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Comprehensive Assessment of Comfort (Motion Sickness) in Vehicles.

Master's thesis in Biomedical Engineering

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Abstract

This study investigates technologies to assess and mitigate motion sickness in vehicles. It aims to evaluate existing technologies for the detection and mitigation of motion sickness in vehicles, analyze their effectiveness, and explore practical applications and improvements for future vehicle systems. The research is divided into two sections: the first is a practical approach given by a literature review of patents related to motion sickness detection and mitigation, followed by a real-world implementation of an experiment based on the findings. The second part evaluates the improvement of the ISO 2631-1 standard for assessing motion sickness, using computational tools.

The literature review identified 23 relevant patents from an initial pool, focusing on technologies and methods related to vehicle dynamics, human physiology, and interactions with the vehicle or passenger. The experimental section involved 14 participants subjected to three different scenarios: anticipatory cues (vibrotactile and auditory) and a control group. Results showed a significant reduction in motion sickness with anticipatory cues compared to the control.

The study also compares the performance of a lower-degree filter with the ISO-provided filter using the Motion Sickness Dose Value (MSDV) metric, demonstrating that lower-grade filters can perform similarly with minimal differences. The findings highlight the need for a more refined research focus and deeper technological analysis, suggesting improvements in patent categorization, experiment design, and consultation with subject matter experts.

Keywords: Motion sickness, Passenger, Comfort, Patent, Detection, Mitigation, Anticipatory-Cues, MSDV, Filter.

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Mateo Nicolás Vega Quezada, Gothenburg, 8- 2024

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1
Introduction

The constant evolution of common transportation has created the need to improve the experience and satisfaction of the user while on travels. Nowadays, transportation systems has been designed to be as efficient and cost-effective as possible while trying to maintain an overall quality of the journey. As travels becomes more frequent for either personal and professional lives, reassuring passenger comfort has become a fundamental aspect of transportation and vehicle evolution and design.

One significant challenge that continues to impact passenger comfort is motion sickness, a condition that affects a considerable portion of travelers. This condition, characterized by symptoms such as dizziness, nausea, and discomfort, can severely detract from the overall travel experience and limit the effectiveness of transportation systems as well as its user acceptance. As technology advances, there is an increasing need to address these issues to improve user satisfaction and broaden the appeal of various transportation modes.

1.1 Background

Passenger comfort has become a crucial focus in modern transportation. The willingness of individuals to choose and remain loyal to specific modes of travel often hinges on their comfort, making it imperative to design transportation systems that can offer an enjoyable and comfortable experience. As technology in the automotive and broader transportation sectors continues to evolve, the integration of advanced comfort-enhancing technologies has become a key area of innovation. Addressing passenger discomfort, particularly motion sickness, has become increasingly relevant.

Various standards have been established to assess and mitigate the effects of motion sickness and ensure passenger comfort. For instance, standard ISO 2631-1, provides guidelines for evaluating human exposure to whole-body vibration. This standard outlines requirements to measure and analyze vibrations that passengers experience during travel. Moreover, it suggest a method in which motion sickness can be assessed. By adhering to ISO 2631-1, manufacturers can design transportation systems that minimize adverse effects associated with vibrations, thereby enhancing passenger comfort.

1.2 Problem definition

Despite numerous advancements in transportation technology, a universal method for enhancing passenger comfort through the detection and mitigation of motion sickness remains challenging. The diversity of discomfort detection and mitigation technologies highlights the complexity of this issue, as solutions that work well in one context may not be effective in another.

Moreover, the ISO 2631-1 reliability had been diminishing in contemporary years. This standard has not been updated to reflect the latest advancements in vehicle design and transportation technologies. As vehicles and modes of transportation have evolved significantly, the existing ISO 2631-1 standard may not fully address the current dynamics and complexities of modern transportation systems and neither the nowadays technology. The need for updated guidelines that incorporate new technologies and contemporary vehicle designs is critical to accurately assess and mitigate motion sickness.

The challenge lies then, in the variability of passenger experiences and the effectiveness of different technologies when applied transportation modes. This study will investigate a range of methods to identify the most promising solutions and assess their potential for improving passenger comfort.

1.3 Aims

The primary aim of this study is to conduct a comprehensive survey of contemporary and innovative techniques for detecting and mitigating passenger discomfort, with a specific focus on motion sickness, across different modes of transportation. This will involve a detailed investigation into current in-vehicle satisfaction measures and the development of a robust framework for future research on passenger well-being.

It will utilize a range of resources, including patent databases and academic literature, to gather insights into the latest advancements in comfort assessment technologies. It will emphasize state-of-the-art solutions for motion sickness assessment and mitigation, providing an overview of their mechanisms, effectiveness, and potential for real-world application.

Additionally, the study aims to empirically investigate selected technologies identified through a comprehensive literature review. Real-world testing will be conducted to evaluate these technologies' effectiveness and feasibility in practical scenarios. As well as revising existing standards to better adapt them to todays' vehicle technology. Case studies will illustrate the potential for implementation.

The study will focus on validating technologies designed to detect and mitigate motion sickness. By examining these technologies in detail, the study aims to contribute to a deeper understanding of their capabilities and limitations, ultimately aiding in the development of more effective solutions for enhancing passenger comfort in modern transportation systems.

2
Theory

This chapter aims to provide a base-ground for the motion sickness phenomena in the context of vehicles. It will explain the mechanism of sensory conflict among different human senses and related cues, along with other human biology related factors. Ongoing research develop strategies, and advancements in vehicle design, to mitigate motion sickness's impact on travel comfort. ISO 2631-1, an international standard, is introduced for evaluating human exposure to whole-body vibration. It provides guidelines, for human response to vibration and how this should be assessed for calculation, including the Motion Sickness Dosage Value (MSDV), and usage in real life scenarios. The chapter extends to filter approximation methods, focusing on the design of low-order filters to approximate ISO 2631-1 weighting curves for motion sickness assessment. The presented second to fifth-order filter approximations and the MSDV score, offer a larger insights into evaluating discomfort.

2.1 On Motion Sickness

The fundamental mechanism underlying motion sickness is a sensory conflict. The human body relies on sensory cues from three primary systems to perceive its position and movement in space: vision (visual cues), the inner ear's vestibular system (balance and spatial orientation), and proprioception (muscle and joint feedback) [1]. Motion sickness occurs when these sensory inputs send conflicting signals to the brain. For instance, reading a book in a moving vehicle creates a sensory mismatch, as the eyes focus on a stationary object while the inner ear detects motion [2]. This sensory conflict disrupts the brain's ability to reconcile the body's spatial orientation, leading to the discomfort associated with motion sickness.

Notably, not everyone is equally susceptible to motion sickness, and its severity can vary significantly from person to person. Some individuals seem immune to its effects, while others experience severe symptoms even during mild motion [3]. Susceptibility to motion sickness can be influenced by various factors, including genetics, previous exposure to motion, age, and individual differences in sensory processing [3]–[5]. Understanding this variability is essential for devising strategies to prevent and manage motion sickness effectively.

Motion sickness can be more than just an inconvenience; it can significantly impact one's ability to enjoy travel or engage in likewise activities. Consequently, there is ongoing research aimed at developing interventions and management strategies. These include techniques like looking at the horizon during travel, acclimatization through gradual exposure, and the use of anti-motion sickness medications, improved vehicle design, also aim to reduce motion sickness. [6].

Kinetosis effects, works as an illustration of the relation between the human sensory systems and the brain's capacity to process information. While it continues to puzzle researchers and affect millions of individuals worldwide, scientific investigations can show mechanisms and offer hope for more effective prevention, detection and mitigations strategies in the future. [7]

2.2 ISO 2631–1:1997

ISO 2631-1 stands as a fundamental international standard that offers guidelines for the evaluation of human exposure to whole-body vibration [8]. Devised by the International Organization for Standardization (ISO), this standard provides a comprehensive framework for assessing the effects of vibration on the human body and is particularly relevant in contexts involving occupational activities, transportation, and various forms of machinery operation.

The primary objective of ISO 2631-1 is to establish criteria for evaluating the effects of whole-body vibration on human comfort, health, and performance. It does so by focusing on the frequency range and the magnitude of vibrations that are perceptible and potentially harmful to individuals. The standard takes into account the variability of human response to vibrations across different frequencies and amplitudes. This is crucial as the human body reacts differently to vibrations depending on their frequency, a phenomenon known as the human body's resonance frequency.

ISO 2631-1 introduces a concept known as the *frequency weighting* that assigns different weights to different frequency components of the vibration signal. This weighting reflects the varying sensitivity of the human body to vibrations at different frequencies. The standard uses some frequency-weighting curves that comprehends W_k, W_d, W_f found in Figure 2.1 and W_c, W_d, W_j curves to define this sensitivities. These curves indicates the sensitivity of the human body to multiple vibration frequencies ranging from 0.5 Hz to 80 Hz when applied from different axes, and are related to different comfortability applications. Health, Comfort, Perceptions applications are done through W_k, W_d, W_c and W_d with the difference that each is applied within different body positions, point of rederences and direction of acceleration; while W_j just for Comfort and Perception. In the other hand W_f is the frequency weighting that evaluates Motion Sickness. It is worth noting that this frequency range aligns with the typical frequencies encountered in many real-world situations involving machinery, vehicles, and other sources of vibration.

In practical terms, ISO 2631-1 provides a comprehensive methodology for measuring and assessing whole-body vibration exposure. It outlines procedures for measuring vibrations, calculating various metrics, and assessing the potential risks and effects of prolonged exposure to specific vibration levels. By considering both the vibration magnitude and the human body's frequency sensitivity, the standard offers a holistic approach to evaluating the impact of vibrations on human comfort and health. In essence, ISO 2631-1 serves as a critical tool for ensuring the well-being and safety of individuals exposed to whole-body vibrations in various occupational and environmental settings.

