Automotive Experiences
Vol. 5 No. 2 (2022) pp. 238-250
p-ISSN: 2615-6202 e-ISSN: 2615-6636

Research Paper

Analysis of User's Comfort on Automated Vehicle Riding Simulation using Subjective and Objective Measurements

Muhammad Nur Aliff Mohd Norzam[1], **Juffrizal Karjanto**[1,2], **Nidzamuddin Md Yusof**[1,2], **Muhammad Zahir Hasan**[3], **Abd Fathul Hakim Zulkifli**[4], **Ahmad Azad Ab Rashid**[5]

[1]Fakulti Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, 76100, Melaka, Malaysia
[2]Centre for Advanced Research on Energy, Universiti Teknikal Malaysia Melaka, 76100, Melaka, Malaysia
[3]Fakulti Teknologi Kejuruteraan Mekanikal dan Pembuatan, Universiti Teknikal Malaysia Melaka, 76100, Melaka, Malaysia
[4]Fakulti Teknologi Kejuruteraan, Universiti Tun Hussein Onn Malaysia, 84500, Pagoh, Malaysia
[5]Malaysian Institute of Road Safety Research (MIROS), 43000, Selangor, Malaysia

juffrizal@utem.edu.my

https://doi.org/10.31603/ae.6913

Check for updates

Published by Automotive Laboratory of Universitas Muhammadiyah Magelang collaboration with Association of Indonesian Vocational Educators (AIVE)

Article Info
Submitted: 22/03/2022
Revised: 28/04/2022
Accepted: 29/04/2022
Online first: 10/05/2022

Abstract

The naturalistic study investigated the potential influence of personal driving preferences (assertive and defensive driving style) on users; comfort when being driven in an automated vehicle with a defensive driving style. Adopted the Wizard of Oz design, the study involved three phases: pre-, during, and post-driven to measure their comfort, perceived safety, and likeness as well as motion sickness propensity through self-report questionnaire and heart rate variation. After answering a set of questionnaires, participants were exposed to simulated driving in an automated vehicle with a defensive driving style. A statistical analysis produced no statistically significant difference between assertive and defensive participants. This indicates an overall preference, perceived comfort without severe motion sickness propensity to the defensive driving style of the autonomous vehicle, regardless of participants' personal driving styles.

Keywords: Autonomous vehicle; Driving style; Human factors; Comfort

1. Introduction

Autonomous driving is expected to change the future of mobility not only improving road safety but also ensuring environmental and social sustainability [1]–[3]. As human faults and errors contributed most to road crashes [4], an automated vehicle (AV) can have as high as a 90% chance to reduce road accidents [5]. According to the American Automobile Association Foundation for Traffic Safety, aggressive driving was the leading cause of 56% of fatal accidents in the United States [6]. Hence, one of the main reasons users prefer to buy an AV is safety [7]. The latest technology equips an AV in sensing, computing, tracking, and controlling [8], [9]. Rendering it essentially as an intelligent robot that maximizes safety and operates solely on optimum logic [10]. Michałowska & Ogłoziński predicted that AVs would be on the road by 2026-2030; however, the way they will drive is yet to be known [11].

Every human driver has his or her way of controlling the vehicle's longitudinal (accelerating and decelerating), lateral (cornering), and vertical (passing through speed hump) acceleration. Lv. et al. categorised "driving style" (DS) – i.e. the way of driving into three groups: aggressive, defensive, and moderate [12]. The aggressive drivers tend to use the throttle and brake pedals more frequently [13]. They prefer to drive the vehicle with more thrills and strive for dynamic vehicle efficiency by driving with high magnitude and sudden accelerations and decelerations. Contrary to this is the defensive DS, which normally involves mild operational activities with small amplitudes and low-frequency movements on the steering wheel, gas pedal, and brake pedal [12]. In between these two extremes is the moderate DS. As each human driver has their preferred DS, the most friendly AV, therefore, should as much possible mirror the human DS [14].

In recent years, automated DS has gotten a lot of attention [15], concentrating on the comfort of the occupants [16]. Prior work has focused on using three different AV DSs (LRT, aggressive and defensive) to investigate the preferred DS of an AV by humans in tri-axial acceleration (longitudinal, lateral, and vertical) [10]. Their work applied a method of "stop and go" at each checkpoint. The participant needed to rate the way the AV's drove at each checkpoint. At the end of their study, they found that the participants preferred a defensive AV DS since they felt more comfortable with the experimented DS. Basu et al. further supported the findings that participants preferred a DS to be significantly more defensive than their own [17]. They conducted their experiment through a driving simulation and make the participant experience and evaluate the AV's simulation with different DSs. Moreover, Karlsson et al. reported that people are commonly converged to a defensive DS, regardless of the driving situation [18]. Ekman et al. investigated how the vehicle's DS affects users' trust in AVs from both DS (aggressive and defensive) in an experiment and found the 'Defensive' DS was more trustworthy than 'Aggressive' DS [19]. It has also been proposed that if the AV drives in a stereotypical human style, its acceptance will also increase [20], [21]. Users from Netherlands [10], United States [17], Sweden [18], [19], and German [22] indicated their preference to be driven in a defensive AV DS. However, in Malaysia, such study has never been done and yet to be explored.

In our work, we designed a methodology where the participant should experience a continuous ride of a defensive AV DS on a road situation with other road users and all the traffic laws applied. The goal of this research is to measure the acceptance of the proposed defensive AV DS, through subjective (e.g., comfort, safety) and objective measurement (e.g., physiological measurement), on the two types of Malaysian drivers (aggressive and defensive) when tested on the suburban type of roads. We hypothesized both types of human drivers to accept and be more comfortable with the proposed AV-DS.

2. Methodology

2.1. *Participants*

The study involved 30 young Malaysian drivers (70% were male) aged 18 to 25 (mean = 20.9, SD = 2.02). Before participating, participants answered questions to determine their type of DS. Taubman-Ben-Ari et al. found relationships between specific DS and sensation-seeking (SS) trait [23], assessed using the questionnaire developed by Zuckerman et al. [24]. Participants with high SS scores between 10 and 19 were classified as aggressive DS drivers (n = 15), while drivers with low SS scores between 0 and 9 as defensive (n = 15) [10].

2.2. *Wizard of Oz – Driving and Interacting*

A Wizard of Oz study in a real-world setting was implemented to investigate the experience of AV passengers without taking existing technology limits into account [25]. Wizard of Oz is a method that allows participants to experience a similar fully automated vehicle riding during the experiment [26].

