Preemptive Interventions for Carsickness Mitigation and Their Effects on Passenger Task Performance

by

Nishant Mangesh Jalgaonkar

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Mechanical Engineering)
in the University of Michigan
2024

Doctoral Committee:

Professor Shorya Awtar, Chair
Dr. Monica Jones
Professor Henry Liu
Professor Bernard Martin
Professor Steven Skerlos

Nishant Mangesh Jalgaonkar

nishjal@umich.edu

ORCID iD: 0000-0002-2655-8999

Dedication

To my parents, family, and T. You are my sun, my moon, and all my stars.

To my friends and loved ones. Eternally grateful.

Acknowledgements

I am grateful to my thesis advisor and mentor, Prof Shorya Awtar, for his expert guidance and support throughout my PhD. He raised the bar and taught me to expect more from myself. I am also grateful for the community of researchers and colleagues he nurtured at the Precision Systems Design Lab. Each and every one of my colleagues (and friends) at the lab played a crucial role in making me the engineer I am today.

I am thankful to my doctoral thesis committee for their thoughtful feedback and steadfast support of my research. In particular, I want to acknowledge Prof Steven Skerlos for giving me my first research opportunity at the university. I also want to acknowledge the expert advice and wisdom provided by Dr Monica Jones and Prof Bernard Martin. Without their guidance, I would not have been successful conducting human subjects research. Lastly, I want to acknowledge the opportunities to share and publicize my research offered by Prof Henry Liu and the folks at Mcity.

I would like to thank the nearly 50 graduate and undergraduate student researchers who have contributed their energy and time towards helping me realize this research. I would also like to thank various staff members at the university whose tireless effort (often behind the scenes) helped smoothly facilitate my research activities over the last 6 years.

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Abstract

The objective of this thesis is to investigate methods to mitigate carsickness using preemptive interventions and their effects on passengers performing tasks. Autonomous, connected, electric, and shared (ACES) technologies promise a transportation future with several benefits including fewer road accidents and fatalities, reduced traffic congestion, lower energy consumption & environmental footprint, reclaimed productivity during commutes, and an equitable access to transportation. But a high incidence of motion sickness among passengers remains a major impediment to widespread adoption of these promising technologies. It includes symptoms such as sweating, nausea, and retching, and it adversely influences the individual's situational awareness, cognitive and motor abilities. It is theorized (e.g., Subjective Vertical Conflict Theory) that motion sickness is caused by a conflict in the sensed and perceived motion of an individual. Therefore, to reduce or eliminate motion sickness the mismatch in sensed and perceived motion of the individual must be minimized.

It is also well-known that, in a traditional vehicle, the non-driving passengers experience greater motion sickness compared to the driver. While the driver anticipates the inertial consequences of their own driving actions, and accordingly makes subtle preemptive corrections (e.g., tighten core muscles, adjust torso or neck), the passenger lacks this anticipation and ends ups passively reacting to the inertial forces. This leads to far greater incidence of motion sickness in passengers of traditional vehicles compared to the driver.

The objective of this research is to recreate this anticipation and preemption for an autonomous vehicle passenger using mechatronic hardware and software. Prior research on preemptive

interventions of mechatronic systems to mitigate motion sickness is limited, and many intellectual gaps remain unanswered. This research proposes two strategies to mitigate motion sickness in car passengers performing tasks. The first strategy is to use preemptive sensory stimuli (a haptic stimuli) to inform the passenger of upcoming vehicle motion (just like a driver who can anticipate the upcoming vehicle motion). The second strategy is to use preemptive motion of a tilting seat to move the passenger in anticipation of upcoming vehicle motion (just like a driver making preemptive adjustments to their posture compatible with anticipated vehicle motion). This research further investigates the effects (if any) of these motion sickness mitigation strategies on the quality and quantity of task performance of the passengers.

There are four key contributions of this thesis. First, a refined model of motion sickness in vehicle passengers was developed. Unlike prior models in the literature, the proposed model combines the subjective vertical conflict (SVC) theory and human motion perception models to accurately predict passenger motion sickness. The proposed model integrated visual and vestibular sensory 6 degree of freedom (DoF) motion signals in an enhanced architecture to predict motion sickness. This model's prediction was compared to experimentally measured motion sickness data from motion simulators as well as on-road vehicle testing, yielding accurate results in both cases. This model can be used to predict motion sickness of passengers in multiple realistic driving conditions.

Second, an experimental vehicle platform (based on a Ram ProMaster Van) was developed to evaluate the efficacy of motion sickness mitigation systems in realistic driving conditions. The vehicle was suitably modified to include instrumentation such as inertial measurement units, sEMG, cameras, GPS, and other sensors to monitor the response of the passenger to vehicle motion, and to track the motion of the vehicle itself. A driving path on the Mcity track was designed

to recreate realistic driving conditions in a safe and controlled environment to ensure high repeatability. Over nearly 200 drives, the mean peak lateral position error was limited to less than 4m (or less than 2x width of the vehicle) and the mean peak variation in lateral and longitudinal acceleration was less than 0.6 m/s^2.

Third, a human participant's experiment using a preemptively triggered haptic active passenger stimulation (h-APS) system was conducted. In addition, the experiment included a non-driving related task (NDRT). The NDRT was designed to mimic the cognitive burdens associated with common everyday tasks such as reading, watching videos, and texting. The experiment consisted of three test conditions. Over thirty participants were recruited as part of this IRB approved study (HUM00199425, Motion Sickness Response in vehicles when using Preemptive Interventions via Active Systems). Twenty-four participants completed their participation in the study (i.e., participated in all three test conditions of the study). The experimental results demonstrated that the h-APS does reduce motion sickness while having no negative effects on the passenger's task performance ability. The data indicated a 15% reduction in the rate of motion sickness accumulation when the haptic stimulation system was operational, even when the participant was performing a NDRT. Also, nearly 75% of the participants indicated a positive preference for the haptic stimuli system.

Fourth, a human participant's experiment using a preemptively triggered tilting active seat system (AST) was conducted. Over forty participants were recruited as part of this IRB approved study (HUM00199425). In addition, this experiment also included a NDRT that was designed to mimic cognitive burdens associated with everyday tasks. Twenty-nine participants completed their participation in the study. The experimental results demonstrated that the AST reduces motion sickness for some of the participants. The data indicated that across all participants, the tilting seat

system reduced the rate of motion sickness accumulation by nearly 10%. Also, when the data was further assessed by gender, the data indicated a 50% reduction in the rate of motion sickness accumulation for the male participants but had no effect on the motion sickness response of female participants. The results also showed that the AST had no negative effects on the passenger's task performance ability. This is the first research of its kind to demonstrate the efficacy of mitigation systems when triggered precisely and preemptively, under realistic driving conditions.

Chapter 1 Introduction and Background

1.1 Introduction and Motivation

Autonomous vehicles or automated vehicles (AVs) are poised to revolutionize transportation of persons and goods in the coming decades [1], [2]. Among the many touted benefits of AVs, AVs are expected to significantly reduce the number of car accidents and associated injuries and deaths by as much as 90% since most accidents are caused by human error [3], [4]. AVs are also expected to have a positive influence on public health and environment by reducing environmental pollution and improving air quality [5], [6]. Another key benefit of AVs is to free up time spent commuting; this time can be spent improving the productivity of the vehicle occupants [7] with some estimates claiming a $500 billion gain to the economy due to productivity gains from AVs allowing repurposing commute times [8]. However, there are many challenges to the widespread adoption of AVs. These include challenges in vehicle sensors and perception [9], control of the vehicle [10], interaction of AVs and pedestrians [11], and trust of AV users in automation [12]. In addition, a key human factors impediment to the widespread adoption of AVs is motion sickness [13], [14], [15], [16], [17].

Motion sickness (MS) is an age old ailment [18], commonly defined as an illness caused in certain susceptible individuals when exposed to certain types of motion (e.g. motion of ships, camels, cars, airplanes, etc.) [19]. Motion sickness is a common ailment, with some estimates suggesting that anywhere between one in two to one in three persons suffer from motion sickness [15]. Motion sickness is associated with many varied symptoms such as nausea, headache, drowsiness, changes in mood, and cold sweats [20], [21], [22]. Motion sickness has a detrimental

effect on a person's motor control and cognitive performance [23], [24], [25], [26], [27]. Motion sickness can be caused by motion associated with cars, airplanes, ships, and even rockets to space [28], [29]. In addition, motion sickness can also occur when using virtual reality and augmented reality systems [30], [31]. This research is limited to motion sickness in cars, also often referred to as carsickness (motion sickness and carsickness are used interchangeably in this thesis). It has been proposed that motion sickness (or carsickness or CS) in a moving vehicle is the consequence of the action of inertial forces associated with frequent accelerations (e.g., speeding, braking, turning) and the resulting postural instability and sensory conflict that is created [28], [32], [33], [34], [35]. However, no single theory has adequately explained the physical manifestation of motion sickness, and this remains an open area of research inquiry.

Currently, the most common method to mitigate carsickness is the use of pharmacological drugs [36], [37], [38], [39]. These include antihistamines such as dimenhydrinate (e.g., Dramamine), antimuscarinic such as scopolamine (e.g., Scopace), and sympathomimetic (e.g., prescription amphetamines). While there are numerous studies proving the efficacy of these drugs in mitigating the symptoms of motion sickness (including carsickness), those same studies have highlighted significant short- and long-term adverse side effects associated with the use of these drugs. These side effects include drowsiness, light-headedness, dizziness, blurred vision, headaches, and diarrhea [40], [41]. Not only do these side effects adversely affect the individual's well-being, but they also prevent the individual from engaging in any NDRT.

In addition to side effects, studies have shown that drugs like dimenhydrinate can be abused for recreational purposes [42], [43]. To avoid undesirable side effects and potential for abuse, alternative remedies that rely on acupressure or natural ingredients (e.g., ginger root) have been developed [44]. However, there are conflicting results on the efficacy of natural ingredients like

ginger root [45], [46] and no evidence to support that acupressure bands prevented motion sickness [47]. Therefore, there remains a need for a viable motion sickness mitigation solution that is both effective and does not have significant side effects that negatively impact the passenger's ability to perform tasks and overall quality of life.

Current insights into the motion sickness response of vehicle occupants can be leveraged to identify new motion sickness mitigation strategies for vehicle occupants. It is well-known that in a traditional (i.e., human driven) vehicle, the driver rarely gets motion sick because they anticipate the inertial consequences of their own driving actions and accordingly makes subtle preemptive corrections (e.g., adjust torso or neck, tighten core muscles, etc.) [48], [49], [50], [51]. On the other hand, the passenger lacks the benefit of anticipation and ends up passively reacting to the inertial forces associated with driving actions. For example, if a vehicle is taking a right turn the vehicle driver preemptively leans into the turn as they are aware of when they will initiate the turn and can prepare for the inertial consequences of a right turn (Fig 1-1). The response of the driver by leaning into the turn aligns the driver's head and torso with the direction of gravito-intertial acceleration (i.e., the direction of the combined acceleration due to motion of vehicle and acceleration due to gravity). If the driver does not lean towards the turn, there is a conflict between the sensed vertical direction (i.e., due gravito-inertial acceleration) and that expected by the driver's internal model in their brain [52]. Hence, leaning into the turn reduces the conflict in sensed verticals which leads to reduced motion sickness (as per Subjective Vertical Conflict Theory, a subset of Sensory Conflict Theory). Whereas a passenger in the same vehicle is unaware of the upcoming vehicle motion and is unable to prepare for the inertial consequences resulting from the vehicle motion, leading them to be swung away from the turn along with the sprung mass of the car (Fig 1-1). This makes the passenger more likely to experience motion sickness compared to the driver. Therefore,

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unlike the driver, the passenger lacks both the information about upcoming vehicle motion, and the ability to alter their posture in preparation for the vehicle motion.

Not all passengers in a car experience motion sickness in the same way. For example, passengers that have a better view of the exterior forward view from their position in the vehicle cabin may experience less motion sickness than other passengers [53]. While not in control of the vehicle like a driver, passengers with a view of the exterior forward view of the vehicle have some ability to anticipate the trajectory the vehicle will take, and passengers can take appropriate corrective actions accordingly. This research finding is corroborated with anecdotal evidence where persons who are most susceptible to motion sickness prefer to sit in the front passenger seat, which affords them the best exterior forward view.
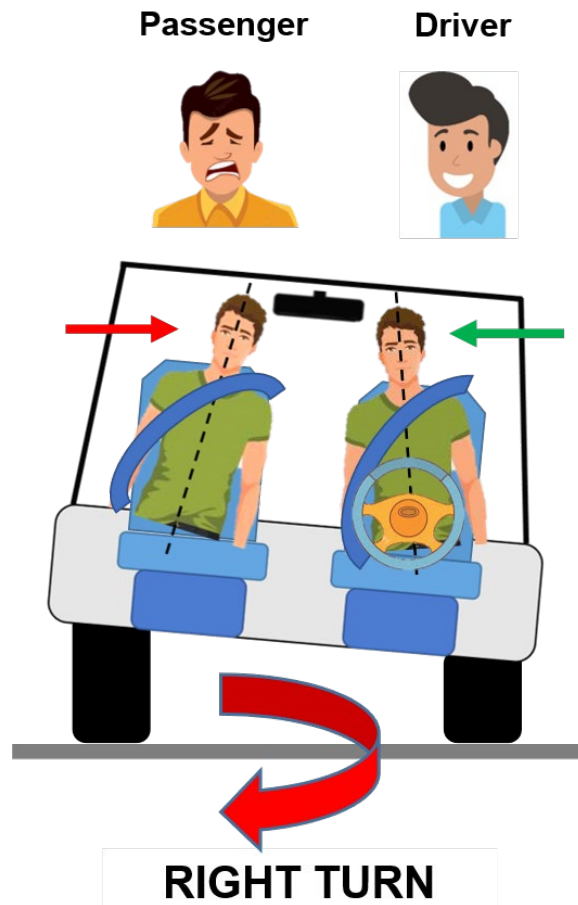
Fig 1-1 Driver and Passenger responses in a manually driven vehicle making a right turn

Currently, the majority of vehicles on the road only have one occupant, the driver. It was reported that over 75% of the works in the US commuted to work by driving alone [54]. However, in the future if most transportation is autonomous, then all vehicle occupants will be passengers (i.e., no drivers). Therefore, the deleterious effects of motion sickness are expected to be more significant.

1.2 Research Objective

Based on the above discussion, the primary objective of this research is to recreate the anticipation and preemption of a typical vehicle driver for a passenger of an autonomous vehicle using various mechatronic hardware and software) to mitigate their motion sickness. This can be accomplished using two different approaches. The first approach relies on providing information to the passenger about the upcoming vehicle motion so that the passenger can anticipate the motion of the vehicle. The passengers can themselves use and respond to this information as they please.

The second approach relies on preemptively moving the passenger in anticipation of the vehicle motion. Moving the passenger will induce a conscious or subconscious adjustment of their posture. In addition, the influence of the motion sickness mitigation interventions on the performance of a vehicle passenger primary tasks will also be investigated. These primary tasks are non-driving related tasks such as reading a book or using personal electronic devices such as smartphones. A secondary objective of this research was to leverage the best understanding of the causes of motion sickness to create motion sickness models. These motion sickness models help predict the motion sickness response of vehicle passengers.

1.3 Organization of the Thesis

Based on the problem statement, the work in this thesis is organized into five research tasks as shown below. The organization of the chapters is based on these tasks:

Task I (Chapter 2 Literature Review): A systematic review of existing literature and studies on the causes of motion sickness, motion sickness models, and motion sickness mitigation solutions for vehicles was conducted. This was done specifically with an emphasis on non-pharmacological solutions to motion sickness that help recreate the anticipation and preemptive actions of a driver for a passenger.

Task II (Chapter 3 Visual-Vestibular Motion Sickness Model): Leveraging current state of the art knowledge on the causes of motion sickness to propose a computer-simulation model of motion sickness. The model estimates the amount of motion sickness of a vehicle passenger via a motion sickness scale commonly used in prior literature. The model uses vestibular and visual sensory motion signals as inputs. The performance of the model is evaluated by comparison with experimental data.

Task III (Chapter 4 Motion Laboratory on Wheels): To investigate the efficacy of motion sickness mitigation solutions in realistic conditions, a custom research vehicle platform was developed based on a Ram ProMaster Cargo van. The research platform has the appropriate onboard computation and instrumentation capabilities to measure the responses of the occupants while keeping them safe. In addition, the vehicle was designed to integrate various mitigation systems investigated in this research. Specific software was developed that leveraged real time data of the vehicle's position to precisely operate the mitigation systems onboard the vehicle. The proposed research platform can be used to investigate not just motion sickness, but also a variety of other physical and physiological phenomenon associated with passengers and drivers of a

moving vehicle.

Task IV (Chapter 5 Haptic Stimuli System to Mitigate Motion Sickness): An experimental investigation of the efficacy of haptic stimuli systems in mitigating motion sickness in vehicle passengers. The haptic stimuli system provides information about upcoming vehicle motion to the passenger. Based on this information, the passenger can respond to the vehicle motion before it occurs. An analysis of the passenger's motion sickness response and task performance is presented, along with an analysis of subjective responses and preferences of the passengers regarding the haptic stimuli system.

Task V (Chapter 6 Tilting Seat System to Mitigate Motion Sickness): An experimental investigation of the efficacy of a tilting seat system in mitigating motion sickness in vehicle passengers. The tilting seat system alters the side-to-side orientation of the seated passenger, and the passenger can further respond to the motion of the seat as they please. An analysis of the passenger's motion sickness response and task performance is presented, along with an analysis of subjective responses and preferences of the passengers regarding the tilting seat system.

1.4 Research Contributions

The intellectual contributions of this thesis to the field are summarized below:

1. A systematic review of existing literature on motion sickness mitigation solutions which is used to identify gaps in existing research and identify promising areas of research inquiry. The specific focus of the review was to identify solutions to reduce motion sickness in vehicle passengers.

2. An improved model of motion sickness estimation using both visually sensed and vestibular sensed motion of the person as model inputs is presented. The proposed model can be used to predict motion sickness response in scenarios such as when the person is performing a task

(e.g., reading a book) in the vehicle. The performance of the model is validated by comparing model estimated motion sickness to experimentally observed motion sickness response of passengers.

3. An experimental research vehicle platform for investigating motion sickness under realistic driving conditions. The design of the research vehicle is unique and allows for the integration of a stimulation and moving seat system. The vehicle also includes software for the precise and preemptive operation of motion sickness mitigation systems.

4. Experimental evaluation of motion sickness mitigation solutions under realistic driving conditions using the above experimental research vehicle platform. Two mitigation solutions are investigated in this research: (a) a haptic stimuli and (b) a tilting seat system. The mitigation solutions leverage anticipation and preemption to influence motion sickness response of participants in the experiment.

Chapter 2 Literature Review

This chapter presents a review of the current literature on motion sickness theory and modelling, and motion sickness mitigation. This chapter is organized into four sections: (2.1) Motion Sickness: Theory & Modelling, (2.2) Motion Sickness Mitigation, (2.3) Discussion, and (2.4) Identified gaps in current research.

2.1 Motion Sickness: Theory & Modelling

While motion sickness has been investigated for over a century and multiple theories have been proposed to elucidate the underlying mechanism of motion sickness, no single theory adequately explaining the manifestation of motion sickness has been proven [32], [55], [56]. The simplest definition of motion sickness is an illness in response to certain (actual) motion (i.e., types and intensity of motion) experienced by a person [57]. This provocative motion may include motion experienced by a person when travelling over land [18], sea [58], air [59], and even space [60]. In addition to the above, in some cases even the perception of motion (and not necessarily actual motion) can induce motion sickness, such as due to virtual or augmented reality experiences [31]. The common symptoms associated with this illness are varied. The most common symptoms include nausea, vomiting, cold sweats, increases in salivation, drowsiness, headaches, and even severe pain [61], [62]. However, motion sickness is a complex illness, and there is a high degree of variability across individuals in how these individuals experience the sickness [63]. It can be challenging to identify when a person is motion sick as some those same symptoms (e.g., drowsiness, headaches) can be potentially be attributed to other causes such as fatigue or boredom

[20]. Therefore, it can be challenging to determine when there is an onset of motion sickness in a person in real world conditions, especially when the symptoms are common such as drowsiness.

There are other symptoms of motion sickness which are less commonly known. Motion sickness adversely influences an individual's situation awareness, cognitive, and motor abilities [23], [24], [25], [27], [64], [65]. Situational awareness is defined as an individual's ability to discern an accurate interpretation of their surroundings and make a reasonable prediction of immediate future states of their surroundings [66]. It has been reported that in instances where a person is disoriented due to motion, they may be unable to discern the difference between loss of situational awareness and motion sickness [66]. Therefore, motion sickness not only has varied symptoms, but it can also influence the person's behavior, mood, and ability to perform tasks.

For motion sickness to occur, the person must be able to sense motion. It is known that a person senses motion using the following biological sensors: (a) Eyes, (b) Vestibular organs, and (c) Proprioception. Eyes have evolved to function as a motion detection system, almost like a camera for the person [67]. Eyes are very good at detecting changes in position of a body (i.e., estimating velocity of body), but are not as accurate at detecting changes in the velocity of the body (i.e., estimating acceleration of body) [68]. The vestibular organs are a complex of biological sensors in the inner ear that help estimate the accelerations, angular velocities, and orientation of the head with respect to the world [69]. The vestibular organs play a critical role in maintaining balance and determining the direction of gravity (or the down direction) on earth. The vestibular organs comprise otolith organs and semicircular canals. The otolith organs are capable of detecting linear accelerations in three directions [69]. The semicircular canals are capable of detecting angular accelerations about three directions [69]. Proprioception is the sensation / detection of the motion of the body by detecting changes in the muscles, tendons, and skin [70]. It is proprioception that

allows a person to detect joint motion and limb position to estimate their posture in the world without the aid of their eyes [71]. Therefore, through a combination of these three sensory mechanisms a person is able to detect and estimate their body's motion.

While multiple organs can detect motion, it is important to determine if a specific organ has a considerable influence on a person's motion sickness response. Prior studies have shown that blind individuals (i.e., whose visual sensory system is compromised) are still susceptible to motion sickness [20], [72]. This means that the cause of motion sickness cannot rely only on the visual sensory system alone. A group of individuals identified in literature that are not susceptible to motion sickness are those with a total loss of vestibular sensory function [73], [74]. This highlights the importance of the vestibular sensory system in being necessarily responsible for motion sickness. Some prior work has also shown that the proprioceptive inputs may influence the motion sickness response [75]. However, these studies of proprioceptive inputs are limited in number, have been conducted in conditions not representative of real-world conditions, and do not inherently negate the contribution of other sensory organs such as eyes and vestibular organs. Across most literature, there is broad agreement that the causes of motion sickness primarily include the influence of visual cues (visually sensed motion, ocular reflexes) [46,54–56] and vestibular cues (sensed head angular velocity and linear acceleration) [25,27,49,57]. Therefore, while all motion sensory organs may influence the motion sickness response of a person in some way, the exact contribution of each sensory organ to motion sickness remains unknown.

The most prominent theories to explain how and why a person experiences motion sickness are summarized in Fig 2-1. The first column of the figure (orange boxes) refers to the motion and environmental stimuli sensed by the biological sensors listed in the second column of figure (yellow boxes). In particular, once provocative motion stimuli are sensed by the biological sensors,

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the sensed motion is processed. Various motion sickness theories have been proposed (green boxes) to relate this processing of the sensed motion to the motion sickness response of an individual (blue boxes). As stated earlier, motion sickness response is complex and is associated with multiple varied symptoms.

Inputs	Sensory Systems	MS Mechanism	Outputs
Visual Linear and Angular Velocity	Visual	Velocity Storage	Nausea
Gravito-Inertial Acceleration	Vestibular (Canal and Otolith)	Eye Movement	Dizzyness
Angular Velocity		Sensory Conflict	Headache
Touch, Muscle Position, Pressure	Proprioceptive	Postural Instability	Cold Sweats
		...	...
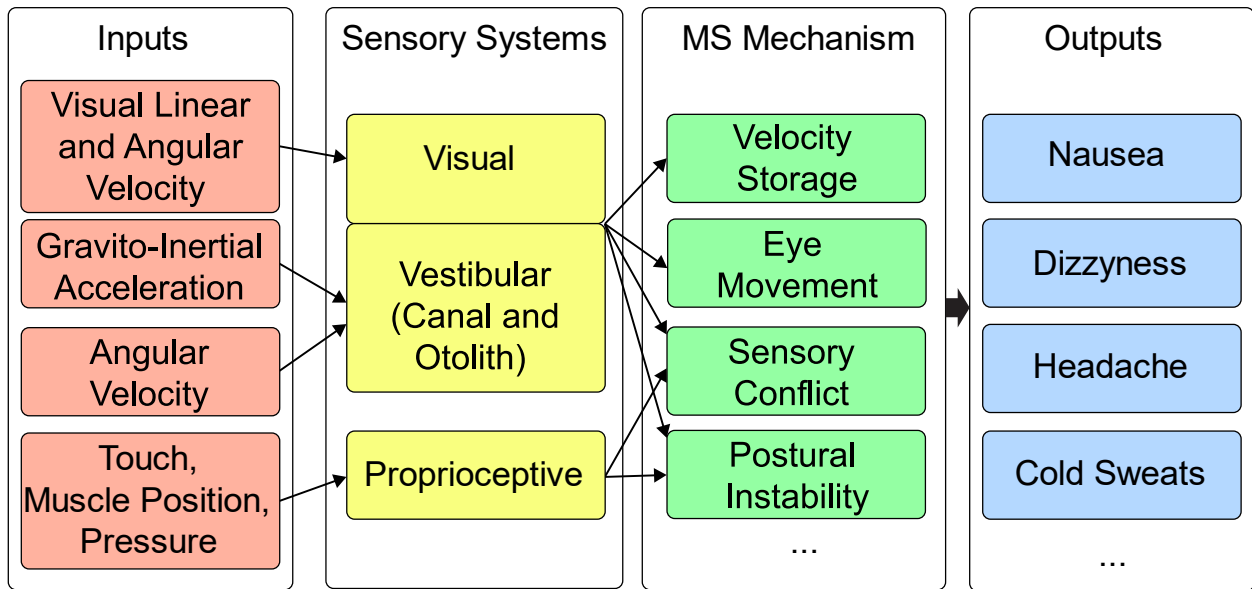
Fig 2-1 Summary of Motion Sickness Causal Mechanism

To explain the cause of motion sickness, the sensory conflict theory was first proposed as early as 1931 and studied extensively over the years [58]. In the sensory conflict theory, the cause of motion sickness is attributed to inter-sensory conflict [55], [76]. The inter-sensory conflict pertains to the conflict in motion cues perceived by the visual sensory system, and the vestibular sensory system. An example of this conflict is attempting to read a book in a moving vehicle. The sense of motion conveyed by the vestibular sensory system (i.e., the motion of the vehicle) and the static sense of motion (i.e., absence of motion) conveyed by the visual system are in conflict with one another [76]. Another inter-sensory cue conflict can exist within the vestibular sensory system itself, between the otolith (linear accelerations) and semicircular canal (rotational velocity), due to coupled dynamics such as that caused by Coriolis acceleration [77]. For example, if the passenger

rotates their head, the pure rotation contributes to linear acceleration at their vestibular organs. It was later suggested that the sensory conflict is further exacerbated by the internal model (or observer) of the passenger's body that exists within the central nervous system – the sensory conflict confuses the internal central nervous system model and exacerbates motion sickness [29], [77], [78]. The subjective vertical conflict theory (SVC) builds on the notion of this internal observer based model and highlights a single conflict as the primary mode of motion sickness – the conflict in the predicted vertical (by internal observer model) and perceived vertical (by motion sensory organs only) [78], [79]. Another version of this theory extends this conflict to the horizontal, called the subjective vertical-horizontal conflict theory [79]. In summary, the sensory conflict theory for motion sickness (and its many variations) is considered the most promising theory and allows for modelling motion sickness as a function of sensed and predicted motion. It is worth noting that the large majority of the experimental data used to evaluate the sensory conflict theory was collected using motion simulators. These motion simulators do not reproduce the motion of moving vehicle completely. Therefore, additional evaluation with more accurate and realistic experimental evidence is required to evaluate the sensory conflict theory. It is also worth noting that the sensory conflict theory does not preclude the inclusion of proprioceptive motion sensation as part of its causal mechanism. However, most motion sickness models based on the sensory conflict theory have not included proprioceptive sensed motion as an input [77]. This is due to the lack of deep understanding of the proprioceptive motion sensation which limits the ability to model it.

Another theory, the postural instability theory, is based on the notion that sensory cues are not devoid of the interaction between the passenger and the environment [35], [51]. This theory states that the passenger's perception of the environment is based on visual, vestibular, and

proprioceptive cues. The hypothesis of this theory is that the passenger's perception of the environment and their inability to maintain postural control under the influence of provocative motion is what leads to motion sickness. Postural instability occurs when the central nervous system is not able to properly integrate sensory signals from visual, vestibular, and proprioceptive systems, leading to a loss maintain muscle balance. While the postural instability theory has been discussed extensively in the literature, the sensory conflict theory has shown more congruence with experimental results [80]. However, more investigations are required to determine if either postural instability theory or sensory conflict theory can effectively explain the causes of motion sickness. For example, a majority of the experimental evidence in support of sensory conflict theory has been collected using motion simulators, and not under realistic driving conditions. However, despite their limitations, the current understanding of the causes of motion sickness can still be used to gain insights into the motion sickness response of vehicle passengers.

Based on individual theories, simulation models have been proposed to predict and estimate motion sickness [29], [78], [79], [81], [82], [83], [84], [85], [86], [87], [88]. It has been purported in the literature that these models can be used to predict, understand, and improve the experiences of vehicle passengers, virtual reality users, and aerospace design, among others [81], [89]. The most prominent motion sickness models presented in the literature are summarized in Table 2-1. Vestibular models of motion sickness only account for the role of the vestibular system whereas visual-vestibular models of motions sickness account for the role of both visual and vestibular sensory systems. Other physiological mechanisms (i.e., postural sway and movement of the center of gravity of the person [90], [91]) can also be used to model motion sickness. Further, data-driven models can also be used to determine the correlation between motion dynamics and motion sickness (i.e., neural networks [92]).

Among the models presented in the literature, a promising vestibular motion sickness model is the subjective vertical mismatch model proposed by Bos et al. [78] and later adapted by Kamiji et al. [85]. The quantitative model takes the vestibular sensory system signals (actual motion) as the model inputs and outputs a motion sickness estimate in the MSI scale. The model has been verified against experimental data and has shown close approximation of experimentally observed data, except at low frequencies (below 0.16 Hz) [85]. Vestibular only models, by definition, do not account for the visual role in motion sickness. For instance, these models are unable to account for a passenger performing a task that taxes their visual sensory system such as reading a book or working on a computer. It is shown in literature that the visual contribution to motion sickness is pronounced in the low frequency range [93]. This highlights the potential of visual- vestibular motion sickness models. Visual-vestibular models are built based on the sensory conflict theory and more closely approximates the sensory systems of the passengers in vehicles, allowing for estimation of motion sickness for passenger performing activities within the vehicle.

AUTHORS & YEAR	TYPE OF MODEL	INPUTS (I) / OUTPUTS (O)	ASSUMPTIONS/ LIMITATIONS	DEGREES OF FREEDOM (DOF)	VISUALLY SENSED MOTION
McCauley et al. (*Mathematical HFR Model)* [82]	Vestibular	I: Sensed specific force of vertical motion O: MSI	Limited to specific force only, and vestibular influence	1 DoF	None
Oman et al. (*Sensory Conflict Theory)* [29], [83]	Visual-Vestibular	I: Sensed motion by visual and vestibular sensors O: Subjective Discomfort	Heuristic model for sensory dynamics, only outputs subjective discomfort. First model to propose internal observer	Not Defined	Not Defined
Bos et al. (*Subjective Vertical Conflict Theory)* [78]	Vestibular	I: Sensed specific force of vertical motion O: MSI	Only vestibular model, no influence of visual sensory system considered	1 DoF	None
Atsumi et al. [84]	Others (Vehicle Motion)	I: Vertical specific force, roll and pitch of vehicle O: Motion sickness level	Output is not in a standard motion sickness scale, correlation model with no physiological	3 DoF	None

			modeling		
Kamiji et al. [85]	Vestibular	I: Sensed motion by vestibular sensors (specific force and angular velocity) O: MSI	Only vestibular model, no influence of visual sensory system considered	6 DoF	None
Khalid et al. *(Subjective Vertical Horizontal Conflict Theory)* [79]	Vestibular	I: Sensed motion by vestibular sensors (specific force and angular velocity) O: Weighted MSI, combination of horizontal and vertical MSI	Only vestibular model, no influence of visual sensory system considered, designed for contemporary ships	6 DoF	None
Braccesi et al. *(UNIPG SeMo)* [86]	Visual-Vestibular	I: Sensed motion by vestibular sensors (specific force), visually perceived linear acceleration O: MSI	Only acceleration, no influence of angular velocity modelled. Uses all acceleration conflicts to predict motion sickness	3 DoF	Linear acceleration of visual flow
Salter et al. [81]	Others (Vehicle motion, Passenger gaze & motion)	I: Field of view, motion of passenger head O: MISC	Data correlation that uses vehicle motion, passenger gaze, and passenger motion. Motion passenger head predicted using multibody dynamics.	3 DoF are used for specific force. Visual DoF is undefined per this paper's definition	Weightage of elements in visual content
Wada et al. [88]	Visual-Vestibular	I: Sensed motion by vestibular sensors (specific force and angular velocity), visually perceived angular velocity O: MSI	Uses camera images to predict visually perceived motion, builds on Bos et al.	6 DoF	Angular velocity of visual flow
Wada et al. [87]	Vestibular	I: Sensed motion by vestibular sensors (specific force) O: MSI	Only vestibular model, no influence of visual sensory system considered	3DoF	None

Table 2-1 Summary of Motion Sickness Estimation Models

A promising visual-vestibular model is the UNIPG SeMo model, which leverages a model for

motion perception using visual sensory system inputs [86]. However, the vestibular component of

the UNIPG SeMo model is not as robust and comprehensive as the Kamiji SVC model as the

former only accounts for linear acceleration inputs, while the latter accounts for both linear acceleration and angular velocity inputs. Other motion sickness models are designed for specific applications such as for virtual reality applications and are not suitable for investigating motion sickness in autonomous vehicles [81], [89]. Based on the models in literature, there is a need for a theoretical model of motion sickness that combines both visual and vestibular sensory systems, allows for simulation of passengers performing tasks inside an autonomous vehicle, and leverages the best understanding of MS causes and mechanisms to provide more generalizability in predictions. In addition, motion sickness models may also need to include the proprioceptive system, if further research demonstrates that the proprioceptive system plays a significant role in the onset of motion sickness.

The models presented in the literature typically output estimates of motion sickness in one of the many scales used to quantify motion sickness. Since there are no 'motion sickness sensors' that can provide objective measurements of motion sickness, subjective scales must be used. Other objective sensor-based measurements of a person's physiological response while motion sick have also been investigated to draw correlations between objective physiological measurements and motion sickness response [94], [95], [96], [97]. These physiological measurements include heart rate, perspiration, breathing rate, brain activity, etc. However, this work is limited, and additional research is required to draw robust numerical relationships between the physiological response and experienced subjective motion sickness.

Since there are no motion sickness sensors, numerical scales based on motion sickness symptoms and/or subjective self-evaluation of motion sickness were developed. These motion sickness scales correlate self-evaluated motion sickness to a numerical value on the scale. The outputs of most motion sickness models typically rely on such numerical scales. The most common

quantitative measures of motion sickness used in models include scales such as motion sickness incidence (MSI), motion sickness susceptibility (MSSQ), misery scale (MISC), and motion sickness dose value (MSDV). Most models typically use MSI (Table 2-1) since there is ample experimental data available that uses the same scale [23], [98], [99].

Motion Sickness Incidence Index (MSI) scale has been defined as the percentage of persons that vomit under a vertical sinusoidal motion with certain magnitude and frequency [100]. The applicability of this scale to studying MS in AVs is potentially limited as passengers are expected to show a wide range of symptoms prior to vomiting. Another frequently used scale for MS is the MSQ scale, which is based on a questionnaire that assesses symptoms such as headache, fatigue, nausea, stomach awareness, blurred vision, cold sweating, and vertigo [101]. Another commonly used scale is the MSSQ scale, which uses a questionnaire that can account for the subject's/participant's susceptibility to MS [102]. Both the MSQ and MSSQ scales are limited by the symptoms they encompass as well as the accuracy of self-reported symptoms due to subjective variability. Other scales such as FMS and MISC [22] are prone to similar limitations.

Jones et al. [103] suggested a new rating scale called the University of Michigan Transportation Research Institute (UMTRI) Motion Sickness Scale, an improvement on the FMS scale, that captures the spectrum of MS symptoms and physiological indicators during realistic driving conditions, making it pertinent to studies that involve MS prediction applied to AVs. In this scale, participants were asked to rate their MS from '0' (no MS at all) to '10' (need to stop the vehicle). They were also instructed to describe in their own words and rate any MS sensations they experience throughout the testing protocol. The descriptions provided were processed and standardized to the MS score. This allows for the person to express their MS beyond a predetermined list of symptoms while considering their own subjective rating and perception of

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symptoms. This allows for the assessment of a wide array of symptoms and intensities, which can be advantageous under realistic driving conditions, where multiple symptoms might be present.

Experimental investigations of motion sickness utilize one or more of the previously described numerical motion sickness scales. Since these scales have been defined based on self-evaluated motion sickness of an individual, it is nearly impossible to compare the motion sickness results from one study to another since it is impossible to account for the subjective motion sickness response when converting motion sickness measurements from one scale to another [104], [105]. Therefore, a key limitation of using subjective numerical motion sickness scales is the inability to perform a fair comparison across motion sickness studies.

2.2 Motion Sickness Mitigation

The review of literature primarily focused on solutions to motion sickness in cars (also known as carsickness). Currently, the most common solution to motion sickness is the use of pharmacological drugs, which have been used for over half a century [106]. These drugs can be divided into the following categories: antimuscarinics (e.g., scopolamine), sympathomimetics (e.g., amphetamine), and antihistamines (e.g., dimenhydrinate) [107]. Antihistamines (more specifically H-1 Antihistamines such as dimenhydrinate and cinnarizine) are the most type of drug used to treat motion sickness [106]. They help reduce motion sickness symptoms as they are an anti-emetic compound (i.e., prevent nausea and vomiting) [108]. Antimuscarinics such as Scopolamine also help reduce motion sickness symptoms by inhibiting gastric emptying impulse (i.e., vomiting) [109]. Numerous studies have shown that these drugs are effective in reducing the symptoms of motion sickness [38], [110], [111]. However, numerous studies have also identified various side effects associated with the use of these drugs such as drowsiness, dry mouth, vertigo, insomnia, and tremors [40], [41]. The evidence suggests that the use of motion sickness mitigation drugs has a direct and negative influence on the persons cognitive ability [41]. In addition, some research has also indicated the potential for abuse and addiction associated with some of these drugs [42], [43]. Therefore, current pharmacological solutions may reduce a passenger's motion sickness symptoms but negatively influence their well-being and ability to perform tasks. Alternative remedies such as the use of ginger root have been proposed to avoid the side effects associated with most motion sickness prevent drugs. While ginger root has no side effects associated with its use, there is conflicting evidence to support that ginger root is more effective than a placebo at reducing the symptoms of motion sickness [45], [46]. Other alternatives such as acupressure (typically in the form of acupressure bands worn by the passenger on their hands) have

also been proposed to reduce motion sickness. Multiple studies have found that acupressure has no effect on reducing motion sickness [47], [112]. Therefore, there remains a need for a viable motion sickness mitigation solution that is both effective and does not have significant side effects that negatively impact the passenger's ability to perform tasks and overall quality of life.

The armed forces (and space programs) have relied on habituation and exposure therapy to prevent motion sickness in soldiers with proven effectiveness [98], [113], [114], [115], [116]. However, there are significant logistical and practical challenges in using habituation and exposure therapy for a civilian population. Typical habituation sessions can last up to 2 hours, requiring exposure to extreme motion (i.e., much larger than expected during realistic conditions), and repeated exposure is required (e.g., once a month or higher frequency) to maintain efficacy for up to 4 months after last exposure [113], [117], [118]. If there are extended periods of no exposure, the person's motion sickness tolerance can decrease. It is assumed that habituation programs for reducing carsickness may require similar or reduced sessions (e.g., 1-hour sessions, once every 2 months). However, further study would be required to develop a habituation program specifically for carsickness. Even with reduced sessions, habituation poses practical challenges in widespread implementation and adoption as a meaningful solution to carsickness. Thus, habituation and other behavioral remedies to carsickness are not a viable and scalable solution to carsickness in AVs. In summary, currently there are no practical, widely adopted carsickness mitigation solutions that are both proven to be effective and that do not have adverse side effects. This unsolved problem has motivated the research and development of various carsickness mitigation and prevention methods in academia and industry.

Based on the current understanding of the causes of carsickness, and methods to mitigate it, Fig 2-2 is a summary of all carsickness mitigation methods that have been attempted so far. This figure

highlights the various parts of the vehicle and passenger system that are used to mitigate carsickness. Potential avenues for interventions to mitigate carsickness include transportation infrastructure (i.e., roads, traffic lights), vehicle hardware and software (i.e., suspension, drivetrain, navigation), and passenger (i.e., drugs, stimuli, active seats). Carsickness mitigation methods such as behavior training (also known as exposure therapy) are also included in the figure for completeness. Similarly making widespread changes to transportation infrastructure to limit carsickness is not a practical approach. Known solutions such as designing roads with less sharp turns or reducing the frequency of stops by increasing the distance between traffic lights are impractical to implement. Further, any non-pharmacological carsickness mitigation method can be classified as active or passive.

Active carsickness mitigation methods (or solutions) have controllable actuation (i.e., actuators that can be controlled and whose behavior can be altered in response to user input or sensor readings or other command strategy). Active solutions can be further classified as those that operate at the vehicle level or at the individual passenger level. There are no known active solutions at the road and infrastructure level. Vehicle level solutions include vehicle hardware such as active suspensions, active chassis, and vehicle software such as AV navigation and control of driving style. Passenger level solutions include solutions that either provide information or alter the posture of the passenger. These include solutions like Active passenger stimuli (e.g., audio stimulus to indicate vehicle is turning), Active restraints (e.g., active tensioning of a seat belt), and active seat (e.g., seat that tilts to lean passenger into the turn). Currently, to the best of the authors' knowledge, no solutions reported in literature leverage the active chassis approach to reduce motion sickness.
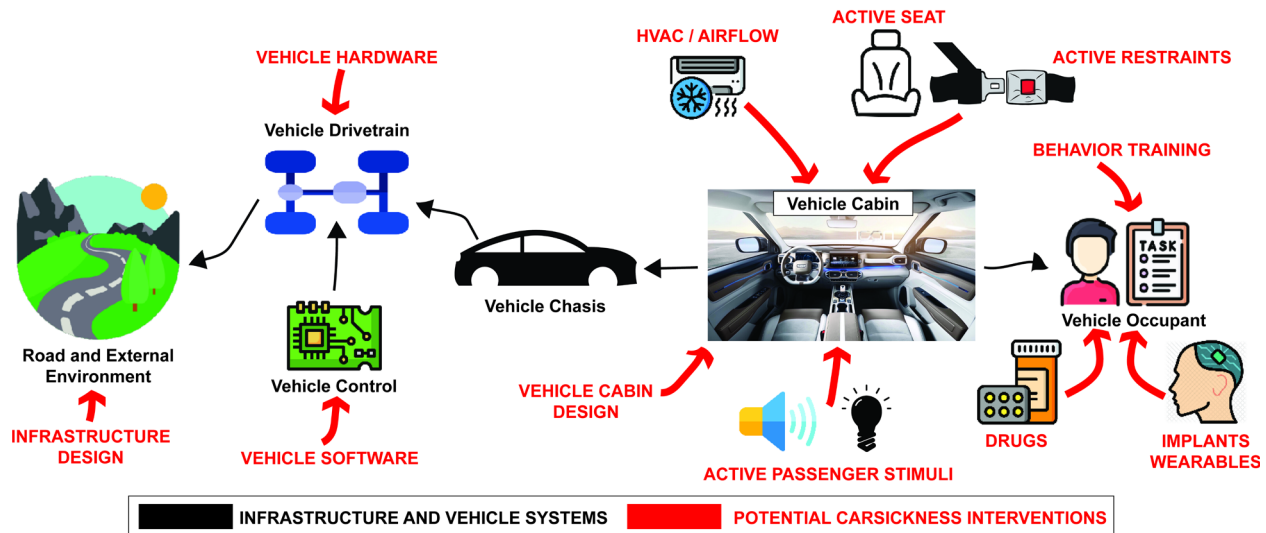
Fig 2-2 Summary of Carsickness Mitigation Strategies

Passive methods to mitigate carsickness (i.e., methods that do not have controllable actuation) have been investigated through research. The most common passive methods are the use of vehicle suspension and use of suspension seats inside the vehicle [80], [81]. Both the vehicle suspension and suspension seats have been shown to have an insignificant influence on carsickness mitigation [3]. While these methods help provide some degree of comfort, a person still experiences significant carsickness. Furthermore, since they operate passively (no controllable actuation), they can only "react" to vehicle motion and cannot operate preemptively in anticipation of vehicle motion. This inherently limits their ability to mitigate carsickness. Other passive methods such as wearable acupressure bands have also been shown to have little to no effect on carsickness, with most positive results being associated with placebo effect [49], [82]. Therefore, passive carsickness mitigation solutions have shown limited efficacy in reducing carsickness.

Prior research has shown that drivers do not experience carsickness. This has been attributed to their being in control of the vehicle, anticipation of upcoming vehicle motion, and their conscious and unconscious preemptive actions resulting from this anticipation [48], [49]. Only active mitigation solutions can be triggered preemptively (i.e., in response to anticipation and can be

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customized to suit the needs of a specific individual in real time). Therefore, this research is primarily focused on active methods to mitigate carsickness since passive methods have shown limited to no efficacy in mitigation carsickness.

The following sections summarize the relevant literature pertaining to the specific active carsickness mitigation methods. Multiple parameters will be used to analyze and compare the various mitigation methods. Some parameters will be specific to the mitigation method, while other parameters are common across all methods. These common parameters include (a) Timing of intervention, (b) Non-driving related task (NDRT) performance, (c) Type of vehicle motion, and (d) Carsickness mitigation outcomes.

Timing of intervention refers to when the intervention is deployed to mitigate carsickness; preemptively in anticipation of vehicle motion, or reactively in response to vehicle motion, or ambient response which occurs throughout the journey independent of specific vehicle motion. NDRT refers to the type of task being performed by the passenger and can include reading or watching videos or games or some combination of the above.

Type of vehicle motion refers to the nature of motion used to induce carsickness, either with motion simulators (static or moving), or real passenger vehicles. Static simulators are vehicle simulators that do not physically move the person as if they are in a vehicle. These simulators can only recreate the visual and/or audio experience of a passenger in a car using videos or displays. They cannot simulate the inertial effects on a passenger in a moving car. Motion simulators are vehicle simulators that move the person as they would if they were in a moving vehicle. These simulators attempt to recreate the accelerations and velocities experienced by a person in a moving car. Motion simulators may also include videos or displays to recreate the visual experience of a passenger in a car in addition to the inertial experience. Passenger cars are vehicles that can be

driven on roads or test tracks with onboard passengers to study their carsickness response. These vehicles are typically modified to include additional sensors to monitor the onboard passenger and their carsickness.

Lastly, Carsickness Mitigation Outcomes refers to the demonstrated reduction or increase or no effect on the carsickness of a person in a car. Typically, there are two methods to assess carsickness mitigation outcomes. The first method consists of recording the subject's/participant's self-reported CS response throughout the study using a subjective scale (e.g., FMS, MSCI, MSI). The second method consists of using some experimental data of the subject/participant (e.g., subject/participant motion as measured by an inertial measurement unit or subject heartrate as measured by a physiological sensor) to estimate CS or comfort. In the second method, there is no self-reported carsickness, only model-based estimations with experimental data as model inputs.

2.2.1 Active Passenger Stimuli Systems (APS)

Active passenger stimuli system is a device or group of devices that provides informative sensory stimuli (i.e., visuals, audio, tactile, olfactory) with encoded information about vehicle motion. In this review, the results from 36 publicly available studies are included and compared (Table 2-2). In addition to the above listed four common parameters, the APS studies are also organized using an additional parameter which is Type of Stimuli. Type of stimuli refers to the sensory stimulus used to encode vehicle motion information. Stimuli can include audio (i.e., verbal commands, beeps), visual (i.e., screens, lights), tactile (i.e., haptics, air puffs), and olfactory stimuli (i.e., scents).

