KTH ROYAL INSTITUTE
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Licentiate Thesis in Vehicle and Maritime Engineering

Motion sickness in autonomous driving

Prediction models and mitigation using trajectory planning

ILHAN YUNUS

Stockholm, Sweden 2024

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Abstract

The development of autonomous vehicles is progressing rapidly through extensive efforts by the automotive industry and researchers. One of the key factors for the adoption of autonomous driving technology is motion comfort and the ability to engage in non-driving tasks such as reading, socialising, and relaxing without experiencing motion sickness while travelling. Therefore, for the full success of autonomous vehicles, it is necessary to learn how to design and control the vehicles to mitigate motion sickness for the passengers.

This thesis aims to investigate methods for prediction of motion sickness in autonomous vehicles and how to mitigate it using vehicle dynamics based solutions, with an emphasis on trajectory planning. As a first step, a review and evaluation of existing motion sickness prediction methods were performed. The review highlighted the importance of accurate motion sickness assessment in the early phases of autonomous vehicle design. Two chosen methods (ISO 2631-based and sensory conflict theory-based) were evaluated to estimate individual motion sickness feelings using measured data and subjective assessment ratings from field tests. It can be concluded that the methods can be adjusted to predict individual motion sickness feelings, as shown by the comparison with the experimental data.

To continue the work, a review of vehicle dynamics based motion sickness mitigation methods for autonomous vehicles was performed. Several chassis control strategies in literature like active suspension, rear-wheel steering and torque distribution have demonstrated the potential help to reduce motion sickness. Another effective approach to mitigate motion sickness in autonomous vehicles is to regulate vehicle speed and path using trajectory planning which was chosen to be further investigated. The trajectory planning was constructed as an optimisation problem where there is a trade-off between motion sickness and manoeuvre time. The impact of the trajectory planning algorithm to reduce motion sickness was analysed by simulating two different vehicle models in specific test manoeuvres. The results indicate that driving style has a significant influence on motion sickness and trajectory planning algorithms should be carefully designed to find a good balance between journey time and motion sickness.

The research presented in this thesis contributes to the development of methodologies for predicting and mitigating motion sickness in autonomous vehicles, helping to achieve the goal of ensuring their overall success.

Keywords:
Motion sickness models, motion sickness mitigation methods, vehicle dynamics, trajectory planning, vehicle control, autonomous driving

Sammanfattning

Utvecklingen av autonoma fordon går snabbt framåt tack vare omfattande insatser från fordonsindustrin och forskare. En av de viktigaste faktorerna för införandet av teknik för autonom körning är åkkomfort och möjligheten att ägna sig åt andra saker än körning, som att läsa, umgås och koppla av, utan att drabbas av åksjuka under resan. För att autonoma fordon ska lyckas fullt ut är det därför nödvändigt att förstå hur man utformar och styr fordonen för att minska risken för att passagerarna drabbas av åksjuka.

Denna licentiatuppsats syftar till att undersöka hur åksjuka kan förutsägas i vägfordon och hur den kan reduceras med hjälp av fordonsdynamikbaserade lösningar, med tonvikt på trajektorieplanering. Som ett första steg genomfördes en granskning och utvärdering av befintliga metoder för åksjukeprediktion. Granskningen belyste vikten av en korrekt bedömning av åksjuka i de tidiga faserna av autonom fordonsdesign. Två valda metoder (ISO 2631-baserad och sensorisk konfliktbaserad) utvärderades för att uppskatta individuell åksjuka med hjälp av uppmätta data och subjektiva bedömningar från fälttester. Slutsatsen är att metoderna kan justeras för att förutsäga individuell åksjuka, vilket framgår av jämförelsen med experimentella data.

För att fortsätta arbetet gjordes en genomgång av fordonsdynamikbaserade metoder för att minska åksjuka i autonoma fordon. Flera chassireglerstrategier i litteraturen, såsom aktiv fjädring, bakhjulsstyrning och drivmomentfördelning, har visat sig kunna bidra till att minska åksjuka. En annan effektiv metod för att minska åksjuka i autonoma fordon är att reglera fordonets hastighet och bana med hjälp av trajektorieplanering, vilket valdes att undersökas ytterligare. Trajektorieplaneringen konstruerades som ett optimeringsproblem där det finns en avvägning mellan åksjuka och manövertid. Effekten av trajektorieplaneringsalgoritmen för att minska åksjuka analyserades genom att simulera två olika fordonsmodeller i specifika testmanövrar. Resultaten indikerar att körstil har en betydande inverkan på åksjuka och att algoritmer för trajektorieplanering bör utformas noggrant för att hitta en bra balans mellan restid och åksjuka.

Forskningen som presenteras i denna uppsats bidrar till utvecklingen av metoder för att förutsäga och mildra åksjuka i autonoma fordon, vilket hjälper till att uppnå målet att säkerställa deras framgång.

Nyckelord:
Åksjukemodeller, metoder för att reducera åksjuka, fordonsdynamik, trajektorieplanering, fordonsreglering, autonom körning

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Last but not least, I would like to thank my family and friends, especially my parents for your unconditional love and endless support.

Gothenburg, May 2024
Ilhan Yunus

Dissertation

This thesis is divided into two parts: Part I gives a brief introduction to the area of research and an overview of the work conducted in this thesis. Part II consists of the following appended papers (**Papers A-D**):

Paper A
I. Yunus, J. Jerrelind and L. Drugge, *Autonomous driving and motion sickness – an outlook on causes, evaluation methods and solutions.* In the Proceedings of the Resource Efficient Vehicle Conference (REV2021), Stockholm, Sweden (June 2021).
DOI: 10.30746/978-91-8040-047-3

Presented by I. Yunus at REV2021. I. Yunus did the literature survey and wrote the manuscript. J. Jerrelind and L. Drugge supervised the work, discussed the research ideas and reviewed the paper.

Paper B
I. Yunus, J. Jerrelind and L. Drugge, *Evaluation of motion sickness prediction models for autonomous driving.* In: Orlova, A., Cole, D. (eds) Advances in Dynamics of Vehicles on Roads and Tracks II. IAVSD 2021. Lecture Notes in Mechanical Engineering, Cham: Springer, 2022. DOI: 10.1007/978-3-031-07305-2_81

Presented by I. Yunus at IAVSD2021, 27th Symposium on Dynamics of Vehicles on Roads and Tracks (Online, 2021). I. Yunus did the literature survey, wrote the manuscript, designed the test, collected and analysed data and performed the simulations. J. Jerrelind and L. Drugge supervised the work, discussed the research ideas and reviewed the paper.

Paper C
I. Yunus, G. Papaioannou, J. Jerrelind and L. Drugge, *A review of vehicle dynamics and control based approaches to mitigate motion sickness in autonomous vehicles.* To be submitted (2024).

I. Yunus did the literature survey and wrote the manuscript. G. Papaioannou, J. Jerrelind and L. Drugge initiated and supervised the work, discussed the paper content and reviewed the paper.

Paper D
I. Yunus, A. Lundin, G. Papaioannou, J. Jerrelind and L. Drugge, *Trajectory planning to minimise motion sickness in autonomous driving.* AVEC’22, 15th International Symposium on Advanced Vehicle Control, AVEC´22, Japan (September 2022).

Presented by I. Yunus at AVEC’22. I. Yunus did the literature survey and wrote the manuscript. I. Yunus and A. Lundin conducted simulations and analyses. G. Papaioannou, J. Jerrelind and L. Drugge supervised the work, discussed the research ideas and reviewed the paper.