Table 2.1: Parameters for the transfer function W_f, given by the ISO 2636-1 [8]. All values are in Hertz[Hz]

Weight	Band-limiting		A-V transition			Upward Step			
	f_1	f_2	f_3	f_4	Q_4	f_5	Q_5	f_6	Q_6
$\mathbf{W}_f$	0.08	0.63	inf	0.25	0.86	0.0625	0.8	0.1	0.80

The standard also includes a mathematical definition for the weighting curves Wk, Wd, Wf, Wc, Wd, Wj. Which include:

1. Parameters for the transfers functions used to reproduce the weightings. Found in table 2.1
2. Transfer Function Equations in which to use the parameters above, this include Band Limiting equations 2.1, 2.2, High Pass filter and Low Pass filter respectively an Acceleration-velocity Transition equation 2.3 and an Upward Step function on equation 2.4.

$$|H_h(p)| = \left| \frac{1}{1 + \sqrt{2}\frac{w_1}{p} + (\frac{w_1}{p})^2} \right| = \sqrt{\frac{f^4}{f^4 + f_1^4}} \tag{2.1}$$

$$|H_l(p)| = \left| \frac{1}{1 + \sqrt{2}\frac{p}{w_2} + (\frac{p}{w_2})^2} \right| = \sqrt{\frac{f_2^4}{f^4 + f_2^4}} \tag{2.2}$$

$$|H_t(p)| = \left| \frac{1 + \frac{p}{w_3}}{1 + \frac{p}{Q_4 w_4} + (\frac{p}{w_4})^2} \right| = \sqrt{\frac{f^2 + f_3^2}{f_3^2}} \cdot \sqrt{\frac{f_4^4 \cdot Q_4^2}{f^4 \cdot Q_4^2 + f^2 \cdot f_4^2(1 - 2Q_4^2) + f_4^4 \cdot Q_4^2}} \tag{2.3}$$

$$|H_s(p)| = \left| \frac{1 + \frac{p}{Q_5 w_5} + (\frac{p}{w_5})^2}{1 + \frac{p}{Q_6 w_6} + (\frac{p}{w_6})^2} \cdot \left(\frac{w_5}{w_6}\right)^2 \right| = \frac{Q_6}{Q_5} \cdot \sqrt{\frac{f^4 \cdot Q_5^2 + f^2 \cdot f_5^2(1 - 2Q_5^2) + f_5^4 \cdot Q_5^2}{f^4 \cdot Q_6^2 + f^2 \cdot f_6^2(1 - 2Q_6^2) + f_6^4 \cdot Q_6^2}} \tag{2.4}$$

The total Weighting Curve is expressed by equation 2.5. Which is general for any weighting curve as the parameters, found in the ISO, can be altered.

$$H_p(p) = H_h(p) \cdot H_l(p) \cdot H_t(p) \cdot H_s(p) \tag{2.5}$$

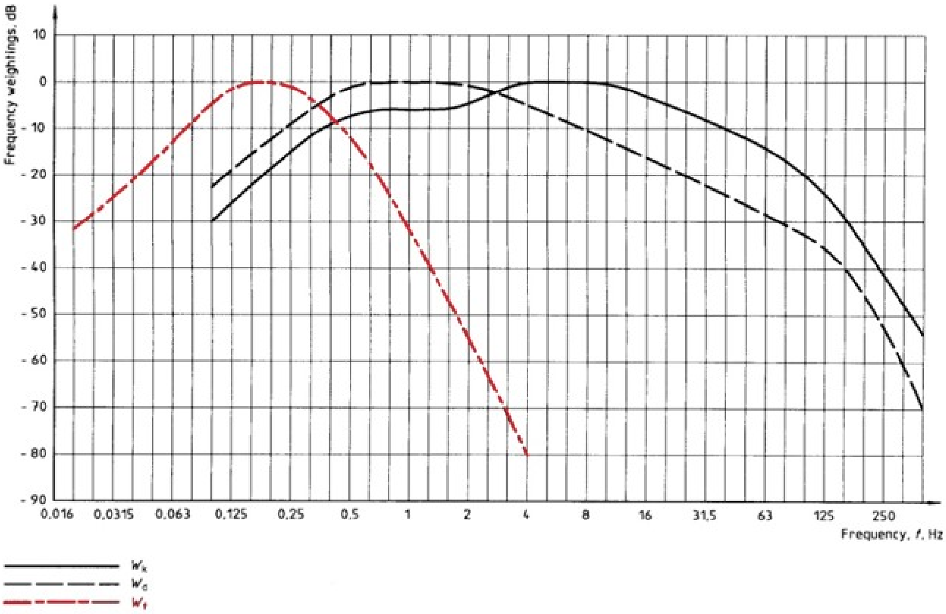

Figure 2.1: Frequency Weightings curves for principal weightings, in red, W_f weighting curve recommended to evaluate comfort to vibration perceived in the z-axis [8].

2.2.1 Motion Sickness Dosage Value score

A second important focus of the ISO 2631-1 [8] is, evaluating the impact of whole-body vibrations on human well-being. It provides a structured framework to assess vibrations from sources like: machinery and vehicles, which can lead to discomfort, motion sickness and health concerns. The range of frequencies used to assess motion sickness, go from 0.1Hz to 0.5Hz, being the W_f weighting curve, identified by the red curve in the Figure 2.1, the the frequency weight applied to acceleration signals to address Motion Sickness [8].

A key aspect is the vibration dose value (VDV), quantifying the cumulative impact of vibrations over time. It considers vibration intensity, duration, and the body's frequency sensitivity. The standard sets daily exposure limits for VDV to ensure safe levels of vibration exposure and is defined by equation 2.6.

$$VDV = \left\{ \int_0^T [a_w(t)]^4 dt \right\}^{\frac{1}{4}} \tag{2.6}$$

Where $a_w(t)$ is the vibration signal after being applied the weighting curve. And T being the total exposure duration.

The standard also introduces the root mean square (RMS) acceleration for assessing vibration intensity found in equation 2.7. It addresses the non-uniform human response to different frequencies through frequency weighting curves. These curves, as mentioned, adjust vibration measurements to match human sensitivity at various frequencies, enhancing the accuracy of vibration assessment for comfort and health concerns.

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t) dt \right] \tag{2.7}$$

The Motion Sickness Dose Value (MSDV) is a crucial parameter derived from the standard that assesses the dynamic response of human bodies to vibrations. It focuses on the changes in acceleration over time, which often contribute to motion sickness and discomfort. MSDV quantifies these variations and aids in evaluating the potential adverse effects of vibrations.

MSDV is calculated by first obtaining the time history of acceleration data and then computing the derivative of this data 2.8. This derivative represents the rate of change of acceleration, reflecting the body's sensitivity to fluctuations. Squaring the derivative values and calculating their mean results in the MSDV value. This process captures the overall magnitude of variations in acceleration and provides a measure of how the body perceives and responds to vibrations.

$$MSDV_z = \left\{ \int_0^T a_w^2(t)dt \right\} \tag{2.8}$$

A second alternative method proposed by the standard to calculate the MSDV is dedicated to constant dosage of vibration. The MSDV then can be estimated from the frequency-weighted RMS 2.7 value in the z axis of a small period of time multiplied by the square root of T_0 that represents such period [8].

$$.MSDV_z = a_w T_0^{\frac{1}{2}} \tag{2.9}$$

MSDV then, is an important parameter to take into account, as it considers other vibration measurements such as, RMS acceleration and the VDV. In depth, it accounts for acceleration changes, which are according to the ISO 2631-1 relevant to human comfort and well being.

2.3 Filter approximation

The paper titled "Low order continuous-time filters for approximation of the ISO 2631-1 human vibration sensitivity weightings" [9] presents a method for designing low-order continuous-time filters to approximate the ISO 2631-1 human vibration sensitivity weightings. The paper notes that, the recent ISO 2631-1 (1997) standard gives high order s-plane equations to describe weighting curves, making it necessary to design more efficient low order filters to approximate these curves in Figure 2.1.

L.Zuo [9] presents a method for designing an optimal least-pth digital filters to approximate the ISO 2631-1 weighting curves. The method involves mapping the specifications of the weighting curves in continuous-time frequency onto the unit circle (z-domain) via the bilinear transformation. An optimal least-pth digital filter is then designed to minimize the difference between the desired frequency response and the actual frequency response of the filter, in this specific case, MATLAB Filter Design Toolbox provides a function that computes the IIR digital filter that best approximates the desired frequency response within single or multiple bands.

The paper presents a second through fifth order quasi-least-square filters obtained by the method for the ISO 2631-1 frequency-weighting curves for vertical and horizontal acceleration. The filters are not optimal least-pth analog filters, but they are effective approximations to the ideal continuous-time frequency response. The paper notes that the low-order quasi-least-square filter approximations, found in equations 2.10-2.13, are preferred in practical applications, especially during a controller design. The ISO 2631-1 standard gives six frequency-weighting curves given as magnitudes W_n, at the one-third octave frequencies f_i: $i = 1, 2, 3, ..., N$. In order to use these weightings in design, it is sometimes necessary to make an approximation of these curves using stable rational transfer functions of the form, the low order quasi-least-square filter approximations for the three additional frequency weightings. The approximated frequency-weighting curve W_f is the one used to assess motion sickness.

2^{nd} Order approximation equation :

$$W_f^{(2)}(s) = \frac{0.8892s}{s^2 + 0.8363s + 1.163} \tag{2.10}$$

3^{rd} Order approximation equation :

$$W_f^{(3)}(s) = \frac{0.05726s^3 + 3.876s}{s^3 + 4.263s^2 + 4.777s + 4.396} \tag{2.11}$$

4^{th} Order approximation equation :

$$W_f^{(4)}(s) = \frac{0.02633s^4 + 0.0238s^3 + 2.286s^2 + 0.2335s + 0.0902}{s^4 + 2.527s^3 + 4.584s^2 + 2.993s + 1.373} \tag{2.12}$$

5^{th} Order approximation equation :

$$W_f^{(5)}(s) = \frac{0.1457s^4 + 0.2331s^3 + 13.75s^2 + 1.705s + 0.3596}{s^5 + 7.757s^4 + 19.06s^3 + 28.37s^2 + 18.52s + 7.230} \tag{2.13}$$

3
Methods

This section outlines the comprehensive methodology employed in investigating discomfort detection and mitigation methods for autonomous driving.

