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Simulator sickness: a comparison between static and dynamic motion platforms in immersive driving simulators

O mal-estar em condução simulada: comparação entre simuladores imersivos de direção com plataforma estática e dinâmica

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ABSTRACT
This paper aims to evaluate and compare drivers' sickness sensation on simulated driving for static and dynamic immersive simulators. For this, the Simulator Sickness Questionnaire (SSQ) was applied to 36 volunteers (18 men and 18 women) of three age groups (19 to 30; 31 to 60; and over 60 years old) who underwent the driving experience simulated. The severity of sickness symptoms in simulated conduction for SSQ and its virtual reality version – Virtual Reality Sickness Questionnaire, VRSQ – was obtained, allowing the comparison of both approaches. Analysis of the results using ANOVA indicates that static simulators cause greater sickness severity than dynamic ones. While the application of SSQ allowed the analysis of drivers' oculomotor symptoms through the two types of platform, the application of VRSQ allowed the analysis of oculomotor and disorientation symptoms.

RESUMO
Este artigo tem por objetivo principal avaliar e comparar a sensação de mal-estar dos condutores em simuladores imersivos dinâmicos e estáticos. Para isso, o Simulator *Sickness Questionnaire* (SSQ) foi aplicado a 36 voluntários (18 homens e 18 mulheres) distribuídos em três faixas etárias (19 a 30; 31 a 60; e maior que 60 anos) que foram submetidos à experiência de condução simulada. A severidade de sintomas de mal-estar em condução simulada foi obtida para o SSQ e para a sua versão adaptada à realidade virtual – *Virtual Reality Sickness Questionnaire*, VRSQ – permitindo comparação das duas abordagens. A análise dos resultados usando ANOVA indica que simuladores estáticos causam maior severidade de mal-estar que os dinâmicos. Enquanto a aplicação do SSQ permitiu a identificação de sintomas oculomotores que afetam os condutores nos dois tipos de plataforma, a aplicação do VRSQ permitiu identificar também sintomas de desorientação.

1. INTRODUCTION

In light of the loss of more than 1.19 million lives in traffic accidents each year (WHO, 2023), there is an increasing global effort to develop safer transportation systems for all users. Successful initiatives based on the Vision Zero approach attribute traffic injuries to shared responsibility, promoting proactive strategies to better understand the interaction between the key contributing factors to road crashes: human behavior, roadway infrastructure, and vehicle characteristics (Treat et al., 1979; ITF, 2016).

Within this framework, driving simulators have emerged as valuable tools for expanding research that integrates these three dimensions – human, road, and vehicle. They are gaining prominence in studies focused on driver behavior with semi-autonomous vehicles (e.g., Sportillo et al., 2018; Zhao et al., 2024), roadway design, and the effectiveness of safety interventions (e.g., Boyle and Lee, 2010; Tang et al., 2025). Given their increasing application in transportation research, it is crucial to understand both the potential and limitations of driving simulators to strengthen their use in road safety studies.

Various types of simulators are used in this field, with significant differences in the technologies employed. In general terms, simulated environments may be presented through flat screens, projection panels, or immersive virtual reality (VR) headsets. Another important aspect in creating realistic simulation experiences is whether the simulator uses a static or dynamic platform (Moll et al., 2023; Andriola et al., 2025; Tang et al., 2025). Static simulators do not involve physical motion – the user remains stationary while interacting with a projected or virtual environment. In contrast, dynamic simulators feature moving platforms that simulate real vehicle motion in sync with the virtual scenario, using actuators to replicate acceleration, braking, cornering, and other forces typically experienced while driving.

Driving simulators can provide realistic data while ensuring controlled and safe testing environments for potentially hazardous scenarios (Classen et al., 2011; Andriola et al., 2025; Moll et al., 2023). However, a key limitation is the physical discomfort or simulator sickness (SS) that may be experienced by participants. The most widely accepted explanation for SS is the sensory conflict theory (Kohl, 1983), which attributes the symptoms to a mismatch between visual, auditory, and motion-related cues perceived by the user (Hettinger et al., 1990; Reason, 1978; Oman, 1990). This neural mismatch - between visual, proprioceptive (muscle-based), and somatosensory (touch-based) signals – can cause a range of symptoms collectively referred to as Simulator Sickness. SS is especially common in situations where users are exposed to visually dynamic environments while their bodies remain still, leading the brain to perceive incoherent motion (Reason and Brand, 1975). This conflict is particularly pronounced in static simulators, where visual and vestibular information - processed by the inner ear and responsible for detecting motion – become misaligned. The optical flow perceived by the driver creates a compelling illusion of self-motion that is not supported by corresponding inertial cues from the vestibular system (Hettinger et al., 1990).

Since the late 1960s, virtual reality has been defined by its ability to generate a three-dimensional perception based on user movement (Sutherland, 1968). This immersive effect is achieved through the display of images from multiple angles and is often enhanced by auditory cues. In driving simulators, immersion is directly linked to the user’s field of view. Studies show that a wider field of view increases the sense of presence, making VR experiences more engaging than those on conventional displays (Stone, 2017). Therefore, the term “immersive” is typically used to describe simulators employing VR headsets, which provide a broad and responsive visual field, closely aligned with head movements to enhance realism.

With the growing use of immersive simulators, enabled by VR technologies that generate vivid, life-like driving environments, it is increasingly important to understand the particularities of simulator sickness in these settings (Kim et al., 2018; Bruck and Watters, 2009; Stone, 2017; Andriola et al., 2025; Facchini et al., 2025). Some authors have coined the term "Cybersickness" to describe discomfort specifically associated with VR, suggesting that visual-vestibular conflicts in immersive environments differ from those in non-immersive settings (Rebenitsch and Owen, 2016; Stanney and Kennedy, 1997). Tools for evaluating Cybersickness are typically adapted from the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993), highlighting the need to tailor measurement instruments to better assess discomfort in VR contexts (Kim et al., 2018; Sevinc and Berkman, 2020). However, no universal consensus on these adaptations has yet been reached.