AUTHOR & YEAR	TYPE OF STIMULI	TIMING OF INTERVENTION	NDRT PERFORMANCE	TYPE OF VEHICLE MOTION	CARSICKNESS MITIGATION OUTCOME
Sang et al., 2003 [116]	Audio – Music	Ambient	None	Motion Simulator	Reduced CS – custom scale
Jeng-Weei Lin et	Visual –	Preemptive –	None	Static	Reduced CS –

al., 2005 [119]	Display	couple seconds prior to motion		Simulator	RSSQ scale
Reschke et al., 2006 [120]	Visual – Stroboscopic Light	Ambient	Reading	Static Simulator	Reduced CS - Miller & Graybiel scale
Kato et al., 2006 [121]	Visual – Display	Ambient	Reading	Passenger car	Reduced CS – Golding (1992) scale
Dahlman et al., 2008 [122]	Audio – Pink Noise	Ambient	None	Motion Simulator	No reduction in CS – Mal score
Morimoto et al., 2008 [123]	Visual – Display	Reactive	Watching Video	Passenger car	Reduced CS – 0 to 10 MS scale
Wada et al., 2012 & 2016 [52], [124]	Audio – Speech	Preemptive – couple seconds prior to motion	None	Passenger car	Reduced CS – Golding (1992) scale
Keshavarz et al., 2014 [125]	Audio – Music	Ambient	None	Static Simulator	Reduced CS – SSAQ scale
Keshavarz et al., 2015 [126]	Olfactory – Floral odors	Ambient	Watching Video	Static Simulator	Reduced CS – FMS and SSQ scales
Bos, 2015 [127]	Haptic – Head Vibrations	Ambient	Audio tasks, letter memorization - assessment showed no effect	Motion Simulator	Reduced CS – MISC scale
Galvez-Garcia et al., 2015 [128]	Galvanic Cutaneous Stimulation (GCS)	Preemptive – 40m before curve in path	None	Static Simulator	Reduced CS – SSQ scale
Miksch et al., 2016 [129]	Visual – Display	Ambient	Reading	Passenger car	Reduced CS – SSQ scale
Galvez-Garcia et al., 2017 [130]	Tactile Stimulation	Preemptive – 40m before curve in path	None	Static Simulator	Reduced CS – SSQ scale
Bin Karjanto et al., 2017 & 2018 [131], [132]	Visual – LED strips	Preemptive – 3 seconds prior to motion	Watching Video	Minivan	Reduced CS – MSAQ scale
Sawabe et al., 2017 [133]	Visual – Virtual Reality Headset	Preemptive – 5 seconds prior to motion	None	Static Simulator	Reduced CS – balance measurements
Hanau et al., 2017 [134]	Visual - Display	Reactive	Reading - assessment showed no effect	Passenger bus	Reduced CS – MSAQ scale
Hock et al., 2017 [135]	Visual – Virtual Reality Headset	Reactive	Video game	Passenger car	No reduction in CS – SSQ scale
McGill et al., 2017 [136]	Visual – Virtual Reality Headset	Reactive	None	Passenger car	Unclear – MSSQ scale
Van Veen et al., 2017 [137]	Visual – Lights on glasses	Reactive	Reading	Passenger car	No measurement of CS – Situational Awareness
D'Amour et al., 2017 [138]	Haptic – Seat vibrations and gusts of air	Ambient	Watching Video	Static Simulator	Reduced CS – FMS scale

Bloch et al., 2018 [139]	Visual – Virtual Reality Headset	Preemptive – couple seconds	Video game	Motion Simulator	Reduced CS – FMS and SSQ scale
Ihemedu-Steinke et al., 2018 [140]	Visual – Virtual Reality Headset	Ambient	Reading	Static Simulator	Reduced CS – SSQ scale
Salter et al., 2019 [141]	Haptic – Bone conducted vibrations	Ambient	Search and Identify - assessment showed no effect	Passenger car	Reduced CS – MISC scale
Meschtscherjakov et al., 2019 [142]	Visual – Display	Reactive	Reading	Passenger car	Reduced CS – MSAQ scale
Mu et al., 2020 [143]	Visual – Display	Ambient	Reading	Passenger car	Reduced CS – MISC scale
Cho et al., 2020 [144]	Visual – Virtual Reality Headset	Reactive	None	Passenger car	Reduced CS – MSQ scale
Md Yusof et al., 2020 [145]	Haptic – Wristband	Preemptive – 3 seconds prior to motion	Watching Video	Passenger car	No reduction in CS – MSAQ scale
Kuiper et al., 2020 [146]	Audio – Speech	Preemptive – 3 seconds prior to motion	None	Motion Simulator	Reduced CS – MISC scale
Galvez-Garcia et al., 2020	Audio – White noise combined with GCS	Preemptive – 40m before curve in path	None	Static Simulator	Reduced CS – SSQ scale
Winkel et al., 2021 [147]	Visual – Virtual Reality Headset	Preemptive – 0.5 seconds prior to motion	Video game	Motion Simulator	No reduction in CS – FMS and MSSQ
Hainich et al., 2021 [148]	Visual – Light strips/band	Preemptive – 2 seconds prior to motion	None	Passenger car	Reduced CS – SSQ scale
Maculewicz et al., 2021 [149]	Audio – simulated engine sounds	Preemptive – 1.5 seconds prior to motion	Reading - assessment showed no effect	Passenger car	Reduced CS – MISC and MSAQ scales
Brietzke et al., 2021 [150]	Visual – Virtual Reality	Reactive	Watching Video	Passenger car	No reduction in CS – custom scale
Guo et al., 2021 [151]	Audio – Speech	Preemptive – 1 seconds prior to motion	None	Motion Simulator	Reduced CS – SSQ and custom scales
Bohrmann et al., 2022 [152]	Visual – LED strips	Reactive	Video game and Reading	Passenger car	Reduced CS – FMS and MSAQ scales
Li et al., 2022 [153]	Haptic – Seat cushion	Preemptive – 1.2 seconds prior to motion	None	Static Simulator	Reduced CS – MISC scale

Table 2-2 Summary of Sensory Stimuli Systems for Motion Sickness Mitigation

Most studies showed that the use of APS led to a reduction in carsickness. Only 6 out of all

stimuli (17%) studies showed either no reduction in carsickness or a mild increase in carsickness.

This aberration in performance (i.e., the six studies showing no reduction or increase in motion sickness) can be attributed to the specific implementation of the APS and/or other experimental protocol deficiencies. The majority of the APS studies involved a reactively triggered stimuli or a sensory stimuli system that is always operational (21 out of 36 studies). Of these 21 studies, 4 studies showed no reduction in carsickness. This means that a majority of reactively triggered sensory stimuli systems have demonstrated the ability to reduce carsickness. Only 15 out of 36 studies (42%) have provided stimuli preemptively, with preemption being as low as 0 seconds in some cases to as high as 5 seconds. This means that the stimuli were provided up to 5 seconds prior to the start of the motion event (i.e., turn or brake). The majority of the preemptively triggered sensory stimuli system studies showed a reduction in carsickness, with only 2 studies showing no reduction in carsickness. No single study compared the performance of reactive and preemptive sensory stimuli systems in reducing carsickness. Based on the number of studies demonstrating a reduction in carsickness, a larger portion of the studies with preemptively triggered sensory stimuli system demonstrated a reduction in carsickness, as compared to studies with reactively triggered sensory stimuli system.

Only 12 out of 36 studies did not involve any NDRT within their investigation (7 studies with preemptive interventions and 5 studies with reactive or ambient interventions). 10 studies involved a reading type NDRT, and 6 studies involved a video watching NDRT. Tasks were performed either on a vehicle mounted screen or handheld tablet. Other studies relied on virtual reality games or projected a view of the road for the passenger. The majority of the stimuli studies provided no analysis of NDRT performance, with only 4 studies providing some analysis of task performance. Of these 4 studies, 2 studies involved a reading task [134], [149], 1 study involved an audio memorization task [127], and 1 study involved a search and identify task [141]. None of these

studies provided justification for their choice of NDRT or how it might be relevant to NDRTs performed by passengers. Also, none of these studies found any negative or positive effect on NDRT performance due to the sensory stimuli system. Therefore, there is insufficient evidence to determine whether the APS systems have any influence on NDRT performance. If APS systems are to effectively reduce carsickness, then they must ideally not negatively affect NDRT performance. More investigations are required to categorize the effects (if any) of APS systems on NDRT performance.

Visual stimuli systems are the most common APS, with 20 studies using some form of visual stimuli such as LED strips, virtual reality headsets, and displays. A variety of reasons are provided to support visual stimuli as the most promising APS. Some studies state that since the eyes sense motion and play a significant role in causing carsickness, by providing corrective visual cues regarding the true motion of the vehicle carsickness can be reduced [134], [136]. Other studies state that visual signals are easily interpreted and will cause least inconvenience to the passenger. To ensure that visual stimuli can be provided even while the passenger is engaged in NDRT, peripheral visual cues or use of VR headsets are proposed [132], [144], [154]. Audio and Haptic stimuli have also been studied, with 6 studies on haptic stimuli and 8 studies on audio stimuli. Both audio and haptic have shown some efficacy in reducing carsickness. Based on this information, it is not possible to determine if one type of stimuli is better than the others. More investigations are required to explicitly compare the efficacy of the several types of stimuli in reducing carsickness.

Lastly, other types of APS systems such as galvanic vestibular stimulation (GVS), galvanic cutaneous stimulation (GCS), olfactory/odor stimuli, and bone conducting vibrations have also been investigated. While these alternative APS systems have shown a reduction in carsickness, they face challenges in their practical applications. GVS and GCS are relatively new and there are

safety concerns with using these methods with pregnant persons or persons with cardiac or other serious medical conditions [155].

Since most studies do not follow a uniform set of experimental conditions, nor recruit similar participants, it is impossible to compare the performance of the various APS systems across the different studies. It is noted that 15 out of the 20 (75%) visual stimuli studies, 5 out of the 6 (83%) haptic stimuli studies, and 7 out of the 8 (88%) audio stimuli studies have shown statistically significant reduction in carsickness (Table 2-2). This presents unmistakable evidence in the favor of APS systems being able to reduce carsickness, however, the most optimum APS or combination of APS remains unknown. Further investigations are required to refine the efficacy of APS in reducing carsickness. It is not clear from the existing evidence if one type of stimuli is better than the others. As mentioned earlier, certain types of stimuli might inherently limit the passenger's ability to perform a task (e.g., visual stimuli will interfere with visual task performance).

It is clear from the current literature that preemptively triggered APS systems can provide anticipation of upcoming vehicle motion and help reduce carsickness. Even in a study involving preemptively triggered sensory stimuli system where no statistically significant reduction in carsickness was observed, a statistically significant improvement in situational awareness was noted [145]. In a car, situational awareness has been defined as having an awareness of the cars current position and behavior of other road users, potential hazards, cars environment, and knowing how these critical variables will change with time [145]. This improved situational awareness due to preemptively triggered stimuli can help passengers stay connected with the intentions of the AV and help build trust [156], [157], [158]. Further study is required to understand if APS triggered preemptively is effective at reducing carsickness as compared to APS triggered reactively. Also, any influence of APS systems on NDR task performance remains unknown.

Unsurprisingly, owing to their simplicity and effectiveness, many diverse types of APS are mentioned in numerous patents. Various embodiments of APS are described within patents (Table 2-6), but the most common types are visual and audio stimuli-based systems. Other types of stimuli in patents include scents (olfactory stimuli) and directed air flows from air conditioning. The APS embodiments in patents include stimuli that are either triggered reactively or preemptively. While no studies have investigated the efficacy of multiple APS systems in combination, such combinations have been claimed in patents (Table 2-6). Typically, these APS concepts in patents are mounted within the vehicle cabin and may leverage lighting in the cabin or heads-up displays on windshields. Overall, APS systems represent one of the most promising and most studied methods to mitigate carsickness.

2.2.2 Active Seat Systems (AST)

Active seat system is a device that adjusts the posture of the passenger by providing relative motion of the seat and/or seated passenger with respect to the vehicle. This seat motion can include both translations and rotations. Prior literature have focused on vertical suspension seats (i.e., 1 DoF, passive and active suspension seats) for vehicles and have concluded that they have no effect on the motion sickness response of passengers [159], [160]. Therefore, suspension seats for vehicles have been excluded from this research.

In this research, the results from 8 publicly available studies are included and compared (Table 2-3). In addition to the above listed four common parameters, the AST studies are also organized using an additional parameter which is Type of AST motion. Type of AST motion refers to the type of relative motion between the AST (and passenger or only passenger) and the vehicle. This relative motion can include three rotations (roll about longitudinal axis, pitch about lateral axis, and yaw about vertical axis) and three translations (surge along longitudinal axis, sway along

lateral axis, and heave along vertical axis) (Fig 2-3).

AUTHOR & YEAR	TYPE OF SEAT MOTION	TIMING OF INTERVENTION	NDRT PERFORMANCE	TYPE OF VEHICLE MOTION	CARSICKNESS MITIGATION OUTCOME
Golding et al., 2003 [89]	Rotational – Pitch	Reactive	None	Motion Simulator	Reduced CS – MISC and MSSQ scales
Frechin et al., 2004 [161]	Rotational – Pitch, Roll, Yaw Translational – Heave	Reactive	None	Passenger car	Unknown, no data available
Joseph et al., 2007 and 2008 [162], [163]	Rotational – Roll	Preemptive – 0.5 seconds prior to motion	None	Motion Simulator	Reduced CS – custom 7-point scale
Mert et al., 2011 [164]	Rotational – Pitch	Reactive	None	Motion Simulator	Reduced CS – MISC scale
Konno et al., 2011 [165]	Rotational – Roll	Reactive	None	Passenger car	Reduced CS – Simulated CS based on passenger motion
Beard et al., 2014 [166]	Rotational – Roll	Reactive	None	Motion Simulator	Inconsistent CS response – MSSQ and custom 7-point scale
Karjanto et al., 2021 [167]	Rotational – Roll (shoulder only)	Preemptive – 3 seconds prior to motion	Reading – no assessment	Passenger car	Reduced CS – MSAQ scale
Brietzke et al., 2021 [150]	Rotational – Pitch	Reactive	Watching Video – no assessment	Passenger car	No reduction in CS – custom scale

Table 2-3 Summary of Active Seat Systems for Motion Sickness Mitigation

It is worth noting that as compared to APS, there are far fewer investigations of AST systems.

There are only 8 studies that use AST as compared to over 36 studies of APS. This is due to the

complexity, practical challenges, and safety regulations associated with integrating an AST system

inside a vehicle as compared to relatively simple APS systems. 5 of the 8 AST studies have shown

a meaningful reduction in motion sickness due to the influence of the AST system. One study

showed inconclusive impact of AST on motion sickness [166] and another study did not include

any data or results pertaining to motion sickness [161]. Of these 8 studies,

the majority included AST systems triggered reactively. Only 2 of the 8 studies triggered the

motion of the AST (and passenger) preemptively, with preemption ranging from 0.5 seconds to 3 seconds. All studies with preemptive action of the active seat system (i.e., 2 out of the 8 AST studies) showed a reduction in motion sickness. Half of the studies with reactively triggered action of the active seat system (i.e., 3 out of the 6 AST studies with reactively triggered action) demonstrated no reduction or inconclusive motion sickness response. Therefore, based on the number of studies demonstrating a reduction in carsickness, a larger portion of the studies with preemptively triggered AST demonstrated a reduction in carsickness, as compared to studies with reactively triggered AST.

It is important to note that only one study compared the efficacy of AST in reducing motion sickness when triggered preemptively (i.e., in anticipation of the motion event) vs reactively (i.e., after the motion event) [162]. That study concluded that AST systems triggered preemptively are better at mitigating motion sickness as compared to those triggered reactively; the mean illness rating for the preemptive condition was 50% lower than the reactive condition. While further investigations are required to strengthen this result, this is an indication that preemptively triggered AST systems can reduce motion sickness more effectively as compared to reactively triggered AST.

Only 2 studies included the passenger performing an NDRT, one study included a reading task, and another study included a video watching task. NDRT tasks were performed either on a vehicle mounted screen or handheld tablet. No study performed an analysis of NDRT performance (i.e., no assessment of quality or quantity of NDRT performance, nor an assessment of cognitive function of the passenger). Therefore, it remains unknown whether the AST systems have any influence on NDRT performance. An effective AST based carsickness mitigation system must ideally not affect NDRT performance negatively. More investigations are required to categorize

the effects (if any) of AST systems on NDRT performance.
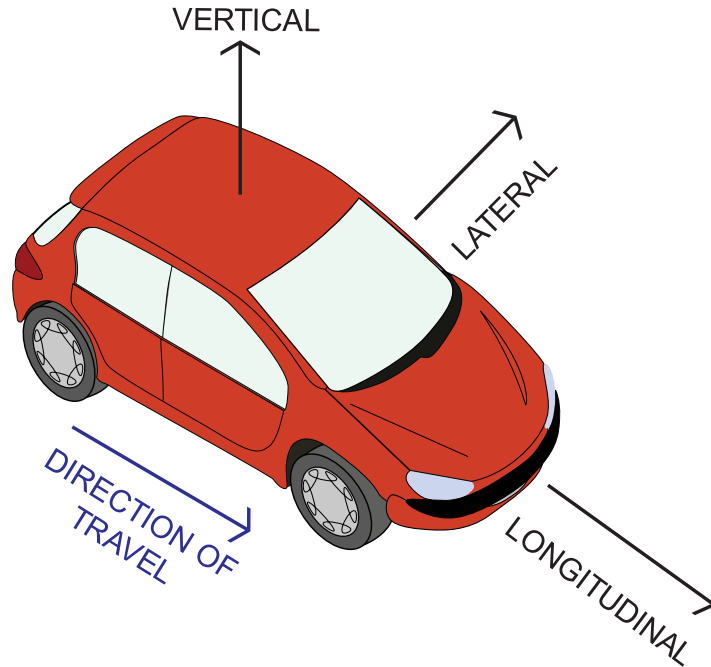
Fig 2-3 Coordinate axes and corresponding motion of a vehicle

Lateral accelerations such as those associated with vehicle turning have a significant influence on motion sickness [16], [168], [169]. Unsurprisingly, 5 of the 8 studies in this review provide roll motion to the seat and/or passenger in response to vehicle turning and producing lateral accelerations. 3 of those 5 studies show statistically significant reduction in carsickness. The remaining 2 studies with roll motion either have no data available or show inconsistent CS response. One study does not "move the seat" to influence passenger posture and instead relies on the activation of pneumatic pads on the seat to produce relative motion of the passenger with respect to the vehicle [167]. In our review, this kind of system was still considered as an AST as it augmented passenger posture within the vehicle. Another unique aspect of that study is that it compares MS mitigation efficacy of an APS system against an AST system and concluded that their AST system outperformed their APS system in MS mitigation (statistically significant result). In contrast, another study that compared visual stimuli and AST found that there was no significant

and substantial reduction in motion sickness [150]. While this is a single data point and by itself does not provide definitive outcome, it highlights the need for more investigations of AST systems and their MS mitigation efficacy.

Only one study emphasized the role of the center of rotation of their AST as integral to the efficacy of MS mitigation [161]. An AST system changes the posture of a passenger to minimize the sensory conflict by aligning the passenger head and torso with the direction of gravito-inertial acceleration. The study claims that to maximize this benefit, the center of rotation (CoR) of the seat must be aligned with the passenger's head (i.e., their vestibular sensor) to minimize the sensed acceleration due to rotation [161]. More thorough investigation is required to determine if the CoR does play a significant role in MS response as that study did not provide any data or results regarding MS response.

Various embodiments of AST are described within patents (Table 2-6). ASTs claimed in patents are often capable of several types of motion, and in some cases are a combination of suspension seats (i.e., vertical motions) and other rotations and/or translation motion in response to vehicle motion. Also, often the AST is combined with some other system (i.e., HVAC or stimuli) within the vehicle to help reduce carsickness. No such combinations have been investigated or reported in research literature, so their efficacy remains unknown.

ASTs present unique regulatory and crash safety challenges that must be investigated to determine the feasibility of AST integration into vehicles [170]. While suspension seats have been integrated into vehicles on road, ASTs that rotate or translate have not been introduced in vehicles so far. Further investigation in safety and regulations is required to determine if ASTs are a viable solution to MS in vehicles.

2.2.3 Vehicle Hardware and Software Systems

Vehicle hardware such as suspension systems and chassis can be designed to mitigate vibrations (and other undesired motion) and reduce carsickness. Similarly, vehicle software and control systems such as drivetrain control (i.e., steering, acceleration, braking) can be designed to mitigate carsickness. For the purposes of this review, only studies that involve human subject experiments were considered. The results from 10 publicly available studies are included (Table 2-4 and Table 2-5). Of the 10 publications, 5 publications focus primarily on hardware systems (Table 2-4) while 5 publications focus primarily on software systems (Table 2-5). In addition to the previously listed four common parameters for study comparison, the vehicle hardware and software system studies are also organized using an additional parameter which is Type of Vehicle Hardware or Software. The type of hardware and software describes the technology implemented.

AUTHOR & YEAR	TYPE OF HARDWARE	TYPE OF CONTROL	TIMING OF INTERVENTION	NDRT PERFORMANCE	TYPE OF VEHICLE MOTION	CARSICKNESS MITIGATION OUTCOME
Golding et al., 2003 [89]	Active Suspension	Gravito-inertial acceleration compensation	Ambient	None	Motion Simulator	Reduced CS – MSSQ
Huo et al., 2015 [171]	Active Suspension	LQR	Reactive	None	Passenger car	Reduced CS – Custom Scale
Ekchian et al., 2016 [172]	Active Suspension	Not Specified	Reactive	Reading	Motion Simulator	Reduced CS (Custom Scale – Self-Reported)
DiZio et al., 2018 [173]	Active Suspension	Not specified	Reactive	Reading – Improved task performance	Motion Simulator	Reduced CS (Custom Scale – Self-Reported)
Cvok et al., 2021 [174]	Active suspension and active seat suspension	LQR	Reactive	Reading, drawing, texting – Improved task performance	Motion simulator	Reduced CS (Custom Scale – Self-Reported)

Table 2-4 Summary of Vehicle Hardware Systems for Motion Sickness Mitigation

AUTHOR & YEAR	TYPE OF SOFTWARE	TYPE OF CONTROL	TIMING OF INTERVENTION	NDRT PERFORMANCE	TYPE OF VEHICLE MOTION	CARSICKNESS MITIGATION OUTCOME
Dillen et al., 2020 [175]	Vehicle control	Driving style selection	Ambient	Video (Screen)	Passenger car	Improved comfort (Custom Scale – Self-Reported)
Jurisch et al., 2020 [176]	Active suspension control	Active roll stabilization	Reactive	None	Motion simulator	No CS improvement (MSQ)

Schockenh off et al., 2020 [177]	Vehicle control	Driving style selection	Ambient	None	Passenger car	Reduced CS (Custom Scale – Self-Reported)
Hong et al., 2022 [178]	Vehicle control	Adaptive model predictive cruise acceleration control (longitudinal)	Preemptive – unspecified time	None	Passenger car	Reduced CS (MSDV-Estimated)
Saruchi et al., 2020 [179]	Vehicle control – steering wheel angle	Fuzzy-PID	Reactive	None	Motion simulator	Reduced CS (MSI-Estimated)

Table 2-5 Summary of Vehicle Software Systems for Motion Sickness Mitigation

Of the 10 studies in vehicle systems mitigation technologies, 1 showed an improvement in passenger comfort, 8 showed an improvement in MS and 1 showed no reduction in MS. They differed not only in the level of improvement, but also in the way in which these improvements were assessed. The first-mentioned study determined the change in passenger comfort response through self-reported comfort scores based on a custom-made scale. As for the remaining 9 studies, the change in MS response was determined through either subject-based questionnaires or through MS model predictions. In general, passenger comfort can be correlated with MS mitigation as both are affected by magnitude of oscillations around a similar frequency range (0.1-5Hz). However, an improvement in passenger comfort is not a sufficient condition for MS mitigation. For instance, a system that reduces vertical acceleration high frequency (>1Hz) head vibrations might not play as significant of a role in MS mitigation, which primarily happens in the 0.1-0.6Hz frequency range [51]. There is no established framework in the studies investigated that provides a quantitative improvement in MS score given a quantitative improvement in comfort. Because of that, it is not possible to claim that technologies which led to an improvement in passenger comfort would also lead to a decrease in MS response.

In terms of the type of intervention, 6 studies presented reactive solutions, 1 presented preemptive solutions and 3 presented ambient solutions. The preemptive solution was software

based as they require some predictive component to anticipate vehicle maneuvers. The preemptive horizon was 20 simulation time steps, but the duration of each time step was not specified. This preemptive solution employed an optimization solution to the vehicle control logic, which allowed the algorithm to predict the set of vehicle actions that would minimize motion sickness. This study assessed the performance of their solution through simulation models, and it was able to demonstrate mitigation of motion sickness.

The 3 ambient solutions consisted of vehicle control strategies through either vehicle driving style selection or constant offsets in vehicle motion. All 3 of these studies were able to demonstrate a reduction in motion sickness. Two of these three studies focused on selecting driving style, and in the third the passenger was permanently aligned with the gravito-inertial acceleration direction. While these studies showed a reduction in motion sickness, selecting driving styles is an inherently restrictive approach. Carsickness can be experienced even under the smoothest driving conditions. There are 5 reactive solutions primarily focused on suspension systems (4 vehicle hardware studies, and 1 vehicle software study) and 1 reactive solution which focused on model-based vehicle control (vehicle software). The model-based vehicle control solution performed wheel-angle optimal trajectory tracking to reduce CS. Of the 5 reactive solutions focused on suspension systems, the majority of them demonstrated a reduction in carsickness (only 1 study showed no reduction in CS). Among all vehicle hardware and software studies (10 studies), only 4 studies included NDRT's in their experiments. Two of the studies included watching a video off a screen mounted on a vehicle and 2 included reading texts off a tablet. One of the studies included reading, drawing, and texting on a tablet. Of those 4 studies with NDRT's, only 2 studies included an assessment of the task performance. Both of those studies demonstrated an improvement in task performance due to the actions of reactively triggered vehicle hardware systems for carsickness

mitigation.

As shown in Table 2-6, multiple patents have been filed on vehicle control solutions for CS mitigation. Among these, 8 patents focused on vehicle control systems, 7 focused on suspension systems. Vehicle control has been shown to be an effective way to improve passenger experience as all solutions analyzed have shown either an improvement in passenger comfort or a decrease in MS.

When designing vehicle control solutions, one must consider the tradeoff between ride comfort and time to reach destination. An increase in acceleration magnitude associated with shorter travel times is likely to yield an increase in MS. In addition, infrastructure and safety impose additional constraints on the possible paths that the vehicle can take. Further, vehicle control solutions are constrained by the hardware limitations of the powertrain systems of vehicles. Thus, while vehicle control can mitigate MS, multiple other factors play a role in a practical solution. This can prevent the applicability of vehicle control MS mitigating algorithms to real world solutions. Active suspension has also been shown to increase comfort and reduce CS. These solutions are particularly useful in decreasing MS due to vertical oscillations, which can arise due to road bumps and uneven terrain. However, these solutions are constrained to the vertical direction and have negligible effect on mitigating MS due to lateral and longitudinal accelerations.

Therefore, while vehicle software and hardware solutions have been shown to decrease MS incidence and improve passenger comfort, there remains a need for a solution capable of mitigating MS and that does not increase travel time, is independent of road and vehicle infrastructure, and is capable of attenuating lateral and longitudinal acceleration.

2.2.4 Other Systems

Other methods to mitigate motion sickness in vehicles have been explored that also include

active systems. However, unlike the previously discussed solutions, these other methods are relatively new or are mentioned in a few studies only. Active restraints to control the posture of the passenger in a moving vehicle have been investigated as a method to relieve motion sickness [180]. In the study, the tension on the restraint was actively controlled and triggered 200ms before the event of the vehicle (i.e., triggered preemptively). The study found no meaningful impact of the restraint on carsickness. The study also included a reading NDRT but provided no assessment of quality of NDRT performance.

Numerous patents have also referenced active systems within the cabin of the vehicle such as lighting which changes in response with the passenger's state of mind or changing the HVAC settings such as temperature or fan speed in anticipation of a passengers estimated carsickness state (Table 2-6). One patent even referenced a device that augments the passenger posture by altering the position of their feet in the car using a moving foot platform [181]. However, there are no peer reviewed publications or studies that experimentally evaluate the efficacy of these systems. Further investigations are required to determine if these systems can effectively mitigate carsickness.

PATENT NO.	SENSORY STIMULI SYSTEM				SEAT SYSTEM	RESTRAINT SYSTEM	VEHICLE SUSPENSION	VEHICLE CONTROL	TIMING OF INTERVENTION
	AUDIO	VISUAL	HAPTIC	OTHER					
US9145129B2 [182]		X		X Air conditioning	X				Reactive
US9868332B2 [183]		X			X		X		Reactive
US10107635B2 [184]								X	Reactive & Preemptive
US9789880B2 [185]	X	X	X	X Air conditioning	X			X	Reactive & Preemptive
US10625556B2 [186]					X		X		Reactive
US9862312B2 [187]		X							Reactive
US10322259B2 [188]				X Electrical Stimulation (e.g., GCS)					Reactive
GB2567856A [189]		X							Reactive
US10625641B2 [190]					X				Reactive
US10259451B2 [191]	X	X	X		X		X	X	Preemptive
US10926773B2 [192]	X	X		X Air conditioning	X				Reactive
US20220001773A1 [193]					X	X			Preemptive
WO2019156657A1 [194]		X							Reactive & Preemptive
US10300760B1 [195]			X				X		Reactive
US11571996B2 [196]				X Air conditioning	X				Reactive & Preemptive
US11130382B2 [197]							X	X	Reactive
US10737053B2 [181]	X	X	X	X Olfactory & Air conditioning					Reactive
US20200317089A1 [198]	X	X	X	X Olfactory	X				Reactive & Preemptive
US11321923B2 [199]	X	X							Reactive & Preemptive
US20210114553A1 [200]	X	X	X	X Productivity Systems	X	X	X	X	Reactive & Preemptive
US20220001893A1 [201]								X	Reactive
US11541797B2 [202]					X		X		Reactive
US20220135054A1 [203]								X	Reactive
US20220001894A1 [204]								X	Reactive & Preemptive
EP3860895A1 [205]				X Man Machine Interface					Reactive
US11338106B2 [206]	X	X							Reactive

Table 2-6 Summary of Motion Sickness Mitigation Systems in Patent Literature

(Note: The 'X' in the table denotes that the patent includes that system or part in its description of the mitigation system)

2.3 Discussion and Conclusions

This chapter presents a summary of the state of the art on the causes of motion sickness and motion sickness modelling. While many theories to explain the cause of motion sickness have been proposed, the sensory conflict theory has been most extensively validated using experimental data. Within the sensory conflict theory, the subjective vertical conflict version of the sensory conflict theory is the one that has been considered the most promising due to congruence with experimental data. The postural instability theory is not too dissimilar to the sensory conflict theory. Both rely on some kind of conflict between actual and sensed motion. The major difference is that the postural instability theory further states that the conflict in actual and sensed motion leads to an inability to maintain postural control which leads to motion sickness. Our research relies on the sensory conflict model of motion sickness since it has (limited) supporting evidence in the literature, and the model is aligned with anecdotal evidence regarding the onset and cause of motion sickness.

Motion sickness is typically quantified using one of the many scales used to quantify motion sickness. Since there are no 'motion sickness sensors' that can provide objective measurements of motion sickness, subjective scales must be used. The UMTRI Motion Sickness Scale (that captures the spectrum of MS symptoms and physiological indicators during realistic driving conditions, making it pertinent to studies that involve MS prediction applied to AVs. The literature review also highlights the need for a theoretical model of motion sickness that combines both visual and vestibular sensory systems, allows for simulation of passengers performing tasks inside an autonomous vehicle, and leverages the best understanding of MS causes and mechanisms to provide more generalizability in predictions. Such models allow for easy evaluation of motion sickness in various scenarios, without the need for complex human subject testing.

This chapter also presented a summary of the state of the art of active carsickness mitigation methods reported in publicly available literature. Prior work has shown the limitations of pharmacological and passive carsickness mitigation solutions. Instead, the review in this chapter covered active passenger stimuli, active seats, vehicle hardware and software solutions, and other active systems that have been investigated to prevent carsickness. These methods have shown promise in reducing motion sickness to varying degrees. Based on the analysis of the state of the art, several limitations were noted.

The majority of the prior literature did not explicitly state the relationship between the mitigation solutions being investigated and motion sickness theory to address how the mitigation solution helps reduce motion sickness. One study (Wada et al., 2012 [52]) explicitly tied their mitigation solution to the subjective vertical conflict theory of motion sickness (which is a subset of the sensory conflict theory). Therefore, there is need for research on motion sickness mitigation solutions that explicitly tie the mitigation solution being investigated to an etiological aspect of motion sickness.

While the benefits of anticipation in mitigating carsickness have been shown through investigations of drivers in vehicles, most carsickness mitigation methods do not leverage this anticipation to perform any preemptive actions to mitigate carsickness for passengers. Of the 55 studies included in this review across various mitigation methods, only 19 studies employ anticipation and preemption (that is only 35% of the studies included in this review). Of these 19 studies, over 80% of them (16 out of 19 studies) demonstrated a reduction in motion sickness. In comparison, the remaining 36 studies employed either reactively or ambient triggered systems. Of these 36 studies, 75% of them (27 out of 36 studies) demonstrated a reduction in motion sickness. Therefore, there is some evidence to suggest that preemptively triggered systems may be more

effective at reducing motion sickness than reactively triggered systems.

Similarly, of the 26 patents included in this review across various mitigation methods, only 10 patents employ some kind of preemption (that is only 39% of the patents included in this review). Leveraging anticipation to take preemptive actions appears to be promising without inherently presenting adverse side effects. Existing investigations that have used preemption have not characterized the influence of amount (e.g., 1 second vs 10 seconds), quality (e.g., precision/repeatability of preemption) of preemption on carsickness mitigation, or combinations of interventions (e.g., combining different sensory stimuli systems or combining stimuli with active seat system). Therefore, there is a need for additional systematic investigations on mitigation solutions that leverage anticipation and preemption for AV passengers.

Current investigations have not studied the interactions between any carsickness mitigation method and performance of NDRTs. Of the 55 studies included in this review across various mitigation methods, 28 include NDRTs (that is 51% of the studies included in this review) and of those only 6 provide an assessment of how well the NDRT was performed (that is only 11% of the studies included in this review). The majority of the studies that include a NDRT are APS system studies (21 out of the 28 studies with NDRT included in this review are APS studies). NDRTs can place a significant cognitive burden on the passenger and reduce their situational awareness. This not only increases their chances of carsickness but might reduce their attention to the mitigation method and thereby affect the efficacy of carsickness mitigation. Ideally, NDRT performance and its evaluation must be a part of research protocols used for the investigation of carsickness mitigation solutions.

There is a need to standardize research methodology and measures for investigating carsickness mitigation. Due to the diversity of experimental methodology and participant sample sizes used in

current literature it is nearly impossible to perform an objective comparison of motion sickness mitigation methods. For example, a visual APS study (Morimoto et al., 2008) had used a 0 to 10 motion sickness scale and had shown a reduction of peak participant motion sickness at the end of the study of 17% due to the stimuli, while another audio APS study (Kuiper et al., 2020) had used the MISC scale and had demonstrated a 29% reduction of peak motion sickness in their participants at the end of the study. While the reduction of motion sickness due to audio stimuli may be higher than visual stimuli, this is insufficient data to be able to claim that audio stimuli is better than visual stimuli due to the considerable number of factors that can influence a persons' motion sickness response which cannot be controlled and made identical across these two studies. For example, the above-mentioned visual stimuli study (Morimoto et al., 2008) was conducted using a real passenger vehicle and the participants were performing a video watching task during the study. However, the above-mentioned audio stimuli study (Kuiper et al., 2020) was conducted using a motion simulator and did not have the participants perform any task. This diversity in experimental methods does not allow for a fair comparison of results across both these studies. In addition, it is also not possible to compare results from one study to another since it is difficult to convert motion sickness measurements from one scale to another accurately [207]. Therefore, standardized research methodology is required to be able to conduct fair and accurate analysis comparing the efficacy of the various motion sickness mitigation solutions being investigated.

Most of the research has relied on the use of static base simulators instead of moving base simulators or real vehicles/cars. Of the 55 studies included in this review, 26 were performed in real cars (that is 47% of the studies included in this review). Of the remaining studies, 11 studies were performed using static simulators (that is 20% of the studies included in this review) and 18 studies were performed using motion simulators (that is 33% of the studies included in this review).

Simulators are unable to create the full inertial forces experienced by a passenger in a moving vehicle [208], [209]. Demonstrating the viability of carsickness mitigation methods in real world driving conditions remains critical to identify promising solutions.

While many promising solutions have been identified for mitigating carsickness in this review, none of these solutions have been proven to be entirely effective or practical. None of these solutions have been deployed in vehicles on the road today. Since carsickness is individual specific, and no single mitigation method has been proven as the best method, there is a need for investigations that compare the efficacy of various carsickness mitigation methods included in this review. The review motivates the need for carsickness mitigation solutions that leverage preemption and anticipation (like that of a driver), that are customizable to individual passengers, and do not influence NDRT performance. The majority of the studies in this review have not proposed solutions that meet all of the above criteria. Therefore, there is room for additional novel solutions to reduce carsickness.

2.4 Identified Gaps in Current Research

Based on the analysis of existing research literature, the following gaps in current research on motion sickness modelling are identified:

1. One of the key deficiencies of MS models in the literature is the inability to accurately predict MS at frequencies below 0.1Hz. Models tend to underestimate the level of MS experiences at this frequency range. One possible explanation for this behavior is that few models consider the contributions of the visual system to MS, focusing primarily on the vestibular system [81], [210]. It has been shown that the visual contributions to MS play a significant role at low frequencies (<0.2Hz) [211].

2. While a few visual-vestibular MS models have been proposed in the literature [86], there

is no established framework within these models for handling both linear specific force and angular velocity visual-vestibular stimuli in three dimensions. These types of inputs are widely present in MS triggering events, such as in the case of a passenger looking at screen inside a moving vehicle. It has been shown increased obstruction of a passenger's view of the outside world leads to increased motion sickness [212]. Therefore, taking it account the contributions of the visual field of view of a passenger has the potential of improving MS modeling prediction.

3. The model parameters must be refined using experimental data so that the model predicted motion sickness can be generalized for as wide a range of population as possible.

Based on the analysis of existing research literature, the following gaps in current research on motion sickness mitigation are identified:

1. The benefits of anticipation in mitigating carsickness have been proven through investigations of drivers in vehicles [48], [146], [213]. Numerous patents for carsickness mitigation solutions also rely on anticipation to make a preemptive intervention (Table 2-6). However, there are no significant investigations leveraging preemptive interventions for motion sickness mitigation. Leveraging anticipation to take preemptive actions appears to be promising without inherently presenting adverse side effects but there is not enough data to support that claim yet. In addition, investigations comparing the efficacy of reactive versus preemptive (based on anticipation) carsickness interventions are required. Such investigations can provide definitive evidence to shape the future of motion sickness mitigation interventions.

2. Current investigations have not studied the interactions between any carsickness mitigation method and performance of NDRTs. NDRTs can place a significant cognitive burden on

the passenger and reduce their situational awareness [23], [214], [215]. This not only increases carsickness but might reduce the passenger's attention to the mitigation method and thereby affect the efficacy of carsickness mitigation. While some studies have mentioned NDRTs in the context of motion sickness mitigation, none have provided a systematic assessment of NDRT performance. Also, there is no standardization of the types of NDRT used in investigations. The ideal carsickness mitigation method must not only reduce/eliminate carsickness but also should not adversely impact NDRT performance.

3. Most research has relied on the use of static base simulators instead of moving base simulators or real vehicles/cars. While simulators can recreate the visual experience, and even the driving interfaces that are like real vehicles, they are unable to create the full range and variation of inertial forces experienced by a passenger in a moving vehicle [208], [209]. In some cases, simplistic motion trajectories are used with simulators which fall short of emulating real world driving conditions. Demonstrating the viability of carsickness mitigation methods in real world driving conditions is required to identify promising solutions.

4. There is a need to standardize research methodology and measures for investigating carsickness mitigation. For example, investigations today use different scales to measure motion sickness including Motion sickness assessment questionnaire (MSAQ), Fast motion sickness scale (FMS), and Motion sickness incidence (MSI) to name a few. It is not possible to compare results from one study to another since it is difficult to convert motion sickness measurements from one scale to another accurately [104], [105].

Chapter 3 Visual-Vestibular Motion Sickness Model

This chapter presents a novel motion sickness estimation model that uses both visually and vestibular sensed motion as model inputs. There is a need for a theoretical model of motion sickness that (a) combines both visual and vestibular sensory systems, (b) allows for simulation of the effect of a passenger performing tasks inside a vehicle on their sensed motion, and (c) leverages the best understanding of MS causes and mechanisms to provide more generalizability in predictions. The proposed model addresses these key gaps in motion sickness modelling motivated earlier in Chapter 2. The proposed model integrates vestibular sensory dynamics, visual motion perception, and visual-vestibular cue conflict to determine the conflict between the sensed and true vertical orientation of the passenger. The model performance was verified by comparing model predicted MS response against experimentally determined motion sickness measures from past investigations.

3.1 Model Description

A motion sickness model is proposed that combines existing models of motion sickness and motion perception in a unique architecture. In the proposed model, a subjective vertical mismatch model is combined with a human perception model in order to estimate motion sickness resulting from visual-vestibular cues. In the field of human motion perception, the vestibular system is often modeled such that it senses head linear acceleration inputs and angular velocity inputs, while the visual system is often modeled such that it senses linear and angular velocities of the objects in the passenger's field of view. The proposed motion sickness estimation model assumes that the visual

system can only estimate angular velocity. Further, for the purposes of this model, it is assumed that the visual and vestibular reference frames are collocated and co-aligned, and they are defined as shown in Fig 3-1. It is assumed that such a reference frame is placed as the midpoint of the line connecting the two ears. This assumption makes it possible to have a unified reference frame for all sensing systems.
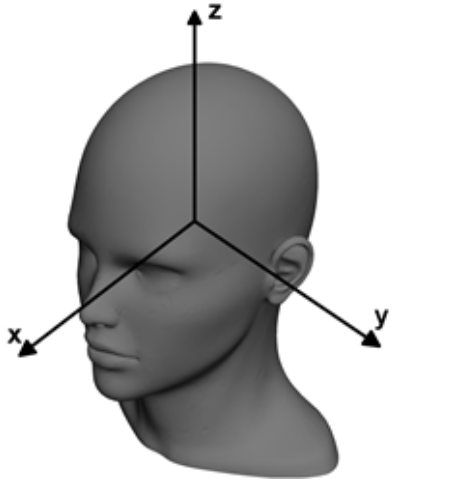
Fig 3-1 Visual-vestibular coordinate frame

In order to account for the visual contribution to motion sickness, it is necessary to include a sensory system model that estimates the perceived head motion based on both visual and vestibular inputs. Telban et al. [210] proposed a human perception model that considers the disparity between the visual and vestibular sensed angular velocities in order to estimate the human perceived angular velocity. Thus, it is possible to integrate Telban's model for the estimation of perceived head motion states with the sensory system model proposed by Kamiji [85] in order to create a visual vestibular motion sickness model. In this work, we have built a visual-vestibular motion sickness (VVMS) model in order to estimate the motion sickness index (MSI) as a function of vestibular and visual inputs, as shown in Fig 3-2. The model combines the three-dimensional vestibular subjective vertical conflict (SVC) model proposed by Kamiji et al. with the visual-vestibular perception model proposed by Telban et al. The inputs to the model are $\mathbf{a}$, ω, ω_{vis}, which are

vectors with three degrees of freedom defining the linear acceleration of the head with respect to the world reference frame, the angular velocity of the head with respect to the world reference frame and the visual perception of angular velocity with respect to the visual background, respectively.

It should be noted that previous models have attempted to integrate SVC theory with visually induced motion sickness. Braccesi et al. [86] has previously integrated a three-dimensional SVC motion sickness model with Telban's model for visual-vestibular human perception. However, Braccesi's model only accounted for linear motion and does not model the effects of angular velocity in causing motion sickness. While Wada et al. [88] model of motion sickness accounts for visually sensed motion in the internal model, the VVMS model uses a human motion perception model in order to account for visually sensed motion.

In an attempt to predict the amount of motion sickness given any kind of motion stimulus, we describe a model using explicit knowledge of the vestibular system. First, the accepted sensory conflict theory is restated in terms of a conflict between a vertical as perceived by the sense organs like the vestibular system and the subjective vertical as determined on the basis of previous experience. Second, this concept is integrated with estimation theory by the use of an internal model. If detailed for vertical motions only, the model does predict typical observed motion sickness characteristics, irrespective of the parameter setting.

By adjusting the model parameters, the model can also quantitatively be adapted to seasickness data from the literature. With this concept, sickness severity (hypothetically) can also be predicted for other motions, irrespective of their origin and complexity.
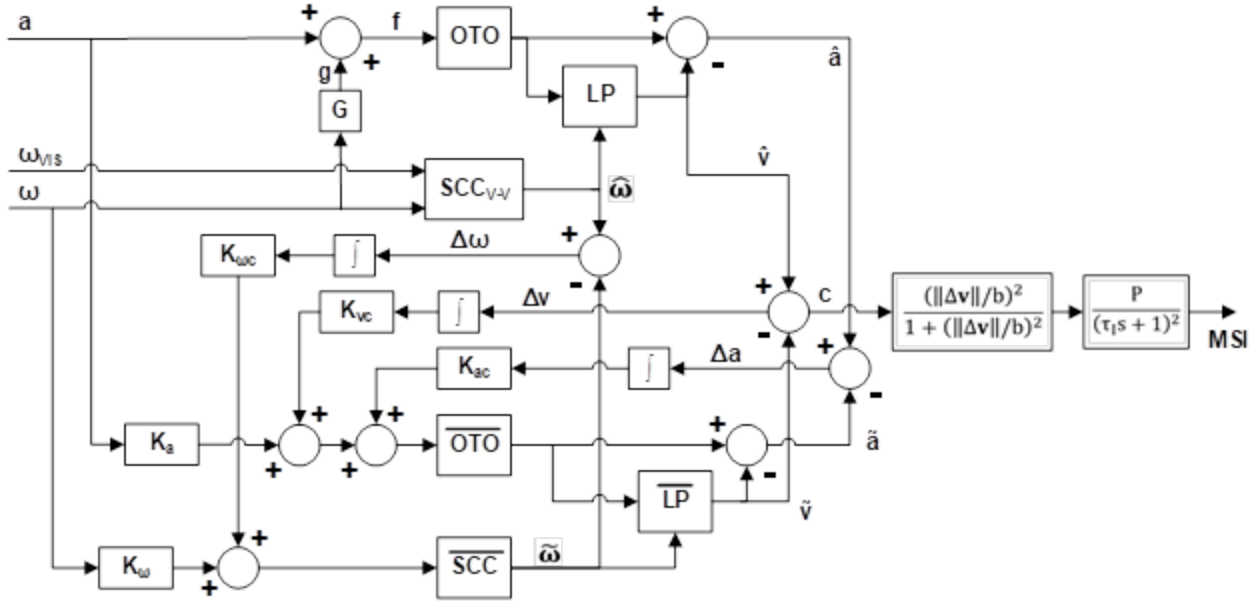
Fig 3-2 Visual-Vestibular Motion Sickness Model

Physically the otolith cannot differentiate between gravitational acceleration and inertial acceleration. Thus, the otolith senses the combined gravito-inertial acceleration (GIA), as shown in equation 3-1 [216]. Where '**a**' is the inertial acceleration and g is the gravitational acceleration. The G block in Fig 3-4 accounts for the change in the direction of gravity with respect to the head reference frame and the relationship is captured by taking a derivative of '**g**' with respect to time, as shown in equation 3-2 [85].

$$\mathbf{f} = \mathbf{a} + \mathbf{g} \qquad (\ 3\text{-}1\ )$$

$$\frac{d\mathbf{g}}{dt} = -\boldsymbol{\omega} \times \mathbf{g} \qquad (\ 3\text{-}2\ )$$

The sensory system model is defined by the architecture that encompasses the otolith transfer function (OTO), the semicircular canal visual-vestibular interaction model (SCCv-v) and the otolith-canal interaction model (LP). The outputs of the sensory model are the human perceived dynamics with respect to the world reference frame, consisting of the perceived GIA, perceived angular velocity and perceived vertical, which are defined as $\hat{\mathbf{f}}$, $\hat{\boldsymbol{\omega}}$, $\hat{\mathbf{v}}$, respectively. The otolith transfer function is assumed to have a unity gain, such that $\hat{\mathbf{f}} = \mathbf{f}$. Bos at al. [78] proposed that this

simplifying assumption does not affect model accuracy. The LP block (Fig 3-5) is defined according to an otolith canal model in which the perceived subjective vertical can be estimated through a low pass filter with the following relationship [77]:

$$\frac{d\hat{\mathbf{v}}}{dt} = \frac{1}{\tau}(\hat{\mathbf{f}} - \hat{\mathbf{v}}) - \hat{\boldsymbol{\omega}} \times \hat{\mathbf{v}} \quad (3\text{-}3)$$

Here, τ is the low pass filter time constant. The first term on the right-hand side of (3) gives the estimate of gravity by otolith afferents only, while the second term gives the change of gravity due to rotation only. The SCCv-v model follows the architecture proposed by [210], shown in Fig 3-3, in order to estimate the perceived angular velocity as a result of both visual and vestibular input signals.
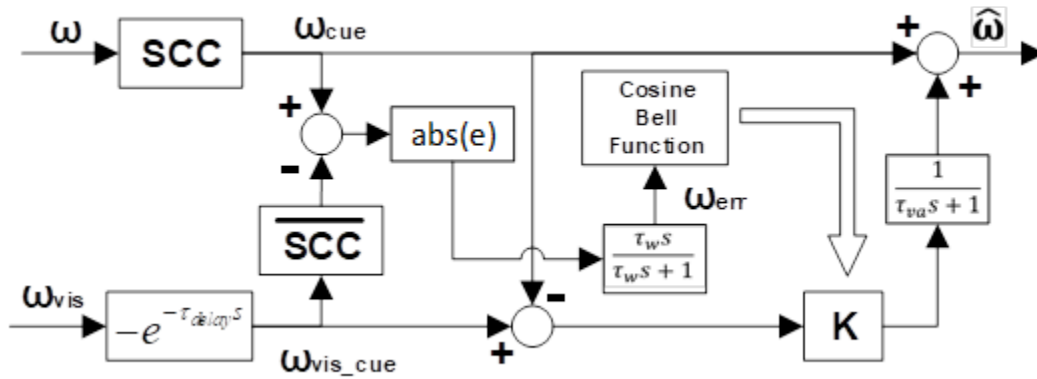
Fig 3-3 Visual-Vestibular interaction to determine the sensed angular velocity – Detailed view of the SCC$_{\text{V-V}}$ block from Fig 3-2

The visual angular velocity input, $\boldsymbol{\omega}_{vis}$ is defined as the visual field angular velocity as seen from the head reference frame. Zacharias et al. [217] used projectors in order to quantify the visual field angular velocity in controlled environments. However, it is desired to determine $\boldsymbol{\omega}_{vis}$ for uncontrolled environments, such as the inside of a vehicle. One approach to determining the visual field motion is to replicate the sensed visual motion through a video recording and process the captured images through visual odometry. Wada et al. [88] proposed that the visual angular velocity input can be estimated using the optical flow of a video through the Farneback method.

