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Illustration: Zeekr's state-of-the-art driving simulator in Gothenburg.
Zhejiang Geely Holding Group's Media Center.

ABSTRACT

Driving simulators have been extensively applied across various study areas, including user performance, user experience and ride comfort. While existing literature provides insights into the applications of driving simulators across diverse research realms, primarily focusing on the physical capabilities of driving simulators, however, comprehensive assessments of the overall benefits and challenges associated with employing driving simulators in studies regarding user studies have been infrequent. Moreover, previous research has often overlooked the distinctions in methodological approaches between studies utilising driving simulators and those employing real vehicles. Consequently, the purpose here was to undertake an interview study to propose guidelines for using high-level driving simulators in studies regarding user performance, experience, and ride comfort. A total of 14 participants were included, comprising six driving simulator technicians and eight researchers with experience in driving simulator studies. The guidelines outline several advantages that simulators provide, such as improved safety, repeatability, fewer practical constraints, controllability and efficiency. Nevertheless, challenges like space limitations, restricted motion realism, hardware dependence, communication difficulties between researchers and technicians, and time-consuming new scenario development could potentially undermine the feasibility of simulations. Moreover, the guidelines suggest simulation study designs with caution against scenarios involving acceleration, deceleration, extensive lateral manoeuvres, and low-light conditions. Crucial aspects include ethical considerations, task duration, data collection, resource allocation, simulation fidelity and environmental factors. Specific guidelines for user performance, experience and ride comfort underscore the importance of prioritising factors and using relative comparison methods for valid and reliable results.

INTRODUCTION

Driving simulators have found application in a spectrum of research domains encompassing user performance [1–5], user experience [6,7], and ride comfort [8,9].The categorisation of driving simulators can be delineated into low-level, mid-level, and high-level configurations based on their physical characteristics[10]. Low-level driving simulators typically feature a computer/working station and a monitor, whereas mid-level driving simulators incorporate advanced imaging technologies with screens and a realistic cab. In certain instances, such as static driving simulators within the low and mid-level categories, participants primarily perceive simulated vehicle motions through visual and auditory stimuli[11]. Finally, high-level driving simulators are characterised by extensive screens (nearly 360°), a comprehensive feedback motion base, and a vehicular cockpit equipped with complete controls[10].

Studies about user performance

Driving simulators have emerged as useful tools for conducting user performance studies, offering a controlled and immersive environment that mimics real-world driving[12–14]. The application in driving performance studies encompasses a wide range of objectives, from assessing the driving performance [5,15] to investigating driver behaviour under different road designs [14,16–18]. One of the primary advantages of driving simulators lies in the ability to offer a safe and controlled environment for investigating various aspects of human response and behaviour [12]. Researchers can explore factors such as reaction times, decision-making abilities, and overall driving proficiency, thereby informing efforts to mitigate risks associated with, for instance, distracted driving [5,15].

Moreover, the controlled setting of driving simulators facilitates the manipulation of experimental variables, contributing to the reliability and reproducibility of research outcomes [19]. In tasks such as lane-keeping [1,2] and lane-changing [4], simulators allow for standardising experimental conditions across participants, minimising variability and enabling the repetition of experiments under consistent conditions. By manipulating factors such as road conditions and traffic density, researchers gain insights into cognitive processes and decision-making[1,2,4].

Another application in user performance studies is in evaluating the impact of road infrastructure designs[14,16]. These simulators offer a cost-effective means of testing different design elements, eliminating the need for physical alterations to road infrastructure. This cost efficiency allows for the exploration of a wide range of design possibilities [14,18]. Researchers can simulate various road configurations, signage layouts [16], and intersection designs [17] to assess their effects on driver behaviour, safety, and efficiency. By observing participants' responses to simulated scenarios, researchers can identify optimal design solutions that enhance traffic flow, reduce congestion, and improve overall road safety. This evidence-based approach facilitates informed decision-making in urban planning, transportation engineering, and infrastructure development, ultimately leading to more efficient, user-friendly, and sustainable road designs [14].

Studies about user experience

Driving simulators are instrumental in driving experience studies, offering researchers insights into various aspects of human behaviour [6] and interaction [7], especially with automated cars[20] or intelligent vehicles [15]. Researchers can simulate scenarios involving mixed traffic environments, assessing how different modes of vehicle operation influence overall the driving experience[21]. Understanding how drivers interact with these technologies is essential for informing the development and deployment of future transportation systems.

The application of driving simulators in user experience studies presents several advantages. Firstly, simulators offer a controlled and safe testing environment for assessing various aspects of intelligent vehicle technologies. This controlled setting allows researchers to systematically evaluate driver acceptance[22] and driver behaviour[21,23] without exposing them to real-world risks. Secondly, driving simulators enable the repetition of experiments under consistent conditions, ensuring reliable data collection and analysis. This repeatability is crucial for validating and fine-tuning vehicle control algorithms and functionalities[24,25].

Studies about ride comfort

Research studies frequently conflate 'ride discomfort' with 'ride comfort', despite their distinction as separate entities[26]. Comfort encompasses physiological and psychological well-being, while discomfort stems from physical constraints and poor biomechanics[27]. A conceptual model of comfort and discomfort suggests that the transition between comfort and discomfort lies at the intersection of two orthogonal axes [26]. According to this model of comfort, negative human responses contribute to ride discomfort, while positive human responses can enhance ride comfort. Thus, analysing both negative and positive aspects of human responses to various stimuli is imperative [28].