To get a better understanding of the motion-sickness-related technologies, an extensive research on patents is vital. The research includes condensing information and elaborating on their overall importance to define the criteria to be used for the patent review. Data collection and analysis is of outmost importance for an extensive patent review on motion sickness. As a support to the patent review an experimental analysis done in a real life scenario testing part of the findings examined in the review. This would include a real-world application of the methods to detect and mitigate motion sickness using cues in a controlled environment.

The second part of this project was based on the performance study of the ISO filter, used for data validation in a real-life scenario and comparison among similar filters. The methodology describes the design and testing of a band pass filter, adhering to the ISO 2631-1 standard. The filter primary purpose is to transform the raw vibration data, which may contain vibrations across a wide range of frequencies, into a format that aligns with the human body's sensitivity to vibrations. Its efficacy was tested through simulated and real-time data determined for each case. Each case has its own methodology regarding the validation of the results.

The methodology should guarantee consistent and precise results given their reliability and validity. Uniformity as well as accuracy is reached trough an structured data collection and experimentation.

3.1 Systematic patent review and real-world application

The primary method of data collection for this study will be a comprehensive review of patents related to Motion Sickness detection and mitigation methods for autonomous driving cars. Patents will be selected based on a set of predefined criteria, such as the relevance of the invention to the topic, the novelty of the invention, and the availability of relevant information. The patent review will include a thorough examination of the claims, specifications, and drawings of each selected patent to identify the key concepts and ideas related to the topic. The patent review will be structured in a systematic and organized manner, including a set of steps and procedures to ensure consistency and accuracy of the data collection process.

The workflow for the patent review will include the following steps:
1. Keyword Selection and Search Strategy
2. Initial Search and Filtering
3. Data Collection and Analysis
4. Categorization and theming

3.1.1 Keyword selection and search strategy

To identify relevant patents, a set of targeted keywords has been chosen, including *Motion Sickness*, *Kinetosis*, *autonomous cars*, *autonomous vehicles*, *detection*, and *mitigation*. These keywords encapsulate the core aspects of the research. The database used for the research was Google Patents' online public database and its advanced search features were utilized to conduct refined searches, allowing keyword variations to be employed effectively. The database exploration was done during March and September of 2023 with patents available in full and filled from the year 2000 while considering worldwide applications as well as each country's registration. For improved readability, patents that were originally filed in a different language were changed for their equivalent in English when available in the United States or any other English-speaking country. Publication status was not taken into account.

3.1.2 Initial search and filtering

An initial search was performed using the selected keywords. The search results were reviewed to eliminate patents that were not directly aligned with motion sickness detection and mitigation in vehicles. By extension, autonomous vehicles where included. This filtering process was based on an evaluation of patent titles, abstracts, and its classifications.

3.1.3 Data collection and analysis

Information about each selected patent was systematically collected, including patent titles, abstracts, inventors, publication dates, and patent numbers. A database was utilized for organized data management. A comprehensive analysis of each patent involved a thorough examination of the patent text, encompassing the description, claims, and included figures.

3.1.4 Categorization and theming

The identified patents were categorized based on recurring themes, methodologies, and proposed technologies. Patterns in the types of motion sickness detection and/or mitigation methods suggested by the patents were identified and tagged accordingly. This categorization enabled the grouping of patents that shared common approaches or utilized similar technologies. The categorization was based on the approach given by the patent to detect or mitigate motion sickness and whether it interacts primarily with the passenger or the vehicle.

3.1.5 Anticipatory cues in a real-world scenario

As result of initial observations brought from the systematic patent review and to complement initial findings, an experimental scenario where participants were deliberately exposed to induced motion sickness to study the effects of cues in motion sickness mitigation through a carefully designed protocol. The experiment entailed a comprehensive process where subjects underwent a series of trials on a moving vehicle aimed at exploring their susceptibility to motion sickness in different scenarios. The participant group was randomly selected, ensuring a diverse representation, while variables such as age, ethnicity, and gender were not specifically considered to maintain an unbiased approach.

To establish consistent and controlled test conditions, all participants experienced a constrained visual field. This strategic restriction was implemented to standardize the testing environment, thereby enhancing the reliability and validity of the experimental outcomes. Throughout the experiment, each participant engaged in multiple sessions, involving a series of driving laps.

The discomfort experienced by participants was systematically evaluated at the end of each lap using the Misery Scale (MISC) [10] (see Table 3.1). This scale served as a quantitative measure to assess participants' perceptions of discomfort and motion sickness. The trials persisted until participants reached a discomfort score of 7 on the MISC, indicating the onset of motion sickness, or until all 16 laps were completed. This approach ensured a comprehensive exploration of the potential range of reactions to induced motion sickness.

Symptoms		MISC
No problems		0
Some discomfort, but no specif symptoms		1
Dizziness, cold/warm, headache, stomach/throat awareness,	vague	2
sweating, blurred vision, yawning, burping, tiredness,	little	3
salivation, but no nausea	rather	4
	severe	5
Nausea	slight	6
	fairly	7
	severe	8
	(near) retching	9
Vomiting		10

Table 3.1: 11 Point Miscery Scale [10]

To mitigate the influence of temporal factors on motion sickness perception, each participant engaged in the experiment across three separate days. This temporal spread ensured that the participants' susceptibility to motion sickness remained consistent across the sessions. The sequence of the three sessions varied among participants, encompassing the following arrangements, with no specific order.

The experimental setup encompassed three distinctive sessions, each designed to assess the impact of specific cues on motion sickness susceptibility. Prior to initiating each ride with participants, a thorough briefing ensured their understanding of the cues and the corresponding actions the car would take. The experimental conditions were structured as follows:

1. Control Drive: The first session served as the control condition, deliberately leaving out any external cues provided to participants during the 16 driving laps. This session aimed to establish a baseline for motion sickness susceptibility in the absence of specific cues.
2. Vibrotactile Cue: The second session introduced a vibrotactile cue, achieved through the use of a vibrating device strategically placed on the seat pads. This tactile cue tactically indicated forthcoming driving maneuvers, including advance, left, right, and brake actions. Each lap consisted of a sequence of these maneuvers, presented randomly to participants.
3. Audio Cue: The third session incorporated an audio cue, which, in a similar manner to the previous session, included sounds coming from the vehicle speaker system, signaling the upcoming driving maneuvers. Like the latter experiments, participants experienced randomized sequences of advance, left, right, and brake actions.

Throughout the experiment, the car navigated along three lines in a straight path, with each action having the potential to repeat twice in a row. This means that the *left* cue will be a change to the left line, *right* cue a change to the left line, *advance* cue an increment in speed and *brake* cue a speed reduction. This randomization of maneuvers aimed to get close to a real-world driving scenario. The arrangement enabled the systematic evaluation of motion sickness susceptibility and its modulation in response to distinct cues across multiple participants, ensuring the robustness and comprehensiveness of the experimental outcomes.

To add a layer of verification, the vertical acceleration of the vehicle was measured to acquire data for calculating the MSDV in each test for every participant. The acceleration data were captured utilizing an Inertial Measurement Unit (IMU), capable of recording vertical, lateral, yaw, pitch, and roll motions in their raw form. Subsequently, these raw signals were processed through the CANape program on a computer, facilitating signal processing and visualization. The collected acceleration data were further subjected to processing in Matlab. This comprehensive approach aimed to ensure uniformity in the experimental conditions. By measuring and processing the vertical acceleration, we sought to verify that each participant was exposed to an equivalent MSDV, therefore minimizing the potential influence of driving styles on the test outcomes. For that, a z-score analysis using a 95% confidence interval is done using the averaged results of the MSDV 2.8 scores for every participant, as seen in Equation 3.1, below.

$$\text{Avg}_{MSDV_i} = \frac{\text{Tot}_{MSDV_i}}{\sqrt{\text{laps}_i}} \tag{3.1}$$

In which Tot_{MSDV} is calculated using equation 2.8, and divided by the square root of the laps done for each participant.

3.2 Filter design and Simulations

Part of the research approach involved the development and testing of a filter that replicates the one found in the ISO 2631-1 [8]. This filter played an important role in both the patent review and experimental driving tests. Its primary function was to carefully select and enhance specific frequency components relevant to passenger comfort from the signals collected by acceleration sensors. Beyond enhancing technical efficiency, this filter also aims to simplify the complex mathematical aspects often associated with the ISO 2631-1 proposed filter, making it more practical for real-world use. This refinement not only boosted technical performance but also allowed for a more practical assessment of passenger comfort during self-driving situations, aligning well with the ISO 2631-1 standard's emphasis on the frequency range that affects human sensitivity to vibration.

Firstly, the recreation of the ISO 2631-1 filter by implementing its different filter components was done. MATLAB software was employed for this task, providing flexibility to customize the filter settings according to research needs. The filter parameters were adjusted to match the W_f frequency range (see Figure 2.1), which relates to how humans perceive motion and are susceptible to motion sickness in vehicles.

Next, a verification by replication of the filters mentioned in the work of Zuo [9], as outlined in their approximation paper, was done. These filters, as transfer functions 2.10, 2.11, 2.12, 2.13 were implemented in MATLAB, allowing the simulation of their performance. The simulation was done using methods such as BODE and frequency sweep.

To verify the filter's effectiveness, a two-step approach was followed. Initially, the experimental based acquired data from driving tests conducted as part of the Case 1 study was used. These driving signals covered a range of real motion scenarios in self-driving situations. Both the designed filter and the ISO-proposed filter were applied to these signals. Then, the MSDV score 2.8 was used to evaluate how different filtering approaches affected the same data.