Publications not included in this thesis

The work carried out during this thesis has also resulted in the following publications:

I. Yunus, F.F. Witjaksono, E.N. Basokur, J. Jerrelind and L. Drugge, *Analysis of human perception models for motion sickness in autonomous driving.* 13th International Conference on Applied Human Factors and Ergonomics (AHFE), New York, USA (July 2022). DOI: 10.54941/ahfe1002473

S. Paganelli, I. Yunus and L. Fagiano, *Comfort-aware trajectory planning in autonomous driving via multi-objective nonlinear model predictive control.* 2022 IEEE Conference on Control Technology and Applications (CCTA), Trieste, Italy (August 2022). DOI: 10.1109/CCTA49430.2022.9966123

Table of contents

Part I

OVERVIEW

1 Introduction

The development within the field of connected and automated vehicles has evolved rapidly during the latest years through major efforts by vehicle engineers and researchers [1][2]. To categorise a vehicle's level of self-driving a six-point scale is often used which is defined in the standard J3016 [3]. The scale ranges from Level 0, indicating no driving automation to Level 5, which represents full driving automation i.e. autonomous driving (AD)[1].

One of the main success factors for autonomous driving is comfort [4], [5]. It is crucial that passengers are able to engage in non-driving related tasks (NDRTs) including reading, resting, and socialising while experiencing no or minimal motion sickness symptoms [6]. According to research studies, the majority of drivers do not become motion sick since they actively engage in controlling the vehicle along the road and align their interpreted sensations of travelling with the sensory information (vestibular, visual etc.) resulting from the vehicle motion. Passengers are passively exposed to the same motion stimulus but since they are out of the control loop and potentially engaged in NDRTs, they are more susceptible to experiencing motion sickness [7]. In automated vehicles, all people in the vehicle will be passengers and the potential risk of motion sickness increases. Therefore, a critical enabler for the overall success of automated vehicles is to be able to design and control them so that the risk of getting motion sick is minimised [8][9][10]. Research is thereby needed to investigate motion sickness, how it can be assessed and to develop mitigation techniques for autonomous driving.

The word motion sickness [11] is believed to originate from the term sea sickness also called kinetosis [12]. Kinetosis is the medical term to describe the motion sickness phenomenon, which is the feeling of not being well and needing to vomit in a moving vehicle such as a car, boat, plane or train. Motion sickness is a very old problem dating back to BC. Although it is an old problem, motion sickness is not completely understood and has been recognised as a complex issue that goes beyond just nausea and vomiting [13].

Motion sickness prediction models are important tools in the early design stage of development on how to design and control autonomous vehicles. Therefore, it is necessary to analyse what kind of vehicle motions (accelerations, vibrations etc.) that induce motion sickness and how it can be assessed. Currently, the existing standard ISO 2631-1:1997 [14] offers a weighting filter based on acceleration that is limited to the vertical direction when calculating the motion sickness dose value (MSDV) for predicting motion sickness. It is necessary to revisit the standard to enhance the methods and models for AD to define the boundaries of motion sickness and to fulfil customer expectations. Human modelling techniques and data analysis can be utilised and extended to create more accurate multi-degrees-of-freedom prediction models that can be run in real-time to assess motion sickness. However, additional research is necessary to develop and combine these models.

Gaining a better understanding of what provokes motion sickness allows for the utilisation of diverse techniques for motion sickness mitigation. These mitigation strategies can help to improve comfort and leverage passenger satisfaction to increase the social acceptance of autonomous vehicles. Mitigation methods from an ergonomic perspective are reviewed and discussed in [15], for example designing vehicle interiors for better passenger visibility [16], incorporating comfortable seating facing different directions [17],

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[1] Autonomous driving (AD): In this thesis, autonomous driving refers to the condition where none of the vehicle occupants are required to perform driving tasks

implementing reclined seating positions [18], redesigning in-vehicle displays [19], and anticipating future motion by employing auditory cues to mitigate motion sickness [20][21]. Another mitigation strategy involves optimising the vehicle motion through vehicle dynamics and control-based solutions, aiming to minimise sudden and specific movements as well as vibrations, for example, using active chassis systems like active suspension [22], brake distribution control [23] and rear-wheel steering [24]. Furthermore, in autonomous vehicles, trajectory planning algorithms [25] can be used to mitigate motion sickness. Integrating motion sickness prediction methods into the development of motion sickness mitigation strategies offers significant advantages, such as reducing development time and costs. Using all these methods together in the autonomous vehicle development process can contribute significantly to decreasing motion sickness and enhancing the travel experience.

1.1 Objective

The overall long-term objective of this PhD research project is to investigate motion sickness prediction models and to mitigate motion sickness using vehicle dynamics based methods for autonomous driving. A visual project description including the focus areas (motion sickness modelling, vehicle chassis control and trajectory planning and tracking) is illustrated in Figure 1.

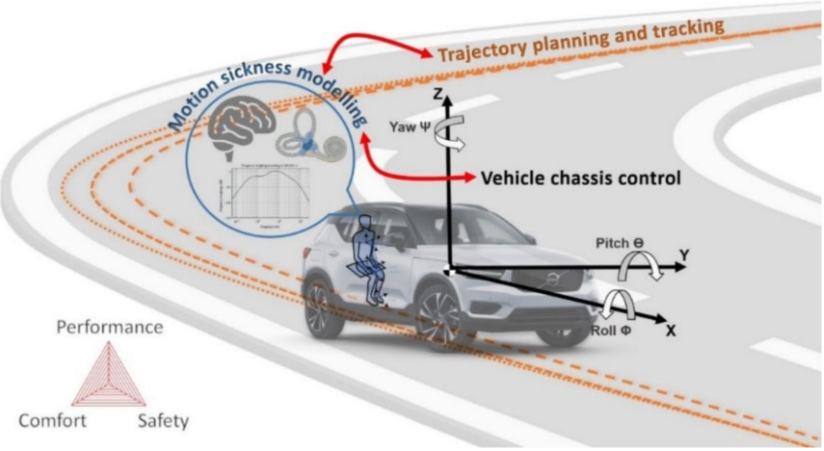

Figure 1. *A visual illustration of PhD project research areas for assessing and mitigating motion sickness in autonomous vehicles.* ***(Paper A)***

This licentiate thesis aims to increase the knowledge regarding the prediction of motion sickness in autonomous vehicles and how to mitigate it using vehicle dynamics based solutions, with an emphasis on trajectory planning. The following topics describe the objectives of the licentiate thesis.

- Investigate theories in the literature about motion sickness and to understand the causes of motion sickness. Identify important human aspects and vehicle motion characteristics affecting motion sickness.
- Investigate existing mathematical methods and models to predict the motion sickness of passengers and evaluate the performance of selected methods with road tests.
- Review the literature regarding different vehicle chassis control strategies and algorithms, such as active suspension, rear-wheel steering etc. which could be used and combined to minimise motion sickness while ensuring driving performance and stability.
- Investigate motion sickness mitigation by using trajectory planning algorithms to identify how autonomous cars shall be controlled (steering, braking and acceleration) to reduce or avoid motion sickness.

1.2 Limitations

This research is focusing on mitigation methods related to vehicle dynamics, thereby motion sickness mitigation methods such as medicine and visualisation aids are not investigated. Furthermore, ergonomic-based methods such as reclining seat [26], anticipatory audio [20] and visual cues [27], as well as the interior design of the vehicle (design constraints like rear seating position, window size, road view etc.) to reduce motion sickness are not taken into account.

1.3 Outline

The outline of this thesis is as follows. Section 1 provides an introduction to the research topic. Section 2 describes motion sickness assessment, while Section 3 introduces some potential motion sickness mitigation methods and more specifically trajectory planning to mitigate motion sickness in autonomous vehicles. A summary of appended papers is given in Section 4. Finally, conclusions, scientific contributions and future work are discussed in Section 5. An overview of how the appended papers relate to the different research areas is illustrated in Table 1.