In this study, two experimenters were involved, namely the Driving Wizard and the Interactive Wizard. The position of the Driving Wizard will be seated at the driver's seat. In contrast, Interactive Wizard and a participant will be sitting at the passenger seat back and beside the Driving Wizard, respectively (see **Figure 1**).

2.2.1. *The Driving Wizard (DW)*

The DW's job was to simulate autonomous driving as if it were being generated by a real AV. Before the experiment, the DW went through a series of driving training to familiarize himself with the designated route by driving based on the range of the pre-defined defensive AV DS. In addition, the DW need to simulate the accelerations and the DS of the vehicle in general with smooth movement without jerks that imitate AV DS [10], [27], [28].

2.2.2. *The Interactive Wizard (IW)*

The IW acts like a middle person between the participant and DW during the experiment. Should the participant require support or decide to end the study at any time, the IW is accessible to assist. While during the simulation of automated driving, the IW took and recorded the required data from the participants and the Instrumented Vehicle.

2.3. *Collection and Analysis of Data*

Two sets of data were measured, (1) vehicle-based and (2) participant-based measurements. The former included the vehicle's tri-axial acceleration, while the participant-based measurements consisted of the dependent variables tested in this study.

2.3.1. *Vehicle-Based Measurement*

Acceleration. The vehicle's acceleration was measured in tri-axial acceleration (longitudinal, lateral, and vertical acceleration). Dominant frequencies below 0.5 Hz were considered low-frequency motion contributing to motion sickness (MS) over participants [29]–[33]. MS indicates an uncomfortable situation and is likely to be avoided in automated driving. The MS was calculated using Motion Sickness Dose Value (MSDV) through Eq. (1).

$$MSDV = \sqrt{\int_0^T [a_w(t)]^2\, dt} \qquad (1)$$

Where a_w is the root mean square of the acceleration that has been weighted with frequency weighing (W_f) and T is the exposure period to the motion.

To quantify the frequency of the simulated accelerations throughout the study, power spectral density (PSD) was calculated and tabulated. PSD describes the acceleration's power as a frequency per unit frequency function. PSD also indicates the consistency of the simulated AD VS by the DW throughout the whole simulated automated driving test rides.

2.3.2. *Participant-Based Measurements*

Test Ride Rating - This study used five separate rating scales, labelled as R1 (Driving Style Reflection), R2 (Driving Style Refinement), R3 (Comfort), R4 (Pleasantness) and R5 (Safety Rating), to elicit the opinions of the participants on the simulated test rides. All of the items were five-point Likert scale, with R1: 1 corresponded to "very true of me" and 5 corresponded to "very untrue of me," R2: 1 corresponded to "the force is much too low" and 5 corresponded to "the force is much too high" R3: 1 corresponded to "very comfortable" and 5 corresponded to "very uncomfortable," R4: 1 corresponded to "very pleasant" and 5 corresponded to "very unpleasant," and R5: 1 corresponded to "very safe" and 5 corresponded to "very dangerous," [10].

Motion Sickness Assessment Questionnaire (MSAQ) - It consists of 16 questions on a 9-point scale (1= not at all, 9 = severely) that was developed by Gianaros et al. [34]. The 16 questions can be divided into four components: gastrointestinal, central, peripheral, and epitope-related symptoms of MS. Therefore, MSAQ can be displayed as a single cumulative score and as four subscores for each configuration.

Heart Rate Variability (HRV) - This study quantified comfort through the presence of MS quantified using HRV measured using ECG sensors. The ability to obtain continuous [35] records of one's physiological state and perform experiments without stopping and collecting data was the basis for quantifying MS using HRV. The measurements of HRV constituted of the mean of heart rate (beats per minute, BPM), the standard deviation of heart rate, and Fast Fourier Transform High Frequency (normalized units) [36].

A within-subject design was implemented for the HRV in three phases: pre-, during, and post-driven. A between-subject design was implemented for the subjective measurements of participants. 1) Test Ride Rating; which Driving Style Reflection (R1), Driving Style Range Refinement (R2), Comfort (R3), Pleasantness (R4), and Safety (R5). 2) Pre- and Post-MSAQ.

2.4. *Instrumented Vehicle*

Instead of a simulator, an instrumented vehicle was used to simulate an AV riding experience or test ride for the participants of this study. Most driving simulators are developed for specific requirements, ignoring other aspects of reality that may affect the results [37]. Besides, part of the study's objective is to make the participants feel like riding a real AV as a passenger while enjoying the ride. Furthermore, a high ecological validity can be achieved when using a real vehicle in an actual road setup where all the traffic laws apply.

This study focused only on the defensive type of the proposed AV DS in the tri-axial accelerations (lateral, longitudinal, and vertical) from the past study [38]. In the longitudinal direction (x-axis), the instrumented vehicle was driven at longitudinal acceleration and deceleration at 1.37 ms^{-2} to 2.45 ms^{-2} and -1.37 ms^{-2} to -3.23 ms^{-2}, respectively, mimicking the suburban speed limit [38]. The lateral acceleration generated during cornering was aimed at approximately 1.47 ms^{-2} to 4.12 ms^{-2}, while the vertical acceleration was from 0 ms^{-2} to 1.57 ms^{-2} [38].

The instrumented vehicle was equipped with an accelerometer, electrocardiogram (ECG), and data acquisition system (DAQ) (see **Figure 1**). The National Instrument cRIO-9030 DAQ and an ADXL335 3-axis accelerometer were used in this investigation. The accelerometer was placed on the center console near the vehicle's center of gravity. The ECG sensor, AD8232 [39], was used to measure the HRV [40], [41]. In addition, the ECG sensor was used along with an optocoupler [42] to isolate the high voltage between the electrical devices and participants. Both accelerometer and ECG sensor were connected to the DAQ and sampled at 250 Hz. 250 Hz was employed as a conservative approach as 125 Hz is deemed a minimum sampling rate in collecting Heart Rate Variability (HRV) data in psychophysiological studies [43].

A device called Automatic Acceleration and Data Controller (AUTOAccD) was installed to assist the driving wizard (DW) in simulating the automated driving test rides according to the defined acceleration condition [27], [44]. AUTOAccD interactively displays and groups real-time acceleration data, allowing the DW to adjust throttle position and speed to deliver the desired simulation.

In this study, a look-alike LiDAR is 3D-printed and placed on the instrumented vehicle's roof to increase the saliency of simulating an AV riding experience.