The exact mechanisms behind Simulator Sickness remain unclear, and there is no definitive mitigation strategy (Stone, 2017; Igoshina et al., 2022). As such, empirical studies are essential to advance understanding of the contributing factors. In this context, the main objective of this article is to evaluate and compare the intensity of Simulator Sickness experienced by drivers using dynamic and static immersive simulators, considering variables such as gender, age, immersion duration, and the presence of road markings (center and edge lines). A specific secondary objective is to compare SS measurements using the traditional SSQ with the Virtual Reality Sickness Questionnaire (VRSQ), which is specifically designed to capture symptoms of Cybersickness in immersive VR environments. This study contributes to the field in two keyways: (i) by providing empirical evidence on the influence of simulator configuration and experimental design on the occurrence of SS; and (ii) by evaluating the suitability of traditional measurement tools in capturing SS symptoms in immersive VR contexts.

The findings aim to support future research and help establish guidelines to reduce participant discomfort during simulator-based experiments, thus increasing the reliability of such tools in studies of driver behavior and road safety.

To achieve these goals, the article is structured into five sections, beginning with this introduction. Section 2 presents the theoretical framework, addressing the symptoms, driver characteristics, and measurement methods associated with SS in virtual reality simulations. Section 3 details the experimental setup. Sections 4 and 5 present, respectively, the results and related discussions, and the final considerations of the study.

2. THEORETICAL FRAMEWORK

The theoretical framework of this article is organized around two key perspectives: factors contributing to discomfort in simulated driving, and the approaches reported in the literature for measuring discomfort resulting from virtual reality (VR) simulation.

2.1. Factors influencing simulator sickness

While some studies suggest that simulator sickness (SS) is primarily caused by simulation settings, others indicate that symptoms may also be linked to individual driver characteristics. Regarding simulator configurations, research has examined factors such as the platform type (static or dynamic), roadway scenario details (alignment and signage) (Igoshina et al., 2022; Andriola et al., 2025), field of view depth and limitations (Carnegie and Rhee, 2015), optical distortion (Kennedy et al., 2000), auditory composition (Keshavarz et al., 2014), and postural stability (Lee et al., 1997; Dennison and D'Zmura, 2018) as potential contributors to discomfort. On the other hand, individual factors such as age (Brooks et al., 2010; Keshavarz et al., 2018), gender (Keshavarz et al., 2018), and prior or frequent simulator use (Howarth and Hodder, 2008) may also influence the level of simulator sickness experienced.

Dynamic simulators significantly enhance the realism of simulated driving by replicating acceleration and other vehicle movements (Baumgartner et al., 2019). However, some studies have reported an increase in SS symptoms with the addition of motion, particularly oculomotor and disorientation-related symptoms (Bruck and Watters, 2009; Dziuda et al., 2014). Conversely, according to the Sensory Conflict Theory (Kohl, 1983), SS results from a mismatch between visual input and perceived motion, suggesting that dynamic motion may help reduce this conflict.

Simulator sickness presents a notable challenge in studies involving older drivers, who are more likely to be affected by SS than younger individuals. This may be due to age-related declines in balance and increased susceptibility to dizziness (Brooks et al., 2010). Beyond physical discomfort, SS can also impact driving behavior. Studies exploring this link have found varied outcomes. For instance, Reinhard et al. (2019) observed delayed braking response times, while Helland et al. (2016) reported lower average driving speeds and fewer steering adjustments. However, other studies suggest that the effect of SS on driving performance may be limited (Igoshina et al., 2022).

When analyzing SS in dynamic driving simulators, Keshavarz et al. (2018) found a significant increase in symptoms among older adults (65+) compared to younger adults (under 25). They also observed that older women were particularly vulnerable to more intense SS symptoms. Overall, women tend to be more susceptible to oculomotor symptoms, likely due to lower postural stability compared to men (Mourant and Thattacherry, 2000; Munafo et al., 2017).

Regarding the impact of prior and regular simulator exposure, drivers accustomed to immersive virtual environments generally experience fewer SS symptoms (Howarth and Hodder, 2008). Such familiarity may stem from the increasing use of virtual reality games (Hill and Howarth, 2000).

In terms of exposure time, immersive static VR simulations have shown minimal SS symptoms for durations up to eight minutes (Nodari et al., 2017). However, SS symptoms tend to increase with longer simulation times. Physiological changes related to the autonomic nervous system have been observed after just five minutes, with significant increases in SS occurring after ten minutes (Min et al., 2004). Notably, this relationship is not strictly linear: a comparison of SS symptoms across exposure durations of 11 minutes, 15-25 minutes, and 45 minutes showed the highest severity at the intermediate duration, with symptoms decreasing thereafter, though remaining higher than at the 11-minute mark (Sinitski et al., 2018).

2.2. Measuring discomfort in virtual driving

Derived from the refinement of the Motion Sickness Questionnaire (MSQ) (Frank et al., 1983) – which includes gastrointestinal symptoms, symptoms related to the central nervous system (e.g., weakness, dizziness, disorientation, confusion), the peripheral nervous system (e.g., sweating, chills), and symptoms associated with annoyance (e.g., irritation, fatigue, tiredness) – discomfort during simulated driving has typically been assessed using the Simulator Sickness Questionnaire (SSQ). This condition is commonly referred to as Simulator Sickness (SS) (Kennedy et al., 1993). The SSQ evaluates three primary symptom clusters: nausea, oculomotor issues, and disorientation. Although it shares similarities with Motion Sickness (MS), SS is generally considered less severe (Kim et al., 2018). The SSQ comprises 16 symptoms and has been adapted into Brazilian Portuguese by Carvalho et al. (2011).

For virtual reality (VR) simulators, additional concepts of discomfort have been proposed: Cybersickness (Stanney and Kennedy, 1997; Stone, 2017), Visually Induced Motion Sickness

(VIMS) (Keshavarz and Hecht, 2012), and Virtual Reality Sickness (Kim et al., 2018). Cybersickness refers to discomfort commonly experienced by users in virtual environments, similar to Motion Sickness, and results from sensory conflict that may cause nausea, headaches, and dizziness (Rebenitsch and Owen, 2016). VIMS refers specifically to symptoms triggered by visually induced motion, even in the absence of physical movement (Kennedy et al., 2010). While all these conditions are rooted in Sensory Conflict Theory (Oman, 1990), each emphasizes different symptom groupings and manifestations. Due to the limited literature on these emerging concepts, the SSQ remains the most widely used instrument for measuring symptoms of Cybersickness and VIMS (Stone, 2017).