For the purposes of the VVMS model, only two conditions of visual angular velocity inputs are considered: (i) the visual input is equal to zero, which is similar to the case of a passenger reading inside a moving vehicle; and (ii) the visual input is identical to the vestibular input, similar to the case of a front seat passenger inside a moving vehicle with an unobstructed view of the surroundings.
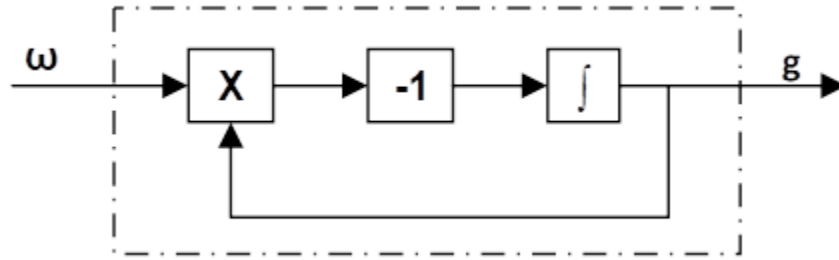
Fig 3-4 Detailed View of the 'G' Block from Fig 3-2
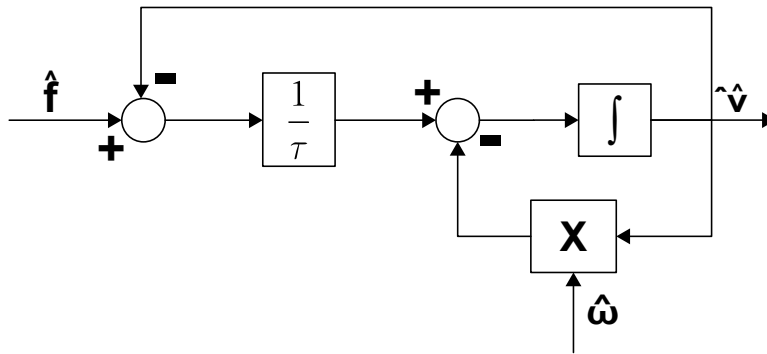
Fig 3-5 Detailed View of the 'LP' Block from Fig 3-2

The input visual angular velocity has a time delay defined by τ_{delay} , which accounts for the delays of the visual receptors, the neural transmissions, and the processing during motion perception [218]. The visual cue is passed through a sensory internal model of the semicircular canals $\overline{SCC_{vis}}$ to produce a predicted vestibular signal that can be compared to the actual vestibular signal. It is assumed that the $\overline{SCC_{vis}}$ transfer function is a perfect copy of the SCC transfer function, which was defined experimentally by prior research [219], such that:

$$\omega_{cue_i} = \frac{\tau_d \tau_a s^2}{(\tau_d s + 1)(\tau_a s + 1)} \omega_i \quad (i = x, y, z) \quad (3\text{-}4)$$

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Where τ_a and τ_d are second order high pass filter time constants. The absolute value of the difference between the vestibular and visual cues passes through an adaptation operator to allow for long-term resolution of steady-state conflict. This adaptation operator is defined as a first order high pass filter with time constant τ_w and its output is a conflict signal ω_{err}. The optokinetic gain K is computed as a function of ω_{err} using a modified cosine bell function with conflict threshold ε, shown in Fig 3-6. The difference between the visual and vestibular cues is multiplied by the optokinetic gain and an optokinetic influence transfer function, which consists of a low pass filter with time constant τ_{va}. This optokinetic influence represents the gradual build-up of self-velocity, or vection, and its output is added to the vestibular cue to yield the perceived angular velocity.
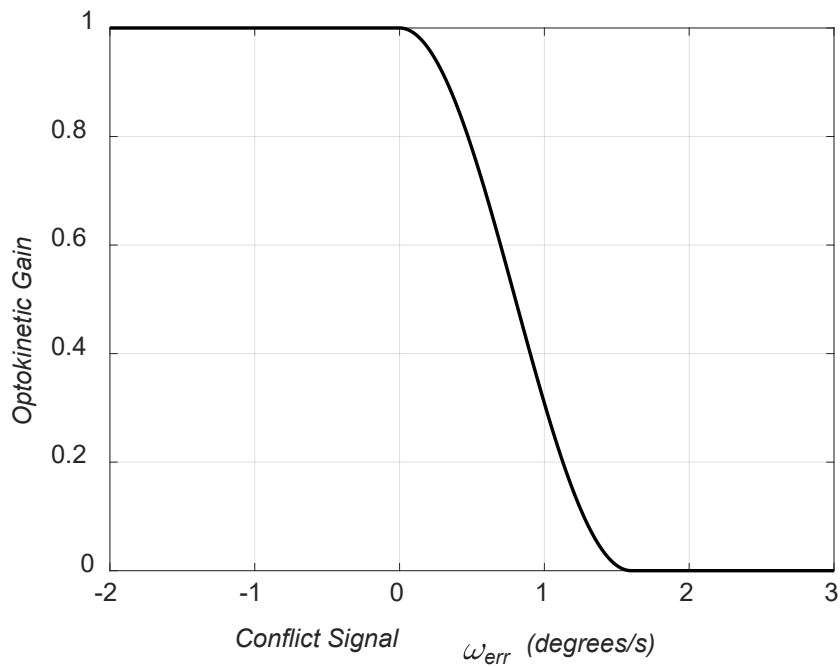
Fig 3-6 Modified Cosine bell function, conflict threshold ε of 1.6°/s

Subjective vertical conflict theory states that motion sickness arises from a conflict between the sensed vertical and the internal model predicted vertical. The internal model tries to replicate the sensory dynamics based on previous experiences and a learning process. The previous experiences help define the estimation gains (Ka and Kω) and the sensory internal models $(\overline{OTO}, \overline{SCC}, \overline{LP})$.

The learning process is achieved using a feedback loop with integral gains (Kac, Kωc, and Kvc), which corrects for the discrepancy between the perceived states and the predicted states. It is assumed that the sensory internal models $\overline{OTO}, \overline{SCC}$ and $\overline{LP}$ are identical to the sensory models OTO, SCC, and LP, respectively. The outputs of the internal model are the predicted GIA, predicted angular velocity and predicted vertical, which are defined as $\tilde{\mathbf{f}}$, $\tilde{\boldsymbol{\omega}}$, $\tilde{\mathbf{v}}$, respectively.

The subjective vertical conflict "c" (from Fig 3-2) is defined as the difference between the perceived and predicted verticals. This conflict passes through a second order Hill function with parameter b in order to account for both the asymptotic behavior of motion sickness and the nonlinear relationship between MSI and conflict level. The output of the hill function passes through a double integrator with leaking time constant τ_I in order to account for the accumulation of motion sickness severity over time. The MSI value is scaled by a factor P, which accounts for the maximum percentage of people that become motion sick under a given circumstance. Table 3-1 shows the nominal model parameter values from previous literature. These parameters were used as a baseline for the presented model. The next section provides a study on the effects of parameter values on output MSI.

VESTIBULAR SYSTEM		VISUAL SYSTEM	
Parameter	Value	Parameter	Value
K_ω	0.8	τ_w	8s
K_a	0.1	ε	1.6deg/s
$K_{\omega c}$	5	τ_{va}	1.6s
K_{vc}	5	τ_{delay}	90ms
K_{ac}	1		
P	85		
τ_I	720s		
B	0.5m/s^2		
τ_d	7s		
τ_a	190s		
OTO	1		
τ	5s		

Table 3-1 Nominal model parameters used in the proposed motion sickness model

3.1.1 Model Parameter Study

The goal of this section is to provide characterization of model parameters that lack physiological justification by assessing its effects on estimated MSI. The parameters that were selected to reflect previous physiological studies include $\tau_d, \tau_a, \tau, \tau_w, \varepsilon, \ \tau_{delay}$ and τ_{va}. Haslwanter et al. [219] obtained the SCC parameters τ_d and τ_a by fitting a vestibular model to experimental data. Graaf et al. [220] proposed an LP time constant, τ, based on experiments with the canal-otolith interaction. Zacharias et al. [217] selected the adaptation operator time constant, τ_w, to reflect the typical latencies observed in simulators. From experiments with angular velocity cues in darkness, Benson [221] obtained a conflict threshold value, ε. From experiments in roll rate perception with visual display, Hosman [218] obtained the value for the visual cue time delay, τ_{delay}. Van der Steen [222] proposed a value for the optokinetic influence time constant, τ_{va} , according to experiments on self-motion.
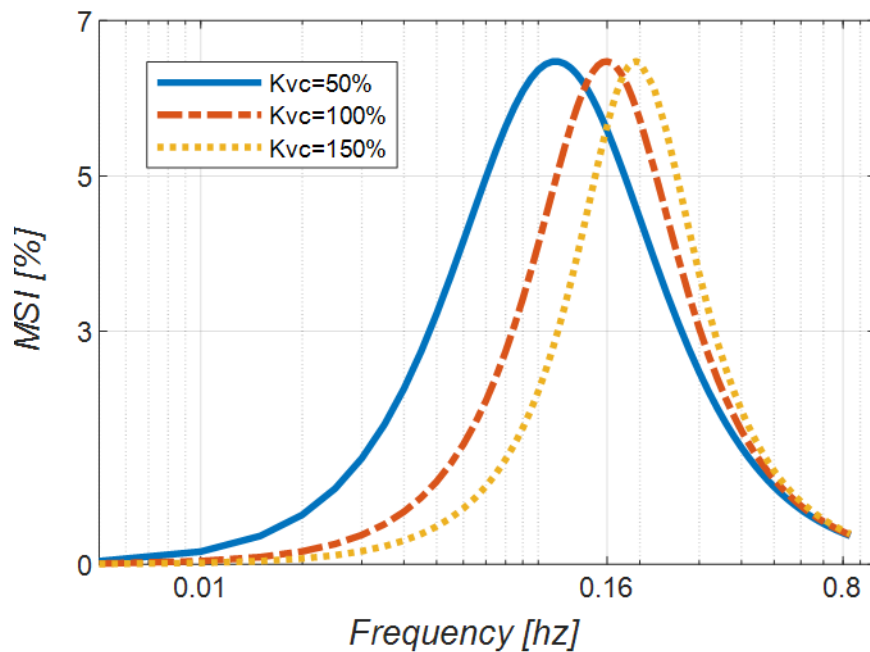
Fig 3-7 Effect on MSI for varying values of internal feedback loop gains, specifically effect of varying Kvc. The plot is generated for a vertical linear acceleration input of 0.1 m/s2 RMS over 120 minutes

The parameters that were selected to fit motion sickness score data include Kω, Ka, Kωc, Kvc, Kac, P, τ_I and b. Kamiji [85] selected Kω, Ka, Kωc, Kvc and Kac in order to yield simulation results comparable to McCauley's [98] dataset on MSI. Bos et al. [78] also selected P, τ_I and b in order to yield simulation results comparable to McCauley's dataset on MSI. A study was performed in order to characterize the effect of the parameters proposed by Kamiji and Bos on estimated MSI. For this study, individual parameters were varied as a percentage of the nominal values provided in Table 3-1, while all other parameters were kept constant. For the purposes of this study, a few parameters were selected to be discussed in detail based on highest impact on MSI.
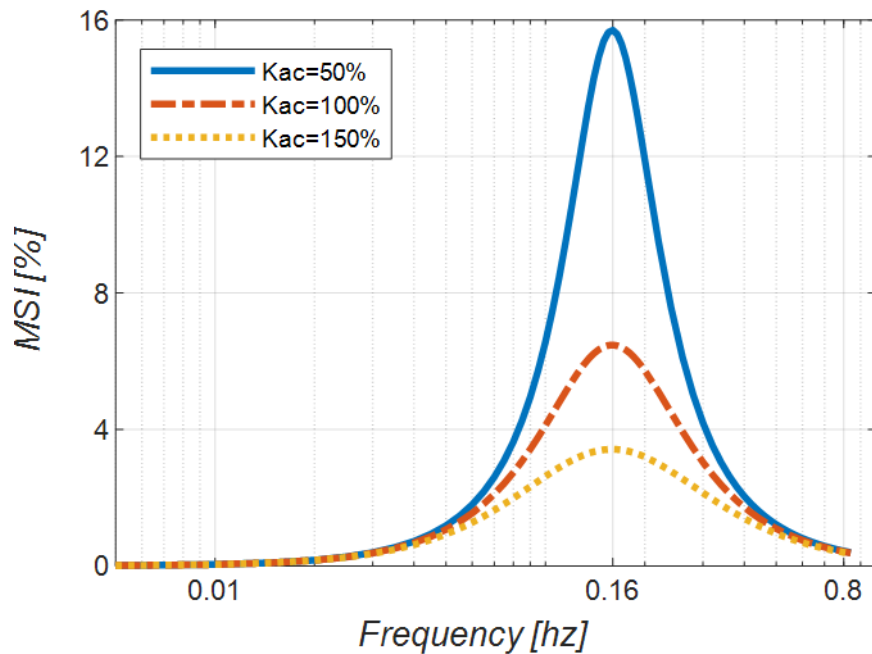
Fig 3-8 Effect on MSI for varying values of internal feedback loop gains, specifically effect of varying Kac. The plot is generated for a vertical linear acceleration input of 0.1 m/s2 RMS over 120 minutes

Fig 3-7 and Fig 3-8 show MSI as a function of frequency for different values of two of the internal model feedback gains. It is important to note that MSI behaves as a band pass filter with bandwidth and center frequency determined by the internal model feedback gain values. As seen

in Fig 3-7, the subjective vertical feedback gain, Kvc, can be tuned in order to select the center frequency for the band pass filter. Lowering the value of Kvc causes the center frequency to decrease without affecting the peak MSI. As seen in Fig 3-8, the linear acceleration feedback gain, Kac, can be tuned in order to select the bandwidth of the band pass filter. Raising the value of Kac causes the bandwidth to increase and the peak MSI to decrease. By manipulating Kvc and Kac, it is possible to account for the different frequency ranges over which certain people become motion sick. While changing Kω, Ka and Kωc caused a vertical offset on the MSI frequency response curve, the shape of the curve remained unchanged.
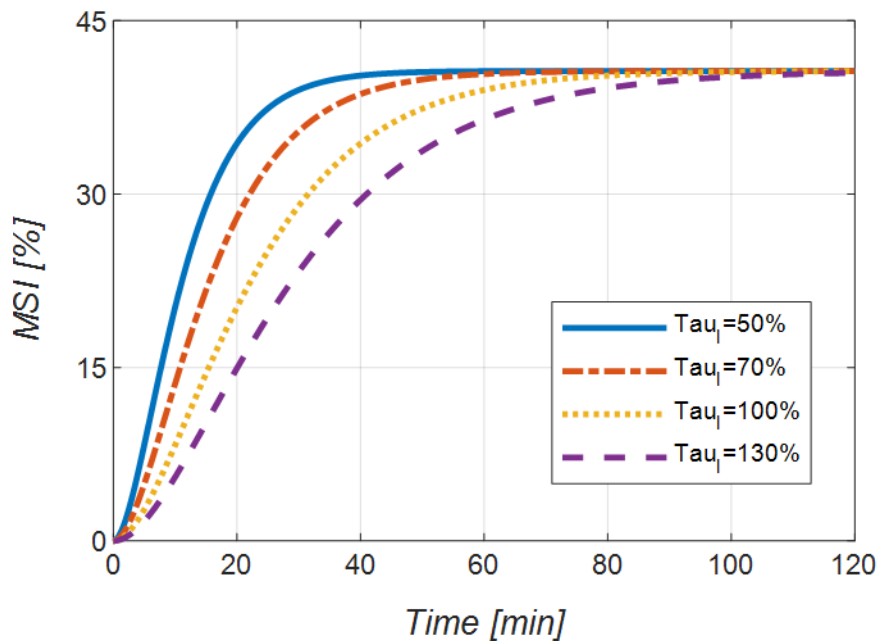
Fig 3-9 Effect on MSI for varying values of internal feedback loop gains, specifically effect of varying τ_I (Tau I). The plot is generated for a vertical linear acceleration input of 0.5 m/s2 RMS over 120 minutes

Fig 3-9 and Fig 3-10 shows MSI as a function of time for different values of the hill function parameter b and the leaking integrator time constant τ_I. As seen in Fig 3-9, the leaking time constant affects how rapidly the MSI reaches its peak value, but it does not affect the peak value itself. Increasing the value of the leaking time constant leads to faster accumulation of MSI over time. As some people become motion sick faster than others, accounting for the time response of

MSI can be relevant in applications where it is desirable to determine MSI over a limited time window. As seen in Fig 3-10, the hill function parameter affects the peak MSI without changing the MSI time response. Decreasing the hill function parameter leads to an increase in peak MSI. As some people are more sensitive to motion sickness than others, accounting for the scalability of MSI can be relevant in applications where it is desirable to determine MSI over different demographics of motion sickness susceptibility. Since the parameter P and MSI are directly proportional, P can be used to linearly scale MSI.
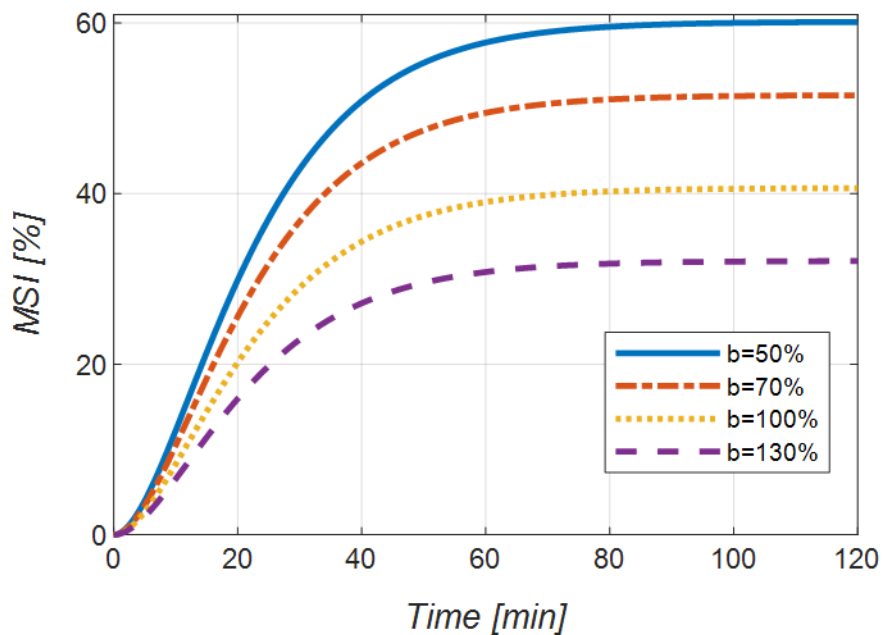
Fig 3-10 Effect on MSI for varying values of internal feedback loop gains, specifically effect of varying "b". The plot is generated for a vertical linear acceleration input of 0.5 m/s2 RMS over 120 minutes

3.2 Model Results & Discussion

As seen in Fig 3-11, the simulated MSI results align with the experimental results obtained by McCauley presented in Fig 3-14. For both, we observe a saddle shaped curve with the peak MSI happening at a frequency of around 0.16Hz. The simulated results were lower in magnitude than the experimental results, which can be accounted for by tuning the model parameters that do not

affect frequency response, such as b and P. Fig 3-12 shows the simulated results of MSI for different angular velocity inputs. It is possible to see that low frequency angular velocities lead to the highest values of MSI. Thus, modeling the visual-vestibular conflict for angular velocities is especially important as the visual component of motion sickness plays a larger role at low frequencies.
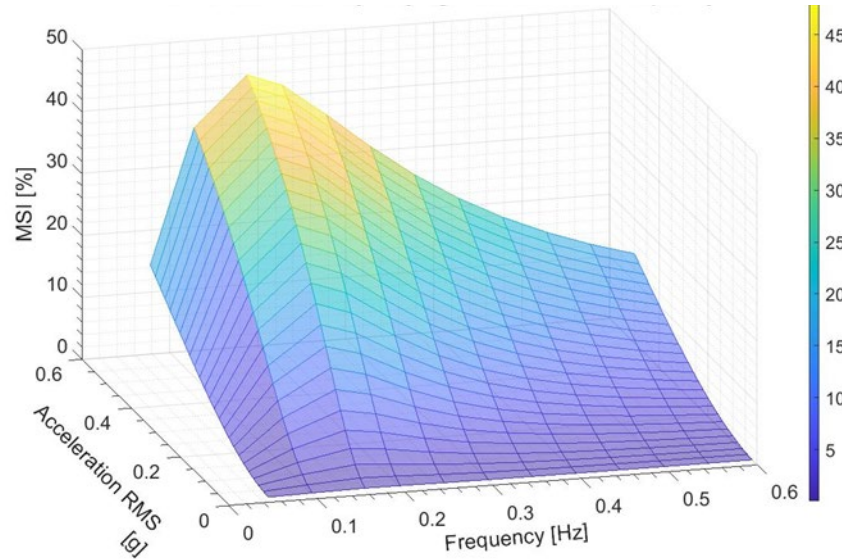
Fig 3-11 Model predicted MSI as a function of frequency and linear acceleration after a 2-hour exposure when there is no conflict between visual and vestibular inputs
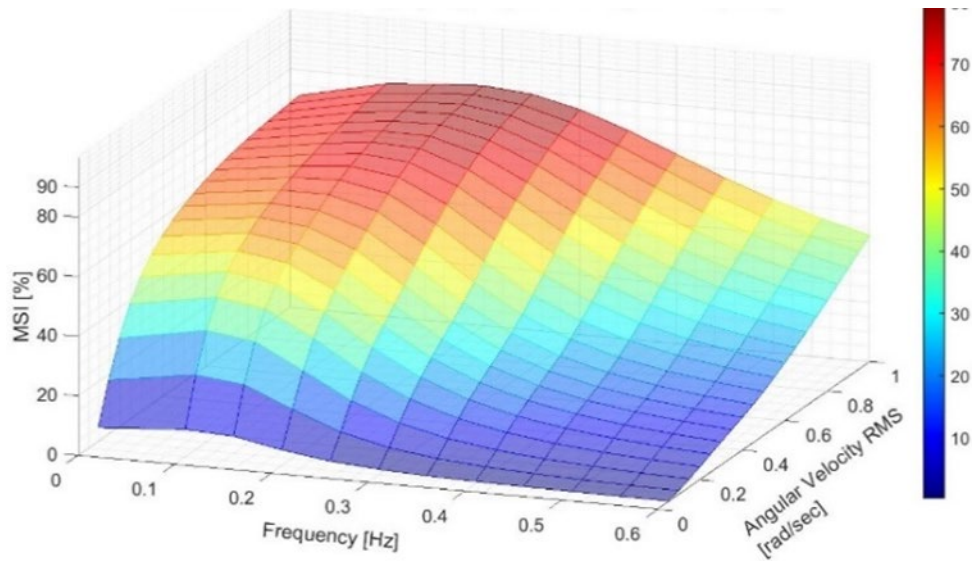
Fig 3-12 Model predicted MSI as a function of frequency and angular velocity after a 2-hour exposure when there is no conflict between visual and vestibular inputs

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Fig 3-13 shows the influence of visual inputs in MSI. The zero visual input condition, or the high conflict condition, is equivalent to a passenger reading inside a moving vehicle. The condition in which the visual input is equal to the vestibular input, or the low conflict condition, is equivalent to a passenger inside a moving vehicle that has full view of the vehicle surroundings. As expected, the high conflict condition led to higher values of MSI. Thus, when estimating motion sickness for passengers performing a task inside a moving vehicle, it is important to account for the mismatch between visual and vestibular information is important for estimating motion sickness.
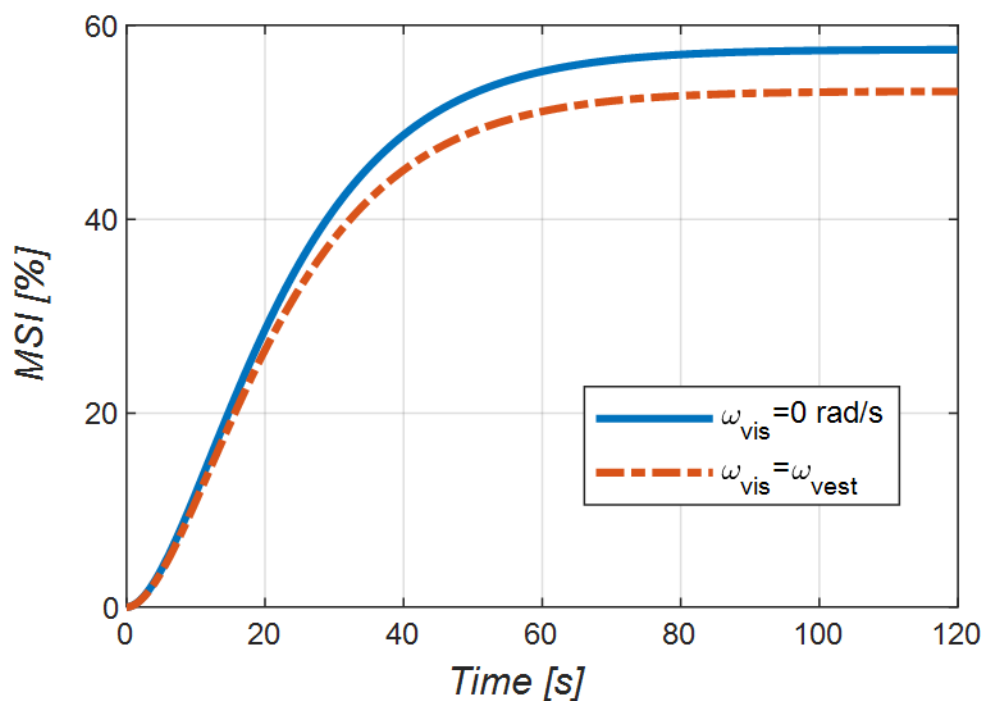
Fig 3-13 Model predicted MSI as a function of time for two levels of visual inputs. The vestibular angular velocity input was the same across both cases and its value was 0.5 rad/s RMS at 0.1 Hz about the X-axis

As seen in Fig 3-15, the visual conflict increases MSI at low frequencies for absolute and normalized values of MSI. This is in congruence with the expected behavior as the visual-vestibular conflict plays a larger role a low frequencies. Thus, in cases where MSI is underestimated by models that only include the vestibular signal, introducing a visual-vestibular interaction component can help correct discrepancies.
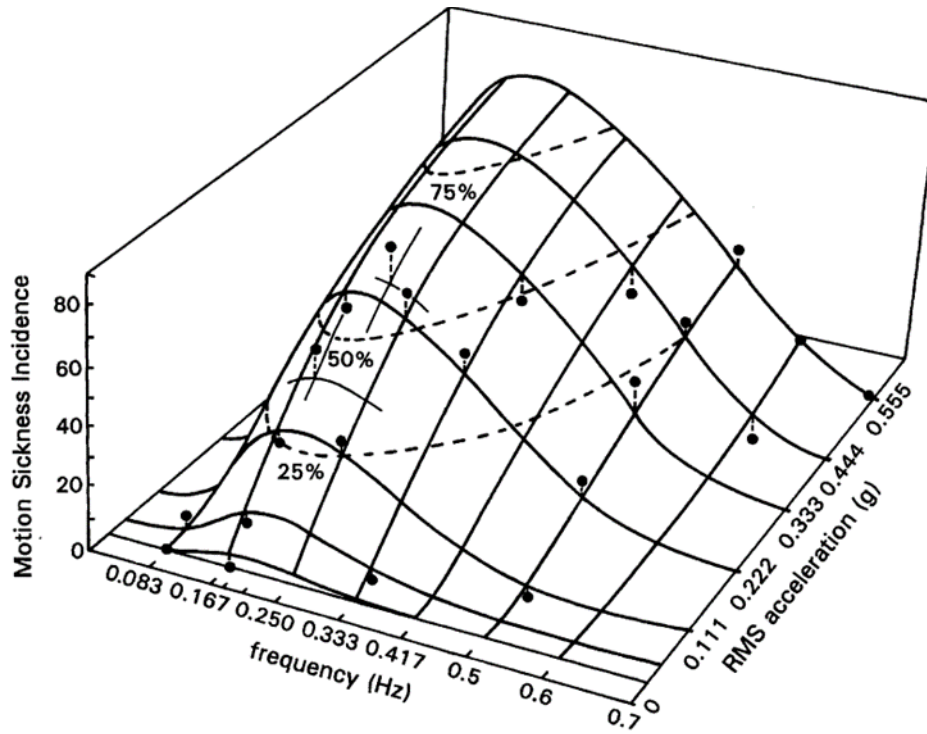
Fig 3-14 Experimental results of MSI as a function of frequency and linear acceleration after 2-hour exposure averaged over 20 participants (Adapted from [78], [98])
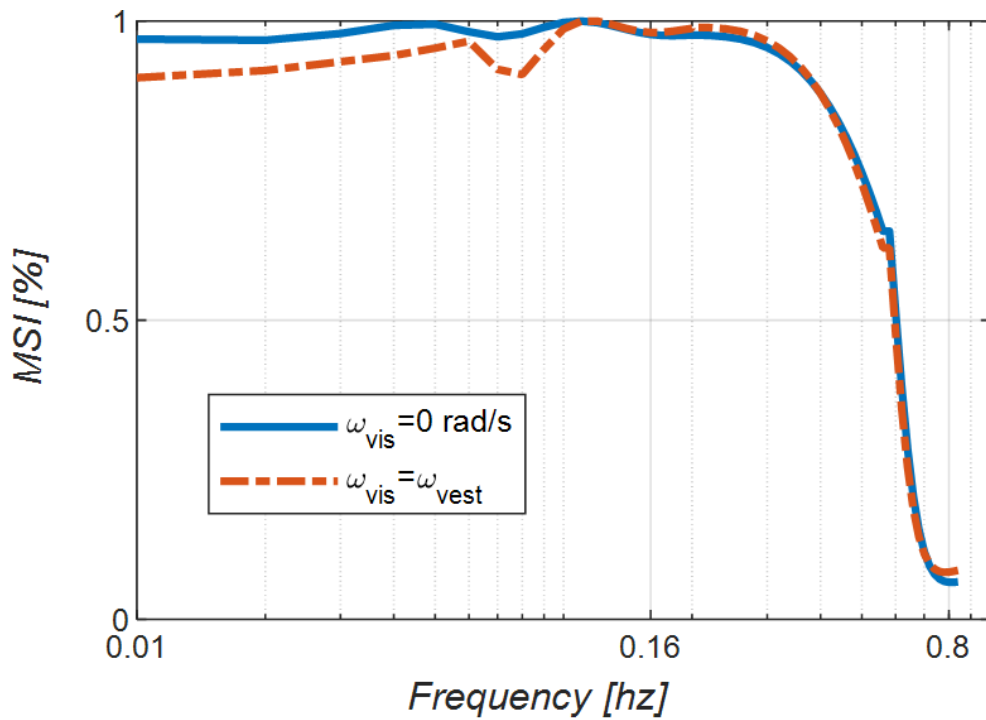
Fig 3-15 Model predicted MSI (normalized) as a function of time for two levels of visual inputs. The vestibular angular velocity input was the same across both cases and its value was 0.5 rad/s RMS at 0.1 Hz about the X-axis

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3.3 Conclusion

In this chapter, a model to predict motion sickness is presented along with a model parameter study to highlight the influence of model parameters on the model's motion sickness predictions. The model predicted motion sickness was compared against experimentally measured motion sickness in literature. However past experimental results are limiting as they do not consider all the inputs that are relevant to MS, especially angular velocity inputs. Future work will include verifying the model MS predictions against other MS datasets and experiments which include rich information about test participants in vehicles performing tasks [103]. These experiments have tracked passenger gaze which can be used to estimate visually perceived motion. Also, the experiment was conducted in real vehicles, in a real-world driving scenario which means that this experimentally measured MS will be as close to real world MS experiences. By tuning the model parameters, the model MS prediction can be improved. Once validated, the model can then be used for designing passenger interactions and experience inside autonomous vehicles and investigate potential motion sickness mitigation strategies. As part of future research, the model can be combined with multibody dynamics simulation models which can simulate vehicle and passenger motion dynamics thereby allowing for the creation of an end-to-end motion sickness simulation that can simulate vehicle route, vehicle motion, passenger motion, and passenger performing tasks in the vehicle.

Chapter 4 Motion Laboratory on Wheels: Development of vehicle based experimental platform to study motion sickness

This chapter presents the development of a vehicle based moving research platform to study the motion sickness response of test subjects (along with their ability to perform NDRTs) in a moving vehicle under realistic driving conditions. Since motion sickness is a complex phenomenon with varied symptoms and responses across individuals, it is necessary to study motion sickness response through human subject experiments. Current motion sickness modelling research (Chapter 2) is not mature enough to replace human subject experiments as the motion sickness models do not have the fidelity and resolution to accurately capture and predict the entire spectrum of motion sickness responses. Therefore, the gold standard for motion sickness research relies on human subject studies.

To elicit a motion sickness response from human subjects/participants, it is necessary to recreate their holistic experience of riding inside a moving vehicle. This holistic experience includes the passenger's visual experience, their inertial motion in the moving vehicle, and other sensations such as audio, touch and odors associated with a moving vehicle. There are three options used in research on motion sickness: (a) static simulators, (b) motion simulators, and (c) vehicles (Chapter 2). Static simulators cannot reproduce the inertial sensation of motion, which is critical to recreate the motion sickness response of a person in a moving car. Motion simulators can reproduce both the visual and inertial sensation of motion. However, motion simulators have a limited range of motion and ability to sustain inertial accelerations for a realistic amount of time. Motion simulators rely on scaling down the longitudinal and lateral motion of a real car (i.e., only producing 50% ~

60% of the acceleration of a real vehicle) since it is not possible for even the most sophisticated motion simulators to fully recreate the experience of being in a moving vehicle [223]. Also, both static and motion simulators are prone to causing 'simulator sickness' in their users which can confound their carsickness response [208]. This simulator sickness can occur due to lack of prior experience with simulators rather than motion like vehicle motion. Therefore, simulators are not an ideal tool to study carsickness response.

Recognizing the above limitations, some prior research has used real vehicles to study motion sickness. Nearly half of the studies (26 out of 55 studies) reviewed in Chapter 2 were conducted using a real vehicle. In most cases, these studies relied on using a passenger car such as a sedan or minivan. One stimuli study used a bus, and another AST study used a van. Each of these research vehicle platforms were unique and customized for a particular study. Therefore, there is no research vehicle that currently exists that would be suitable for the experiments proposed in our research. There is a need for customization and modification of the vehicle. Also, there are practical challenges involved in accessing and sharing these research vehicles across different research studies. For example, some of these research vehicles are based in Europe and are meant to be driven on different sides of the road. In other cases, the research vehicles did not have sufficient space for the integration of the mitigation systems studied in this research. For the investigations described in this research, the research vehicle would have to satisfy specific requirements. This chapter presents those requirements and the development of the Motion Laboratory on Wheels (M-LoW) platform that was designed to support the unique requirements of this research.

4.1 Limitations of Vehicle Simulators: Static and Motion Simulators

There are multiple reviews on the state of the art of vehicle simulators around the world [224],

[225], [226], [227]. These simulators offer many benefits, including (a) easy experimental evaluation of new automotive technologies such as advanced driver assistance systems (i.e., reduce time, costs, and complexity), (b) an important training tool for drivers on new automotive technology, and (c) provide a safe and repeatable environment for experimentation [228]. In this chapter, vehicle simulators have been broadly classified into two types: (a) static and (b) motion simulators (Chapter 2).

Fig 4-1 University of Michigan Transportation Research Institute's (UMTRI's) Fixed-Base Simulator (Static Simulator) [229]

Static simulators (also known as fixed base simulators) are vehicle simulators that do not physically move the person as if they are in a vehicle. These simulators can only recreate the visual and/or audio experience of a passenger in a car using videos or displays. Some may even recreate other sensations of being in a moving vehicle such as haptic vibrations. However, they cannot simulate the inertial effects on a passenger in a moving car such as the accelerations associated with a vehicle cornering or braking. Examples of static simulators commonly used in research include the UMTRI Fixed Base Simulator (Fig 4-1) [230], the Dynamic Research Inc. (DRI)

driving simulator [231], and the Dutch Organization for Applied Scientific Research (TNO) driving simulator [232]. Numerous validation studies have shown that these simulators can reasonably approximate the visual and audio experience of a moving vehicle, and can be used to investigate the behavioral consequences of drivers in various situations [225], [233]. However, static simulators cannot be used to effectively study motion sickness associated with moving vehicles. Motion sickness in vehicles is a consequence of the actual and sensed motion (both visually and through the vestibular organs, Chapter 2). Static simulators can only recreate the visual sensation of motion, not the inertial sensation of motion. In addition, static simulators can cause 'simulator sickness' which can confound a person's carsickness response [225]. Simulator sickness is a type of motion sickness typically experienced during or after exposure to virtual environments such as those used in static and motion simulators [234]. Therefore, static simulators cannot be used to study carsickness response as they do not recreate inertial motion of a moving vehicle and can cause confounding response due to simulator sickness.

Motion simulators (also known as moving base simulators) are vehicle simulators that move the person as they would if they were in a moving vehicle. These simulators attempt to recreate the accelerations and velocities experienced by a person in a moving car. Motion simulators may also include videos or displays to recreate the visual experience of a passenger in a car in addition to the inertial experience. Current research literature includes several extensive reviews of the motion simulators developed globally [235], [236]. Examples of motion simulators commonly used in research include the National Advanced Driving Simulator (NADS) (Fig 4-2) [237], University of Leeds Driving Simulator (UoLDS) [238], and the SIMONA Research Simulator (SRS) (Fig 4-3) [239]. These motion simulators vary in the degrees of freedom of motion they provide, amount of acceleration and angular velocities, and the mechanisms used to provide the

motion [236]. However, even the most advanced motion simulators cannot replicate the motion of a vehicle exactly.

Fig 4-2 National Advanced Driving Simulator (NADS) at the Driving Safety Research Institute, The University of Iowa [240]

NADS is one of the most sophisticated motion simulator which is capable of providing peak vertical accelerations of 1g (9.8 m/s^2) and peak lateral accelerations of 0.6g (6 m/s^2), with a peak velocity of less than 15 mph (< 7 m/s) [237]. These accelerations are representative of a real vehicle, but the peak velocity of a vehicle can be much higher than 15 mph during realistic driving conditions. Since the maximum range of motion is limited to just under 10m, this limits the amount of time that the simulator can sustain acceleration. For example, a car taking a turn at a roundabout at a speed of 15 mph (6.7 m/s) traverses a distance of approximately 30m to 45m [241]. At a constant speed, this can take the vehicle approximately 6 seconds. The NADS motion simulator cannot simulate that amount of acceleration (and duration of acceleration) which is experienced during this motion and must rely on motion scaling to approximate this motion [223]. Validation

studies of motion simulators have suggested that even with motion scaling, motion simulators cannot capture the full experience of passenger in a moving vehicle [238], [242].

Fig 4-3 SIMONA Research Simulator at The Delft University of Technology [243]

In summary, the following are the key limitations of static and motion simulators in investigating the motion sickness response of vehicle passengers (i.e., carsickness):

1. Static simulators cannot recreate the inertial motion experienced by vehicle passengers, and therefore cannot illicit an accurate motion sickness response. Static simulators cannot cause motion sickness response due to the inertial consequences of being in a moving vehicle.

2. Motion simulators can recreate some of the inertial motion experienced by vehicle passengers, but the duration and amplitude of these accelerations and motions is limited and cannot reproduce the full inertial consequences of a moving vehicle.

3. Both static and motion simulators are prone to simulator sickness, and this can confound the motion sickness results associated with being a vehicle passenger. It is impossible to

isolate the effects of simulator sickness from the effects of motion sickness due to moving vehicles.

4.2 Current Research Vehicle Platforms

Several publications in prior literature specifically discuss the development of these research vehicle platforms to study human factors such as motion sickness and situational awareness in vehicle passengers [244], [245]. These research vehicle platforms are highly diversified in their capabilities and applications. Some studies rely on largely unmodified passenger vehicles [121]. Other studies make minimal modifications to suit the study designs such as adding onboard displays [123], [129], [137] or basic instrumentation [52], [135], [136], [141]. The instrumentation often includes sensors such as inertial measurement units to estimate the acceleration of the vehicles, and other sensors to track the speed of the vehicle. In summary, these research vehicles are highly customized and, in most cases, require at least some modifications before they can be used to study the effects of motion sickness. It is highly impractical to share or access these vehicles across different research groups or studies due to practical and logistical constraints. In most cases, each research group designs and builds their own research vehicle platform to study the effects of a moving vehicle on a person. This section is focused on discussing the capabilities of the most sophisticated and capable research vehicle platforms in literature, namely the research platforms developed by (a) Jones et al. [244], (b) Karjanto et al. [245], and (c) Hainich et al. [148]. These three research vehicles are representative of the other research vehicles reported in literature (Chapter 2).

Jones et al. research vehicle is a four door 2007 Honda Accord sedan. The vehicle was equipped with various sensors that allowed for measuring the motion of the vehicle. The instruments included inertial measurement units, GPS, cabin temperature and humidity, and seat pressure

sensors. In addition, the cabin was also equipped with RGB and depth sensing cameras to track the movement of the occupants. The camera also captured the facial expressions of the occupants. The primary purpose of the research vehicle was to study the motion sickness response of various participants. The research vehicle required a human driver who was trained to ensure repeatability in driving. The vehicle was also designed to be operated on both a test track and public roads. Since the vehicle was a sedan, there was enough space for four occupants. This research vehicle is primarily used to understand the motion sickness response of vehicle occupants, not to investigate motion sickness mitigation systems. There was limited space for integration of certain MS mitigation systems such as an active seat. For example, an active seat system requires a lot of cabin space, and in prior research they have used a large van instead of sedan for such experiments [161]. In addition, the research vehicle does not restrict the outside view for the occupants. Prior work has shown the role that visual information can play in motion sickness response [246]. When investigating motion sickness mitigation systems, this visual information is a source of uncontrolled variance in the data [247]. While allowing an unobstructed view of the outside environment for occupants is more natural, it is typically obstructed for motion sickness mitigation research [148], [245].

Karjanto et al. research vehicle is a Renault Espace IV minivan (year not reported). The vehicle was modified to block the occupants' view of the outside environment as this research vehicle was developed to study motion sickness mitigation systems. By blocking the outside view, the researchers hope to keep the occupants focused on the NDRT. Curtains on the vehicle windows were used to block the outside view. The curtains allow for flexibility with regards to vehicle setup, allowing for both obstructed and unobstructed view of the outside depending on the needs of the research study. The vehicle was equipped with various sensors that allowed for measuring the

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motion of the vehicle. The instruments included accelerometers, GPS, and observation cameras. The research vehicle required a human driver who was trained to ensure repeatability in driving. The vehicle is instrumented with a driver feedback device called Automatic Acceleration and Data Controller (AUTOAccD) [248]. While Jones et al. relied on driver training, this research vehicle relies on the AUTOAccD device to ensure repeatability in driving. A key limitation of this research vehicle is that it relies on manual triggering of the MS mitigation systems being investigated. An onboard researcher uses visual markers placed on the test track, along with apriori knowledge of the research vehicle path, to manually trigger the onboard motion sickness mitigation system. This manual triggering of the MS mitigation systems leads to imprecision when investigating preemptively triggered mitigation systems. Studies with this research vehicle do not provide any information regarding the precision of this triggering [132], [145], [167].

Hainich et al. research vehicle (called FASCar-II) is a Volkswagen Passat Wagon minivan. Unlike the previously discussed research vehicles, this vehicle is capable of automated driving. However, it is not allowed to operate on public roads in automated driving mode. The automatic driving mode can only be used on a test track. The vehicle relies on laser scanners and long-range radar sensors on the front and rear bumpers to perceive its environment. This data along with high precision GPS and inertial measurement units that measure the vehicle motion are used to support the automated driving mode. Like the Karjanto et al. research vehicle, the FASCar-II also uses curtains to limit the occupants view outside the vehicle. However, unlike any of the previously discussed research vehicles, since FASCar-II can be controlled automatically, they rely on software triggered mitigation systems. FASCar-II uses steering wheel information to determine when to trigger the MS mitigation system onboard the vehicle. Specifically, the vehicle relied on visual stimuli for motion sickness mitigation. Using the automated vehicles controllers, 2 seconds prior

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to the steering wheel input, the sensory stimuli system is triggered. A software triggered sensory stimuli system is expected to be more precise than a manually triggered system. However, this study does not provide any information regarding the precision of sensory stimuli system triggering.

In summary, there are a variety of research vehicles used to study motion sickness in vehicles. They are often customized and suited for specific experimental study requirements. To ensure repeatability in driving, they either rely on training drivers or on software control of the vehicle. However, the precision of software control of vehicle comes at the cost of technical complexity and prohibitive cost as compared to manually driven vehicles. Also, automated vehicles pose regulatory and safety problems when operated on public roads. Therefore, they are typically restricted to test track use only.

4.3 Requirements for Motion Laboratory on Wheels

Based on the design of research vehicles discussed above, and the needs of this research study in investigating the motion sickness mitigation systems, the following requirements must be met for by a motion laboratory on wheels:

1. *Ability to emulate driving environment for vehicle occupants* – The research vehicle must recreate the experience of an automated vehicle for the occupants. This means that the occupants must believe that the vehicle is controlled by a computer, and not a human operator. This perception can also be created through deception, such as using the "Wizard of Oz" approach developed by prior studies [247]. By creating a physical barrier between the vehicle operator and the passenger which limits the passenger ability to determine how the vehicle is controlled, the passenger can be deceived into believing that a manually driven vehicle is actually an automated vehicle.

2. *Precise/Repeatable driving* – Typically studies involve some kind of repeated driving style across various test conditions. Across these repeated driving instances, it is necessary to ensure repeatable driving so that the occupant experiences similar accelerations and other vehicle motions. Since motion sickness response is closely related to vehicle motion, repeatable vehicle motion across test conditions is required to analyze the effect of any mitigation system fairly and accurately.

3. *Sufficient space and ability to integrate motion sickness mitigation systems* – Certain mitigation systems investigated in this study such as the active seat system require sufficient cabin space inside the vehicle for operation. Sedans and other passenger vehicles have limited cabin space.

4. *Blocking/Limiting the vehicle occupant's view of the outside* – Since information about the vehicle's environment influence motion sickness response, the view of the outside is a source of uncontrolled variance in the motion sickness. To isolate and study the efficacy of MS mitigation systems, it is necessary to be able to control and limit the view of the outside environment of the research vehicle. The vehicle must have the ability to turn the outside view of the vehicle ON or OFF for the vehicle passengers, depending on the experimental needs.

5. *Instrumentation to capture the motion of both vehicle and its occupants, and physiological response of occupants* – Motion of the vehicle and the occupant are correlated to the occupant's motion sickness response. A research vehicle used to study motion sickness must have sufficient instrumentation to characterize the motion of both the vehicle and the occupant. In addition, since motion sickness is a physiological response, instrumentation should include measurements of occupant's physiological parameters such as heart rate,

heart rate variability, perspiration, muscle activity, etc.

6. *Precise/Repeatable triggering of the motion sickness mitigation system* – A key component of this research is the accurate and precise preemptive triggering of the mitigation systems. Manual triggering of the mitigation systems is prone to human error. Therefore, a software-controlled automated operation of the MS mitigation system along with an assessment of its precision is required to assess the efficacy of preemptively triggered MS mitigation systems.

4.4 Development of Motion Laboratory on Wheels Research Platform

This section provides a discussion of the development of the vehicle platform including onboard power, onboard computation and instrumentation, and real time software used to trigger onboard systems preemptively in anticipation of vehicle motion events. In addition, other research tools critical to studying motion sickness with human subjects/participants such as the representative NDRT, and UMTRI motion sickness scale are also discussed in this section.

4.4.1 Vehicle: Ram ProMaster Cargo Van

An exhaustive search was conducted to find a vehicle that met the above-identified requirements for a motion laboratory on wheels. A 2018 Ram ProMaster Cargo Van was chosen as the vehicle platform for the Motion Laboratory on Wheels (Fig 4-4). The van has a unibody chassis, like most passenger vehicles, and has similar driving characteristics as some large passenger utility vehicles (i.e., SUVs). The unibody construction also offers the benefits of improved handling and quieter cabin, just like typical passenger vehicles [249]. The van also has sufficient space to accommodate the integration of the various mitigation systems involved in this study, along with the sensors and computation required to support the study. The van is manually operated and rated to carry

passengers onboard.

To emulate the experience of an automated vehicle, the van relies on the "Wizard of Oz" approach discussed earlier. There is a physical barrier separating the driver from the vehicle occupant (Fig 4-5). The physical barrier splits the van into two spaces: the occupant space (blue box), and the researcher space (green box) (Fig 4-5). The researcher space is used to drive the vehicle and monitor the onboard participant. The occupant space is where the onboard participant is seated and includes various instruments to monitor the participant. As part of the experimental design, to eliminate variance in motion sickness response due to visual information of the outside environment, the vehicle was designed to restrict the occupant's view of the outside environment. In addition, by limiting the view of the outside environment, passengers cannot memorize or learn the test path used for the study thereby preventing any learned effects from biasing the data.

The van has sufficient space in the "occupant" area, allowing for more than one person to occupy the vehicle and for researchers to interact with and instrument the test participants in the beginning of the study (Fig 4-6). The occupant area was modified to allow for the integration of up to two tilting seat (i.e., active seat) systems using a system of floor mounted rails to attach different seat systems to the van floor. The walls of the van are wide enough (unlike a typical sedan or minivan) such that a tilting seat can tilt left or right for up to $15°$ without any danger of contacting the walls. Since the view of the outside environment is restricted for the participant, the occupant area was modified to include sufficient lighting and an air conditioning system to ensure a consistent and comfortable temperature and environment.

Since the van is manually operated to emulate automated driving, it relies on extensive driver training for consistency. Drivers practiced and memorized the path used during the study. In addition, acceleration data from their driving was analyzed and used to provide feedback to drivers

to reduce variance in their driving. In addition, driving aids such as software-controlled LED lights are used to inform the driver when to stop and start driving again to ensure repeatable braking and stop behavior. The LED lights were installed in the driver space, in easy view of the driver. With appropriate driver training and custom driving aids, the drivers were able to follow the designed path closely.

