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Experimental Studies of Motion Comfort & Sickness for Autonomous Driving

Bachelor Thesis Mechatronics

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Abstract

Since autonomous vehicles are the future of the car industry it is important to be completely comfortable in an autonomous car, and a challenge for this is to overcome the issue of motion sickness. Motion sickness is caused by conflicts that create a discrepancy between the vestibular system's sense of movement and the visually perceived movement, it causes symptoms of motion sickness such as nausea, dizziness, sweating or even vomiting. To be able to have a better understanding of the effects of vibrations on motion sickness, two experiments were performed. The first experiment had the main purpose of making an assessment on the lateral and longitudinal motions on a flat road. The second experiment had a track with downhill and uphill slopes to give a possibility to analyze the effect of vibrations in the vertical direction. During both experiments, the participants were asked to read given texts with the aim of removing expected information about the car's trajectory. Subjective measurements were made on these experiments in the form of using the Misery scale (MISC) questionnaire the to measure the level of motion sickness. For the objective measurement of motion sickness, the Motion Sickness Dose Value (MSDV) was calculated, which is based on ISO 2631-1:1997. MSDV was assessed from a vertical, lateral and longitudinal axis on participants collected data through experiments. An analysis was performed on the objective measurement as well as subjective measurement to be further discussed for finding a correlation in motion sickness predictability.

Keywords: Motion sickness, accelerations, vibrations, MSSQ, MISC, MSDV.

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Abbreviations

CAN	Controller Area Network
DFT	Discrete Fourier transform
ECU	Electronic Control Units
FFT	Fast Fourier Transform
FMS	Fast Motion Sickness Scale
IMU	Inertial Measurement Unit
ISO	International Organization for Standardization
MEMS	Micro-Electro-Mechanical Systems
MISC	Misery Scale
MSAQ	Motion Sickness Assessment Questionnaire
MSDV	Motion Sickness Dose Value
MSSQ	Motion Sickness Susceptibility Questionnaire
OPM	Occupant's Preference Metric
r.m.s	Root Mean Square
SSQ	Simulator Sickness Questionnaire
W_d	Frequency weighting for health and comfort in horizontal direction
W_f	Frequency weighting for motion sickness in vertical direction
W_k	Frequency weighting for motion sickness in lateral direction

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1 Introduction

This project is made on behalf of Volvo Cars.

1.1 Background

The future of the car industry is to develop autonomous vehicles, which will have significant benefits. Not only for greater efficiency and safety on the road but it will also offer the driver to preform non-driving related tasks since the autonomous vehicle is driving by itself. The goal is for the driver and passengers to fully enjoy the journey and comfortably being able to focus on performing non-driving tasks such as reading, socializing or simply just relaxing. However, to be completely comfortable in an autonomous car, a major challenge is to overcome motion sickness with symptoms such as fatigue, dizziness, nausea and in severe cases even vomiting.

Motion sickness in a vehicle is caused by the vibrations that can be felt when riding in a car. One of the reasons why motion sickness occurs is due to the low situation awareness when preforming non-driving related tasks, this leads to an information mismatch between the signals that the brain receives from the body and the vestibular organ which does not correspond to the visual sense (Ishmael et al., 2014). To investigate motion sickness in cars it is necessary to begin with literature studies and experimental research.

1.2 Purpose

The goal of this thesis project is to investigate assessment methods of motion sickness in vehicles, in particular for autonomous cars, to understand the correlation between the human and vehicle. Accelerations will be measured on human subjects in a vehicle at a real test environment and the data will be used for further analysis to detect motion sickness. The provided data analysis and conclusions can be a base for further studies to minimalize motion sickness with the purpose of improving the comfort of journeys in the future of autonomous cars.

1.3 Limitations

The limitations that have been made prior to this study are:

- This study will mainly focus on assessing motion sickness and will thus not evaluate how the comfort levels are experienced.

- Data for how physiological parameters are affected by motion sickness will be obtained based on literature, however, this will not be further analyzed due to time constraints of the study.
- The motions of pitch, roll and yaw of vehicle and passenger will not be taken in consideration when analyzing data.

2 Motion Sickness Studies

Here, the theoretical background is given about different ways of explaining and understanding motion sickness, such as the function of the vestibular system and various theories behind motion sickness. It is also further explained how motion sickness can be assessed through both objective and a subjective approach.

2.1 Motion Sickness Theories

It is still not entirely known why motion sickness occurs, but there are different theories existing in the literature to explain it. This chapter will start by describing the functions of the vestibular system in detail in order to create an understanding for how it plays a role in the understanding of motion sickness. Motion sickness is mainly explained by two leading theories that interpret the origins of motion sickness. These theories are sensory conflict theory and postural instability theory and will be explained further in this chapter.

2.1.1 Vestibular System

The ear is often associated with hearing, but it is not only for hearing, since in the inner ear there is also the vestibular system which is known as the balance organ. The vestibular system detects head movements and positions, for example it detects whether the body is experiencing an acceleration, how the body relates to gravity and how the head rotates (Verrecchia, 2018). The front part of the inner ear takes care of the auditory function while the end part, consisting of the labyrinth, takes care of the transduction of static inertial forces (Goldberg et al., 2012).

The labyrinth consists of three semicircular canals, that can be seen in Figure 2.1, and are placed orthogonally to each other in the anterior, lateral and posterior position and these contribute to sense the rotational accelerations in pitch, yaw and roll (Pfeiffer et al., 2014). Verrecchia (2018) means that the part of the canals that is in the anterior position detects rotations of the head in a lateral axis, for example when nodding. The lateral canal senses rotations of the head in a vertical axis, for example when the head goes from left to right or vice versa. The third canal in the posterior position detects movements in an antero-posterior axis, this is when the head rotates such that the ear rests against the shoulder. There are lots of hair cells in the three semicircular canals and a fluid that corresponds to the endolymph department (Verrecchia, 2018). A rotation of the head causes the fluid in the canals to move, corresponded to the movement, and the result is that the hair cells in the canals are bent. This stimulation sends nerve impulses to the brain to sense that a movement is taking place.

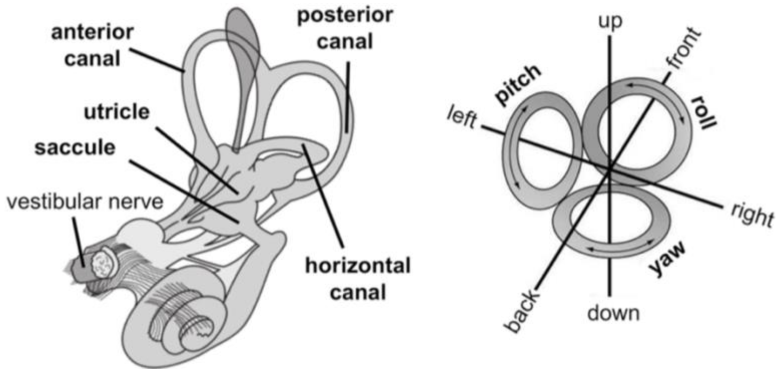


Figure 2. 1 *Anatomy of the vestibular system*

Note. The anatomy of the vestibular system with the location of the three semicircular canals (Pfeiffer et al., 2014).

Verrecchia (2018) continues with describing the sacculus, which detects movements in the vertical plane, and utriculus, which detects movements in the lateral plane. The membrane which is binding the sacculus and the utriculus is called the otolith membrane which contains of thousands of crystals and also hair cells. In the case of linear accelerations or in the case of positional changes that are affected by the gravitational field, a movement takes place in the crystals and they will bend the hair cells. Verrecchia (2018) gives the example that the otolith membrane in the sacculus is constantly pulled downwards due to gravity, as can be seen in Figure 2.2, and the membrane of the utriculus moves sideways at lateral slope.

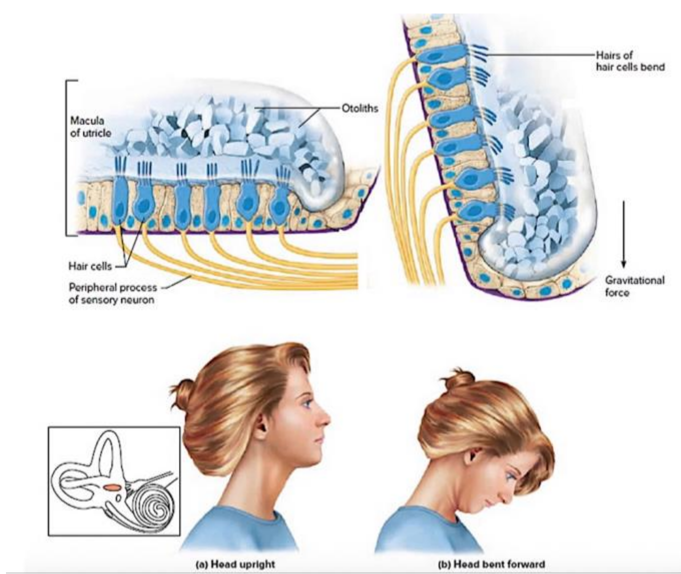


Figure 2. 2 *The otolith membrane*

Note. The figure shows the utricle in (a) head upright and (b) head bent forward and how the hair cells are bent from the crystals (Health Jade Team 2021).

2.1.2 Sensory Conflict Theory

The origin of motion sickness is explained through the sensory conflict theory developed by Reason and Brand as early as 1975. Reason and Brand explains with this theory is how motion sickness originates from the visual, somatosensory system that includes touch, pressure, pain and temperature, and the vestibular system does not communicate as they usually do with each other, thus creating an imbalance between them (Reason, 1978). Thus, when two different signals come to the brain regarding the state of motion, the result will be experiencing symptoms of motion sickness.

According to Table 2.1, two main categories are distinguished:

1. a visual mismatch with the somatosensory and/or vestibular systems
2. disagreement in canal and otolith because the visual is lacking

Both categories concern two types: (1) when both signals are inconsistent or not simultaneously related to each other and (2-3) when only one signal is received in the absence of the other systems.

Table 2. 1 *The different types of conflict and categories of mismatch*

Types of conflict	Categories of mismatch	
	Visual (I) - Somatosensory (II)	Canal (I) - Otolith (II)
Type 1 I and II signal simultaneously with contradictory information	Moving around when wearing an optically distorting device.	Performing a pirouette while tilting the head.
Type 2 Signal I is received in the absence of signal II	Driving a car in a simulator with a motionless base but with a moving visual display.	Moving the head in an area with no gravity.
Type 3 Signal II is received in the absence of signal I	Reading a book inside a moving car.	Rotating the head around a non-vertical axis.

Note. The table gives examples for each type and categories.

Reason (1978) believes that the first main category of imbalance is that all circumstances that cause motion sickness occur due to sensory rearrangement. A conflict takes place between the sensory information that is signaled at the present moment and the signal from the immediate past.

The second main category presupposes that in order for motion sickness to arise, the vestibular system must be implicated, either directly or indirectly, regardless of what the other senses are in conflict with. The vestibular system is affected by linear accelerations or angular accelerations, therefore the susceptibility to motion sickness must be due to a change in a velocity component (Reason, 1978).

2.1.2 Postural Instability Theory

The theory of postural instability, which holds that postural instability can develop motion sickness, was introduced by Riccio and Stoffregen (1991) and is an alternative theory to the sensory conflict theory. The postural instability theory emphasizes the interaction between action and perception when describing motion sickness. According to Riccio and Stoffregen (1991) postural instability occurs when people need to maintain their balance under conditions of modified visual response. Prolonged posture in such instability is the cause of various symptoms of motion sickness.

2.2 Objective Measurement

This chapter consists of the objective method of measuring motion sickness. The method is mainly based on International Organization for Standardization (ISO) 2631-1:1997 and how different direction of accelerations influences motion sickness.

2.2.1 ISO 2631–1:1997

To mathematically assess motion sickness during experimental studies the Motion Sickness Dose Value (MSDV), presented in ISO 2631-1:1997, was used. The ISO 2631-1 standard is part of the international standards established by international technical committees to define whole-body vibrations in relation to health, comfort, and motion sickness. The whole-body vibration is measured according to a coordinate system in transitional motions (lateral, longitudinal and vertical) and rotational motion (roll, pitch and yaw). Vibration is measured in relation between the human body and the surface that causes vibration. Figure 2.3 below is presenting how ISO 2631-1 defines three different basicentric axes of the human body, including seated position, standing position and recumbent position.