Various factors contributing to ride discomfort have been categorised into ambient factors (e.g., thermal comfort and noise), dynamic factors (e.g., vibration and acceleration) and ergonomic factors (e.g., functionality and seat comfort) [29–32]. Vibrations have been highlighted as one influencing factor of ride discomfort [28]. The impact of vibration varies under different driving scenarios and differs along with duration [33]. Driving simulators have been integrated into the examination of ride comfort [8], encompassing the analysis of vibrations. Various simulator configurations, such as shaker-based and hexapod-based driving simulators, have been employed to delve into the nuances of ride comfort. Shaker-based driving simulators employ a rigid platform mounted on a shaker to generate the necessary vibrations for investigation and are capable of providing vibrations up to 200Hz [34]. A comprehensive review by [35] has systematically outlined a variety of studies that concentrate on exploring the impact that amplitude, frequency, and direction of vibration have on human responses to vibrations using shaker-based driving simulators. This type of simulator has evolved to generate precise vibrations, allowing controlled experimentation with various frequency ranges and amplitudes. Recent advancements include improved frequency response, thereby expanding the spectrum of vibrations relevant to ride comfort. Despite these advancements, limitations persist. Shaker-based systems have traditionally limited motion capabilities, constraining the simulation of dynamic driving conditions and hindering complex ride comfort studies. The predominantly unidirectional functioning presents difficulties in reproducing the multidirectional movements observed in real-world driving. Accurately reproducing real road irregularities remains complex, limiting the simulation of diverse road surfaces. Compared to advanced motion platforms, shaker-based systems may provide a less immersive driving experience, potentially impacting the ecological validity of ride comfort studies.

Hexapod-based driving simulators have evolved to offer an expanded range of motion, surpassing that of conventional systems, thereby facilitating a more thorough simulation of dynamic driving conditions [9]. Technological advancements in hexapod systems now permit the simulation of multidirectional movements, closely mirroring the intricate motion patterns encountered in real-world driving scenarios [8]. Notably, hexapod-based systems have demonstrated progress in replicating actual road irregularities, thereby enhancing the fidelity of simulations involving diverse road surfaces. The heightened immersion provided by hexapod-based simulators contributes to a more realistic driving experience, bolstering the ecological validity of ride comfort studies and achieving a closer approximation to real-world conditions. It is important to acknowledge, however, that the extended range of motion in hexapod-based systems may elevate the susceptibility to motion sickness among participants, potentially influencing the validity of outcomes in studies involving human subjects.

Study purpose

The utilisation of driving simulators in automotive development have been investigated across diverse research realms. The focus has primarily centred on the physical capabilities of driving simulators. Comprehensive assessments of the overall benefits and challenges associated with employing driving simulators in studies regarding user performance and experience have been infrequent. Moreover, previous research has often overlooked the distinctions in methodological approaches between studies utilising driving simulators and those employing real vehicles. The purpose of this study is to deliberate on the benefits and constraints of employing driving simulators, particularly high-level driving simulators, alongside feasible and unfeasible study designs when integrating simulators in user experience studies. Furthermore, it seeks to propose guidelines for utilising high-level driving simulators in research concerning user experience, performance, and ride comfort.

METHOD

In this semi-structured interview study, a total of 14 participants were involved. The participant group comprised six technicians specialising in driving simulators (Te1–Te6) and eight researchers (R1–R8) with experience in conducting studies utilising driving simulators. The technicians were primarily tasked with overseeing the software aspects of the driving simulator, with Te1, Te5 and Te6 also having responsibilities related to the hardware. These researchers and technicians were chosen due to their extensive experience in using high-level driving simulators. The selection process involved a "snowball" approach, where participants were identified and recommended by others, who were already part of the study. The content of the interview questions directed to both the technicians and researchers was about the advantages and limitations associated with the utilisation of driving simulators. Additionally, insights were sought into methodologies deemed viable or unviable when employing high-level simulators for research purposes. The interview questions utilised are presented in Table 1.

Table 1. *The questions used in the interview study*

Research background	What kind of studies have you used/prepared driving simulators for?
	What types of simulators have you used?
Advantages and limitations of utilizing simulators	What do you think are the advantages of using driving simulators compared with using real vehicles?
	What do you think are the limitations of using driving simulators compared with using real vehicles?
	Do you think using a simulator would increase or decrease the time needed for the researchers?
	Do you think using a simulator would increase or decrease the quality of output from the researchers' job?
Viable or unviable research areas	What kind of studies do you think the simulators are useful for?
	What kind of studies do you think the simulators are not useful for?
Application in ride comfort studies	Do you think the driving simulators could be used for seat/ride comfort studies?
	What do you think are the limitations of driving simulators when applied in studies of seat/ride comfort?
	Is it possible to investigate the vibration discomfort when driving on country roads or over speed bumps using driving simulators?