Fig 4-4 Motion Laboratory on Wheels (drivers' side external view)

Driver training ensured that the mean deviation in longitudinal and lateral acceleration across all rides. To demonstrate this, an analysis of a subset of the data was conducted. From data for over 70 rides, it was shown that mean deviation in both lateral and longitudinal acceleration was limited to less than 0.6 m/s^2 (Fig 4-7). Also, the GPS based position of the vehicle across over 70 rides is shown in Fig 4-8, Left. The mean lateral deviation from the designed path was 1.5m or less than the width of the van. The maximum lateral deviation from the designed path was 4m or just over two times the full width of the van (Fig 4-8, Right).
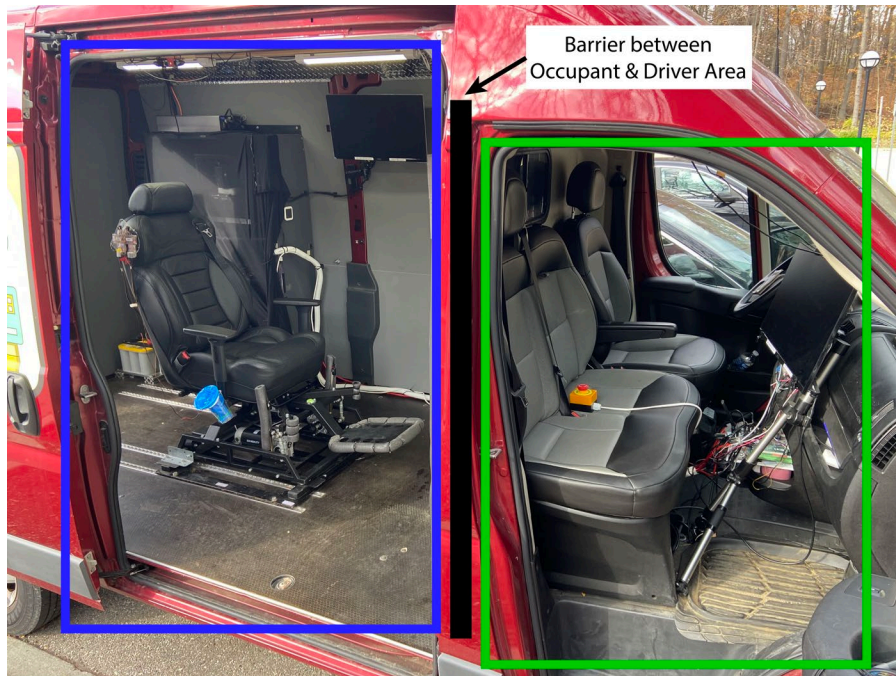
Fig 4-5 Motion Laboratory on Wheels (passengers' side external view), Physical barrier separating the "Driver" area (green box) from the "Occupant" area (blue box)

Fig 4-6 Detail view of the occupant space with no external view.
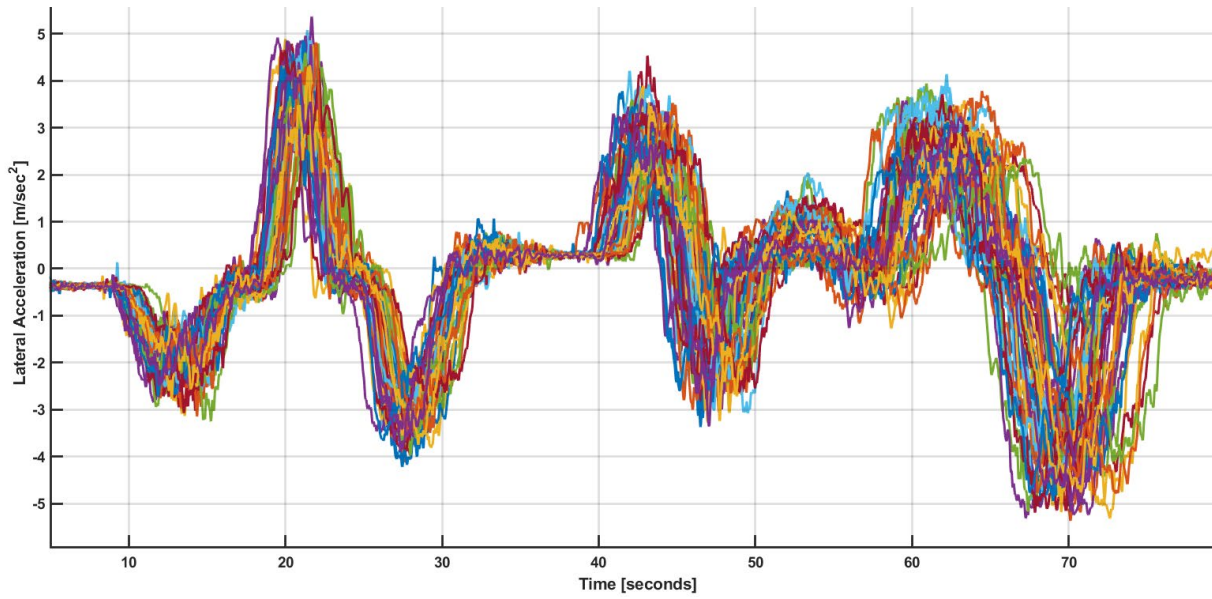
Fig 4-7 Sample lateral acceleration data of Motion Laboratory on Wheels for over 70 drives
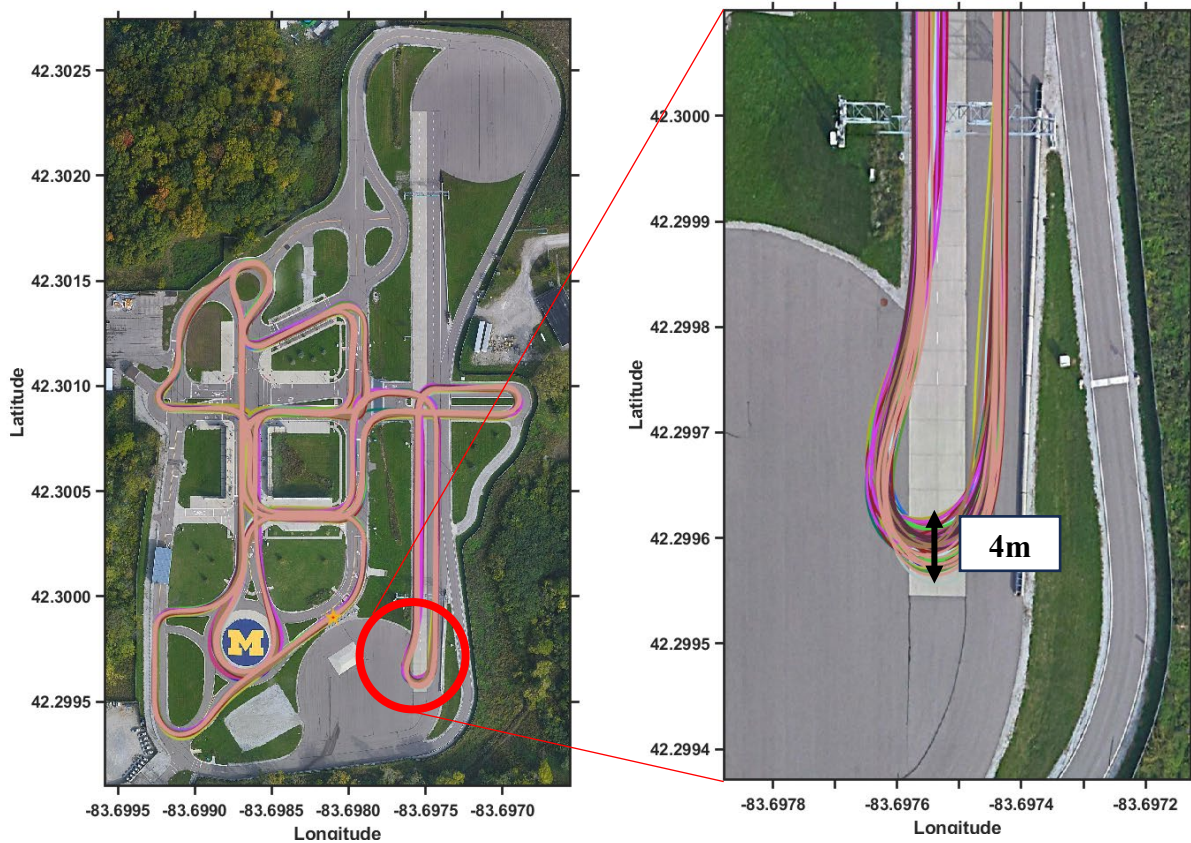
Fig 4-8 (Left) GPS Position of Motion Laboratory on Wheels for over 70 drives overlaid on satellite image of the Mcity test track. (Right) Detailed view of path section with maximum path error of 4m or just over width of the van (shown in by red circle in Left image)

4.4.2 Onboard Power

Any moving research platform would require computation to acquire data from various sensors and conduct pre-programmed actions to support the experiment. This computation and instrumentation would require electrical power. An approximate power budget was used to determine the onboard power requirements based on conservative estimates of the quantity of onboard systems (Table 4-1). Power consumption information was extracted from component data sheets or reasonable estimates of other similar components. Major components such as the computer, tilting seat, data acquisition, and displays draw the most power. Other items such as computer peripherals (e.g., keyboard, mouse, USB Hubs), instrumentation, and audio system draw less power even though multiple units are used onboard the vehicle. The total continuous power requirement is approximately 1700 W with a total peak power requirement of 2300 W.

ONBOARD COMPONENT	MAX QUANTITY	CONTINUOUS POWER [W]	PEAK POWER [W]
Computer	1	400	650
LED Display	3	250	250
Computer Peripherals	Multiple	120	120
Haptic Stimuli System	1	30	60
Instrumentation & Data Acquisition	Multiple	260	260
Tilting Seat System	1	400	750
Audio System (Microphones & Speakers)	Multiple	180	180
TOTAL POWER [W]		**1640**	**2270**

Table 4-1 Approximate Power Budget for Onboard Components

Onboard an internal combustion vehicle such as the Ram ProMaster van, the most common electrical power available is DC power generated by the alternator (which converted the engines output mechanical power to electrical power) and stores it in batteries. However, most onboard components were designed to be operated by AC power from the electrical grid. Therefore, an

inverter was used to convert the vehicles DC power to AC power. The van's alternator was rated for approximately 1700 W. Therefore, to account for the peak power consumption, an auxiliary battery system was included (Fig 4-9). The auxiliary batteries are connected to the vehicle battery for trickle charging. To ensure that the vehicle battery is protected from being completely depleted, an automatic battery isolation system was used to isolate the vehicle battery from the auxiliary batteries. In case the auxiliary batteries are depleted, an external battery charger port was also included to recharge the auxiliary batteries using power from the grid (and not the engine). Therefore, any component requiring electrical power and with power consumption less than the capacity of the vehicle alternator can be integrated into the research vehicle.

Fig 4-9 Onboard Auxiliary Power System, including (a) 2x Auxiliary high-capacity batteries (green box), (b) an automatic battery isolation system (blue box), and (c) external battery charging system (red box)

4.4.3 Onboard Computation

To support all data acquisition and software control of the MS mitigation systems, an onboard computer was required. This computer was also the primary interface for the onboard researcher. A custom computer was built to provide sufficient computing and processing power. The computer used an Intel Core i9-10900K 10-Core CPU, capable of a clock speed of 3.7 GHz during normal operation and 5.3 GHz during 'turbo' mode. The computer had a RAM of 32 GB and an internal solid state memory drive of 1 TB. The computer had multiple USB ports to interface with the various instrumentation and data acquisition systems on board. It also had enough ports to communicate with the various displays, audio systems, and other computer peripherals (e.g., keyboards, mouse) required to interact with the computer.

4.4.4 Onboard Instrumentation

The van is fitted with various sensors to track the motion of the vehicle and its occupants. The onboard instrumentation consisted of two types of instrumentation: (a) instrumentation to track the motion of the vehicle, and (b) instrumentation to track the motion and physiological response of the vehicle occupant. A complete list of sensors and instrumentation is described in Table 4-2. To communicate with all the sensors, open-source Arduino microcontrollers were used. Typically, sensors communicated the data to Arduino via analog connections or via Inter-Integrated Circuit (I2C) digital communication. USB communication was used to interface the Arduino microcontrollers with the computer. To streamline all data acquisition, a data acquisition program was written using MATLAB software.

To track the motion of the vehicle, inertial measurement units and GPS sensors were used. An inertial measurement unit (IMU) was placed at or close to the center of gravity of the vehicle. This IMU was used to record the acceleration and angular velocity of the vehicle with respect to the

world in 3D space. A precision GPS sensor was used to record the real time position of the vehicle, along with GPS estimated vehicle speed, heading, and altitude. Since the vehicle was driven manually, sensors were used to track the steering wheel position, and to determine when the accelerator and brake were pressed by the driver. These sensors were used to record data used for driver training and to track driving precision across different drivers. Additionally, contact pressure sensors were placed on the accelerator and brake pedals to track when the driver applied pressure on those pedals during driving. Brake and accelerator pedal data was also used for driver training and ensuring consistency across drives. A camera vision and (AruCo) marker-based position tracking sensor was used to track the steering wheel rotation precisely and accurately to within a few degrees [250]. In addition, a combined temperature and humidity sensor was used to track the occupant's environment and ensure consistency across repeated test participations.
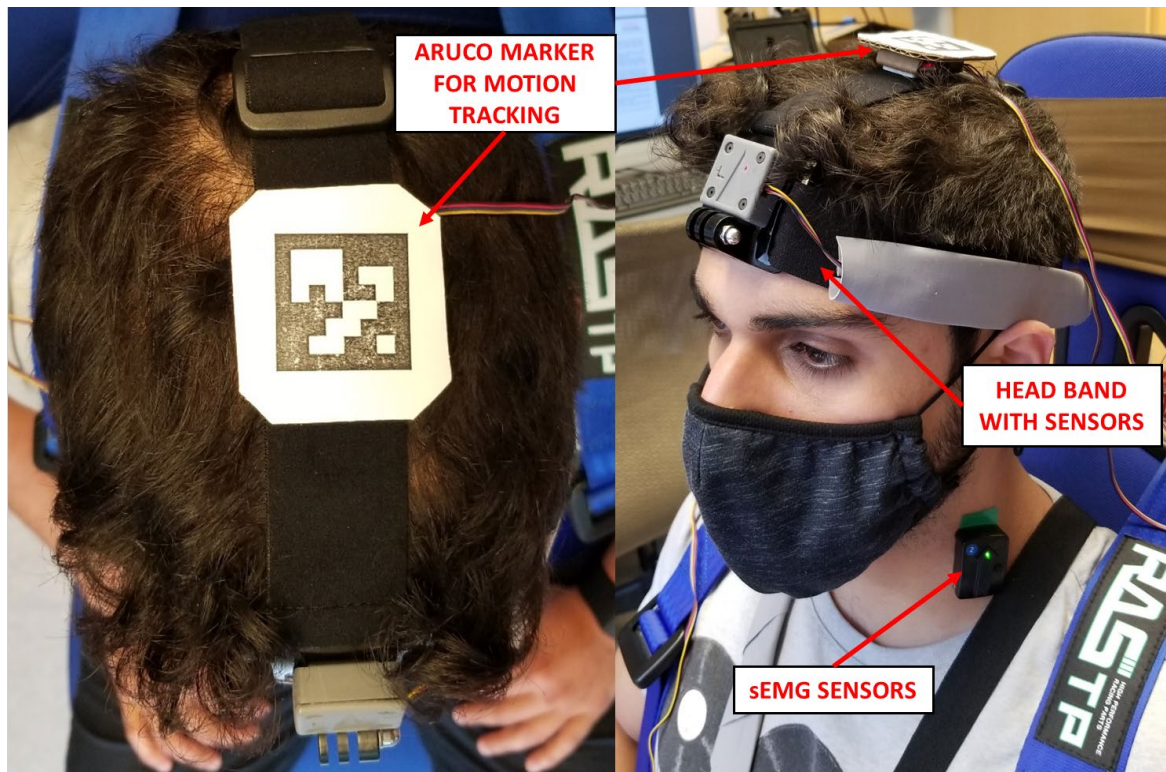
Fig 4-10 Demonstration of the instrumentation used to track passenger position and physiological response. Detailed view of the sensors used to track motion and position of head, and muscle activity at the participants neck and upper back.

Various sensors were used to track the motion and physiological response of the occupants (Fig 4-10 and Fig 4-11). Various inertial measurement units were placed on the occupant's head and torso to track the accelerations and angular velocities of their body in the vehicle. In addition, a camera vision and AruCo marker-based motion tracking sensor was also used to accurately track the angular position of their head with respect to the vehicle as inertial measurement units are susceptible to drift and cannot provide accurate angular position measurements. In some cases, in response to vehicle motion, it is possible that the occupant will simply activate their muscles to

Fig 4-11 Demonstration of the instrumentation used to track passenger position and physiological response. Detailed view of the torso instrumentation and wrist based physiological sensor to track heart rate and perspiration of the occupant

oppose it. This response cannot be recorded by inertial measurement units as the occupant's body does not move with respect to the vehicle or the world. To record muscle activity, surface electromyography (sEMG) sensors were placed at the occupant's sternocleidomastoid and

trapezius muscles. Muscle activity at these specific muscles has been investigated in prior research to comment on motion sickness response, stress, and overall comfort in a vehicle [251], [252]. A research grade wrist based physiological sensor, E4 Empatica, was used to measure the occupant's physiological response in the moving vehicle such as heart rate, heart rate variability, perspiration, and skin temperature [253]. Since there is a physical barrier between occupant and driver areas in the vehicle, multiple cameras, and a two-way audio communication system (consisting of microphones and speakers) was used to facilitate communication between the onboard researcher and the occupant for safety. The video was also used to track and monitor the overall demeanor of the occupant as they experienced motion sickness.

SENSOR	LOCATION	MEASUREMENT	ERROR / RESOLUTION
ICM-20948 9-axis IMU	Occupant Head and Torso Vehicle center of gravity and base of occupant seat	Acceleration, Angular velocity, and Magnetic field in 3 dimensions each	Acceleration: ± 4g, 16 bit Angular velocity: ± 500°/s, 16 bit Magnetic field: ± 4900µT, 16 bit
BNO-080 9-axis IMU	Occupant Head and Torso Vehicle center of gravity and base of occupant seat	Angular position in 3 dimensions	Rotation Dynamic Error: 2.5° Rotation Static Error: 1.5° Rotation Heading Drift: 0.5°/min
GPS NEO-M9N	Vehicle center of gravity (roof mounted antenna)	GPS Position, Speed, and Heading of vehicle	Position Accuracy: ± 1.5 m Heading Accuracy: ± 1° Speed Accuracy: ± 0.05 m/s
DHT22 Temperature and Humidity	Occupant area in vehicle	Temperature and Relative Humidity	Temperature Accuracy: ± 0.5°C Humidity Accuracy: ± 5%
Force Sensitive Resistor	Vehicle brake and accelerator pedals	Contact pressure of driver when pressing pedals	Force Error: ± 6%
E4 Empatica Physiological Sensor	Occupant wrist, worn on non-dominant hand	Heartrate Skin temperature	Heartrate Accuracy: ± 12 bpm Temperature Accuracy: ± 0.5°C
Delsys Wireless sEMG	Occupant neck and back	Muscle activity	Range: 11 mV Channel Noise: < 1µV RMS
AruCo Marker Position Tracking	Occupant Head and Torso Vehicle steering wheel	Angular position	Angular position error: ± 2°

Table 4-2 Summary of Instrumentation Sensors

4.4.5 Real Time GPS-based System Triggering Software

To investigate the efficacy of preemptive solutions to motion sickness mitigation using real vehicles and under realistic driving conditions, it was critical to (accurately and) precisely trigger the actions of the mitigation systems onboard the research vehicle. To ensure precise and accurate triggering, a real time global positioning system (GPS) based stimuli triggering software was used (Fig 4-12). The software used apriori knowledge of the test path.

For example, if the research vehicle is approaching a right turn on the predetermined path, the software used the real time GPS position to determine if the vehicle had entered the predefined geofence (Time A, Fig 4-12). When the software determined that the vehicle had entered the geofence (Time B, Fig 4-12), using real time instantaneous GPS position and vehicle speed, the software determined the instantaneous time to the start of the motion event (i.e., right turn). If the instantaneous time to the start of the motion event was approximately equal to (or less than) the preemption time (e.g., 3 seconds), the software triggered the appropriate mitigative system onboard the vehicle.

In addition, the software can also account for variations in the driving styles of different drivers. For example, if it is known from prior data that driver 'A' tends to slow down more than usual when approaching a specific right turn (during Time B, Fig 4-12), then the software can slightly alter the preemption time for that right turn event to account for the reduced speed of driver 'A' to ensure that the mitigation system is not triggered too early (i.e., more than the defined preemption time to the start of the turn).

The software ensured that the average error in preemption times was 300 milliseconds, with a median error of 120 milliseconds (Fig 4-13). The inter-quartile range is approximately 200 milliseconds. Across all the data collected experimentally (over 2000 preemptive trigger events),

less than 7% (135 preemptive trigger events) of the preemption times are outliers (Fig 4-13). Prior work on preemptively triggered sensory stimuli systems had not provided any information regarding the precision of the sensory stimuli system triggering. This is the first research that establishes a precision benchmark for future studies using preemptively triggered sensory stimuli systems.
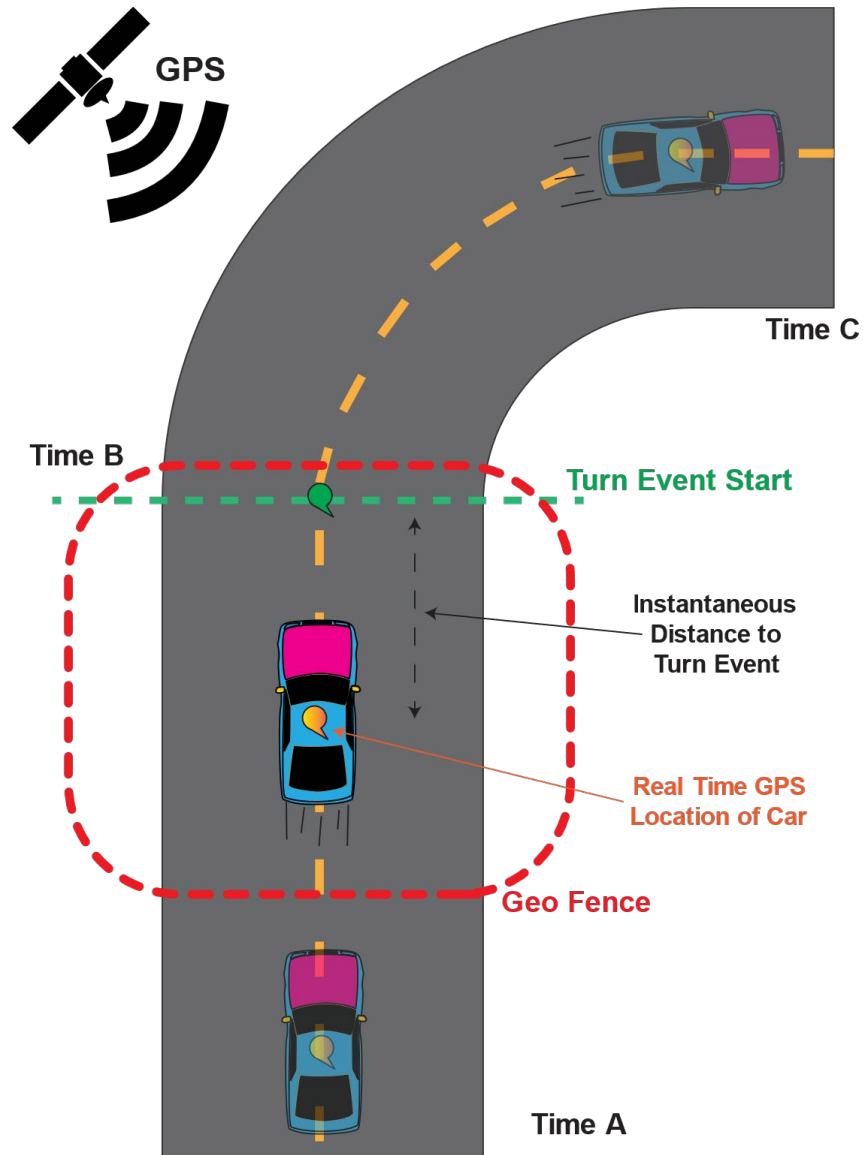
Fig 4-12 Real Time GPS-Based Preemptive Triggering of Mitigative Systems
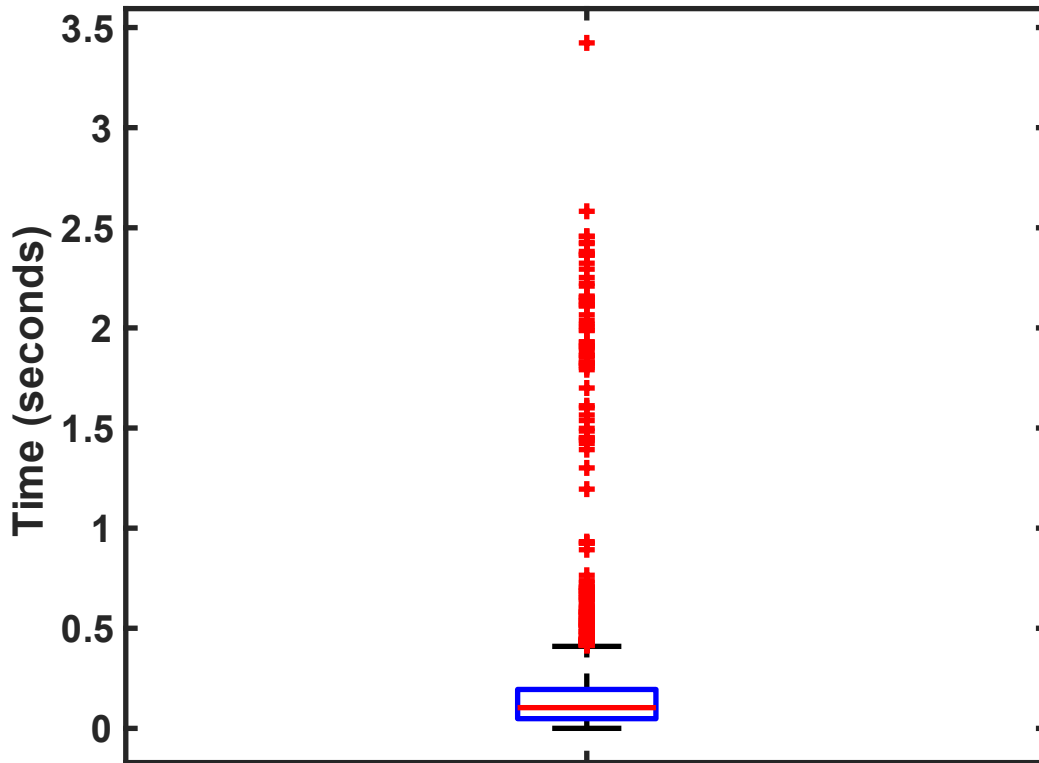
Fig 4-13 Boxplot of Error in Preemption Trigger Times

4.5 Development of Other Research Tools

In addition to the M-LoW research vehicle, this study required other crucial research tools to address the gaps identified in current literature (Chapter 2). These include: (a) A Representative Non-Driving Related Task (NDRT or task) and (b) University of Michigan Transportation Research Institute (UMTRI) motion sickness scale.

4.5.1 Representative Task: Non-Driving Related Task (NDRT)
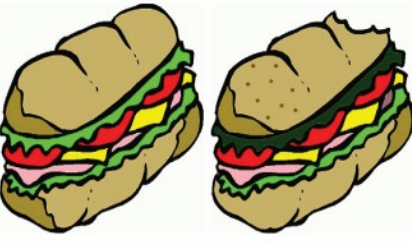
Typical tasks used in prior literature include (a) N-back [254], (b) Reading, (c) Watching videos, (d) Listening to audio, and (e) playing video games (Section 2.2). While these types of tasks have been widely used in prior research, it is worth noting that these tasks tend to be monotonous and only partially engage the cognitive system of a person. In a real, more natural scenario, a vehicle occupant can perform a large variety of tasks in succession or even simultaneously. Examples of

naturalistic tasks include holding a conversation with other occupants or over the phone, eating, watching and listening to videos, and some combination thereof [7]. Therefore, a representative non-driving related task must capture this wide spectrum of cognitive engagement. The NDRT in this study is designed to be a combination of low and high cognitive loading questions to better represent the wide range of cognitive burdens an occupant might experience in natural real-world conditions. The task used in this study was administered as a Qualtrics survey on a tablet.

Low cognitive loading questions rely on lower order cognitive functions such as sensation, perception, memory, and attention and concentration [255], [256], [257]. Questions such as spotting the difference between two images, searching for words in an alphabet grid, or finding a hidden object in an image are all considered low cognitive loading (Fig 4-14). High cognitive loading questions rely on a combination of lower and higher order cognitive functions. In addition to lower order cognitive functions, higher order cognitive functions such as language and verbal skills, executive functioning and critical reasoning are required for high cognitive loading questions [255], [256], [257]. Questions such as reading and comprehension, finding a path on a map, arithmetic, and filling in the missing pattern are considered high cognitive loading (Fig 4-15). The task used in the study was adapted from prior research [103].

Participants were asked to perform the task in a lab setting first, before performing the task in the research vehicle. This task performance was used as a baseline measure to assess a candidate's task performance in ideal conditions and identify any bias in the data. For example, if a participant struggles with getting high accuracy in answering word search questions in the lab setting, then they will likely have poor accuracy with word search questions during the experiment too. This result may not be influenced by their motion sickness or any mitigation system.
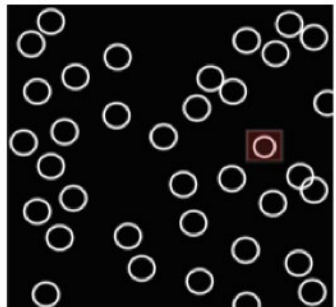
Fig 4-14 Example of Low Cognitive Loading Question Types used in this NDRT
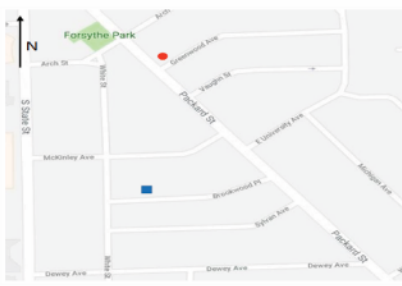
Fig 4-15 Example of High Cognitive Loading Question Types used in this NDRT

4.5.2 Motion Sickness Scale and Self-Reporting

Since there are no direct objective measurements of motion sickness response, the quantification of motion sickness response relies on subjective self-reported estimates in one of the many motion sickness scales used in research (see Chapter 2). Objective sensory measurements of a person's physiological response (e.g., heart rate, brain activity) have been correlated with their motion sickness response in prior literature. However, the correlations of motion sickness with physiological response are not currently robust or reliable enough to capture the nuances of motion sickness. This combined with the high person to person variability in symptoms associated with motion sickness makes subjective evaluation the best way to estimate motion sickness.

The UMTRI Motion Sickness Scale is an improvement on the Fast Motion Sickness Scale. The UMTRI scale has been described in prior literature as a scale that goes from 0 to 10, with 0 being no motion sickness and 10 being such high motion sickness that the person would like the vehicle to come to a stop immediately (Fig 4-16) [103]. Unlike the MISC or other similar scales, the UMTRI scale does not correlate the motion sickness scores to specific symptoms. This allows the scale to account for individual variability. For example, an individual may experience significant motion sickness but may not vomit. Other individuals may vomit even under mild motion sickness conditions. A numerical scale based on the individual's self-perceived intensity of sickness, as opposed to specific symptoms or outcomes, allows for more accurate estimation of motion sickness.

Participants in this research were shown a visual reference of the UMTRI Motion Sickness scale at multiple times prior to in-vehicle testing (Fig 4-16). In addition to the scale, the participants were also given an extensive (but not exhaustive) list of possible symptoms associated with motion sickness (Table 4-3) [244]. These symptoms were a compilation of symptoms commonly

associated with motion sickness in prior research. It was important to 'educate' the participants about these symptoms so they could be more self-aware of their own motion sickness response and report any changes promptly. However, they were told not to limit themselves to the symptoms listed and could report any change in their overall experience during the in-vehicle testing. The researcher would prompt the participants to report their motion sickness score every 90 seconds. By recording motion sickness response throughout the experiment, we could track the rate of motion sickness accumulation.

UMTRI Motion Sickness Scale

Fig 4-16 UMTRI Motion Sickness Scale with smiley face visual aids shown to study participants

SENSATION GROUP	EXAMPLES
Discomfort felt at the head	Sensations can include tension or pressure, fogginess, a fullness of the head, headaches, changes in mood, irritability, eye strain
Body temperature changes	Sensations of being very warm or cold, feeling of body warmth, excessive sweating, clammy/cold sweats
Drowsiness	Yawning, shortness of breath or heavy/labored breathing, feeling of haze or drowsiness, fatigued/tired, inability to concentrate or focus
Dizziness	Lightheaded-ness, feeling shaky, disoriented, sense of spinning, dizziness with eyes open/eyes closed, whirling, tilting, rocking, falling or motion, imbalance
Unpleasant feelings in the mouth	Sensations can include increased salivation or drooling, dry mouth, burping
Discomfort felt at the stomach	Sensations include general nausea, feeling ill or uneasy, hypersensitivity and awareness of stomach movements, queasiness, feeling like imminent vomiting or vomiting, feeling bloated
Others	Any sensation that is abnormal or atypical leading to feeling unpleasant

Table 4-3 Summary of common symptoms and sensations associated with Motion Sickness

4.6 Conclusion

This chapter presents the design and development of the Motion Laboratory on Wheels (M-LoW) research vehicle platform. The M-LoW is a unique research platform that allows for the study of an occupant's response (i.e., physiological, cognitive, and physical or biomechanical response) including motion sickness and comfort, in a moving environment. The M-LoW was designed to ensure that the research vehicle could emulate the experience of riding in an automated vehicle for its occupants using the Wizard of Oz approach. Through extensive training of the drivers, highly repeatable driving was ensured even though the vehicle was manually driven. Over hundreds of drives, the peak mean lateral position error of vehicle on the path was less than 4m. In addition, mean variation in lateral and longitudinal acceleration of the vehicle was limited to less than $0.6m/s^2$.

The vehicle included multiple sensors to track its real time motion and GPS position. The M-LoW also included software capable of precisely and preemptively triggering various onboard motion sickness mitigation systems such as a haptic stimuli and tilting seat system. Throughout the study, the mean error in preemption times was limited to 200 milliseconds (less than 10% error) with minimal outlier events (less than 7% of all events). The M-LoW also included various sensors and instrumentation so that the occupant's motion and physiological responses to vehicle motion can be captured. In addition to the M-LoW, this chapter also presented other key research tools such as the vehicle path, representative task, and the UMTRI motion sickness scale.

Chapter 5 Haptic Stimuli System to Mitigate Motion Sickness

This chapter presents the experimental design, execution, and results from a human subject study (or experiment) evaluating the efficacy of a preemptively triggered haptic stimuli system in mitigating motion sickness. Prior research has shown that haptic stimuli can help reduce CS. However, investigations studying efficacy of preemptively triggered haptic stimuli in reducing CS when the passenger is performing tasks and performed under realistic driving conditions are limited (see Chapter 2, Section 2.4).

A study was conducted to quantify passenger CS response while performing representative task along with preemptively triggered haptic stimuli. Twenty-four healthy adults with varying levels of self-reported motion sickness susceptibility participated in the study, across three test conditions conducted over three days, on a closed test track in a research vehicle (M-LoW). This is the first in-vehicle study that assessed both CS response and quality of passenger task performance for a diverse sample of passengers under realistic driving conditions (on a test track).

5.1 Introduction and Background

It is expected that passengers of autonomous vehicles will want to focus on work and/or entertainment during their commute [7]. Engaging in these work or entertainment activities/tasks in a moving vehicle significantly exacerbates carsickness (CS) or motion sickness and leads to increased discomfort [7], [15], [103], [258], [259], [260]. In addition to causing discomfort, CS in moving vehicles can also significantly impact the performance of tasks, such as motor and arithmetic skills [23], [25], [26], [27], [64]. Therefore, mitigating CS while preserving task

performance is a key adoption challenge that needs to be solved to realize the future that autonomous vehicles promise (AV) [16], [61], [261].

It has been observed that in manually driven cars, the driver is never carsick. Drivers are road focused (i.e., observing the road ahead) and are in control of the car [48], [49]. This allows drivers to anticipate how the car (and by extension they themselves) will move in response to the road and their driving actions. It has been theorized that drivers use this information to take subtle preemptive corrective actions (e.g., move their head and stiffen their neck muscles, activate their core muscles, etc.) in response to car motion [48], [49], [61]. This combination of anticipation (of what is about to happen next) and the corrective preemptive actions leads to drivers not feeling CS. The benefits of anticipation can be recreated for passengers using sensory stimuli systems. Based on a review of current literature (see Chapter 2), there is evidence to indicate that preemptively triggered sensory stimuli can help reduce carsickness, and that preemptively triggered sensory stimuli may be more effective than reactively triggered sensory stimuli at reducing carsickness (based on the higher proportion of preemptively triggered sensory stimuli studies demonstrating a reduction carsickness as compared to reactively triggered sensory stimuli studies). Therefore, this research leverages the benefits of preemptively triggered sensory stimuli, while addressing some of the gaps in existing research literature.

Sensory stimuli systems provide passengers with information about vehicle motion events encoded in various sensory stimuli and help reduce carsickness [125], [129], [132], [141], [145], [193], [262]. Sensory stimuli can include visual stimuli, auditory stimuli, olfactory stimuli, and touch stimuli [137], [145]. Specifically, preemptively triggered sensory stimuli systems can provide anticipatory information about the upcoming vehicle motion to the passenger which helps reduce carsickness [49], [128], [147], [148], [149], [262], [263]. For example, a preemptively

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triggered audio stimulus can provide encoded information about upcoming vehicle motion through audio such as a single "beep" sound indicating a left turn and a double "beep" sound indicating a right turn. However, the experimental methods used in the studies from current literature have many limitations (Chapter 2, Section 2.4). Namely, these limitations include: (a) lack of realistic driving conditions due to the use of static or motion simulators instead of real vehicles (limitations of vehicle simulators described in Chapter 4), (b) lack of precise preemptive triggering of the sensory stimuli system, and (c) inclusion of the passenger performing a representative NDR task along with an assessment of the task performance.

This research addresses the above gaps in prior work by investigating the efficacy of preemptively triggered APS systems in mitigating CS as evaluated under realistic driving conditions while the passenger is performing a representative real-world task. It is expected that the sensory stimuli system will warn the passenger about upcoming vehicle motion, allowing the passenger to take actions to minimize their sensory conflict, thereby leading to a reduction in their motion sickness. This research leverages the M-LoW research vehicle platform to recreate realistic driving conditions, run on a closed test track to ensure safety and repeatability (see Chapter 4). This research also leverages the UMTRI motion sickness scale, and various instrumentation described in Chapter 4 to track the motion of the vehicle, the passenger, and the passenger's physiological response to the moving vehicle. Also, this research utilizes a representative NDR task (Chapter 4, Section 4.5.1) that will place a cognitive load on the passenger while they are seated in the M-LoW so that their carsickness response can be investigated while they perform a task.

A haptic (or vibrotactile) APS was chosen (as compared to audio or visual APS) as it is expected to be least distracting for a passenger performing a task. It was assumed that visual APS was likely

to interfere with the NDR task that a passenger was performing. Similarly audio stimuli may also distract from the task. For example, audio stimuli might interfere with the passenger having a conversation and visual stimuli might take attention away from the NDR task at hand for the passenger. In addition, it was important to ensure that the specific sensory stimuli chosen must be easy for the passenger to understand. Prior literature has compared error in responding to several types of sensory stimuli, including visual, audio, and haptic. This prior literature demonstrated that there was no significant difference between the response error across visual, audio, and haptic stimuli [264]. Also, current literature already has some evidence that preemptively activated haptic stimuli systems have demonstrated the ability to reduce CS [127], [130], [138], [167], [263]. Therefore, to minimize distraction to the passenger performing a task and provide them with the easiest sensory stimuli to interpret, a haptic APS system was chosen.

Across the current literature on preemptively triggered sensory stimuli studies, varying preemption times between 0 to 5 seconds have been used. There is no evidence to determine the most optimal preemption time to be used. The most common preemption time that was used across most studies demonstrating reduction in carsickness was 3 seconds. It is also known from prior literature on driver perception response times that a driver can take up to 3 seconds to perceive and response to an unexpected situation [265]. Since this research is attempting to recreate the driver experience for the passenger, a preemption time of 3 seconds was chosen. Due to practical constraints, this research did not attempt to determine the optimal preemption time.

5.2 Design of Experiment

This study focused on investigating two specific hypotheses: (1) that preemptively triggered haptic APS can reduce CS even when the passenger is performing a task, and (2) that preemptively triggered haptic APS can help improve task performance of the passenger. Investigating these

hypothesis will help address the gaps in current research identified in Chapter 2. Therefore, to evaluate the performance of the haptic APS, an experiment with three test conditions was devised. The experiment includes two independent variables: haptic stimuli and representative tasks (Table 5-1). Haptic stimuli being 'ON' means that for that test condition the haptic system was operational whereas 'OFF' means the haptic system was not operational. When the haptic system was operational, it provided preemptive stimuli to the passenger informing them about upcoming vehicle motion (additional details on haptic stimuli system are presented in section 5.4). Similarly, representative task being 'ON' means the participant was performing a task during that test condition whereas 'OFF' means the participant was not performing a task. The study has three test conditions as the haptic APS OFF and task OFF test condition was not included (i.e., TC 4).

Since prior research has already demonstrated that performing a task exacerbates CS [103], [260], a comparison between TC 4 and TC 2 is not required. Similarly, prior research has shown that preemptively activated APS systems can be effective in reducing CS [49], [262]. Therefore, a comparison between TC4 and TC1 is not required. Therefore, an experiment with all four test conditions was not required for this study to address the hypothesis defined earlier. To investigate the first hypothesis, that preemptively triggered haptic APS can reduce CS even when the passenger is performing a task, a comparison of motion sickness response and task performance across TC 1 and TC 3 is required. Investigating the second hypothesis, that preemptively triggered haptic APS can help improve task performance of the passenger, required a comparison of motion sickness response and task performance across TC 2 and TC 3.

TEST CONDITION	INDEPENDENT VARIABLES		DEPENDENT VARIABLES
	HAPTIC STIMULI	TASK	1. Self-reported motion sickness scores
TC 1	ON	OFF	2. Accuracy of responses
TC 2	OFF	ON	3. Percentage of questions skipped
TC 3	ON	ON	4. Response time of questions

			5. Qualitative description of experience

Table 5-1 Summary of Experimental Test Conditions and Variables for Haptic APS Experiment

A within-subject design was implemented since motion sickness response has high variation across different individuals, and within subject studies are ideally suited to deal with this variation [266]. Within subject studies also offer other benefits such as less noise in the data, as compared to between subject designs. The order of test conditions was randomized using Latin square randomization to eliminate any order effects and biases. Since it is known that passengers can learn and get habituated to the motion sickness elicited during the study, it was important to eliminate learned effects through the use of randomization of test conditions. Test conditions were conducted with a minimum separation of 48 hours to ensure that any accumulated CS response would not persist from one test condition to the other [244]. All experimental protocols and procedures were evaluated and approved by the University of Michigan Institutional Review Board to ensure the physical safety, data privacy, and confidentiality of any participant in the study [HUM00199425].

5.3 Haptic Stimuli Study Protocol

A systematic and repeatable protocol for researcher and participant interaction was developed to ensure near identical interaction of researchers with participants across repeated participation for test conditions (i.e., repeated participation refers to participating in the multiple test conditions of this experiment). Any deviation in how the researcher interacts and prepares the participant for the test condition can lead to an uncontrolled variance in the experimental data. Broadly, the protocol consists of four stages: (a) Reception, (b) Vehicle Preparation, (c) Vehicle Drive, and (d) Post Vehicle Drive (Table 5-2). This four-stage protocol is repeated for every test condition that a participant participates in.

The first stage is the Reception stage. The research team greeted the participants and as required

by IRB protocols stepped the participant through a consent form and a description of the test condition (Table 5-2, Consent). The researcher also collected demographic and other basic information from the participants, including their height, weight, age, and gender (Table 5-2, Personal Info). To ensure that the participant has a similar motion sickness response across test conditions, the researcher collected information about the participants diet, sleep, physical activity, and mental state to look for any notable deviations from the participants' typical schedule (Table 5-2, Food & Activities). The participant was then instrumented with the various sensors (see Chapter 4, Section 4.4.4) used to track the motion of their head and torso (Table 5-2, Sensor placement). The researcher introduced the representative task to the participant and provided training to help the participant build familiarity with the type of questions and how to answer them (Table 5-2, Task training). After receiving the training, the participant performed the baseline task (Table 5-2, Baseline task). After completing the baseline task, the participant was introduced to the haptic stimuli system used in the study, and they got a chance to experience the haptic stimulation associated with various vehicle motion (Table 5-2, APS training). The purpose of the APS training is for the participant to build familiarity with the haptic stimuli system, and learn the sensory encoding used to provide information about upcoming vehicle motion. As part of the APS training, the researcher would provide haptic signals to the participant and ask them to verbally respond with the vehicle motion event that was encoded in the signal. Only after the participant had accurately identified the sensory encoding multiple times, would the researcher proceed to the next step of the protocol. Finally, once the participant was comfortable with both the task and haptic stimulation system, the researcher introduced the UMTRI motion sickness scale to the participant (Table 5-2, UMTRI motion sickness scale training). It was important for the participants to understand the motion sickness scale as they will use that scale to self-report their motion sickness

response. To ensure that the participant had understood the motion sickness scale, the researcher would address any questions or clarifications that the participant had regarding the motion sickness scale. The researcher also used role play activities with the participant so that the participant could practice using the motion sickness scale. Once the participant was familiar with the motion sickness scale, the researcher could take the participant to the research vehicle for the next stage of the protocol.

PROTOCOL STAGE	RECEPTION	VEHICLE PREPARATION	VEHICLE DRIVE	POST VEHICLE DRIVE
ACTIVITIES	• Consent • Personal Info • Food & Activities • Sensor placement • Task training • Baseline Task • APS training • UMTRI motion sickness scale training	• Seat participant in occupant space • Safety briefing • APS training • Task training • UMTRI motion sickness scale training	• Drive vehicle on test path • Onboard researcher prompts for self-reported motion sickness score • Onboard researcher monitors participant for safety	• Participant recovery from motion sickness • Remove all sensors • Subjective Responses Questionnaire

Table 5-2 Summary of Haptic Stimuli study protocol stages and associated activities

The second stage is Vehicle Preparation. The researcher brought the participant to the M-LoW and seated the participant in the occupant space (Chapter 4, Section 4.4.1). The participant was secured using a seat belt. The participant was given a safety briefing to ensure that the participant knew what they can do to keep themselves safe during the test (Table 5-2, Safety briefing). The safety briefing included instructions on how the participant can request to stop the vehicle at any time during the study. The researcher reminded the participant about the haptic APS and task that they will perform during the study (Table 5-2, APS and Task training). Finally, the researcher reminded the participant about the motion sickness scale and addressed any questions the participant might have. These training sessions were repeated to ensure that the participant did not forget or misremember anything, which may influence the results of the study. After this, the

researcher secured the door of the vehicle, and the next stage of the study protocol could begin.

The third stage of the study is Vehicle Drive. The onboard researcher (seated in the driver space of the motion laboratory on wheels) spoke to the participants and checked if they were ready to begin the study. The participant was told that the onboard researcher would be onboard the vehicle to monitor the participants carsickness and would not be involved in driving the vehicle. The M-LoW was driven on the test path. While the vehicle was being driven, the onboard researcher routinely (every 90 seconds) prompted the participant to report their motion sickness score. In addition, the onboard researcher used video cameras in the occupant space to monitor the participants for their safety. Once the vehicle had driven the entirety of the test path or the participant had reported a MS score of 10 (i.e., asking the vehicle to be stopped), the vehicle would stop, and the next stage of the study protocol would begin.

The fourth and last stage of the study protocol is the Post Vehicle Drive. The participant and onboard researcher exited the M-LoW. The participant was allowed to recover from their motion sickness. Once the participant had recovered from their motion sickness, all sensors would be removed. The researcher then asked the participant questions to describe the participants experience inside the motion laboratory on wheels while it was being driven in the previous stage. This included questions about the participants' subjective experience performing tasks, qualitative descriptions of their motion sickness response, and their preferences for the haptic stimulation system.

5.4 Haptic Stimuli System

A haptic system providing stimuli from the seat was chosen for this study. Prior research on response times to type of stimuli had shown that haptic stimuli elicited response times as fast (possibly even faster) than audio or visual stimuli [267]. Also, unlike visual or audio stimuli, haptic

stimuli are less likely to interfere with the passenger performing a task.

A commercially available seat massager was modified to provide haptic stimuli through the seat (Fig 5-1). Through benchtop testing and evaluation, a vibration frequency of approximately 30 Hz was selected to prevent annoyance or discomfort for the seat occupant. The stimuli were encoded as follows: "left turn" events were indicated by vibration at the left-back position (LB), "right turn" events were indicated by vibrations at the right-cushion position (RB), and "brake/stop" events was indicated by vibrations at all positions (RB, LB, RC, LC). The vibrations were provided for 3 seconds, an alternating cycle vibration ON and vibrations OFF, each cycle lasting 0.5 seconds. The pilot study helped ensure that the haptic stimuli was easy to understand and interpret.

Fig 5-1 Haptic Stimuli System using commercially available Seat Cover

A custom controller board (Fig 5-2) was designed using off the shelf motor controller chips

(DRV 8871 chips). An Arduino UNO was used to provide the PWM input signals to each of the four haptic motors (Motor 1 to Motor 4 in Fig 5-2) in the seat. The circuit required a 12V DC power supply with a peak current consumption of 5A. The real time GPS-based triggering software would determine if the upcoming vehicle motion were a left or right turn, or a brake event. Based on the type of event, the software would trigger and activate the corresponding haptic stimulation via the controller board.
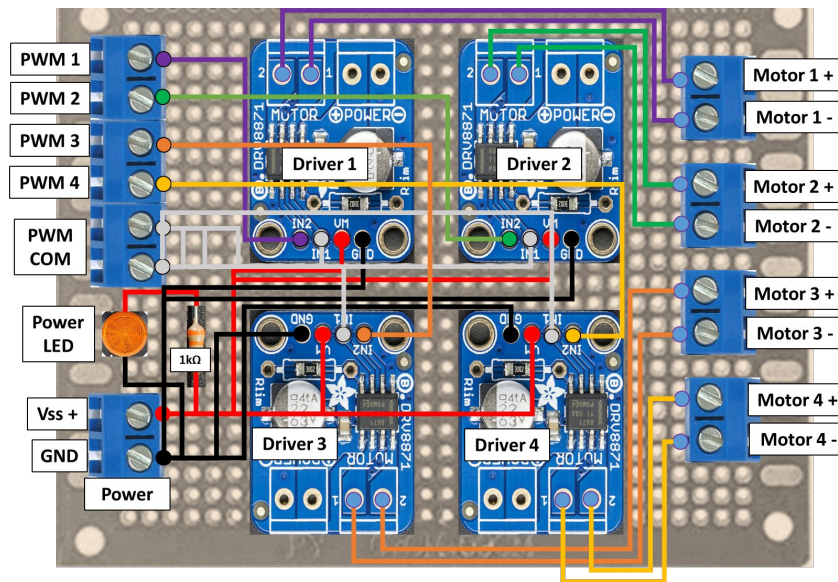
Fig 5-2 Haptic Motor Controller Board

5.5 Study Participants

Thirty-five participants were recruited for the study. Of those participants, only twenty-four completed their participation in the study (i.e., they completed all three test conditions) (Fig 5-3). This represents an attrition of approximately 30%, which is similar to prior studies [260]. Of these twenty-four participants, thirteen were female and eleven were male. The average age of the male participants was twenty-five years (25yrs ± 5yrs), and the average age of the female participants was twenty-four years (24yrs ± 5yrs). There was no statistically significant difference in the age of the participants, such that age of participants would not influence their carsickness response.
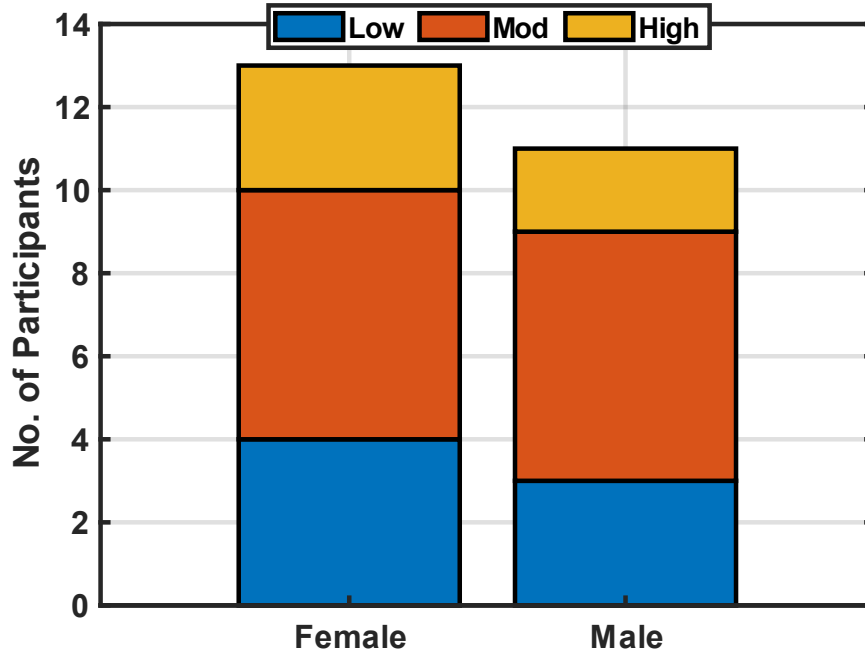
Fig 5-3 Summary of Study Participant Demographics (participants that completed participation) including self-reported motion sickness susceptibility for Haptic APS Study

Participants self-reported their motion sickness susceptibility and motion sickness frequency. Based on their susceptibility and frequency, participants were grouped into three categories of motion sickness response: low, moderate, and high motion sickness susceptibility. By grouping participants by their motion sickness susceptibility, the influence of the preemptive tilting seat could be assessed by their susceptibility. A numeric value was assigned to self-reported susceptibility and frequency. To indicate their motion sickness susceptibility, participants could select one of five options: (a) Not at All, (b) Minimally, (c) Moderately, (d) Very, and (e) Extremely. Each of those options is assigned a numerical score between 1 and 5, with "Not at All" being assigned a score of 1 and "Extremely" being assigned a score of 5. To indicate their frequency of motion sickness, participants could select one of four options: (a) Never, (b) Rarely, (c) Sometimes, and (d) Frequently. Each of those options is assigned a numerical score between 1 and 4, with "Never" being assigned a score of 1 and "Frequently" being assigned a score of 4. For each participant, by summing their response score, they were bucketed into one of the three

categories of motion sickness response (i.e., Low = sum less than equal to 4, Mod = more than or equal to 5 and less than or equal to 7, High = more than or equal to 8 and less than or equal to 9).