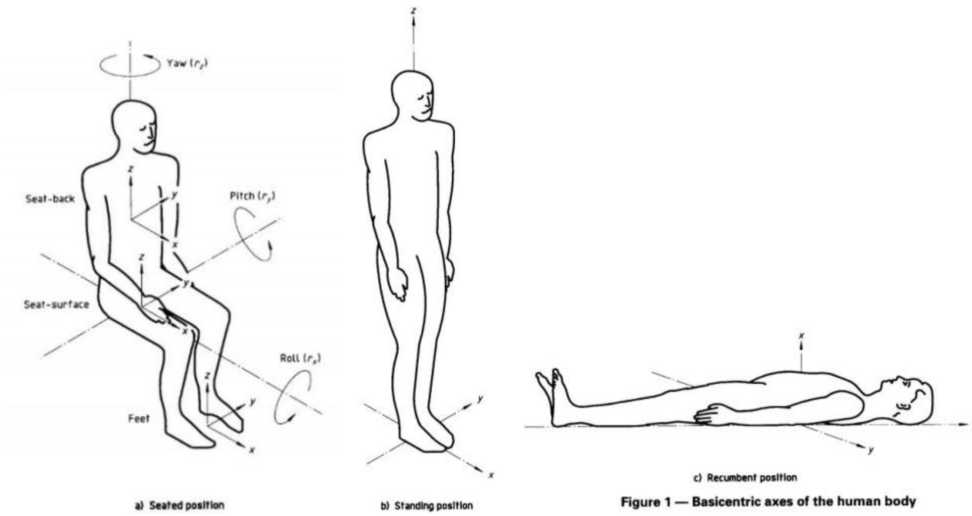


Figure 2. 3 *Basicentric axes of the human body*

Note. The figure is showing the axis of the body in (a) seated position, (b) standing position and (c) recumbent position, (ISO 2631-1:1997).

The evaluation of vibration measurements in ISO 2631-1 includes weighted root-mean-square acceleration (r.m.s) which is measured in m/s^2 for transitional motions presented in following equation:

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2\,(t)dt\right]^{\frac{1}{2}} \qquad (2.1)$$

where,

a_w (t) denotes weighted acceleration as a function of time, [m/s^2]

T denotes duration of measurements in seconds [s].

Frequency weightings are used to measure human response to frequency such as to evaluate frequency-weighed acceleration on health, comfort, and motion sickness. ISO 2631-1 provides a guide for the application of these frequency-weighting curves as well as parameters of the transfer functions for respective weightings. The transfer function is calculated as a product of following factors:

$$H(p) = H_h(p) \cdot\ H_l(p) \cdot\ H_t(p) \cdot\ H_s(p) \qquad (2.2)$$

where,

p = j2πf and denotes imaginary angular frequency

H_h and H_l define the product of band-limiting transfer function and the product of H_t and H_s define the actual weighting transfer function.

Band-limiting (Factors used for transfer function estimation including two-pole filter Butterworth characteristic and Q representing parameters for general frequency weightings based on acceleration as input, where, Q1=Q2=1/$\sqrt{2}$):

- High pass:

$$|H_h(\mathrm{p})| = \left|\frac{1}{1+\sqrt{2}\frac{\omega_1}{p}+\left(\frac{\omega_1}{p}\right)^2}\right| = \sqrt{\frac{f^4}{f^4+f_1^4}} \tag{2.3}$$

where,
$\omega_1 = 2\pi f_1$
$f_1 =$ corner frequency (intersection of asymptotes).

- Low pass:

$$|H_l(\mathrm{p})| = \left|\frac{1}{1+\frac{\sqrt{2p}}{\omega_2}+\left(\frac{p}{\omega_2}\right)^2}\right| = \sqrt{\frac{f_2^4}{f^4+f_2^4}} \tag{2.4}$$

where,
$\omega_2 = 2\pi f_2$
$f_2 =$ corner frequency.

Acceleration-velocity transition (Factor used for transfer function estimation and is proportional to acceleration and velocity for both low and high frequencies):

$$|H_t(\mathrm{p})| = \left|\frac{1+\frac{p}{\omega_3}}{1+p/(Q_4\omega_4)\ +\left(\frac{p}{\omega_4}\right)^2}\right| = \sqrt{\frac{f^2+f_3^2}{f_3^2}}\sqrt{\frac{f_4^4Q_4^2}{f^4Q_4^2+f^2f_4^2(1-2Q_4^2)+f_4^4Q_4^2}} \tag{2.5}$$

where,
$\omega_3 = 2\pi f_3$
$\omega_4 = 2\pi f_4$.

Upward step (Factor used for transfer function estimation, steepness is about 6dB per octave, proportionality to jerk):

$$|H_s(\text{p})| = |\frac{1 + \frac{p}{(Q_5\omega_5)} + \left(\frac{p}{\omega_5}\right)^2}{1 + p/(Q_6\omega_6) + \left(\frac{p}{\omega_6}\right)^2} \left(\frac{\omega_5}{\omega_6}\right)^2\Big| = \frac{Q_6}{Q_5}\sqrt{\frac{f^4Q_5^2 + f^2f_5^2(1-2Q_5^2) + f_5^4Q_5^2}{f^4Q_6^2 + f^2f_6^2(1-2Q_6^2) + f_6^4Q_6^2}} \quad (2.6)$$

where,

$\omega_5 = 2\pi f_5$

$\omega_6 = 2\pi f_6$.

Frequency weightings for transitional motions from ISO 2631–1:1997, presented in Figure 2.4:

- W_k denotes vertical direction and a lying vertical direction excluding head.
- W_d denotes lateral and longitudinal directions and horizontal in a lying direction.
- W_f denotes motion sickness in low-frequency, only vertical direction.

Additional Frequency weightings including rotational motions are presented in Figure 2.5. The additional Frequency weightings are although not analyzed further in thesis.

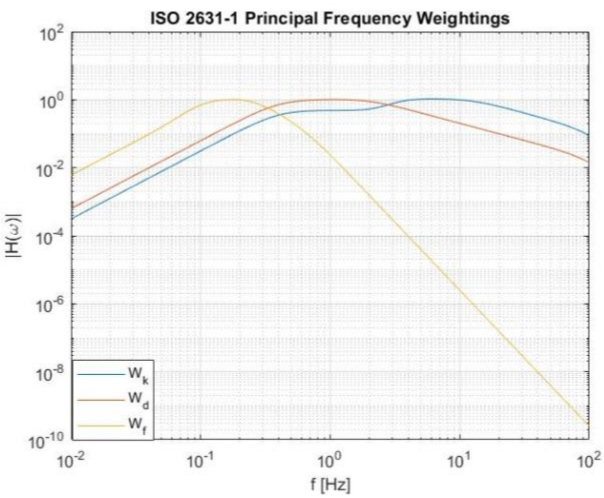


Figure 2. 4 *Frequency weightings curves for principal weightings*

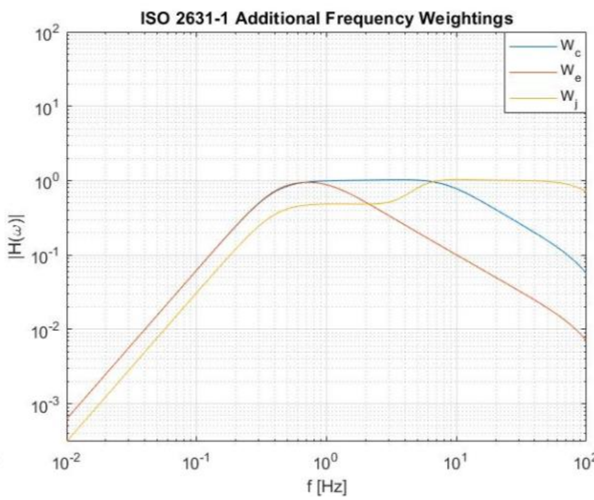


Figure 2. 5 *Frequency weightings curves for additional weightings*

Note. Figure 2.4 is showing the frequency weightings of W_k, W_d and W_f and figure 2.5 is showing the frequency weightings of W_c , W_e and W_j. These figures are directly inspired by ISO 2631-1:1997.

Figure 2.4 and Figure 2.5 is obtained from the data provided in ISO 2631-1 and shows weighting curves considering health, comfort, and motion sickness. In particular interest for this project is W_f representing motion sickness weighting filter. It can be noticed that the Bandwidth representing frequency, where motion sickness is most recognizable, is significantly lower compared to the two other curves presenting health and comfort.

The frequency range for motion sickness in ISO 2631-1 is in between 0.1-0.5 Hz. According to Turner and Griffin (1999) the greatest sensitivity for motion sickness in vertical motion is in range

0.125 Hz and 0.25 Hz which is within a limit presented in ISO 2631-1. The highest sensitivity obtained for health and comfort is in remarkably larger range. For W_k the highest sensitivity is around 4 Hz to 20 Hz and for W_d it lies around 0.5 to 2 Hz.

The frequency weighting of the acceleration is presented as:

$$a_w(t) = \left[\sum_i (W_i a_i)^2\right]^{\frac{1}{2}} \tag{2.7}$$

where,

a_w denotes the frequency-weighted acceleration [m/s^2]
W_i denotes the weighting factor for the *i*:th one-third octave band
a_i denotes the r.m.s. acceleration for the *i*:th one-third octave band

MSDV is presented in ISO 2631-1 as a measurement of motion sickness in relation to the body vibration. The higher value of MSDV indicates a higher occurrence for motion sickness. MSDV (*m/s* ^{1,5}) should be determined from motion measurements during the full period of exposure:

$$MSDV_Z = \left\{\int_0^T [a_w(t)^2]dt\right\}^{\frac{1}{2}} \tag{2.8}$$

where,

a_w(t) denotes the frequency-weighted acceleration in the z direction, [m/s^2]
T denotes the total period during which motion could occur [s].

2.2.2 Primary Studies

The vibration effects on motion sickness commonness investigated in ISO 2631-1 only considers the vertical axes. Vertical acceleration is corelated to ride quality but poorly corelated to motion sickness (Bae et al., 2019). The experiment done by Wang et al. (2020) analyses the comfort of users that was based on vehicles collected data and various physiological characteristics of passengers. The acceleration data was collected from X-axis (longitudinal acceleration), Y-axis (lateral acceleration) and Z-axis (vertical acceleration). It is observed in their study, that longitudinal acceleration and lateral acceleration change significantly during vehicle maneuvers while there are no notable variations in vertical acceleration. Therefore, the following section will be focused on horizontal acceleration.

Turner and Griffin (1999) studied motion sickness in public road transport, and it has been found that the low-frequency horizontal acceleration has biggest impact on motion sickness. It is claimed that the dependency of motion sickness occurrence increases with decreasing frequencies below 0.125 Hz. Golding, and Markey (1996) noticed that, horizontal motion oscillation is considered about twice as nauseogenic as in vertical motion for participants that are sitting upright, in respect of time exposure, to reach respective motion sickness level. The impact of horizontal oscillation for motion sickness is investigated further by Donohew and Griffin (2004). In their studies, the effect of lateral oscillation between 0.0315 and 0.2 Hz is investigated. The frequency weightings for lateral acceleration were developed based on data collected in experiment and previously conducted experiments of studying lateral motion in range 0.2 to 0.8Hz. This provides frequency weighing's for the lateral motion in range 0.0315 to 0.8 Hz that corresponds to procedure for vertical motion which is based on incidences of vomiting. Table 2.2 presents the parameters for lateral acceleration weighting.

Table 2. 2 *Parameters for lateral acceleration weighting*

Band -limiting				a-v transition			Upward step				Gain
f1	Q1	f2	Q2	f3	f4	Q4	f5	Q5	f6	Q6	K
0.02	$1/\sqrt{2}$	0.63	$1/\sqrt{2}$	∞	0.25	0.86	∞	1	∞	1	0.55

Note. This table is showing parameters for estimation lateral acceleration frequency weightings. Parameters f_1 - f_6 are representing frequencies and Q_1 - Q_6 represents quality factors. The weighting gain is suggested to K=55. This table is directly inspired of Donohew and Griffin (2004).

The methodology for lateral frequency weighing is based on the same procedure as presented in ISO 2631-1. The product of component filters is used to calculate the transfer function. Based on the transfer function equations from ISO 2631-1 and the provided parameters, the frequency weighting curves for principal weightings are extended by frequency weightings in lateral motion in Figure 2.6. Transfer function estimated for lateral motion, is used in this thesis to calculate the MSDV for analyzing the longitudinal and lateral vibration.