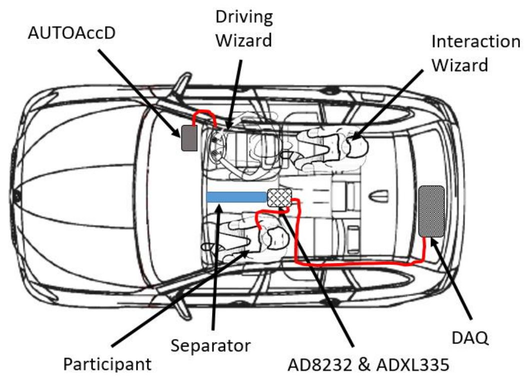

Figure 1. The instrumented vehicle layout

2.5. *Procedure*

The study was divided into three phases. Phases 1, 2, and 3 took about 5, 10, and 5 minutes respectively (see **Figure 2**). The three-phase design followed the suggested methodology by Laborde, Mosley, and Thayer [43] (resting, reactivity and recovery) in collecting the HRV.

Upon the participant's arrival, the IW explained the activities during the whole study. First, the participants answered the pre-experiment questionnaire and placed the ECG sensors on their bodies. Then, IW guided the participants to the instrumented vehicle, and Phase 1 began. Phase 1 happened inside the instrumented vehicle when it was static before the driven (test ride) phase. Phase 2 occurred when the defensive AV DS was simulated. Finally, Phase 3 happened after the defensive AV DS test ride simulation.

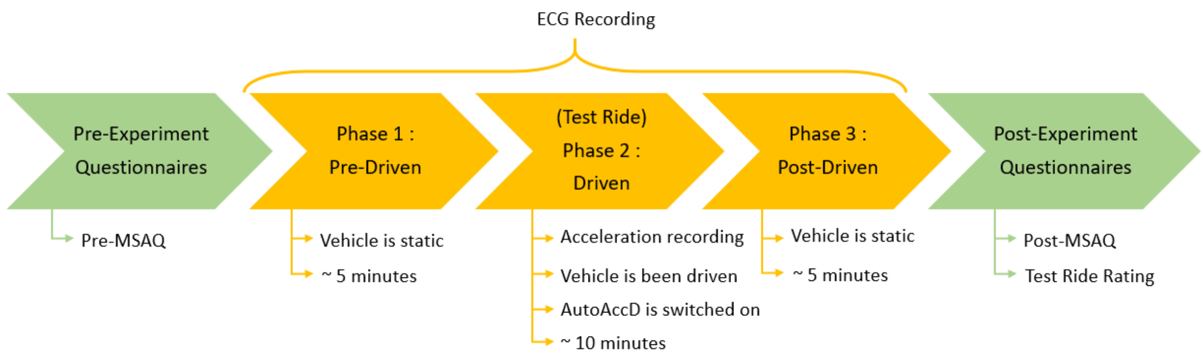

Figure 2. The phase of the experiment

After finishing the test ride, participants answered the post-experiment questionnaires based on the experience they gained. Participants completed the questionnaire immediately after exiting the instrumented vehicle [45]. Finally, the participants removed the ECG sensor, being debriefed, and compensated (RM 30 ~ USD 10) for their participation.

3. Results and Discussion

3.1. Results

3.1.1. Test Rides' Consistency

The distribution of acceleration over the frequency spectra of all 30 test drives of 30 participants was plotted as a function of power spectral density (PSD). PSDs were plotted in the tri-axial directions on semi-log graphs (see **Figure 3**). The dominant frequency of the PSD in the x-axis, y-axis, z-axis was below 0.2, 0.3, and 0.2 Hz, respectively.

3.1.2. Test Ride Rating Analysis

The Mann-Whitney U-test was employed to determine the difference between the acceptance of two types of drivers (assertive and defensive drivers) when evaluating longitudinal acceleration, longitudinal deceleration, and lateral acceleration (see **Table 1**).

Power analysis of the actual sample sizes of the 30 participants for longitudinal acceleration and deceleration, and lateral acceleration were 0.078, 0.053, and 0.069, respectively. Due to the low power achieved (< 0.80 [46]), power analysis is performed between the two participant types (assertive and defensive) with a probability of making a type II error (β = 20%) and a large effect size (r = 0.5). The total sample sizes required for this Mann-Whitney U test were 898, 9686, and 1338 for longitudinal acceleration and deceleration, and lateral acceleration, respectively, to show any significant difference between the two types of participants.

3.1.3. Motion Sickness Assessment

3.1.3.1. Motion Sickness Dose Value (MSDV)

Since the frequencies below 0.5 Hz and peaks near 0.2 Hz strongly correlated with motion sickness [29], [30], [32], [33], only longitudinal and lateral directions of MSDV were plotted (see **Figure 4**).

The distribution of mean MSDV with frequency-weighted acceleration on the x-axis and y-axis was about the same. Also, the mean, standard deviation (SD), and coefficient of variation (CoV) of the MSDV generated by the DW were calculated on all 30 test drives, proving high reliability and consistency (see **Table 2**).

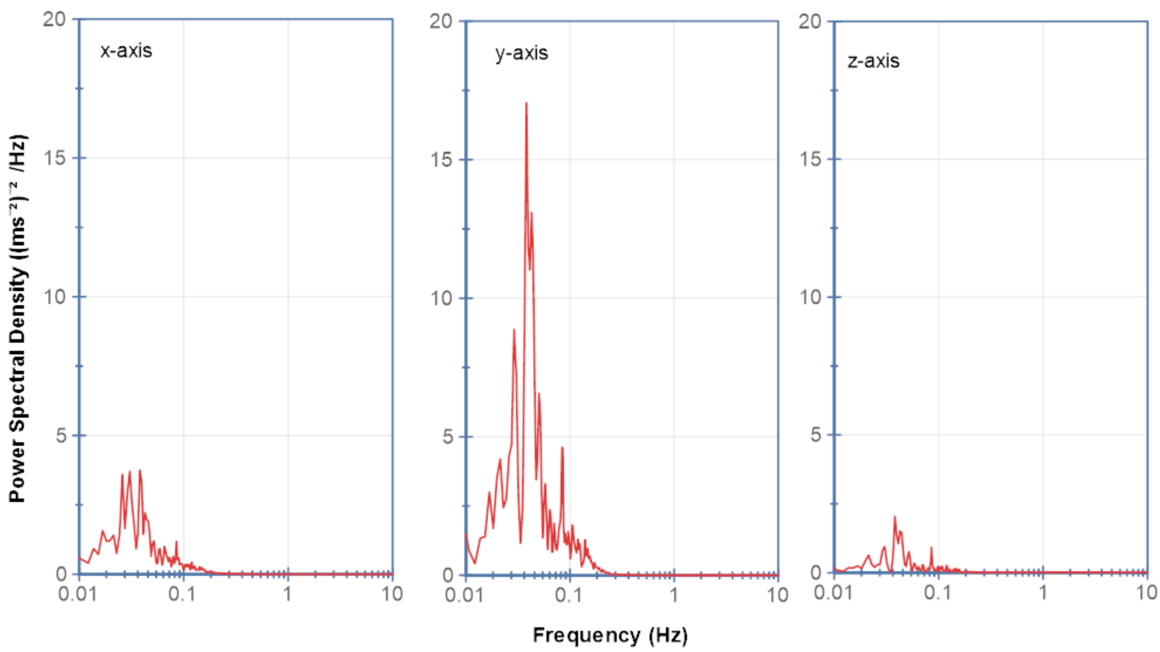

Figure 3. PSDs of acceleration in x-, y- and z-axis.