Seven participants (four females + three males) were categorized as low motion sickness susceptibility, twelve participants (six females + six males) were categorized as moderate motion sickness susceptibility, and five participants (three females + two males) were categorized as high motion sickness susceptibility.

5.6 Research Vehicle Path

The test vehicle (Section 4.4) was run at the Mcity test facility for all test conditions (Fig 5-4). A path was designed to traverse the various driving environments at Mcity, to ensure that the participants experience a suitable range of motion events and time between events (e.g., short vs. long right turns). The peak lateral and longitudinal acceleration associated with the path are 6 m/s^2 and 4 m/s^2, respectively. These accelerations are typical of everyday driving conditions [244].

Each test condition included 3 loops of the designed path, with each loop consisting of numerous brake/stop events, left turns, and right turns. The path consisted of 18 left turns, 10 right turns, and 13 stop events. The approximate ratio of left turns, to right turns, and stop events was representative of naturalistic driving as determined from large scale driving datasets [244]. The time between turns and stops varied between 3 seconds to as much as 10 seconds. The detailed description and driving instructions for the path are summarized in Table 5-3. Each loop of the path took approximately 8 minutes to complete, for a total time of approximately 24 minutes for all 3 loops.
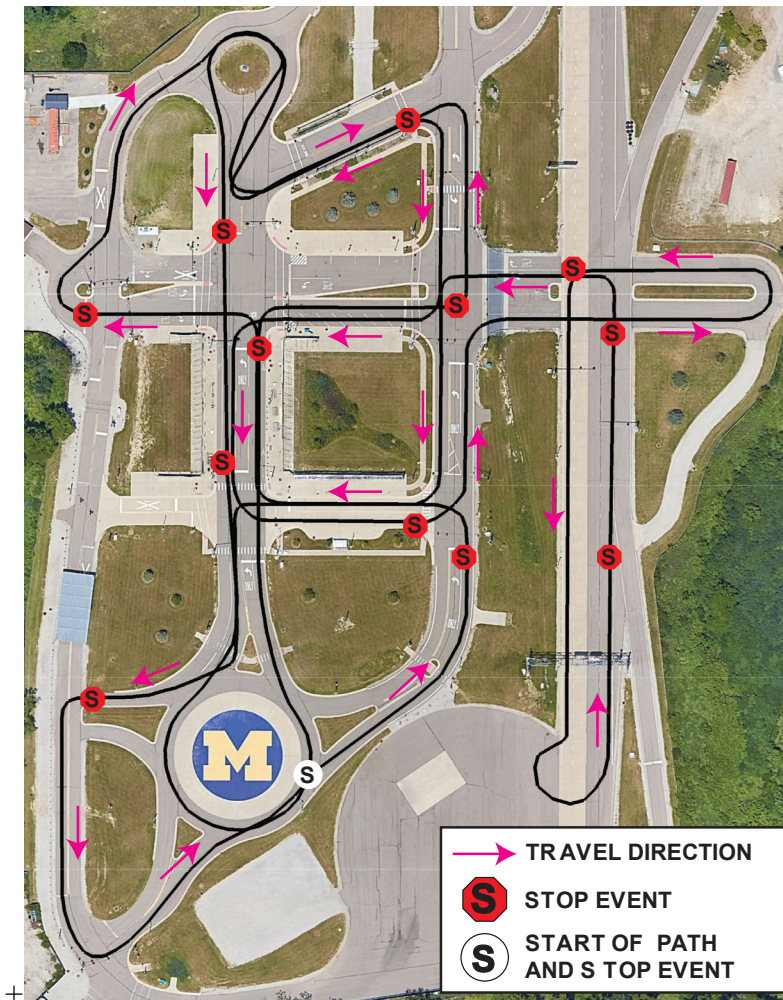
Fig 5-4 Test path on the Mcity Test Track for Haptic APS Study

EVENT	DRIVING INSTRUCTIONS	EVENT	DRIVING INSTRUCTIONS
Start Event	a) 15 mph b) Slight left	Event 17	a) Left (Left turning lane)
Event 1	a) Stop at light b) Left	Event 18	a) Rolling left
Event 2	a) Rolling right	Event 19	a) Rolling right
Event 3	a) Rolling left (Oncoming traffic)	Event 20	a) Rolling left
Event 4	a) Stop at cone b) Right (Toward circle) c) 12 mph	Event 21	a) Roundabout, 15 mph
Event 5	Right at traffic circle, 12 mph	Event 22	a) North exit b) Stop at light
Event 6	a) Sharp left under canopy	Event 23	a) 15 mph b) Stop at light c) Right (Ignore parking lines)
Event 7	a) Stop at sign	Event 24	a) Stop at flagged cone

	b) Right		b) Left
Event 8	a) Rolling right (Ignore parking lines)	Event 25	a) Left under canopy
Event 9	a) Rolling left	Event 26	a) 12 mph b) Sharp right (Around cone)
Event 10	a) Rolling left	Event 27	a) Left into traffic circle, 12 mph
Event 11	a) Stop at light b) Left	Event 28	a) Exit South, 15 mph b) Stop at light
Event 12	a) Rolling right	Event 29	a) 15 mph b) Stop at light c) 15 mph d) Sharp right (Ignore lane lines)
Event 13	a) U-turn, 10 mph b) 12 mph	Event 30	a) Stop at sign b) Left
Event 14	a) Stop at cone b) Left	Event 31	a) Rolling left (re-enter roundabout)
Event 15	a) 15 mph b) U-turn (South Circle), 9 mph c) Exit into right-most lane	Event 32	a) 15 mph (toward Start Event) b) Stop (toward Start Event) c) Repeat APS path
Event 16	a) 15 mph b) Stop at cone c) 15 mph d) Stop at cone		

Table 5-3 Summary of Test Path and Driving Instructions for Haptic APS Study

5.7 Experimental Results

This section describes the results of analysis of three types of data collected during the study. This data represents a subset of the total data collected during the experiments. The three types of data are: (a) Self-Reported Motion Sickness Score, (b) Task Performance, and (c) Subjective Participant Responses. The motion sickness scores are based on the UMTRI Motion Sickness Scale described earlier (Section 4.5.2). Task performance data consists of accuracy and response time (additional details are described in Section 4.5.1). Subjective Participant Responses were collected in response to questionnaires administered to all participants at the end of the study.

5.7.1 Motion Sickness Response

In Fig 5-5, the mean CS scores for all twenty-four participants across all three test conditions are plotted as a function of time. Initially the CS response seems similar across all three test

conditions (before 5mins). The difference in rate of accumulation of CS is most apparent between 5mins and 15mins. The rate of CS accumulation is highest for TC 2 (i.e., APS OFF Task ON), and lowest for TC 1 (i.e., APS ON Task OFF). The rate of CS accumulation for TC 3 (i.e., APS ON Task ON) is slightly higher than for TC 1. This data supports the hypothesis that even when the participant is performing a task, the preemptively triggered haptic stimuli system can help reduce the rate of CS accumulation. As expected, the CS score is lowest (at 23mins) for TC 1 where the participant is not performing a task and the haptic stimuli system is operational. The CS score is highest for TC 2, where the haptic stimuli system is not operational, but the participant is performing a task.

CS scores aggregated across all participants may obscure trends in CS response by motion sickness susceptibility. In Fig 5-6, the mean and median CS scores for all 7 low motion sickness susceptibility participants are plotted as a function of time. In Fig 5-7, the mean and median CS scores for all 12 moderate motion sickness susceptibility participants are plotted as a function of time. In Fig 5-8, the mean and median CS scores for all 5 high motion sickness susceptibility participants are plotted as a function of time. A striking observation is that the peak CS score for low susceptibility participants, irrespective of test condition, is significantly lower than both moderate and high susceptibility participants (~4 vs ~6, 30% lower). This aligns with the expectation that participants with low susceptibility for CS will not experience as significant CS as other individuals for the same vehicle motion.
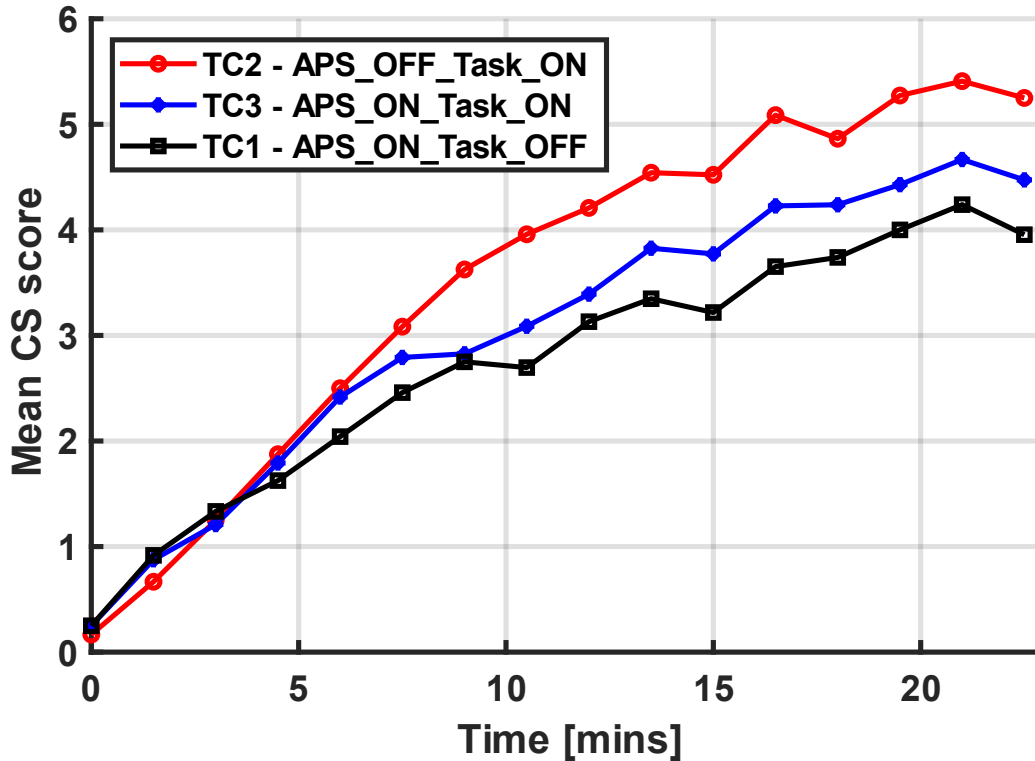
Fig 5-5 Mean Motion Sickness Scores across all Haptic APS Study Participants, grouped by Test Conditions

Another observation is that the CS score responses by test condition differ the most for moderate susceptibility participants, with a difference of >1.5 in the mean CS score between TC 3 and TC 2. This trend in data is similar to CS response by participant motion sickness susceptibility reported in prior experiments that have used the same motion sickness scale [103]. Finally, it is observed that the mean CS score trend for high susceptibility participants has similar peaks across all test conditions, but the rate of accumulation of CS is fastest for TC 2 (APS is OFF). Therefore, CS response as a function of participant motion sickness susceptibility provides additional insights into the influence of APS and task performance. To ensure that these trends in CS response are meaningful, statistical analysis to determine their significance is required.

A Linear Mixed Modelling (LMM) approach with random intercept and slope was used to statistically model the CS response data across all participants. Linear modelling is sufficient as

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the modelling error over the experimental data was minimal. The fixed effects for the model include test conditions (i.e., TC 1, TC 2, and TC 3) and time (i.e., 0 mins, 1.5 mins… 24 mins). The random slope for CS response measures individual variability over time for participants for a given test condition. Models with participant gender and age as fixed effects were also investigated to determine that they had no significant effect on the results (p-value > 0.2).
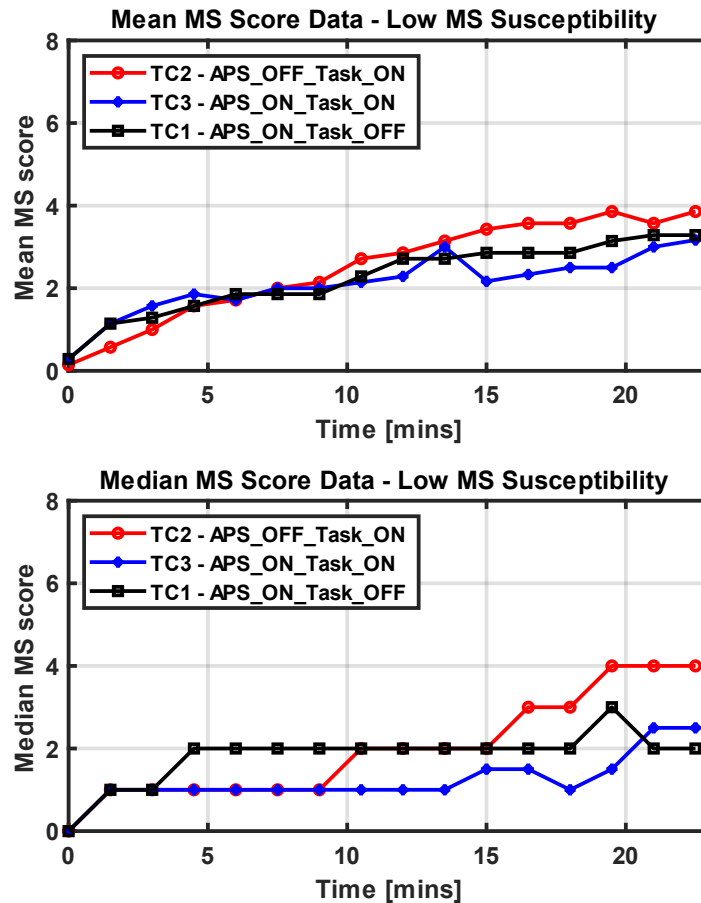
Fig 5-6 Mean (Top) and Median (Bottom) Motion Sickness Scores for All Low Susceptibility Participants

The results of the LMM are summarized in Table 5-4. The model uses TC 2 as a reference condition for analysis. The intercept refers to the CS score at time 0 min (i.e., beginning of the test condition). From the results, at the beginning of all three test conditions, the CS score across all participants is close to 0 (yet significantly non-zero), and there is no statistically significant

difference between the test conditions. This is expected as the experiment is designed to ensure that participants have the same or similar CS at the beginning of all the test conditions. Additionally, the first significant difference in CS response (i.e., difference in CS score) between TC 3 and TC 2 occurs approximately at 12 min, as compared to the 6 min for TC 1 and TC 2. This means that performing a task degrades efficacy of APS in mitigating CS.
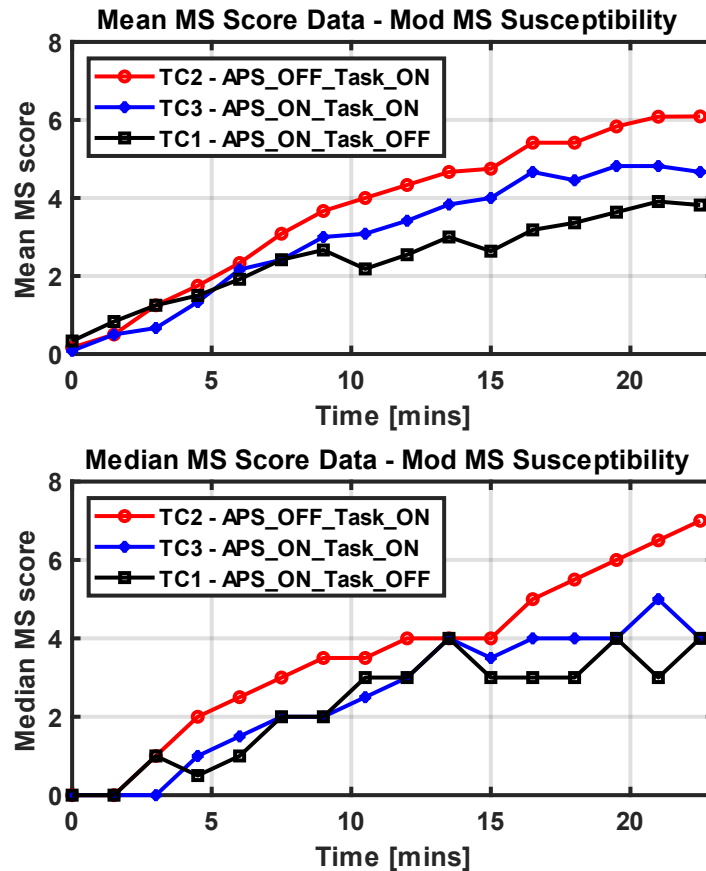
Fig 5-7 Mean (Top) and Median (Bottom) Motion Sickness Scores for All Moderate Susceptibility Participants

The slope refers to the rate of accumulation of CS over the test condition. The difference in rate of accumulation of CS across test conditions is statistically significant, with the lowest rate for CS accumulation being associated with the TC 1 condition. The effect of performing a task on rate of CS accumulation is apparent, as the rate for TC 3 is ~30% higher than TC 1. However, without the mitigative action of the APS, the rate of CS accumulation would be even higher, as the rate for TC

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2 is ~15% higher than TC 3.
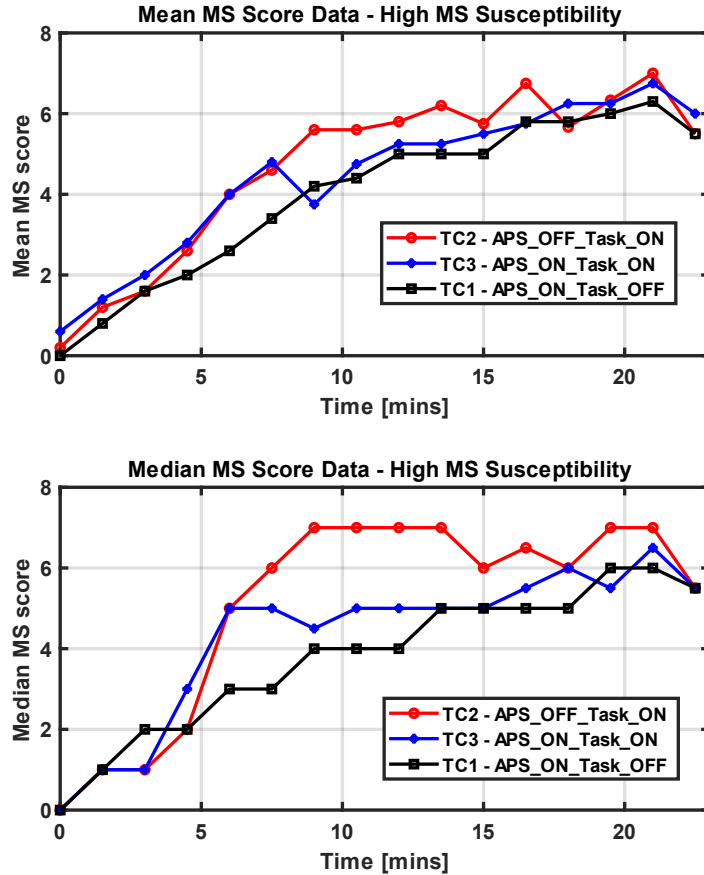
Fig 5-8 Mean (Top) and Median (Bottom) Motion Sickness Scores for All High Susceptibility Participants

FIXED EFFECT COEFFICIENT	ESTIMATE	STANDARD ERROR	P-VALUE
Intercept of TC 2 (APS_OFF_Task_ON) Reference Condition	0.873	0.228	1.35 e-4
Δ Intercept TC 1 (APS_ON_Task_OFF) vs TC 2	0.045	0.186	8.11 e-1
Δ Intercept TC 3 (APS_ON_Task_ON) vs TC 2	0.030	0.180	8.68 e-1
Slope of TC 2 (APS_OFF_Task_ON) Reference Condition	0.260	0.023	2.58 e-28
Δ Slope TC 1 (APS_ON_Task_OFF) vs TC 2	-0.080	0.014	3.57 e-8
Δ Slope TC 3 (APS_ON_Task_ON) vs TC 2	-0.032	0.014	2.50 e-2

Table 5-4 Linear Mixed Effects Model Results (Fixed Coefficient Results) for Haptic APS Study

5.7.2 Task Performance

Task performance was quantified using the following parameters: (a) accuracy of responses, (b) percentage of skipped questions, and (c) response time for answering questions. Accuracy of responses was defined as the ratio between the number of questions answered correctly and the sum of the number of questions answered correctly, questions answered incorrectly, and questions skipped. This sum of questions represents the total number of questions viewed by a participant during the test condition. The percentage of skipped questions was defined as the ratio between the number of skipped questions and the total number of questions viewed by the participant during the test condition. The response time for answering questions was defined as the time between the participant first viewing a question to them either finalizing their response or skipping the question. Of the 24 participants, task performance data for 4 participants was corrupted or lost due to system errors. Of these four participants, one participant was a low susceptibility female, one participant was a low susceptibility male, and remaining two participants were moderate susceptibility males. Therefore, task performance data analysis was only performed on data from 20 participants.

Since the task performance was a continuous paired non-parametric dataset, Wilcoxon Signed-Rank analysis was used to statistically model task performance to determine significance. Task performance aggregated across all 20 participants for a given test condition and compared against baseline task performance is summarized in Table 5-5. In addition, comparison of task performance across the test conditions (namely TC 2 and TC 3) is also summarized in Table 5-5. Task performance in both TC 2 and TC 3 conditions is far worse than baseline, across all participants. The accuracy was significantly lower for TC 2 and TC 3 as compared to baseline, when aggregated across all questions and when further analyzed by aggregating across questions of the same cognitive burden (i.e., low vs. high cognitive burden questions). This trend is

corroborated by prior research that has shown that task performance degrades when the task is performed in a moving environment like a car.

PARAMETER	BASELINE	TC 2 – APS OFF	Δ BASELINE & TC 2	TC 3 – APS ON	Δ BASELINE & TC 2	Δ TC 3 & TC 2
Mean Accuracy across all questions	96% ± 5%	85% ± 9%	Baseline > TC 2 ***	84% ± 10%	Baseline > TC 3 ***	TC 3 ~ TC 2
Mean Accuracy of only low cognitive questions	99% ± 2%	95% ± 8%	Baseline > TC 2 *	94% ± 9%	Baseline > TC 3 **	TC 3 ~ TC 2
Mean Accuracy of only high cognitive questions	94% ± 8%	77% ± 14%	Baseline > TC 2 ***	77% ± 14%	Baseline > TC 3 ***	TC 3 ~ TC 2
Mean Percentage of skipped questions	0% ± 1%	1% ± 2%	TC 2 > Baseline *	1% ± 2%	TC 3 > Baseline *	TC 3 ~ TC 2
Mean Response time across all questions	19s ± 5s	30s ± 10s	TC 2 > Baseline ***	35s ± 15s	TC 3 > Baseline ***	TC 3 ~ TC 2
Mean Response time across only low cognitive questions	9s ± 3s	23s ± 9s	TC 2 > Baseline ***	28s ± 14s	TC 3 > Baseline ***	TC 3 ~ TC 2
Mean Response time across only high cognitive questions	26s ± 7s	35s ± 13s	TC 2 > Baseline ***	41s ± 18s	TC 3 > Baseline ***	TC 3 ~ TC 2

Table 5-5 Summary of Task Performance Statistical Analysis by Test Conditions. Note: * p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001

A comparison of task performance between TC 2 and TC 3 is required to determine the influence of APS on quality of task performance. Across all the data in Table 5-5, there is no statistically significant difference in quality of task performance across both those test conditions. For accuracy, the means across both TC 2 and TC 3 are similar and within only a couple of percent points of each other. For response time, the means across both TC 2 and TC 3 vary by as much as 6 seconds of each other, but this difference is not statistically significant, and the size of this effect

is small to moderate in relation to their respective standard deviations.

Table 5-6 summarizes task performance analysis within a test condition aggregated across questions of the same cognitive burden. As expected, the mean accuracy of responses is higher for low cognitive burden questions when compared to high cognitive burden questions across all tasks. Similarly, the mean response time if higher for high cognitive burden questions when compared to low cognitive burden questions across all tasks.

TASK	QUESTION COGNITIVE BURDEN	MEAN ACCURACY	Δ LOW & HIGH	MEAN RESPONSE TIME	Δ LOW & HIGH
Baseline	Low	99% ± 2%	Low > High **	9s ± 3s	High > Low ***
	High	94% ± 8%		26s ± 7s	
TC 2 – APS OFF	Low	95% ± 5%	Low > High ***	23s ± 9s	High > Low **
	High	77% ± 14%		35s ± 13s	
TC 3 – APS ON	Low	94% ± 9%	Low > High ***	28s ± 14s	High > Low **
	High	77% ± 14%		41s ± 18s	

Table 5-6 Summary of Task Performance Statistical Analysis within Test Conditions. Note: * p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001

5.7.3 Subjective Participant Responses

Every participant was interviewed after their participation in every test condition and asked to describe their experience qualitatively. The interview consisted of various open and close ended questions to determine the quality of the participants experience during the test condition. Participants were asked about their overall experience inside the test vehicle to determine if any environmental factors such as temperatures or smells influenced their CS response. None of the participants reported any issues with these environmental factors during the study. Similarly, none of the participants reported any discomfort or annoyance associated with the instrumentation and sensors that were used to collect data. When asked about their experience performing the task

during the study, 21 out of 24 participants (88%) indicated that it was harder to perform the task in a moving car as compared to the baseline task performed in a room. This is corroborated by the trend in quantitative data observed in the previous section.

When asked about their experience with the haptic stimuli during the study, 21 out of 24 (88%) participants indicated that the haptic stimuli system was comfortable and did not cause any annoyance or discomfort. The primary complaint of the remaining 3 participants was that they found it hard to simultaneously focus on both the stimuli and the task. This is corroborated by the quantitative data observed in the previous section where there is no statistically significant difference between task performance for TC 2 and TC 3. The efficacy of the haptic stimuli is dependent on the participant's ability to accurately decipher the upcoming motion events from the stimuli they received. When asked if they found the stimuli to be informative (i.e., decipher the motion events from stimuli), 23 out of 24 (96%) participants indicated that APS was informative across both TC 1 and TC 3. Of those 23 participants, 3 participants initially struggled to decipher the first couple motion events but reported that they were able to quickly learn and accurately decipher all remaining events. This data supports the claim that the haptic stimuli used in this study is intuitive, easy to decipher, and causes minimal discomfort or annoyance to participants.

At the end of the study, after participants had successfully completed participation in all test conditions, participants were asked if they liked the haptic stimuli system and would use the same or similar system in a car as a passenger. The goal of this question was to determine the participants overall preference for the haptic stimuli system, in addition to their subjective CS score. Of the 24 participants, 18 participants (75%) indicated a positive preference for haptic stimuli as they believed the haptic stimuli system helped reduce their CS (as stated explicitly in their responses). Of those 18 participants, 4 participants had low motion sickness susceptibility, 10 participants had

moderate motion sickness susceptibility, and 4 participants had high motion sickness susceptibility. This means that over 80% of both moderate and high susceptibility participants found the haptic stimuli to be helpful in mitigating their CS. This trend in data is notable because even though the peak CS response for high motion sickness susceptibility participants did not differ due to the influence of stimuli, the qualitative preference for haptic stimuli indicates the significance of the positive effect of stimuli on CS. This is the first study to report qualitative data of this kind indicating a strong subjective preference for a haptic stimuli system that helps reduce CS.

5.8 Discussion

The data from this study indicated that nearly 90% of the participants could understand the haptic signals. This demonstrates that a preemptively activated haptic stimuli system can provide meaningful information to a passenger regarding the vehicle's upcoming motion. Even though the study participant had a cognitive burden due to the task, they could successfully interpret the stimuli and discern the upcoming motion of the vehicle.

The data from this study shows that a haptic stimuli system can help reduce CS, even when the person is performing a task. The mean motion sickness score data across all study participants shows a 1-unit difference (using the UMTRI motion sickness scale) in the peak motion sickness score at the end of TC 2 where the haptic stimuli system was OFF as compared to the motion sickness score at the end of TC 3 where the haptic stimuli system was ON. In addition, the rate of accumulation of motion sickness is approximately 13% lower for TC 3 as compared to TC 2. However, when the participant is performing a task, the haptic stimuli is less effective in reducing CS. The rate of accumulation of motion sickness is approximately 30% lower for TC 1 as compared to TC 2. Therefore, as measured by rate of motion sickness accumulation, task

performance reduces the efficacy of the haptic stimuli system by almost 50%. One plausible reason for this might be that when the participant was performing the task, they found it hard to focus on the stimuli signals. Even if they were able to pay attention to the signals, the cognitive demand of both the stimuli and task might have been overwhelming for the participant. If this were the case, it would be reasonable to expect a degradation in task performance due to the additional cognitive burden of the haptic stimuli system. However, the task performance data demonstrated that the haptic stimuli system had no effect on quality of task performance. There was no statistically significant difference in accuracy, skipped questions, or response times across the test conditions.

While the quantitative data on task performance did not demonstrate any influence of the haptic stimuli system, subjective participant responses after their participation in the study indicated a strong positive preference for the haptic stimuli system. One plausible reason for this may be that the haptic stimuli system might have had a positive influence on the participants' mood or overall demeanor due to the reduction in motion sickness. This may explain why the majority of the participants indicated a preference for the haptic stimuli system, even if the task performance data did not differ significantly across test conditions. In addition, this outcome may also indicate a deficiency in the motion sickness scale used in this study as a suitable metric for the motion sickness and comfort experience of the participant. While the UMTRI motion sickness scale allows for flexibility in how the participant can self-assess and report changes in their motion sickness state, some participants may find it challenging to be sensitive to subtle changes in their overall mood or demeanor. As a result, even though they may have a positive experience with the haptic stimuli system, that outcome may not be visible in their motion sickness scores.

Even though the motion sickness data shows very little difference in the peak mean CS scores for low and high motion sickness susceptibility participants across all test conditions, their

subjective participant responses still indicated a positive preference for the haptic stimuli system. More than 50% of the low susceptibility participants, and more than 80% of the high susceptibility participants indicated a preference for the haptic stimuli system. This data seems to indicate that the positive utility of the haptic stimuli system may not be identifiable only by the subjective CS scores of the participants. For moderate motion sickness susceptibility participants, there was a significant difference in their CS scores across test conditions, and unsurprisingly more than 80% of the moderate susceptibility participants also indicated a strong positive preference for the haptic stimuli system. This result indicates that those participants belonging to groups most vulnerable to motion sickness (i.e., moderate, and high susceptibility) may value any reduction in motion sickness more than other groups (i.e., low susceptibility). It is reasonable to observe that preference for the haptic stimuli is lower for the low susceptibility participants as compared to high susceptibility participants. Since low susceptibility participants did not experience the same amount of CS as the high (or even moderate) susceptibility participants, the discomfort associated with CS may not be valued as highly by them as compared to moderate or high susceptibility participants. Therefore, studies on motion sickness mitigation must analyze motion sickness response along with participant motion sickness susceptibility. This result also highlights the importance of post study subjective and qualitative data collection from participants to get a more detailed picture of their experience in the study. Without the qualitative data on preference for the haptic stimuli system, the positive influence of the haptic stimuli system for high susceptibility participants may have been lost.

While the results from this study are significant, this study has some practical limitations. First, there are limitations in participant recruitment. While the total number of participants in the study is higher than or the same as the typical range for similar studies, a larger pool of participants will

lead to higher quality data and more statistical power. This larger pool of participants must represent a broader range of motion sickness susceptibilities, age, height, weight, and any other factors which may influence a person's motion sickness response. Also, it is difficult to recruit participants with a high susceptibility to motion sickness as they are reluctant to participate in a study that will make them sick, and they are also more likely to drop out of a study if they begin their participation (i.e., higher attrition rate as compared to low susceptibility participants). High motion sickness susceptibility individuals are most vulnerable to motion sickness in vehicles, and as indicated by the results of this study, value a reduction in their motion sickness highly.

Second, the use of a test track to operate the research vehicle ensures participant safety but limits realistic recreation of the experience of a person in a car. For example, a car on the highway may turn for many seconds, but the path used in this study only has a maximum separation between events of 10 to 15 seconds. Lastly, it is nearly impossible to ensure identical experimental and physiological conditions for participants across the three test conditions. The study design requires that participants have nominal sleep, physical activity, and diet across the various test conditions, but it is impossible to recreate these perfectly. Any variance in the participants' physiological conditions or experimental conditions (i.e., driving) can influence the participant's motion sickness response in an unknown manner, which can introduce noise in the data.

Despite these limitations, the findings from this study are significant. This is the first study to investigate preemptively activated haptic stimuli systems using a real car which relies on automated software activation of the haptic stimuli system for precise preemption. All other studies on preemptively activated stimuli using real cars have relied on manual/human activation of the sensory stimuli system. This is the first study to provide a detailed analysis of the participant's task performance and demonstrate that an effective sensory stimuli system can both reduce motion

sickness and have no negative side effects on a passenger's ability to perform a wide range of tasks. In addition, the results from this study also highlight the importance of including a task when assessing motion sickness mitigation, as performing the task reduced the efficacy of the mitigation system. Lastly, this is the first study of its kind to also use post participation questionnaires to gauge the participants subjective response and experience while participating in the study. Through these subjective responses, this study was able to show a strong positive preference for haptic stimuli system even in participants who did not show a reduction in their motion sickness score.

These results motivate the need for future research using similar or improved study designs, especially with regards to precise preemption for the sensory stimuli systems. In addition, many intellectual areas of inquiry remain unaddressed by prior literature and this study. This study used a preemption of 3 seconds as that was similar to the preemption used in prior literature and similar to the perception and response times of drivers. However, the optimum preemption time to maximize motion sickness mitigation remains unknown. This study, like most of the prior literature, only used a single type of sensory stimuli system (haptic). However, there may be an optimal combination of stimuli (e.g., haptic, and visual or visual and audio) that may both reduce motion sickness and improve the passengers' task performance.

5.9 Conclusion

In this chapter, the results from the study to investigate the efficacy of a preemptively triggered haptic stimuli in mitigating CS are presented (N=24 participants). The results from the study demonstrated that a haptic stimuli system triggered preemptively can help reduce CS, even when the participant is performing a representative task. The haptic stimuli system reduced the peak mean motion sickness score by 20% (1-unit) and reduced the rate of accumulation of motion sickness by 13% across all participants. The most dramatic difference in motion sickness response

was observed in moderate susceptibility participants who saw a reduction in peak mean motion sickness score of over 30%.

The results from the analysis of task data showed that the preemptively triggered haptic stimuli had no statistically significant influence on task performance. The results from the study also underscored the importance of collecting subjective and qualitative responses from participants regarding their experience in the study and their preference for the haptic stimuli system. This qualitative data can provide a more detailed picture of the overall experience of a participant, which may not be captured by their motion sickness response (i.e., motion sickness scores). Lastly, results motivate the need for future research using similar or improved study designs to investigate open research questions such as optimal amount of preemption, and optimal type or combination of types of sensory stimulation.

Chapter 6 Tilting Seat System to Mitigate Motion Sickness

This chapter presents the experimental design, execution, and results from a human subject study (or experiment) evaluating the efficacy of a preemptively triggered tilting seat system (AST) in mitigating carsickness. Limited evidence in prior literature has shown that preemptively triggered tilting seat systems can help reduce CS (Chapter 2, Section 2.2.2). However, there are no investigations studying the efficacy of preemptively triggered tilting seats in reducing CS that are both (a) conducted under realistic driving conditions and (b) with an assessment of the passengers NDRT performance.

To address this gap, a human subject study was conducted to quantify a vehicle occupant's CS response while performing representative task along with preemptively triggered tilting seat. Twenty-nine healthy adults with varying levels of self-reported motion sickness susceptibility participated in the study, across two test conditions conducted over two different days, on a closed test track in the research vehicle (M-LoW) described in Chapter 4. This is the first in-vehicle study with a tilting seat system that assessed both CS response and quality of passenger task performance for a diverse sample of passengers with varying motion sickness susceptibility under realistic driving conditions (on a test track).

6.1 Introduction and Background

Prior research literature has explored the possibility of recreating the driver's anticipatory information and preemptive corrective actions for vehicle passengers. Specifically, it has been proposed that the use of active seats or tilting seat or moving seat systems can be used to alter the

posture of a passenger (just like a driver). This approach has shown positive results when applied to high speed trains, where tilting train cabins have helped reduce motion sickness in train passengers [268], [269] (see Chapter 2, Section 2.2.2). It is expected that by leaning the passengers' body and head into the turn, the sensory conflict is reduced by aligning their head and torso with the direction of gravito-inertial acceleration, thereby reducing their motion sickness.

Various studies have investigated the effects of moving seats on carsickness of passengers [89], [150], [161], [162], [164], [165], [166], [167] (see Chapter 2, Section 2.2.2). The majority of the relevant prior work (6 out of 8 studies discussed in Chapter 2) focused on moving seats that are triggered reactively (i.e., after the start of the vehicle motion event such as a turn); while only two studies investigated the efficacy of preemptively triggered moving seat systems. Of the 6 studies with reactively triggered active seats, only 3 studies demonstrated a reduction in carsickness. Whereas all of the preemptively triggered active seat studies (all 2 studies) demonstrated a reduction in carsickness. In addition, one study from prior literature also demonstrated that preemptively triggered moving seats are more effective at reducing motion sickness as compared to reactively triggered seats [162]. Therefore, there is evidence in support of preemptively triggered active seats being effective at reducing carsickness. However, as noted in Chapter 2, the experimental methods used in all of the above studies from current literature have many limitations (Chapter 2, Section 2.4). Namely, these limitations include: (a) lack of realistic driving conditions due to the use of static or motion simulators instead of real vehicles (limitations of vehicle simulators described in Chapter 4), (b) lack of precise preemptive triggering of the AST system, and (c) inclusion of the passenger performing a representative NDR task along with an assessment of the task performance

This research addressed the above identified gaps in prior literature. This study investigated the

efficacy of a tilting seat system, that preemptively leaned a passenger into turns, in mitigating CS as evaluated under realistic driving conditions while the passenger was performing a representative real-world task. The study was performed using an instrumented test vehicle (M-LoW) run on a closed test track to ensure safety and repeatability (see Chapter 4). This research also leveraged the UMTRI motion sickness scale, and various instrumentation described in Chapter 4 to track the motion of the vehicle, the passenger, and the passenger's physiological response to the moving vehicle. Also, this research utilized a representative NDR task (Chapter 4, Section 4.5.1) that placed a cognitive load on the passenger while they were seated in the M-LoW so that their carsickness response can be investigated while they perform a task.

Across the limited current literature on preemptively triggered tilting seat studies, preemption times of either 0.5 or 3 seconds have been used (only 2 studies). There is no evidence to determine the most optimal preemption time to be used. According to prior literature on preemptively triggered sensory stimuli systems for carsickness mitigation, the most common preemption time that was used was 3 seconds. It is also known from prior literature on driver perception response times that a driver can take up to 3 seconds to perceive and response to an unexpected situation [265]. This research attempted to recreate the driver's experience for the passenger to reduce their carsickness. For example, just as a driver uses anticipatory information to lean into a turn, this research proposed using a preemptively triggered tilting seat to lean the passenger into the turn. Therefore, a preemption time of 3 seconds (i.e., seat begins to move 3 seconds prior to vehicle turning) was chosen for this study. There are only 2 studies demonstrating the efficacy of preemptively triggered tilting seats, and these studies have many limitations. Therefore, it was important for this study to address those gaps in prior literature and demonstrate the efficacy of preemptively triggered tilting seats. That investigation was prioritized over an investigation to

determine an optimal preemption time.

6.2 Design of Experiment

This study focused on investigating two specific hypotheses: (1) that preemptively triggered tilting seats can reduce CS even when the passenger is performing a task, and (2) that preemptively triggered tilting seat system can help improve task performance of the passenger. Investigating these hypotheses helped address the gaps in current research identified in Chapter 2. Therefore, to evaluate the performance of tilting seat system, an experiment with two test conditions was devised. The experiment included one independent variable, namely the tilting seat system (Table 6-1). Tilting Seat system being 'ON' meant that for that test condition the seat system was operational whereas 'OFF' meant the seat system was not operational. When the tilting seat system was operational, the tilting seat system would move the passenger in anticipation of the vehicle motion (additional details on tilting seat system are presented in Section 6.4). The study had two test conditions as the AST system OFF and task OFF test (i.e., TC 3) condition and AST system ON and task OFF condition (i.e., TC 4) were not included.

Since prior research has already established that performing a task exacerbates CS [103], [260]. Therefore, a comparison between TC 3 and TC 2 is not required. Similarly, prior literature has shown that preemptively triggered tilting seat systems can be effective in reducing CS when the passenger is not performing a task [162], [163]. Therefore, a comparison between TC4 and TC1 is not required. Thus, due to evidence in prior literature and practical considerations, only two test conditions were included in this study. An experiment with all four test conditions was not required for this study to address the hypotheses defined earlier. To investigate both hypotheses a comparison of motion sickness scores and task performance across TC 1 and TC 2 is required.

TEST CONDITION	INDEPENDENT VARIABLE	DEPENDENT VARIABLES
	TILTING SEAT SYSTEM	1. Self-reported motion sickness scores
TC 1	ON	2. Accuracy of responses 3. Percentage of questions skipped
TC 2	OFF	4. Response time of questions 5. Qualitative description of experience

Table 6-1 Summary of Experimental Test Conditions and Variables for Tilting Seat Experiment

A within-subject design was implemented since motion sickness response has high variation across different individuals, and within subject studies are ideally suited to deal with this variation [266]. Within subject studies also offer other benefits such as less noise in the data, as compared to between subject designs. The order of test conditions was randomized using Latin square randomization to eliminate any order effects and biases. Since it is known that passengers can learn and get habituated to the motion sickness elicited during the study, it was important to eliminate learned effects through the use of randomization of test conditions. Test conditions were conducted with a minimum separation of 48 hours to ensure that any accumulated CS response would not persist from one test condition to the other [244]. All experimental protocols and procedures were evaluated and approved by the University of Michigan Institutional Review Board to ensure the physical safety, data privacy, and confidentiality of any participant in the study [HUM00199425].

6.3 Tilting Seat Study Protocol

A systematic and repeatable protocol for researcher and participant interaction was developed to ensure near identical interaction of researchers with participants across repeated participation for test conditions (i.e., repeated participation refers to participating in the multiple test conditions of this experiment). Any deviation in how the researcher interacts and prepares the participant for the test condition can lead to an uncontrolled variance in the experimental data. Broadly, the protocol consists of four stages: (a) Reception, (b) Vehicle Preparation, (c) Vehicle Drive, and (d)

Post Vehicle Drive (Table 6-2). This four-stage protocol is repeated for every test condition that a participant participates in.

The first stage is the Reception stage. The research team greeted the participants and as required by IRB protocols stepped the participant through the consent form and a description of the test condition (Table 6-2, Consent). The researcher also collected demographic and other basic information from the participants, including their height, weight, age, and gender (Table 6-2, Personal Info). To ensure that the participant has a similar motion sickness response across test conditions, the researcher collected information about the participant's diet, sleep, physical activity, and mental state to look for any notable deviations from the participants' typical schedule (Table 6-2, Food & Activities). The participant was then instrumented with the various sensors (see Chapter 4, Section 4.4.4) used to track the motion of their head and torso (Table 6-2, Sensor placement). The researcher introduced the representative task to the participant and provided training to help the participant build familiarity with the type of questions and how to answer them (Table 6-2, Task training). After receiving the training, the participant performed the baseline task (Table 6-2, Baseline task). Finally, once the participant had completed the baseline task, the researcher introduced the UMTRI motion sickness scale to the participant (Table 6-2, UMTRI motion sickness scale training). It was important for the participants to understand the motion sickness scale as they will use that scale to self-report their motion sickness response. To ensure that the participant had understood the motion sickness scale, the researcher would address any questions or clarifications that the participant had regarding the motion sickness scale. The researcher also used role play activities with the participant so that the participant could practice using the motion sickness scale. Once the participant was familiar with the motion sickness scale, the researcher could take the participant to the research vehicle for the next stage of the protocol.

PROTOCOL STAGE	RECEPTION	VEHICLE PREPARATION	VEHICLE DRIVE	POST VEHICLE DRIVE
ACTIVITIES	• Consent • Personal Info • Food & Activities • Sensor placement • Task training • Baseline Task • UMTRI motion sickness scale training	• Seat participant in occupant space • Safety briefing • Tilting Seat training • Task training • UMTRI motion sickness scale training	• Drive vehicle on test path • Onboard researcher prompts for self-reported motion sickness score • Onboard researcher monitors participant for safety	• Participant recovery from motion sickness • Remove all sensors • Subjective Responses Questionnaire

Table 6-2 Summary of Tilting Seat Study Protocol stages and associated activities

The second stage is Vehicle Preparation. The researcher brought the participant to the M-LoW and seated the participant in the occupant space (Chapter 4, Section 4.4.1). The participant was secured using a seat belt. The participant was given a safety briefing to ensure that the participant knew what they can do to keep themselves safe during the test (Table 6-2, Safety briefing). The researcher introduced the participant to the tilting seat system (Table 6-2, Tilting seat training). The researcher triggered the tilting seat, just as it would while the vehicle was moving so that the participants could familiarize themselves with the motion of the tilting seat and acclimate to it. The researcher also reminded the participants about the task that they will perform during the study (Table 6-2, Task training). Finally, the researcher reminded the participant about the motion sickness scale and addressed any questions the participant might have. These training sessions were repeated to ensure that the participant did not forget or misremember anything, which may influence the results of the study. After this, the researcher secured the door of the vehicle, and the next stage of the study protocol could begin.

The third stage of the study is Vehicle Drive. The onboard researcher (seated in the driver space of the motion laboratory on wheels) spoke to the participants and checked if they were ready to begin the study. The participant was told that the onboard researcher would be onboard the vehicle

to monitor the participants carsickness and would not be involved in driving the vehicle. The M-LoW was driven on the test path. While the vehicle was being driven, the onboard researcher routinely (every 90 seconds) prompted the participant to report their motion sickness score. In addition, the onboard researcher used video cameras in the occupant space to monitor the participants for their safety. Once the vehicle had driven the entirety of the test path or the participant had reported a score of 10 (i.e., asking the vehicle to be stopped), the vehicle would stop, and the next stage of the study protocol would begin.

The fourth and last stage of the study protocol is the Post Vehicle Drive. The participant and onboard researcher exited the M-LoW. The participant was allowed to recover from their motion sickness. Once the participant had recovered from their motion sickness, all sensors would be removed. The researcher then asked the participant questions to describe the participants experience inside the motion laboratory on wheels while it was being driven in the previous stage. This included questions about the participants' subjective experience performing tasks, qualitative descriptions of their motion sickness response, and their preferences for the tilting seat system.