To comprehensively assess the filter's performance, the results were compared with those produced by the ISO-proposed filter. This comparison provided a clear measure of how effectively the filter could perform in different driving scenarios.

4

Results

The results section of the motion sickness study highlights important findings from the data collected during both phases, systematic patent review and real-world application for the practical focus of the study and the Filter design and simulations, of the ISO 2631-1 filter. The section presents key findings related to the found patents, such as type of technology being used and principal object of interaction. It also presents participants' responses to the practical experiments based on the patents findings as well as the results for the filter simulation. Statistical analyses, graphical representations, and measurements are employed to provide a comprehensive overview of motion sickness trends.
The presentation of these findings sets the stage for a detailed examination and interpretation in the subsequent discussion section.

4.1 Systematic patent review and real-world application

This section focuses on the categorization of collected patents based on their primary focus and relevance to the present study. The section list and classifies in Table 4.1 the patents identified. The principal parameter used for classification was whether the patent focal is detection or mitigation of motion sickness. Moreover, the patents were also categorized based on their interactions with the actors involved, whether they mainly affect the vehicle or the passenger. As it can be seen in the Appendix A.1, the compiled patents are the ones with the most relevance to the present study. The position in the table do not represent any specific importance. The following table uses the number of the table listed in the Appendix A.1.

	Detection	**Mitigation**	**Both**
Passenger	17	**12**, **14**, **15**, **19**, 23	**7**, 20
Vehicle	1	2	18, 21
Combined	3, 4, 10	**6**, 8, **11**, **13**, 16, **22**	5, 7, 9

Table 4.1: Resume of the patents found divided by its method and principal interaction

The results of the patent review, are summarized in Table 4.1, as detailed in Annex A A.1, it shows the various approaches of assessing motion sickness in vehicles. The columns indicate whether the primary focus of each patent is detection, mitigation, or if it through fully describe both methods, while the rows specify whether the main interaction is with the passenger, the vehicle, or both equally. It is noteworthy that although there are similarities among the methods described in each patent, manufacturers utilize different technologies and emphasize on diverse parameters when evaluating comfort. Both mitigation and detection methods as well as interactions with passengers and vehicles, are commonly addressed within each patent. However, in the table, patents are classified based on their primary focus in motion sickness assessment. Additionally, patents that employ cues or similar methods to mitigate motion sickness are highlighted, nine in total.

When it comes to detection, patents such as (1) [11] or (10) [12] focus solely on detection, although they use contrasting methods to achieve it. For instance, (1) [11] relies on the dynamics or movement of the vehicle in motion, while (10) [12] uses a combination of parameters such as physiological data, activity of the passenger, and dynamics of the vehicle as well.

It is also possible to find detection methods or devices labeled as prediction, likelihood, or estimation of motion sickness. The main difference with the first type is that they do not confirm if the vehicle occupant is in a kinetosis state but suggest that there is a chance of it by comparing to already set parameters or thresholds. For instance, (7) [13] focuses on the MSDV, (8) [14] predicts using a score calculated on the system inputs, (11) [15] uses occupants' profiles, (17) [16] analyzes the given data through a machine learning algorithm, and (18) [17] compares the sensed data to a given threshold. Systems like (6) [18], base the prediction on parameters of the route and the likelihood of them causing motion sickness while traveling. Additionally, patents where occupants' activity is recorded and evaluated can be found in (16) [19] and (9) [20] and the prediction, along with other parameters is based on it. It important to mention that, although these patents have a focus on prediction they do not only focus on that, as they also have a mitigation part discussed further.

When focusing on detection methods, it is essential to define the main point of the detection method. In this context, the subjects of detection can be categorized into humans, distinguished by both physiological and behavioral aspects, and vehicles, encompassing dynamic attributes such as acceleration and velocity, as well as external factors affecting the vehicle. These factors include elements like temperature, humidity, pressure, route conditions, the immediate surroundings, and traffic. Furthermore, combinations of both human and vehicle subjects are also prevalent.

Turning to methods exclusively centered around passenger sensing, approaches such as the one found in (9) [20] involve the detection of blood pressure and circulation through cameras. In contrast, (1) [11] solely relies on vehicle dynamics for assessment, specifically considering the vehicle's vertical acceleration.

For a more comprehensive vehicle environment sensing approach, (6) [18] and (12) [12] incorporate a camera to record the front of the vehicle for mitigation purposes, which is their main focus. Additionally, (13) [21] analyzes the desired route taken by the vehicle based on the vertical acceleration it is expected to produce, determined by GPS. Patent (14) [22] presents a more comprehensive mode of detection by combining sensing the vehicle's surroundings, including road conditions, proximity to others, and topology, using means such as radars or GPS, along with vehicle dynamics to sense acceleration.

Moving on to the prevalent method of detection, it involves the combination of both human and vehicle factors. In these cases, the vehicle assesses motion sickness using data from both subjects and vehicle. Patents that fit this description include (3) [23], (4) [24], (5) [25], (7) [13], (8) [14], (10) [26], (18) [17], (20) [27], (23) [28]. These patents incorporate a variety of sensors to monitor the situation comprehensively, including skin sensors for temperature and humidity, blood pressure, and circulation on the vehicle occupant side, as well as acceleration, velocity, route conditions, and the overall vehicle atmosphere.

In addition to these, a more user-inclusive approach, patents like (17) [16] and (22) [29] which has been tested in [30] combine both sensing methods but include user input in their parameters. User input is considered, as it can affect the system's output based on the occupant's conscious actions. In a predictive sensing approach, (21) [31] utilizes a prediction model based on a combination of occupant and vehicle data. In this specific case, the detection method is not performed in real-time but is done before the ride through predictive analysis.

In the aspect of mitigation itself, it is possible to find mitigation dedicated methods and devices. Technologies with a more focused mitigation approach can be found in patents (2) [24], (12) [12],(13) [21],(14) [22],(15) [32],(19) [33],(22) [29], (23) [28], although these base their mitigation method in different technologies. Patent (2) [24], for instance, rely on the car dynamics to damp the seat and compensate for the vibrations. In contrast, technologies such as the ones found on patents (12) [12],(13) [21], (14) [22] start their mitigation using data from the environment surrounding the car using different strategies. Patent (12) [12] and (19) [33] aim to mitigate motion sickness by showing visual cues to the passenger, while (12) focuses more on displaying images taken from the front, (19) approach is more directed towards mimicking the exterior through varied visual stimuli not limited to video, such as light arrays. In a very similar way patent (14) [22] is designed to compensate the external stimuli caused while driving; it does not only include video display, such as the previous, but also passenger seat adjustment, or other different type of sensory cues. In the other hand, Patent (13) [21] approach is more focused on deciding the least motion sickness producing route based on parameters set by the user. Patent (15) [32], goes a step further and includes input information as the ones found in the previous patents, surrounding stimuli sensing, as well as route information; In contrast to the previous patents, passenger information like susceptibility health are also required inputs. The technology will actuate its mitigation by applying the better stimuli related to the input parameter which its limits have been previously set by the user, either by recommendation or automatically. Audio cues, alerts, massages, climate adjustment and calming music are some of this stimuli.

Technologies such as (22) [29], although it has a detection component, part of its technology is also based on a very robust mitigation method; Change of mode of operation(autonomous to manual), providing cues that include haptic, visual, sound for next maneuvers, mitigation of frequencies(inducing frequencies, active suspension) are some of the ways in which it tries to mitigate the motion sickness previously detected. Another technology (23) [28], despite it being focused in mitigation, its robustness comes from its detection component. The system measures future trajectory of the car and actively change seat or headrest, based on a biomechanical model, to compensate for those motion

sickness triggers.
Among the approaches for both detection and mitigation, we can find patents that utilize a combination of methods. Patents (3) [23], (4) [24], (5) [25], and (20) [27] share a common characteristic in that they employ a mixed approach for detection, utilizing signals from both vehicle measurements and physiological data.

In (3) [23], the device's controller determines the existence of a motion sickness condition based on signals obtained from galvanic sensors, electroencephalograph sensors, and various vehicle dynamics sensors including accelerometers, speed sensors, tilt sensors, GPS systems, weather sensors, and other environmental monitoring systems. Upon detecting a motion sickness condition, the device actuates an apparatus called MSDM, which generates shock pulses for passengers or activates alarms under certain conditions.

Similarly, device (4) [24] collects signals from both passenger and vehicle dynamics. The system's mitigation strategy for motion sickness involves displaying treatments and indications targeted towards passengers. Examples of these motion sickness counteractions include autogenic feedback, breathing control exercises, non-invasive vagal maneuvers, visual images, audible alerts through vehicle speakers, and displays.

In (5) [25], the focus shifts towards mitigation. A motion sickness reduction unit receives data on sensory conflict levels calculated based on current travel conditions, travel patterns, and motion sickness severity. These measurements collectively assess the overall motion sickness level and generate adjustments to the travel conditions. Similar to previous patents, data for these measurements is sourced from both vehicle dynamics and passenger physiological data.

Patent (20) [27], while also employing a robust system for motion sickness detection using both methods, focuses solely on passenger-oriented mitigation. It involves brainwave analysis to identify stages of the trip where motion sickness may occur; new brainwave patterns are compared against a threshold, and the device attempts to regulate them back within the acceptable limits by using counteracting brainwaves.

4.1.1 Anticipatory cues in a real-world scenario

The data collection process started with a total of 42 tests. 14 participants were studied and each of them took part in all of the 3 sessions. As per this study, any participant not able to finish the proposed methodology, the 20 laps, was considered outlier and was not taken into account for the MISC analysis.

Figure 4.1 shows the average MISC, in every lap, of all the participants that finalized the test. As it can be seen, *Vibrotactile* (in yellow) and *Audio* (in blue) cues, scored lower values than the MISC used for *Control*. The final scores, after 16 laps, for each cue can be found in Table 4.2. Control cue curve shows the largest average value in most of the laps. Audio cue scores reflect a lower value than control however is not as low as the scores for Vibrotactile cues.