The interviewees' responses were video recorded, transcribed verbatim, and subsequently subjected to an analytical framework comprising content analysis, thematic analysis, and comparative analysis. The initial phase, employing content analysis methodology, conducted a systematic examination of the recorded data, thereby enabling the identification of prevalent themes, recurrent keywords, and underlying conceptual elements. The most mentioned themes and keywords were identified [36]. In the subsequent phase, which employed thematic analysis, the interview data underwent systematic coding based on discerned themes and keywords [36], which included comparisons between the utilisation of simulators and real cars, as well as distinctions in simulator utilisation across diverse study objectives. Furthermore, within this phase, emerging themes were discerned from broader thematic constructs, thereby allowing for a nuanced exploration beyond predefined categories. The final phase involved the utilisation of comparative analysis methodology to scrutinise discrepancies and commonalities in responses across diverse interviewees, fostering a deeper comprehension of varied viewpoints and experiences. Through the combination of these analytical approaches, the objective was to probe the content encapsulated within the interview recordings, thereby unveiling insights pivotal to informing the study's overarching conclusions.

RESULTS

In this section, the feedback obtained from the interviews is presented question by question. For each question, the most cited responses are enumerated, accompanied by further elucidations provided by the interviewees regarding these answers.

Type of research studies conducted using driving simulators

The focus areas of the studies conducted by the researchers are presented in Table 2. Five researchers used driving simulators for a driver behaviour study while three researchers focused on investigating driver experience. They also utilised simulators for studies related to vehicle dynamics, simulator fidelity, aerodynamics, driving safety, road safety, multi-model interaction, seat architecture and road design. The driving simulators utilised in their studies are all high-level simulators.

Table 2. *The focus of the study using driving simulators*

	R1	R2	R3	R4	R5	R6	R7	R8
Driver behaviour		×	×	×	×			×
Driver experience			×	×			×	
Vehicle dynamics						×		
Simulator fidelity						×		
Aerodynamics	×							
Driving safety		×						
Road safety		×						
Multi-model interaction							×	
Seat architecture							×	
Road design								×

Advantages of driving simulators compared to real vehicles

Figure 1 presents a graphical representation of the most frequently cited advantages of utilising driving simulators as reported by the interviewees. In the bar chart, respondents who provided this response are depicted in darker colour, contrasting with respondents who did not mention this advantage, represented in a lighter shade. The interview findings depicted in Figure 1 highlight several benefits associated with the use of driving simulators compared to real vehicles, such as 'safety,' 'repeatability,' 'reduced practical constraints,' 'controllability,' and 'efficiency.'

Notably, ‘safety’ and ‘repeatability’ emerged as paramount advantages acknowledged by both technicians and researchers. The safety afforded by driving simulators facilitates the exploration of driving scenarios that may be challenging or impractical to test in real-world settings (Te1–Te6, R2–R8). Furthermore, the repeatability feature supports comparative studies across diverse demographic groups or vehicle designs, enabling researchers to discern nuanced variations (Te1–Te6, R2–R8).

Researchers (R2–R8) and technicians (Te1, Te2, Te4–Te6) valued the capability of driving simulators to isolate variables and conduct experiments with fewer practical constraints or in ideal environments. Moreover, the controllability of driving simulators empowers researchers to create specific driving situations for systematic observation, experimentation, and research (Te1, Te3–Te5, R2–R5, R7, R8). Additionally, the efficiency of driving simulators is enhanced by the ability to switch between different road profiles and vehicle models (Te1–Te3, R1, R4, R5, R7, R8).

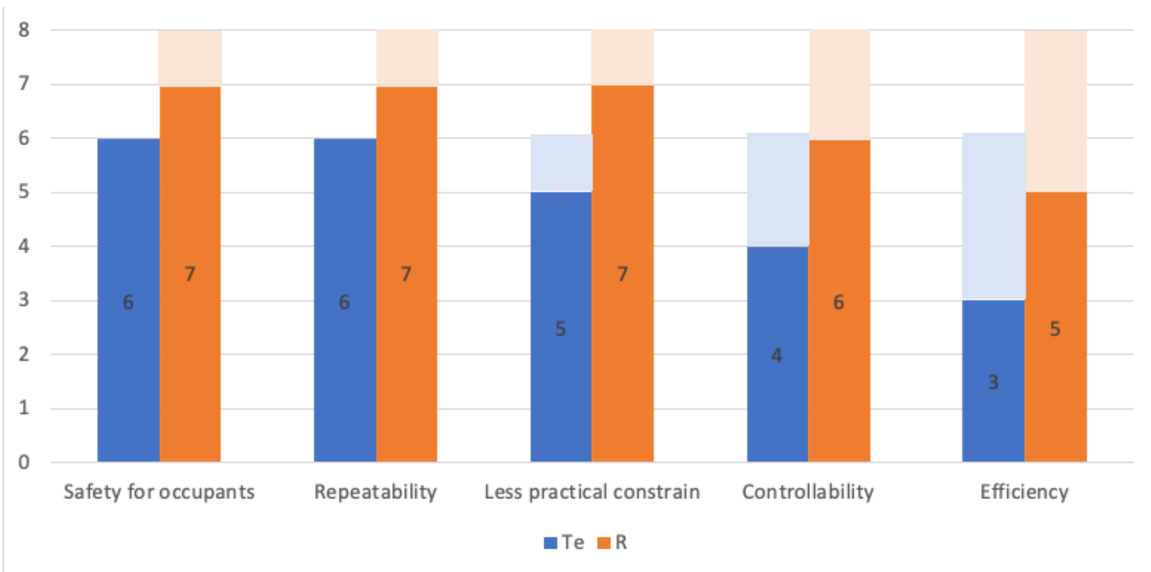

Figure 1. *The advantages of using driving simulators compared to using real vehicles. 'Te' represents 'Technician' while 'R' represents 'Researcher'. The number of respondents is highlighted in the figure.*