6.4 Tilting Seat System: Hardware and Control

A commercially available active seat system was modified to suit the needs of this study. A DoF Reality P3 active seat [270] was modified to suit the needs of this study (Fig 6-1). While the P3 system is capable of rotational motion about 3 axis, only the roll motion (i.e., rotation about the longitudinal or front and back axis) was used in this study. Thus, in this study the P3 active seat was operated as a tilting seat only. Since a commercially available active seat was used for this study, it limited the modifications which could be made to the seat. For example, the center of rotation of the seat could not be modified. Also, the peak tilt angle was limited to 7 degrees. Despite these limitations, the P3 active seat was suitably modified to suit the specific needs of this research.
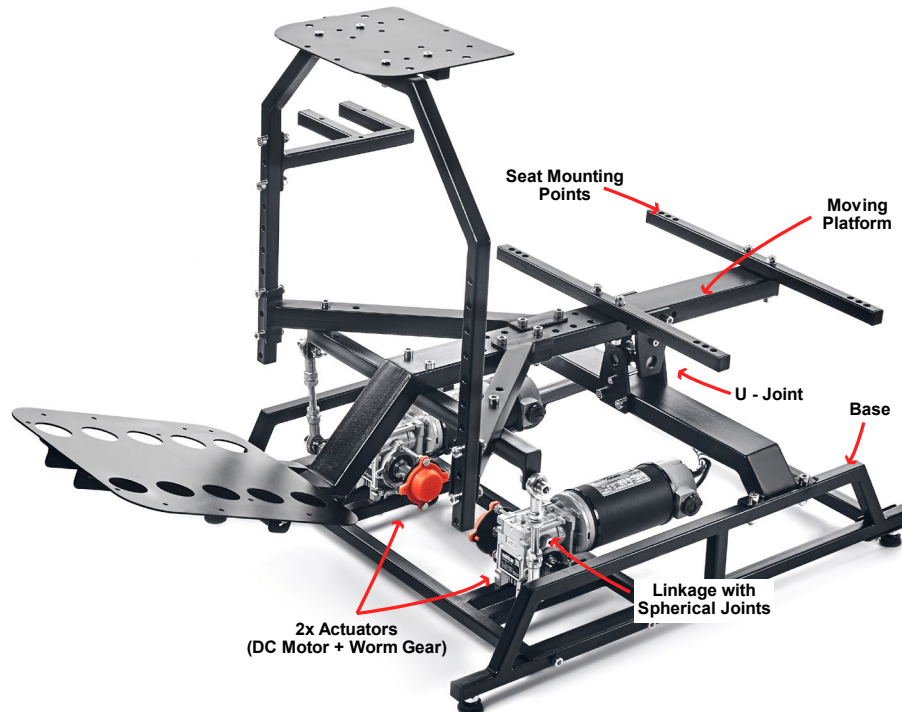
Fig 6-1 DoF Reality P3 Tilting Seat System

The tilting seat system relied on a parallel mechanism to provide the motion (Fig 6-1). It consisted of a 'moving platform' that can move with respect to the 'base'. The moving platform was connected to the base via a universal joint (U-joint) and via linkages attached to the two actuators (Fig 6-1). The actuators are mounted to the base (Fig 6-1). Both actuators consist of a brushed DC motor with a worm drive gear box (Fig 6-2). To control the motion of the seat, a National Instruments myRIO microcontroller was used to implement a closed control logic on both actuators (high level control logic for the tilting seat) (Fig 6-3). The base was rigidly mounted to the research vehicle (M-LoW), to the floor of the vehicle in the occupant space. The participant sat on a seat that was rigidly mounted to the moving platform using the seat mounting points on the platform. The seat was equipped with a 'belt-in-seat' system to keep the participant safe.
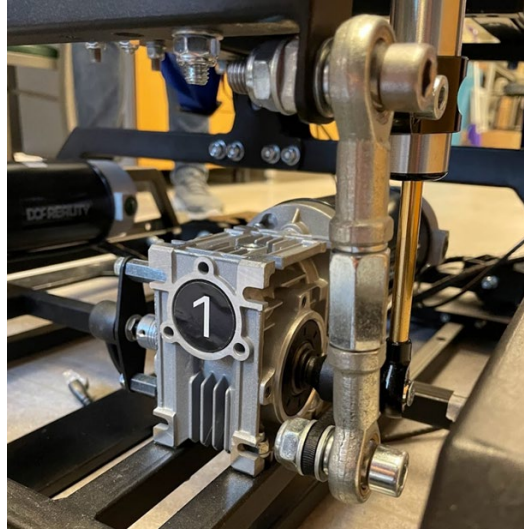
Fig 6-2 Tilting Seat Actuator with Linkages

The Real time GPS based triggering software (Section 4.4.5) determined the type of motion event (i.e., left turn or right turn, short turn vs long turn). Based on the type of motion event, a seat position trajectory, which was designed a 5th order Gaussian curve (equation 6-1), was selected. An inverse kinematic model was devised to convert the seat position trajectory to its corresponding actuator angular position trajectory. This commanded actuator position is used to command the motion of each individual actuator using a motor position control loop (Fig 6-4, described in detail below).

$$Seat\ Position\ (\theta) = a_1 e^{-\left((t-b_1)/c_1\right)^2} + a_2 e^{-\left((t-b_2)/c_2\right)^2} + a_3 e^{-\left((t-b_3)/c_3\right)^2} + a_4 e^{-\left((t-b_4)/c_4\right)^2} +$$

$$a_5 e^{-\left((t-b_5)/c_5\right)^2} ;\ \ t \to time \qquad (\ 6\text{-}1\ )$$
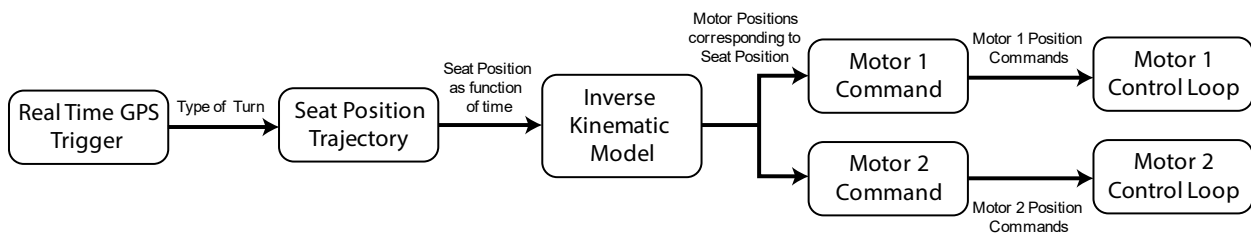
Fig 6-3 High Level Control Logic for Tilting Seat System Control

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The trajectory for the seat angle was designed as a 5th order Gaussian curve as it provided an easy method to plot a trajectory by defining certain points on the trajectory and minimizing acceleration and jerk due to motion (i.e., smooth motion curve) (see Fig 6-5 as an example). It was assumed that the acceleration of the moving seat must be minimal so as to not contribute to motion sickness in addition to the motion sickness from the moving vehicle. Also, as per the study requirements, the seat trajectory would be such that the seat would begin moving 3 seconds prior to the start of the vehicle turn. Using the above constraints and requirements, the specific seat trajectory was determined using curve fitting tools.

The equations used to define the seat motion trajectory as a function of time are shown in equation 6-1. Table 6-3 is a summary of the parameters used to define three types of trajectories, (Trajectory 1) one with no time spent holding the peak position, and two others (Trajectory 2) with 2 seconds and 5 seconds (Trajectory 3) of holding the seat at the peak position, respectively.

GAUSSIAN CURVE CONSTANTS	TRAJECTORY 1	TRAJECTORY 2	TRAJECTORY 3
a1	1.851	5.348	2.0
a2	-3.441	-465.9	-0.619
a3	0.002	471	0.039
a4	5.263	1.949	2.0
a5	0	0	7.567
b1	4.500	6.499	9.693
b2	-1167	3.729	4.999
b3	5.724	3.735	6.0
b4	4.499	8.190	4.303
b5	0	0	6.999
c1	0.659	1.313	1.346
c2	637.5	1.539	825.2
c3	6.356	1.545	0.052
c4	2.339	1.475	1.335
c5	0	0	4.364

Table 6-3 Gaussian Curve Constants for different Tilting Seat Motion Trajectories

The trajectory was designed such that the seat would begin moving/tilting before the acceleration due to the turn. The seat would hold its peak position as the vehicle acceleration peaked, and the seat would return to its starting position in phase (i.e., at the same time) or after (i.e., at a time after) the acceleration of the vehicle is nearly zero. The trajectory of the tilting seat (black) and vehicle lateral acceleration (blue) associated with a left turn is shown Fig 6-5. The trajectory was designed to provide a preemption of 3 seconds (i.e., the seat would begin moving 3 seconds prior to the start of the turn). The tilting seat reaches its peak position (7-degree with respect to its' base which is rigidly mounted to the vehicle) and then returns to its starting position after the acceleration due to the turn has ended. The trajectory moved the seat to near its full range of motion of the tilting seat system of 7-degree roll. It is worth noting that since the purpose of the tilting seat system was to align the participant head and torso with the direction of gravito-inertial acceleration, the tilt of the seat should correspond to the amount of lateral acceleration of the vehicle. However, the maximum tilt possible with the seat is 7 degrees (due to hardware limitations), which corresponds to a lateral acceleration of approximately 1 m/sec^2. Since the participants in this study would experience lateral accelerations that are as small as or greater than 1 m/sec^2, the seat trajectory was designed to achieve its peak position for all turn events in this study.

The same seat motion trajectory was used for both left and right turns, by simply flipping the direction. Since certain motion events were longer than others, some trajectories were designed to reach the peak position and hold its position for a few seconds before returning to the start position. As shown in Fig 6-6, for a long right turn, the seat trajectory holds its' peak position for approximately five seconds before returning to the starting position.

The details of the motor position control loop are shown in Fig 6-4. A rotary potentiometer was used as a position sensor for each individual actuator, attached to the worm gear output (or load) shaft. A closed loop feedback and feedforward position control scheme was implemented. The feedforward controller was designed to account for losses in the system such as friction. The PID feedback controller was tuned to account for varying passenger weights and inertial acceleration due to the moving vehicle. As shown in Fig 6-5 and Fig 6-6, the motor position controller is able to move the tilting seat as commanded with minimal error even when the vehicle is moving. The mean error in peak seat position (i.e., 7 degree) was limited to less than 1 degree across all rides. As shown in Fig 6-7, the median error in peak seat position or target position was 0.3 degree.
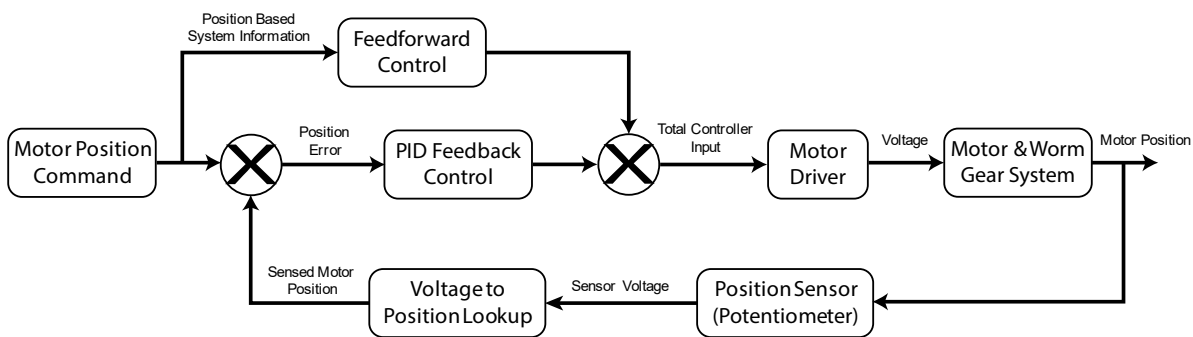
Fig 6-4 Low Level Control Logic, Detailed View of Motor Control Loop from Fig 6-3
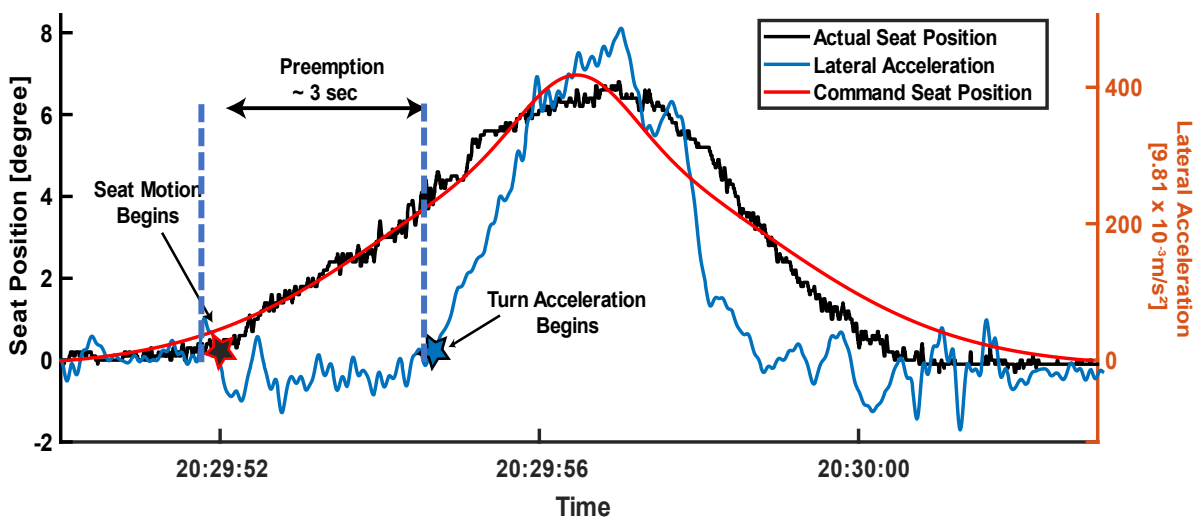
Fig 6-5 Trajectory of Tilting Seat and Lateral Acceleration of the vehicle for Left Turn

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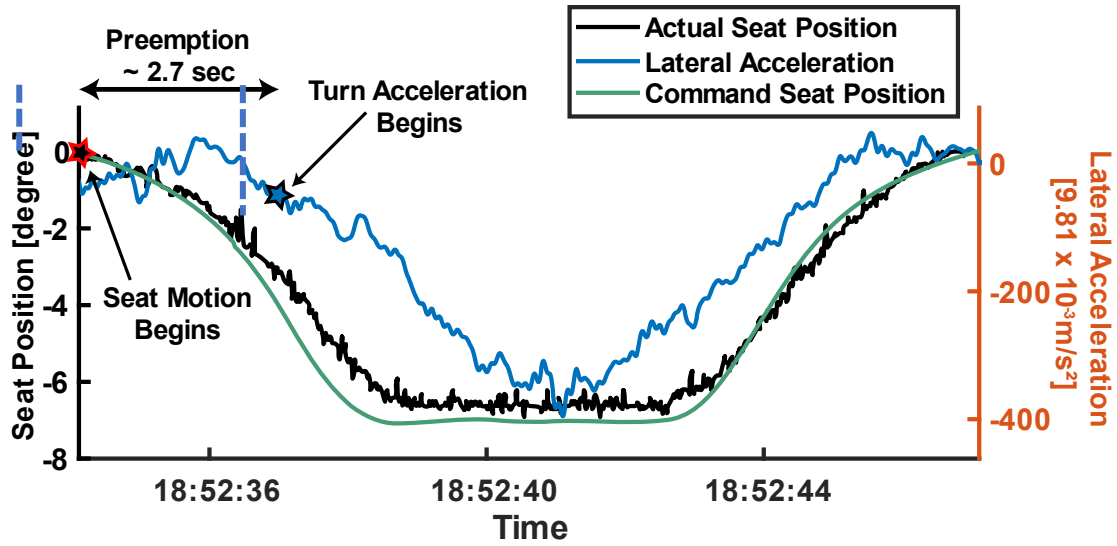
Fig 6-6 Trajectory of Tilting Seat and Lateral Acceleration of the vehicle for Right Turn
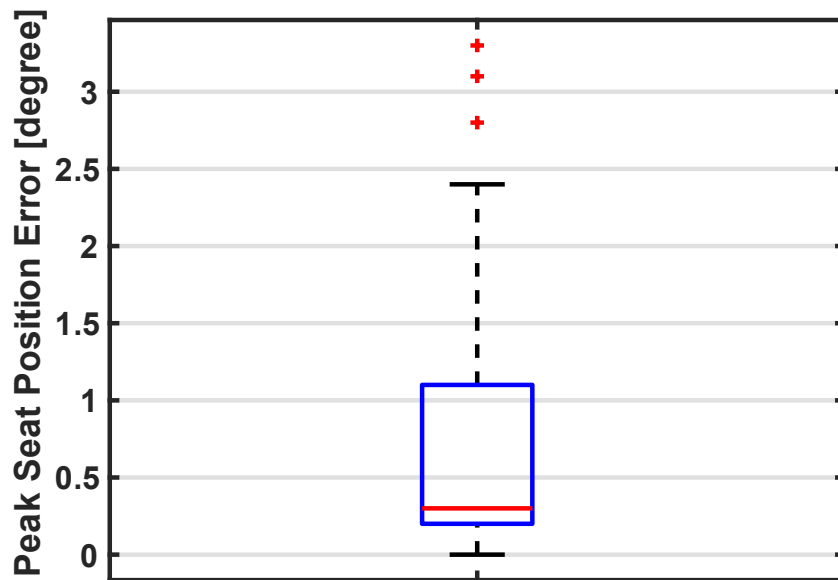
Fig 6-7 Boxplot of Error in Peak Seat Position across all drives

6.5 Study Participants

Over forty participants were recruited for the study. Of those participants, only twenty-nine completed their participation in the study (i.e., they completed all two test conditions) (Fig 6-8). This represents an attrition of 28%, which is similar to the attrition in the APS study and prior research [260]. Of these twenty-nine participants, twelve were male and seventeen were female.

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The average age of the male participants was twenty-five years (25yrs ± 4yrs), and the average age of the female participants was twenty-five years (25yrs ± 4.5yrs) (Fig 6-8). There was no statistically significant difference in the age of the participants, such that age of participants would not influence their carsickness response.

Participants self-reported their motion sickness susceptibility and motion sickness frequency. Based on their susceptibility and frequency, participants were grouped into three categories of motion sickness response: low, moderate, and high motion sickness susceptibility. By grouping participants by their motion sickness susceptibility, the influence of the preemptive tilting seat could be assessed by their susceptibility. A numeric value was assigned to self-reported susceptibility and frequency. To indicate their motion sickness susceptibility, participants could select one of five options: (a) Not at All, (b) Minimally, (c) Moderately, (d) Very, and (e) Extremely. Each of those options is assigned a numerical score between 1 and 5, with "Not at All" being assigned a score of 1 and "Extremely" being assigned a score of 5. To indicate their frequency of motion sickness, participants could select one of four options: (a) Never, (b) Rarely, (c) Sometimes, and (d) Frequently. Each of those options is assigned a numerical score between 1 and 4, with "Never" being assigned a score of 1 and "Frequently" being assigned a score of 4. For each participant, by summing their response score, they were bucketed into one of the three categories of motion sickness response (i.e., Low = sum less than equal to 4, Mod = more than or equal to 5 and less than or equal to 7, High = more than or equal to 8 and less than or equal to 9).

Ten participants (five females + five males) were categorized as low motion sickness susceptibility, eighteen participants (eleven females + seven males) were categorized as moderate motion sickness susceptibility, and one participants (one female + zero male) were categorized as high motion sickness susceptibility. The majority of the participants were moderate and low

susceptibility. Unlike the previous APS study, recruiting high motion sickness susceptibility participants proved to be challenging.
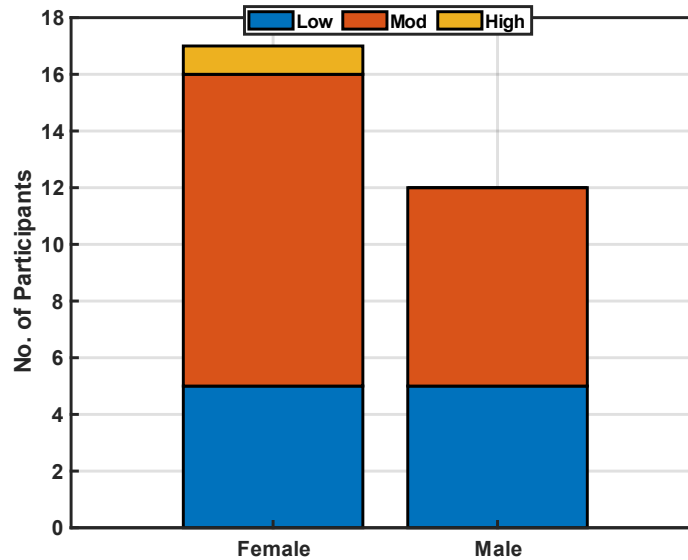
Fig 6-8 Summary of Tilting Seat System Study Participant Demographics including self-reported motion sickness susceptibility

6.6 Research Vehicle Path

The test vehicle (Section 4.3) was run at the Mcity test facility for all test conditions (Fig 6-9). A path was designed to traverse the various driving environments at Mcity, to ensure that the participants experience a suitable range of motion events and time between events (e.g., short vs. long right turns). The path was limited to different types of left and right turns only. No braking or stop events were included. This was to limit the motion of the tilting seat system to roll. Further research is required to determine optimal seat motion for stop events. The peak lateral associated with the path was 6 m/s^2. This lateral acceleration are typical of everyday driving conditions [244].
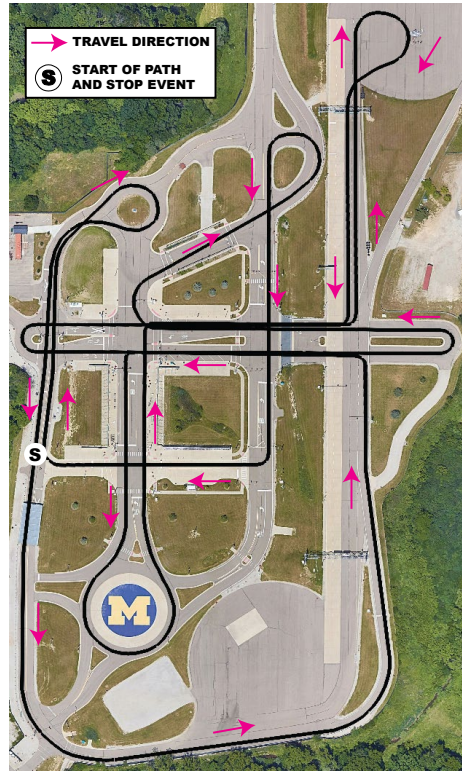
Fig 6-9 Test path on the Mcity Test Track for Tilting Seat Study

Each test condition included 3 loops of the designed path, with each loop consisting of numerous left turns and right turns. The path consisted of 9 left turns and 7 right turns. The time between turns varied between 3 seconds to as much as 10 seconds. The duration of the turns also varied, as some turns (e.g., about traffic circles) were longer than others. Thus, the participants could not learn or memorize the test path, and it represented realistic driving conditions by recreating similar accelerations as everyday driving. The detailed description and driving instructions for the path are summarized in Table 6-4. Each loop of the path took approximately 6.5 minutes to complete, for a total time of approximately 20 minutes for all 3 loops.

EVENT	DRIVING INSTRUCTIONS	EVENT	DRIVING INSTRUCTIONS
Start Event	a) 15 mph b) Rolling Left	Event 9	a) Left (About traffic circle), 10 mph b) Exit circle, 15 mph
Event 1	a) Rolling Left	Event 10	a) Left (About traffic circle), 10 mph b) Exit circle, 15 mph

Event 2	a) Rolling Left	Event 11	a) Rolling right b) 12 mph
Event 3	a) Rolling Left b) 12 mph	Event 12	a) Left (About traffic circle) b) Exit circle, 12 mph
Event 4	a) Left (About traffic circle), 12 mph b) Exit circle,15 mph	Event 13	a) Rolling Right
Event 5	a) Rolling Right b) 12 mph	Event 14	a) Rolling Right
Event 6	a) Rolling Left b) 12 mph	Event 15	a) Right (About traffic circle), 12 mph b) Exit circle, 12 mph
Event 7	a) Right (About traffic circle) b) Exit circle, 12 mph	Event 16	a) 15 mph (towards Start Event) b) Repeat path
Event 8	a) Rolling Right		

Table 6-4 Summary of Test Path and Driving Instructions for Tilting Seat Study

6.7 Experimental Results

This section describes the results of analysis of three types of data collected during the study. This data represents a subset of the total data collected during the experiments. The three types of data are: (a) Self-Reported Motion Sickness Score, (b) Task Performance, and (c) Subjective Participant Responses. The motion sickness scores are based on the UMTRI Motion Sickness Scale described earlier (Section 4.5.2). Task performance data consists of accuracy and response time (additional details are described in Section 4.5.1). Subjective Participant Responses were collected in response to questionnaires administered to all participants at the end of the study.

6.7.1 Motion Sickness Response

In Fig 6-10, the mean CS scores for all twenty-nine participants across both test conditions are plotted as a function of time. Initially the CS response seems similar across both test conditions (before 5 mins). The difference in the rate of accumulation of CS is most apparent between 5mins and 15mins. The rate of CS accumulation is highest for TC 2 (i.e., AST OFF), and lowest for TC 1 (i.e., AST ON). This data supports the hypothesis that even when the participant is performing a

task, the preemptively triggered tilting seat system can help reduce the rate of CS accumulation. As expected, the final CS score is lower (at 19.5mins) for TC 1 as compared to TC 2. However, a small dip is observed in the final CS score (at 19.5mins) for TC 2. This sudden reduction in CS score may have been due to the inherent nonlinearity in a person's motion sickness response caused by the body's motion sickness recovery mechanism. Another possible reason for a sudden reduction in CS score may have been due to the participant disengaging from the task, leading to temporary relief. This may explain why the sudden dip is more pronounced in the TC 2 condition when the tilting seat system was not operational.

A further analysis to determine the final MS score for all participants across test conditions showed that for 15 out of 29 (7 females + 8 males, 52%) participants the final MS score was higher for TC2 as compared to TC1. This is an indication that the tilting seat system is able to keep the CS score lower for at least 50% of the participants. 7 out of 29 (4 females + 3 males) participants had the same final CS score across both test conditions, and 7 out of 29 (6 females + 1 male) participants had a higher final CS score for TC 1 as compared to TC 2 (the delta was within 2 points on the UMTRI scale). These results are summarized in Table 6-5. This motivated the need for analysis of CS score data by gender of the participant. The mean CS score was obscuring nuanced differences in the motion sickness response of the participants.

Further analysis of the data revealed that there was a difference in CS response as a function of the gender and motion sickness susceptibility of the participants. The mean CS scores for all twelve male participants across both test conditions are plotted as a function of time in Fig 6-11. There is a significant noticeable difference in both the rate of accumulation of CS score and peak CS score across test conditions for male participants. Both the final CS score and rate of accumulation of CS was drastically lower for TC 1 as compared to TC 2. Therefore, the tilting seat had a significant

influence on the CS response of the male participants.
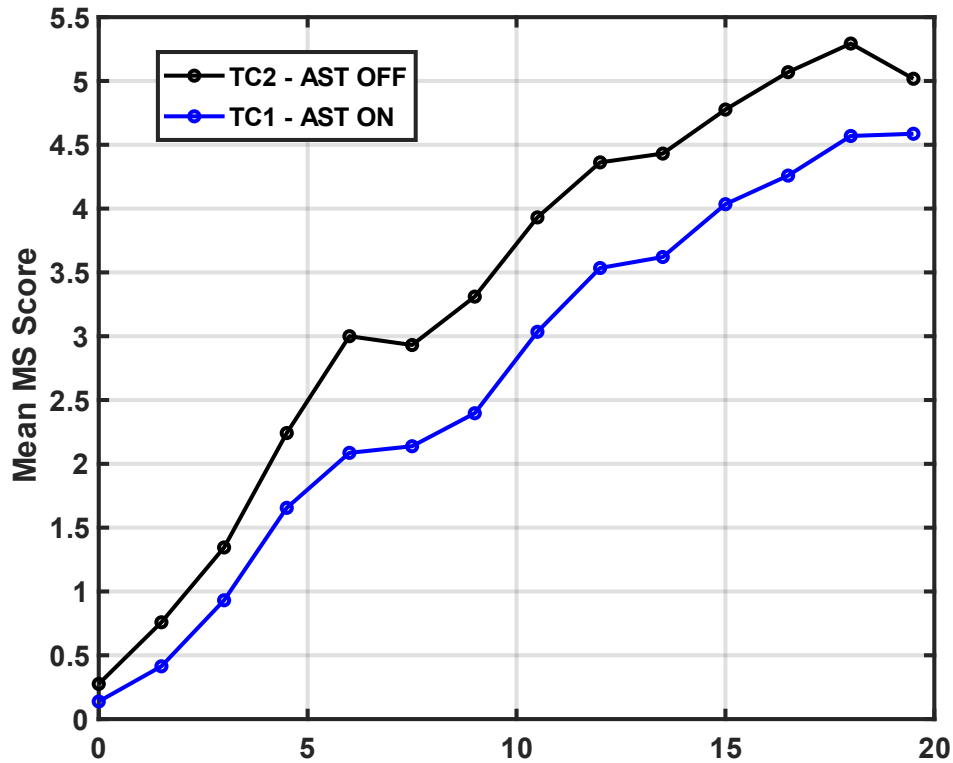
Fig 6-10 Mean Motion Sickness Scores across all Tilting Seat Study Participants, grouped by Test Conditions

FINAL CS SCORE	LOW SUSCEPTIBILITY		MODERATE SUSCEPTIBILITY		HIGH SUSCEPTIBILITY		TOTAL
	FEMALE	MALE	FEMALE	MALE	FEMALE	MALE	
TC 2 > TC 1	1/5	5/5	6/11	3/7	0/1	0/0	15/29
TC 2 ~ TC 1	1/5	0/5	2/11	3/7	1/1	0/0	7/29
TC 2 < TC 1	3/5	0/5	3/11	1/7	0/1	0/0	7/29

Table 6-5 Final CS Score Data Summary across test conditions and gender of participants

However, the CS response for the female participants was very different from that of the male participants. The mean CS scores for all seventeen female participants across both test conditions are plotted as a function of time Fig 6-12. There is almost no noticeable difference in the rate of CS accumulation across test conditions, with the CS score for TC 1 rising slightly higher than the CS score for TC 2 towards the end of the study. This data indicates that the preemptively triggered

tilting seat system has no influence on CS response of female participants. There are several possible causes of this disparity in CS response of female participants versus male participants.
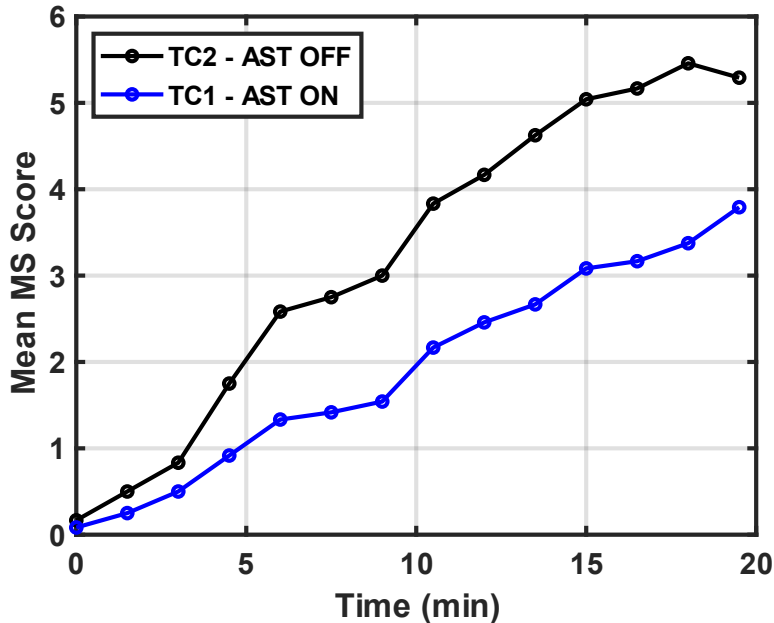
Fig 6-11 Mean Motion Sickness Scores across Male Participants Only, grouped by Test Condition

One possible reason for the disparity in female and male participant CS response may be due to the disparity in the number of female versus male participants. Since there are more female participants (as compared to males), and one of the female participants has high motion sickness susceptibility (no high susceptibility males), the female participant data may be disproportionately affecting the aggregated CS score data. A sensitivity analysis was performed to study the effect of this disparity. Data from certain female participants was removed from analysis to achieve parity between the number of male and female participants (equal numbers), including by motion sickness susceptibility. By ensuring equal numbers of male and female participants of each motion sickness susceptibility group, one set of participants should not be able to disproportionately affect the aggregated CS score data. Different strategies were used to determine which female participants to exclude. First, the high susceptibility female participant data was excluded as there

was no corresponding data for a male high susceptibility participant. Second, four moderate susceptibility females were randomly selected and removed from the data analysis to ensure an equal number of males and females. The mean CS scores for one such reduced female datasets is shown in Fig 6-13. As is evident from the figure, there is no statistically significant difference between the mean CS score trends for all seventeen female participants (Fig 6-12) versus a randomly chosen group of twelve female participants (Fig 6-13). Therefore, the CS score trend in female participant data is not sensitive to the response of a few participants only, and instead is representative of most female participants of the study.

The CS scores aggregated across all participants may obscure the contrast in CS response by test conditions across motion sickness susceptibility and gender. In Fig 6-14, the mean CS scores for low susceptibility participants across both test conditions are plotted as a function of time. In Fig 6-14 (Left) the mean data for all five male participants with low motion sickness susceptibility is plotted. From this data, it is observed that the tilting seat system (AST) is able to reduce the male participants' motion sickness. Both the peak CS score and rate of accumulation of CS for TC 1 was lower than that for TC 2. The data seems to indicate that a preemptively triggered tilting seat system helps reduce motion sickness for low susceptibility male participants.
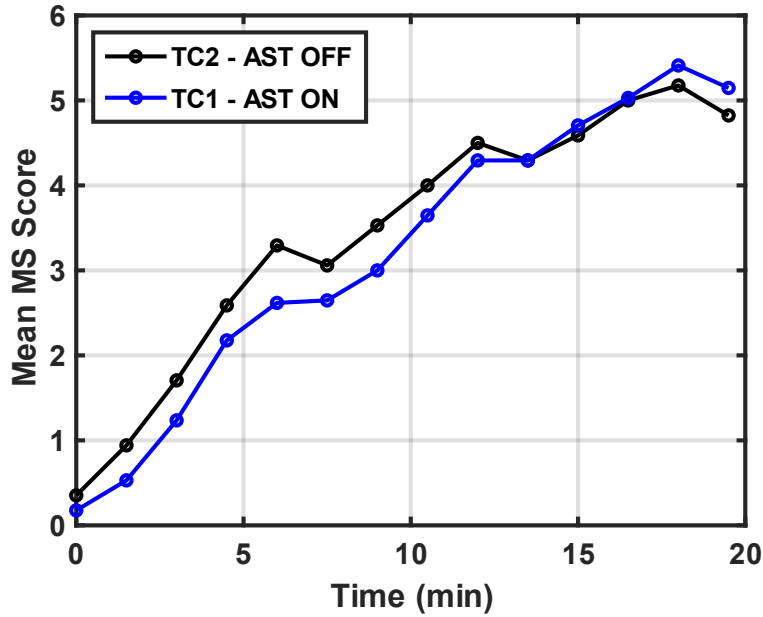
Fig 6-12 Mean Motion Sickness Scores across Female Participants Only, grouped by Test Condition
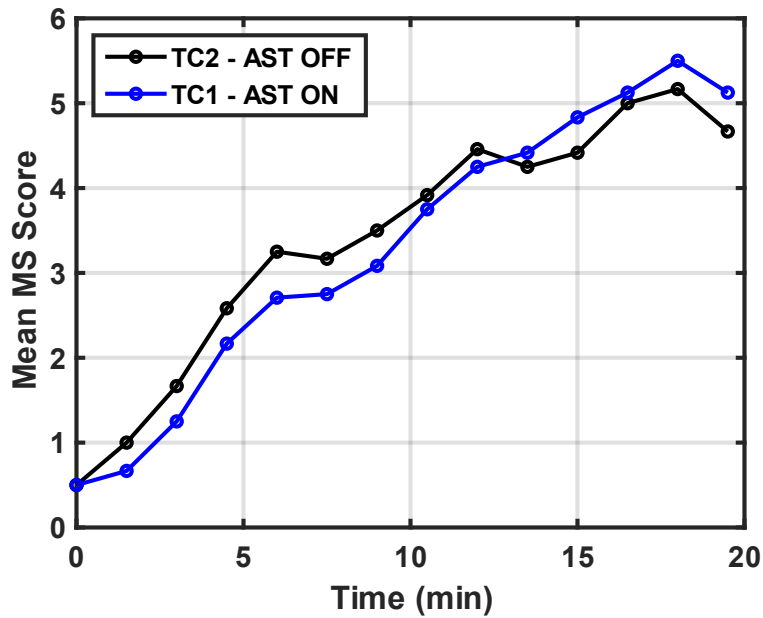
Fig 6-13 Mean Motion Sickness Scores across one set of randomly selected Female Participants Only, grouped by Test Condition. 12x female participants, equal to number of male participants

In Fig 6-14 (Right) the mean data for all five female participants with low motion sickness susceptibility is plotted. From this data, it is observed that the tilting seat system is not able to reduce the female participants' motion sickness. The peak CS score and rate of accumulation of

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CS appears to be similar, irrespective of test condition. In the second half of the study (at approximately 10 mins), the CS score for TC 1 is higher than the CS score for TC 2. The data seems to indicate that a preemptively triggered tilting seat system does not help reduce motion sickness for the low susceptibility female participants. It is also worth noting that, irrespective of test condition, the CS scores for male low susceptibility participants appears to be higher than the scores for female low susceptibility participants.
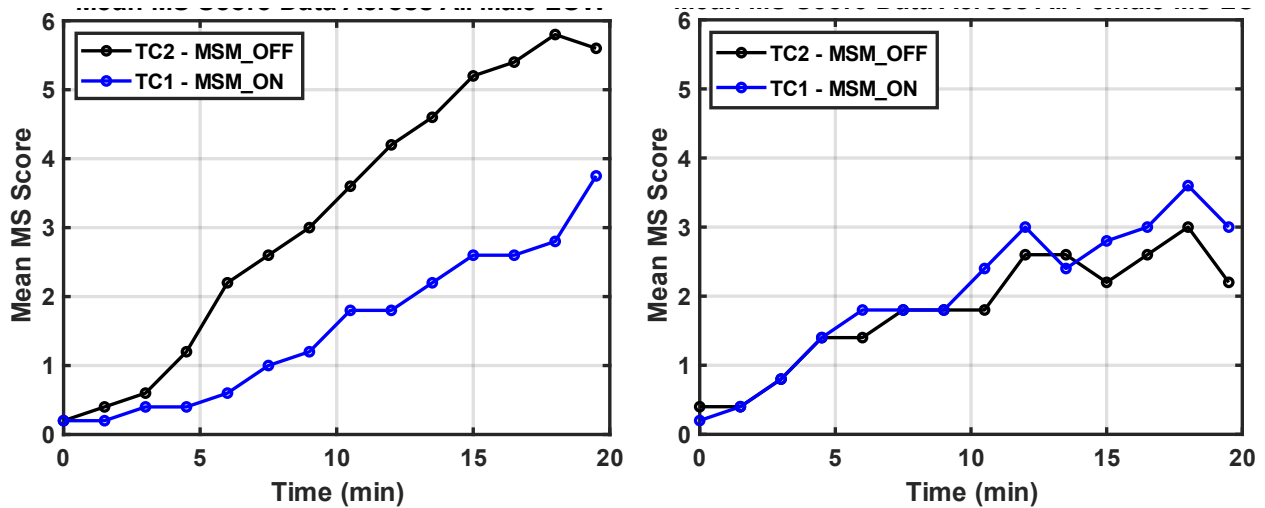
Fig 6-14 (Left) Mean Motion Sickness Scores across Low Susceptibility Male participants. (Right) Mean Motion Sickness Scores across Low Susceptibility Female participants

A similar trend in CS score data is observed for moderate susceptibility male and female participants. In Fig 6-15, the mean CS scores for moderate susceptibility participants across both test conditions are plotted as a function of time. In Fig 6-15 (Left) the mean data for all seven male participants with moderate motion sickness susceptibility is plotted. From this data, it is observed that the tilting seat system (AST) is able to reduce the male participants' motion sickness. Both the peak CS score and rate of accumulation of CS for TC 1 was lower than that for TC 2. However, as shown in Fig 6-15 (Right) the mean data for all moderate susceptibility female participants does not show a decrease in CS score due to the tilting seat. Therefore, across both low and moderate

susceptibility participants, the preemptively triggered tilting seat system is able to reduce motion sickness for male participants, but not for female participants of this study. To ensure that these trends in CS response are meaningful, statistical analysis to determine their significance was required.

A Linear Mixed Modelling (LMM) approach with random intercept and slope was used to statistically model the CS response data across all participants. Linear modelling is sufficient as the modelling error over the experimental data was minimal. The fixed effects for the model include test conditions (i.e., TC 1, TC 2, and TC 3) and time (i.e., 0 mins, 1.5 mins… 19.5 mins). The random slope for CS response measures individual variability over time for participants for a given test condition. Additional models with participant age as a fixed effect were also investigated to determine that it had no significant effect on the results. This result was expected as the experiment design and participant eligibility and selection criteria were deliberately chosen to ensure no significant effects due to participant age. The results of the LMM for all twenty-nine participants over the entire duration of the study (0 mins to 19.5 mins) are summarized in Table 6-6. The model uses TC 2 as a reference condition for analysis. The intercept refers to the CS score at time 0 mins (i.e., beginning of the test condition).
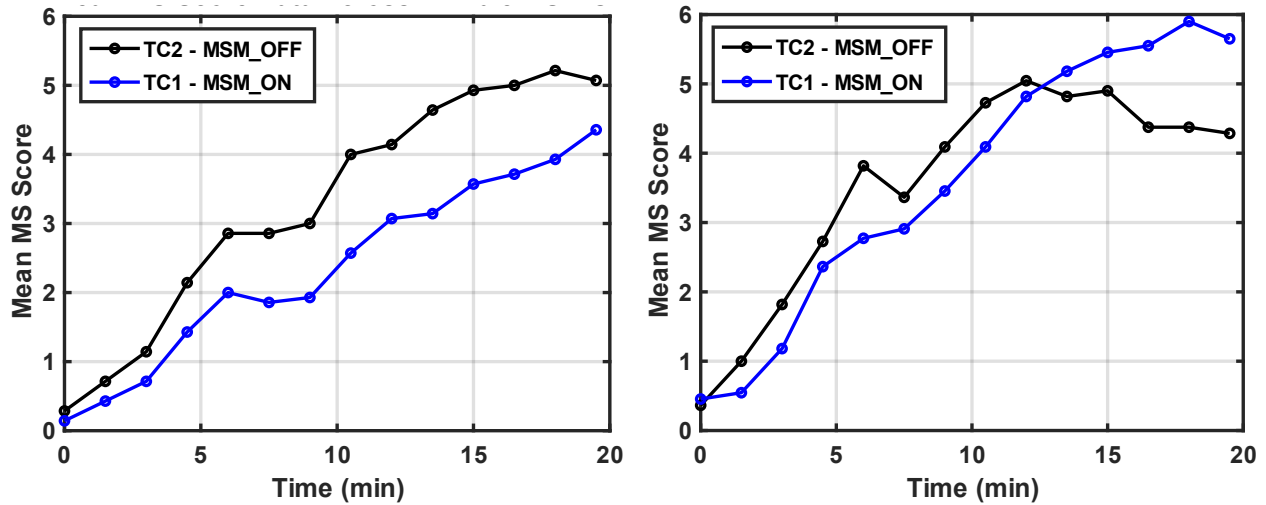
Fig 6-15 (Left) Mean Motion Sickness Scores across Moderate Susceptibility Male participants. (Right) Mean Motion Sickness Scores across Moderate Susceptibility Female participants

FIXED EFFECT COEFFICIENT	ESTIMATE	STANDARD ERROR	P-VALUE
Intercept of TC 2 (AST_OFF) Reference Condition	0.841	0.204	4.31 e-5
Δ Intercept TC 1 (AST_ON) vs TC 2	-0.493	0.147	8.38 e-4
Slope of TC 2 (AST_OFF) Reference Condition	0.256	0.025	1.90 e-23
Δ Slope TC 1 (AST_ON) vs TC 2	-0.018	0.013	1.63 e-1

Table 6-6 Linear Mixed Effects Model Results (Fixed Coefficient Results) for Tilting Seat Study

From the results, at the beginning of both test conditions, the CS score across all participants is nearly 0 (yet significantly non-zero). There is a small (yet statistically significant) difference between the test conditions, with the intercept of TC 2 being larger than TC 1. This is expected as the experiment is designed to ensure that participants have the same or similar CS at the beginning of all the test conditions. The slope refers to the rate of accumulation of CS over the test condition. The difference in rate of accumulation of CS across test conditions is not statistically significant, with the lowest rate for CS accumulation being associated with the TC 1 condition.

Since the motion sickness response of participants has some non-linearity, an additional mixed

model was developed over a smaller time period of the study which had a lower model error. Based on the model fit statistics, the time period between 0mins and 12mins was modelled as it had nearly 50% better model fit and at the same time provided enough time for motion sickness accumulation to be meaningful. The results of the LMM over a portion of the study (0mins to 12mins) are summarized in Table 6-7. From the results, at the beginning of both test conditions, the CS score across all participants is close to 0 (yet significantly non-zero). The difference in rate of accumulation of CS across test conditions is statistically significant, with the lowest rate for CS accumulation being associated with the TC 1 condition. The rate of CS accumulation for TC 1 is nearly 20% lower than for TC 2. This indicates that the tilting seat has a statistically significant reduction in the CS response of the participants.

FIXED EFFECT COEFFICIENT	ESTIMATE	STANDARD ERROR	P-VALUE
Intercept of TC 2 (AST_OFF) Reference Condition	0.430	0.167	1.04 e-2
Δ Intercept TC 1 (AST_ON) vs TC 2	-0.272	0.147	6.35 e-2
Slope of TC 2 (AST_OFF) Reference Condition	0.339	0.029	7.86 e-28
Δ Slope TC 1 (AST_ON) vs TC 2	-0.062	0.021	2.48 e-3

Table 6-7 Linear Mixed Effects Model Results (Fixed Coefficient Results) for Tilting Seat Study, from 0mins to 12mins for all participants

While the experiment was designed to have an even balance between participant genders, the data indicated a significant influence due to participant gender. Therefore, additional LMM models were used to statistically model male and female participant data. The results of the LMM of only female participant data, over different time periods, are summarized in Table 6-8. From the results, as expected, the intercepts for TC 1 and TC 2 are close to each other. While the experiment was designed to ensure participants have similar CS at the beginning of all test conditions, this was impossible to enforce. Also, there was no statistically significant difference in rate of accumulation

of CS scores across test conditions (0mins to 12mins). There is a small statistically significant effect on rate of CS score accumulation across test conditions when modelled over the entire 19.5mins duration. However, the model fit error is larger for this mixed model. This data indicates that the tilting seat does not have any statistically significant effect on the CS response of female participants. However, the LMM results of only male participant data paints a different picture.

LINEAR MIXED MODEL RESULTS OVER 0MINS TO 19.5MINS			
FIXED EFFECT COEFFICIENT	ESTIMATE	STANDARD ERROR	P-VALUE
Intercept of TC 2 (AST_OFF) Reference Condition	1.159	0.287	6.36 e-5
Δ Intercept TC 1 (AST_ON) vs TC 2	-0.582	0.193	2.77 e-3
Slope of TC 2 (AST_OFF) Reference Condition	0.232	0.037	7.27 e-10
Δ Slope TC 1 (AST_ON) vs TC 2	0.038	0.017	2.42 e-2
LINEAR MIXED MODEL RESULTS OVER 0MINS TO 12MINS			
Intercept of TC 2 (AST_OFF) Reference Condition	0.671	0.238	5.15 e-3
Δ Intercept TC 1 (AST_ON) vs TC 2	-0.401	0.203	4.86 e-2
Slope of TC 2 (AST_OFF) Reference Condition	0.332	0.041	1.36 e-14
Δ Slope TC 1 (AST_ON) vs TC 2	-0.001	0.028	9.82 e-1

Table 6-8 Linear Mixed Effects Model Results (Fixed Coefficient Results) for Tilting Seat Study, Female Participant Data only

The results of the LMM of only male participants' data, over different time periods, are summarized in Table 6-9. From the results, the intercepts for both test conditions are non-zero but with no statistical significance (i.e., the null hypothesis of intercept being 0 cannot be ignored). This is supported by the experiment design where all participants should have the same or similar CS score at the beginning of all test conditions. The noteworthy result is the difference in rate of accumulation of CS across test conditions. The results indicate that the tilting seat system dramatically reduced the rate of CS accumulation for male participants (statistically significant)

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by over 30% when modelled over the entire 19.5mins duration. When modelled over a duration of 12mins (with better model fit), the results indicate that the tilting seat system reduced the rate of CS accumulation for male participants (statistically significant) by over 40%. These results indicated that the tilting seat system helped reduce the CS response of male participants.

LINEAR MIXED MODEL RESULTS OVER 0MINS TO 19.5MINS			
FIXED EFFECT COEFFICIENT	ESTIMATE	STANDARD ERROR	P-VALUE
Intercept of TC 2 (AST_OFF) Reference Condition	0.448	0.248	7.15 e-2
Δ Intercept TC 1 (AST_ON) vs TC 2	-0.343	0.189	7.04 e-2
Slope of TC 2 (AST_OFF) Reference Condition	0.287	0.029	1.18 e-20
Δ Slope TC 1 (AST_ON) vs TC 2	-0.093	0.017	3.73 e-8
LINEAR MIXED MODEL RESULTS OVER 0MINS TO 12MINS			
Intercept of TC 2 (AST_OFF) Reference Condition	0.087	0.195	6.56 e-1
Δ Intercept TC 1 (AST_ON) vs TC 2	-0.091	0.190	6.34 e-1
Slope of TC 2 (AST_OFF) Reference Condition	0.348	0.037	1.86 e-17
Δ Slope TC 1 (AST_ON) vs TC 2	-0.150	0.027	5.66 e-8

Table 6-9 Linear Mixed Effects Model Results (Fixed Coefficient Results) for Tilting Seat Study, Male Participant Data only

In summary, the CS response results from this study paint a confusing picture. Aggregated data across all 29 participants showed that a preemptive tilting seat can reduce carsickness (slightly). However, when the CS response is analyzed by gender, we saw that the preemptive tilting seat had a dramatic reduction of CS for male participants, while it had no statistically significant effect on female participant CS response. Despite identical experimental conditions and strict participant inclusion and exclusion criteria, the CS response varied as a function of the gender of the participant. It is likely that a larger sample size of participants (recommend more than 50) can provide more insight and data to reduce this disparity in motion sickness response due to gender.

6.7.2 Representative Task Performance

Task performance was quantified using the following parameters: (a) accuracy of responses, (b) percentage of skipped questions, and (c) response time for answering questions. Accuracy of responses was defined as the ratio between the number of questions answered correctly and the sum of the number of questions answered correctly, questions answered incorrectly, and questions skipped. This sum of questions represents the total number of questions viewed by a participant during the test condition. The percentage of skipped questions was defined as the ratio between the number of skipped questions and the total number of questions viewed by the participant during the test condition. The response time for answering questions was defined as the time between the participant first viewing a question to them either finalizing their response or skipping the question. Of the 29 participants, task performance data for 5 participants was corrupted or lost due to system errors. Of these five participants, one participant was a moderate susceptibility female, one participant was a low susceptibility female, one participant was a low susceptibility male, and remaining two participants were moderate susceptibility males. Therefore, task performance data analysis was only performed on data from 24 participants.

Since the task performance data was a continuous paired non-parametric dataset, Wilcoxon Signed-Rank analysis was used to statistically model task performance to determine significance. Task performance data was aggregated across all 24 participants and comparison of task performance across the test conditions (namely TC 1 and TC 2) is summarized in Table 6-10. A comparison of task performance between TC 1 and TC 2 is required to determine the influence of tilting seat system on quality of task performance. Across all the data in Table 6-10, there is no statistically significant difference in quality of task performance across both those test conditions. For accuracy, the means across both TC 2 and TC 1 are similar and within only a couple of percent

points of each other. For response time, the means across both TC 2 and TC 1 vary by as much as 3 seconds of each other, but this difference is not statistically significant, and the size of this effect is small to moderate in relation to their respective standard deviations. This means that the tilting seat system had no statistically significant influence on task performance.

Since there was a significantly different CS response due to gender of the participant, the task performance was also analyzed by participant gender. Task performance data was aggregated across all 15 female participants and comparison of task performance across the test conditions (namely TC 1 and TC 2) is summarized in Table 6-11. Across most of the data for female participant task performance, there was no statistically significant difference in quality of task performance across both those test conditions. Notably, there was a small (yet statistically significant) spike in accuracy of high cognitive burden questions in TC 1 condition. This is an indication that while the tilting seat might have had a negative influence on their CS response, it may have slightly improved their task performance. For response time, the means across both TC 2 and TC 1 vary by as much as 7 seconds of each other, but this difference was not statistically significant.

Since the tilting seat system had a significant reduction on the CS response of male participants, a similar positive influence on task performance was expected. Task performance data was aggregated across all 9 male participants and comparison of task performance across the test conditions (namely TC 1 and TC 2) is summarized in Table 6-12. Across all the data, there is no statistically significant difference in quality of task performance across both those test conditions. For accuracy, the means across both TC 2 and TC 1 are similar and within only a couple of percent points of each other. For response time, the means across both TC 2 and TC 1 vary by as much as 8 seconds of each other, but this difference is not statistically significant. This means that the tilting

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seat system had no statistically significant influence on task performance of male participants.