The VRSQ (Virtual Reality Sickness Questionnaire) was developed as an adaptation of the SSQ for use in virtual reality environments (Kim et al., 2018). It focuses on assessing oculomotor and disorientation symptoms by selecting specific items from those clusters in the original SSQ. The VRSQ retains the structure of the SSQ but limits its scope to the two symptom constructs most relevant in immersive VR contexts. In contrast, the SSQ groups symptoms into three constructs – Nausea, Oculomotor, and Disorientation – whereas the VRSQ is limited to just Oculomotor and Disorientation (Table 1).

Table 1: Synthesis of the constructs proposed in the SSQ and VRSQ

		SSQ			**VRSQ**	
	Symptoms	**Nausea**	**Oculomotor**	**Disorientation**	**Oculomotor**	**Disorientation**
1	General discomfort	●	●		●	
2	Fatigue		●		●	
3	Headache		●			●
4	Eyestrain		●		●	
5	Difficulty focusing		●	●	●	
6	Increased salivation	●				
7	Sweating	●				
8	Nausea	●		●		
9	Difficulty concentrating	●	●			
10	Fullness of head			●		●
11	Blurred vision		●	●		●
12	Dizzy (eyes open)			●		
13	Dizzy (eyes closed)			●		●
14	Vertigo			●		●
15	Stomach awareness	●				
16	Burping	●				

3. EXPERIMENT DEVELOPMENT

The experiment consisted of conducting driving tests using immersive driving simulators. This study was carried out in three stages: (i) experimental planning; (ii) data collection using the SSQ; and (iii) analysis of simulated driving discomfort based on the constructs proposed by the SSQ and VRSQ.

3.1. Experimental planning

The experiment was designed to include five controllable factors, selected for their relevance based on the literature review: gender, age, immersion time in the simulator, simulator platform type, and presence of centerline and edge road markings. Each factor was tested at different levels to assess potential changes in driver discomfort in simulated environments, depending on the combination of levels. Table 2 presents the tested factors and their respective levels.

Table 2: Controllable factors and analysis levels

Fator controlável	Níveis	Descrição níveis
Gender	2	female; male
Age	3	19-30 years; 31-60 years, over 60 years
Imersion Time	2	6 minutes; 11 minutes
Simulator platform	2	static; dynamic
Road markings	2	yes; no

In the experimental design, the combination of all possible levels of the factors constitutes a full factorial experiment – resulting in 48 combinations for the controllable factors presented in Table 2. However, when the number of factors is large or resources are limited, it is common to adopt a fractional factorial design. The experimental design (DOE – Design of Experiments) was developed using the Minitab software. A fractional factorial design involves conducting only a selected subset of trials from the full factorial design (Federer and Raktoe, 2005). This approach reduces the volume of data collection by excluding higher-order interactions, provided that orthogonality between variables is maintained (Hair et al., 2019). By applying this method, the number of combinations was reduced, allowing the study to be conducted with 36 combinations of controllable factors.

The experiment sought to test different scenario configurations, which depended on the experimental design. Two virtual highway scenarios were defined: one with central and edge lane markings, and another without any road markings. All simulations were conducted under daylight and stable weather conditions. The type of simulator platform and the exposure time were also defined according to the experimental plan. It is worth noting that while horizontal signage contributed to composing distinct scenarios, it was treated as a complementary variable. The literature suggests that simulator type and driver characteristics are more relevant for evaluating simulator sickness.

The study focused on comparing the effects of simulator sickness (SS) between static and dynamic simulator platforms. To control for potential influences of age and gender, the sample was stratified to ensure a balanced distribution of these variables across experimental conditions. This strategy allowed the analysis to isolate the effect of simulator type on SS while minimizing confounding factors. Future research could explore the role of these individual characteristics in greater depth.

Participants were licensed drivers who had held a category B license (vehicles up to 3.5 tons and with up to 8 passenger seats) for over one year, drove at least three times per week, and had experience driving on highways (at least once per month in the past year). This ensured the recruitment of volunteers familiar with real-world driving environments similar to those simulated. Recruitment was conducted through an online registration form widely disseminated on social media, aiming to reach a broad demographic. After registration, the research team contacted each candidate to confirm their eligibility, particularly regarding highway driving experience and familiarity with automatic transmission. Once verified, participants received detailed instructions and a confirmed appointment for their simulation session.

3.2. The experiment

The immersive driving simulator used in this study was developed by BS MOTION (Figure 1). Its main feature is a high degree of immersion by combining virtual reality with motion simulation. The simulator includes a car-like seat with pedals for acceleration, braking, and clutch. The base has two degrees of motion via electric actuators. Participants drove vehicles with automatic transmission. Virtual reality was provided using Oculus Rift headsets and headphones to enhance sensory immersion.

(a) (b)

Figure 1. (a) Driving scenario and (b) participant in virtual reality simulated driving.

The simulated route was built on Unity 3D by the VizLab/UNISINOS team. The first segment (approx. 2.5 km) of BR-290 highway near Porto Alegre allowed participants to adapt to the simulator. The second segment (approx. 3.2 km) was the experimental scenario, featuring a single-lane road with curves and slopes. Two versions of this segment were created: one with and one without road markings. The segment lengths were defined considering: (i) the total simulation time should be about 8 minutes – previously associated with mild to moderate SS (Nodari et al., 2017); and (ii) the availability of modeled scenario content.

Data on simulator sickness were collected at two points: (i) before entering the simulator (pre-test) and (ii) after completing the simulation (post-test), using the Brazilian Portuguese version of the SSQ (Carvalho et al., 2011).