***Table 1**. Overview of contributions from the appended papers to the focus areas.*

Research areas	Review	Simulations	Experiments
Motion sickness modelling	Paper A	Paper B	Paper B
Vehicle dynamics control	Paper C	-	-
Trajectory planning	Paper C	Paper D	-

2 Motion sickness assessment

This section presents existing methods which try to assess the level of motion sickness, either subjectively (based on what an individual experiences and feels) or objectively (based on some measure). In subsection 2.3 the evaluation of objective methods with subjective methods is discussed.

2.1 Subjective methods

Different questionnaires have been developed throughout the years in order to subjectively assess motion sickness during and/or after experiments. Motion sickness is not only depending on the situation during the experiments but is also determined by for example the test subject's sensitivity to becoming motion sick, if the test subject has been eating and sleeping well before the experiments and so on. Therefore, there are also questionnaires that are used before the experiments to learn more about the specific test person. **Paper A** provides more detailed information on motion sickness questionnaires in the literature, which differ in their usage and structure.

In order to determine test subjects' susceptibility to motion sickness, Reason and Brand developed the Motion Sickness Susceptibility Questionnaire (MSSQ), which was later revised and improved by Golding [28]. The MSSQ can be used to detect individual differences and gives an advantage in the participant selection process for motion sickness experiments involving different motion types (e.g., boats, cars, planes, and trains). A shorter version of the questionnaire (MSSQ-Short) was developed by Golding [29], which maintains accuracy and is more time efficient. This questionnaire was created to determine how sensitive test subjects are to motion sickness and what type of motion is most likely to induce it.

To easily and rapidly evaluate the motion sickness status of the test subjects during experimental tests Bos et al. [30] developed a simplified subjective rating system, the Misery Scale (MISC), see Table 2. Due to its simplicity, the MISC is frequently used in experimental studies where the test subjects verbally report their motion sickness score (from a score of 0: no problems to a score of 10: vomiting).

***Table 2**. The Misery Scale (MISC)* [30]

Symptom		Score
No problems		0
Slight discomfort but no specific symptoms		1
Dizziness, warm, headache, stomach awareness, sweating, etc.	vague	2
	some	3
	medium	4
	severe	5
Nausea	some	6
	medium	7
	severe	8
	retching	9
Vomiting		10

During experimental tests, asking the test subjects about their symptoms and feeling of motion sickness is the ground truth defining the severity of the motion sickness feeling. Although some studies have found a correlation, there is currently no direct standalone physiological signal available to measure the progression of motion sickness. While vomiting is the final result; other symptoms also count as some degree (severity level) of motion sickness. Therefore, it is crucial also to investigate objective motion sickness estimation methods that use for example accelerations as inputs to correlate with subjective motion sickness ratings.

2.2 Objective methods

In the development of autonomous vehicles, objective methods that utilise physical measures as inputs to estimate motion sickness levels would be highly beneficial to be able to mitigate motion sickness. As already mentioned, motion sickness can fluctuate individually depending on both movement-related and non-movement-related factors. This makes it challenging to objectively evaluate the level of motion sickness, as it can alternate during the journey as well as alternate on an individual basis. A short background of different motion-based objective motion sickness estimation methods in the literature is introduced and discussed in this section.

During World War II, there was a renewed need and increased interest in motion sickness research. During this era, Alexander et al. [31] reported on a series of experimental studies that utilised simulators to investigate the phenomenon [32]. Numerous laboratory tests were then conducted to understand the characteristics of motion stimuli that provoke motion sickness. These studies focused on the empirically derived relationship between motion sickness incidence and acceleration through a black box modelling approach, without exploring the underlying mechanism of motion sickness. Furthermore, these studies were often limited in scope and primarily focused on continuous fixed amplitude and frequency motion, which may not always accurately represent real-world transportation situations. In reality, transportation events can be more complex, involving different directions of motion and discrete events due to factors such as traffic conditions, including braking, acceleration, turning, and a combination of these or encountering sudden speed bumps.

The study by O’Hanlon and McCauley [33] was one of the earliest investigations to evaluate the relationship between different acceleration frequencies and motion sickness incidence (MSI) which is defined as the percentage of people who experienced vomiting. It was concluded that the main cause of provoking motion sickness at sea is low-frequency vertical oscillations. O’Hanlon and McCauley [34] proposed a function to calculate MSI based on the frequency and RMS value of the vertical acceleration and the duration of exposure. Lawther and Griffin [35] determined the frequency weighting for vertical oscillations to calculate one of the most common motion sickness analysis metrics, known as the Motion Sickness Dose Value (MSDV). The MSDV caused by vertical motion is formulated as Equation 1 and is defined in ISO 2631, which is approximately linearly related to the MSI index [36].

$$MSDV_z = \left(\int_0^T \left(a_{z,w}(t)\right)^2 dt\right)^{\frac{1}{2}} \tag{1}$$

where $a_{z,w}$ is frequency-weighted acceleration in the vertical direction and T is the exposure time in seconds.

Studies have shown that in road transportation, vertical vibrations tend to occur in higher frequency bands which affect ride comfort but do not induce motion sickness [37][38]. However, longitudinal and lateral movements in the frequency range of 0.1 to 0.5 Hz commonly occur in road transportation, which causes motion sickness. The literature contains several laboratory experimental studies which have been used to design weighting filters for longitudinal and lateral directions so that all three directions can be taken into account when calculating MSDV. Some examples of frequency filters for different directions are shown in Figure 2. The ISO-2631 specifies the frequency weighting for vertical acceleration, denoted as W_f (z-axis). The longitudinal acceleration weighting filter, W_f (x-axis), is approximately designed based on [39], while the lateral acceleration weighting filter, W_f (y-axis), is taken from [40].

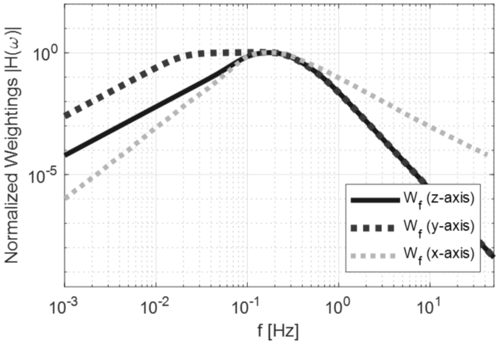

Figure 2*. Motion sickness frequency weightings (****Paper B****)*

Furthermore, the literature presents findings indicating that rotational oscillations also have an effect on motion sickness [41]. When people are travelling, complex conditions appear, and people are exposed to various combinations of vibrations that cause motion sickness. Therefore, more advanced motion sickness estimation methods are needed which include the vestibular organ dynamics and the mechanism of motion sickness.

Motion sickness is widely believed to be caused by a conflict between signals received from the vestibular system and the expected signals calculated in the brain (internal), as a concept of the sensory conflict theory proposed by Reason [42]. Figure 3 shows a block diagram representing the general structure of motion sickness models based on the sensory conflict theory. The vestibular organs include semi-circular canals for detecting angular motions and otoliths for detecting gravito-inertial acceleration, and their dynamics can be modelled with transfer functions.

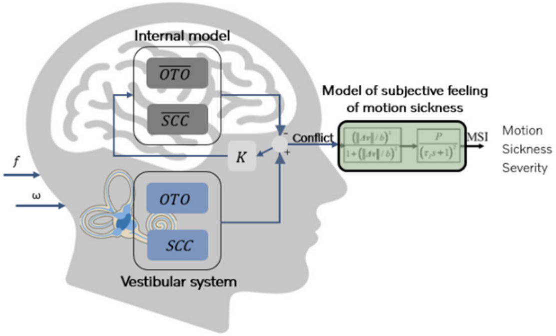

***Figure 3**. Sensory conflict theory-based motion sickness models (**Paper B**)*

Various approaches are used in modelling motion sickness including the mechanism, each with its own strengths and weaknesses [43]. The sensory conflict theory-based models explain the mechanism of motion sickness using a modelled vestibular system and the brain, in other words, the Central Neural System (CNS). The neural mismatch model was proposed by Reason [44], and later mathematically modelled by Oman [45]. Bos and Bles [46] proposed the 1D-SVC (Subjective Vertical Conflict) theory model, which is an alternative to Oman's model and introduces the concept of subjective vertical conflict, which is a conflict between perceived verticality by the sensory organs and determined verticality based on previous experience. The 1D-SVC model was validated using the O'Hanlon and McCauley experimental data [33] to study the relationship between sensory conflict and motion sickness. To study motion sickness in rail vehicles, Braccesi and Cianetti [47] proposed a vestibular (UNIPG) 3D model and a visual-vestibular (UNIPGSeMo) model that have been experimentally validated. Wada et al. [48] expanded the subjective vertical conflict model and created the 6D-SVC model which includes six degrees of freedom motions.