Table 1. Analysis for longitudinal acceleration (long. acc.), longitudinal deceleration (long. dec.), and lateral acceleration (lat. acc.) on assertive (ass.) and defensive (def.) participants.

Rating	Participant (Median)	Direction	Mann-Whitney U Test
DS Reflection	Ass. (2.00)	Long. Acc.	U = 101, z = -0.476, p = 0.653
	Def. (2.00)		
	Ass. (3.00)	Long. Dec.	U = 119.5, z = 0.302, p = 0.775
	Def. (2.00)		
	Ass. (2.00)	Lat. Acc.	U = 96.5, z = -0.709, p = 0.512
	Def. (2.00)		
DS Refinement	Ass. (3.00)	Long. Acc.	U = 100, z = -0.624, p = 0.624
	Def. (3.00)		
	Ass. (3.00)	Long. Dec.	U = 99.5, z = -0.602, p = 0.595
	Def. (3.00)		
	Ass. (3.00)	Lat. Acc.	U = 83.5, z = -1.283, p = 0.233
	Def. (2.00)		
Comfort	Ass. (2.00)	Long. Acc.	U = 79, z = -1.519, p = 0.174
	Def. (1.00)		
	Ass. (2.00)	Long. Dec.	U = 109, z = -0.134, p = 0.902
	Def. (2.00)		
	Ass. (2.00)	Lat. Acc.	U = 73.5, z = -1.714, p = 0.106
	Def. (2.00)		
Pleasantness	Ass. (2.00)	Long. Acc.	U = 94, z = -0.859, p = 0.461
	Def. (2.00)		
	Ass. (2.00)	Long. Dec.	U = 98, z = -0.652, p = 0.567
	Def. (1.00)		

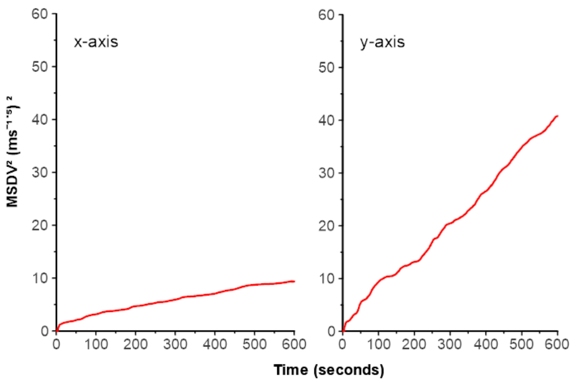

Figure 4. MSDV with frequency-weighted acceleration in the longitudinal (x-axis) and lateral (y-axis) direction.

Table 2. Mean, standard deviation (SD) and coefficient of variation (CoV) for MSDV for the entire test rides

	Mean ($ms^{-1.5}$)	SD	CoV(%)
$MSDV_x$	3.14	0.46	14.67
$MSDV_y$	6.49	0.80	12.37
$MSDV_z$	1.30	0.40	30.37

3.1.3.2. Motion Sickness Assessment Questionnaire (MSAQ)

The Wilcoxon Signed-rank test was performed on pre- and post-MSAQ data to determine if the test drive induced MS in all participants. Both types of participants (assertive and defensive) showed no statistical differences between pre- and post-MSAQ scores, except for peripheral-related constructs (see **Table 3**).

Power analysis of the actual sample sizes of the 30 participants for pre- and post-MSAQ in both types of drivers was 0.083. Due to the low power achieved (< 0.80 [46]), power analysis is performed between the MSAQ in two conditions with a probability of making a type II error (β = 20%) and large effect size (r = 0.5). The total sample sizes required for this Wilcoxon Signed-rank Test were 772, to show any significant difference between the two types of participants.

The Mann-Whitney U-test was also run to determine the statistical differences between the two driver types in the MSAQ differences ($MSAQ_{post}$ - $MSAQ_{pre}$), no statistical differences are shown.

3.1.3.3. Heart Rate Variability (HRV)

A two-way mixed ANOVA test was used to determine whether there was an interaction between within-subject (the phases of the experiment), between-subject (type of participants), and within-subject and between-subject of the measured HRV (see **Table 4**).

Table 3. Wilcoxon Signed-rank Test (WSRT) for the pre- and post-MSAQ scores for the two types of participants

Participant	MSAQ	Situation	Median	WSRT
Assertive	G	Pre	11.11	*z = 1.00, p = 0.317*
		Post	11.11	
	C	Pre	11.11	*z = 1.00, p = 0.317*
		Post	11.11	
	P	Pre	11.11	*z = -2.53, p = 0.011**
		Post	11.11	
	S	Pre	13.89	*z = 1.73, p = 0.084*
		Post	13.89	
	O	Pre	11.81	*z = -0.26, p = 0.796*
		Post	11.81	
Defensive	G	Pre	11.11	*z = 1.29, p =0 .197*
		Post	11.11	
	C	Pre	11.11	*z = 0.95, p = 0.344*
		Post	11.11	
	P	Pre	11.11	*z = -2.06, p = 0.039**
		Post	11.11	
	S	Pre	11.11	*z = 1.60, p = 0.109*
		Post	11.11	
	O	Pre	11.81	*z = 0.76, p = 0.448*
		Post	11.81	

** Indicates that the H0 was rejected, (p<0.05)*

Table 4. Results of the two-way mixed ANOVA for the HRV

Measured HRV	Two-way mixed ANOVA		
	Interaction of within-subject	Interaction of between-subject	Interaction between within-subject and between-subject
Mean of HR	✓	×	×
SD of HR	×	×	×
FFT HF (n.u.)	✓	×	×

✓ Indicates that there is an interaction

× Indicates that there is no interaction

Mean of HR

A correction was made using Hyunh-Feldt correction since the Mauchly's Test of Sphericity was violated $\chi^2(2) = 9.196$, p = 0.010. There was no statistically significant interaction between both types of participant and HR_mean, F (1.685, 47.175) = 0.961, p = 0.370, partial $\eta^2 = 0.033$, $\varepsilon = 0.842$. For within-subject interaction, there was statistically significant difference in mean HR_mean at the different time points, F (1.685, 47.175) = 17.967, p < 0.0005, partial $\eta^2 = 0.391$. After further analysis using Wilcoxon Signed-rank Test, there was statistically significant difference result between pre- and post-experiment z = -3.180, p = 0.001. For between-subject interaction, there was no statistically significant difference in mean HR between intervention groups F (1, 28) = 0.036, p = 0.851, partial $\eta^2 = 0.001$.