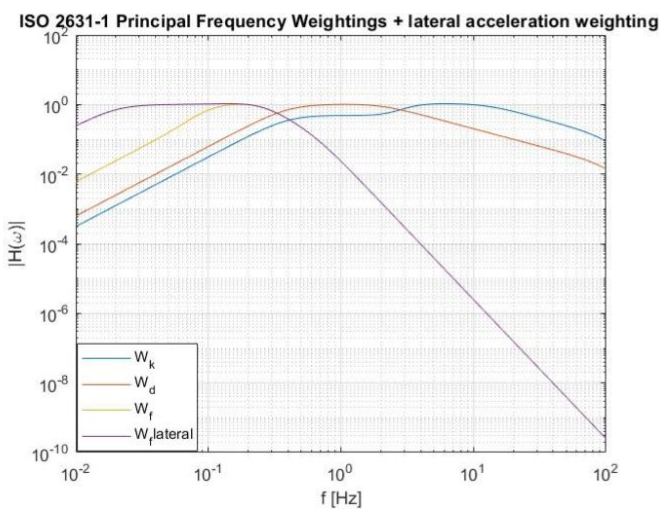


Figure 2. 6 *Frequency weightings curves for principal weightings including lateral acceleration weightings*

Note. This figure is showing extended version of Frequency weightings curves for principal weightings with lateral acceleration weightings included. This figure is directly inspired by (ISO 2631-1:1997).

2.2.3 Acceleration Limits

Along with motion sickness, the comfort of traveling is an important aspect for autonomous future. Motion sickness can cause a dislike of drivers to autonomous driving and even switching to manual mode (Sever et al., 2020). Sever et al. (2020) believes that motion sickness can be reduced trough minimalizing MSDV when a decreasing in the acceleration and jerks is experienced by the vestibular system. Longitudinal acceleration is measured in acceleration and braking in x-direction. Lateral acceleration is created by a centrifugal force and can be noticed on cornering or in changing a line. Jerk is a change of acceleration with respect to time which can appear at swift lane changes and entrances and exits of curves (Svensson, L. & Eriksson, J., 2015).

The acceleration and jerk are two of many aspects that can influence motion sickness and even the comfort experience of journey. There is no significant known data considering acceleration limits for motion sickness only. In this thesis the assumption is that better comfort experience counteracts nausea.

In experimental studies focusing on lateral acceleration and carried out in different environments in China it is shown that the lateral acceleration limits depend on the driving environment (Xu, et al., 2015). The study of Xu et al. showed that on highways, the lateral accelerations are in majority less than 1.8m/s^2 which provided very good comfort experience for passengers. In mountain areas increases the risk for lateral acceleration that can exceed medium comfort limit, estimated to around 3.6 m/s^2. With slow speed in a mountain area lateral acceleration significantly exceeded the discomfort level with over 5 m/s^2.

Bae et al. (2019) propose a summary of both lateral and longitudinal acceleration limits and even jerk threshold depending on driving habits that it is based on the widely literature researched carried by authors.

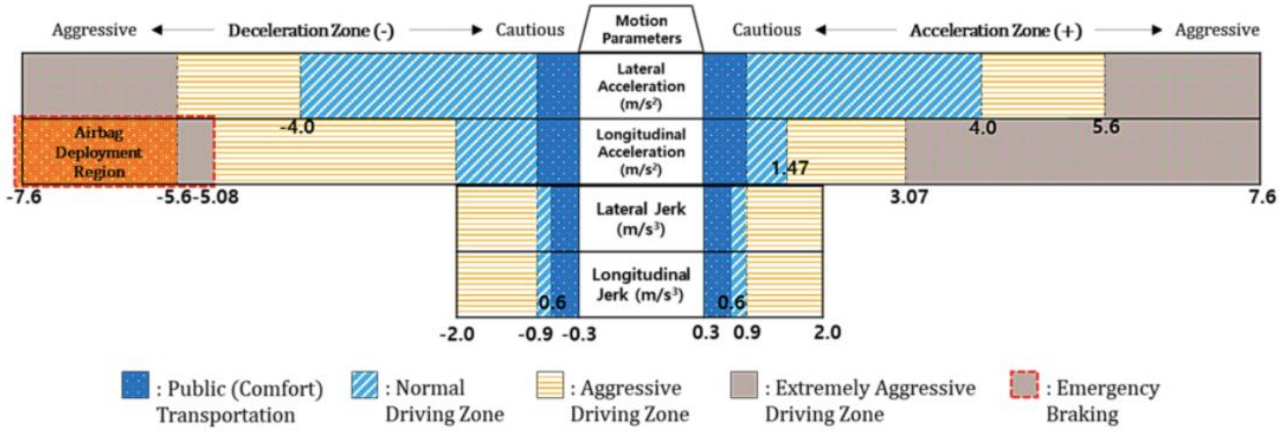


Figure 2. 7 *Proposed occupant's preference metric*

Note. This figure shows the proposed limits in color coding where dark blue is public transportation, light blue is normal driver, yellow is an aggressive driver, orange is an extremely aggressive driver and red is emergency breaking (Bae et al., 2019).

Scientific articles used for figure 2.7 includes various scenarios such as public transport, passenger cars (autonomous and human manual driving) and heavy trucks, and it is divided into parameters related to vehicle motion and four driving type. The acceleration and jerk regions were divided into categories to distinguish driving behavior. The standard values used are limited in the range from 0.9 to 1.47 m/s^2 for longitudinal acceleration and in the range from 0.9 to 4 m/s^2 for lateral acceleration. Limits for jerk are considered same for both longitudinal and lateral acceleration in the range of 0.3 to 0.9 m/s^3. For a decent comfort experience and to minimalize occurrence of motion sickness, the proposed limits should be set under 0.9 m/s^2 for acceleration and 0.6 m/s^3 for jerk.

The vertical motion and vibration parameters are related to road surface condition or, for instance, mechanical structure of the vehicle (Bae et al., 2019). Nevertheless, vertical acceleration can affect the comfort and the experienced quality of the journey for the passengers. Therefore, it is recommended to establish limits of acceleration for vertical motion. In Leon-Vargas et al. (2017) the improvement of travel comfort with focus on active suspension system is investigated. In the study, the vertical acceleration limits are used as one of the parameters and is established to -1.2 m/s^2 for lower limits and 1.2 m/s^2 for upper limits. The vertical acceleration limits for train and elevator are also investigated in Alter (2020) and Jeon et al. (2015), where it can be found that the numbers are very similar. Jeon et al. (2015) determinate vibration serviceability for passengers' comfort in a relation between bridge- high speed train. The European Standards (2002) recommendation for vertical acceleration limit is used in the study of Jeon et al. (2015). The level of "very good" (1.0 m/s^2) is chosen as the vibration serviceability vertical acceleration limit for the study. The level of "good" is set to 1.3 m/s^2 and acceptable up to 2m/s^2. Vertical acceleration is commonly used in elevators. Based on Alter (2020), the 1,5 m/s^2 acceleration limits were a borderline case for comfort experience.

Based on literature studies, the following acceleration limits for experimental studies can be estimated for horizontal and vertical motion considering normal driving scenario that minimalize risk for motion sickness occurrence. The threshold value of lateral comfort acceleration is about 1.8 m/s^2 for very good comfort and up to 3.6 m/s^2 for medium comfort. The threshold value of comfort for longitudinal acceleration is in range 0.9 to 2 m/s^2 and medium comfort is set up to 3 m/s^2. Based on human driving test, while breaking the acceleration is in range –0.5 to -2 m/s^2 (Bae et al. 2020). The threshold value of llongitudinal and lateral jerk is in the range of 0.3 to 0.6 m/s^3. The vertical acceleration should not extend 2 m/s^2. The summary of comfort limits is presented in a table below.

Table 2. 3 *Comfort limits for lateral, longitudinal, and vertical motion including jerk*

	Comfort	**Medium Comfort**	**Discomfort**
Lateral motion	1.80 m/s^2	4.00 m/s^2	>5.00 m/s^2
Longitudinal motion	1.47 m/s^2	2.00 – 3.00 m/s^2	>3.00 m/s^2 (2.00 m/s^2 while braking)
Vertical	1.00 m/s^2	1,50 m/s^2	>2.00 m/s^2
Jerk **(Lateral + Longitudinal)**	0.30 – 0.60 m/s^3	0.6 -0.9 m/s^3	> 0.90 m/s^3

Note. This table presents the comfort limits for lateral, longitudinal, and vertical motion based on the literature studied.

2.3 Subjective Measurement

As have been mentioned, the objective way of measuring motion sickness is through MSDV. For investigating motion sickness, the different limits of acceleration are used and the vestibular system gives an insight of why motion sickness occurs. Motion sickness can, however, only be obtained in a subjective way by using questionnaires on people who are exposed to motion sickness.

2.3.1 Motion Sickness Questionnaire

The goal with this section of the thesis is to make a simple comparison between the various available questionnaires in order to find out which of them is most relevant to this study. To do this, it is important to have knowledge of why motions sickness questionnaires are needed, and also how the questionnaires are structured.

In addition to questionnaires, there are also different measuring scales. These scales are designed to be useful mainly for measuring motion sickness during the experiment or at a certain time. This because an experiment or a simulation for motion sickness constantly changes the form of movements and so on, therefore the level of motion sickness is also affected and it is then advantageous to make measurements in an effective way. The comparison will be made between following questionnaires and scales:

- Simulator Sickness Questionnaire
- Motion Sickness Susceptibility Questionnaire
- Motion Sickness Assessment Questionnaire
- Misery Scale
- Fast Motion Sickness Scale

Difficulties with motion sickness began when the boat was invented, when all passengers were exposed to seasickness. Therefore, research was started on what factors causes motion sickness in order to find a solution to the problem. The history of motion sickness questionnaires started with the Pensacola Motion Sickness Questionnaire developed by Kellogg et al. (1965) and in Figure 2.8 it is possible to follow the development of the different questionnaires. When World War II broke out, Kennedy and Frank (1985) believed it was more than necessary to continue the study of motion sickness since many men in the military needed to be transported across the sea and seasickness distracted them from their duties. It was no longer only seasickness that caused motion sickness, but motion sickness was also experienced within troops that was transported by train, car and for pilots and navigators who felt airsickness.

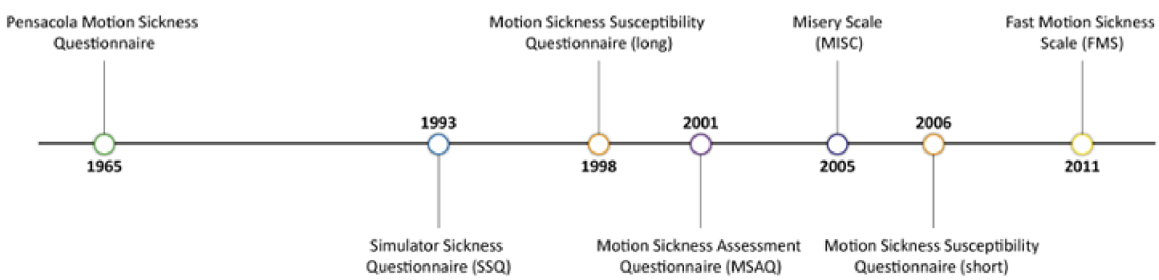


Figure 2. 8 *Timeline of the development of different questionnaires*

2.3.1.1 Simulator Sickness Questionnaire

The Simulator Sickness Questionnaire (SSQ) was developed by Kennedy et al. (1993), and was specifically created to be used in a simulation environment and is therefore measuring visually induced motion sickness. The questionnaire was validated through simulators of marine aircraft and helicopters. The questionnaire is directly inspired by the Pensacola Motion Sickness Questionnaire (MSQ) that was developed in 1965 by Kellogg, Kennedy and Graybiel. The Pensacola motion sickness questionnaire has a sample of 28 symptoms, see Figure 2.9, of which

12 of them have been eliminated for the SSQ since Kennedy et al. (1993) believed that some of the symptoms were not relevant in a simulation.

MSQ Symptom	*Retained for SSQ*	*Eliminated for SSQ*
General discomfort	X	
Fatigue	X	
Boredom		X
Drowsiness		X
Headache	X	
Eyestrain	X	
Difficulty focusing	X	
Increased salivation	X	
Decreased salivation		X
Sweating	X	
Nausea	X	
Difficulty concentrating	X	
Depression		X
Fullness of head	X	
Blurred vision	X	
Dizziness (eyes open)	X	
Dizziness (eyes closed)	X	
Vertigo	X	
Visual flashbacks		X
Faintness		X
Awareness of breathing		X
Stomach awareness	X	
Decreased appetite		X
Increased appetite		X
Desire to move bowels		X
Confusion		X
Burping	X	
Vomiting		X

Figure 2. 9 *Symptoms in SSQ and MSQ*

Note. The figure shows which symptoms are eliminated from MSQ when creating SSQ (Kennedy et. al., 1993).