Limitations of driving simulators compared to real vehicles

In Figure 2, the limitations of using driving simulators are depicted. Among technicians, the predominant concerns revolve around space limitation and limited motion realism, identified as the most significant drawbacks of utilising simulators. The space limitation prevents simulators from accurately replicating certain driving environments, such as acceleration and deceleration scenarios, as well as lateral sharp turns or sudden swerves (Te1–Te6, R1, R2, R4–R6, R8). The constraints on motion realism could lead to a lack of immersion and realism in simulated driving experiences, potentially compromising the validity and effectiveness of the simulation for research or training purposes (Te1–Te6, R3–R6, R8).

Half of the technicians (Te1, Te2, Te4) and researchers (R2–R4, R6) identified the dependency on hardware capabilities as a significant limitation of driving simulators. While certain simulators feature electric vibration platforms or acoustic exciters to replicate high-speed driving and high-frequency vibrations, others utilise hydraulic vibration platforms to simulate low-speed driving and uneven terrain. Researchers were concerned about the inability to realise various driving scenarios due to hardware constraints, requiring them to carefully design experiments based on available equipment. Consequently, researchers rely on technicians to navigate these limitations and design experiments accordingly.

The communication between researchers and technicians must commence from the inception of experiment design due to the constraints imposed by the hardware limitations of simulators. However, both parties often encounter difficulties in communication during this process (Te3, Te4, Te6, R2, R3, R5, R6). Technicians may struggle to comprehend the driving scenarios researchers aim to replicate and the parameters needed to measure in the experiments, while researchers may not fully understand the hardware limitations of the simulator.

Some technicians (Te1–Te3, Te6) and researchers (R2, R3, R5) pointed out that preparing new driving scenarios is time-consuming, with a portion of time dedicated to communication between both parties. Additionally, acquiring the necessary software and hardware resources as well as installing and debugging them requires lengthy cycles (Te1–Te3, Te5, Te6).

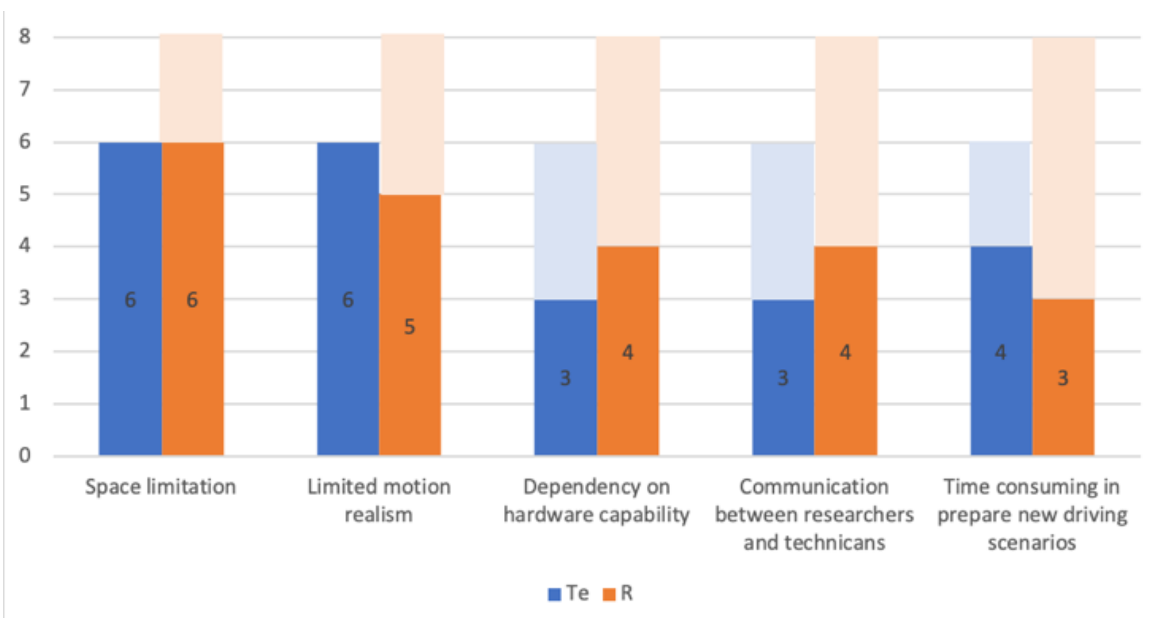

Figure 2. *The limitations of using driving simulators compared to using real vehicles. 'Te' represents 'Technician' while 'R' represents 'Researcher'. The number of respondents is highlighted in the figure.*

All researchers (R1–R8) and technicians (Te1–Te6) agreed that using a simulator would reduce the time required to conduct research studies in the long term, particularly those that pose challenges in real-world settings. However, they also noted again that the time needed to develop new scenarios for studies might be prolonged compared to studies involving real vehicles.

Additionally, all researchers (R1–R8) and technicians (Te1–Te6) emphasised that the quality of output from studies utilising driving simulators is dependent on the study purpose. They observed that the quality might diminish due to the constrained level of realism (Te1, Te3–Te6, R2, R3, R5, R6, R8). Nonetheless, they acknowledged that the controlled and repeatable environment offered by simulators contributes to enhancing study quality and enables the execution of studies that are not feasible in real-world settings.