Standard deviation (SD) of HR

A correction was made using Hyunh-Feldt correction since the Mauchly's Test of Sphericity was violated $\chi^2(2) = 11.140$, p = .0004. There was no statistically significant interaction between type of drivers and SD of HR, F (1.616, 45.256) = 0.888, p < 0.398, partial $\eta^2 = 0.031$, $\varepsilon = 0.808$. For within-subject interaction, there was no statistically significant difference in mean SD of HR at the different time points, F (1.616, 45.256) = 1.824, p < 0.179, partial $\eta^2 = 0.061$. For between-subject interaction, there was no statistically significant difference in mean SD of HR between both types of participant F (1, 28) = 0.155, p = 0.697, partial $\eta^2 = 0.005$.

Fast Fourier Transform High Frequency (FFT HF) - normalized unit (n.u.)

Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction, $\chi^2(2) = 1.06$, $p = 0.589$. There was no statistically significant interaction between the type of drivers and FFT HF (n.u.), $F(2, 56) = 0.861$, $p = 0.428$, partial $\eta2 = 0.030$. For within-subject interaction, there was a statistically significant difference in mean FFT HF (n.u.) at the different time points, $F(2, 56) = 10.492$, $p < 0.0005$, partial $\eta^2 = 0.273$. After further analyzes using Wilcoxon Signed-rank Test, there was statistically significant difference result between pre- and during experiment $z = -3.744$, $p < .0005$. For between-subject interaction, there was no statistically significant difference in mean FFT HF (n.u.) between intervention groups $F(1, 28) = 0.657$, $p = 0.424$, partial $\eta^2 = 0.023$.

3.2. Discussion

3.2.1. Test Rides' Consistency

PSD_x was produced by the vehicle's acceleration and deceleration, while PSD_y was produced by the vehicle's cornering (right and left). For PSD_z, the vertical acceleration is produced by the road surface. In 30 test rides, the dominant frequency of PSD in the x- and y-axis were below 0.2 and 0.3 Hz, respectively (see **Figure 3**). As some of the road surfaces on the selected route were not smooth, PSD_z was found to be dominant at around 0.2 Hz. Since vibrations below 0.5 Hz are evaluated as low frequency; therefore, it imposed a low-frequency motion. Longitudinal and lateral movements with frequencies below 0.5 Hz and peaks at about 0.2 Hz are highly correlated with motion sickness [29], [30], [32], [33]. The simulated test rides recorded the highest amplitude of PSD in lateral compared to longitudinal and vertical acceleration (see **Figure 3**).

3.2.2. Test Ride Rating Analysis

3.2.2.1. Driving Style Rating

The overall score of the self-rating showed no differences between the two types of participants ($p > 0.05$) in the longitudinal accelerations and decelerations and cornering of the simulated Defensive AV test rides (see **Table 1**). Furthermore, based on the median rating, all participants preferred the simulated Defensive AV DS regardless of participants' DS types (assertive and defensive). Overall, the median of the defensive DS participant was smaller than their assertive counterpart. This finding aligns with the hypothesis – i.e. regardless of DS type, drivers would prefer to be in a more defensive DS of AVs [10], [17], [47], [48].

Both types of participants indicated that they were satisfied with the induced force in acceleration, deceleration, and cornering DW simulated. In the DS Refinement rating, the defensive participants reported the generated acceleration was slightly more than what they would expect during cornering. This proved drivers with defensive DS preferred to be driven with lower accelerations [19]. Meanwhile, the assertive participants stated the simulated DS was neutral to their DS in the longitudinal deceleration. Since they tend to drive with sharp and abrupt decelerations [13], they experienced that the Defensive AV DS was less thrilling and challenging.

3.2.2.2. Comfort, Pleasantness, and Safety

Both types of participants showed no differences ($p > 0.05$) in terms of comfort, pleasantness, and safety for the longitudinal acceleration and deceleration and cornering of the simulated Defensive AV test rides (see **Table 1**). Both participants pointed to the lowest median rating in all directions of the proposed AV DS. Also, the median of the defensive type of participant was smaller than the assertive type of participant (refer to Section 3.2.2.1 for discussion).

For the comfort rating, assertive participants scored slightly higher than defensive participants in longitudinal accelerations. They preferred to drive with more acceleration as they sought more sensation for their comfort [13]. Besides that, both types of participants expressed safe feelings during the driving session. They felt so because the 'Defensive' style of movement was perceived as more trustworthy [17], [20], [49] so the chances of an accident are low.

3.2.3. Motion Sickness Assessment

3.2.3.1. Motion Sickness Dose Value (MSDV)

The dosage of motion sickness (MS) experienced by each participant throughout the 10 minutes is varied in different directions (see **Table 2**). In $MSDV_x$, the participants did not experience MS due to very low dosage. While in $MSDV_y$, they experienced a mild MS.

This was because of the participants' bodies swaying in higher magnitude during the lateral direction than in the longitudinal direction. Previously, changes in body sway were reported to develop MS [50]–[52]. Furthermore, there is a relationship between the head roll angle and lateral acceleration during driving [53]. In cornering situations, passengers tend to tilt their heads in the direction of lateral acceleration. Compared to the longitudinal direction, passengers' heads move in high magnitude in the lateral direction, and therefore, they easily feel MS. A past study on train passengers found that passengers felt more MS in the tilting trains than the non-tilting trains [54]. However, within the current study, the participants showed that they felt comfortable towards the proposed Defensive AV DS in a lateral direction (refer to Section 4.2.2) even though they were exposed to a mild dosage of MS. A longer exposure (> 10 minutes) could provide a different result.

The dosage of MS experienced by each participant was almost the same since the value of standard deviations were low (<1) but relatively high in coefficient of variances (CoV), especially in the z-axis (see **Table 2**). The low standard deviation was due to the high consistency of test rides – the accelerations, decelerations, and cornering each participant experienced were within the acceptable range.