2.3 Motion sickness evaluation

The evaluation of motion sickness prediction models using measured data and subjective assessment ratings from field tests are shortly discussed in this section.

Proposed objective methods found in the literature are commonly analysed by collecting subjective motion sickness ratings. For example, in train research studies, Kufver [49] proposed a net dose model for predicting subjective nausea values (Nausea Rating). In the study by Persson [50] motion sickness estimation methods were analysed through on-track testing and compared with subjective motion sickness scores. In Salter's [6] study, a motion sickness model was proposed to predict motion sickness within autonomous vehicles. The subjective average MISC scores were collected for different seating orientations and then compared to the MISC-predicted scores obtained from the proposed model to evaluate the model performance. More recently, while many studies have focused on predicting group average subjective ratings, the study by Irmak [51] involved fitting model data to individual personal MISC scores for slalom manoeuvres performed in a passenger vehicle.

In **Paper B**, two motion sickness prediction methods, ISO-2631-based and 6D-SVC model, were implemented to capture individual passenger motion sickness feelings by using measured data and subjective assessment ratings. Starting with the ISO-2631 standard method as a basis, the approach was later extended to include longitudinal and lateral weighting filters (see Figure 2) to calculate $MSDV_{total}$. The sensory conflict theory-based 6D-SVC model was implemented and tuned to be able to capture the motion sickness adaptation behaviour of individual participants.

The experimental data in **Paper B** was collected during predefined test scenarios at Säve Airport (T1) and Volvo Cars Demo Center (T2) (see Figure 4) using IMUs on the human body and the test vehicle. Selection of the test participants was performed by using the short MSSQ. To avoid that the test participants were able to anticipate upcoming vehicle motions by seeing the steering wheel and the pedal movements, the test vehicle was equipped with a separator panel between the driver and the test participants. During the experiments, participants verbally rated their subjective motion sickness feeling using a simplified version of the MISC while they were performing a reading task and were instructed to not look outside. The results from the subjective motion sickness scales (simplified MISC scores) were compared with motion sickness estimation methods to evaluate prediction performance.

Figure 4**. Säve Airport (left) and Volvo Cars Demo Center (right) –* ***Paper B

Figure 5 shows the comparison of self-ratings for two test participants, P2 and P4, at test track T1 with calculated $MSDV_{total}$ based on the ISO-2631 approach and the MSS (Motion Sickness Severity) from the 6D-SVC model. Test participant P4's self-rating aligns well with both the $MSDV_{total}$ (top left) and the MSS of the 6D-SVC model (bottom left). The self-rating scores for P2 show that motion sickness adaptation appears, whereas the $MSDV_{total}$ (top right) shows a cumulative growth and the prediction results are not fitting with the individual motion sickness feelings. This means that the ISO-2631 based method fails to predict individual motion sickness if any motion sickness adaptation occurs.

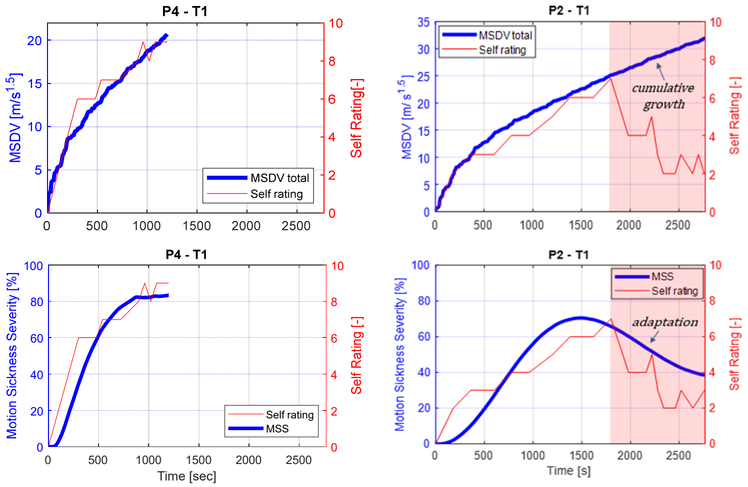

Figure 5. *Self-ratings for participants P2 and P4 at T1 compared to* $MSDV_{total}$ *(top) and MSS of the 6D-SVC model (bottom)* ***(Paper B)***

The results show that by tuning the parameters of the 6D-SVC model, it is able to predict the motion sickness adaptation of participant P2 during the tests at T1 (bottom right in Figure 5). The comparison with the experimental results concluded that the applied estimation models can be used to estimate the motion sickness feeling of individuals.

The study in **Paper B** pointed out that adaptation during experiments is an important property that needs to be considered by motion sickness prediction models. Individual differences could be based on the different amounts of conflict signals generated within the brain processes. However, **Paper B** hypothesized that passengers' reactions could differ in response even to the same amount of conflict signals, which may have resulted in varying levels of motion sickness severity. In this consideration, an adaptation term was proposed after introducing the conflict signal generation. The adaptation term was selected for each individual from the range of 0 to 1 and model parameters after the conflict signal were tuned to identify motion sickness adaptation. The model outputs were then adjusted to fit the experimental subjective rating results. Even though the model fits relatively well with the experiments, further investigation is still needed to test the hypothesis and understand the mechanism of motion sickness within the brain processes. The benefit of the proposed approach is that accurately predicting motion sickness in the case of adaptation has the potential to increase the operating time of future autonomous vehicles. More information about the study can be found in **Paper B.**

3 Mitigation methods

Since the primary cause of motion sickness is motion itself, thereby controlling the vehicle's motion could be used as an effective approach to mitigate motion sickness. Vehicle dynamics is the study of vehicle motion while designing the mechanical properties of vehicle components such as suspension systems. Electronic advancements (control units, sensors, actuators etc.) have been integrated into vehicle dynamics systems, allowing for the control of the vehicle's motion using actuators. Developing vehicle dynamics and control systems helps to characterise the vehicle's motion and aims to increase safety and comfort. Several previous studies have demonstrated the potential to enhance motion comfort using vehicle dynamics based methods as discussed in **Paper A** and **Paper C**. For example, using suspension control to improve ride comfort [52] where eliminating the vehicle's body motion caused by road disturbances is the primary objective of the active suspension system. Moreover, this system also has the capability to impact the roll motion when cornering and pitch motion during acceleration or braking. Experimental evidence by DiZio et al. [22] suggests that using an active suspension system can reduce vertical vibrations which may lead to an improvement in passengers' reading ability and thereby also a reduction in motion sickness. Another example is brake distribution control, proposed by Tavernini et al. [23], which can effectively control a vehicle's pitch motion by dynamically adjusting the brake force distribution during braking events. Rear-wheel steering, described by Utbult [24], can regulate lateral acceleration and yaw motion, while active anti-roll bars, as studied by Agrawal and Gustafsson [53], can help to control the roll motion. Furthermore, Jurisch et al. [54] conducted simulator studies on active roll stabilisation and rear-wheel steering which however showed no significant effect, possibly due to poorly tuned controllers. These studies demonstrate that implementing these techniques in autonomous driving platforms has the potential to alleviate motion sickness. Therefore, further investigations are needed to determine the effectiveness of active chassis control systems in reducing motion sickness in autonomous vehicles.