Viable or unviable study designs

Figures 3 and 4 delineate the research domains conducive and unsuitable for driving simulator application, respectively. Consensus among technicians and researchers (Te1–Te5, R1–R8) highlighted the suitability of simulators for relative value investigations over absolute value studies. They advocated for simulator utilisation in research domains like human-machine interaction (Te2, Te5, R1–R4, R7, R8), road safety (Te2, R1–R4, R7), driving safety (Te2, Te6, R1–R4), and driver behaviour (Te5, R2–R4, R8). Technicians also accentuated simulators' efficacy in component/design optimisation. Nonetheless, acknowledging spatial constraints, technicians pointed out that simulators are ill-suited for protracted acceleration, deceleration, and extensive lateral manoeuvres.

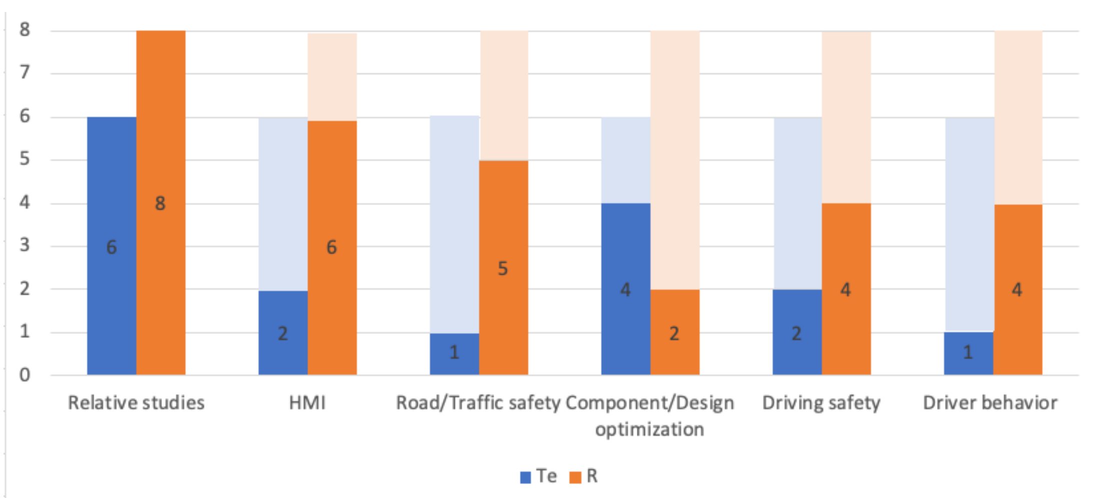

Figure 3. *The studies that driving simulators are useful for. 'Te' represents 'Technician' while 'R' represents 'Researcher'. The number of respondents is highlighted in the figure.*

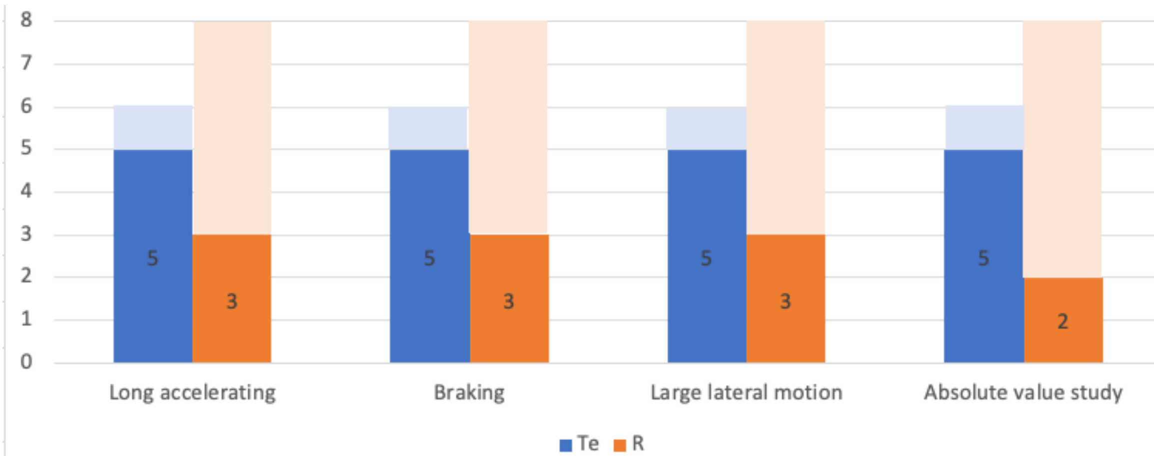

Figure 4. *The studies that driving simulators are not useful for. 'Te' represents 'Technician' while 'R' represents 'Researcher'. The number of respondents is highlighted in the figure.*

Moreover, researchers also discussed the challenges of using driving simulators in driving safety and driver behaviour studies. One significant limitation is the potential lack of full ecological validity, as simulators may not replicate all nuances of real-world driving experiences (R3, R4, R8). Participant behaviour in a simulated environment may differ, impacting the generalisability of study findings (R2–R5, R8). Additionally, driving simulators may not be suitable for investigations focused on driving in dark driving conditions (R2, R5, Te3), traversing snowy terrain (R5, Te3), or evaluating inter-vehicle spacing (R2).