The SSQ is completed by letting the participant make an evaluation of their experience in the 16 symptoms shown in Figure 2.10. The questionnaire is usually done by the participant as a test after the experiment, but it can also be asked directly to the participant during the experiment. Kennedy et al. (1993) has given each symptom a scale from 0 to 3 where 0 is "none", 1 is "mild", 2 is "moderate" and 3 is "severe". Then one makes a summary of the symptoms that belong to each subscale. The subscales are marked with:

- Nausea (N), with symptoms such as nausea, stomach awareness, increased salivation and burping.
- Oculomotor (O) with the symptoms of eyestrain, difficulty focusing, blurred vision and headache.
- Disorientation (D) such as dizziness and vertigo.

Instructions: Circle how much each symptom below is affecting you right now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. "Fullness of the Head"	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

Figure 2. 10 *Simulator Sickness Questionnaire*

Note. This figure is showing the final version of SSQ (Kennedy et. al., 1993).

2.3.1.2 Motion Sickness Susceptibility Questionnaire

The Motion Sickness Susceptibility Questionnaire (MSSQ) was created to understand how susceptible a participant is to motion sickness and more specifically, what type of transportation movement was the cause of motion sickness. It was originally developed by Reason and Brand in 1975 and was in 1998 modified by Golding to improve and simplify the design (Golding, 1998). The review in this report will be on Goldings modified version.

The MSSQ starts off by a couple of questions regarding personal details. The questionnaire consists of a total of 10 different questions. The questionnaire is divided in two sections, section A and section B. Section A is designed to find out information regarding the participants childhood experience of motion sickness. The following questions in section B are concerned with the experience of the past 10 years (Griffin & Howarth, 2000).

However, the MSSQ is considered to be a questionnaire with a very long content. According to Griffin and Howarth (2000) the consequence given by this is that the implementation of the questionnaire may take some time to complete. There is also a risk of not getting a correct answer with errors or not getting an answer at all due to "fatigue of the questionnaire" because of its length. Consequently, Golding (2006) developed a shorter alternate of the questionnaire, which can be found in Appendix A, and was developed to be more useful, more accurate and more time efficient. It still had the different sections A and B but each consisted of only one question, with a total number of four questions. The short questionnaire was also designed to address issues with low disease frequency by removing them as questions (Golding, 2006).

2.3.1.3 Motion Sickness Assessment Questionnaire

In contrast to the many contributions for developing a questionnaire that predicts overall susceptibility to motion sickness, there have been fewer contributions to the development of a questionnaire that assesses the experience of motion sickness across a broad range of contexts. The Gianaros et al. (2001) therefore developed the Motion Sickness Assessment Questionnaire (MSAQ) with the aim to development a questionnaire that was measuring multiple dimensions of motion sickness, and to measure the symptoms that is relevant to motion sickness.

The MSAQ has been developed by analyzing four different dimensions of motion sickness, they are defined as:

- gastrointestinal (G) – feelings such as sickness of stomach or nausea
- central (C) – such as feeling disoriented or lightheaded
- peripheral (P) – the feeling of being sweaty or cold sweating
- sopite-related (S) – feelings of tiredness, drowsiness or being fatigued

In the questionnaire, seen in Figure 2.11, they are defined solely as (G), (C), (P) and (S) (Gianaros et al., 2001).

***Instructions.* Using the scale below, please rate how accurately the following statements describe your experience**

Not at all — Severely

1——2——3——4——5——6——7——8——9

1. I felt sick to my stomach (G)	9. I felt disoriented (Q
2. I felt faint-like (C)	10. I felt tired/fatigued (S)
3. I felt annoyed/irritated (S)	11. I felt nauseated (G)
4. I felt sweaty (P)	12. I felt hot/warm (P)
5. I felt queasy (G)	13. I felt dizzy (C)
6. I felt lightheaded (C)	14. I felt like I was spinning (C)
7. I felt drowsy (S)	15. I felt as if I may vomit (G)
8. I felt clammy/cold sweat (P)	16. I felt uneasy (S)

Figure 2. 11 *The Motion Sickness Assessment Questionnaire*

The questionnaire for assessment of motion sickness have been based on the previously existing questionnaires such as the Nausea Profile (NP) that was developed 1996 by Muth, Stern, Thayer and Koch. The Nausea Profile measures nausea in general and is as MSAQ a multidimensional questionnaire. It consists of three subscales, the somatic distress such as feeling of being hot, weak or fatigued. The gastrointestinal distress is the feelings of stomach distress such as illness or sickness and emotional distress that concerns being nervous or worried. The Nausea Profile provides either a total score or scores for subscales (Keshavarz & Hecht, 2011).

This was done to validate and correlate with the point system from NP in order to construct the new motion sickness assessment questionnaire. Thus, it means that the various elements of the questionnaire can also be found in the already existing forms of NP. The difference between NP and MSAQ, is how motion sickness is measured, and that MSAQ measures a larger number of the sopite-related aspects (Gianaros et al., 2001). After thorough tests, it turned out that the MSAQ was a valid instrument for assessing motion sickness since the score was in an agreement with the previous questionnaires.

The MSAQ can, by using the total score on the entire questionnaire or with the help of sub-scores, assess both the total experience of motion sickness and/or the four previously mentioned dimensions. Thus, MSAQ can be used to estimate motion sickness in a multidimensional way (Gianaros et al., 2001).

2.3.1.4 Misery Scale

The Misery Scale (MISC) was developed by Bos, MacKinnon and Patterson in 2005 and it is characterized by its simplified rating system for evaluating motion sickness (Bos et al., 2005). The scale begins from the score 0, that would be “no problems”, and ends with the score 10 that is vomiting. In between the scores, there are gradations of different symptoms of motion sickness. The score of 1 is when the participant feels uneasy, score 2-5 is when the participant is feeling dizziness, warmth, headache, stomach awareness or sweating with different degrees. Nausea is scored between 6-9 depending on the degree of nausea (Bos et al., 2010).

The scale is shown in Figure 2.12 and can be used by measuring the motion sickness level of the participant by making short beaks during the experiment so the participant can fill in their ratings. This scale can also be used during the actual experiment by simply asking the participant for a rating by asking the questions directly (Bos et al., 2010).

Symptom		score
No problems		0
Uneasiness (no typical symptoms)		1
Dizziness, warmth, headache, stomach awareness, sweating, . . .	vague	2
	slight	3
	fairly	4
	severe	5
Nausea	slight	6
	fairly	7
	severe	8
	(near) retching	9
Vomiting		10

Figure 2. 12 *The Misery Scale*

2.3.1.5 Fast Motion Sickness Scale

The fast motion sickness scale (FMS) was developed in 2011 by Behrang Keshavarz and Heiko Hecht with the purpose to be a very simplified and a fast classification system for assessing motion sickness. The disadvantage of many motion sickness questionnaires is that due to their length or thesis complexity, they can't be used during an experiment. Therefor Keshavarz and Hechts FMS scale consists of a single question that aims to be used repeatedly during the experiment. The participant is expected to give a verbal rating of how they are feeling with focus on nausea, general discomfort and stomach problems.

The scale has a measuring system that rates with a range of 0 to 20, where 0 is “no motion sickness at all” and 20 is “frank sickness”. Keshavarz and Hecht (2011) believes this way of measurement is beneficial since it measures the development of motion sickness carefully during a given time period and that it takes too long to repeat questionnaires that consist of several questions.

3 Methodology

3.1 Objective Measurement

This section will include the choice of seat accelerometer and motion capture suit for the experiment, how the experiment was prepared and completed. Also, the test vehicle data setup will be presented.

3.1.1 Seat Accelerometer

An accelerometer could be placed under a seated person, to measure the given acceleration in the directions along the body, that is forward, backward and side to side. The choice of accelerometer to be used was discussed according to the current existing three main types of accelerometers on the market, which are piezoelectric, piezoresistive and capacitive Micro-Electro-Mechanical Systems (MEMS).

When an accelerometer is manufactured the MEMS manufacturing technology is used, which refers to capacitive accelerometers. This technology may also be applied for piezoelectric accelerometers. The capacitive MEMS accelerometer works through capacitance changes at an acceleration (Hanly, 2016). Since capacitive MEMS are DC-connected, it is most suitable for measuring low-frequency vibrations, however, it does have a limited acceleration level and bandwidth.

The piezoresistive accelerometer, unlike the MEMS, has a wide bandwidth which enables it to perform measurements on high-frequency data such as shock events. It is therefore most suitable for areas where the frequency and amplitude would be high (Hanly, 2016).

With this comparison of the different varieties, and with the design of the experiment in mind, the decision was to use both MEMS accelerometer and a piezoelectric accelerometer of the model "CCLD Triaxial Seat Accelerometer Types 4515 - B" for the motion sickness assessment.

3.1.2 Test Preparation

Prior to the experiment, two test tracks were chosen. One test track was located in Säve Airport which was suitable for measuring vibrations in lateral and longitudinal motion, while the other test track located in the Volvo Cars Demo Center had downhill and uphill slopes with the purpose to analyze if the track had an impact on vertical motion. The test car used in both experiments was a Volvo XC90.

To create visualization of the test tracks in Säve Airport, the Inertial Measurement Unit (IMU) is used. The visualization of the route in Volvo Cars Demo Center is not created due to confidentiality clause. Pao (2018) explains IMU as a sensor device that together with other electronic devices can detect changes of the environment. With assistance from a sensor fusion software, that combines the data from every sensor in IMU, the accurate data of the localization, orientation and route was provided for both experiments seen in Figure 3.1. The IMU device can measure the vehicles acceleration in six degrees of freedom, with a 3-axis accelerometer and 3-axis gyroscope. The accelerometers measure linear acceleration for horizontal and vertical axis in a particular motion, where the integration of the acceleration provides the estimated velocity for the test car and further integration provides the position of the vehicle. The gyroscope, on the other hand, measures the rotation velocity of pitch, roll and yaw, where the integration can determinate the objects orientation in 3D. A combination of the data from the gyroscope and the acceleration provides the angular position.

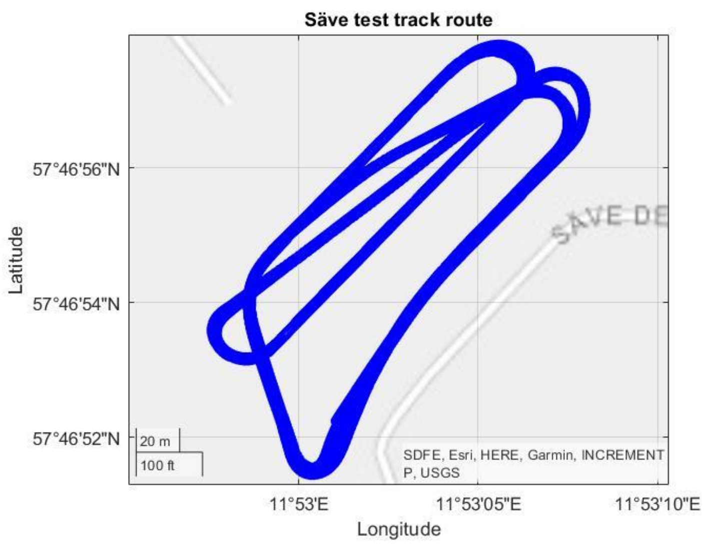


Figure 3. 1 *The route of Säve Airport*

In order to select suitable participants for the first experiment, potential participants needed to fill in a MSSQ questionnaire. An email with information regarding the experiment and a link to a created questionnaire an online questionnaire was sent to 42 potential participants. Based on the submitted answers as seen in Figure 3.2, 9 participants were selected with varied, low, average and high, susceptibility to motion sickness (mean = 19.02, standard deviation = 9.13), this in order to compare the participants' results.