3.2.3.2. Motion Sickness Assessment Questionnaire (MSAQ)

The overall score for MSAQ and all its constructs (except for peripheral construct) showed no significant differences between two different situations (pre- and post-experiment) for both types of participants (see **Table 3**). This indicates all participants do not experience any MS throughout the test ride. There was a significant difference between pre- and post-experiment for both types of participants in peripheral-related MSAQ due to Malaysia's tropical temperature. The participants might already feel hot and sweaty prior to answering the pre-MSAQ. However, after completing Phase 3, participants stated they were not sweaty or hot anymore due to the lower temperature inside the instrumented vehicle during the post-MSAQ session. Therefore, further analysis (WSRT) was employed to determine whether $MSAQ_{post}$ - $MSAQ_{pre}$ were different between the two types of drivers. The analysis revealed no significant difference and therefore suggested participants did not experience MS after the test rides.

3.2.3.3. Heart Rate Variability (HRV)

Since there was an interaction of within-subject for the measured HRV in the mean of HR, further analysis was done using WSRT (see **Table 4**). The analysis produced a statistical difference for HR readings between pre- and post-experiment (pre-experiment readings were higher than the post-experiment readings). Previous studies found the increase of MS is positively correlated with increased BPM [49], [55]–[58]. As the mean of HR of the participants was decreased from pre-experiment to post-experiment, this indicates participants experienced no MS. The recorded value of FFT HF (n.u.) of participants also showed an interaction of within-subject through analysis two-way Mixed ANOVA. Further WSRT analysis revealed an interaction between pre- and during the experiment. Since participants' FFT HF (n.u.) were smaller during the experiment compared to pre-experiment, participants felt and experienced mild MS when they were inside the experimental vehicle throughout the ride because of the decreasing HF [59]. This result was depicted through MSDV (see **Figure 4**) since the value of MSDV was increasing, and therefore, MS keeps developing as participants spent a longer time in the experimental vehicle. But there was no interaction between the readings for pre- and post-experiment. Overall, the participants were comfortable and do not feel MS after experiencing the test ride with the defensive AV DS.

4. Conclusion

The goal of this research was to measure the acceptance of the proposed defensive automated vehicle (AV) driving style (DS), through subjective (e.g., comfort, safety) and objective measurement (e.g., physiological measurement), on the two types of Malaysian drivers (aggressive and defensive) when tested on the suburban type of roads. The study implemented a defensive DS setting to the instrumented vehicle, and both DS types of participants were expected to accept and feel comfortable with the proposed defensive AV DS. The 30 test rides driving wizard (DW) simulated showed a high consistency. The dominant frequency of the PSD obtained was below 0.5 Hz for the three axes. Therefore, the test rides were considered as low-frequency motions potentially contributing to the development of MS. The test rides generated a dosage that each participant does not or experienced very little motion sickness in the longitudinal direction but might experience mild motion sickness in the lateral direction. However, the subjective measurements (self-rating questionnaires) showed that both types of participants accepted and preferred the simulated defensive AV DS. Heart rate variability (objective measurement) also indicated no MS was experienced by both types of participants. As both DS types of participants preferred and felt comfortable with the proposed defensive AV DS, the hypothesis of this study was supported.

Limitation

The results we obtained applies only to the Instrumented Vehicle of this study. If the AUTOAccD is applied to the other type of vehicle, the riding experience felt by the participant will be different since the two cars have different suspension designs and different dynamical characteristics. However, the participant is expected to feel comfortable if the same range of acceleration, deceleration, and cornering is applied to the other type of vehicle. In the work of [10], they used Renault Espace IV (large MPV) to run their experiment. They obtained the same results as in this study.

Acknowledgments

The authors fully would like to thank the Malaysia Ministry of Education (MOE), Universiti Teknikal Malaysia Melaka (UTeM), and Universiti Tun Hussein Onn Malaysia (UTHM) for the research facilities and support to make this vital research viable and effective. This research is fully supported by a Fundamental Research Grant Scheme (FRGS) with project code FRGS/1/2020/TK02/UTEM/02/1.

Author's Declaration

Authors' contributions and responsibilities

Conceived and designed the experiments (M.N.A.M.N, J.K, N.M.Y); Performed the experiments (M.N.A.M.N, J.K); Analyzed and interpreted the data (M.N.A.M.N, J.K); Wrote the original paper (M.N.A.M.N, J.K); and Wrote the revised manuscript (M.N.A.M.N, J.K, N.M.Y, M.Z.H, A.F.H.Z, A.A.A.R).

Funding

This research is fully supported by a Fundamental Research Grant Scheme (FRGS) with project code FRGS/1/2020/TK02/UTEM/02/1.

Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

References

[1] D. J. Fagnant and K. Kockelman, "Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations," *Transportation Research Part A: Policy and Practice*, vol. 77, pp. 167–181, 2015, doi: 10.1016/j.tra.2015.04.003.

[2] R. Krueger, T. H. Rashidi, and J. M. Rose, "Preferences for shared autonomous vehicles," *Transportation Research Part C: Emerging Technologies*, vol. 69, pp. 343–355, 2016, doi: 10.1016/j.trc.2016.06.015.

[3] D. Nicolaides, D. Cebon, and J. Miles, "An autonomous taxi service for sustainable urban transportation," *2017 Smart Cities Symposium Prague, SCSP 2017 - IEEE Proceedings*, 2017, doi: 10.1109/SCSP.2017.7973353.

[4] Bureau of Infrastructure, "Transport and Regional Economics (BITRE), Road trauma Australia, 2014 statistical summary bitre, Canberra ACT," Canberra, 2015.

[5] J. Arbib and T. Seba, "Rethinking Transportation 2020-2030," 2017.

[6] AAA Foundation for Traffic Safety, "Aggressive Driving: Research Update," Washington, DC, 2009.

[7] Z. Htike, G. Papaioannou, E. Siampis, E. Velenis, and S. Longo, "Minimisation of Motion Sickness in Autonomous Vehicles," *IEEE Intelligent Vehicles Symposium, Proceedings*, no. January 2021, pp. 1135–1140, 2020, doi: 10.1109/IV47402.2020.9304739.

[8] M. Elbanhawi, M. Simic, and R. Jazar, "In the Passenger Seat: Investigating Ride Comfort Measures in Autonomous Cars," *IEEE Intelligent Transportation Systems Magazine*, vol. 7, no. 3, pp. 4–17, 2015, doi: 10.1109/MITS.2015.2405571.

[9] J. Van Brummelen, M. O'Brien, D. Gruyer, and H. Najjaran, "Autonomous vehicle perception: The technology of today and tomorrow," *Transportation Research Part C: Emerging Technologies*, vol. 89, no. January, pp. 384–406, 2018, doi: 10.1016/j.trc.2018.02.012.