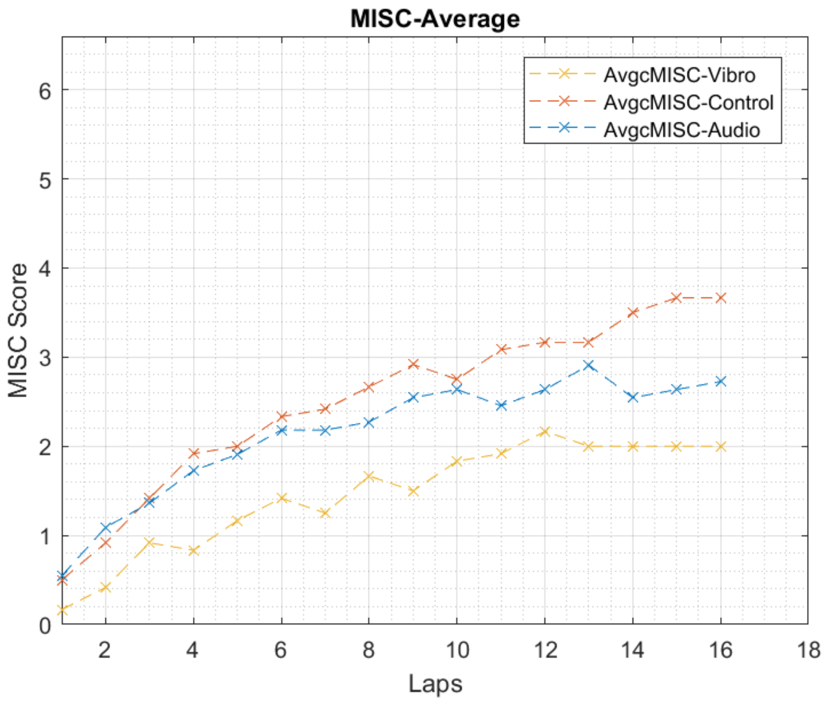

Figure 4.1: MISC Average for every lap of every Subject that finalized the test, separated by cues.

Cues	Average MISC
Control	3.67
Vibrotactile	2.73
Audio	2.00

Table 4.2: Final Average MISC for the Control, Vibrotactile and Audio cue

In a more detailed analysis, on Figure 4.2 illustrates the distribution analysis of the results from the last lap for participants who successfully completed the experiment, where the data was normalized as the maximum possible value is 7, since the design of the experiment did not allow for more. The box plots display the cues that had a more pronounced impact on the subjects toward the conclusion of the test, as determined by the median of the MISC in each cue test. The plot includes also information on the number of subjects where the cues had varying effects, as indicated by the data shown in the interquartile range (IQR). The whiskers denote the maximum and minimum values reached in each test. Furthermore, consideration is given to the identification of outliers, prompting an examination of how many subjects should be excluded due to an outlier status. This analysis provides a nuanced understanding of the distribution patterns and offers insights into the variability of participants' responses to different cues. The data of the box plots, excluding the outliers, can be found in Table 4.3.

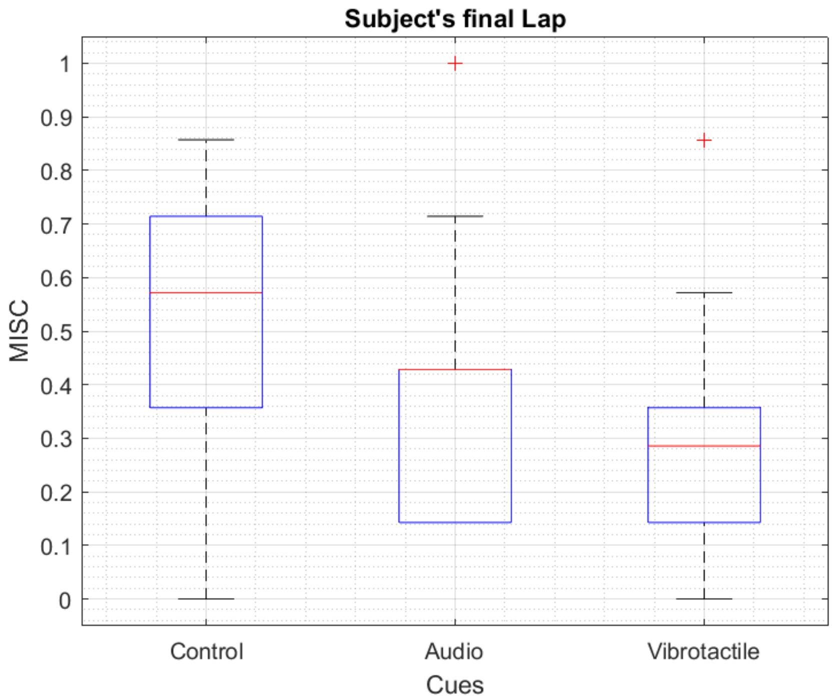

Figure 4.2: Box plot analysis of the MISC for subject that finalized the test

In the leftmost box plot, in Figure 4.2, representing the control test, the median is 0.57, with upper and lower quartiles at 0.71 and 0.36, respectively. The minimum and maximum values are 0 and 0.86. These statistical values signify central tendencies and the spread of data. The median of 0.57 indicates that 50% of the data falls below this value, distributed between 0 and 0.57, while the upper 50 % is more condensed in this area, as the difference is just 0.29.

In the case of the audio test, positioned in the middle of the plot, the minimum value equals the lower quartile at 0.14, suggesting that most of the subjects' MISC scores are clustered in values lower than the median. However, because the median value is equal to the upper quartile, it indicates that the central tendency of the data is focused on the higher levels of the distribution. In any case, both the median and the interquartile range (IQR) are less than the control box plot. The audio test also includes an outlier positioned at 1.00, signifying that in this specific case, one subject had the maximum MISC score but is left out due to its result being too far from the common range of results.

Finally, the Vibrotactile cue box plot, the IQR is comparatively narrower than its previous, spanning a range of 0.22, with a median of 0.29. Despite this, the upper quartile is positioned at 0.36, rendering the data more evenly distributed than the the other two scenarios. This box plot shows as one of where the data is more focused, given the concentration of data in lower values proximate to the median. An outlier at 0.86 is also present. Out of all, this cue portrays lower values and IQR than the previous two conditions.

To validate the results presented in MISC, an analysis of the MSDV was conducted to verify the motion sickness dosage for each participant. Table 4.4 presents the results for

Table 4.3: Result for the different cues tests obtained from the boxplot on figure 4.2

Cues	Median	Upper Quartile	Lower Quartile	Maximum	Minimum
Control	0.57	0.71	0.36	0.86	0.00
Audio	0.43	0.43	0.71	1.00	0.14
Vibrotactile	0.29	0.36	0.14	0.57	0.00

every lap of each participant in the respective tests.

Table 4.4: Final average MSDV for participants calculated as equation 3.1

Participant	Control	Audio	Vibrotactile
1	2.80	2.65	2.71
2	2.63	3.08	2.73
3	3.18	2.65	2.52
4	2.54	2.81	2.90
5	2.58	2.68	2.47
6	2.89	2.89	3.21
7	4.15	2.37	2.58
8	3.73	3.59	3.00
9	3.02	2.90	3.27
10	3.90	3.49	3.06
11	3.12	3.83	3.05
12	3.09	2.79	3.30
13	3.62	3.26	2.85
14	3.70	3.85	3.41

After conducting a Z-score analysis on the results presented in Table 4.5, it is observed that none of the participants can be identified as an outlier. All Z-scores fall within the 95% confidence interval, meaning all subjects lie within a range of -1.96 to 1.96 standard deviations.

Table 4.5: Z-scores for every MSDV score obtained from the performed tests

Participant	Control	Audio	Vibrotactile
1	-0.776	-0.883	-0.741
2	-1.111	0.038	-0.669
3	-0.050	-0.867	-1.365
4	-1.288	-0.525	-0.100
5	-1.212	-0.815	-1.525
6	-0.613	-0.357	0.897
7	1.801	-1.462	-1.161
8	0.997	1.132	0.210
9	-0.363	-0.342	1.125
10	1.313	0.920	0.412
11	-0.181	1.642	0.391
12	-0.232	-0.579	1.215
13	0.786	0.420	-0.263
14	0.928	1.677	1.573

None of the laps for any participant can be considered an outlier as all of them lie within the confidence interval.

4.2 Filter design and Simulations

The filter components, including High-pass, Low-pass, Acceleration-velocity transition, and Upward step, have been implemented using MATLAB, following the equations 2.10, 2.11, 2.12, and 2.13 as described in the Theory section. The result of these implementations can be seen in Figure 4.3, employing the parameters in the Table 2.1, detailed in Section 2.