3.3. Analysis of simulated driving discomfort

Simulator Sickness (SS) was assessed following previous studies (Nodari et al., 2017; Andriola et al., 2025), using a weighted average of symptom intensities and weighting factors for each construct. Symptoms were rated on a 0 to 3 scale: 0 (none), 1 (mild), 2 (moderate), and 3 (severe). Weighting factors are shown in Table 3. The SSQ used the original weights (Kennedy et al., 1993), while the VRSQ used adapted weights (Kim et al., 2018). Constructs (Nausea, Oculomotor, and Disorientation) are measured by summing the respective symptom scores.

Table 3: Weights for the constructs that compose simulator sickness

	Nausea (N)	Oculomotor (O)	Disorientation (D)	Total
SSQ	N × 9.54	O × 7.58	D × 13.93	(N+O+D) × 3.74
VRSQ	-	O × 0.12	D × 0.15	(O+D) / 2

The conversion from a qualitative scale to a numerical and proportional scale was based on standard practices in studies utilizing the Simulator Sickness Questionnaire (SSQ) and similar instruments (Kennedy et al., 1993; Kim et al., 2018; Andriola et al., 2025; Facchini et al., 2025). This approach enables the quantification of symptoms and facilitates statistical comparisons across different experimental conditions.

Differences in symptoms before and after the simulation were assessed by analyzing the mean of the paired differences, using the t-statistic (Hair et al., 2019). Variations in the severity of discomfort across combinations of experimental factors were evaluated using analysis of variance (ANOVA). Although the normality assumption was not met for the dataset, both the paired t-test and ANOVA were applied to the sample of 36 participants. It is important to note that these tests are robust to violations of normality, particularly when the sample size exceeds 30, as established by the Central Limit Theorem (CLT). Thus, the validity of both the t-test and ANOVA is preserved under moderate deviations from normality (Hair et al., 2019), especially in paired designs where comparisons are made within the same group. In this study, the paired t-test was applied to both symptom constructs and total indices derived from the SSQ and VRSQ. Homogeneity of variances - an assumption more critical for ANOVA than normality - was also verified. Therefore, the results are expected to remain reliable despite the observed non-normal distribution. ANOVA was conducted to identify differences in simulator-induced discomfort severity according to platform type (static vs. dynamic), gender, age group, road marking presence, and immersion duration.

4. RESULTS

This section presents the results of the experiment conducted with 36 volunteer drivers who participated in simulated driving sessions. The participants – 18 men and 18 women, including young, middle-aged, and older adults - were assigned to one of two scenarios (with or without road edge markings) and drove using either a static or dynamic simulator platform for 6 or 11 minutes, according to the experimental design, which defined these variables as controllable factors (Table 1). Symptom scores reported before and after the simulation enabled the calculation of indices for the constructs of Nausea (N), Oculomotor symptoms (O), and Disorientation (D), using the weighting proposed by the SSQ (Kennedy et al., 1993), as well as indices for Oculomotor (O) and Disorientation (D) symptoms using the VRSQ weighting (Kim et al., 2018). Due to differences in the weighting magnitudes, the indices obtained using the SSQ were generally higher than those from the VRSQ, as shown in Figure 2. Overall, the severity of discomfort symptoms was greater when using the static simulator compared to the dynamic one.

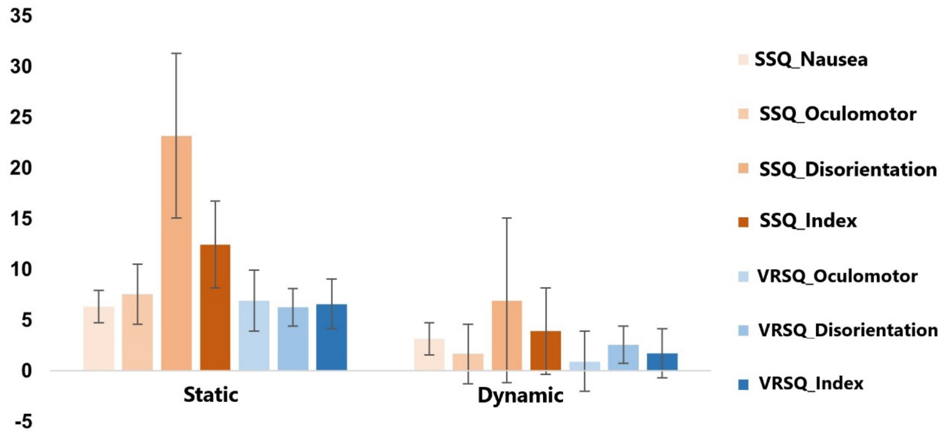

Figure 2. Average SS Index and Symptom Construct Index by simulator type.

The differences between pre- and post-test symptoms, analyzed by symptom constructs (O, N, and D), were assessed using paired t-tests. Since the analysis compares participants' evaluations before and after the simulated driving session, negative values may appear in the symptom scores. Table 4 shows statistically significant differences (t > |1.96| or p-value < 0.05 at a 95% confidence level) in simulator sickness indices measured by both the SSQ and VRSQ – across total scores and individual symptom constructs. In addition to the t-statistics, Table 4 also presents the mean differences and standard deviations for each symptom, reflecting the variability in these measurements.

Table 4: Paired t-test for simulator sickness symptoms measured by the SSQ and VRSQ

Questionnaire	Index (0: pre-test; 1: post-test)	*d*	Standard Deviation	t	p-value
SSQ	Nausea0 - Nausea1	-4.77	11.29	-2.54	0.02
	Oculomotor0 - Oculomotor1	-4.63	13.23	-2.10	0.04
	Disorientation0 - Disorientation1	-15.08	23.85	-3.79	0.00
	SSQ_index0 - SSQ_index1	-8.21	15.86	-3.10	0.00
VRSQ	Oculomotor0 - Oculomotor1	-3.94	11.35	-2.08	0.04
	Disorientation0 - Disorientation1	-4.44	6.76	-3.94	0.00
	VRSQ_index0 - VRSQ_index1	-4.19	7.95	-3.16	0.00

d: mean difference (post-test minus pre-test); t = paired t-test statistic.

A multivariate analysis of variance (ANOVA) was conducted on data from 36 participants to examine the effects of controllable factors and their interactions on simulator-induced discomfort, as shown in Table 5.