[10] N. M. Yusof, J. Karjanto, J. Terken, F. Delbressine, M. Z. Hassan, and M. Rauterberg, "The exploration of autonomous vehicle driving styles: Preferred longitudinal, lateral, and vertical accelerations," *AutomotiveUI 2016 - 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Proceedings*, pp. 245–252, 2016, doi: 10.1145/3003715.3005455.

[11] M. Michałowska and M. Ogłoziński, "Autonomous vehicles and road safety," *Communications in Computer and Information Science*, vol. 715, pp. 191–202, 2017, doi: 10.1007/978-3-319-66251-0_16.

[12] C. Lv, X. Hu, A. Sangiovanni-Vincentelli, Y. Li, C. M. Martinez, and D. Cao, "Driving-Style-Based Codesign Optimization of an Automated Electric Vehicle: A Cyber-Physical System Approach," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 4, pp. 2965–2975, 2018, doi: 10.1109/TIE.2018.2850031.

[13] E. Gilman, A. Keskinarkaus, S. Tamminen, S. Pirttikangas, J. Röning, and J. Riekki, "Personalised assistance for fuel-efficient driving," *Transportation Research Part C: Emerging Technologies*, vol. 58, no. PD, pp. 681–705, 2015, doi: 10.1016/j.trc.2015.02.007.

[14] P. Bazilinskyy, T. Sakuma, and J. de Winter, "What driving style makes pedestrians think a passing vehicle is driving automatically?," *Applied Ergonomics*, vol. 95, no. February, p. 103428, 2021, doi: 10.1016/j.apergo.2021.103428.

[15] G. M. I. Voß, C. M. Keck, and M. Schwalm, "Investigation of drivers' thresholds of a subjectively accepted driving performance with a focus on automated driving," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 56, pp. 280–292, 2018, doi: 10.1016/j.trf.2018.04.024.

[16] H. Bellem, T. Schönenberg, J. F. Krems, and M. Schrauf, "Objective metrics of comfort: Developing a driving style for highly automated vehicles," *Transportation Research Part F: Traffic Psychology and Behaviour*, 2016, doi: 10.1016/j.trf.2016.05.005.

[17] C. Basu, Q. Yang, D. Hungerman, M. Singhal, and A. D. Dragan, "Do you want your autonomous car to drive like you?," *arXiv*, pp. 417–425, 2017, doi: 10.48550/arXiv.1802.01636.

[18] J. Karlsson, S. van Waveren, C. Pek, I. Torre, I. Leite, and J. Tumova, "Encoding Human Driving Styles in Motion Planning for Autonomous Vehicles," in *ICRA International Conference on Robotics and Automation*, 2021, no. Icra, pp. 1050–1056, doi: 10.1109/icra48506.2021.9561777.

[19] F. Ekman, M. Johansson, L. O. Bligård, M. A. Karlsson, and H. Strömberg, "Exploring automated vehicle driving styles as a source of trust information," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 65, pp. 268–279, 2019, doi: 10.1016/j.trf.2019.07.026.

[20] S. Hecker, D. Dai, and L. Van Gool, "Learning Accurate, Comfortable and Human-like Driving," *arXiv*, 2019, doi: https://doi.org/10.48550/arXiv.2007.07218.

[21] X. Sun *et al.*, "Exploring Personalised Autonomous Vehicles to Influence User Trust," *Cognitive Computation*, vol. 12, no. 6, pp. 1170–1186, 2020, doi: 10.1007/s12559-020-09757-x.

[22] K. Mühl, C. Strauch, C. Grabmaier, S. Reithinger, A. Huckauf, and M. Baumann, "Get Ready for Being Chauffeured: Passenger's Preferences and Trust While Being Driven by Human and Automation," *Human Factors*, vol. 62, no. 8, pp. 1322–1338, 2020, doi: 10.1177/0018720819872893.

[23] O. Taubman-Ben-Ari, M. Mikulincer, and O. Gillath, "The multidimensional driving style inventory - Scale construct and validation," *Accident Analysis and Prevention*, vol. 36, no. 3, pp. 323–332, 2004, doi: 10.1016/S0001-4575(03)00010-1.

[24] M. Zuckerman, D. Michael Kuhlman, M. Joireman, and H. Kraft, "Five robust questionnaire scale factors of personality without culture," *Personality and Individual Differences*, vol. 12, no. 9, pp. 929–941, 1993.

[25] K. Kim and M. Park, "Guiding Preferred

Driving Style Using Voice in Autonomous Vehicles : An On-Road Wizard-of-Oz Study," *Association for Computing Machinery, New York, NY, USA*, pp. 352–364, 2021, doi: 10.1145/3461778.3462056.

[26] P. Wang, S. Sibi, B. Mok, and W. Ju, "Marionette: Enabling On-Road Wizard-of-Oz Autonomous Driving Studies," *ACM/IEEE International Conference on Human-Robot Interaction*, vol. Part F1271, pp. 234–243, 2017, doi: 10.1145/2909824.3020256.

[27] J. Karjanto, N. M. Yusof, J. Terken, F. Delbressine, M. Rauterberg, and M. Z. Hassan, "Development of On-Road Automated Vehicle Simulator for Motion Sickness Studies," *International Journal of Driving Science*, vol. 1, no. 1, pp. 1–12, 2018, doi: 10.5334/ijds.8.

[28] J. Karjanto *et al.*, "An On-Road Study in Mitigating Motion Sickness When Reading in Automated Driving," *Journal of Hunan University (Natural Sciences)*, vol. 48, no. 3, 2021.

[29] M. Turner and M. J. Griffin, "Motion sickness in public road transport: Passenger behaviour and susceptibility," *Ergonomics*, vol. 42, no. 3, pp. 444–461, 1999, doi: 10.1080/001401399185586.

[30] B. E. Donohew and M. J. Griffin, "Motion sickness: Effect of the frequency of lateral oscillation," *Aviation Space and Environmental Medicine*, vol. 75, no. 8, pp. 649–656, 2004.

[31] M. J. Griffin and M. M. Newman, "An experimental study of low-frequency motion in cars," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 218, no. 11, pp. 1231–1238, 2004, doi: 10.1243/0954407042580093.

[32] A. Lawther and M. J. Griffin, "Prediction of the incidence of motion sickness from the magnitude, frequency, and duration of vertical oscillation," *Journal of the Acoustical Society of America*, vol. 82, no. 3, pp. 957–966, 1987, doi: 10.1121/1.395295.

[33] J. F. Golding, M. A. G., and G. Michael A., "A motion sickness maximum around the 0.2 Hz frequency range of horizontal translational oscillation.," *Aviation, space, and environmental medicine*, vol. 72, no. 3, pp. 188–198, 2001.