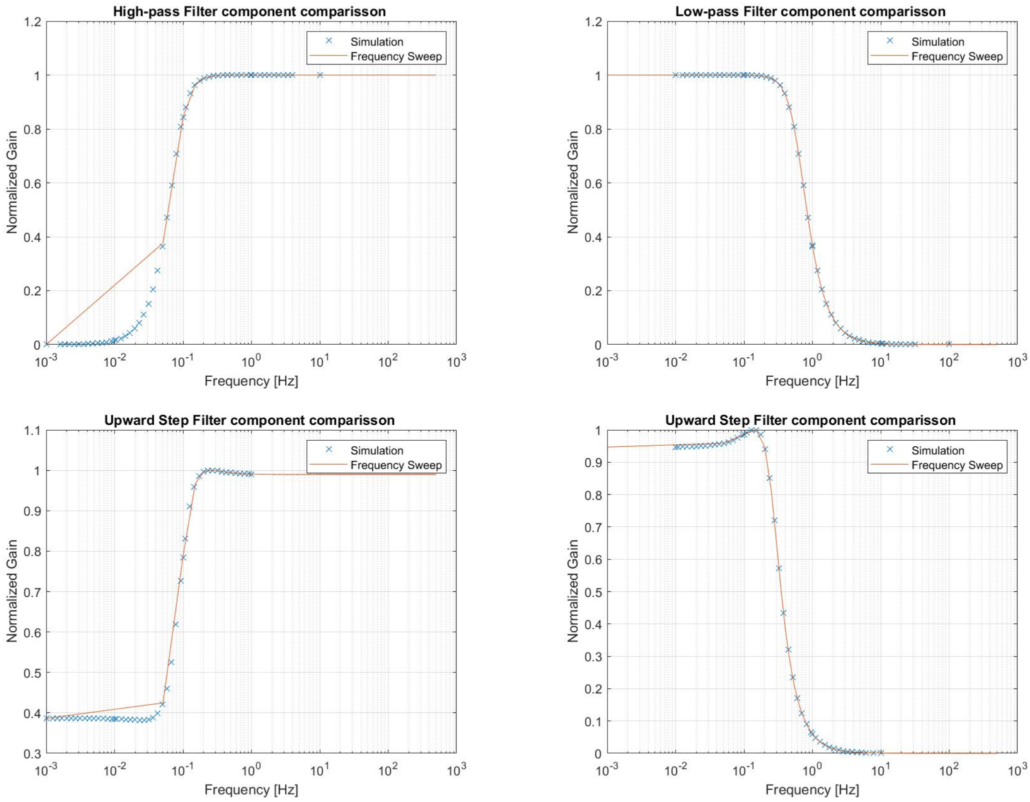

Figure 4.3: Filter components for W_f as described by equations and parameters in section 2.

Figure 4.3 shows the Frequency analysis of each filter's component. Each graph shows both the simulation down by MATLAB using the BODE function, identified by the blue crosses. The frequency sweep method is also showed for each filter component, in an orange line. Both curves overlap around the cutoff frequency and had being normalized for its magnitude. In the figure is also noticeable that the order of magnitude of the cutoff frequency for each is around 10^{-1}, which complies to the cutoff frequency for the W_f curve according to the ISO 2631-1.

The result of the total Weighting function described by the equation 2.5 results in equation W$_f$ 4.1, and its simulation result can be seen in Figure 4.4. As well as described for the figure 4.3, both methods had been applied off frequency analysis had been applied. Again, both curves overlap and have a cutoff frequency at $f_{cutoff} = 0.18[Hz]$

$$W_f = \frac{1.592 \times 10^{-07}s^5 + s^4 + 0.4909s^3 + 0.1542s^2}{0.02587s^8 + 0.2307s^7 + 1.052s^6 + 2.439s^5 + 3.621s^4 + 3.19s^3 + 1.805s^2 + 0.5886s + 0.09975} \tag{4.1}$$

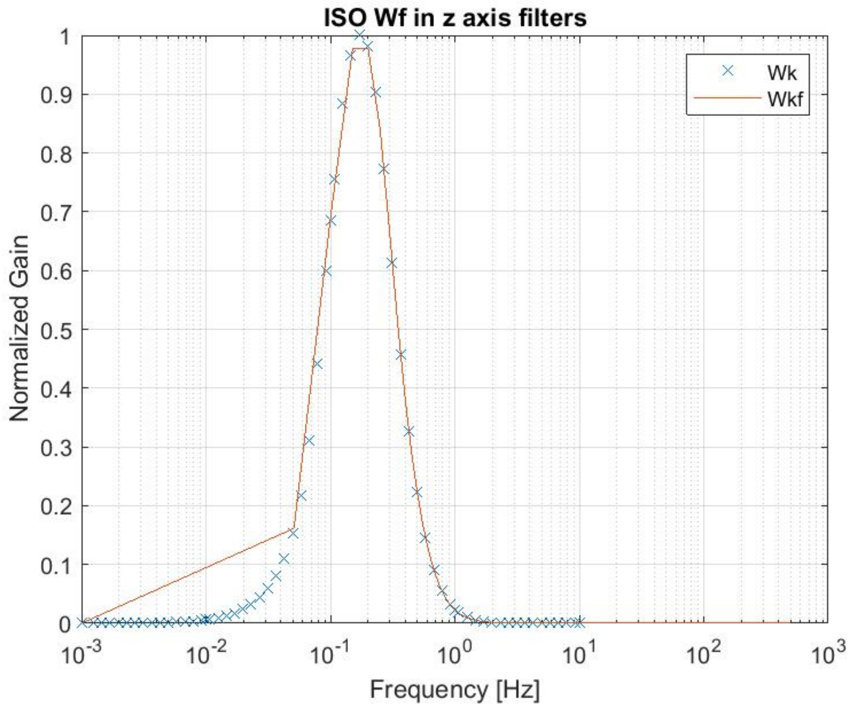

Figure 4.4: Simulated W_f filter using the parameters found in the ISO 2631-1 described in Section 2

Continuing with the scripted methodology, the filter approximation has been examined through simulation, involving the equations at different orders (2nd, 3rd, 4th and 5th grade) as described by 2.10, 2.11, 2.12 and 2.13 from Theory section. The outcome of this simulation is visualized in Figure 4.5. All graphs had been identified by different plot lines and each represents each approximation. Although, the plots would only overlap around the cutoff frequency $f_{cutoff} = 0.18[Hz]$ when the Gain is $G = 1$; it is still noticeable that they would diverge when the Gain is lower than $G = 0.4$

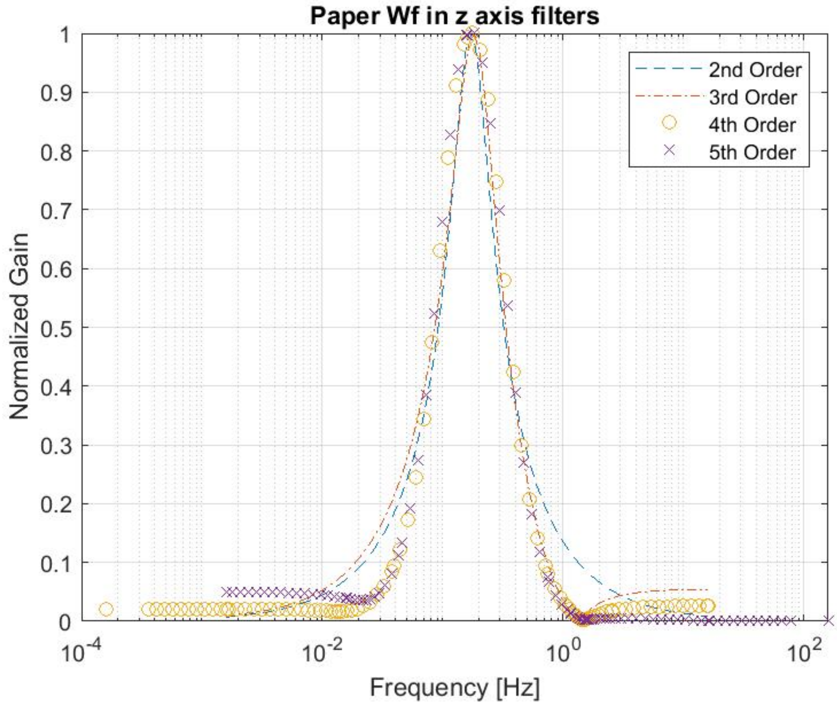

Figure 4.5: Frequency analysis for L. Zuo [9] equations to approximate W_f to 2^{nd}, 3^{rd}, 4^{th} and 5^{th}

In the next phase, the MSDV score is computed using the equation 2.8 applied to the filtered acceleration signal acquired through experimental trials a_w. In Figure 4.6 the processed outcomes for the 2^{nd} to the 5^{th} Order approximated filters by [9] and for the ISO 2631-1 [8] are shown. The resultant MSDV score for each filter is found in Table 4.6 after $T = 78.12[s]$. Each plotted line portrays the cumulative MSDV value per unit step, result of being evaluated using Equation 4.2.

$$MSDV_{cum}(t) = \sum_{i=k}^{t} \text{MSDV}_i \tag{4.2}$$

being k equal to the unit step, equivalent to the sample rate.

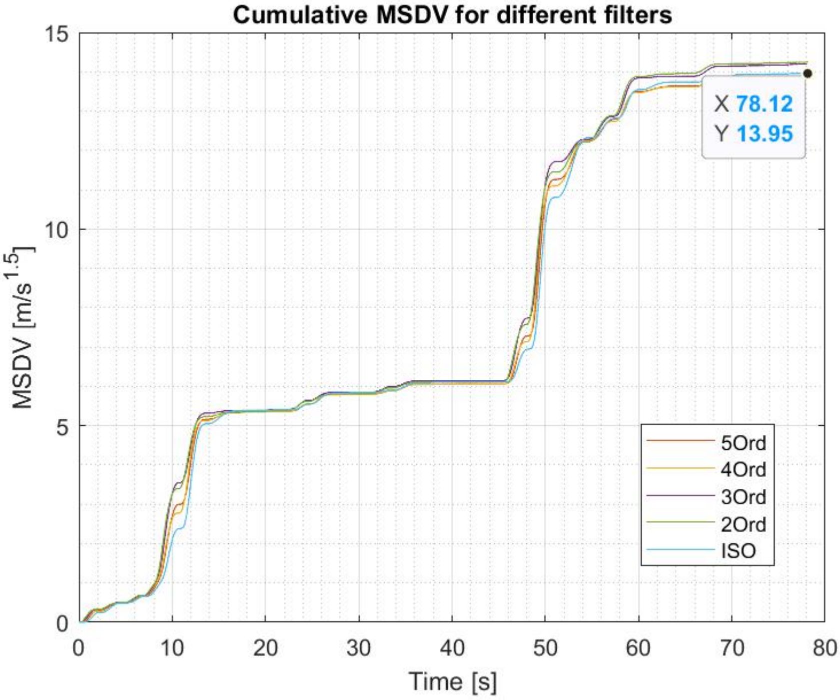

Figure 4.6: W_f weighting filter approximated to order 2,3,4 and 5

Filter	MSDV
ISO	13.95
2^{nd}	14.24
3^{rd}	14.29
4^{th}	13.83
5^{th}	13.87

Table 4.6: Final MSDV for the signal using the filter from the ISO2631-1 [8] and L. Zuo [9]

Figure 4.6, can also show some the behaviour of the vehicle during the test. For instance, around time $T = 10[s]$ and time $T = 50[s]$, acceleration peaks occur causing a raise in the MSDV during these time frames. Although, in most of the graph the result of the filtered signals are unidentifiable, during these time frames the behaviour of the filters is more evident, evidence of the performance of the different filters for shifts in acceleration behaviour.