Table 5: Analysis of variance for simulator sickness indices

Index	Controllable Factor	Mean Square	F (α=0.05)	p-value
SSQ_O	Plataform	615.00	42.81	0.02
SSQ_O	Gender*Lane markings	318.26	22.16	0.04
SSQ_O	Lane markings*Immersion time	276.75	19.27	0.05
SSQ_O	Lane markings*Plataform	331.22	23.06	0.04
VRSQ_Total	Simulator	278.46	19.80	0.05
VRSQ_O	Simulator	329.22	18.96	0.05
VRSQ_D	Simulator	231.94	20.87	0.04

While the overall severity index from the SSQ (SSQ_Total) does not show significant differences across driver characteristics, scenario type (with or without road markings), or simulator platform, the VRSQ Total does vary significantly depending on the platform type. Among the indices measured by the SSQ, only the Oculomotor symptom group shows a significant difference in simulator sickness severity between static and dynamic platforms. Simulator sickness tends to be more severe when using a static platform. Figure 3 displays the mean differences and illustrates the variability of Oculomotor symptoms using standard deviation across each controllable factor.

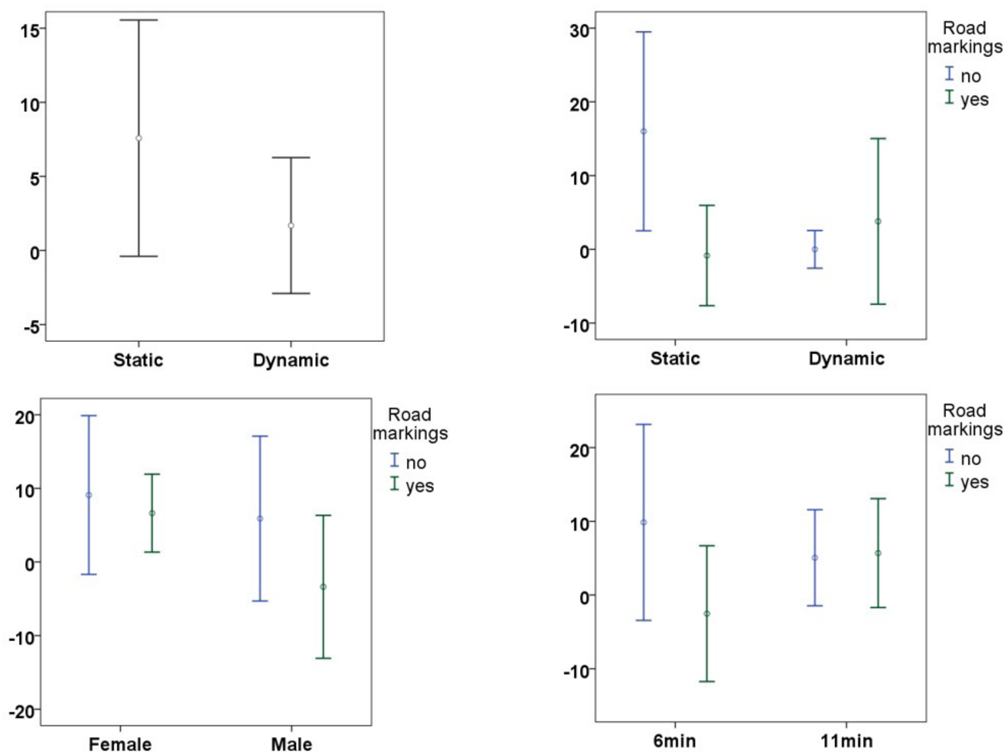

Figure 3. Significant differences in simulator sickness (oculomotor symptoms) for the analyzed controllable factors, (a) platform type; (b) platform type and road markings; (c) driver gender and road markings; (d) immersion time and road markings.

The interaction between simulator type and the presence of edge lines was also significant, highlighting that the severity of simulator sickness on the static platform is further intensified when edge lines are absent. Interactions between the presence of edge lines, driver gender, and immersion time also contributed to variations in discomfort: women were more severely affected, particularly in scenarios without edge lines; and longer immersion times increased simulator sickness in conventional scenarios (with edge lines) – a pattern that reversed in scenarios without line markings. A previous study had already suggested that women may be more sensitive to the effects experienced in simulated driving compared to men (Keshavarz et al., 2018). The greater severity of oculomotor symptoms observed in women, as shown in Figure 3, may be attributed to the theory of lower postural stability (Cobb et al., 1999; Mourant and Thattacherry, 2000; Stoffregen et al., 2017).

Simulator sickness measured using the VRSQ generated scores for oculomotor symptoms, disorientation, and a total index. The type of platform – static or dynamic – had a significant impact on driver discomfort: the dynamic platform resulted in less severe symptoms than the static one, as illustrated in Figure 4. Although some studies have linked increased movement to greater discomfort (Bruck and Watters, 2009; Dziuda et al., 2014), dynamic simulation may help reduce or eliminate the multisensory conflicts responsible for motion-induced sickness (Reason and Brand, 1975).