Application in ride comfort studies

Figure 5 delineates the limitations associated with employing driving simulators in research pertaining to ride comfort. Technicians (Te1, Te3–Te6) and researchers (R1, R5, R6, R8) emphasised the driving simulator's capacity to generate vibrations, which is integral to simulating ride experiences. Human response to vibration is pivotal for assessing ride comfort; thus, the vibration frequency range that driving simulators can produce becomes a critical consideration in experimental design.

Moreover, concerns arise regarding the realism of motion experienced by participants, which may compromise study validity (Te1, Te3, Te6, R2, R4, R5). Driving simulators often need motion scaling to ensure that the simulated motion aligns with real driving experiences (Te1, Te3–Te5, Te7, Te8). This adjustment is necessary because the motion platforms of driving simulators may not fully replicate the sensations and dynamic characteristics of real vehicles in motion. By applying motion scaling, the simulator's motion can better reflect real-world driving manoeuvres such as acceleration, deceleration, and turning, enhancing the simulator's fidelity and realism.

However, the motion scaling parameter is set based on the technician's subjective perception, which can vary among different individuals.

Notably, driving simulators may inadequately replicate the sensory engagement inherent in real driving, posing challenges in ensuring coherence across various modalities and potentially compromising the transferability of findings to real-world contexts (Te3, Te6, R1, R3–R5). The possibility of experiencing motion sickness in driving simulators increased compared to real vehicle rides due to factors such as inconsistencies in perception, incomplete accuracy in motion simulation, prolonged exposure and continuity, and changes in sensations in virtual environments (Te5, R2, R3, R8). Some researchers (R2, R6, R8) have proposed that maintaining a cooler environment temperature accompanied by appropriate lighting could help mitigate the risk of simulator sickness. Meanwhile, the prolonged task duration could increase the possibility of simulator sickness. However, the effectiveness of this approach may vary depending on the individual characteristics of participants.

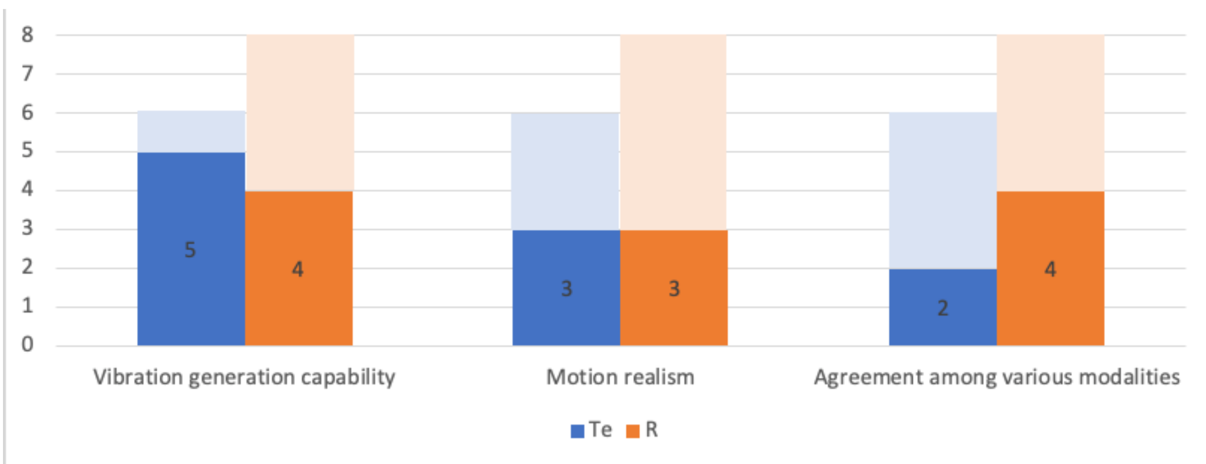

Figure 5. *The limitations of using driving simulators in studies regarding ride comfort. 'Te' represents 'Technician' while 'R' represents 'Researcher'. The number of respondents for is highlighted in the figure.*

DISCUSSION

This study outlined the advantages and limitations of driving simulators compared to real vehicles in research across diverse research domains. Driving simulators offer enhanced safety, repeatability, reduced practical constraints, controllability, and efficiency, facilitating controlled experimentation. With these advantages, researchers could delve into intricate driving dynamics and phenomena, unlocking insights that may otherwise be unattainable using traditional approaches. However, limitations include space constraints, limited motion realism, and hardware dependency, which may compromise simulation validity. Communication challenges between researchers and technicians also arise.

Ride comfort studies in driving simulator

Consistent with earlier research [19,37], the current study affirms the enhanced safety, repeatability, and controllability provided by driving simulators. The controlled and repeatable setup ensures participant safety and enables precise manipulation of experimental variables, enhancing research reliability.

The current study emphasised the benefit of isolating variables and conducting experiments with fewer practical constraints or even in optimal environments. Previous research [38,39] pointed out the influence of agreement among various modalities on experienced dynamic discomfort. However, participants struggled to define the threshold of mismatch between sounds and vibrations. By employing a driving simulator, sounds and vibrations can be isolated to explore their agreement in the early stage of concept design.