Vehicle dynamics and chassis control systems characterise vehicle motion; however, the primary influencing factor remains the driving style, which determines the vehicle's movement by controlling speed and steering. In autonomous vehicles, speed and steering will be controlled by trajectory planning and tracking algorithms. Thus, autonomous driving algorithms are crucial, needing to meet passenger preferences and contribute to the adoption of autonomous vehicles by society.

3.1 Trajectory planning

The research gap in trajectory planning and tracking from the perspective of ride comfort is highlighted in [55] and [25]. The driving style of developed AVs can be subjectively aggressive, as it might cause excessive, unexpected head and body motion and the likelihood of motion sickness will potentially be increased [56]. To increase the comfort feeling, driving characteristics need to be optimised for AVs. However, reduced vehicle speed to minimise motion sickness can cause a negative effect on traffic, while passenger dissatisfaction might also be increased because of the longer journey times [57]. Therefore, it is important to find out the correct balance between the passenger’s motion sickness and journey time in order to fulfil the expectations. The review study in **Paper C** investigated vehicle dynamics based motion sickness mitigation methods and highlighted the potential of the trajectory planning algorithms for autonomous driving. A summary of trajectory planning approaches for mitigating motion sickness is described in this section.

Commonly, motion planning for autonomous driving is split into several aspects: route planning, path planning, manoeuvre planning, and trajectory planning [58]. Trajectory planning is one of the challenging and critical functional layers which is determining a sequence of vehicle control inputs (steering, braking and acceleration) that will allow an autonomous vehicle to go from a starting point to a goal point [59]. The experimental studies presented in [38] showed that it can result in subjectively aggressive driving that may increase passengers' motion sickness feeling. The review study by Elbanhawi et al. [55] discussed factors impacting autonomous vehicle use and introduced the importance of developing autonomous vehicle path-planning algorithms for passenger comfort and motion sickness, while also proposing passenger-aware planning factors along with potential research solutions. Claussmann et al. [60] and Gonzalez et al. [61] emphasise the importance of developing trajectory planning and tracking algorithms for pleasant driving in autonomous driving. All of these previous studies have highlighted that the problem of minimising motion sickness in autonomous driving can be approached using trajectory planning algorithms.

The studies by Htike et al. [25] discussed the trade-off between severity levels of motion sickness and journey time, while also introducing the optimal control problem for trajectory optimisation. The problem of minimising the journey time or lap time, called minimum-lap-time (MLT) optimisation has been extensively studied in the context of motorsport applications. Massaro and Limebeer [62] conducted a comprehensive systematic review that covers a historical overview of MLT optimisation and simulation from the 1950s to the 2010s. The review explains the principles behind the design of optimal control problems and discusses various solution methods along with their applications. The MLT problem can be redesigned to include motion sickness metrics in the problem, in order to find the best trade-off between motion sickness and travel time. The solution of the optimum control problem can enable safe and comfortable travel within a desired time frame while minimising the risk of motion sickness.

The goal of optimal control theory is to find a control input sequence for a dynamical system over time that optimises an objective function. Dynamic programming, direct methods, and indirect methods are three numerical approaches for solving optimal control problems. Direct optimization using nonlinear programming (NLP) is considered one of the most effective methods for solving optimal control problems, which offers a larger convergence domain and requires less initial value accuracy to achieve convergence. The continuous Optimal Control Problem (OCP) is converted by the direct method into a finite-dimensional nonlinear programming problem, which can be solved through the use of NLP solvers like SNOPT (Sparse Nonlinear OPTimizer), IPOPT (Interior Point OPTimizer), KNITRO (Nonlinear Interior Trust Region Optimization), etc. GPOPS-II, a commercially available optimum control software, was developed to interface with nonlinear programming (NLP) solvers, which allows users to formulate an optimal control problem with high flexibility [63].

The optimisation problem described in **Paper D** was formulated using point mass and single-track (bicycle) vehicle models that consider different driving styles to find the best trajectories that minimise motion sickness and manoeuvre time. Optimal vehicle motion control inputs (steering, braking and acceleration) were calculated using the GPOPS-II optimisation software package [64].

A trajectory optimisation problem that considers cost functions for both journey time (J_{time}) and motion sickness ($J_{comfort}$) was formulated while taking into account the vehicle and road-related constraints (vehicle dynamics, path, time, distance bounds, power characteristics, torque, steering limit boundaries etc.). The solution of the optimisation problem should enable a comfortable journey with satisfying journey time while minimising motion sickness. The objective function of the optimal control problem is presented in Equation 2.

$$\min_{\mathrm{u}} \left(k \cdot J_{time} + (1-k) \cdot J_{comfort}\right) \tag{2}$$

where k is a weighting parameter.

The optimisation problem was solved under three test manoeuvres; a 90-degree turn, a hairpin (U-turn) and a chicane (S-turn) (for more details see **Paper D**). The simulation results for the chicane (see Figure 6) show a significant path difference when optimising for minimum time compared to maximum comfort, i.e. minimum motion sickness. However, when considering the point mass and bicycle vehicle model, the fidelity of the model has a minor influence on the planned path.

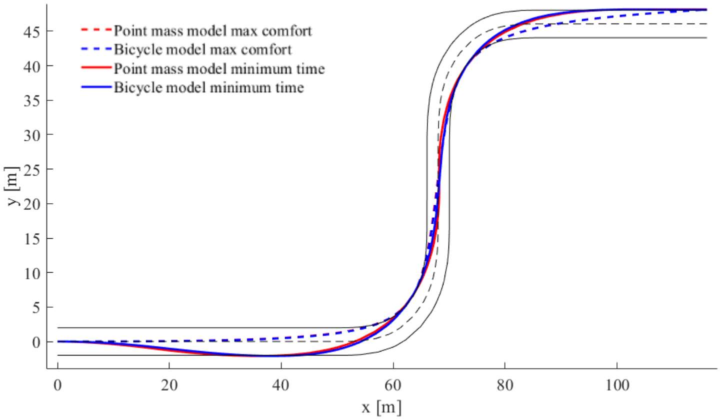

Figure 6. *The optimal path for maximum comfort and minimum time for the chicane (S-turn) for the two different models (**Paper D)***

To calculate the motion sickness levels and evaluate the performance of the proposed trajectory planning algorithms, ISO 2631-based MSDV and the 6D-SVC motion sickness model were used. Figure 7 shows the Pareto front optimisation results for different weighting parameters (selecting $0 \le k \le 1$ from Equation 2) for the chicane.

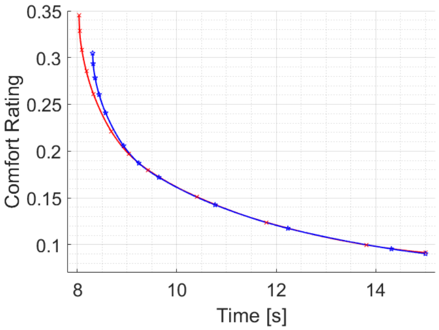

Figure 7. *Pareto front optimisation for the chicane (S-turn) (red: point mass, blue: bicycle vehicle model) (**Paper D**)*

The results illustrate that minimising the manoeuvre time reduces the comfort level (a high comfort rating means high motion sickness severity). The difference in comfort ratings between the two models is more significant when it comes to high-speed (minimum time) manoeuvres. The results in **Paper D** also show that integrating the single-track vehicle model into the optimisation problem provides more realistic planned acceleration profiles when focusing on minimising the manoeuvre time. Therefore, **Paper D** motivate that trajectory planning with the help of high-fidelity vehicle models could provide more accurate motion sickness analyses of driving styles for high-speed (minimum time) driving conditions. The simulation results show that the driving style greatly influences motion sickness, which needs to be tuned carefully depending on personal preferences.