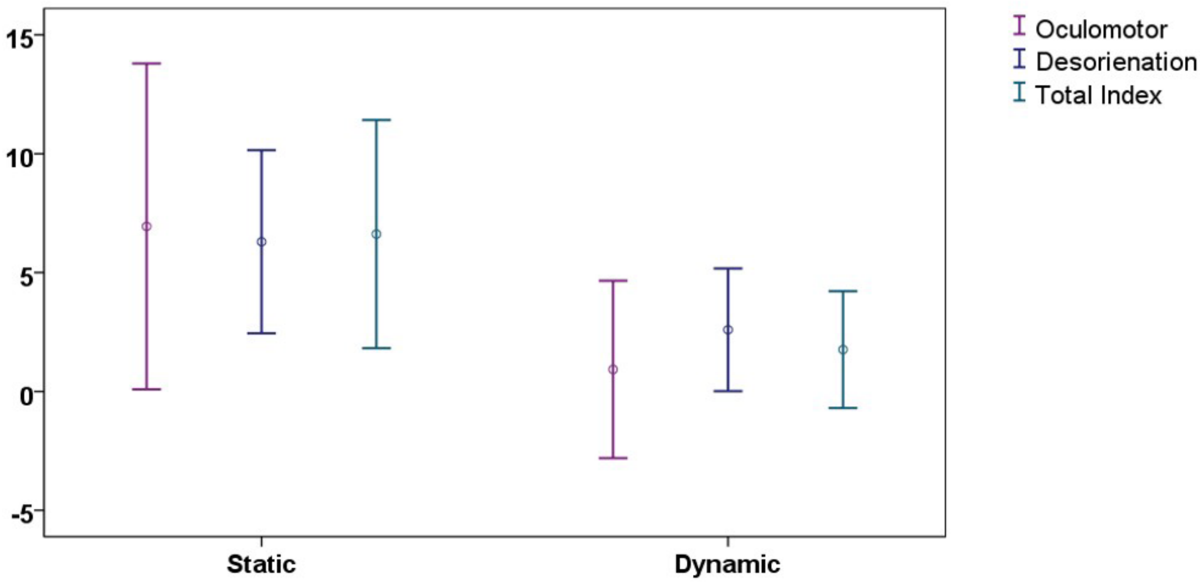

Figure 4. Types of Platform and the Effect of Simulator Sickness Based on the VRSQ.

Overall, the analysis of variance for simulator sickness effects revealed different outcomes for the SSQ and the VRSQ. The disorientation symptom showed a significant difference in the VRSQ but not in the SSQ, which can be attributed to the different ways symptoms are grouped in each tool. For instance, the VRSQ includes headache as part of the disorientation construct, whereas the SSQ does not. Conversely, dizziness with eyes open is included in the SSQ's disorientation group but is not considered in the VRSQ.

5. FINAL CONSIDERATIONS

This study aimed to evaluate and compare the sensation of discomfort experienced by drivers using dynamic and static immersive driving simulators, contributing to the improvement of simulation-based experimental research. The results demonstrated that dynamic platforms are consistently associated with lower severity of discomfort symptoms, both in the total scores and in the Oculomotor and Disorientation constructs of the VRSQ.

The comparative analysis between the Simulator Sickness Questionnaire (SSQ) and the Virtual Reality Sickness Questionnaire (VRSQ) revealed that the adaptation of the SSQ for virtual reality - namely, the VRSQ - was more effective in capturing the effects of dynamic platforms on both symptom dimensions and overall discomfort. In contrast, the SSQ only identified differences in oculomotor symptoms, suggesting that the VRSQ may offer greater sensitivity for evaluating immersive virtual reality experiences.

Beyond platform type, the results indicated that immersion time, presence of road edge lines, and driver gender significantly influence SS severity. Notably, the absence of edge lines intensified symptoms on static platforms, and longer immersion times increased discomfort in conventional scenarios. Women reported more severe oculomotor symptoms, particularly in scenarios without edge lines - possibly due to gender-related differences in postural stability.

These findings align with international literature suggesting that dynamic platforms can mitigate the multisensory conflicts responsible for simulator sickness. However, unlike studies that associate increased movement with greater discomfort, this research suggests that synchronized dynamic motion may actually reduce SS symptoms. The comparison between SSQ and VRSQ also contributes to the literature by showing that these tools capture symptoms differently, with the VRSQ identifying significant differences not detected by the SSQ.

The findings have practical implications for improving the design of future simulator-based experiments - particularly in Brazil, where the use of immersive simulators in driving research is still limited. Identifying the variables that influence SS severity can help refine experimental protocols, reduce participant dropout, and enhance data quality. Moreover, the comparison between SSQ and VRSQ highlights the need to adapt measurement instruments to immersive virtual reality contexts.

Among the limitations of this study is the small sample size, which may restrict the generalizability of the findings. Although the sample was stratified by gender and age, future studies could further explore the influence of these and other individual characteristics using broader age ranges. Additionally, familiarity with video games has been cited in the literature as a factor that may affect simulator sickness and should be considered in future research. Finally, further investigation into the influence of other experimental scenario variables is recommended.

AUTHORS' CONTRIBUTIONS

TBT: Data curation, Formal analysis, Writing – original draft, Writing – review and editing, Conceptualization; LBK: Data curation, Formal analysis, Writing – original draft, Writing – review and editing, Conceptualization; CF: Data curation, Writing – review and editing; CTN: Data curation, Writing – original draft, Writing – review and editing, Conceptualization; AMLU: Formal analysis, Writing – original draft, Writing – review and editing, Conceptualization.

CONFLICTS OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE-ASSISTED TECHNOLOGY

The authors declare that an artificial intelligence tool was used to support the translation of the text into English. No other part of the research or manuscript preparation involved the use of artificial intelligence tools.

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REFERENCES

Andriola, C.; G.R. Di Rado; D.S. Presta García et al. (2025) Classification of driving simulators validation: a case study using an immersive driving simulator. *Accident; Analysis and Prevention*, v. *213*, p. 107944. DOI: 10.1016/j.aap.2025.107944. PMid:39946862.

Baumgartner, E.; A. Ronellenfitsch; H.C. Reuss et al. (2019) Using a dynamic driving simulator for perception-based powertrain development. *Transportation Research Part F: Traffic Psychology and Behaviour*, v. *61*, p. 281-290. DOI: 10.1016/j.trf.2017.08.012.

Boyle, L.N. and J.D. Lee (2010) Using driving simulators to assess driving safety. *Accident; Analysis and Prevention*, v. *42*, n. 3, p. 785-787. DOI: 10.1016/j.aap.2010.03.006. PMid:20380903.

Brooks, J.O.; R.R. Goodenough; M.C. Crisler et al. (2010) Simulator sickness during driving simulation studies. *Accident; Analysis and Prevention*, v. *42*, n. 3, p. 788-796. DOI: 10.1016/j.aap.2009.04.013. PMid:20380904.