The raw score was obtained through calculating the separate scores of part A (child) and part B (adult). MSA is part A and is scored as total number of ticked boxes, where the number scores are written at the bottom of each column. The score 0-3 is given for each ticked box, where column "t" counts as a 0, see Appendix A. This total sickness score is then, as shown in equation 3.2, multiplied with 9. The product is then divided by 9 subtracted with the number of types not experienced. MSB if part B and is calculated in the same way as MSA (Golding, 2006).

$$MSA = \frac{(total\ sickness\ score\ as\ a\ child) \times 9}{(9 - number\ of\ types\ not\ experienced\ as\ a\ child)} \tag{3.1}$$

The raw score is found by summarizing part A and B, as equation 3.2 shows:

$$MSSQ_{raw\ score} = MSA + MSB \tag{3.2}$$

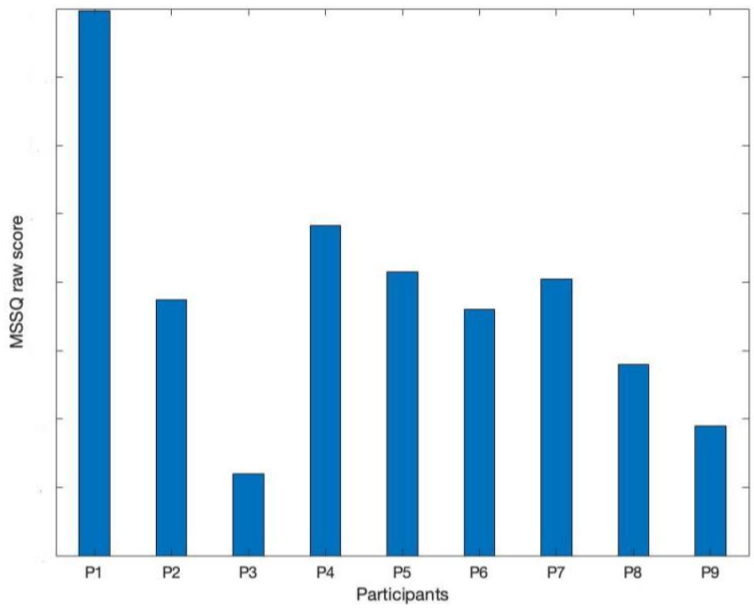


Figure 3. 2 *The raw scores for each participant according to MSSQ-Short*

Note. The participants names are replaced with P1, P2 etc.

The gender distribution of the 9 participants that took part in the first experiment was distributed as 5 women and 4 men, with an age distributed between 23 to 60 years (mean = 32.5 years, standard deviation = 12.57 years). Out of these 9 participants, 4 was selected for the second experiment, of which 3 women and 1 man, with an age distribution of 23 to 27 (mean = 25.25 years, standard deviation = 1.48 years).

To be able to make measurements on the participant's kinematics, "Xsen's MVN Awinda Full Body Strap Set" was used. The package consisted of 18 motion trackers, of which 17 of these were attached to a suit and was distributed over the body such as the Figure 3.3 shows. These sensors are connected according to a biomechanical model of the human skeleton that needs to be calibrated to the participant wearing the suit.

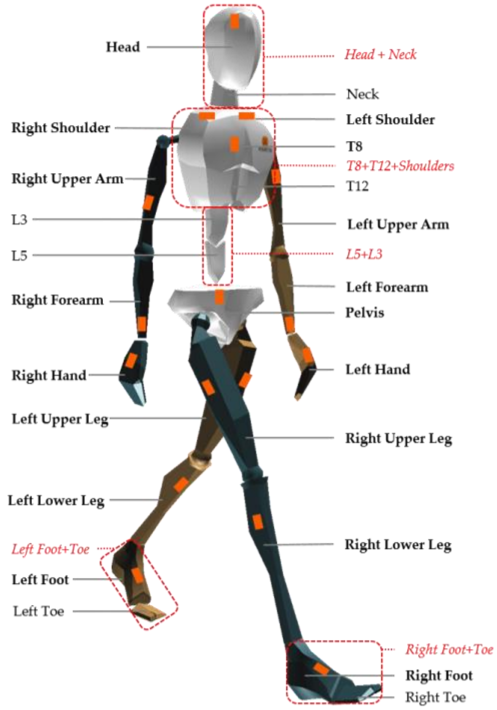


Figure 3. 3 *The distribution of the 17 motion trackers on the participants body segments*

Note. Karatsidis et. al., 2017.

3.1.3 Test Procedure

On the day of the experiment, the participants were informed about the structure of the experiment and that they could cancel the test at any time simply by saying “stop”. Thereafter, the participant needed to put on all equipment in the form of motion trackers to then be calibrated. The calibration was done by keeping a neutral position, a straight position with the arms at the side of the body. Then the participant would take a few steps forward with a natural gait and then turn around to return to the initial position. The movements were captured through sensor readings in the program "MVN Analyze Software".

After calibration, the participant also needed to wear equipment for physiological measurement in form of electrocardiogram (ECG) which measures heart rate, electroencephalography (EEG) which measures brain activity, galvanic skin response (GSR) which measures body temperature and respiration physiology (RSP) which measures respiration. To attach the disposable electrodes for the ECG measurement, the skin needed to be cleaned and scrubbed, then two electrodes were attached to each side of the neck and one to the left forearm. An EEG band was placed on the head, a breathing band sensor was placed around the torso and for the GSR, two electrons were attached to the index and middle fingers of the left hand.

When the participant had put on all the equipment, they were directed to the car. The participant was seated in the front passenger seat and was facing forward. The passenger's seat was equipped with the seat accelerometers. The passenger was shielded from the driver, with the reason that the participant would not be able to see the steering wheel and thus be able to predict the turn during the experiment. In the right side of the back seat sat a person who would monitor the data received by the car and on the left side sat a person who had the task of asking the participant about his/her condition and taking notes.

The questionnaire, MISC, was used in order for the participants to communicate their experience of their motion sickness level during the experiment. In order for the participants to be able to rank the feeling of motion sickness correctly, they needed to become familiar with the ranking system on the MISC scale and therefore an informative text was created so that they could read it at the beginning of the session. During each session, the participant was asked "how they are feeling right now" at a regular interval by a person seated in the back. The participant would then give an integer of the MISC scale and this verbal answer was registered with pen and paper by the person who asked the question.

The participants had been given the task of reading different texts that was printed out. There was a total of 10 texts, where each text was followed by three different questions with three answer options. The participant was also instructed not to look out of the car window but to, as well as possible, concentrate only on the given texts.

Thereafter, the experiment begun by starting the car and driving on the test track according to previously determined instructions. The driver would drive continuously for one hour or until the participant felt uncomfortable with the experienced level of motion sickness and voluntarily ended the test.

3.1.4 Electrical Architecture of the Vehicle

A data logger, which was battery-powered, was placed in the back of the car with the purpose to measure and record data, see Figure 3.4. To be able to record the data given from the CAN bus it is necessary to use CAN datalogger. This, since it is not possible for humans to read the raw data given by the CAN bus (CSS Electronic 2021). The data logger that was used was "Dewesoft datalogger" which is an electronic device that can measure and record data over a longer period and the process can be described as "data logging" (Dewesoft, 2020).

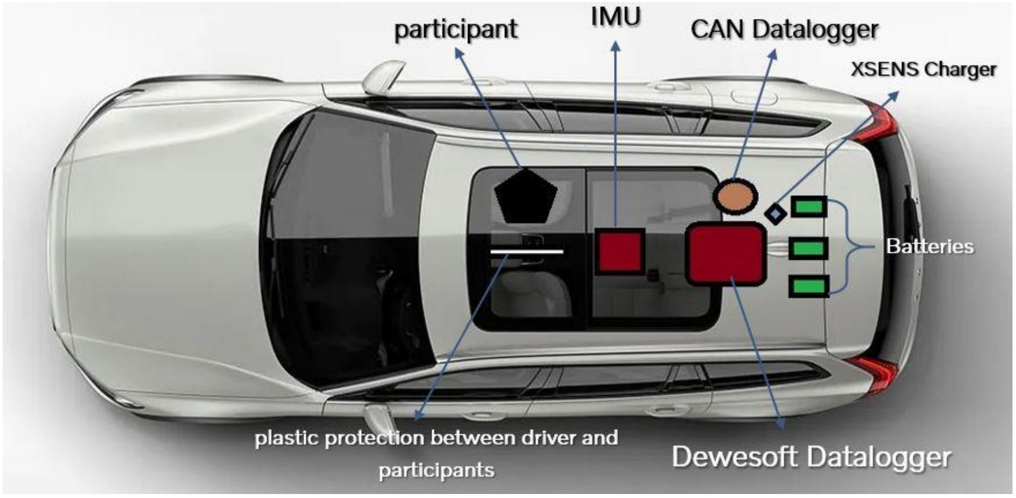


Figure 3. 4 *Electrical architecture of the vehicle*

Note. The data acquisition system for measuring data from the accelerometer. From Volvo Cars.

The seat accelerometer is connected to the data logger through signal inputs, whereas the output is connected to the Controller Area Network System (CAN Bus). The structure of CAN is described with help of CSS Electronics (2021). CAN enables the Electronic Control Units (ECU) to connect with the whole system. The parts of ECU are interconnected through the CAN bus, and the information between each ECU can be shared. The ECU in an automotive CAN bus system are the parts of the whole car network for instance, one ECU for airbag, one ECU for engine control unit etc. CAN bus includes two wires (CAN low and CAN high). As can be seen in Figure 3.5 the information from one ECU is transmit via the CAN bus and all other ECU can get the information, check it, and decide to receive it or ignore it (CSS Electronics, 2021).

Figure 3. 5 *Connection of ECUs to the CAN bus*

Note. From CSS Electronics.

3.2 Subjective Measurement

Because every questionnaire is different there are some advantages and disadvantages with them, and which scale or questionnaire that would be most appropriate for this thesis was discussed and depended on the form of the experiment.

3.2.1 Chosen Questionnaire

To complete the study and thus get a measurement on a larger scale, the decision was to use two different questionnaires. The questionnaires that would be used was MSSQ-short and MISC. These were chosen when the experiment was planned, so that the decision would be based on the design of the experiment.

Since MSSQ provides historical information regarding the participant, it was discussed that it could be useful in a preliminary investigation to assess who could be an interesting participant, in a perspective of motion sickness. However, since the MSSQ has a very long content, and the consequence would be that it was time consuming and with a risk of the potential participants to not give correct answers due to its length, the MSSQ-long was excluded and only the MSSQ-short would be appropriate to use. Thus, the idea of the MSSQ-short was to use it to find participants because it is short and simple enough to get an insight into the participant's sensitivity to motion sickness.

Since the experiment was time-limited, a shorter form of questionnaire was discussed to be more sufficient. Therefore, MISC was used with the idea that the participant could orally state a number that represents the experience of motion sickness during the course of the experiment and it provided a measurement that could easily be compared between all participants. The advantage of this scale is that it has a very broad way of assessing motion sickness. However, the scale indicates that motion sickness occurs in a special order that does not always have to be the case, because all individuals' symptoms of motion sickness are distinct and therefore it can be difficult to use a form of ranking.

4 Results

It is of interest to find the correlation between motion sickness, given by the MISC ratings and accelerations given by MSDV. For obtaining a greater dataset, the experiment in both tracks will be combined. Only two of the participants will be utilized in the analysis of potential relation of MSDV and MISC.

4.1 Objective Measurement

This section will present the results of objective measurement. The main goal is to calculate MSDV for participants using piezoelectric accelerometer referred as “Seat accelerometer” and MEMS accelerometer. There are two test tracks used for the experimental test and the MSDV is calculated for each participant with respect to longitudinal, lateral, and vertical motion for respective test track. The coordinates of used accelerometers are adjusted to ISO 2631-1 presented in figure 2.4

(a). Data collected from all participants is then analyzed and combined as "Total MSDV". More detailed process of the calculation of MSDV is analyzed from the data of a selected participants, which is based on the test track in Volvo Cars Demo Center.

4.1.1 Process of Calculating MSDV

Objective data collected during experimental test is processed with help of Dewesoft software and converted to MATLAB readable file. Figures in section 4.1 are created with help of MATLAB software. Figure 4.1 and Figure 4.2 presents the original signal collected from car data in x, y and z direction for MEMS accelerometer and Seat pad accelerometer.