4 Summary of appended papers

Paper A: *Autonomous driving and motion sickness – an outlook on causes, evaluation methods and solutions*
I. Yunus, J. Jerrelind, and L. Drugge
In the Proceedings of the Resource Efficient Vehicle Conference (REV2021), Stockholm, Sweden (June 2021).

The topic of motion sickness in autonomous vehicles is multidisciplinary and may include a wide variety of research disciplines. This makes it difficult to provide a fully covered review. This paper highlights the risk of motion sickness in autonomous vehicles and briefly investigates motion sickness assessment methods and suggests some possible mitigation strategies that can include motion sickness models in the development of autonomous vehicles.

First, the causes of motion sickness and some of the current motion sickness assessment methods were reviewed. This study points out that motion sickness prediction models are crucial in the early design stage of development on how to control and design autonomous vehicles. Additionally, it has given a perspective on motion sickness prevention techniques based on vehicle dynamics and control.

The review study highlighted that to reduce the risk of motion sickness in autonomous vehicles, advanced strategies in vehicle dynamics control and motion planning control can be developed and tuned with the help of motion sickness prediction models. Therefore, further research is needed in these areas. Lastly, this study provides some suggestions for future research; there is a need for a method for reliably assessing motion sickness in order to design and integrate motion sickness mitigation strategies for autonomous vehicles for the success of the technology.

Paper B: *Evaluation of motion sickness prediction models for autonomous driving*
I. Yunus, J. Jerrelind and L. Drugge
In: Orlova, A., Cole, D. (eds) Advances in Dynamics of Vehicles on Roads and Tracks II. IAVSD 2021. Lecture Notes in Mechanical Engineering, Cham: Springer, 2022

The goal of the work presented in this paper was to review and apply two motion sickness prediction methods (ISO-2631 and the 6D-SVC model) and evaluate their ability to estimate individual motion sickness feelings using measured data and subjective assessment ratings from field tests.

As a starting point, the ISO-2631 standard approach was employed, which was then extended to include longitudinal and lateral weighting filters. The study highlights the importance of including habituation as a factor that motion sickness prediction algorithms need to take into account. The 6D-SVC model, which is based on the sensory conflict theory, was implemented and tuned such that it could capture the motion sickness adaption behaviour of individual participants. The application of the motion sickness estimating methods can be adjusted to predict individual motion sickness feelings, as shown by the comparison with the experimental data.

The main scientific contribution of this paper is the evaluation of motion sickness models as well as highlighting the importance of accurate motion sickness assessment in the early phases of autonomous vehicle design. To design and include motion sickness mitigation solutions for autonomous cars, future studies will still need to investigate objective methodologies and models for reliably assessing motion sickness.

Paper C: *A review of vehicle dynamics and control based approaches to mitigate motion sickness in autonomous vehicles*
I. Yunus, G. Papaioannou, J. Jerrelind and L. Drugge
To be submitted for publication (2024).

This article provides a literature review that focuses on vehicle dynamics based motion sickness mitigation methods for autonomous vehicles.

There are several established mitigation approaches in the literature to minimise the severity of motion sickness. However, there is a lack of existing publications specifically focusing on vehicle dynamics and control based solutions and information surrounding potential strategies utilising vehicle dynamics systems. Previous research studies have demonstrated that some of the vehicle dynamics based strategies have the potential to mitigate motion sickness. For instance, active suspension systems can be utilised to minimise vehicle body motion caused by road disturbances and improve ride comfort. These systems also influence roll and pitch during cornering, as well as passengers' perception of accelerations. Controlling angular motions and reducing specific vibrations can be achieved by utilising active seat suspensions. Furthermore, by utilising brake force distribution control pitch motion and perceived longitudinal acceleration can be controlled. Roll motion can also be controlled by active anti-roll bars and lateral movement can be regulated by rear-wheel steering. Moreover, in the context of autonomous driving, the driving style can be controlled by trajectory planning and tracking algorithms. These established strategies were reviewed, demonstrating their ability to reduce provocative motions, thereby improving passenger comfort, while also addressing motion sickness mitigation. Research findings indicate that utilising vehicle dynamics is a direct and effective way to mitigate motion sickness. Thus, it is expected that more strategies using vehicle dynamics systems will be proposed by researchers in the future, increasing the attention directed towards this research area.

The main scientific contribution of this review study is to highlight the importance of motion-based motion sickness prediction models and suggestions for potential vehicle dynamics based solutions that contribute to the design of autonomous vehicles and reduce the risk of motion sickness in such vehicles.

Paper D: *Trajectory planning to minimise motion sickness in autonomous driving*
I. Yunus, A. Lundin, G. Papaioannou, J. Jerrelind and L. Drugge
AVEC’22, 15th International Symposium on Advanced Vehicle Control, Japan (September 2022).

This paper focuses on analysing an optimal control problem to find the optimal trajectory that minimises motion sickness and manoeuvring time using a point-mass model and a single-track vehicle model considering different driving styles.

Vehicle motion control inputs (steering, braking and acceleration) were calculated using an optimisation software package under different driving conditions. The effectiveness of the suggested trajectory planning algorithms was assessed. Pareto front analyses were performed by adjusting the weight parameters of the two terms in the cost function representing motion sickness level and travel time. Motion sickness levels are calculated using the MSDV based on the ISO-2631 standard and the 6D-SVC motion sickness model.

The main scientific contribution of this paper is highlighting with simulations that driving style has a significant impact on motion sickness and should be carefully considered based on personal preference. The findings demonstrate that selecting the correct vehicle model is needed for achieving realistic trajectory planning under high-speed (minimum time) driving conditions. This can further enhance trajectory planning algorithms and enable more accurate analysis of driving styles in terms of motion sickness.

5 Concluding remarks

The main goal of this licentiate thesis is to investigate motion sickness prediction methods and vehicle dynamics based motion sickness mitigation with a focus on trajectory planning solutions. Literature studies were carried out in **Papers A** and **C** while the research for **Paper B** was focused on the evaluation of motion sickness prediction methods through experimental tests. In addition, the potential application of mitigating motion sickness in the context of autonomous driving using trajectory planning was investigated in **Paper D**. The main scientific contributions within this thesis work are summarised in this section.

The brief overview of motion sickness assessment and mitigation methods presented in **Paper A** identified potential research gaps within the research field, such as motion sickness modelling and vehicle dynamics based mitigation methods. In **Paper C**, a more in-depth review of motion sickness mitigation methods in autonomous vehicles was provided, emphasizing a potential solution through the application of vehicle dynamics based mitigation methods in autonomous driving.

For the purpose of capturing individual experiences of motion sickness, two prediction methods were implemented and evaluated during road tests, as presented in **Paper B**. The prediction results showed a good correlation with the subjective individual motion sickness feelings scores, indicating that these motion sickness prediction methods can be utilised as tools for autonomous vehicle development. Moreover, the proposed tuned model in **Paper B** is also beneficial to capture adaptation. However, it should be kept in mind that in the motion sickness evaluation experiments, a limited number of test subjects were used for the analysis of motion sickness feelings. Initial personal conditions (hunger level etc.) of the test subjects and their body posture and postural stability during the tests were not considered. Environmental factors, including temperature, which can lead to symptoms such as sweating, also have the potential to affect the subjective scores of motion sickness. Additionally, the repetition of patterns of vehicle motion caused by the test circuit design could affect motion sickness severity and cause habituation.

Finally, trajectory planning was investigated in **Paper D** as a motion sickness mitigation method for autonomous driving. The trade-off between motion sickness and manoeuvre time was analysed by simulating different vehicle models in various manoeuvres considering different driving styles. The simulation results show that the driving style greatly influences motion sickness, which needs to be tuned carefully depending on personal preferences. The results of the short manoeuvre simulations presented in **Paper D** can be expanded to represent more realistic driving and need to be validated through experimental testing in the future. The simulations were also limited by the road and vehicle model fidelity for trajectory planning optimisation, and traffic interactions and route design were not considered.