Bruck, S. and P.A. Watters (2009) Estimating cybersickness of simulated motion using the Simulator Sickness Questionnaire (SSQ): a controlled study. In *Proceedings of the 2009 6th International Conference on Computer Graphics, Imaging and Visualization: New Advances and Trends, CGIV2009*. New York: IEEE. DOI: 10.1109/CGIV.2009.83

Carnegie, K. and T. Rhee (2015) Reducing visual discomfort with HMDs using dynamic depth of field. *IEEE Computer Graphics and Applications*, v. *35*, n. 5, p. 34-41. DOI: 10.1109/MCG.2015.98. PMid:26416360.

Carvalho, M.R.; R.T. Costa and A.E. Nardi (2011) Simulator Sickness Questionnaire: tradução e adaptação transcultural Simulator Sickness Questionnaire: translation and cross-cultural adaptation. *Jornal Brasileiro de Psiquiatria*, v. *60*, n. 4, p. 247-252. DOI: 10.1590/S0047-20852011000400003.

Classen, S.; M. Bewernitz and O. Shechtman (2011) Driving simulator sickness: an evidence-based review of the literature. *The American Journal of Occupational Therapy*, v. *65*, n. 2, p. 179-188. DOI: 10.5014/ajot.2011.000802. PMid:21476365.

Cobb, S.V.G.; S. Nichols and A. Ramsey (1999) Virtual Reality-Induced Symptoms and Effects (VRISE). *Presence*, v. *8*, n. 2, p. 169-186. DOI: 10.1162/105474699566152.

Dennison, M. and M. D'Zmura (2018) Effects of unexpected visual motion on postural sway and motion sickness. *Applied Ergonomics*, v. *71*, p. 9-16. DOI: 10.1016/j.apergo.2018.03.015. PMid:29764619.

Dziuda, Ł.; M.P. Biernacki; P.M. Baran et al. (2014) The effects of simulated fog and motion on simulator sickness in a driving simulator and the duration of after-effects. *Applied Ergonomics*, v. *45*, n. 3, p. 406-412. DOI: 10.1016/j.apergo.2013.05.003. PMid:23726466.

Facchini, G.; A.M. Larranaga; F.A. Cândido dos Santos et al. (2025) Virtual reality in stated preference survey for walkability assessment. *Transportation Research Part D, Transport and Environment*, v. *139*, p. 104545. DOI: 10.1016/j.trd.2024.104545.

Federer, W.T. and B.L. Raktoe (2005) Fractional factorial designs. In Kotz, S.; N. Balakrishnan; C.B. Read et al. (eds.) *Encyclopedia of Statistical Sciences.* Hoboken: Wiley. DOI: 10.1002/0471667196.ess0818.pub2.

Frank, L.H.; R.S. Kennedy; R.S. Kellogg et al. (1983) *Simulator sickness: a reaction to a transformed perceptual world. 1. Scope of the problem* (NAVTRAEQUIPCEN TN-65). Orlando: Naval Training Equipment Center.

Hair, J.F.; B.J. Babin; R.E. Anderson et al. (2019) *Multivariate Data Analysis* (8th ed.). Upper Saddle River: Cengage.

Helland, A.; S. Lydersen; L.E. Lervåg et al. (2016) Driving simulator sickness: Impact on driving performance, influence of blood alcohol concentration, and effect of repeated simulator exposures. *Accident; Analysis and Prevention*, v. *94*, p. 180-187. DOI: 10.1016/j.aap.2016.05.008.

Hettinger, L.J.; K.S. Berbaum; R.S. Kennedy et al. (1990) Vection and simulator sickness. *Military Psychology*, v. *2*, n. 3, p. 171-181. DOI: 10.1207/s15327876mp0203_4. PMid:11537522.

Hill, K.J. and P.A. Howarth (2000) Habituation to the side effects of immersion in a virtual environment. *Displays*, v. *21*, n. 1, p. 25-30. DOI: 10.1016/S0141-9382(00)00029-9.

Howarth, P.A. and S.G. Hodder (2008) Characteristics of habituation to motion in a virtual environment. *Displays*, v. *29*, n. 2, p. 117-123. DOI: 10.1016/j.displa.2007.09.009.

Igoshina, E.; F.A. Russo; R. Shewaga et al. (2022) The relationship between simulator sickness and driving performance in a high-fidelity simulator. *Transportation Research Part F: Traffic Psychology and Behaviour*, v. *89*, p. 478-487. DOI: 10.1016/j.trf.2022.07.015.

ITF (2016) *Zero Road Deaths and Serious Injuries: Leading a Paradigm Shift to a Safe System.* Paris: OECD Publishing. DOI: 10.1787/9789282108055-en.

Kennedy, R.S.; J. Drexler and R.C. Kennedy (2010) Research in visually induced motion sickness. *Applied Ergonomics*, v. *41*, n. 4, p. 494-503. DOI: 10.1016/j.apergo.2009.11.006. PMid:20170902.

Kennedy, R.S.; N.E. Lane; K.S. Berbaum et al. (1993) Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, v. *3*, n. 3, p. 203-220. DOI: 10.1207/s15327108ijap0303_3.

Kennedy, R.S.; K.M. Stanney and W.P. Dunlap (2000) Duration and exposure to virtual environments: sickness curves during an across sessions. *Presence*, v. *9*, n. 5, p. 463-472. DOI: 10.1162/105474600566952.

Keshavarz, B. and H. Hecht (2012) Visually induced motion sickness and presence in videogames: the role of sound. *Proceedings of the Human Factors and Ergonomics Society*, v. *56*, n. 1, p. 1763-1767. DOI: 10.1177/1071181312561354.

Keshavarz, B.; L.J. Hettinger; R.S. Kennedy et al. (2014) Demonstrating the potential for dynamic auditory stimulation to contribute to motion sickness. *PLoS One*, v. *9*, n. 7, e101016. DOI: 10.1371/journal.pone.0101016. PMid:24983752.

Keshavarz, B.; R. Ramkhalawansingh; B. Haycock et al. (2018) Comparing simulator sickness in younger and older adults during simulated driving under different multisensory conditions. *Transportation Research Part F: Traffic Psychology and Behaviour*, v. *54*, p. 47-62. DOI: 10.1016/j.trf.2018.01.007.

