Dr. Akash's research centers on developing human-aware automated systems, focusing particularly on modeling and optimizing human behavior and cognitive states to enhance interactions between humans and intelligent automation.

6 Organisers

- Dr Chen Peng is a Research Fellow at the Institute for Transport Studies, University of Leeds. Her research interests include user comfort in automated driving, automated driving styles, communication strategies, inclusive designs in transport, and human-technology interaction. She received her PhD in human factors in automated driving as a Marie Curie Fellow from the University of Leeds.
- Dr Pavlo Bazilinskyy is an assistant professor at TU Eindhoven focusing on AI-driven interaction between automated vehicles and other road users. He finished his PhD at TU Delft in auditory feedback for automated driving as a Marie Curie Fellow, where he also worked as a postdoc. He was the head of data research at NEXTdriver. Pavlo is the treasurer of the Marie Curie Alumni Association (MCAA) and was a director of the Research and Innovation unit of the Erasmus Mundus Association (EMA).
- Yueteng Yu is is a PhD candidate in Human-Machine Interfaces (HMIs) for automated driving at Queensland University of Technology. His research focuses on multimodal HMI, situation awareness, and user experience in Level 3+ automated vehicles. He earned an MSc in Human-Computer Interaction from the University of Nottingham and conducted research with Tsinghua University's HCI group. His experience spans both academia and industry, including work as a UX researcher with car manufacturers and as a Software Engineer.
- Professor Natasha Merat, OBE, is an experimental psychologist and research group leader of the Human Factors and Safety Group at the Institute for Transport Studies, University of Leeds. She also leads the Automation theme at Leeds and is responsible for the strategic direction of research conducted at Virtuocity. Her main research interests are in understanding the interaction of road users with new technologies. She applies this interest to studying factors such as driver distraction and driver impairment, and she is an internationally recognised expert in studying the human factors implications of highly automated vehicles.

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References

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[2] Brinnae Bent, Benjamin A. Goldstein, Warren A. Kibbe, and Jessilyn P. Dunn. 2020. Investigating sources of inaccuracy in wearable optical heart rate sensors. *npj Digital Medicine* 3, 1 (Feb. 2020), 1–9. doi:10.1038/s41746-020-0226-6 Number: 1 Publisher: Nature Publishing Group.

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[4] Vadim Butakov and Petros Ioannou. 2015. Driving Autopilot with Personalization Feature for Improved Safety and Comfort. *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC* 2015-Octob (2015), 387–393. doi:10.1109/ITSC.2015.72 Publisher: IEEE ISBN: 9781467365956 TLDR: This paper presents methodology that allows automatic autopilot personalization based on driver performance models, which takes into account driver's preferences for a particular trip and manual parameters fine-tuning by the driver..

[5] Foroogh Hajiseyedjavadi, Erwin R. Boer, Richard Romano, Evangelos Paschalidis, Chongfeng Wei, Albert Solernou, Deborah Forster, and Natasha Merat. 2022. Effect of environmental factors and individual differences on subjective evaluation of human-like and conventional automated vehicle controllers. *Transportation Research Part F: Traffic Psychology and Behaviour* 90 (Oct. 2022), 1–14. doi:10.1016/j.trf.2022.07.018

[6] Franziska Hartwich, Matthias Beggiato, and Josef F. Krems. 2018. Driving comfort, enjoyment and acceptance of automated driving–effects of drivers' age and driving style familiarity. *Ergonomics* 61, 8 (2018), 1017–1032. doi:10.1080/00140139.2018.1441448 Publisher: Taylor & Francis TLDR: Younger drivers showed higher comfort, enjoyment and acceptance with familiar automated-driving styles, whereas older drivers preferred unfamiliar, automated driving styles tending to be faster than their age-affected manual driving styles..

[7] Franziska Hartwich, Cornelia Hollander, Daniela Johannmeyer, and Josef F. Krems. 2021. Improving Passenger Experience and Trust in Automated Vehicles Through User-Adaptive HMIs: "The More the Better" Does Not Apply to Everyone. *Frontiers in Human Dynamics* 3, June (2021). doi:10.3389/fhumd.2021.669030 TLDR: Investigating the effects of user group-specific HMI effects on passenger experience shows the potential of increasing the system transparency of higher-level automated vehicles through HMIs to enhance users' passenger experience and trust and consolidates previous findings on varying user requirements based on individual characteristics..

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[10] Pascal Jansen, Mark Colley, Svenja Krauß, Daniel Hirschle, and Enrico Rukzio. 2025. OptiCarVis: Improving Automated Vehicle Functionality Visualizations Using Bayesian Optimization to Enhance User Experience. doi:10.1145/3706598.3713514 arXiv:2501.06757 [cs] TLDR: OptiCarVis facilitates a comprehensive design space exploration, enhancing in-vehicle interfaces for optimal passenger experiences and broader applicability, and demonstrates OptiCarVis's efficacy in significantly improving trust, acceptance, perceived safety, and predictability without increasing cognitive load..

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[16] Vishnu Radhakrishnan, Natasha Merat, Tyron Louw, Michael G. Lenné, Richard Romano, Evangelos Paschalidis, Foroogh Hajiseyedjavadi, Chongfeng Wei, and Erwin R. Boer. 2020. Measuring drivers' physiological response to different vehicle controllers in highly automated driving (HAD): Opportunities for establishing real-time values of driver discomfort. *Information (Switzerland)* 11, 8 (2020), 1–14. doi:10.3390/INFO11080390 TLDR: The results suggest that SCR values are more sensitive than HRV-based measures to continuously evolving situations that induce discomfort, which may help improve acceptance of AV controllers..

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[19] Joseph Smyth, Stewart Birrell, Roger Woodman, and Paul Jennings. 2021. Exploring the utility of EDA and skin temperature as individual physiological correlates of motion sickness. *Applied Ergonomics* 92, January 2020 (2021), 103315. doi:10.1016/j.apergo.2020.103315 Publisher: Elsevier Ltd TLDR: This study is in agreement that these measures are related to MS but evidenced a total lack of reliability for these measures at an individual level for both simulator and on-road experimentation..

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