5.1 Recommendations for future work

This section gives some ideas for future studies.

The existing methods in the literature to estimate motion sickness have been validated under specific laboratory test conditions. Although laboratory tests do not precisely replicate real-world driving scenarios, the existing motion sickness models still have proven valuable and can offer estimates of motion sickness severity for passengers with some appropriate assumptions. However, further exploration of motion-based experiments is necessary to propose improved motion sickness prediction methods and adapt them to the complexities of on-road conditions.

The previous research shows that precision in the human perception model is an important factor in predicting motion sickness accurately. Another interesting topic is how human perception models and motion sickness models can be combined and enhanced to improve the assessment of mitigation strategies. Furthermore, adaptation, recovery and psychological factors are important phenomena to include in motion sickness modelling for better prediction of motion sickness severity. For example, the term protective adaptation describes the process where prolonged exposure to certain stimuli tends to reduce motion sickness [65] and experiments have shown that the rate of adaptation varies among test subjects. The study [65] by Dobie and May integrated psychological factors into Benson's physiological concept [66], introducing the psycho-physiological model of motion sickness. This approach could be used to integrate adaptation, recovery and psychological factors into mathematical models of motion sickness. Collaborating with medical research centres and laboratories could be investigated to enhance knowledge related to the motion sickness models. Another extension could be to include vision and other sensory system-brain interactions in the motion sickness model.

There is still a need for exploring various vehicle motion control strategies and algorithms, like active suspension and rear-wheel steering, to reduce motion sickness while preserving driving stability. Conducting simulations enables the evaluation of how these control strategies impact the overall driving experience of autonomous driving vehicle platforms.

Another recommendation related to mitigation methods is to implement more advanced and realistic trajectory planning algorithms including high-order vehicle models to control the vehicle control inputs (steering, braking and acceleration) to better capture the relationship between the manoeuvre time and motion sickness. The studies can be continued by analysing the 6 DoF vehicle motions to investigate the effect on motion sickness and give ideas on which motions to focus on when developing trajectory planning algorithms.

Finally, the effect of proposed trajectory planning algorithms can be assessed in real-world road tests to gain more confidence in the simulations conducted in **Papers B** and **D**. This will be a good basis for examining possibilities to reduce motion sickness in autonomous driving.

References

[1] P. Mallozzi, P. Pelliccione, A. Knauss, C. Berger, and N. Mohammadiha, “Autonomous Vehicles: State of the Art, Future Trends, and Challenges,” in *Automotive Systems and Software Engineering: State of the Art and Future Trends*, Y. Dajsuren and M. van den Brand, Eds. Cham: Springer International Publishing, 2019, pp. 347–367.

[2] D. Parekh *et al.*, “A Review on Autonomous Vehicles: Progress, Methods and Challenges,” *Electronics*, vol. 11, no. 11, p. 2162, 2022.

[3] S. A. E. International, “Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles,” *SAE Int.*, vol. 4970(724), pp. 1–5, 2018.

[4] D. Paddeu, G. Parkhurst, and I. Shergold, “Passenger comfort and trust on first-time use of a shared autonomous shuttle vehicle,” *Transp. Res. Part C Emerg. Technol.*, vol. 115, p. 102604, 2020.

[5] C. Diels and J. E. Bos, “Self-driving carsickness,” *Appl. Ergon.*, vol. 53, no. March, pp. 374–382, 2016.

[6] S. Salter, C. Diels, P. Herriotts, S. Kanarachos, and D. Thake, “Model to predict motion sickness within autonomous vehicles,” *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.*, vol. 234, no. 5, pp. 1330–1345, 2020.

[7] 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, 1991.

[8] C. Diels, “Will autonomous vehicles make us sick?,” *Contemp. Ergon. Hum. Factors 2014*, pp. 301–307, 2014.

[9] J. Iskander *et al.*, “From car sickness to autonomous car sickness: A review,” *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 62, pp. 716–726, 2019.

[10] B. Sivak, Micheal, Schoettle, “Motion Sickness in Self-Driving Vehicles,” *Rep. No. UMTRI-2015-12*, no. April, 2015.

[11] J. A. Irwin, “The Pathology of Sea-Sickness,” *Lancet*, vol. 118, no. 3039, pp. 907–909, 1881.

[12] A. Koch, I. Cascorbi, M. Westhofen, M. Dafotakis, S. Klapa, and J. P. Kuhtz-Buschbeck, “See-und Reisekrankheit: Therapeutische Strategien und neurophysiologische Aspekte der Kinetosen,” *Dtsch. Arztebl. Int.*, vol. 115, no. 41, pp. 687–696, 2018.

[13] J. R. Lackner, “Motion sickness: More than nausea and vomiting,” *Exp. Brain Res.*, vol. 232, no. 8, pp. 2493–2510, 2014.

[14] ISO 2631-1, “Evaluation of human exposure to whole-body vibration,” pp. 8–30, 1997.

[15] C. Diels, Y. Ye, J. E. Bos, and S. Maeda, “Motion Sickness in Automated Vehicles: Principal Research Questions and the Need for Common Protocols,” *SAE Int. J. Connect. Autom. Veh.*, vol. 5, no. 2, 2022.

[16] C. Diels, J. Bos, K. Hottelart, and P. Reilhac, “Motion Sickness in Automated Vehicles: The Elephant in the Room,” *Meyer, G., Beiker, S. Road Veh. Autom. 3. Lect. Notes Mobility. Springer*, pp. 121–129, 2016.

[17] S. Salter, C. Diels, P. Herriotts, S. Kanarachos, and D. Thake, “Motion sickness in automated vehicles with forward and rearward facing seating orientations,” *Appl. Ergon.*, vol. 78, pp. 54–61, 2019.

[18] D. Bohrmann and K. Bengler, “Reclined Posture for Enabling Autonomous Driving,” in *Human Systems Engineering and Design II*, 2020, pp. 169–175.

[19] K. Kato and S. Kitazaki, “A study for understanding carsickness based on the sensory conflict theory,” *SAE Tech. Pap.*, no. 724, 2006, doi: 10.4271/2006-01-0096.

[20] O. X. Kuiper, J. E. Bos, C. Diels, and E. A. Schmidt, “Knowing what’s coming: anticipatory audio cues can mitigate motion sickness,” *Appl. Ergon.*, vol. 85, p. 103068, 2020.

[21] J. Maculewicz, P. Larsson, and J. Fagerlönn, “Intuitive and subtle motion-anticipatory auditory cues reduce motion sickness in self-driving cars,” *Int. J. Hum. Factors Ergon.*, vol. 8, no. 4, pp. 370–392, 2021.

[22] P. DiZio *et al.*, "An active suspension system for mitigating motion sickness and enabling reading in a car," *Aerosp. Med. Hum. Perform.*, vol. 89, no. 9, pp. 822–829, 2018.

[23] D. Tavernini, E. Velenis, and S. Longo, "Feedback brake distribution control for minimum pitch," *Veh. Syst. Dyn.*, vol. 55, no. 6, pp. 902–923, 2017.

[24] J. Utbult, "A Study on Low-Speed Maneuverability and Highway Lateral Comfort," *Master Thesis, Chalmers Univ. Technol.*, 2017.

[25] Z. Htike and et al., "Fundamentals of motion planning for mitigating motion sickness in automated vehicles," *IEEE Trans. Veh. Technol.*, vol. 71, no. 3, pp. 2375–2384, 2021.

[26] Daimler, "Kinetosis - nausea when travelling by vehicle," 2019. https://www.daimler.com/magazine/mobility/motion-sickness-kinetosis-product-development.html (accessed Oct. 23, 2020).