Additionally, driving simulators could enhance efficiency by facilitating rapid transitions between various components, structures, and vehicle models. In studies involving real vehicles [38], participants undergo tests in one car before switching to another, potentially altering their subjective assessments over time. By utilising driving simulators, the experimental process becomes streamlined, enabling researchers to explore a broader array of scenarios and configurations within a condensed timeframe. As a result, studies can be conducted more expeditiously and comprehensively, aiding in the identification of optimal designs and configurations to enhance vehicle performance and comfort.

Overall, the capability of driving simulators to create controlled, reproducible, and customisable experimental environments enhances the study of ride comfort by allowing researchers to isolate variables, manipulate driving conditions, and rapidly switch test objects in a safe and controlled setting. Limitations include space constraints and limited motion realism, which pose challenges that could undermine the validity of simulations.

To mitigate this limitation, most advanced driving simulators have integrated a moving platform within the horizontal plane to afford supplementary longitudinal and lateral motions [11].

Additionally, several motion-cueing algorithms, including the washout filter algorithm, adaptive filter algorithm, optimal filter algorithm, and model predictive control-based algorithm, have been implemented to translate authentic vehicular motions into viable driving simulator dynamics [11]. A second constraint encountered in driving simulators concerns their capacity to accurately reproduce high-frequency vibrations [40]. To scrutinise the system's response under exposure to high-frequency vibrations, the installation of extra actuators is contemplated. However, the precise control of these supplementary actuators and their harmonisation with the driving simulator platform necessitate meticulous consideration [40].

Simulator sickness is another potential limitation mentioned in the interview study. Reducing simulator sickness involves optimising technical parameters like frame rates and resolution, ensuring gradual exposure, and maintaining comfortable environmental conditions with appropriate lighting and ventilation [41]. Smooth transitions and motion, along with ergonomic seating arrangements, also play crucial roles in minimising discomfort during simulator use. Encouraging regular breaks, educating users about managing symptoms, and monitoring participant feedback are additional strategies to mitigate simulator sickness. Recognising individual differences in susceptibility is essential for tailoring interventions effectively. By employing these strategies, users can experience a more comfortable and enjoyable interaction with virtual reality or driving simulators.

User performance and experience studies in driving simulators

When employing driving simulators in research, it is crucial to acknowledge the distinctions in experimental approaches compared to studies involving real vehicles. It is moreover essential to carefully select and tailor driving scenarios that are appropriate for simulation within the virtual environment of a driving simulator.

The focus on occupant experience differs between a stationary car and a moving car [39,42]. Therefore, studies using driving simulators for studying stationary and moving vehicles could be distinctly designed. In stationary vehicles, occupants focused mainly on ergonomic factors such as ingress, HMI system, legroom, and seat comfort as well as ambient factors including temperature and sound. The limitations in representing real vehicles may impede the accurate simulation of, for instance, ingress, legroom and seat comfort. However, using simulators for an investigation of the HMI system could provide study diversity and enhance efficiency. Conversely, studying moving vehicles using driving simulators offers dynamic scenarios to assess occupant experiences. Additionally, the simulated environment allows participants to engage in real-time decision-making. Hence, the researchers could require participants to make subjective judgements whenever they perceived a certain sensation or while riding. The facilitation of data collection on participant interactions with moving vehicles enables detailed analysis. Nevertheless, challenges such as motion realism, space limitations, and potential perception biases necessitate careful consideration.

Previous study [39] concluded that the overall ride comfort varied depending on driving scenarios. Moreover, individual comfort factors change during dynamic driving. Therefore, it could be beneficial to assess various driving scenarios (e.g., bumpy roads, speed bumps, driving on smooth surfaces, driving on rough terrain, and cornering) for occupant experience studies. However, the interviews indicated that riding experiences during acceleration, deceleration, and cornering may not be accurately captured when using driving simulators.

Moreover, the interviewees do not recommend employing driving simulators for investigating occupant performance in scenarios involving driving in low-light conditions or icy surfaces, or for estimating inter-vehicle distances.
Furthermore, interviewees suggested prioritising relative value studies over absolute value studies when investigating ride comfort. Since simulators may not fully replicate the complexities of real-world driving, focusing on relative value studies allows researchers to assess changes or differences within the simulated environment rather than attempt a direct comparison with real-world measurements. This approach helps account for the inherent differences in simulation conditions and scaled motions, ensuring more reliable results.

Additionally, methodologies employed in driving simulators need to minimise the impact of the virtual environment on participants' behaviour and responses. Factors such as simulator fidelity, motion cues, and visual displays can affect participants' responses and may not accurately reflect real-world driving experiences. For instance, reduced risk perception and diminished physical sensations in simulators can affect decision-making and spatial awareness. The awareness of being part of a study and the potential for simulator-induced discomfort further influence participant behaviour. Researchers should mitigate biases and consider these factors to ensure the validity and reliability of driving simulator studies. They could also consider the potential impact of the virtual testing environment on participants' behaviour and responses.

Guidelines for using high-level driving simulators in user studies

The findings from literature and the current interview study are merged into guidelines on how to conduct user studies, particularly focusing on user performance, experience, and ride comfort in high-level driving simulators (Table 3). These guidelines are aimed to help researchers use driving simulators in user studies, while they also address potential limitations and carefully design studies with regard to validity.