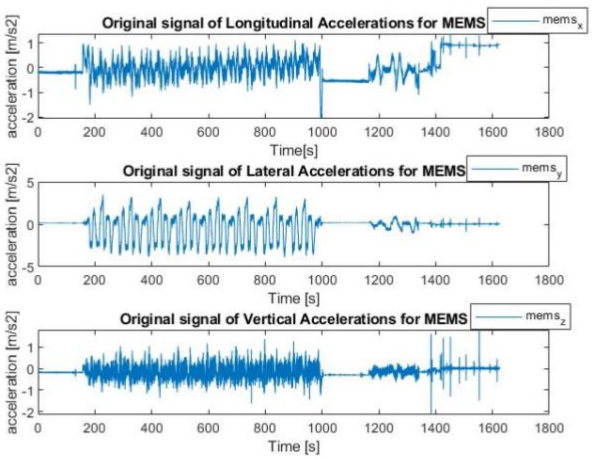


Figure 4. 1 *Original signal in x, y, z direction*

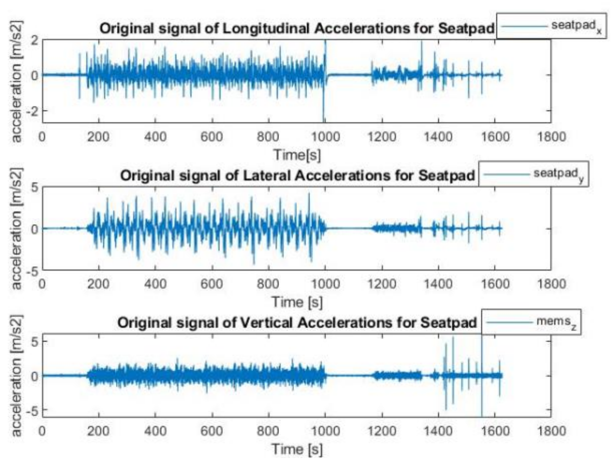


Figure 4. 2 *Original signal in x, y, z direction for Seat pad. for MEMS*

Figure 4.3 is showing the original signal from MEMS accelerometer as well as the Seat pad accelerometer, for closer observation of the signal's behavior and comparison of signals for further analysis. It can be observed, in Figure 4.3 that the amplitude of the MEMS accelerometer is smaller compared to Seat pad accelerometer. The differences may depend on different location of the sensor in the vehicle, the calibration of the accelerometers as well as the different sensitivity on low-frequency accelerations, where the low-frequency accelerations are of main interest for calculating the MSDV. Although the signals have various amplitudes and phase shifts, it can be assumed that the behavior of the signals remain alike.

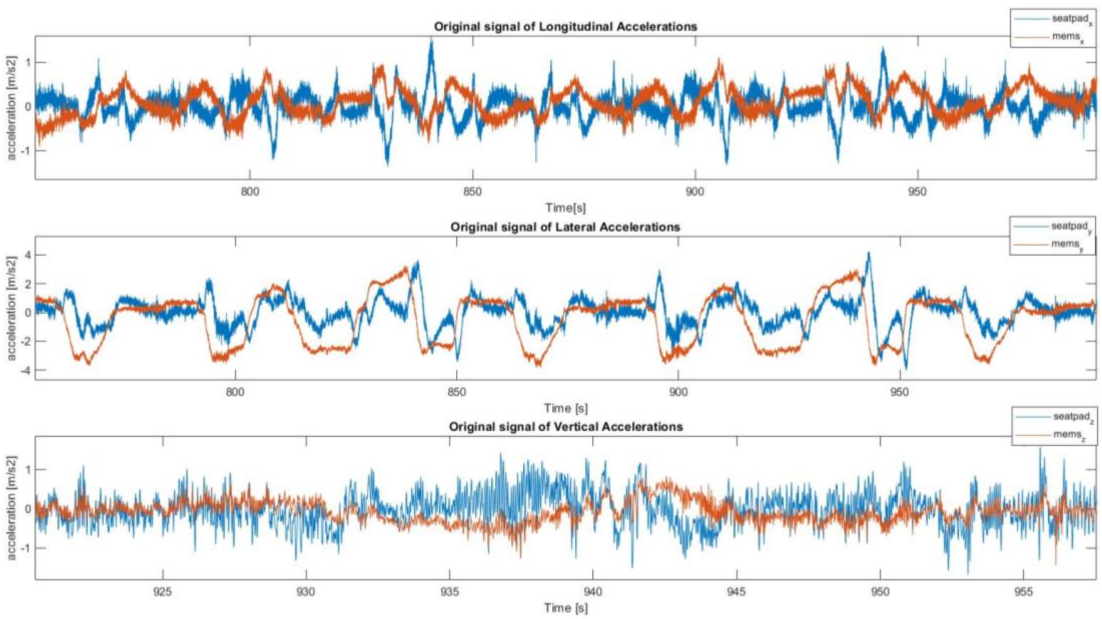


Figure 4. 3 *Original signal in x, y, z direction for both MEMS and Seat pad accelerometers.*

Note. The blue line represents the original signal for Seat accelerometer and the red line represents the original signal for MEMS accelerometer.

The Fast Fourier Transform (FFT) is used to convert signals from time domain to frequency domain *((fft(signal) in Matlab)* (McKelvey, 2020). FFT is an algorithm that determines Discrete Fourier transform (DFT) of an input signal faster than computing the form from the standard definition. For further analyzing of the signal, and enable graph presentation of the signal, the power spectrum is created (Harvey & Cerna, 1993). Figure 4.4 presents one-sided power spectrum discarding negative components of the signal and multiply positive components by a factor of 2. As observed in Figure 4.4 the single sided power spectrum for the MEMS accelerometer gives better response as can be seen in terms of higher "peaks".

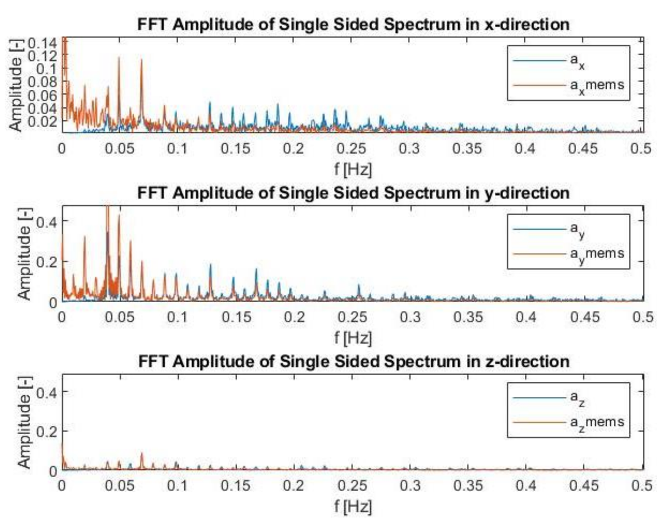


Figure 4. 4 *Single side power spectrum for computed signals for low frequencies in x, y and z direction.*

Note. The blue color signal represents power spectrum for Seat pad and red color signal represents power spectrum for MEMS.

According to ISO 2631-1 equation (2.2) was presented for "z" (vertical) frequency weighting filter to calculate $MSDV_z$, while lateral "y" frequency weighting is used to calculate $MSDV_{x,y}$ (Donohew and Griffin, 2004). For calculation of MSDV, the created frequency weighted signal is transformed back to time domain with help of inverse FFT command in MATLAB (*(ifft)signal)*. The created frequency weighted signal in the frequency domain is presented in Figure 4.5 for MEMS and Figure 4.6 for Seat pad.

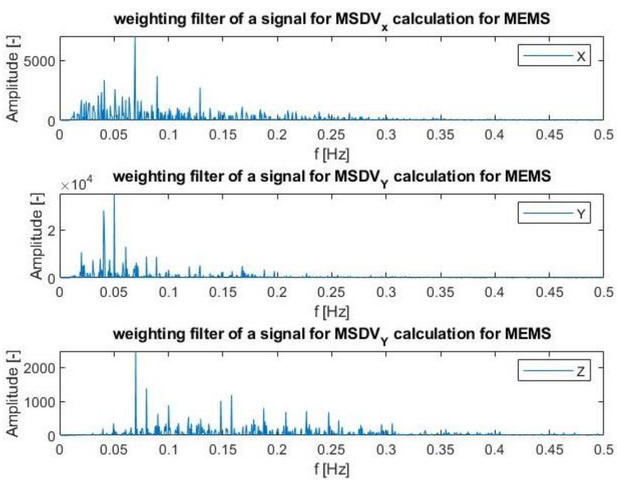


Figure 4. 5 *Frequency weighted signal for MSDV for MEMS*

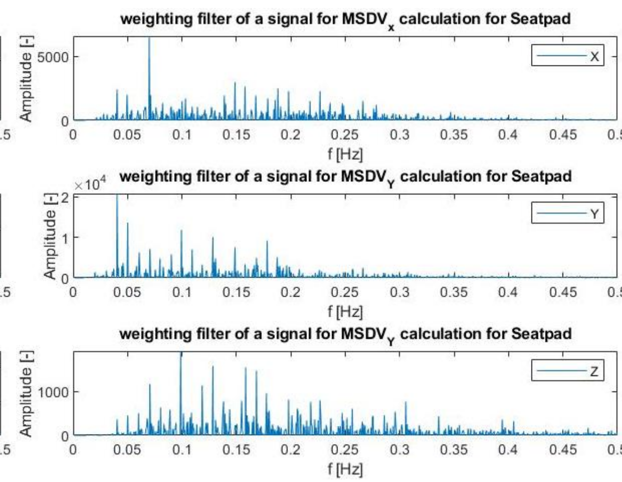


Figure 4. 6 *Frequency weighted signal for MSDV for Seat Pad.*

Note. Figure 4.5 and figure 4.6 show the frequency weighted signals created with respect to low frequency in range 0 Hz to 0.5 Hz of the signal.

For calculation of MSDV, created frequency weighted signal is transformed back to time domain with help of inverse FFT command in MATLAB (*(ifft)signal)* (McKelvey, 2020). Figure 4.7 and Figure 4.8 is showing the frequency weighted signal converted to time domain along with the original signal, more clearly is presents the differences between the original signal and the signal after the operations. The figures present MEMS and Seat accelerometer in x, y and z direction.

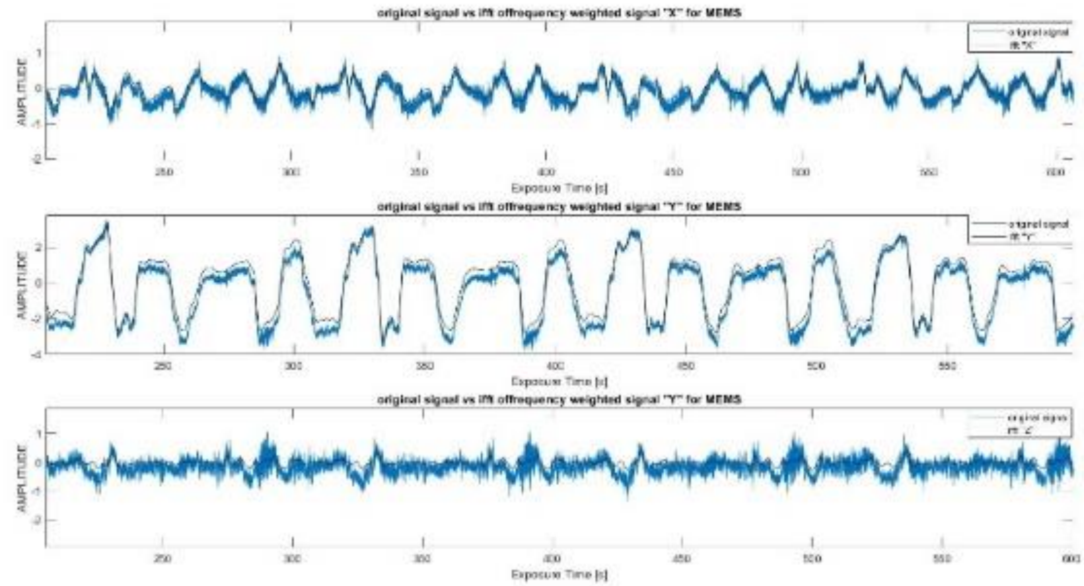


Figure 4. 7 *Original signal versus ifft of frequency weighted signal for MEMS.*

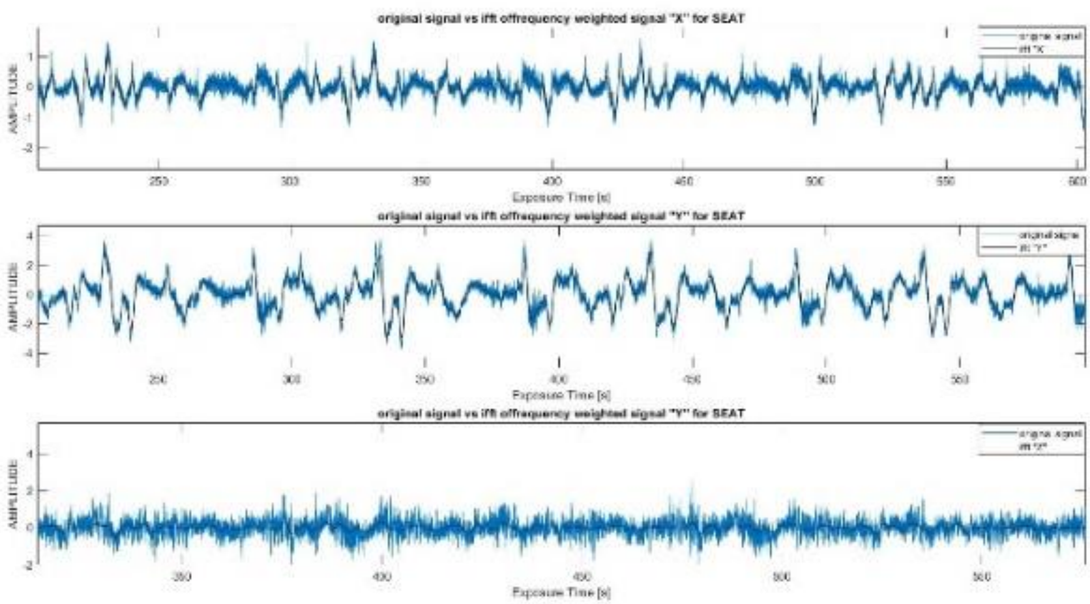


Figure 4. 8 *Original signal versus ifft of frequency weighted signal for Seat pad.*

Note. Blue line presents the original signal of the collected data in time domain while the black line presents the frequency weighed signal in time domain.