[27] J. Karjanto, N. M. 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," *Transp. Res. part F traffic Psychol. Behav.*, vol. 58, pp. 678–692, 2018.

[28] J. F. Golding, "Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness," *Brain Res. Bull.*, vol. 47, no. 5, pp. 507–516, 1998.

[29] J. F. Golding, "Predicting individual differences in motion sickness susceptibility by questionnaire," *Pers. Individ. Dif.*, vol. 41, no. 2, pp. 237–248, 2006.

[30] J. E. Bos, S. N. MacKinnon, and A. Patterson, "Motion sickness symptoms in a ship motion simulator: Effects of inside, outside, and no view," *Aviat. Sp. Environ. Med.*, vol. 76, no. 12, pp. 1111–1118, 2005.

[31] S. J. Alexander, M. Cotzin, C. J. Hill Jr., E. A. Ricciuti, and G. R. Wendt, "Wesleyan University Studies of Motion Sickness: I. The Effects of Variation of Time Intervals Between Accelerations Upon Sickness Rates," *J. Psychol.*, vol. 19, no. 1, pp. 49–62, 1945.

[32] T. G. Dobie, *Motion Sickness: A Motion Adaptation Syndrome*, vol. 6. Springer, 2019.

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

[34] 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," *Hum. Factors Res. Inc. Tech. Rep.*, pp. 1733–2, 1976.

[35] A. Lawther and M. J. Griffin, "Prediction of the incidence of motion sickness from the magnitude, frequency, and duration of vertical oscillation," *J. Acoust. Soc. Am.*, vol. 82, no. 3, pp. 957–966, 1987.

[36] S. A. E. Nooij, "A review on the effects of motion characteristics on motion sickness incidence," *Max Planck Inst. Biol. Cybern.*, no. Technical Report No. 197, 2018.

[37] M. Turner, "A description of low frequency motion in road coaches," in *Proceedings UK Informal Group on Human Response to Vibration*, 1992, pp. 323–339.

[38] M. Turner and M. J. Griffin, "Motion sickness in public road transport: The effect of driver, route and vehicle," *Ergonomics*, vol. 42, pp. 1646–1664, 1999.

[39] M. J. Griffin and K. L. Mills, "Effect of frequency and direction of horizontal oscillation on motion sickness," *Aviat. Sp. Environ. Med.*, vol. 73, no. 6, pp. 537–543, 2002.

[40] B. E. Donohew and M. J. Griffin, "Motion sickness: Effect of the frequency of lateral oscillation," *Aviat. Sp. Environ. Med.*, vol. 75, no. 8, pp. 649–656, 2004.

[41] J. A. Joseph and M. J. Griffin, "Motion sickness: Effect of the magnitude of roll and pitch oscillation," *Aviat Sp. Env. Med*, vol. 79, pp. 390–396, 2008.

[42] J. T. Reason, "Motion sickness adaptation: A neural mismatch model," *J. R. Soc. Med.*, vol. 71, no. 11, pp. 819–829, 1978.

[43] R. Lewkowicz, "Modeling Motion Sickness," *Polish J. Aviat. Med. Bioeng. Psychol.*, vol. 22, no. 3, pp. 32–42, 2017.

[44] J. T. Reason, "Motion sickness adaptation: A neural mismatch model," *J. R. Soc. Med.*, vol.

71, no. 11, pp. 819–829, 1978.

[45] C. M. Oman, “Motion sickness: A synthesis and evaluation of the sensory conflict theory,” *Can. J. Physiol. Pharmacol.*, vol. 68, no. 2, pp. 294–303, 1990.

[46] J. E. Bos and W. Bles, “Modelling motion sickness and subjective vertical mismatch detailed for vertical motions,” *Brain Res. Bull.*, vol. 47, no. 5, pp. 537–542, 1998.

[47] C. Braccesi and F. Cianetti, “Motion sickness. Part I: development of a model for predicting motion sickness incidence,” *Int. J. Hum. Factors Model. Simul.*, vol. 2, no. 3, p. 163, 2011.

[48] T. Wada, N. Kamij, and S. Doi, “A Mathematical Model of Motion Sickness in 6DOF Motion and Its Application to Vehicle Passengers,” *arXiv Prepr. arXiv1504.05261*, 2015.

[49] J. Kufver B., Förstberg, “A net dose model for development of nausea,” *Linköping Statens väg- och Transp. VTI särtryck 330*, 1999.

[50] R. Persson, “Tilting trains: Technology, benefits and motion sickness,” *Licent. thesis, KTH R. Inst. Technol.*, 2008.

[51] 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, 2021.

[52] H. E. Tseng and D. Hrovat, “State of the art survey: active and semi-active suspension control,” *Veh. Syst. Dyn.*, vol. 53, no. 7, pp. 1034–1062, 2015.

[53] H. Agrawal and J. Gustafsson, “Investigation of active anti-roll bars and development of control algorithm,” *Master Thesis, Chalmers Univ. Technol.*, 2017.

[54] M. Jurisch, C. Holzapfel, and C. Buck, “The influence of active suspension systems on motion sickness of vehicle occupants,” *2020 IEEE 23rd Int. Conf. Intell. Transp. Syst.*, pp. 1–6, 2020.

[55] M. Elbanhawi, M. Simic, and R. Jazar, “In the passenger seat: Investigating ride comfort measures in autonomous cars,” *IEEE Intell. Transp. Syst. Mag.*, vol. 7, no. 3, pp. 4–17, 2015.

[56] G. Papaioannou, D. Ning, J. Jerrelind, and L. Drugge, “A K-Seat-Based PID Controller for Active Seat Suspension to Enhance Motion Comfort,” *SAE Int. J. Connect. Autom. Veh.*, vol. 5, no. 12-05-02–0016, pp. 189–199, 2022.

[57] G. Papaioannou, Z. Htike, C. Lin, E. Siampis, S. Longo, and E. Velenis, “Multi-Criteria Evaluation for Sorting Motion Planner Alternatives,” *Sensors*, vol. 22, no. 14, p. 5177, 2022.

[58] C. Katrakazas, M. Quddus, W. H. Chen, and et al., “Real-time motion planning methods for autonomous on-road driving: State-of-the-art and future research directions,” *Transp. Res. Part C Emerg. Technol.*, vol. 60, pp. 416–442, 2015.

[59] C. Badue, R. Guidolini, R. V Carneiro, and et al., “Self-driving cars: A survey,” *Expert Syst. Appl.*, vol. 165, p. 113816, 2021.

[60] L. Claussmann, M. Revilloud, D. Gruyer, and et al., “A review of motion planning for highway autonomous driving,” *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 5, pp. 1826–1848, 2019.

[61] D. González, J. Pérez, V. Milanés, and et al., “A review of motion planning techniques for automated vehicles,” *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 4, pp. 1135–1145, 2015.

[62] M. Massaro and D. J. N. Limebeer, “Minimum-lap-time optimisation and simulation,” *Veh. Syst. Dyn.*, vol. 59, no. 7, pp. 1069–1113, 2021.

[63] Z. Htike, “Control for motion sickness minimisation in autonomous vehicles,” *PhD thesis, Cranf. Univ.*, 2021.

[64] M. A. Patterson and A. V. Rao, “GPOPS - II: A MATLAB software for solving multiple-phase optimal control problems using hp-adaptive gaussian quadrature collocation methods and sparse nonlinear programming,” *ACM Trans. Math. Softw.*, vol. 41, no. 1, 2014.

[65] T. G. Dobie, “Psychological Mechanisms That Exacerbate Motion Sickness,” in *Motion Sickness: A Motion Adaptation Syndrome*, Cham: Springer International Publishing, 2019, pp. 113–127.

[66] A. J. Benson, “Motion sickness,” *Ernsting, K. Aviat. Med. Butterworths, London*, vol. 2nd ed., p. pp.318–338, 1988.

Part II

PAPERS A-D