PARAMETER	TC 2 – AST OFF	TC 1 – AST ON	Δ TC 1 & TC 2
Mean Accuracy across all questions	84% ± 8%	85% ± 8%	TC 1 ~ TC 2
Mean Accuracy of only low cognitive questions	88% ± 8%	87% ± 6%	TC 1 ~ TC 2
Mean Accuracy of only high cognitive questions	79% ± 12%	83% ± 13%	TC 1 ~ TC 2
Mean Percentage of skipped questions	1% ± 1%	1% ± 1%	TC 1 ~ TC 2
Mean Response time across all questions	27s ± 8s	27s ± 12s	TC 1 ~ TC 2
Mean Response time across only low cognitive questions	23s ± 7s	26s ± 12s	TC 1 ~ TC 2
Mean Response time across only high cognitive questions	30s ± 14s	29s ± 20s	TC 1 ~ TC 2

Table 6-10 Summary of Task Performance Statistical Analysis by Test Conditions for All Participants. Note: * p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001

PARAMETER	TC 2 – AST OFF	TC 1 – AST ON	Δ TC 1 & TC 2
Mean Accuracy across all questions	84% ± 8%	86% ± 8%	TC 1 ~ TC 2
Mean Accuracy of only low cognitive questions	91% ± 8%	87% ± 6%	TC 1 ~ TC 2
Mean Accuracy of only high cognitive questions	78% ± 12%	85% ± 10%	TC 1 > TC 2 *
Mean Percentage of skipped questions	2% ± 2%	2% ± 1%	TC 1 ~ TC 2
Mean Response time across all questions	27s ± 9s	25s ± 6s	TC 1 ~ TC 2
Mean Response time across only low cognitive questions	23s ± 8s	26s ± 11s	TC 1 < TC 2
Mean Response time across only high cognitive questions	30s ± 16s	23s ± 8s	TC 1 ~ TC 2

Table 6-11 Summary of Task Performance Statistical Analysis by Test Conditions for Female Participants. Note: * p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001

PARAMETER	TC 2 – AST OFF	TC 1 – AST ON	Δ TC 1 & TC 2
Mean Accuracy across all questions	83% ± 7%	84% ± 10%	TC 1 ~ TC 2
Mean Accuracy of only low cognitive questions	85% ± 8%	88% ± 6%	TC 1 ~ TC 2
Mean Accuracy of only high	81% ± 11%	79% ± 16%	TC 1 ~ TC 2

cognitive questions			
Mean Percentage of skipped questions	1% ± 1%	1% ± 0%	TC 1 ~ TC 2
Mean Response time across all questions	26s ± 7s	32s ± 17s	TC 1 ~ TC 2
Mean Response time across only low cognitive questions	24s ± 6s	26s ± 15s	TC 1 ~ TC 2
Mean Response time across only high cognitive questions	30s ± 11s	38s ± 29s	TC 1 ~ TC 2

Table 6-12 Summary of Task Performance Statistical Analysis by Test Conditions for Male Participants. Note: * p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001

6.7.3 Subjective Participant Response

Every participant was interviewed after their participation in every test condition and asked to describe their experience qualitatively. The interview consisted of various open and close ended questions to determine the quality of the participants experience during the test condition. Participants were asked about their overall experience inside the test vehicle to determine if any environmental factors such as temperatures or smells influenced their CS response. None of the participants reported any issues with these environmental factors during the study. Similarly, none of the participants reported any discomfort or annoyance associated with the instrumentation and sensors that were used to collect data. Like the APS study, when participants were asked about their experience performing the task during the study, majority of the participants indicated that it was harder to perform the task in a moving car as compared to the baseline task performed in a room.

When asked about their overall comfort and ability to notice the motion of the tilting seat system, 23 out of 29 (80%) participants indicated that they did not find the motion of the tilting a source of annoyance or discomfort or even noticeable. The remaining 6 participants found the seat motion to be noticeable, especially during sharp turns, but did not find it to cause any discomfort. Since the motion sickness response varied by the gender of the participants, their subjective

preferences were also analyzed by participant gender. 12 out of 17 (71%) of female participants indicated that they did not find the motion of the tilting a source of annoyance or discomfort or even noticeable. This indicates that while the tilting seat system did not reduce motion sickness for most female participants, majority of those participants did not find the motion of the tilting seat to be annoying or noticeable. 11 out of 12 (92%) of male participants indicated that they did not find the motion of the tilting a source of annoyance or discomfort or even noticeable. This indicates that not only did the tilting seat system reduce motion sickness for male participants, the motion of the seat also did not cause any annoyance. This data supports the claim that at least for some of the study participants, the chosen tilting seat trajectory was both effective in reducing CS and did not cause any annoyance.

At the end of the study, after the participants had successfully completed participation in all test conditions, participants were asked if they liked the tilting seat system and would the same or similar system in a car as a passenger. The goal of this question was to determine the participants overall preference for a tilting seat system, in addition to their subjective CS score. Of the 29 participants, 20 participants (70%) indicated a positive preference for the tilting seat system. Some participants believed that the tilting seat system helped them perform the task better. Other participants believed that the tilting seat increased their overall comfort and reduced their motion sickness. Specifically, one male participant mentioned that the tilting seat leaned them into the turn allowing them to relax their body which increased overall comfort. This data is summarized in Table 6-13.

Of those 20 participants with a positive preference for the tilting seat system, 9 participants (9/17, 53%) were female and 11 participants (11/12, 92%) were male. This indicates that while the CS score data suggests that the tilting seat did not reduce motion sickness for female participants,

about half of them still indicated a positive preference for the tilting seat system. When asked to expand on the reason for their preference, some of these female participants indicated that they believed the tilting seat system made it easier to perform the task. One female participant indicated that the tilting seat system made the ride feel smoother. Further analysis looked at the combination of tilting seat experience and preference. Across 12 male participants, 11 participants indicated that they have, both a preference for the tilting seat system and did not find the motion of the seat to be noticeable or annoying. Only 1 male participant indicated that they did not prefer the tilting seat system and found the motion of the seat to be noticeable. One male participant's feedback was that they did not find the motion of the seat to be proportional to the intensity of the turn.

The data for female participants was more varied. Across the 17 female participants, 9 participants indicated a positive preference for the tilting seat system, and 7 of these 9 found the motion of the seat to not be noticeable or annoying. The remaining 8 female participants indicated that they do not prefer the tilting seat system, and 5 of these 8 found the motion of the seat to not be noticeable or annoying.

PREFERENCE FOR TILTING SEAT	MOTION OF SEAT NOTICEABLE	MOTION SICKNESS SUSCEPTIBILITY						TOTAL
		LOW		MODERATE		HIGH		
		FEMALE	MALE	FEMALE	MALE	FEMALE	MALE	
Yes	No	3/5	5/5	4/11	6/7	0/1	0/0	18/29
Yes	Yes	1/5	0/5	1/11	0/7	0/1	0/0	2/29
No	No	0/5	0/5	5/11	0/7	0/1	0/0	5/29
No	Yes	1/5	0/5	1/11	1/7	1/1	0/0	4/29

Table 6-13 Summary of Tilting Seat Preference and Motion of Seat Noticeable subjective responses across all participants

This data is an indication that the tilting seat system may have had a positive effect on the overall experience of the female participants, and this positive effect was (possibly) not captured by their self-reported CS score data or task performance data. This is the first study to report

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qualitative data of this kind indicating a subjective preference for a tilting seat system that has mixed efficacy in reducing CS.

6.8 Discussion

The data from this study shows an unexpected and unexplainable influence of a tilting seat system on motion sickness. The data from this study shows a difference in CS response as a function of gender of the participant. There is limited evidence in prior literature to suggest that the carsickness response varies as a function of participant gender [63]. Therefore, it is unlikely that the disparity in CS score was simply due to gender effects.

The preemptively triggered tilting seat reduces motion sickness for male participants but had no effect on the motion sickness response of the female participants of the study. Yet, just over half the female participants still indicated a positive preference for the tilting seat system. When combined with the data on female participant task performance (which showed a small positive effect on task performance of female participants), it is possible that the tilting seat system might have had a positive effect on the female participants, and this effect was not observable in their self-reported CS scores. This may be due to the inherent limitation of the self-reported CS score system which is subjective in nature and is susceptible to the varying levels of participant's self-awareness.

Majority of the male participants who indicated a preference for the tilting seat system also indicated that they did not find the motion of the seat noticeable or annoying. This was by design, as the trajectory of the seat motion was chosen to minimize acceleration and provide a smooth motion. Nearly half of the participants who did not prefer the tilting seat system also indicated that they found the motion of the seat noticeable (but not necessarily annoying). This data seems to indicate that the trajectory and type of motion of the tilting seat might play a significant role in CS

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mitigation, and its subjective perception and acceptance by passengers. Further investigation is required to determine optimal seat motion trajectories that will maximize both CS mitigation and positive preference for the tilting seat.

The available data from this study does not provide a clear indication of why the CS response of the participants varied by gender. One possible reason could be the lack of repeatability in experimental conditions. However, the data across all participants shows minimal error in seat motion, vehicle driving experience, and preemptive triggering of the seat. Therefore, it is unlikely that poor experimental repeatability was the cause for this variance in CS response. Another possible reason could be the participants themselves, in that the participants in this study had some unknown or unconscious prejudice against the tilting seat system. However, participants were recruited from a participant pool of hundreds of potential candidates and were not given any specific information about the expected relationship between the tilting seat system and CS response which could have biased them. Therefore, it is unlikely that an unknown bias or prejudice is responsible for the disparity in CS mitigation across participant gender. It is likely that a larger sample size of participants may help address this disparity in CS scores and provide definitive insights regarding the behavior of the tilting seat system. Using the CS score data from this study, future researchers can use statistical power estimation and statistical sample size estimation tools to determine the minimum number of participants required to provide definitive insights.

The data also shows that the tilting seat has no statistically significant influence on task performance. This means that the tilting seat system can reduce motion sickness for the male participants of the study without interfering with their task performance. While there is no measurable difference in task performance, the majority of the male participants indicated a strong preference for the tilting seat system. Some of the male participants also mentioned that the tilting

seat system "seemed" to help them perform the task better. Similarly, even female participants who did not see a reduction in motion sickness indicated that the tilting seat system "seemed" to help them perform the task better. For female participants, the response time for high cognitive burden questions reduced when the tilting seat system was on (statistically significant). There was no other statistically significant difference in task performance. Therefore, while the task was meticulously designed to be a faithful representation of real-world tasks that a passenger may perform, further development and improvements may be required to be able to detect more nuanced changes in the quality of task performance. This development may include investigating different types of questions and/or other modes of task performance assessment such as gaze tracking of the passenger. For example, by tracking the gaze of the passenger we can determine differences in time spent looking/gazing at the tablet to perform the task and time spent looking elsewhere.

While the results from this study are significant, this study has some practical limitations which limit the realism of the test conditions. First, there are limitations in participant recruitment. While the total number of participants in the study is within the typical range for similar studies, a larger pool of participants (recommend more than 50) will lead to higher quality data. Also, it is difficult to recruit participants with a high susceptibility to motion sickness as they are reluctant to participate in a study that will make them sick, and they are also more likely to drop out of a study if they begin their participation (i.e., higher attrition rate as compared to low susceptibility participants).

Second, the use of a real vehicle on a test track ensures participant safety but limits realistic recreation of the experience of a person in a car. For example, a car on the highway may turn for many seconds, but the path used in this study only has a maximum separation between events of

10 to 15 seconds. Similarly, the path used in this study does not include braking or stop events, which is unlike real world driving conditions. Lastly, it is nearly impossible to ensure identical experimental and physiological conditions for participants across the three test conditions. While the study design requires that participants have nominal sleep, physical activity, and diet across the various test conditions, it is impossible to recreate these perfectly.

Despite these limitations, this is the first study of its kind to investigate the effects of a preemptively triggered tilting seat system on CS response while the participants are performing a task. This is the first study to investigate the differences in CS response due to tilting seat system and task performance on participants grouped by their motion sickness susceptibility. The study included driving participants in a real vehicle under realistic driving conditions simulated on a test track. Lastly, this is the first study of its kind to also use post participation questionnaires to gauge the participants subjective response and experience while participating in the study. Through these subjective responses, this study was able to show a positive preference for the tilting seat system even in participants who did not show a reduction in their motion sickness score.

These results motivate the need for future research using similar or improved study designs, especially with regards to optimal preemption for the CS mitigation systems. This study used a preemption of 3 seconds as that was similar to the preemption used in prior literature and similar to the perception and response times of drivers. However, the optimum preemption time to maximize motion sickness mitigation remains unknown. This study, like most of the prior literature on preemptively triggered tilting seat systems only used the tilting seat to mitigate CS. However, there may be an optimal combination of various CS mitigation systems such as combining sensory stimuli with tilting seat that can be more effective at reducing CS and may even improve the passengers task performance.

6.9 Conclusion

In this chapter, the results from the study to investigate the efficacy of a preemptively triggered tilting seat system in mitigating CS are presented (N=29 participants). The results from the study demonstrate that a preemptively triggered tilting seat can reduce CS, at least for some participants, even when the participant is performing a representative task. Even the participants who did not see a reduction in CS indicated a positive preference for the tilting seat system as they believed it helped them perform the task better. However, this was not observable in the statistical analysis of the task performance data.

Lastly, results motivate the need for future research using similar or improved study designs to investigate open research questions such as optimal amount of preemption, and optimal type of seat motion. Further investigations are required to understand the full extent of the positive and negative effects of preemptively activated stimuli systems on a vehicle passenger's motion sickness response and overall well-being.

Chapter 7 Conclusion & Future Work

The first significant contribution of this research was an improved model to predict motion sickness response of a person when they are riding in a vehicle. Unlike the previous MS models presented in literature, the model proposed and validated in this research includes visually sensed motion (in addition to vestibular sensed motion) as a model input to predict motion sickness. This contribution is significant, as the proposed model has a more accurate prediction of motion sickness in response to low frequency motion (i.e., at or below 0.1Hz) as compared to models in prior literature. A more accurate motion sickness prediction model can allow for benchtop evaluation of motion sickness response, without the need for complex human subject experiments. In addition, accurate predictions of motion sickness response can be used to trigger motion sickness mitigation systems onboard a vehicle. However, the proposed model does have some limitations that must be addressed in future research.

A key limitation of the proposed model is that it relies on visual and vestibular motion sensory organs only. The proposed model does not include the proprioceptive organ. As stated in Chapter 2, the proprioceptive organ is a major motion sensing organ of the body. However, unlike the eyes or the vestibular organs, the understanding of how the proprioceptive organ works and senses motion is limited. Due to this limited understanding of the proprioceptive organ, there are no mathematical models in existing research literature describing its function. Therefore, a key area of future research investigation is to develop a better understanding of the physiological and biological mechanisms of how the proprioceptive organ senses motion, which can then be used to create mathematical models of the proprioceptive organ.

In addition, current literature on motion sickness modelling and theory does not provide insights into the relative contribution of the various sensory organs to motion sickness. For example, while we know that eyes, vestibular organs, and proprioceptive organs can all sense motion, it is not known if the motion sensed by one of those organs plays a more significant role than the others in causing motion sickness. This insight can not only help improve our understanding of how a person gets motion sick, but it can also improve the predictions of motion sickness models. Similarly, current literature on the causes of motion sickness is limited by the lack of deeper understanding of the human brain. For example, it is not known how the brain (and the nervous system) processes the sensed motion leading to a person feeling motion sick. While there are many theories attempting to explain the brain's processing of the sensed motion, there is no definitive evidence in support of those theories in current literature. Therefore, a key area of future research investigations is to develop a better understanding of the physiological and neurological processes of the brain, in response to a person experiencing motion which leads to motion sickness.

The second significant contribution of this research was the development of a unique research vehicle platform (the M-LoW) to study motion sickness response of passengers under realistic driving conditions. Some of the unique qualities of the M-LoW include the real time GPS information based precise preemptive triggering of the onboard mitigation systems. The M-LoW also included extensive instrumentation to track the motion of the vehicle, the motion of the passenger, and the passenger's physiological response while in a moving vehicle. The M-Low also had sufficient space for the integration of multiple motion sickness mitigation systems such as the haptic stimuli and tilting seat system used in this research. However, the M-LoW had some practical limitations.

The M-LoW was a manually driven vehicle and had to rely on the Wizard of Oz approach (from

existing research literature) to emulate autonomous vehicle driving. Manual driving, even after extensive training of the drivers, led to some variation in the vehicle speed and acceleration across the participants. Since motion sickness response is closely related to the actual motion (and sensed motion) of a person, any variation in actual motion of a passenger due to inconsistencies in driving can lead to uncontrolled variance in the motion sickness response. To address this limitation, a proposed improvement for future research with the M-LoW would be to give the M-LoW some type of automated driving capability to reduce variability in vehicle acceleration and speed due to manual driving.

The third significant contribution of this research was the experiment design, execution, and results from a human subject's study evaluating the efficacy of preemptively triggered haptic stimuli system in reducing carsickness in passengers performing a NDR task, under realistic driving conditions. With data from 24 participants of varying motion sickness susceptibility, it was demonstrated that not only did the preemptively triggered haptic stimuli system reduce their carsickness, but it did so without negatively affecting the participant's ability to perform tasks. This contribution is significant as this was the first research study to evaluate the effect of a participant performing a task on the efficacy of sensory stimuli system in reducing carsickness under realistic driving conditions. The data also demonstrated that when a participant is performing a task, the preemptive haptic stimuli system was not as effective at reducing carsickness as when the participant was not performing a task. Also, this was the first study to provide an assessment of the participant's task performance under the influence of preemptive haptic stimuli system. The data demonstrated that the preemptive haptic stimuli system had no effect on the participant's task performance. In addition, this was the first study to use questionnaires to gauge the subjective experience of the participants, in addition to their self-reported motion sickness scores to get a

better understanding of the participant's overall experience while participating in the study. The data demonstrated that even participants who did not show a reduction in their motion sickness score still indicated a positive preference for the haptic stimuli system. Despite its many 'firsts', this study had its share of limitations.

A key limitation of this study was participant recruitment. While the total number of participants in this study was higher than or the same as the typical range for similar studies, a larger pool of participants would lead to higher quality data and more statistical power. This larger pool of participants must represent a broader range of motion sickness susceptibilities, age, height, weight, and any other factors which may influence a person's motion sickness response. Also, it was difficult to recruit participants with a high susceptibility to motion sickness as they are reluctant to participate in a study that will make them sick, and they are also more likely to drop out of a study if they begin their participation (i.e., higher attrition rate as compared to low susceptibility participants). High motion sickness susceptibility individuals are most vulnerable to motion sickness in vehicles, and as indicated by the results of this study, value a reduction in their motion sickness highly.

Another key limitation of this study was in the choice of sensory stimuli (haptic) and encoding (i.e., mapping of specific stimuli signals to vehicle motion) of the vehicle motion to the chosen sensory stimuli. Based on prior literature, it was assumed that haptic stimuli would be least distracting and easy to interpret. However, thorough investigation is required to evaluate this assumption. This future research should explicitly test and compare the CS mitigation efficacy of (a) different types of sensory stimuli and (b) different encoding for the same sensory stimuli to determine the most optimal type and encoding of sensory stimuli to maximize CS mitigation, under realistic driving conditions. In addition, while extensive benchtop testing was conducted to

determine the haptic sensory encoding and majority of the participants reported that they could easily decode the haptic stimuli to determine the upcoming vehicle motion event, further investigations are required to determine the optimal encoding of vehicle motion information to the haptic stimuli. The optimal encoding may mean that all of the participants (instead of ~90% of the participants in this study) would be able to decode information about upcoming vehicle motion, which may further reduce their motion sickness response. To address this limitation, future research should determine which type of sensory stimuli and associated encoding is most effective at reducing carsickness, even when the passenger is performing a task. Only by investigating various types of sensory stimuli, including combinations of sensory stimuli (e.g., both audio and haptic stimuli or both visual and audio stimuli), can it be determined which type (or combination) of stimuli system is most effective at reducing carsickness.

The fourth (and final) significant contribution of this research was the experiment design, execution, and results from a human subject's study evaluating the efficacy of preemptively triggered tilting seat system in reducing carsickness in passengers performing a NDR task, under realistic driving conditions. With data from 29 participants of varying motion sickness susceptibility, it was demonstrated that the preemptively triggered tilting seat system dramatical reduced carsickness for some of the participants (~50% reduction in rate of carsickness accumulation of male participants) but had no impact on the carsickness response of remaining participants (female participants showed no change in carsickness response). The data also demonstrated that the tilting seat helped reduce carsickness without negatively affecting the participant's ability to perform tasks. This was the first study to provide an assessment of the participant's task performance under the influence of preemptive tilting seat system. The data demonstrated that the preemptive tilting seat system had no effect on the participant's task

performance. In addition, this was the first study to use questionnaires to gauge the subjective experience of the participants, in addition to their self-reported motion sickness scores to get a better understanding of the participant's overall experience while participating in the study. The data demonstrated that even participants who did not show a reduction in their motion sickness score still indicated a positive preference for the tilting seat system. Despite its many 'firsts', this study had its share of limitations.

A key limitation of this study was the unexpected carsickness response of male versus female participants. As stated in Chapter 6 (Section 6.8), it is likely that a larger sample size of participants would provide more insights to explain this unexpected carsickness response. While the total number of participants in this study was higher than or the same as the typical range for similar studies, a larger pool of participants (recommend more than 50) would lead to higher quality data and more statistical power. This larger pool of participants must represent a broader range of motion sickness susceptibilities, age, height, weight, and any other factors which may influence a person's motion sickness response.

Another limitation of this study was that only a tilting seat was used which could move the passenger in response to the vehicle making a turn (i.e., only lateral accelerations), instead of a tip-tilt seat that could move the passenger in response to both vehicle making turns and stops (i.e., both longitudinal and lateral accelerations). This study was intentionally limited in scope to just tilting motion as this research is part of a step by step, thorough investigation process. It is recommended that the efficacy of preemptively triggered (only) tilting seat first be established, followed by efficacy of preemptively triggered (only) tipping seat, finally leading to an investigation of preemptively triggered combined tipping and tilting seat. In addition, this study had practical constraints due to limited access to the test track. Since real world driving includes

both longitudinal and lateral accelerations, future research to address this limitation must investigate the efficacy of a tip-tilt seat system in reducing carsickness.

Similarly, future research must also determine the optimal seat motion trajectory that can maximize motion sickness mitigation. In this study, it was assumed that a smooth and slow trajectory of the seat would be least noticeable for participants and would cause least additional acceleration of the passenger's head and torso (thereby not causing motion sickness due to seat motion). While the subjective participant data from the tilting seat study appears to support the above assumption, further systematic investigation are required to determine the optimal seat motion trajectory (for both tip and tilt motion) which maximizes carsickness mitigation. For example, it is likely that the assumption that a slow and smooth trajectory would be the right choice for a tilting seat. However, further optimization of the trajectory using methods other than Gaussian curves may lead to better CS mitigation outcomes.

Lastly, this study leveraged a commercially available active seat to move the participant during the study. As noted earlier, using a commercially available active seat limited the modifications which could be made to how the seat would move the passenger. For example, the seat had a maximum tilt of 7 degrees which limited the amount of alignment of the person's head and torso with the gravito-inertial acceleration direction for turns with lateral accelerations greater than 1 m/sec^2. Similarly, the center of rotation of the tilting seat used in this study was located just below the participant. Prior literature has some evidence to indicate that the center of rotation of a tilting seat can influence carsickness response [166]. Therefore, it is recommended that for future research, an active seat be developed which would allow for more flexibility in modifying its operating parameters (e.g., maximum tilt, center of rotation of tilt, etc.) to study how the attributes of the tilting seat may influence carsickness response of the passengers.

It is also worth noting that there are critical areas of future research that are common to both the haptic stimuli and tilting seat study mentioned above. First, across both the studies a preemption time of 3 seconds was chosen as the above studies were attempting to recreate the experience of a driver for the vehicle passenger, and prior literature had established that a driver's perception and response time to vehicle events can be as large as 3 seconds. However, the optimal preemption time for maximizing carsickness mitigation remains unknown. Further investigations are required to determine optimal preemption times, and if they differ due to (a) whether a participant is performing a task or not, (b) type or combination of carsickness mitigation system (e.g., sensory stimuli and/or tilting seat system), (c) type of vehicle motion, and (d) due to individual variability in preference.

Second, both of the above studies relied on self-reported subjective measurements of the participants motion sickness response. Self-reported subjective measurements of motion sickness are commonly used in current research as there are no objective measurements of motion sickness, and correlations with physiological parameters such as heart rate or perspiration are currently not robust enough to replace self-reported measurements. However, self-reported measurements of motion sickness, irrespective of the motion sickness scale used, are susceptible to error due to individual variability. For example, if a participant is not sensitive to the subtle changes in their motion sickness response, they will not report a change in their motion sickness scores, leading to lost data. Future research should address this limitation by strengthening correlations between objective physiological measurements of a participant (e.g., heart rate, perspiration, muscle activity, etc.) and their motion sickness response. The physiological data collected from the studies in this research can be used to strengthen the correlations between objective physiological measurements of a participant and their motion sickness response. The ideal goal of this future

research should be to develop a new method to measure the motion sickness response of an individual as objectively as possible.

Third, both of the above studies limited the view of the outside environment for the participants. This was done to reduce uncontrolled variance in motion sickness response of participants due to high variability in motion sickness response across individuals as a function of their analysis of the vehicle's environment. However, realistic driving includes vehicles with windows and passengers have at least some view of the outside environment. Therefore, there is a need for future research evaluating the efficacy of preemptive haptic stimuli system and tilting seat system with the participant being able to view the outside environment of the vehicle.

In summary, despite its limitations, this research identified two promising strategies for motion sickness mitigation and provides strong experimental evidence in support of their efficacy. This research is the first of its kind to use a real research vehicle, recreate realistic driving conditions, and assess both motion sickness response and quality of task performance under the influence of preemptively triggered motion sickness mitigation systems.

Bibliography

[1]   P. G. Saranti, D. Chondrogianni, and S. Karatzas, "Autonomous Vehicles and Blockchain Technology Are Shaping the Future of Transportation," in *Data Analytics: Paving the Way to Sustainable Urban Mobility*, E. G. Nathanail and I. D. Karakikes, Eds., in Advances in Intelligent Systems and Computing. Cham: Springer International Publishing, 2019, pp. 797–803. doi: 10.1007/978-3-030-02305-8_96.

[2]   W. D. Montgomery, "Public and Private Benefits of Autonomous Vehicles," Jun. 2018, Accessed: Sep. 28, 2023. [Online]. Available: https://trid.trb.org/view/1522211

[3]   A. Faisal, M. Kamruzzaman, T. Yigitcanlar, and G. Currie, "Understanding autonomous vehicles: A systematic literature review on capability, impact, planning and policy," *Journal of Transport and Land Use*, vol. 12, no. 1, pp. 45–72, 2019.

[4]   Đ. Petrović, R. Mijailović, and D. Pešić, "Traffic Accidents with Autonomous Vehicles: Type of Collisions, Manoeuvres and Errors of Conventional Vehicles' Drivers," *Transportation Research Procedia*, vol. 45, pp. 161–168, Jan. 2020, doi: 10.1016/j.trpro.2020.03.003.

[5]   P. A. Singleton, J. De Vos, E. Heinen, and B. Pudāne, "Chapter Seven - Potential health and well-being implications of autonomous vehicles," in *Advances in Transport Policy and Planning*, vol. 5, D. Milakis, N. Thomopoulos, and B. van Wee, Eds., in Policy Implications of Autonomous Vehicles, vol. 5. , Academic Press, 2020, pp. 163–190. doi: 10.1016/bs.atpp.2020.02.002.

[6]   R. E. Stern *et al.*, "Quantifying air quality benefits resulting from few autonomous vehicles stabilizing traffic," *Transportation Research Part D: Transport and Environment*, vol. 67, pp. 351–365, Feb. 2019, doi: 10.1016/j.trd.2018.12.008.

[7]   M. Sivak and B. Schoettle, "Would Self-Driving Vehicles Increase Occupant Productivity?," The University of Michigan, Ann Arbor, USA, Technical Report SWT-2016-11, Sep. 2016.

[8]   "Morgan Stanley: Autonomous Cars Self-Driving the New Auto Industry Paradigm," presented at the Morgan Stanley Research, Morgan Stanley, Nov. 2013.

[9]   Q. Chen, Y. Xie, S. Guo, J. Bai, and Q. Shu, "Sensing system of environmental perception technologies for driverless vehicle: A review of state of the art and challenges," *Sensors and Actuators A: Physical*, vol. 319, p. 112566, Mar. 2021, doi: 10.1016/j.sna.2021.112566.

[10] J. Guanetti, Y. Kim, and F. Borrelli, "Control of connected and automated vehicles: State of the art and future challenges," *Annual Reviews in Control*, vol. 45, pp. 18–40, Jan. 2018, doi: 10.1016/j.arcontrol.2018.04.011.

[11] J. M. Owens, R. Greene-Roesel, A. Habibovic, L. Head, and A. Apricio, "Reducing Conflict Between Vulnerable Road Users and Automated Vehicles," in *Road Vehicle Automation 4*, G. Meyer and S. Beiker, Eds., in Lecture Notes in Mobility. Cham: Springer International Publishing, 2018, pp. 69–75. doi: 10.1007/978-3-319-60934-8_7.

[12] J. Haspiel *et al.*, "Explanations and Expectations: Trust Building in Automated Vehicles," in *Companion of the 2018 ACM/IEEE International Conference on Human-Robot*

Interaction, in HRI '18. New York, NY, USA: Association for Computing Machinery, Mar. 2018, pp. 119–120. doi: 10.1145/3173386.3177057.

[13]   C. Diels, J. E. Bos, K. Hottelart, and P. Reilhac, "Motion Sickness in Automated Vehicles: The Elephant in the Room," in *Road Vehicle Automation 3*, G. Meyer and S. Beiker, Eds., in Lecture Notes in Mobility. , Cham: Springer International Publishing, 2016, pp. 121–129. doi: 10.1007/978-3-319-40503-2_10.

[14]   A. Dam and M. Jeon, "A Review of Motion Sickness in Automated Vehicles," in *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, New York, NY, USA: Association for Computing Machinery, 2021, pp. 39–48. Accessed: Jan. 12, 2022. [Online]. Available: https://doi.org/10.1145/3409118.3475146

[15]   M. Sivak, M. Sivak, and B. Schoettle, *Motion Sickness in Self-Driving Vehicles*. 2015.

[16]   C. Diels, "Will autonomous vehicles make us sick?," in *Contemporary Ergonomics and Human Factors 2014*, S. Sharples and S. Shorrock, Eds., Taylor & Francis, 2014, pp. 301–307. doi: 10.1201/b16742-56.

[17]   T. Wada, "Motion sickness in automated vehicles," in *Advanced Vehicle Control AVEC'16*, CRC Press, 2016.

[18]   D. Huppert, J. Benson, and T. Brandt, "A Historical View of Motion Sickness—A Plague at Sea and on Land, Also with Military Impact," *Front Neurol*, vol. 8, p. 114, Apr. 2017, doi: 10.3389/fneur.2017.00114.

[19]   T. G. Dobie, "Motion Sickness," in *Motion Sickness: A Motion Adaptation Syndrome*, T. G. Dobie, Ed., in Springer Series on Naval Architecture, Marine Engineering, Shipbuilding and Shipping. , Cham: Springer International Publishing, 2019, pp. 1–32. doi: 10.1007/978-3-319-97493-4_1.

[20]   J. R. Lackner, "Motion sickness: more than nausea and vomiting," *Exp Brain Res*, vol. 232, no. 8, pp. 2493–2510, 2014, doi: 10.1007/s00221-014-4008-8.

[21]   J. E. Bos, S. N. MacKinnon, and A. Patterson, "Motion Sickness Symptoms in a Ship Motion Simulator: Effects of Inside, Outside, and No View," vol. 76, no. 12, p. 9, 2005.

[22]   A. J. C. Reuten, S. A. E. Nooij, J. E. Bos, and J. B. J. Smeets, "How feelings of unpleasantness develop during the progression of motion sickness symptoms," *Exp Brain Res*, vol. 239, no. 12, pp. 3615–3624, Dec. 2021, doi: 10.1007/s00221-021-06226-1.

[23]   P. Matsangas, M. E. McCauley, and W. Becker, "The Effect of Mild Motion Sickness and Sopite Syndrome on Multitasking Cognitive Performance," *Hum Factors*, vol. 56, no. 6, pp. 1124–1135, Sep. 2014, doi: 10.1177/0018720814522484.

[24]   M. E. McCauley, E. C. Pierce, and P. Matsagas, "The High-Speed Navy: Vessel Motion Influences on Human Performance," *Naval Engineers Journal*, vol. 119, no. 1, pp. 35–44, 2007, doi: 10.1111/j.0028-1425.2007.00002.x.

[25]   J. Dahlman, T. Falkmer, and S. Nählinder, "Perceived Motion Sickness and Effects on Shooting Performance Following Combat Vehicle Transportation," *Journal of Human Performance in Extreme Environments*, vol. 9, no. 2, Nov. 2006, doi: 10.7771/2327-2937.1045.

[26]   J. Dahlman, T. Falkmer, and F. Forsman, "Perceived Motion Sickness and Effects on Performance Following Naval Transportation," *Journal of Human Performance in Extreme Environments*, vol. 10, no. 1, Oct. 2012, doi: 10.7771/2327-2937.1046.

[27]   C. A. Duncan, C. J. Hickey, and J. M. Byrne, "The effects of a moving environment on postural control and task performance during manual materials handling, visual tracking and

arithmetic tasks," *International Journal of Industrial Ergonomics*, vol. 66, pp. 221–229, Jul. 2018, doi: 10.1016/j.ergon.2018.03.007.

[28] J. F. Golding, "Motion sickness," in *Handbook of Clinical Neurology*, vol. 137, Elsevier, 2016, pp. 371–390. doi: 10.1016/B978-0-444-63437-5.00027-3.

[29] C. M. Oman, "Sensory conflict in motion sickness: An observer theory approach," Jul. 1989. Accessed: Nov. 09, 2019. [Online]. Available: https://ntrs.nasa.gov/search.jsp?R=19900013641

[30] W. Chung and M. Barnett-Cowan, "Influence of Sensory Conflict on Perceived Timing of Passive Rotation in Virtual Reality," *Multisensory Research*, vol. 1, no. aop, pp. 1–23, Apr. 2022, doi: 10.1163/22134808-bja10074.

[31] U. Laessoe, S. Abrahamsen, S. Zepernick, A. Raunsbaek, and C. Stensen, "Motion sickness and cybersickness – Sensory mismatch," *Physiology & Behavior*, vol. 258, p. 114015, Jan. 2023, doi: 10.1016/j.physbeh.2022.114015.

[32] W. Bles, J. E. Bos, B. de Graaf, E. Groen, and A. H. Wertheim, "Motion sickness: only one provocative conflict?," *Brain Research Bulletin*, vol. 47, no. 5, pp. 481–487, Nov. 1998, doi: 10.1016/S0361-9230(98)00115-4.

[33] G. Bertolini and D. Straumann, "Moving in a Moving World: A Review on Vestibular Motion Sickness," *Front. Neurol.*, vol. 7, 2016, doi: 10.3389/fneur.2016.00014.

[34] W. Bles, J. E. Bos, and H. Kruit, "Motion sickness," *Current Opinion in Neurology*, vol. 13, no. 1, pp. 19–25, Feb. 2000.

[35] G. E. Riccio and T. A. Stoffregen, "An ecological Theory of Motion Sickness and Postural Instability," *Ecological Psychology*, vol. 3, no. 3, pp. 195–240, Sep. 1991, doi: 10.1207/s15326969eco0303_2.

[36] B. J. Yates, A. D. Miller, and J. B. Lucot, "Physiological basis and pharmacology of motion sickness: an update," *Brain Research Bulletin*, vol. 47, no. 5, pp. 395–406, Nov. 1998, doi: 10.1016/S0361-9230(98)00092-6.

[37] A. Shupak and C. R. Gordon, "Motion Sickness: Advances in Pathogenesis, Prediction, Prevention, and Treatment," *Aviation, Space, and Environmental Medicine*, vol. 77, no. 12, pp. 1213–1223, Dec. 2006.

[38] Z. Nachum, A. Shupak, and C. R. Gordon, "Transdermal Scopolamine for Prevention of Motion Sickness," *Clin Pharmacokinet*, vol. 45, no. 6, pp. 543–566, Jun. 2006, doi: 10.2165/00003088-200645060-00001.

[39] T. G. Dobie, "Pharmacological Treatment of Motion Sickness," in *Motion Sickness: A Motion Adaptation Syndrome*, T. G. Dobie, Ed., in Springer Series on Naval Architecture, Marine Engineering, Shipbuilding and Shipping. , Cham: Springer International Publishing, 2019, pp. 183–217. doi: 10.1007/978-3-319-97493-4_10.

[40] C. D. Wood, J. E. Manno, B. R. Manno, H. M. Redetzki, M. Wood, and W. A. Vekovius, "Side effects of antimotion sickness drugs," *Aviat Space Environ Med*, vol. 55, no. 2, pp. 113–116, Feb. 1984.

[41] A. Weerts, N. Pattyn, P. Van de Heyning, and F. Wuyts, "Evaluation of the effects of anti-motion sickness drugs on subjective sleepiness and cognitive performance of healthy males," *J Psychopharmacol*, vol. 28, no. 7, pp. 655–664, Jul. 2014, doi: 10.1177/0269881113516201.

[42] A. G. Halpert, M. C. Olmstead, and R. J. Beninger, "Mechanisms and abuse liability of the anti-histamine dimenhydrinate," *Neuroscience & Biobehavioral Reviews*, vol. 26, no. 1, pp. 61–67, Jan. 2002, doi: 10.1016/S0149-7634(01)00038-0.

[43] R. Malcolm and W. C. Miller, "Dimenhydrinate (Dramamine) Abuse: Hallucinogenic Experiences with a Proprietary Antihistamine," *AJP*, vol. 128, no. 8, pp. 1012–1013, Feb. 1972, doi: 10.1176/ajp.128.8.1012.

[44] A. Brainard and C. Gresham, "Prevention and Treatment of Motion Sickness," *AFP*, vol. 90, no. 1, pp. 41–46, Jul. 2014.

[45] M. Sutton, A. L. Mounsey, and R. G. Russell, "Treatment of motion sickness," 2012, Accessed: Jan. 13, 2022. [Online]. Available: https://mospace.umsystem.edu/xmlui/handle/10355/14840

[46] P. L. Palatty, R. Haniadka, B. Valder, R. Arora, and M. S. Baliga, "Ginger in the Prevention of Nausea and Vomiting: A Review," *Critical Reviews in Food Science and Nutrition*, vol. 53, no. 7, pp. 659–669, Jan. 2013, doi: 10.1080/10408398.2011.553751.

[47] K. E. Miller and E. R. Muth, "Efficacy of Acupressure and Acustimulation Bands for the Prevention of Motion Sickness," *Aviation, Space, and Environmental Medicine*, vol. 75, no. 3, pp. 227–234, Mar. 2004.

[48] A. Rolnick and R. E. Lubow, "Why is the driver rarely motion sick? The role of controllability in motion sickness," *Ergonomics*, vol. 34, no. 7, pp. 867–879, Jul. 1991, doi: 10.1080/00140139108964831.

[49] T. Wada, S. Fujisawa, and S. Doi, "Analysis of driver's head tilt using a mathematical model of motion sickness," *International Journal of Industrial Ergonomics*, vol. 63, pp. 89–97, Jan. 2018, doi: 10.1016/j.ergon.2016.11.003.

[50] J. E. Bos, W. Bles, and E. L. Groen, "A theory on visually induced motion sickness," *Displays*, vol. 29, no. 2, pp. 47–57, Mar. 2008, doi: 10.1016/j.displa.2007.09.002.

[51] T. Fukuda, "Postural Behaviour and Motion Sickness," *Acta Oto-Laryngologica*, vol. 81, no. 3–6, pp. 237–241, Jan. 1976, doi: 10.3109/00016487609119955.

[52] T. Wada, H. Konno, S. Fujisawa, and S. Doi, "Can Passengers' Active Head Tilt Decrease the Severity of Carsickness?: Effect of Head Tilt on Severity of Motion Sickness in a Lateral Acceleration Environment," *Hum Factors*, vol. 54, no. 2, pp. 226–234, Apr. 2012, doi: 10.1177/0018720812436584.

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

[54] S. C. Davis and R. G. Boundy, *Transportation Energy Data Book: Edition 40*, 40th ed. Oak Ridge National Laboratory, 2022. [Online]. Available: https://tedb.ornl.gov/wp-content/uploads/2022/03/TEDB_Ed_40.pdf

[55] J. T. Reason and J. J. Brand, *Motion sickness*. in Motion sickness. Oxford, England: Academic Press, 1975, pp. vii, 310.

[56] B. Cohen, M. Dai, S. B. Yakushin, and C. Cho, "The neural basis of motion sickness," *Journal of Neurophysiology*, vol. 121, no. 3, pp. 973–982, Mar. 2019, doi: 10.1152/jn.00674.2018.

[57] A. Koohestani *et al.*, "A Knowledge Discovery in Motion Sickness: A Comprehensive Literature Review," *IEEE Access*, vol. 7, pp. 85755–85770, 2019, doi: 10.1109/ACCESS.2019.2922993.

[58] Claremont, CA, "The psychology of sea-sickness," *Psyche*, vol. 11, pp. 86–90, 1931.

[59] S. E. Phelps, "Airsickness treatment and prevention: Recommendations regarding antiemetics and/or acustimulation," Mar. 2007, Accessed: Jan. 08, 2021. [Online]. Available: https://utmb-ir.tdl.org/handle/2152.3/76

[60] J. R. Lackner and P. DiZio, "Space motion sickness," *Exp Brain Res*, vol. 175, no. 3, pp. 377–399, Nov. 2006, doi: 10.1007/s00221-006-0697-y.

[61] J. Iskander *et al.*, "From car sickness to autonomous car sickness: A review," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 62, pp. 716–726, Apr. 2019, doi: 10.1016/j.trf.2019.02.020.

[62] C. Diels and J. E. Bos, "Self-driving carsickness," *Applied Ergonomics*, vol. 53, pp. 374–382, Mar. 2016, doi: 10.1016/j.apergo.2015.09.009.

[63] S. Klosterhalfen, F. Pan, S. Kellermann, and P. Enck, "Gender and race as determinants of nausea induced by circular vection," *Gender Medicine*, vol. 3, no. 3, pp. 236–242, Sep. 2006, doi: 10.1016/S1550-8579(06)80211-1.

[64] J. Smyth, S. Birrell, A. Mouzakitis, and P. Jennings, "Motion Sickness and Human Performance – Exploring the Impact of Driving Simulator User Trials," in *Advances in Human Aspects of Transportation*, vol. 786, N. Stanton, Ed., in Advances in Intelligent Systems and Computing, vol. 786. , Cham: Springer International Publishing, 2019, pp. 445–457. doi: 10.1007/978-3-319-93885-1_40.

[65] B. D. Lawson, S. A. Smith, S. J. Kass, R. S. Kennedy, and E. R. Muth, "Vestibular Stimuli May Degrade Situation Awareness Even When Spatial Disorientation is not Experienced," ADP013883, Feb. 2003. Accessed: Oct. 11, 2023. [Online]. Available: https://apps.dtic.mil/sti/citations/ADP013883

[66] N. A. Stanton, P. R. G. Chambers, and J. Piggott, "Situational awareness and safety," *Safety Science*, vol. 39, no. 3, pp. 189–204, Dec. 2001, doi: 10.1016/S0925-7535(01)00010-8.

[67] G. Johansson, "Visual Motion Perception," *Scientific American*, vol. 232, no. 6, pp. 76–89, 1975.

[68] J. López-Moliner, "Perception of acceleration in motion-in-depth with only monocular and both monocular and binocular information," *Psicológica*, vol. 24, pp. 93–108, 2003.

[69] B. L. Day and R. C. Fitzpatrick, "The vestibular system," *Current Biology*, vol. 15, no. 15, pp. R583–R586, Aug. 2005, doi: 10.1016/j.cub.2005.07.053.

[70] A. Prochazka, "Proprioception: clinical relevance and neurophysiology," *Current Opinion in Physiology*, vol. 23, p. 100440, Oct. 2021, doi: 10.1016/j.cophys.2021.05.003.

[71] J. L. Taylor, "Proprioception," in *Encyclopedia of Neuroscience*, L. R. Squire, Ed., Oxford: Academic Press, 2009, pp. 1143–1149. doi: 10.1016/B978-008045046-9.01907-0.

[72] Graybiel, A, "Susceptibility to acute motion sickness in blind persons.," *Aerosp Med*, vol. 41, no. 6, pp. 650–653, Jun. 1970.

[73] M. Dai, T. Raphan, and B. Cohen, "Labyrinthine lesions and motion sickness susceptibility," *Exp Brain Res*, vol. 178, no. 4, pp. 477–487, Apr. 2007, doi: 10.1007/s00221-006-0759-1.

[74] W. H. Johnson, F. A. Sunahara, and J. P. Landolt, "Importance of the vestibular system in visually induced nausea and self-vection," *J Vestib Res*, vol. 9, no. 2, pp. 83–87, 1999.

[75] P. H. Leimann, R. L. Baistrocchi, and P. I. Moia, "Neuropsychiatric observations of proprioceptive sensitivity in motion sickness susceptibility," *Aviat Space Environ Med*, vol. 59, no. 11 Pt 1, pp. 1083–1088, Nov. 1988.

[76] J. T. Reason, "Motion Sickness Adaptation: A Neural Mismatch Model," *J R Soc Med*, vol. 71, no. 11, pp. 819–829, Nov. 1978, doi: 10.1177/014107687807101109.

[77] J. E. Bos and W. Bles, "Theoretical considerations on canal–otolith interaction and an observer model," *Biol Cybern*, vol. 86, no. 3, pp. 191–207, Mar. 2002, doi: 10.1007/s00422-001-0289-7.

[78] J. E. Bos and W. Bles, "Modelling motion sickness and subjective vertical mismatch detailed for vertical motions," *Brain Research Bulletin*, vol. 47, no. 5, pp. 537–542, Nov. 1998, doi: 10.1016/S0361-9230(98)00088-4.

[79] H. Khalid, O. Turan, and J. E. Bos, "Theory of a subjective vertical–horizontal conflict physiological motion sickness model for contemporary ships," *J Mar Sci Technol*, vol. 16, no. 2, pp. 214–225, Jun. 2011, doi: 10.1007/s00773-010-0113-y.

[80] L. A. Warwick-Evans, N. Symons, T. Fitch, and L. Burrows, "Evaluating sensory conflict and postural instability. theories of motion sickness," *Brain Research Bulletin*, vol. 47, no. 5, pp. 465–469, Nov. 1998, doi: 10.1016/S0361-9230(98)00090-2.

[81] S. Salter, C. Diels, P. Herriotts, S. Kanarachos, and D. Thake, "Model to predict motion sickness within autonomous vehicles," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 234, no. 5, pp. 1330–1345, Apr. 2020, doi: 10.1177/0954407019879785.

[82] J. F. O'Hanlon and M. E. McCauley, "Motion sickness incidence as a function of the frequency and acceleration of vertical sinusoidal motion," *AEROSPACE MED.*, vol. 45, no. 4, pp. 366–369, 1974.

[83] C. M. Oman, "A heuristic mathematical model for the dynamics of sensory conflict and motion sickness," *Acta Oto-Laryngologica. Supplementum*, vol. 392, pp. 1–44, 1982.

[84] B. Atsumi, H. Tokunaga, H. Kanamori, T. Sugawara, E. Yasuda, and H. Inagaki, "Evaluation of vehicle motion sickness due to vehicle vibration," *JSAE Review*, vol. 23, no. 3, pp. 341–346, Jul. 2002, doi: 10.1016/S0389-4304(02)00197-2.

[85] Norimasa Kamiji, Yoshinori Kurata, Takahiro Wada, and Shun'ichi Doi, "Modeling and validation of carsickness mechanism," in *SICE Annual Conference 2007*, Takamatsu, Japan: IEEE, Sep. 2007, pp. 1138–1143. doi: 10.1109/SICE.2007.4421156.

[86] C. Braccesi and F. Cianetti, "Motion sickness. Part I: development of a model for predicting motion sickness incidence," *International Journal of Human Factors Modelling and Simulation*, vol. 2, pp. 163–187, Jan. 2011, doi: 10.1504/IJHFMS.2011.044492.

[87] T. Wada, "Computational Model of Motion Sickness Describing the Effects of Learning Exogenous Motion Dynamics," *Frontiers in Systems Neuroscience*, vol. 15, 2021, doi: 10.3389/fnsys.2021.634604.

[88] Wada T. ,. Kawano, J. ,. Okafuji, Y. ,. Takamatsu, A. ,. and Mitsuhiro, M., "A Computational Model of Motion Sickness Considering Visual and Vestibular Information," 2020.

[89] J. F. Golding, W. Bles, J. E. Bos, T. Haynes, and M. A. Gresty, "Motion Sickness and Tilts of the Inertial Force Environment: Active Suspension Systems vs. Active Passengers," *Aviation, Space, and Environmental Medicine*, vol. 74, no. 3, pp. 220–227, Mar. 2003.

[90] J.-R. Chardonnet, M. A. Mirzaei, and F. Mérienne, "Features of the Postural Sway Signal as Indicators to Estimate and Predict Visually Induced Motion Sickness in Virtual Reality," *International Journal of Human–Computer Interaction*, vol. 33, no. 10, pp. 771–785, Oct. 2017, doi: 10.1080/10447318.2017.1286767.

[91] V. C. Le, M. L. H. Jones, C. Kinnaird, V. J. Barone, T. Bao, and K. H. Sienko, "Standing balance of vehicle passengers: The effect of vehicle motion, task performance on post-drive balance," *Gait & Posture*, vol. 82, pp. 189–195, Oct. 2020, doi: 10.1016/j.gaitpost.2020.08.123.

[92] S. 'Atifah Saruchi, M. H. Mohammed Ariff, H. Zamzuri, N. Hassan, and N. Wahid, "Artificial neural network for modelling of the correlation between lateral acceleration and

head movement in a motion sickness study," *IET Intelligent Transport Systems*, vol. 13, no. 2, pp. 340–346, Feb. 2019, doi: 10.1049/iet-its.2018.5264.

[93] H. B.-L. Duh, D. E. Parker, J. O. Philips, and T. A. Furness, "'Conflicting' Motion Cues to the Visual and Vestibular Self- Motion Systems Around 0.06 Hz Evoke Simulator Sickness," *Hum Factors*, vol. 46, no. 1, pp. 142–153, Mar. 2004, doi: 10.1518/hfes.46.1.142.30384.