[34] P. J. Gianaros, E. R. Muth, J. T. Mordkoff, M. E. Levine, and R. M. Stern, "A questionnaire for the assessment of the multiple dimensions of motion sickness," *Aviation Space and Environmental Medicine*, vol. 72, no. 2, pp. 115–119, 2001.

[35] L. Alexandros and X. Michalis, "The physiological measurements as a critical indicator in users' experience evaluation," in *Proceedings of the 17th Panhellenic Conference on Informatics - PCI '13*, 2013, pp. 258–263, doi: 10.1145/2491845.2491883.

[36] A. M. A. Zaidi, M. J. Ahmed, and A. S. M. Bakibillah, "Feature extraction and characterization of cardiovascular arrhythmia and normal sinus rhythm from ECG signals using LabVIEW," *2017 IEEE International Conference on Imaging, Vision and Pattern Recognition, icIVPR 2017*, no. November, 2017, doi: 10.1109/ICIVPR.2017.7890871.

[37] J. A. Molino, K. S. Opiela, B. J. Katz, and M. J. Moyer, "Validate First; Simulate Later: A New Approach Used at the FHWA Highway Driving Simulator," *Proceedings of Driver Simulation Conference, North America, Orando, FL*, pp. 411–420, 2005.

[38] J. Karjanto, N. M. Yusof, J. Terken, F. Delbressine, M. Z. Hassan, and M. Rauterberg, "Simulating autonomous driving styles: Accelerations for three road profiles," *MATEC Web of Conferences*, vol. 90, pp. 1–16, 2017, doi: 10.1051/matecconf/20179001005.

[39] ANALOG, "Analog Device AD8232." 2012.

[40] A. S. Prasad and N. Kavanashree, "ECG Monitoring System Using AD8232 Sensor," *Proceedings of the 4th International Conference on Communication and Electronics Systems, ICCES 2019*, no. Icces, pp. 976–980, 2019, doi: 10.1109/ICCES45898.2019.9002540.

[41] A. Rahman, T. Rahman, N. H. Ghani, S. Hossain, and J. Uddin, "IoT Based patient monitoring system using ECG sensor," *1st International Conference on Robotics, Electrical and Signal Processing Techniques, ICREST 2019*, pp. 378–382, 2019, doi: 10.1109/ICREST.2019.8644065.

[42] Broadcom, "Broadcom Optocoupler PS2506-1-A.," 2017. .

[43] S. Laborde, E. Mosley, and J. F. Thayer,

"Heart rate variability and cardiac vagal tone in psychophysiological research - Recommendations for experiment planning, data analysis, and data reporting," *Frontiers in Psychology*, vol. 8, no. FEB, pp. 1–18, 2017, doi: 10.3389/fpsyg.2017.00213.
[44] J. Karjanto, N. Md. Yusof, J. Terken, F. Delbressine, M. Z. Hassan, and M. Rauterberg, "Simulating autonomous driving styles: Accelerations for three road profiles," *MATEC Web of Conferences*, vol. 90, p. 1005, 2017, doi: 10.1051/matecconf/20179001005.
[45] T. A. Louis, P. W. Lavori, J. C. Bailar, and M. Polansky, "Crossover And Self-Controlled Design In Clinical Research, New England Journal Of Medicine," vol. 310, no. 1, pp. 24–31, 1984.
[46] J. Cohen, "Statistical power analysis for the social sciences," 1988.
[47] Z. Ma and Y. Zhang, "Investigating the Effects of Automated Driving Styles and Driver's Driving Styles on Driver Trust, Acceptance, and Take Over Behaviors.," *In Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 64, no. 1, pp. 2001–2005, 2020.
[48] P. Rossner and A. C. Bullinger, "How do you want to be driven? investigation of different highly-automated driving styles on a highway scenario," in *International Conference on Applied Human Factors and Ergonomics*, 2019, pp. 36–43.
[49] F. Pyre, "Analysis of physiological responses induced by motion sickness and its detection based on ocular parameters," 2021.
[50] T. A. Stoffregen and L. J. Smart, "Postural instability precedes motion sickness," *Brain Research Bulletin*, vol. 47, no. 5, pp. 437–448, 1998, doi: 10.1016/S0361-9230(98)00102-6.
[51] E. Faugloire, C. T. Bonnet, M. A. Riley, B. G. Bardy, and T. A. Stoffregen, "Motion sickness, body movement, and claustrophobia during passive restraint," *Experimental brain research*, vol. 177, no. 4, pp. 520–532, 2007.
[52] T. A. Stoffregen, L. J. Hettinger, M. W. Haas, M. M. Roe, and L. J. Smart, "Postural instability and motion sickness in a fixed-base flight simulator," *Human Factors*, vol. 42, no. 3, pp. 458–469, 2000, doi: 10.1518/001872000779698097.
[53] S. A. Saruchi *et al.*, "applied sciences Novel Motion Sickness Minimization Control via Fuzzy-PID Controller for Autonomous Vehicle," *Applied Sciences (Switzerland)*, 2020.
[54] H. Suzuki, H. Shiroto, and K. Tezuka, "Effects of low frequency vibration on train motion sickness," *Quarterly Report of RTRI (Railway Technical Research Institute) (Japan)*, vol. 46, no. 1, pp. 35–39, 2005, doi: 10.2219/rtriqr.46.35.
[55] L. LaCount *et al.*, "Static and dynamic autonomic response with increasing nausea perception.," *Aviation, space, and environmental medicine*, vol. 82, no. 4, pp. 424–433, 2011, doi: 10.3357/asem.2932.2011.
[56] H. Chu, M.-H. Li, S.-H. Juan, and W.-Y. Chiou, "Effects of transcutaneous electrical nerve stimulation on motion sickness induced by rotary chair: a crossover study," *The Journal of Alternative and Complementary Medicine*, vol. 18, no. 5, pp. 494–500, 2012.
[57] F. M. Sulzman, "Life sciences space missions. Overview," *Journal of Applied Physiology*, vol. 81, no. 1, pp. 3–6, 1996.
[58] C. S. Stout, W. B. Toscano, and P. S. Cowings, "Reliability of psychophysiological responses across multiple motion sickness stimulation tests.," *Journal of Vestibular Research : Equilibrium & Orientation*, vol. 5, no. 1, pp. 25–33, 1995.
[59] L. T. LaCount *et al.*, "Dynamic cardiovagal response to motion sickness: A point-process heart rate variability study," *Computers in Cardiology*, vol. 36, pp. 49–52, 2009.