Furthermore, the percentage deviation of the filter results, between the approximation and the ISO standard can be visualized in Figure 4.7. Computed using the Equation 4.3,

$$\text{MSDV}(t) = \sum_{i=1}^{t} \frac{\text{MSDV}_{ISO} - \text{MSDV}_{approx}}{\text{MSDV}_{ISO}} \times 100 \tag{4.3}$$

Here, the MSDV result of the ISO applied filter is compared against the approximation filters proposed by L. Zuo [9] and outputs a percentage deviation. Therefore, lower percentage scores, mean a bigger resemblance to the ISO filter. In Figure 4.7, where it can be seen that the the periods of bigger difference occur at the time $T = 10[s]$ and the

$T = 50[s]$; being the 2^{nd} order filter is the one with the greatest contrast and the 5^{th} being the one with minimal divergence. Similar behaviour can be inferred from the Figure 4.6.

Final values for the complete MSDV processed data can be seen in Table 4.7. The result indicates the difference in result at the end end of sampled data, which is in this case $T = 78.12[s]$ as well. It can be seen that the lowest scores were obtained by the highest order filters, $\text{MSDV}_{\text{diff}} = 0.627\%$ for the 5^{th} order filter, in ascendant order until the 2^{nd} order filter, which is the highest percentage being with $\text{MSDV}_{\text{diff}} = 2.062\%$

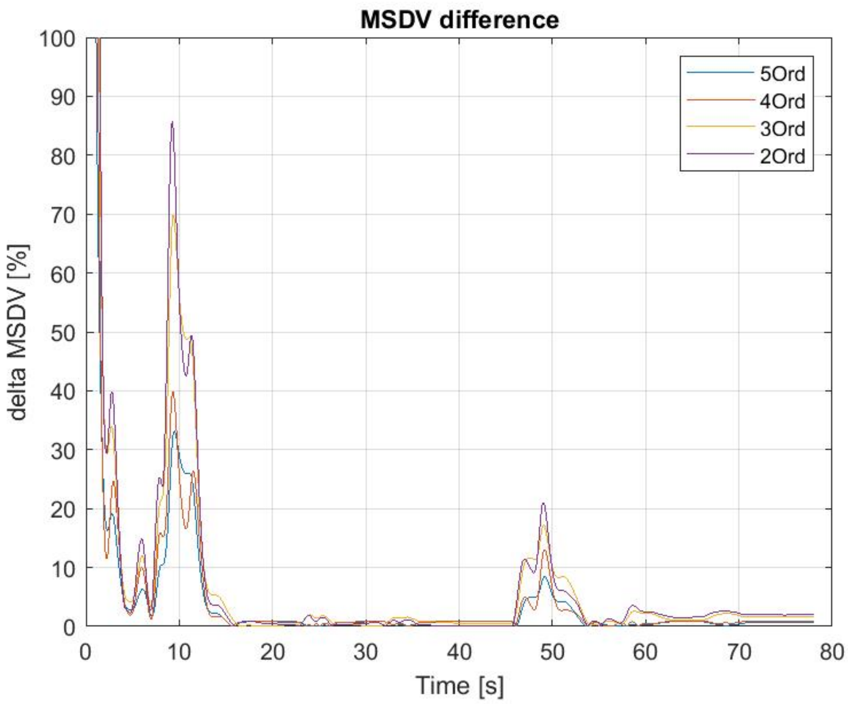

Figure 4.7: MSDV comparison for the signal using the filter from the ISO2631-1 [8] as reference to evaluate L. Zuo [9] filters performance

Filter	MSDV difference [%]
2^{nd} Order	2.062
3^{rd} Order	1.713
4^{th} Order	0.856
5^{th} Order	0.627

Table 4.7: MSDV final values comparison for the signal using the filter from the ISO2631-1 [8] as reference to evaluate L. Zuo [9] filters performance

5
Discussion

The primary objective of this study was to identify and evaluate technologies applicable for the detection and mitigation of motion sickness, addressing the current scarcity and development of such solutions. The integration of these approaches seeks to bridge the gap between theoretical innovations and practical implementations. The first stage of the research included a systematic patent review combined with a real-world application derived from the first, aiming to discover and test practical technologies to enhance vehicle comfort. The goal was to identify solutions that can be implemented to reduce motion sickness in real-world scenarios. In a second phase, the study focused on computational simulations to provide a proof of concept for the applicability of filters in assessing motion sickness in vehicles. This phase aimed to determine the usefulness of replicating the current filters described by the ISO2631-1, therefore enabling their more efficient use in real-time applications.

5.1 Systematic patent review and real-world application

The patent review revealed several innovative approaches to motion sickness detection and mitigation. Although there is no real consensus on just a single type of technology to be used to assess motion sickness. Part of the patents examined included the use of physiological data (heart rate, skin response, brain waves), vehicle dynamics(accelerometer, gyroscope, route) and integrated systems that combine multiple data sources.

The review highlighted the importance of using combined data sources. Systems that integrate physiological data along with vehicle dynamics were found to be the most robust, as they can capture a broader range of factors that can influence motion sickness. This compound approach may allow to get a more accurate detection and intervention, potentially improving passenger comfort significantly.

In terms of mitigation, several patents proposed interventions hugely based on their own detected motion sickness signals. Meaning that, the mitigation system work around on the acquired signal. These include, among others, adaptive seating arrangements for vibration reduction, adaptive route change and mitigation cues the latter being the more remarkably one given its incidence. Visual as well as audio cues and, less common, haptic cues designed to counteract the onset and sensor conflict of motion sickness. With these method being the most easy to reproduce and showing significant impact.

The effectiveness of this cues is explored in the real-world application to provide more insights about them. More specifically, the MISC scores exhibits different trends for the three cues that were employed during the experimental phase: Control, Audio, and Vibrotactile cues. To be more precise, Control cue tests evidence a higher MISC in comparisson with both Audio and Vibrotactile cues. Therefore, explaining that audio and vibrotactile cues relieve symptoms of discomfort. There could be several reasons on why is this behaviour observed, including: sensory conflict, cue effectiveness, and subject predisposition.

Initially, the control cue is the test with less sensory input information. It corresponds to a situation where the subjects can experience acceleration, however there is lack of any additional sensory information or feedback. In contrast, audio and vibrotactile cue tests add different stimuli that can enhance and compensate for the motion. Theory suggest that kinetosis is caused by a disparity among the vestibular, visual and proprioceptive senses. With no present cues, during control tests, participants rely only on vestibular input; consequently resulting in a stronger sensory conflict and thus a higher MISC. These can be observed in the table 3.1 where Control reaches $MISC_{avg} = 3.67$. These results are being corroborated in the Figure 4.1 where the control cue plot initiates by having a higher tendency, diverging from the audio and vibrotactile cues plots.

A second explanation for the results come in form of how well the cues are being presented to participants. Both audio and vibrotactile cues present a lower MISC result, than control cue, in participants. However, tests with audio cues presented higher MISC values than the tests with vibrotactile cues, as seen in Figure 4.1 and 4.2. As seen in the boxplot, all of the participants experimented at least a degree of motion sickness, supported by the whiskers of the audio cues box that start at $MISC_{avg} = 0.14$, see table 4.2. Additionally it is observable that, there is an outlier that exceeds the ones saw on the control test and the vibrotactile, reaching the maximum normalized value. This suggest that the audio cue is not as effective and may not completely resolve sensory conflicts. By taking the outlier of the audio cue test into account, it is inferable that the cue is more counterproductive for some part of the population. In contrast, the vibrotactile cue test showed less variability in results, as indicated by the smaller size of the boxes in the plot. Evidenced by the slope of the MISC average progression through the laps in Figure 4.1. The results, suggest that vibrotactile cues provide better sensory integration for participants, as indicated by the cluster of results inclined towards lower MISC values. This indicates that while both types of cues can mitigate motion sickness to some extent, vibrotactile cues are more consistently effective across the participant population.

Test subjects are susceptible in different degree to motion sickness, as well as the influence of different type of cues affect them differently. Benefits from either test can be observed in the individuals that reached $MISC_{avg} = 0$ at the end of each test. In figure 4.1, it is possible to observe that both control cues and vibrotactile cues test had participants that experienced close to none motion sickness. The reason of this could be explained that some of the participants, for instance, find the control cue less disruptive and more natural. A higher tolerance to kinetosis response for varying conditions is also explained by participant specific factor, such as previous experience, individual comfort levels or even sensory processing of each. Since its observed in the MSDV results on table 4.6 and corroborated by table 4.5, there is no conclusive evidence that show that the driving style had an influence in the test, as all the test landed between a 95% confidence interval; In other words, differences between MISC results can not be explained by this factor. Then, it is also important to take into account the cognitive factor of the test. As participants were aware of the discomfort conditions they were subject to, they might consciously or subconsciously adjust their expectations according to the provided cues, therefore impact on the reported MISC.

5.2 Filter design and Simulations

The objective of this case was to evaluate the design for the filters that can assess motion sickness. These filters were based on the ISO 2631-1 criteria and implemented using the L. Zuo methodology. To begin with, the sum of the implemented filters produce the weighting function (w_f) equation 4.1, that would later works as the foundation for the comparison with the ones designed in L. Zuo paper.