Kim, H.K.; J. Park; Y. Choi et al. (2018) Virtual reality sickness questionnaire (VRSQ): Motion sickness measurement index in a virtual reality environment. *Applied Ergonomics*, v. *69*, p. 66-73. DOI: 10.1016/j.apergo.2017.12.016. PMid:29477332.

Kohl, R.L. (1983) Sensory conflict theory of space motion sickness: an anatomical location for the neuroconflict. *Aviation, Space, and Environmental Medicine*, v. *54*, n. 5, p. 464-465. PMid:6870740.

Lee, G.C.H.; Y. Yoo and S. Jones (1997) Investigation of driving performance, vection, postural sway, and simulator sickness in a fixed-based driving simulator. *Computers & Industrial Engineering*, v. *33*, n. 3-4, p. 533-536. DOI: 10.1016/S0360-8352(97)00186-1.

Min, B.C.; S.C. Chung; Y.K. Min et al. (2004) Psychophysiological evaluation of simulator sickness evoked by a graphic simulator. *Applied Ergonomics*, v. *35*, n. 6, p. 549-556. DOI: 10.1016/j.apergo.2004.06.002. PMid:15374762.

Moll, S.; G. López; D. Llopis-Castelló et al. (2023) Drivers' behaviour when overtaking cyclists on rural roads: Driving simulator validation using naturalistic data Transport. *Transportation Research Part F: Traffic Psychology and Behaviour*, v. *95*, p. 391-404. DOI: 10.1016/j.trf.2023.05.011.

Mourant, R.R. and T.R. Thattacherry (2000) Simulator Sickness in a virtual environments driving simulator. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, v. 44, n. 5, p. 534-537. DOI: 10.1177/154193120004400513.

Munafo, J.; M. Diedrick and T.A. Stoffregen (2017) The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects. *Experimental Brain Research*, v. *235*, n. 3, p. 889-901. DOI: 10.1007/s00221-016-4846-7. PMid:27915367.

Nodari, C.T.; M. Castilhos de Oliveira; M.R. Veronez et al. (2017) Avaliação do realismo e da sensação de mal-estar (simulator sickness) no uso de simulador imersivo de direção. In *Anais do XXXI Congresso da ANPET*. Rio de Janeiro: Associação Nacional de Pesquisa e Ensino em Transportes, p. 3103-3115.

Oman, C.M. (1990) Motion sickness: a synthesis and evaluation of the sensory conflict theory. *Canadian Journal of Physiology and Pharmacology*, v. *68*, n. 2, p. 294-303. DOI: 10.1139/y90-044. PMid:2178753.

Reason, J.T. (1978) Motion sickness adaptation: a neural mismatch model. *Journal of the Royal Society of Medicine*, v. *71*, n. 11, p. 819-829. DOI: 10.1177/014107687807101109. PMid:731645.

Reason, J.T. and J.J. Brand (1975) *Motion Sickness.* Oxford: Academic Press.

Rebenitsch, L. and C. Owen (2016) Review on cybersickness in applications and visual displays. *Virtual Reality*, v. *20*, n. 2, p. 101-125. DOI: 10.1007/s10055-016-0285-9.

Reinhard, R.T.; M. Kleer and K. Dreßler (2019) The impact of individual simulator experiences on usability and driving behavior in a moving base driving simulator. *Transportation Research Part F: Traffic Psychology and Behaviour*, v. 61, p. 131-140. DOI: 10.1016/j.trf.2018.01.004.

Sevinc, V. and M.I. Berkman (2020) Psychometric evaluation of Simulator Sickness Questionnaire and its variants as a measure of cybersickness in consumer virtual environments. *Applied Ergonomics*, v. *82*, p. 102958. DOI: 10.1016/j.apergo.2019.102958. PMid:31563798.

Sinitski, E.; A.A. Thompson; P.C. Godsell et al. (2018) Postural stability and simulator sickness after walking on a treadmill in a virtual environment with a curved display. *Displays*, v. *52*, p. 1-7. DOI: 10.1016/j.displa.2018.01.001.

Sportillo, D.; A. Paljic and L. Ojeda (2018) Get ready for automated driving using Virtual Reality. *Accident; Analysis and Prevention*, v. *118*, p. 102-113. DOI: 10.1016/j.aap.2018.06.003. PMid:29890368.

Stanney, K.M. and R.S. Kennedy (1997) The psychometrics of cybersickness. *Communications of the ACM*, v. *40*, n. 8, p. 67-68.

Stoffregen, T.A.; C.-H. Chang; F.-C. Chen et al. (2017) Effects of decades of physical driving on body movement and motion sickness during virtual driving. *PLoS One*, v. *12*, n. 11, e0187120. DOI: 10.1371/journal.pone.0187120. PMid:29121059.

Stone, W.B. (2017) *Psychometric Evaluation of the Simulator Sickness Questionnaire as a Measure of Cybersickness*. Iowa: Iowa State University. Disponível em: <http://lib.dr.iastate.edu/etd> (acesso em 16/02/2022).

Sutherland, I.E. (1968) A head-mounted three dimensional display. In *Fall Joint Computer Conference*. New York: ACM Digital Library, p. 5-10.

Tang, Y.M.; D. Zhao; T. Chen et al. (2025) A systematic review of abnormal behaviour detection and analysis in driving simulators. *Transportation Research Part F: Traffic Psychology and Behaviour*, v. *109*, p. 897-920. DOI: 10.1016/j.trf.2025.01.002.

Treat, J.; N. Tumbas and S. McDonald (1979) Tri-level study of the causes of traffic accidents. executive summary. *Vision Research*, v. *42*, n. 21, p. 2419-2430.

WHO (2023). *Global Status Report on Road Safety 2023*. Geneva: World Health Organization, Disponível em: <https://iris.who.int/handle/10665/375016> (acesso em 16/02/2022).

Zhao, H.; M. Meng; X. Li et al. (2024) A survey of autonomous driving frameworks and simulators. *Advanced Engineering Informatics*, v. *62*, p. 102850. DOI: 10.1016/j.aei.2024.102850.