The MSDV is then calculated with help of the equation (2.8) presented in section 2.2.1.

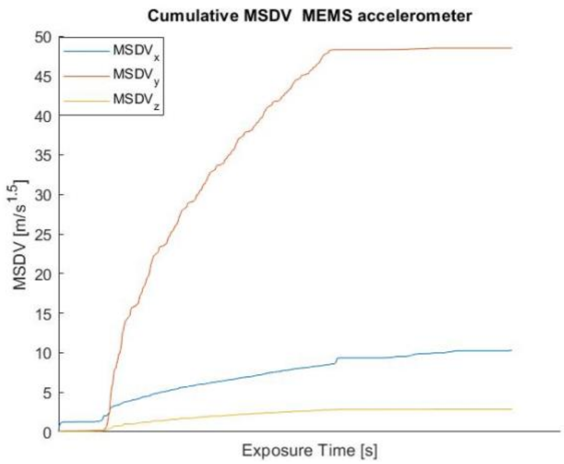


Figure 4. 9 *MSDV for MEMS accelerometer*

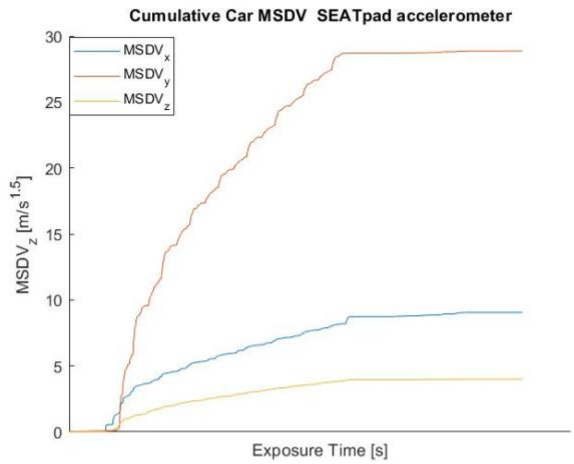


Figure 4. 10 *MSDV for Seat pad accelerometer***.**

Note. Blue line presents the original signal of the collected data in time domain while the black line presents the frequency weighed signal in time domain.

The r.m.s acceleration should always be included in calculation of MSDV, therefore the r.m.s. value is developed from signal based on equation (2.1) introduced in chapter 2.2.1 and with help of MATLAB command (*(rms)signal)*.

Based on introduced calculation for the participants it can be concluded that the MEMS accelerometer provides better sensitivity on low-frequency motion and therefore more accurate MSDV.

4.1.2 MSDV for All Participants

The following results will be presented solely based on the collected data from the MEMS accelerometer. The MSDV is derived similarly for all participants, and the results is presented in the figures below.

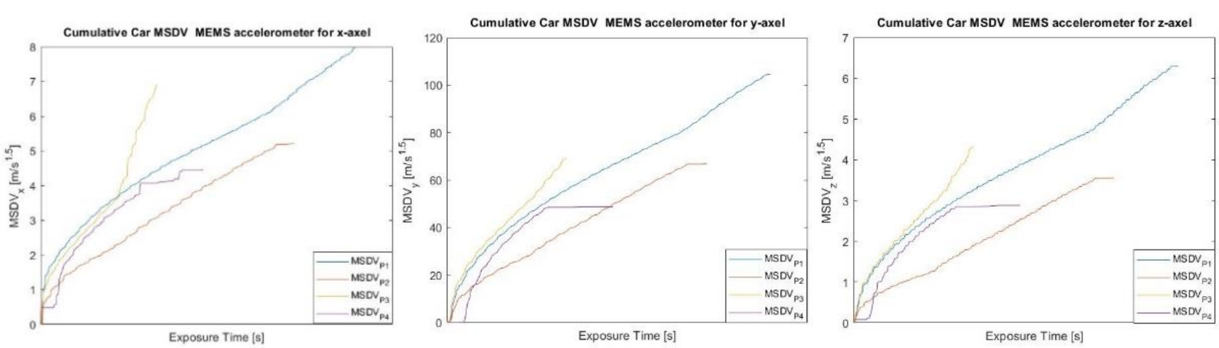


Figure 4. 11 *Cumulative MSDV for all participants based on Volvo Cars Demo Center.*

Note. The plots present the cumulative MSDV for all participants in x, y and z motion, where x motion presents by first plot from left side, y motion in middle plot and z motion presents by first plot from the right side.

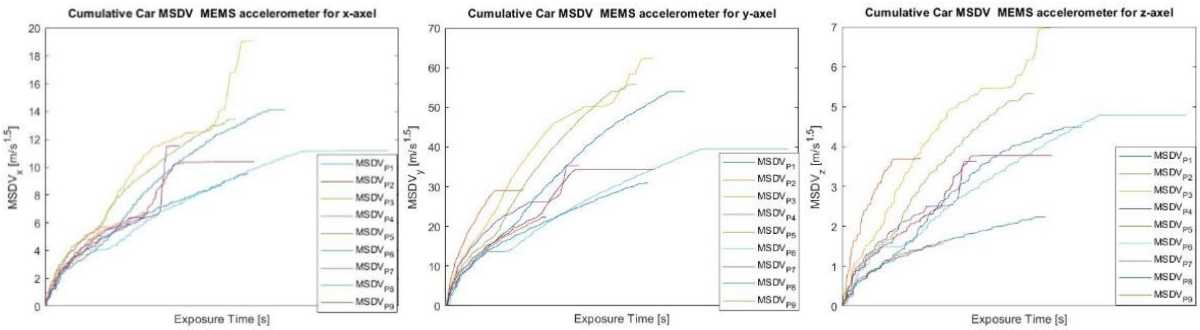


Figure 4. 12 *Cumulative MSDV for all participants based on Säve Airport.*

Note. The plots present the cumulative MSDV for all participants in x, y and z motion, where x motion presents by first plot from left side, y motion in middle plot and z motion presents by first plot from the right side.

The most significant value of MSDV is caused by the lateral motion. This is valid for both the track in Volvo Demo Center as well as in Säve Airport for all participants. The longitudinal motion is not a crucial parameter for motion sickness prediction, although there is a major difference in the range of MSDV in the Demo Center facility in comparison to the MSDV for Säve Airport. MSDV in vertical motion is similar for both experiments and remains under $10m/s^{1.5}$.

4.1.3 Acceleration Limits

The figure 4.13 shows the rout of Säve Airport with respect to the comfort acceleration limits shown in table 2.3 under chapter 2.2.3. Thresholds for comfort in horizontal motion is chosen as shown in table 2.3 for "comfort" for best assessment of sensitive section of track. The blue line presents section where the limit of comfort is extended which can potentially increase motion sickness occurrence. The maps are created with help od MATLAB software.

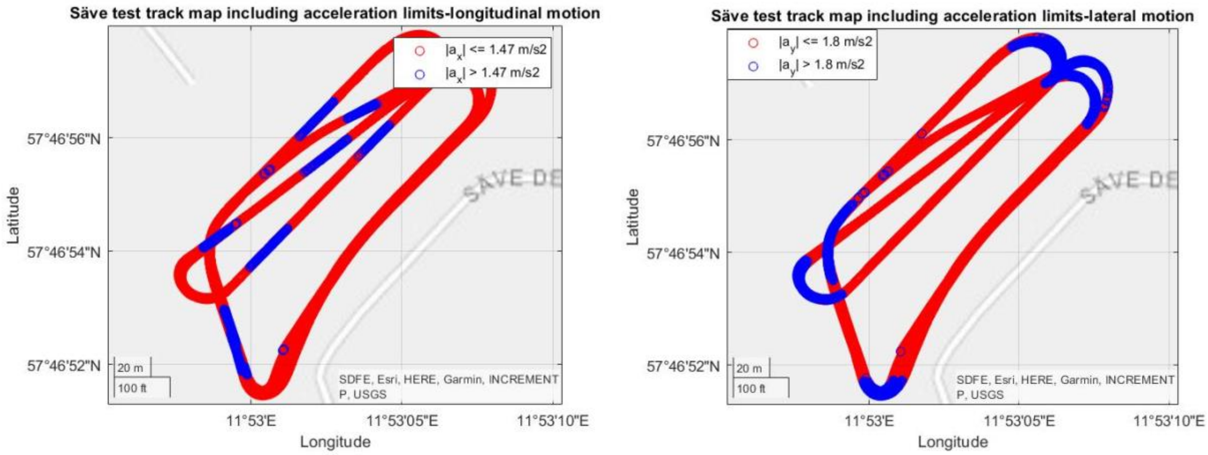


Figure 4. 13 *The acceleration limits of the route of Säve Airport*

Note. Figure 4.13 presents a map of Säve Airport test track with respect to longitudinal, lateral, and vertical acceleration limits.

4.2 Subjective Measurement

4.2.1 Statistical Analysis of the Questionnaires

The black dotted line on figure 4.14 is showing the mean values of all participants on each test track. The figure is also showing how many participants dropped out of the experiment due to the sickness level being too high, a total of 10 participants dropped out. Several participants also seem to have developed a resistance to motion sickness as their results show how the sickness level is falling and rising, while for other participants there was a continuous increase in motion sickness.

It can also be seen that the average value of all participants was more susceptible to motion sickness at Demo Center for each time interval than at Säve Airport. Therefore, the average MISC value indicates that motion sickness develops to a higher level at Demo Center as a consequence of the downhill and uphill slopes in the vertical direction.

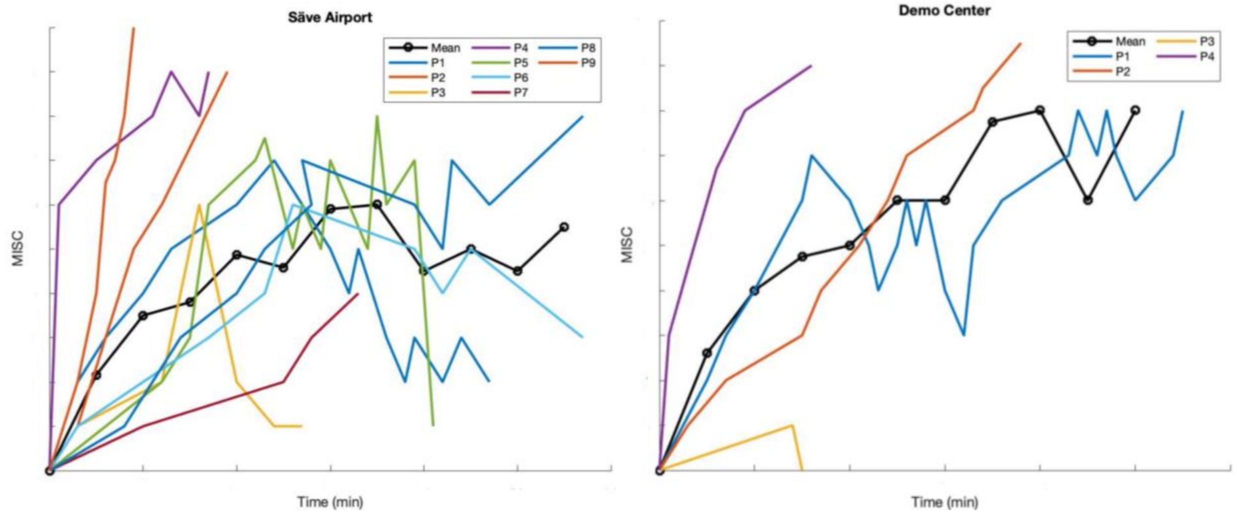


Figure 4. 14 *MISC score related to time*

Note. The left figure is showing the results of the MISC score in Säve Airport and the right one is in Demo Center. The black dotted line is showing the averaged MISC scores over all participants per time interval, and the rest of the lines represents each participants score in the specific time interval.