[94] R. Liu, S. Cui, Y. Zhao, X. Chen, L. Yi, and A. D. Hwang, "VIMSNet: an effective network for visually induced motion sickness detection," *SIViP*, vol. 16, no. 8, pp. 2029–2036, Nov. 2022, doi: 10.1007/s11760-022-02164-9.

[95] L. LaCount *et al.*, "Dynamic cardiovagal response to motion sickness: A point-process heart rate variability study," in *2009 36th Annual Computers in Cardiology Conference (CinC)*, Sep. 2009, pp. 49–52. Accessed: Oct. 17, 2023. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/5445472

[96] T. Irmak, D. M. Pool, and R. Happee, "Objective and subjective responses to motion sickness: the group and the individual," *Exp Brain Res*, vol. 239, no. 2, pp. 515–531, Feb. 2021, doi: 10.1007/s00221-020-05986-6.

[97] C.-T. Lin, C.-L. Lin, T.-W. Chiu, J.-R. Duann, and T.-P. Jung, "Effect of respiratory modulation on relationship between heart rate variability and motion sickness," in *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Aug. 2011, pp. 1921–1924. doi: 10.1109/IEMBS.2011.6090543.

[98] M. E. McCauley, J. W. Royal, C. D. Wylie, J. F. O'Hanlon, and R. R. Mackie, "Motion Sickness Incidence: Exploratory Studies of Habituation, Pitch and Roll, and the Refinement of a Mathematical Model:," Defense Technical Information Center, Fort Belvoir, VA, Apr. 1976. doi: 10.21236/ADA024709.

[99] M. Turner and M. J. Griffin, "Motion sickness in public road transport: The relative importance of motion, vision and individual differences," *British Journal of Psychology*, vol. 90, no. 4, pp. 519–530, 1999, doi: 10.1348/000712699161594.

[100] International Organization for Standardization, "ISO 2631-1:1997." ISO, Geneva, Switzerland, Jun. 1997. Accessed: Oct. 17, 2023. [Online]. Available: https://www.iso.org/standard/7612.html

[101] A. Graybiel, R. Kellogg, and R. Kennedy, "Motion Sickness Symptomatology of Labyrinthine Defective and Normal Subjects During Zero Gravity Maneuvers," 1964.

[102] J. T. Reason, "Relations Between Motion Sickness Susceptibility, the Spiral After-Effect and Loudness Estimation," *British Journal of Psychology*, vol. 59, no. 4, pp. 385–393, 1968, doi: 10.1111/j.2044-8295.1968.tb01153.x.

[103] M. L. H. Jones, V. C. Le, S. M. Ebert, K. H. Sienko, M. P. Reed, and J. R. Sayer, "Motion sickness in passenger vehicles during test track operations," *Ergonomics*, vol. 62, no. 10, pp. 1357–1371, Oct. 2019, doi: 10.1080/00140139.2019.1632938.

[104] K. N. de Winkel, T. Irmak, V. Kotian, D. M. Pool, and R. Happee, "Relating individual motion sickness levels to subjective discomfort ratings," *Exp Brain Res*, vol. 240, no. 4, pp. 1231–1240, Apr. 2022, doi: 10.1007/s00221-022-06334-6.

[105] A. Reuten, J. Bos, and J. B. Smeets, "The metrics for measuring motion sickness: Driving Simulation Conference Europe 2020," *Driving Simulation Conference Europe 2020 VR proceedings*, pp. 183–186, 2020.

[106] L. Murdin, J. Golding, and A. Bronstein, "Managing motion sickness," *BMJ*, vol. 343, p. d7430, Dec. 2011, doi: 10.1136/bmj.d7430.

[107] J. F. Golding and M. A. Gresty, "Pathophysiology and treatment of motion sickness," *Current Opinion in Neurology*, vol. 28, no. 1, pp. 83–88, Feb. 2015, doi: 10.1097/WCO.0000000000000163.

[108] T. S. Schaefer and P. M. Zito, "Antiemetic Histamine H1 Receptor Blockers," in *StatPearls*, Treasure Island (FL): StatPearls Publishing, 2023. Accessed: Oct. 09, 2023. [Online]. Available: http://www.ncbi.nlm.nih.gov/books/NBK533003/

[109] A. Spinks, J. Wasiak, E. Villanueva, and V. Bernath, "Scopolamine for preventing and treating motion sickness," *Cochrane Database of Systematic Reviews*, no. 3, 2004, doi: 10.1002/14651858.CD002851.pub2.

[110] J. M. Furman, D. A. Marcus, and C. D. Balaban, "Rizatriptan reduces vestibular-induced motion sickness in migraineurs," *J Headache Pain*, vol. 12, no. 1, pp. 81–88, Feb. 2011, doi: 10.1007/s10194-010-0250-z.

[111] D. A. Marcus and J. M. Furman, "Prevention of motion sickness with rizatriptan: a double-blind, placebo-controlled pilot study," *Med Sci Monit*, vol. 12, no. 1, pp. PI1–PI7, Dec. 2005.

[112] L. A. Warwick-Evans, I. J. Masters, and S. B. Redstone, "A double-blind placebo controlled evaluation of acupressure in the treatment of motion sickness," *Aviat Space Environ Med*, vol. 62, no. 8, pp. 776–778, Aug. 1991.

[113] C. D. Wood *et al.*, "Habituation and Motion Sickness," *The Journal of Clinical Pharmacology*, vol. 34, no. 6, pp. 628–634, 1994, doi: 10.1002/j.1552-4604.1994.tb02016.x.

[114] N. Takeda, M. Morita, A. Horii, S. Nishiike, T. Kitahara, and A. Uno, "Neural mechanisms of motion sickness," *The journal of medical investigation : JMI*, vol. 48, pp. 44–59, Mar. 2001.

[115] U. Schwarz and V. Henn, "Vestibular habituation in student pilots," *Aviat Space Environ Med*, vol. 60, no. 8, pp. 755–761, Aug. 1989.

[116] F. D. Y. P. Sang, J. P. Billar, J. F. Golding, and M. A. Gresty, "Behavioral Methods of Alleviating Motion Sickness: Effectiveness of Controlled Breathing and a Music Audiotape," *Journal of Travel Medicine*, vol. 10, no. 2, pp. 108–111, Mar. 2003, doi: 10.2310/7060.2003.31768.

[117] M. Dai, T. Raphan, and B. Cohen, "Prolonged reduction of motion sickness sensitivity by visual-vestibular interaction," *Exp Brain Res*, vol. 210, no. 3, pp. 503–513, May 2011, doi: 10.1007/s00221-011-2548-8.

[118] R. M. Rine, M. C. Schubert, and T. J. Balkany, "Visual-Vestibular Habituation and Balance Training for Motion Sickness," *Physical Therapy*, vol. 79, no. 10, pp. 949–957, Oct. 1999, doi: 10.1093/ptj/79.10.949.

[119] J. Jeng-Weei Lin, D. Parker, M. Lahav, and T. Furness, "Unobtrusive vehicle motion prediction cues reduced simulator sickness during passive travel in a driving simulator," *Ergonomics*, vol. 48, no. 6, pp. 608–624, May 2005, doi: 10.1080/00140130400029100.

[120] M. F. Reschke, J. T. Somers, and G. Ford, "Stroboscopic Vision as a Treatment for Motion Sickness: Strobe Lighting vs. Shutter Glasses," *Aviation, Space, and Environmental Medicine*, vol. 77, no. 1, pp. 2–7, Jan. 2006.

[121] K. Kazuhito and K. Satoshi, "A Study of Carsickness of Rear-seat Passengers due to Acceleration and Deceleration when Watching an In-vehicle Display," *Review of automotive engineering*, vol. 27, no. 3, pp. 465–469, Jul. 2006.

[122] J. Dahlman, A. Sjörs, T. Ledin, and T. Falkmer, "Could sound be used as a strategy for reducing symptoms of perceived motion sickness?," *J NeuroEngineering Rehabil*, vol. 5, no. 1, p. 35, Dec. 2008, doi: 10.1186/1743-0003-5-35.

[123] A. Morimoto, N. Isu, T. Okumura, Y. Araki, A. Kawai, and F. Masui, "Image Rendering for Reducing Carsickness in Watching Onboard Video Display," in *2008 Digest of Technical Papers - International Conference on Consumer Electronics*, Las Vegas, NV, USA: IEEE, Jan. 2008, pp. 1–2. doi: 10.1109/ICCE.2008.4587866.

[124] T. Wada and K. Yoshida, "Effect of passengers' active head tilt and opening/closure of eyes on motion sickness in lateral acceleration environment of cars," *Ergonomics*, vol. 59, no. 8, pp. 1050–1059, Aug. 2016, doi: 10.1080/00140139.2015.1109713.

[125] B. Keshavarz and H. Hecht, "Pleasant music as a countermeasure against visually induced motion sickness," *Applied Ergonomics*, vol. 45, no. 3, pp. 521–527, May 2014, doi: 10.1016/j.apergo.2013.07.009.

[126] B. Keshavarz, D. Stelzmann, A. Paillard, and H. Hecht, "Visually induced motion sickness can be alleviated by pleasant odors," *Exp Brain Res*, vol. 233, no. 5, pp. 1353–1364, May 2015, doi: 10.1007/s00221-015-4209-9.

[127] J. E. Bos, "Less sickness with more motion and/or mental distraction," *VES*, vol. 25, no. 1, pp. 23–33, Mar. 2015, doi: 10.3233/VES-150541.

[128] G. Gálvez-García, M. Hay, and C. Gabaude, "Alleviating Simulator Sickness with Galvanic Cutaneous Stimulation," *Hum Factors*, vol. 57, no. 4, pp. 649–657, Jun. 2015, doi: 10.1177/0018720814554948.

[129] M. Miksch, M. Steiner, M. Miksch, and A. Meschtscherjakov, "Motion Sickness Prevention System (MSPS): Reading Between the Lines," in *Adjunct Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, in AutomotiveUI '16 Adjunct. New York, NY, USA: Association for Computing Machinery, Oct. 2016, pp. 147–152. doi: 10.1145/3004323.3004340.

[130] G. Gálvez-García, J. Albayay, L. Rehbein, and F. Tornay, "Mitigating Simulator Adaptation Syndrome by means of tactile stimulation," *Applied Ergonomics*, vol. 58, pp. 13–17, Jan. 2017, doi: 10.1016/j.apergo.2016.05.004.

[131] J. Bin Karjanto *et al.*, "Situation Awareness and Motion Sickness in Automated Vehicle Driving Experience: A Preliminary Study of Peripheral Visual Information," in *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*, in AutomotiveUI '17. New York, NY, USA: Association for Computing Machinery, Sep. 2017, pp. 57–61. doi: 10.1145/3131726.3131745.

[132] J. Karjanto, N. Md. Yusof, C. Wang, J. Terken, F. Delbressine, and M. Rauterberg, "The effect of peripheral visual feedforward system in enhancing situation awareness and mitigating motion sickness in fully automated driving," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 58, pp. 678–692, Oct. 2018, doi: 10.1016/j.trf.2018.06.046.

[133] T. Sawabe, M. Kanbara, and N. Hagita, "Diminished reality for acceleration stimulus: Motion sickness reduction with vection for autonomous driving," in *2017 IEEE Virtual Reality (VR)*, Los Angeles, CA, USA: IEEE, 2017, pp. 277–278. doi: 10.1109/VR.2017.7892284.

[134] E. Hanau and V. Popescu, "MotionReader: Visual Acceleration Cues for Alleviating Passenger E-Reader Motion Sickness," in *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*, in

AutomotiveUI '17. New York, NY, USA: Association for Computing Machinery, Sep. 2017, pp. 72–76. doi: 10.1145/3131726.3131741.

[135] P. Hock, S. Benedikter, J. Gugenheimer, and E. Rukzio, "CarVR: Enabling In-Car Virtual Reality Entertainment," in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, in CHI '17. New York, NY, USA: Association for Computing Machinery, May 2017, pp. 4034–4044. doi: 10.1145/3025453.3025665.

[136] M. McGill, A. Ng, and S. Brewster, "I Am The Passenger: How Visual Motion Cues Can Influence Sickness For In-Car VR," in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, in CHI '17. New York, NY, USA: Association for Computing Machinery, May 2017, pp. 5655–5668. doi: 10.1145/3025453.3026046.

[137] T. van Veen, J. Karjanto, and J. Terken, "Situation Awareness in Automated Vehicles through Proximal Peripheral Light Signals," in *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, in AutomotiveUI '17. New York, NY, USA: Association for Computing Machinery, Sep. 2017, pp. 287–292. doi: 10.1145/3122986.3122993.

[138] S. D'Amour, J. E. Bos, and B. Keshavarz, "The efficacy of airflow and seat vibration on reducing visually induced motion sickness," *Exp Brain Res*, vol. 235, no. 9, pp. 2811–2820, Sep. 2017, doi: 10.1007/s00221-017-5009-1.

[139] M. Bloch, "Alleviating Motion Sickness through Presentations on Interior Panels of Autonomous Vehicles." Accessed: Sep. 15, 2023. [Online]. Available: https://essay.utwente.nl/76160/

[140] Q. C. Ihemedu-Steinke, P. Halady, G. Meixner, and M. Weber, "VR Evaluation of Motion Sickness Solution in Automated Driving," in *Virtual, Augmented and Mixed Reality: Interaction, Navigation, Visualization, Embodiment, and Simulation*, vol. 10909, J. Y. C. Chen and G. Fragomeni, Eds., in Lecture Notes in Computer Science, vol. 10909. , Cham: Springer International Publishing, 2018, pp. 112–125. doi: 10.1007/978-3-319-91581-4_9.

[141] S. Salter, C. Diels, S. Kanarachos, D. Thake, P. Herriotts, and D. A. Depireux, "Increased bone conducted vibration reduces motion sickness in automated vehicles," *International Journal of Human Factors and Ergonomics*, vol. 6, no. 4, pp. 299–318, Jan. 2019, doi: 10.1504/IJHFE.2019.105358.

[142] A. Meschtscherjakov, S. Strumegger, and S. Trösterer, "Bubble Margin: Motion Sickness Prevention While Reading on Smartphones in Vehicles," in *Human-Computer Interaction – INTERACT 2019*, D. Lamas, F. Loizides, L. Nacke, H. Petrie, M. Winckler, and P. Zaphiris, Eds., in Lecture Notes in Computer Science. Cham: Springer International Publishing, 2019, pp. 660–677. doi: 10.1007/978-3-030-29384-0_39;jlz.

[143] Y.-T. Mu, W.-C. Chien, and F.-G. Wu, "Providing Peripheral Trajectory Information to Avoid Motion Sickness During the In-car Reading Tasks," in *Human Systems Engineering and Design II*, vol. 1026, T. Ahram, W. Karwowski, S. Pickl, and R. Taiar, Eds., in Advances in Intelligent Systems and Computing, vol. 1026. , Cham: Springer International Publishing, 2020, pp. 216–222. doi: 10.1007/978-3-030-27928-8_33.

[144] H. Cho and G. J. Kim, "RoadVR: Mitigating the Effect of Vection and Sickness by Distortion of Pathways for In-Car Virtual Reality," in *26th ACM Symposium on Virtual Reality Software and Technology*, in VRST '20. New York, NY, USA: Association for Computing Machinery, Nov. 2020, pp. 1–3. doi: 10.1145/3385956.3422115.

[145] N. Md Yusof, J. Karjanto, J. Terken, F. Delbressine, and M. Rauterberg, "Gaining Situation Awareness through a Vibrotactile Display to Mitigate Motion Sickness in Fully-Automated

Driving Cars," *International Journal of Automotive and Mechanical Engineering*, vol. 17, pp. 7771–7783, Apr. 2020, doi: 10.15282/ijame.17.1.2020.23.0578.

[146] O. X. Kuiper, J. E. Bos, E. A. Schmidt, C. Diels, and S. Wolter, "Knowing What's Coming: Unpredictable Motion Causes More Motion Sickness," *Hum Factors*, p. 0018720819876139, Oct. 2019, doi: 10.1177/0018720819876139.

[147] K. N. de Winkel, P. Pretto, S. A. E. Nooij, I. Cohen, and H. H. Bülthoff, "Efficacy of augmented visual environments for reducing sickness in autonomous vehicles," *Applied Ergonomics*, vol. 90, p. 103282, Jan. 2021, doi: 10.1016/j.apergo.2020.103282.

[148] R. Hainich, U. Drewitz, K. Ihme, J. Lauermann, M. Niedling, and M. Oehl, "Evaluation of a Human–Machine Interface for Motion Sickness Mitigation Utilizing Anticipatory Ambient Light Cues in a Realistic Automated Driving Setting," *Information*, vol. 12, no. 4, Art. no. 4, Apr. 2021, doi: 10.3390/info12040176.

[149] J. Maculewicz, P. Larsson, and J. Fagerlönn, "Intuitive and subtle motion-anticipatory auditory cues reduce motion sickness in self-driving cars," *Int. J. Human Factors and Ergonomics*, vol. 8, no. 4, 2021.

[150] A. Brietzke, R. P. Xuan, A. Dettmann, and A. C. Bullinger, "Concepts for Vestibular and Visual Stimulation to Mitigate Carsickness in Stop-and-Go-Driving," in *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)*, Sep. 2021, pp. 3909–3916. doi: 10.1109/ITSC48978.2021.9564691.

[151] Y. Guo, Q. Sun, Y. Su, Y. Guo, and C. Wang, "Can driving condition prompt systems improve passenger comfort of intelligent vehicles? A driving simulator study," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 81, pp. 240–250, Aug. 2021, doi: 10.1016/j.trf.2021.06.007.

[152] D. Bohrmann, A. Bruder, and K. Bengler, "Effects of Dynamic Visual Stimuli on the Development of Carsickness in Real Driving," *IEEE Trans. Intell. Transport. Syst.*, vol. 23, no. 5, pp. 4833–4842, May 2022, doi: 10.1109/TITS.2021.3128834.

[153] D. Li and L. Chen, "Mitigating motion sickness in automated vehicles with vibration cue system," *Ergonomics*, vol. 65, no. 10, pp. 1313–1325, Oct. 2022, doi: 10.1080/00140139.2022.2028902.

[154] E. Kim, H. Gil, J. Ryu, I. Oakley, and G. Shin, "The effect of peripheral cues on motion sickness mitigation when using a VR HMD in a car," Oct. 2022, Accessed: Sep. 20, 2022. [Online]. Available: https://scholarworks.unist.ac.kr/handle/201301/59289

[155] F. MacPherson and L. Colvin, "Transcutaneous Electrical Nerve Stimulation (TENS). Research to support clinical practice," *BJA: British Journal of Anaesthesia*, vol. 114, no. 4, pp. 711–712, Apr. 2015, doi: 10.1093/bja/aev055.

[156] C.-C. Chang *et al.*, "Using a Situational Awareness Display to Improve Rider Trust and Comfort with an AV Taxi," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 63, no. 1, pp. 2083–2087, Nov. 2019, doi: 10.1177/1071181319631428.

[157] L. Petersen, D. Tilbury, X. J. Yang, and L. Robert, "Effects of Augmented Situational Awareness on Driver Trust in Semi-Autonomous Vehicle Operation," Jul. 2017, Accessed: Sep. 19, 2023. [Online]. Available: http://deepblue.lib.umich.edu/handle/2027.42/137707

[158] L. Petersen, L. Robert, J. Yang, and D. Tilbury, "Situational Awareness, Driver's Trust in Automated Driving Systems and Secondary Task Performance," Social Science Research Network, Rochester, NY, SSRN Scholarly Paper ID 3345543, Feb. 2019. doi: 10.2139/ssrn.3345543.

[159] A. Ananthakrishnan, J. Moeller, and D. Schilberg, "The analysis of the influence of suspension parameters in reducing motion sickness in vehicles," in *2020 21st International Conference on Research and Education in Mechatronics (REM)*, Dec. 2020, pp. 1–5. doi: 10.1109/REM49740.2020.9313898.

[160] K. Kia, P. W. Johnson, and J. H. Kim, "Comparisons of Whole Body Vibration, Muscle Activity and Non-driving Task Performance between Different Seat Suspensions in an Autonomous Passenger Car Application," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 62, no. 1, pp. 1848–1852, Sep. 2018, doi: 10.1177/1541931218621421.

[161] M. M. Frechin, S. B. Ariño, and J. Fontaine, "ACTISEAT: Active vehicle seat for acceleration compensation," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 218, no. 9, pp. 925–933, Sep. 2004, doi: 10.1243/0954407041856809.

[162] J. A. Joseph and M. J. Griffin, "Motion Sickness from Combined Lateral and Roll Oscillation: Effect of Varying Phase Relationships," *Aviation, Space, and Environmental Medicine*, vol. 78, no. 10, pp. 944–950, Oct. 2007, doi: 10.3357/ASEM.2043.2007.

[163] J. A. Joseph and M. J. Griffin, "Motion Sickness: Effect of Changes in Magnitude of Combined Lateral and Roll Oscillation," *Aviation, Space, and Environmental Medicine*, vol. 79, no. 11, pp. 1019–1027, Nov. 2008, doi: 10.3357/ASEM.2208.2008.

[164] A. Mert and W. Bles, "Impact of alignment to gravito-inertial force on motion sickness and cardiopulmonary variables," *Aviat Space Environ Med*, vol. 82, no. 7, pp. 694–698, Jul. 2011, doi: 10.3357/asem.2920.2011.

[165] H. Konno, S. Fujisawa, T. Wada, and S. Doi, "Analysis of motion sensation of car drivers and its application to posture control device," in *SICE Annual Conference 2011*, Sep. 2011, pp. 192–197.

[166] G. F. Beard and M. J. Griffin, "Motion sickness caused by roll-compensated lateral acceleration: Effects of centre-of-rotation and subject demographics," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 228, no. 1, pp. 16–24, Jan. 2014, doi: 10.1177/0954409712460981.

[167] N. M. Y. Juffrizal Karjanto, F. D. Jacques Terken, N. M. Y. Juffrizal Karjanto, and F. D. Jacques Terken, "An On-Road Study in Mitigating Motion Sickness When Reading in Automated Driving," *Journal of Hunan University Natural Sciences*, vol. 48, no. 3, Art. no. 3, 2021, Accessed: Jan. 21, 2022. [Online]. Available: http://jonuns.com/index.php/journal/article/view/536

[168] B. Cheung and A. Nakashima, "A Review on the Effects of Frequency of Oscillation on Motion Sickness," DEFENCE RESEARCH AND DEVELOPMENT TORONTO (CANADA), Oct. 2006. Accessed: Jan. 13, 2022. [Online]. Available: https://apps.dtic.mil/sti/citations/ADA472991

[169] J. Smyth, P. Jennings, P. Bennett, and S. Birrell, "A novel method for reducing motion sickness susceptibility through training visuospatial ability – A two-part study," *Applied Ergonomics*, vol. 90, p. 103264, Jan. 2021, doi: 10.1016/j.apergo.2020.103264.

[170] J. Wang, N. Yang, and T. Liu, "Safety of active pre-collision seat rotation strategies for autonomous vehicles: injury risk evaluation of occupant's neck," *International Journal of Crashworthiness*, vol. 28, no. 2, pp. 288–297, Mar. 2023, doi: 10.1080/13588265.2022.2075099.

[171] S. Huo, L. Yu, L. Ma, and L. Zhang, "Ride Comfort Improvement in Post-Braking Phase Using Active Suspension," in *Volume 6: 11th International Conference on Multibody Systems, Nonlinear Dynamics, and Control*, Boston, Massachusetts, USA: American Society of Mechanical Engineers, Aug. 2015, p. V006T10A072. doi: 10.1115/DETC2015-46878.

[172] J. Ekchian *et al.*, "A High-Bandwidth Active Suspension for Motion Sickness Mitigation in Autonomous Vehicles," presented at the SAE 2016 World Congress and Exhibition, Apr. 2016, pp. 2016-01–1555. doi: 10.4271/2016-01-1555.

[173] P. DiZio *et al.*, "An Active Suspension System for Mitigating Motion Sickness and Enabling Reading in a Car," *Aerospace Medicine and Human Performance*, vol. 89, no. 9, pp. 822–829, Sep. 2018, doi: 10.3357/AMHP.5012.2018.

[174] I. Cvok, M. Hrgetić, M. Hoić, J. Deur, D. Hrovat, and H. Eric Tseng, "Analytical and Experimental Evaluation of Various Active Suspension Alternatives for Superior Ride Comfort and Utilization of Autonomous Vehicles," *Journal of Autonomous Vehicles and Systems*, vol. 1, no. 1, p. 011004, Jan. 2021, doi: 10.1115/1.4048584.

[175] N. Dillen, M. Ilievski, E. Law, L. E. Nacke, K. Czarnecki, and O. Schneider, "Keep Calm and Ride Along: Passenger Comfort and Anxiety as Physiological Responses to Autonomous Driving Styles," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, in CHI '20. New York, NY, USA: Association for Computing Machinery, Apr. 2020, pp. 1–13. doi: 10.1145/3313831.3376247.

[176] M. Jurisch, C. Holzapfel, and C. Buck, "The influence of active suspension systems on motion sickness of vehicle occupants," in *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)*, Rhodes, Greece: IEEE, Sep. 2020, pp. 1–6. doi: 10.1109/ITSC45102.2020.9294311.

[177] F. Schockenhoff, H. Nehse, and M. Lienkamp, "Maneuver-Based Objectification of User Comfort Affecting Aspects of Driving Style of Autonomous Vehicle Concepts," *Applied Sciences*, vol. 10, no. 11, p. 3946, Jun. 2020, doi: 10.3390/app10113946.

[178] J. H. Hong, J. S. Kim, Y. S. Quan, T. Park, C. S. An, and C. C. Chung, "Adaptive Cruise Control with Motion Sickness Reduction: Data-driven Human Model and Model Predictive Control Approach," in *2022 IEEE 25th International Conference on Intelligent Transportation Systems (ITSC)*, Macau, China: IEEE, Oct. 2022, pp. 1464–1470. doi: 10.1109/ITSC55140.2022.9922485.

[179] S. 'Atifah Saruchi *et al.*, "Novel Motion Sickness Minimization Control via Fuzzy-PID Controller for Autonomous Vehicle," *Applied Sciences*, vol. 10, no. 14, Art. no. 14, Jan. 2020, doi: 10.3390/app10144769.

[180] C. Kremer, M. Tomzig, N. Merkel, and A. Neukum, "Using Active Seat Belt Retractions to Mitigate Motion Sickness in Automated Driving," *Vehicles*, vol. 4, no. 3, Art. no. 3, Sep. 2022, doi: 10.3390/vehicles4030046.

[181] C. Ketels, R. GOODRICH, M. K. Benson, and A. H. BRANSDORFER, "Occupant comfort system," US10737053B2, Aug. 11, 2020 Accessed: Mar. 30, 2023. [Online]. Available: https://patents.google.com/patent/US10737053B2/en

[182] P. F. Worrel, D. S. Crombez, and R. A. Trombley, "Vehicle occupant comfort," US9145129B2, Sep. 29, 2015 Accessed: Nov. 10, 2019. [Online]. Available: https://patents.google.com/patent/US9145129/en?oq=prevent+motion+sickness+in+cars

[183] Z. M. Anderson *et al.*, "Methods and systems for controlling vehicle body motion and occupant experience," US9868332B2, Jan. 16, 2018 Accessed: Mar. 30, 2023. [Online]. Available: https://patents.google.com/patent/US9868332B2/en?oq=US9868332B2

[184] D. L. Larner and J. S. Russell, "Method and system for determining and dynamically updating a route and driving style for passenger comfort," US10107635B2, Oct. 23, 2018 Accessed: Feb. 12, 2020. [Online]. Available: https://patents.google.com/patent/US10107635B2/en?oq=9%2c145%2c129

[185] M. Sweeney and E. Bartel, "Sensory stimulation system for an autonomous vehicle," US9789880B2, Oct. 17, 2017 Accessed: Jun. 18, 2020. [Online]. Available: https://patents.google.com/patent/US9789880B2/en?oq=US9789880B2

[186] J.-S. Plante, M. Denninger, G. Julio, P. Chouinard, P. Larose, and C. Fraser, "Dynamic motion control system using magnetorheological fluid clutch apparatuses," US10625556B2, Apr. 21, 2020 Accessed: Sep. 19, 2023. [Online]. Available: https://patents.google.com/patent/US10625556B2/en?oq=US10625556B2

[187] M. Sivak and B. SCHOETTLE, "Universal motion sickness countermeasure system," US9862312B2, Jan. 09, 2018 Accessed: Mar. 30, 2023. [Online]. Available: https://patents.google.com/patent/US9862312B2/en?oq=US9862312B2

[188] O. STONEMAN, C. L. COLLING, M. D. HUDSON, and A. RIVERA, "Systems and methods for mitigating motion sickness in a vehicle," US10322259B2, Jun. 18, 2019 Accessed: Sep. 19, 2023. [Online]. Available: https://patents.google.com/patent/US10322259B2/en?oq=US10322259B2

[189] S. Spencer, "Anti-motion sickness device," GB2567856A, May 01, 2019 Accessed: Jul. 02, 2020. [Online]. Available: https://patents.google.com/patent/GB2567856A/en?q=motion+sickness,kinetosis&q=comfort&assignee=Jaguar+Land+Rover+Limited,Jaguar+Cars,Jaguar+Stahlwarenfabrik+Gmbh,Jaguar+Stahlwarenfabrik+Gmbh,Jaguar+International+Corporation&language=ENGLISH&type=PATENT&num=25

[190] J.-M. Park, "Gyro seat and vehicle including the same," US10625641B2, Apr. 21, 2020 Accessed: Jul. 02, 2020. [Online]. Available: https://patents.google.com/patent/US10625641B2/en?q=motion+sickness,kinetosis&q=comfort&assignee=Hyundai+Motor+Company,Hyundai+Motor+Company+Co+Ltd,Hyundai+Electronics+America&language=ENGLISH&type=PATENT&num=25

[191] J. Wan, W. Ng, M. E. DeCaluwe, and M. Jodorkovsky, "Motion sickness mitigation system and method," US10259451B2, Apr. 16, 2019 Accessed: Jun. 18, 2020. [Online]. Available: https://patents.google.com/patent/US10259451B2/en?oq=US10%2c259%2c451B2

[192] V. G. Vulcu, "Systems and methods for mitigating motion sickness in a vehicle," US10926773B2, Feb. 23, 2021 Accessed: Sep. 19, 2023. [Online]. Available: https://patents.google.com/patent/US10926773B2/en?oq=US10926773B2

[193] D. Bohrmann, "Device for Reducing Kinetosis-Related Disorders of an Occupant During Driving Mode of a Vehicle," US20220001773A1, Jan. 06, 2022 Accessed: Mar. 30, 2023. [Online]. Available: https://patents.google.com/patent/US20220001773A1/en

[194] A. B. Al-Khafaji, A. SOLOUKMOFRAD, and D. L. Boston, "Vehicle lighting system," WO2019156657A1, Aug. 15, 2019 Accessed: Jul. 02, 2020. [Online]. Available: https://patents.google.com/patent/WO2019156657A1/en?q=motion+sickness,kinetosis&q=comfort&assignee=Ford+Motor+Co,Ford+Global+Tech+Llc

[195] R. W. Aikin and T. Stefanov-Wagner, "Fully-actuated suspension system," US10300760B1, May 28, 2019 Accessed: Jul. 02, 2020. [Online]. Available: https://patents.google.com/patent/US10300760B1/en?q=motion+sickness,kinetosis&q=comfort&assignee=apple+inc.&language=ENGLISH&type=PATENT

[196] S. Maeshiro, "Suspended vehicle seating system," US11571996B2, Feb. 07, 2023 Accessed: Sep. 19, 2023. [Online]. Available: https://patents.google.com/patent/US11571996B2/en?oq=US11571996B2

[197] L. Nong, "Vehicle and methods for improving stability and occupant comfort," US11130382B2, Sep. 28, 2021 Accessed: Sep. 19, 2023. [Online]. Available: https://patents.google.com/patent/US11130382B2/en?oq=US11130382B2

[198] T. Friedrich, "System and Method for Reducing Kinetosis Symptoms," US20200317089A1, Oct. 08, 2020 Accessed: Sep. 19, 2023. [Online]. Available: https://patents.google.com/patent/US20200317089A1/en?oq=US20200317089A1

[199] M. B. Rober et al., "Immersive display of motion-synchronized virtual content," US11321923B2, May 03, 2022 Accessed: Sep. 19, 2023. [Online]. Available: https://patents.google.com/patent/US11321923B2/en?oq=US11321923B2

[200] S. Awtar, N. M. JALGAONKAR, and D. S. SCHULMAN, "Passenger State Modulation System For Passenger Vehicles Based On Prediction And Preemptive Control," US20210114553A1, Apr. 22, 2021 Accessed: Sep. 19, 2023. [Online]. Available: https://patents.google.com/patent/US20210114553A1/en?oq=US20210114553A1

[201] R. Tartz, "Motion sickness detection system for autonomous vehicles," US20220001893A1, Jan. 06, 2022 Accessed: Sep. 19, 2023. [Online]. Available: https://patents.google.com/patent/US20220001893A1/en?oq=US20220001893A1

[202] M. DHAENS, "Systems and methods for minimizing motion sickness in vehicles," US11541797B2, Jan. 03, 2023 Accessed: Sep. 19, 2023. [Online]. Available: https://patents.google.com/patent/US11541797B2/en?oq=US11541797B2

[203] Y. Nakamura and M. Naito, "Motion sickness estimation device, motion sickness reducing device and motion sickness estimation method," US20220135054A1, May 05, 2022 Accessed: Sep. 19, 2023. [Online]. Available: https://patents.google.com/patent/US20220135054A1/en?oq=US20220135054A1

[204] M.-K. Yeom and I.-S. Kim, "System for controlling autonomous vehicle for reducing motion sickness," US20220001894A1, Jan. 06, 2022 Accessed: Sep. 19, 2023. [Online]. Available: https://patents.google.com/patent/US20220001894A1/en?oq=US20220001894A1

[205] A. BOURRELLY, C. Bougard, C. Bourdin, and J. Bonnet, "Method for the preventive detection of motion sickness and vehicle implementing this method," EP3860895A1, Aug. 11, 2021 Accessed: Mar. 30, 2023. [Online]. Available: https://patents.google.com/patent/EP3860895A1/en

[206] D. A. Fabry, J. R. Burwinkel, J. L. Crukley, and K. K. Jensen, "Hearing assistance devices with motion sickness prevention and mitigation features," US11338106B2, May 24, 2022 Accessed: Mar. 30, 2023. [Online]. Available: https://patents.google.com/patent/US11338106B2/en

[207] A. H. Wertheim, J. E. Bos, and A. J. Krul, "Predicting motion induced vomiting from subjective misery (MISC) ratings obtained in 12 experimental studies," p. 16, 2001.

[208] N. M. Pawar, A. K. Yadav, and N. R. Velaga, "A comparative assessment of subjective experience in simulator and on-road driving under normal and time pressure driving

conditions," *International Journal of Injury Control and Safety Promotion*, vol. 0, no. 0, pp. 1–16, Aug. 2022, doi: 10.1080/17457300.2022.2114091.

[209] H. Bellem, M. Klüver, M. Schrauf, H.-P. Schöner, H. Hecht, and J. F. Krems, "Can We Study Autonomous Driving Comfort in Moving-Base Driving Simulators? A Validation Study," *Hum Factors*, vol. 59, no. 3, pp. 442–456, May 2017, doi: 10.1177/0018720816682647.

[210] R. Telban and F. Cardullo, "An integrated model of human motion perception with visual-vestibular interaction," in *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Montreal,Canada: American Institute of Aeronautics and Astronautics, Aug. 2001. doi: 10.2514/6.2001-4249.

[211] C. Diels and P. A. Howarth, "Frequency Characteristics of Visually Induced Motion Sickness," *Hum Factors*, vol. 55, no. 3, pp. 595–604, Jun. 2013, doi: 10.1177/0018720812469046.

[212] O. X. Kuiper, J. E. Bos, and C. Diels, "Looking forward: In-vehicle auxiliary display positioning affects carsickness," *Applied Ergonomics*, vol. 68, pp. 169–175, Apr. 2018, doi: 10.1016/j.apergo.2017.11.002.

[213] P. Stahl, B. Donmez, and G. A. Jamieson, "Anticipation in Driving: The Role of Experience in the Efficacy of Pre-event Conflict Cues," *IEEE Trans. Human-Mach. Syst.*, vol. 44, no. 5, pp. 603–613, Oct. 2014, doi: 10.1109/THMS.2014.2325558.

[214] G. Tillman, D. Strayer, A. Eidels, and A. Heathcote, "Modeling cognitive load effects of conversation between a passenger and driver," *Atten Percept Psychophys*, vol. 79, no. 6, pp. 1795–1803, Aug. 2017, doi: 10.3758/s13414-017-1337-2.

[215] V. Melnicuk, S. Thompson, P. Jennings, and S. Birrell, "Effect of cognitive load on drivers' State and task performance during automated driving: Introducing a novel method for determining stabilisation time following take-over of control," *Accident Analysis & Prevention*, vol. 151, p. 105967, Mar. 2021, doi: 10.1016/j.aap.2020.105967.

[216] D. M. Merfeld, "Modeling the vestibulo-ocular reflex of the squirrel monkey during eccentric rotation and roll tilt," *Exp Brain Res*, vol. 106, no. 1, pp. 123–134, Sep. 1995, doi: 10.1007/BF00241362.

[217] G. L. Zacharias, "Motion Sensation Dependence on Visual and Vestibular Cues," Massachusetts Institute of Technology, 1977.

[218] R. J. A. W. Hosman and J. C. Vandervaart, "Perception of roll rate from an artificial horizon and peripheral displays," presented at the Massachusetts Inst. of Tech., 19th Annual Conference on Manual Control, Massachusetts Inst. of Tech., 19th Annual Conference on Manual Control, Jan. 1983. Accessed: Oct. 17, 2023. [Online]. Available: https://ntrs.nasa.gov/citations/19890068177

[219] T. Haslwanter, R. Jaeger, S. Mayr, and M. Fetter, "Three-dimensional eye-movement responses to off-vertical axis rotations in humans," *Experimental Brain Research*, vol. 134, no. 1, pp. 96–106, Aug. 2000, doi: 10.1007/s002210000418.

[220] B. De Graaf, J. E. Bos, W. Tielemans, F. Rameckers, A. H. Rupert, and F. E. Guedry, "Otolith Contribution to Ocular Torsion and Spatial Orientation During Acceleration.," NAVAL AEROSPACE MEDICAL RESEARCH LAB PENSACOLA FL, NAVAL AEROSPACE MEDICAL RESEARCH LAB PENSACOLA FL, ADA320766, Sep. 1996. Accessed: Oct. 17, 2023. [Online]. Available: https://apps.dtic.mil/sti/citations/ADA320766

[221] A. J. Benson, E. C. Hutt, and S. F. Brown, "Thresholds for the perception of whole body angular movement about a vertical axis," *Aviat Space Environ Med*, vol. 60, no. 3, pp. 205–213, Mar. 1989.

[222] F. A. M. van der Steen, "Self-motion perception," Doctoral Thesis, TU Delft, Delft, Netherlands, 1998.

[223] A. Berthoz *et al.*, "Motion Scaling for High-Performance Driving Simulators," *IEEE Transactions on Human-Machine Systems*, vol. 43, no. 3, pp. 265–276, May 2013, doi: 10.1109/TSMC.2013.2242885.

[224] E. Blana, "A Survey of Driving Research Simulators Around the World.," *Institute of Transport Studies*, vol. University of Leeds, Dec. 1996.

[225] N. A. Kaptein, J. Theeuwes, and R. van der Horst, "Driving Simulator Validity: Some Considerations," *Transportation Research Record*, vol. 1550, no. 1, pp. 30–36, Jan. 1996, doi: 10.1177/0361198196155000105.

[226] P. Kaur, S. Taghavi, Z. Tian, and W. Shi, "A Survey on Simulators for Testing Self-Driving Cars," in *2021 Fourth International Conference on Connected and Autonomous Driving (MetroCAD)*, Apr. 2021, pp. 62–70. doi: 10.1109/MetroCAD51599.2021.00018.

[227] D. Serje and E. Acuña, "Driving and Flying Simulators: A Review on Relevant Considerations and Trends," *Transportation Research Record*, vol. 2676, no. 3, pp. 551–570, Mar. 2022, doi: 10.1177/03611981211052963.

[228] V. De Nalda Tárrega, A. Soler, N. Palomares, J. Silva, J. Laparra, and J. Solaz, "Human Autonomous Vehicle (HAV): From sickness prevention to emotional response," presented at the 13th International Conference on Applied Human Factors and Ergonomics (AHFE 2022), 2022. doi: 10.54941/ahfe1002487.

[229] A. Pradhan, "Driving Simulator," UMTRI Driving Simulator. Accessed: Oct. 26, 2023. [Online]. Available: https://www.umtri.umich.edu/research/facilities-and-labs/driving-simulator/

[230] C. C. MacAdam, P. A. Green, and M. P. Reed, "AN OVERVIEW OF CURRENT UMTRI DRIVING SIMULATORS," *UMTRI Research Review*, vol. 24, no. 1, Jul. 1993, Accessed: Oct. 26, 2023. [Online]. Available: https://trid.trb.org/view/383844

[231] D. H. Weir and S. M. Bourne, "An Overview of the DRI Driving Simulator," *SAE Transactions*, vol. 104, pp. 107–112, 1995.

[232] B. Kappe, W. van Winsum, and P. van Wolffelaar, "A cost-effective driving simulator," in *DSC2002*, in Actes INRETS. Paris: INRETS Renault, Sep. 2002.

[233] S. Katz, P. Green, and J. Fleming, "Calibration and Baseline Driving Data for the UMTRI Driver Interface Research Vehicle," University of Michigan, Transportation Research Institute, Ann Arbor, USA, UMTRI-95-2, May 1995.

[234] N. Dużmańska, P. Strojny, and A. Strojny, "Can Simulator Sickness Be Avoided? A Review on Temporal Aspects of Simulator Sickness," *Frontiers in Psychology*, vol. 9, 2018, Accessed: Oct. 26, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fpsyg.2018.02132

[235] J. J. Slob, "State of the Art Driving Simulators, a Literature Survey," Eindhoven University of Technology, Eindhoven, Netherlands, DCT 2008.107, Aug. 2008. [Online]. Available: https://www.semanticscholar.org/paper/State-of-the-Art-Driving-Simulators%2C-a-Literature-Slob/68607a6048238a5159149969b056eb4e8648363a

[236] M. Ghafarian, M. Watson, N. Mohajer, D. Nahavandi, P. M. Kebria, and S. Mohamed, "A Review of Dynamic Vehicular Motion Simulators: Systems and Algorithms," *IEEE Access*, pp. 1–1, 2023, doi: 10.1109/ACCESS.2023.3265999.

[237] C. Schwarz, T. Gates, and Y. E. Papelis, "Motion Characteristics of the National Advanced Driving Simulator," presented at the Driving Simulation Conference, North America 2003 (DSC-NA 2003)Ford Motor Company, 2003. Accessed: Oct. 27, 2023. [Online]. Available: https://trid.trb.org/view/899757

[238] E. Blana, "The behavioural validation of driving simulators as research tools: a case study based on the Leeds Driving Simulator," phd, University of Leeds, 2001. Accessed: Oct. 27, 2023. [Online]. Available: https://etheses.whiterose.ac.uk/11329/

[239] O. Stroosma, M. M. (René) Van Paassen, and M. Mulder, "Using the SIMONA Research Simulator for Human-machine Interaction Research," in *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Austin, Texas: American Institute of Aeronautics and Astronautics, Aug. 2003. doi: 10.2514/6.2003-5525.

[240] "NADS-1 Simulator | University of Iowa Driving Safety Research Institute." Accessed: Oct. 27, 2023. [Online]. Available: https://dsri.uiowa.edu/nads-1

[241] "Roundabouts: An Informational Guide".

[242] R. A. Wynne, V. Beanland, and P. M. Salmon, "Systematic review of driving simulator validation studies," *Safety Science*, vol. 117, pp. 138–151, Aug. 2019, doi: 10.1016/j.ssci.2019.04.004.

[243] "SIMONA · Delft University of Technology," SIMONA. Accessed: Oct. 27, 2023. [Online]. Available: https://cs.lr.tudelft.nl/simona

[244] M. L. H. Jones *et al.*, "Development of a Vehicle-Based Experimental Platform for Quantifying Passenger Motion Sickness during Test Track Operations," presented at the WCX World Congress Experience, Apr. 2018, pp. 2018-01–0028. doi: 10.4271/2018-01-0028.

[245] J. Karjanto, N. Md. 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, p. 2, Nov. 2018, doi: 10.5334/ijds.8.

[246] M. J. Griffin and M. M. Newman, "Visual field effects on motion sickness in cars," *Aviat Space Environ Med*, vol. 75, no. 9, pp. 739–748, Sep. 2004.

[247] S. Baltodano, S. Sibi, N. Martelaro, N. Gowda, and W. Ju, "The RRADS platform: a real road autonomous driving simulator," in *Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, in AutomotiveUI '15. New York, NY, USA: Association for Computing Machinery, Sep. 2015, pp. 281–288. doi: 10.1145/2799250.2799288.

[248] J. Karjanto, N. Yusof, J. M. B. Terken, F. L. M. Delbressine, M. Z. B. Hassan, and G. W. M. Rauterberg, "Simulating autonomous driving styles: accelerations for three road profiles: 2nd International Conference on Automotive Innovation and Green Vehicle (AiGEV 2016)," *MATEC Web of Conferences*, vol. 90, no. 01005, pp. 1–16, 2017, doi: 10.1051/matecconf/20179001005.

[249] D. P. Babu and V. N. Reddy, "Design and Analysis of Automobile Frame," *International Journal of Scientific Engineering and Technology Research*, vol. 05, no. 51, pp. 10437–10444, Dec. 2016.

[250] M. Kalaitzakis, B. Cain, S. Carroll, A. Ambrosi, C. Whitehead, and N. Vitzilaios, "Fiducial Markers for Pose Estimation," *J Intell Robot Syst*, vol. 101, no. 4, p. 71, Mar. 2021, doi: 10.1007/s10846-020-01307-9.

[251] F. Buyuklu, E. Tarhan, and L. Ozluoglu, "Vestibular functions in motion sickness susceptible individuals," *Eur Arch Otorhinolaryngol*, vol. 266, no. 9, pp. 1365–1371, Sep. 2009, doi: 10.1007/s00405-009-0927-6.

[252] K. Kia, P. W. Johnson, and J. H. Kim, "The effects of different seat suspension types on occupants' physiologic responses and task performance: implications for autonomous and conventional vehicles," *Applied Ergonomics*, vol. 93, p. 103380, May 2021, doi: 10.1016/j.apergo.2021.103380.

[253] "E4 wristband | Real-time physiological signals | Wearable PPG, EDA, Temperature, Motion sensors." Accessed: May 02, 2021. [Online]. Available: https://www.empatica.com/research/e4/

[254] A. S. Gevins *et al.*, "Effects of prolonged mental work on functional brain topography," *Electroencephalography and Clinical Neurophysiology*, vol. 76, no. 4, pp. 339–350, Oct. 1990, doi: 10.1016/0013-4694(90)90035-I.

[255] P. S. Sachdev *et al.*, "Classifying neurocognitive disorders: the DSM-5 approach," *Nat Rev Neurol*, vol. 10, no. 11, Art. no. 11, Nov. 2014, doi: 10.1038/nrneurol.2014.181.

[256] C. D. Wickens, "Multiple resources and performance prediction," *Theoretical Issues in Ergonomics Science*, vol. 3, no. 2, pp. 159–177, Jan. 2002, doi: 10.1080/14639220210123806.

[257] P. D. Harvey, "Domains of cognition and their assessment," *Dialogues Clin Neurosci*, vol. 21, no. 3, pp. 227–237, Sep. 2019, doi: 10.31887/DCNS.2019.21.3/pharvey.

[258] J. Pawlak, J. W. Polak, and A. Sivakumar, "A framework for joint modelling of activity choice, duration, and productivity while travelling," *Transportation Research Part B: Methodological*, vol. 106, pp. 153–172, Dec. 2017, doi: 10.1016/j.trb.2017.10.010.

[259] P. A. Singleton, "Discussing the 'positive utilities' of autonomous vehicles: will travellers really use their time productively?," *Transport Reviews*, vol. 39, no. 1, pp. 50–65, Jan. 2019, doi: 10.1080/01441647.2018.1470584.

[260] N. Isu, T. Hasegawa, I. Takeuchi, and A. Morimoto, "Quantitative analysis of time-course development of motion sickness caused by in-vehicle video watching," *Displays*, vol. 35, no. 2, pp. 90–97, Apr. 2014, doi: 10.1016/j.displa.2014.01.003.

[261] J. Smyth, P. Jennings, and S. Birrell, "Are You Sitting Comfortably? How Current Self-driving Car Concepts Overlook Motion Sickness, and the Impact It Has on Comfort and Productivity," in *Advances in Human Factors of Transportation*, vol. 964, N. Stanton, Ed., Cham: Springer International Publishing, 2020, pp. 387–399. doi: 10.1007/978-3-030-20503-4_36.

[262] O. X. Kuiper, J. E. Bos, C. Diels, and E. A. Schmidt, "Knowing what's coming: Anticipatory audio cues can mitigate motion sickness," *Applied Ergonomics*, vol. 85, p. 103068, May 2020, doi: 10.1016/j.apergo.2020.103068.

[263] D. Li and L. Chen, "Mitigating Motion Sickness in Automated Vehicles with Vibration Cue System," *Ergonomics*, vol. 0, no. ja, pp. 1–21, Jan. 2022, doi: 10.1080/00140139.2022.2028902.

[264] D. Hecht and M. Reiner, "Sensory dominance in combinations of audio, visual and haptic stimuli," *Exp Brain Res*, vol. 193, no. 2, pp. 307–314, Feb. 2009, doi: 10.1007/s00221-008-1626-z.

[265] P. L. Olson, "Driver Perception Response Time," *SAE Transactions*, vol. 98, pp. 851–861, 1989.

[266] G. Charness, U. Gneezy, and M. A. Kuhn, "Experimental methods: Between-subject and within-subject design," *Journal of Economic Behavior & Organization*, vol. 81, no. 1, pp. 1–8, Jan. 2012, doi: 10.1016/j.jebo.2011.08.009.

[267] A. W. Y. Ng and A. H. S. Chan, "Finger Response Times to Visual, Auditory and Tactile Modality Stimuli," in *IMECS 2012*, Hong Kong, 2012.

[268] B. Cohen *et al.*, "Motion sickness on tilting trains," *The FASEB Journal*, vol. 25, no. 11, pp. 3765–3774, 2011, doi: https://doi.org/10.1096/fj.11-184887.

[269] J. Förstberg, "Ride comfort and motion sickness in tilting trains," 2000, Accessed: Feb. 22, 2021. [Online]. Available: http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-2985

[270] "Professional Motion Simulator 2,3,6 Axis Platforms for business Flight and Racing games," Affordable Motion Simulator Platform DOF Reality. Accessed: Nov. 14, 2023. [Online]. Available: https://dofreality.com/professional-motion-simulator-platforms-for-business-arcade-centers-event-rental/