The frequency analysis of each filter component can be seen in Figure 4.3. Both employed methods, found in the ISO2631-1 standard, displayed the same results and validate the filter design. It is noted, that the cutoff frequency for each component aligns with the standard, showcasing a successful implementation of the filters. The result of the synthesized filter that corresponds to the total weighting function W_f can be found in figure 4.4. This curve, complies with the result of the curve found in the ISO2631-1 on figure 2.1. These results demonstrated coherence within MATLAB BODE function and the frequency sweep method, which indicates an accurate implementation and therefore could be used for further analysis.

To evaluate the filters performance, the proposed approximations (2^{nd}, 3^{rd}, 4^{th}, and 5^{th}) of the filters were studied. In Figure 4.5, it can be found that there is divergence between filters. However, in the critical region, around the cutoff frequency, the deviation of the curves is minimal in comparison to where the Gain score is the lowest (less than $G = 0.4$). This behavior can be explained by the polynomial degree of the approximated equations, which mean that, lower degree equations have a poorer performance than their higher degree counterparts, for instance the ISO standard. Despite of this, it is observed that as the frequency approaches the cutoff point with a Gain $G = 1$, the divergence within filters are enough comparable. Therefore, as the values where the Gain score is the maximum and closest within each other, the implemented filters are suitable for further comparison analysis in their performance.

The cumulative MSDV analysis is computed for every filter using the acceleration signal a_w obtained from a real scenario test. Figure 4.6 displays the cumulative MSDV values for the filter approximated from 2^{nd} to the 5^{th} order. It is possible to see that during peaks, when there is a significant alteration in the curve, around $T = 10$ and $T = 50$, the divergence between MSDV responses is greater, than on a steady state, when there are not significant changes in MSDV. This behaviour could be explained by considering the motion done by the vehicle during the data collection, including additional force components.

The filters, in lower orders were limited to remove basic acceleration components, close to the cutoff frequency, in contrast to the ISO filter which effectively suppressed them; evidence of that is shown as a lower response compared to the other filters, see Figure 4.6.

As the MSDV is a measure of the whole journey of the vehicle, it is possible to compare the final values of the whole experiment. The value that better approach the ISO filter in the final MSDV, is the 5^{th} progressively decreasing in similarity as it reduces the order filter until reaching the 2^{nd} order result, see Table 4.6. A confirmation of these behaviour, can be seen in Figure 4.7, where the comparison in percentage of the MSDV of the approximation against the ISO is done. For the final value, the comparison has a consistent pattern; being the MSDV 5^{th} order filter $\text{MSDV}_{diff} = 0.627\%$ and the 2^{nd} order filter with the biggest difference of $\text{MSDV}_{diff} = 2.062\%$. There exists significant difference where $T = 10$ and $T = 50$ as additional accelerations were undertaken, these values can be explained as in that point the value of reference ISO MSDV, is negligible in comparison to the rest of the MSDVs filter results. In the case of $T = 0$, the values raise to infinite as the division is done by MSDV_{ISO}=0, these values should not be taken into account as they do not reflect the real difference between the approximated filters and the ISO Filter.

In general, regarding motion sickness assessment, it is possible to say that the 5^{th} order filter approximation had a much better performance than its counterparts being the one that has a better alignment with the ISO2336-1 standard; despite it having a more intensive computationally task than the rest but being significantly less than the ISO one, as it is 3 orders smaller. The choice of the filter, however, should be considered as trade off between, the computational complexity of the equations and the accuracy of them in reference to the ISO standard. This has special relevance if the main purpose of the MSDV is set to be used in real-time applications.

5.3 Limitations

One of the key limitations identified during the patent research is the disparity between the availability of data and the lack of detailed, focused information on the actual technologies employed by companies or inventors. This limitation hinders the ability to reproduce results based on the inventions and reveals a deficiency in the application of scientific methods. Additionally, the broad scope of the investigation resulted in scattered information collection, making it challenging to categorize each patent into specific sections. Very few patents were clearly focused solely on mitigation or detection, as many adopted a combined approach, though typically developed from one side. Focusing on the practical test itself, some other limitations were identified that could impact the reliability of the results. A small participant pool, limited diversity among participants, the technology employed to carry on the experiments, and constraints in test conditions, were some of the variables that could be revised.

Further limitations of the study include the assumption that ISO 2631-1, particularly the weighting factor W_f , accounts for all considerations necessary to measure motion sickness. The study is also constrained by the inclusion of only a single portion of real-life data to test, rather than multiple samples.

6
Conclusion

A comprehensive study of motion sickness technologies was done and it was possible to draw insights in different aspects of an assessment in comfortability. The study was divided in two phases, a real-world scenario that provided practical methods , and a computational scenario where the ISO 2631-1 was assessed. Efficient ways to detect and mitigate motion sickness were tested as well as identifying improvements on the current methods to evaluate motion sickness.

The real-world testing was able to provide information on how effective are proposed detection and mitigation methods. There are several amount of technologies and methods to assess motion sickness, a single type of solution was not found. Although, it was observable that a more broad spectrum of motion sickness detection method was more popular, where a combined passenger and vehicle signals were used. Moreover, there is an inclination towards mitigation methods that include cues that alert passengers on maneuvers, this methods are relatively easy to implement and test. The research demonstrated that cue based technologies can improve the comfort of passengers by mitigating motion sickness. Vibrotactile cues were found to be more effective than audio based cues in alleviating motion sickness symptoms.

From the second phase, on filters performance to assess motion sickness based on the ISO 2631-1. The frequency analysis and MSDV analysis of the filters output indicated that the 5^th order filter approximation is the closest and better aligned to the one provided by the ISO standard, showing slightly better performance than lower order approximations. Despite having a higher computational complexity in comparison with the later, the 5^th order filter is more suitable for real-time applications than the ISO proposed one. Although, a balance between computational efficiency and accuracy should be taken into consideration.

As recommendations and future work. It is advisable to have a shorter scope of technologies that assess motion sickness. For instance, technologies that mainly focus on the use of cues to mitigate motion sickness. Establishing defined criteria for what can constitute detection or mitigation can help in comparative analyses between patents. In addition to draw better insights of the technical aspects of each patent.

As per the reliability of the results in the practical test. Can be corrected through increasing and diversifying the pool of participants. Refining the experimental design and better controls can minimize the collection of irrelevant variables, standardize procedures, protocols for data collection and better monitoring of experimental conditions.

Regarding the computational tests,future work should incorporate more diverse data samples and evaluate the impact of varied maneuvers on the MSDV calculation. Additionally, exploring more sophisticated models and other contributing factors to motion sickness will provide a more comprehensive understanding of the phenomenon to develop a closer approach to motion sickness assessment.

The implications of this study are substantial for developing technologies that help mitigating motion sickness discomfort. By refining the research focus and engaging stakeholders in a more efficient way, a new study can unlock the full potential of the technologies pointed and develop a more practical and reliable solution.

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Patent Table

Table A.1: Patent Review

No.	Patent	Publication Title	Organization	Publication Date	Ref
1	US7437219B2	Method for the prevention of motion sickness, and apparatus for detecting and signaling potentially sickening motions	Netherlands Organization for Applied Scientific Research TNO	2002	[11]
2	US20190202324A1	Motion sickness mitigation	Faurecia Automotive Seating LLC	2017	[24]
3	US10322259B2	Systems and methods for mitigating motion sickness in a vehicle	GM Global Technology Operations LLC	2017	[23]
4	US20190133511A1	Occupant motion sickness sensing	Lear Corp	2019	[34]
5	US20220135054A1	Vehicle motion sickness estimation device, vehicle motion sickness suppression device, and vehicle motion sickness estimation method	Mitsubishi Electric Corp.	2020	[25]
6	EP3888958B1	Method of mitigating motion sickness in an autonomous vehicle	ClearMotion Inc	2017	[18]
7	GB2567856B	Anti-motion sickness device	Jaguar Land Rover Ltd	2017	[13]

8	US20220001893A1	Motion sickness detection system for autonomous vehicles	Qualcomm Inc	2021	[14]
9	US20220219705A1	Method for predicting and mitigating interference caused by motion sickness	Mercedes Benz Group AG	2019	[20]
10	DE102021207945A1	Method and device for detecting a kinetosis-critical condition of a vehicle occupant in a vehicle	Volkswagen AG	2021	[26]
11	US10259451B2	Motion sickness mitigation system and method	GM Global Technologies	2017	[15]
12	US20060015000A1	System, method and apparatus for preventing motion sickness	Samuel Kim	2006	[12]
13	US10107635B2	Method and system for determining and dynamically updating a route and driving style for passenger comfort	Waymo LLC	2018	[21]
14	US20200317089A1	System and Method for Reducing Kinetosis Symptoms	Bayerische Motoren Werke AG	2020	[22]
15	DE102015011708A1	Method for reducing kinetosis-related disorders	Mercedes Benz Group AG	2016	[32]
16	US20170267253A1	Avoiding or alleviating travel sickness in a vehicle	Ford Global Technologies LLC	2017	[19]
17	US20210154430A1	Systems and methods for predicting and preventing motion sickness	Mobilex Ltd	2021	[16]

18	US20210031789A1	Travel sickness estimation system, moving vehicle, travel sickness estimation method, and travel sickness estimation program	Panasonic Intellectual Property Management Co Ltd	2021	[17]
19	US20170291538A1	Universal Motion Sickness Countermeasure System	University of Michigan	2017	[33]
20	KR20210158525A	System for reducting mortion sickness for driving of autonomous vehicle	Hyundai Motor Company	2021	[27]
21	US11738773B2	System for controlling autonomous vehicle for reducing motion sickness	Hyundai Motor Co, Kia Corp	2020	[31]
22	US9868332B2	Methods and systems for controlling vehicle body motion and occupant experience	Bridgestone Americas Inc	2014	[29]
23	US20220001773A1	Device for Reducing Kinetosis-Related Disorders of an Occupant During Driving Mode of a Vehicle	Mercedes Benz Group AG LLC	2019	[28]

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