To validate the scores from the MSSQ it was compared with the mean of the observed MISC scores. Despite the fact that some participants showed, according to MSSQ, that they were not particularly susceptible to motion sickness, they received a relatively high average on the MISC scale, see Figure 4.15. This may have been due to the fact that the participants needed to read a text during the course of the experiment, required to do so may have led the head movement to, over a longer period, develop motion sickness.

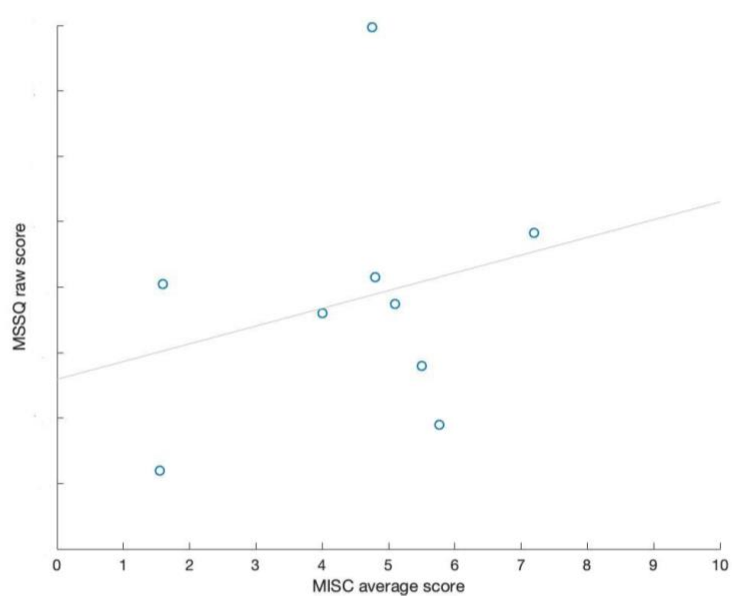


Figure 4. 15 *MSSQ raw score vs. MISC average score*

Note. The MSSQ raw score is plotted against the average of MISC scores of each participant. The line represents the best linear fit.

4.3 Relation between MSDV and MISC score

The potential relation between the objective measurement in terms of MSDV and the subjective measurement with the MISC questionnaire is analyzed based on two participants. The examples are based on the data from both test tracks for participant 1 (P1) and participant 2 (P2).

The fist participant completed the experiment at Volvo Cars Demo test track with the duration of around one hour of driving. As seen in Figure 4.16, the MISC score for the participant 1 varies from slight dizziness and sweating to severe nausea. The MSDV is constantly increasing until the end of the experiment and reaches the highest level among all participants. Similar behavior is observed in both test tracks. The second test was finished due to small MISC values experienced toward the end of the experiment and provides much smaller MSDV.

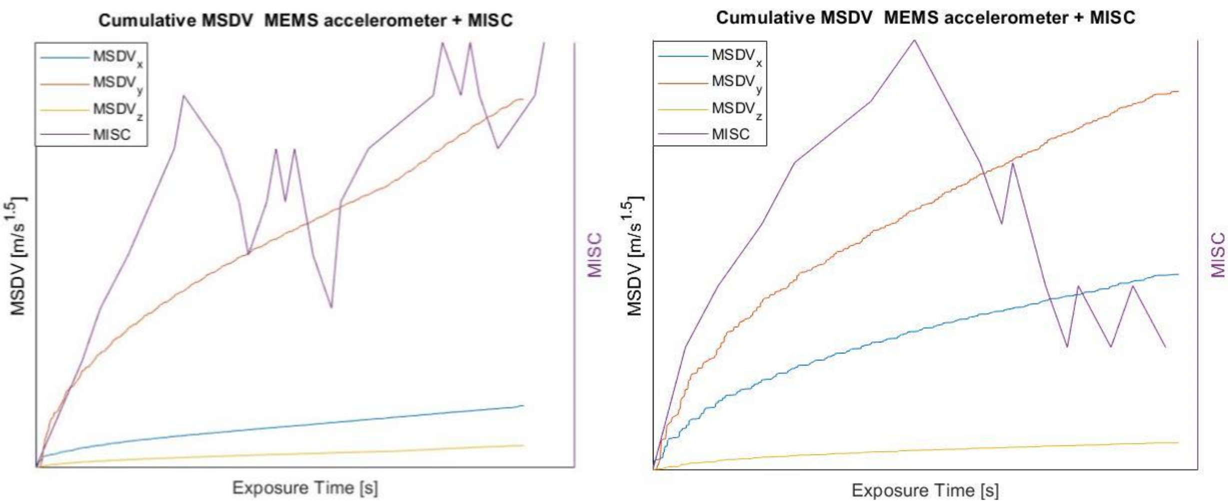
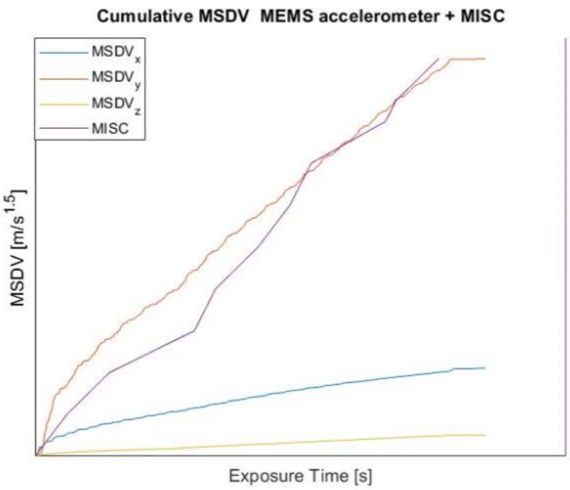


Figure 4. 16 *Volvo Cars Demo Center test track vs Säve airport for participant 1*

Note. Figure 4.16 presents MSDV for MEMS accelerometer and MISC for participant 1 from Volvo Cars Demo Center (left side) and Säve Airport (right side). The red line presents lateral MSDV, the blue line is longitudinal MSDV, and the yellow line is vertical MSDV. The purple line presents the MISC values experienced by participant during the experiment.

The MSDV for participant 2, as well as the MISC score is constantly rising for both Volvo Cars Demo Center as well as Säve Airport, see Figure 4.17. At Demo Center test track the test got interrupted by participant 2. For the test track in Säve Airport the participant reached a very high score from the MISC scale and remains until the end of the experiment where the participant immediately interrupted the experiment due to feeling extremely uncomfortable. The MSDV grows significantly even after reaching the very high score and stabilizes shortly before interrupting of experiment.



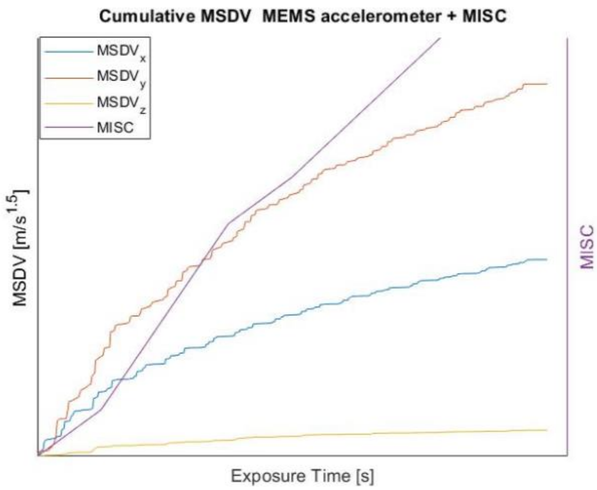


Figure 4. 17 *Volvo Cars Demo Center test track vs Säve airport for participant 2*

Note. Figure 4.17 presents MSDV for MEMS accelerometer and MISC for participant 2 from Volvo Cars Demo Center (left side) and Säve Airport (right side). The red line presents lateral MSDV, the blue line is longitudinal MSDV, and the yellow line is vertical MSDV. The purple line presents the MISC values experienced by participant during the experiment.

5 Discussion

Motion sickness is correlated with information from the various sensory subsystems, such as the vestibular system which is essential to motion sickness since the semicircular canals detect angular velocity and the otolith organs detect linear accelerations. Thus, the motion sickness in this experiment may be due to an increased sensory conflict due to the removal of the visual road since the participant had to read. This means that the expected information about the car's trajectory disappears. The stability of the head is maintained when the visual information is available and since the participants in the experiment were told to read the given text, it may have been another factor in the onset of motion sickness since the postural instability was affected.

Because the MISC scale considers that motion sickness develops in a certain way, it does not measure certain dynamic parts of motion sickness. Not all individuals develop motion sickness as suggested in MISC. For example, some participants developed the feeling of “nausea”, which gives a score of 6 according to the scale, earlier than they experienced the feeling of sweating which gives a score from 2 to 5. This can give a misleading result. Even the best linear fit from Figure 4.15 can be misleading since the number of participants was too low to conclude on a suitable line.

Based on the results from the objective measurement, the low-frequency horizontal acceleration has most significant impact on MSDV. The result confirms assumptions presented in the chapter of Primary Study as horizontal, more specifically the lateral motion, is primarily responsible for motion sickness in a vehicle. The longitudinal MSDV is higher for Säve Airport test track which was an expected result. This, since it occurs multiple velocity changes during the experiment in form of acceleration and braking which has biggest impact on the longitudinal axis. Vertical MSDV remains low for both test tracks, since both test tracks are smooth surface. However, there is remarkably higher range of value in lateral MSDV in Demo Center compared with the test track at Säve Airport. This may be affected by two factors. Firstly, there was a more aggressive style of driving at Volvo Cars Demo Center that contributed to an experience of jerk and could therefore cause higher MSDV values. The second factor is considering the curvature shape in Demo Center, which can possibly contribute to higher range of values for the lateral MSDV.

It is difficult to establish if there is a clear correlation between motion sickness experienced by participants and the collected data, based on human vibration, and its influence on motion sickness. A larger number of participants would be needed to be able to make a clearer conclusion regarding the correlation between MSDV and the actual perceived motion sickness. The MSDV was increasing constantly while the experience of motion sickness could vary between the participants and wasn't necessarily correlating with MSDV. Although the MSDV was increasing, it could be moderate and thus not reaching high values since some of the participants dropped out of the experiment. Therefore, it could indicate higher probability of motion sickness if the duration of traveling was longer for these participants. Based on chapter 4.3, the example of participant one can be established that although MSDV is growing the participant is developing a tolerance during the experiment which can lead to a smaller value of MSDV.

6 Conclusion

In this thesis, an experiment was done with support from methods found in literature studies of motion sickness. The conclusion from the literature studies was that the movement, for example from transportation by a vehicle can cause a conflict between the sensory inputs. This creates disturbances in the feeling of stability and balance caused by a deviation between the vestibular system's sense of movement and the visual experienced the movement. These abnormalities create uncomfortable feelings and give symptoms of motion sickness which can be, for example, nausea, dizziness, sweating or even vomiting.

ISO 2631-1 also gave recommended values for acceptable vibration exposure to the human body, the effective vibrations are between the frequency range of 0.1 Hz and 0.5 Hz. Based on both literature study review and from the results of the conducted experimental studies, it is stated that it is a great risk of developing motion sickness when the vibrations are in a very low frequency range, especially in lateral motion. Furthermore, the acceleration limits are established as an additional cause for a better understanding of motion sickness.

MSDV was calculated for all participants based on the collected data from the vehicle together with the MISC scores collected by a person seated in the back of vehicle during the test session. The result of the experimental studies and possible dependencies are discussed.

The conclusion that can be drawn, after the experiments were performed, was that the lateral motion in low frequencies is one of the main causes of the occurrence of motion sickness in vehicles. However, the main reason of the occurrence of motion sickness may depend on personal sensitivity of the directional vibrations. Based on the conducted experiment, vertical motion did not show any significant difference in MSDV and can therefore not be further analyzed for the effect on motion sickness. Two potential correlations were found between MISC and MSDV, one where the risk of developing motion sickness increases over time and the other that a tolerance to motion sickness may also develop, which lowers the total value of MSDV.

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Appendix

Appendix A – MSSQ-short

1. Please State Your **Age** .... Years. *2.* Please State Your Sex (tick box) **Male** [ ] 1 **Female** [ ] 2

This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.

Your CHILDHOOD Experience Only (before 12 years of age), for each of the following types of transport or entertainment please indicate:

3. **As a CHILD (before age 12),** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	**Never Felt Sick**	**Rarely Felt Sick**	**Sometimes Felt Sick**	**Frequently Felt Sick**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

Your Experience over the LAST 10 YEARS (approximately), for each of the following types of transport or entertainment please indicate:

4. **Over the LAST 10 YEARS,** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	**Never Felt Sick**	**Rarely Felt Sick**	**Sometimes Felt Sick**	**Frequently Felt Sick**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

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