Table 3. *Guidelines based on interview results and the literature*

General advantages of using simulators	*Encourage researchers to apply the advantages:* • Safety • Repeatability • Reduced practical constraints • Controllability • Efficiency
General limitations of using simulators	Encourage researchers to weigh these factors: • Space limitations • Restricted motion realism • Hardware dependence • Communication difficulties between researchers and technicians • Time consuming for new scenario development
Types of studies suggested in simulators	Encourage the use of simulators for experiments requiring: • Reduced risk • Controlled environments • Precise manipulation of variables • Rapid transitions between study objects
Types of studies not suggested in simulators	Caution against using simulators for studies involving: • Acceleration and deceleration • Extensive lateral manoeuvres • Low-light conditions • Icy surfaces • Estimation of inter-vehicle distances Discourage the use of simulators for absolute value studies that directly compare with real-world measurements
Design of simulator studies	Ethical Considerations: • Ensure participant safety and well-being throughout the experimental procedures. Task Duration: • Consider the duration of simulation sessions and potential effects on participant experience and behaviour. • Implement breaks or rest periods to mitigate the impact of prolonged simulation exposure. Data collection: • Consider the methods for collecting subjective judgements before, during and after the test scenarios (e.g., interviews, questionnaires, estimation scales and instant judgements). • Consider adding objective data collection during the simulation if useful for the study (e.g., vibrations, noise and ride motion of the vehicle).

Setup of simulators	Resource Allocation: • Allocate resources to support the design, implementation, and analysis of the simulation study. • Select appropriate driving scenarios tailored to the capabilities and limitations of the simulator. • Ensure that control conditions are designed and implemented to isolate specific variables of interest. Simulation Fidelity: • Assess the fidelity of the simulator in replicating real-world driving dynamics. • Minimise biases and ensure the fidelity of the simulation environment. • Consider the trade-offs between simulator realism and practical constraints. Environmental Factors: • Control environmental factors such as lighting and temperature within the simulation environment. • Consider how environmental factors may influence participant behaviour and responses.
Specific guidelines for user performance	• Encourage the use of simulators for dynamic scenarios that require real-time decision-making by participants. • Caution against scenarios that may not accurately capture real-world driving experiences, such as low-light conditions.
Specific guidelines for user experience	• Prioritise the investigation of ergonomic factors, HMI systems, ambient conditions, and the perception variation under various conditions. • Acknowledge limitations in simulating real-world factors like ingress and legroom.
Specific guidelines for user ride comfort	Assess various driving scenarios: • Recommend assessing various driving scenarios (e.g., bumpy roads) to study ride comfort. • Acknowledge challenges in replicating real-world sensations like acceleration and deceleration in simulators. Prioritise relative value studies: • Emphasise relative value studies over absolute value studies to account for differences in simulation conditions and scaled motions. • Encourage detailed analysis of changes or differences within the simulated environment. Minimise impact of virtual environment: • Mitigate biases caused by simulator fidelity, motion cues, and visual displays to ensure the validity and reliability of results. • Consider potential impacts on participant behaviour and responses, such as reduced risk perception and simulator-induced discomfort.

CONCLUSION

In conclusion, the results from the literature and the interview study provide useful guidelines for utilising high-level driving simulators in user studies, together with remarks/explanations/ observations about their advantages, limitations, and factors to consider. By adhering to these guidelines, researchers can capitalise on the several advantages that simulators provide, such as improved safety, repeatability, fewer practical constraints, controllability and efficiency. Nevertheless, challenges like space limitations, restricted motion realism, hardware dependence, communication difficulties between researchers and technicians, and time consumption for new scenario development could potentially undermine the validity of simulations.

Regarding investigating ride comfort using driving simulators, the interviewees emphasised the advantage of isolating variables and conducting experiments in fewer physical constraint environments, which could help to provide insights into the impact of various variables at an early stage of concept design. Driving simulators also enhance efficiency by facilitating rapid transitions between components, structures, and vehicle models. The guidelines delineate the types of studies that are suitable for simulation, emphasising scenarios requiring reduced risk, controlled environments, and precise manipulation of variables. Caution is advised for studies involving specific conditions such as acceleration and deceleration, extensive lateral manoeuvres, and low-light environments.

Environmental factors, simulation fidelity, feedback mechanisms, ethical considerations, task duration, and resource allocation are all crucial aspects to consider when designing and conducting simulator-based studies. Moreover, specific guidelines tailored to user experience, performance, and ride comfort highlight the importance of prioritising certain factors and using relative comparison methods to ensure valid and reliable results.

In stationary vehicles, occupants focus on ergonomic factors and ambient factors. While accurately simulating real stationary vehicle conditions can be challenging, using simulators for an HMI system investigation could enhance study diversity and efficiency. Studying moving vehicles with driving simulators provides dynamic scenarios for assessing occupant experiences. Participants can thus engage in real-time decision-making and provide subjective judgments when they need during the ride. This facilitates detailed analysis of participant interactions with moving vehicles, despite challenges such as motion realism, space limitations, and potential perception biases.

It is suggested to prioritise relative value studies over absolute value studies to minimise the bias induced by simulation conditions and scaled motions. Due to physical limitations, the design of experiments to study occupant experience using driving simulators needs to avoid driving scenarios such as acceleration, deceleration, large lateral motion, and driving in darkness. Additionally, studies in driving simulators should minimise the impact of the virtual environment on participants' behaviour and responses.

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