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Mitigate Motion Sickness in Self-Driving Cars

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Submission date:	January 2018
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Abstract

Motion sickness is an ancient problem lacking a silver bullet solution. Passengers are more prone to motion sickness than drivers, so as autonomous cars becomes the norm in the future, car sickness is projected to become a major problem. Motion sickness is expected to cause discomfort for hundreds of millions of people around the world. This does however give auto-manufactures an opportunity to differentiate themselves in the market if a good technical solution is developed. Motion sickness is quite complex, depending on sensory inputs and how the brain interprets them. Based on understanding how motion sickness occurs several strategies and techniques that can be useful against it is discussed. Validating the measures is currently done in an expensive and inaccurate manner, slowing down the research overall and makes smaller iterative improvements difficult. Autonomous cars allows for a new paradigm in motion sickness research, as driving patterns can be close to identical for participants. As test cars are driven with computer precision, research can be conducted in realistic scenarios instead of simulators which can't copy acceleration realistically, as well as causes simulator sickness which influences the results. If biometric data can be gathered in a non-intrusive manner and can be used to measure motion sickness in an accurate manner, data can be gathered cheaply and abundantly enough, to allow for a machine learning solution to replace current mathematical models of motion sickness.

Sammendrag

Reisesyke er et eldgammelt problem uten noen enkel løsning. Fordi passasjerer har lettere for å bli bilsyk enn de som kjører og fordi selvkjørende biler blir den nye normen i fremtiden, kommer bilsyke til å bli mye mer vanlig enn det er i dag. Bilsyke er forventet å føre til ubehag for flere hundre millioner mennesker rundt om i verden, men gir samtidig bilprodusenter en mulighet til å differensiere seg i markedet ved å utvikle gode tekniske løsninger. Bilsyke er komplisert, og er avhengig av signaler som sansene våre sender til hjernen og hvordan hjernen tolker disse signalene. Basert på kunnskap om hvordan bilsyke utvikler seg blir flere strategier og teknikker diskutert om hvordan man kan minske risikoen for å bli bilsyk. Å teste om disse tiltakene fungerer er i dag gjort med dyre og unøyaktige forsøk, noe som gjør forskningen langsom. I tillegg gjør dagens forskningsmetoder det vanskelig å finne små, iterative forbedringer. I og med at selvkjørende biler kan kjøre identisk fra forsøk til forsøk tillater de et nytt paradigme i bilsyke forskning. Når man kan gjøre et forsøk med identiske parametere på veien kan man gjøre forsøk under realistiske omstendigheter, i stedet for i simulatorer hvor man ikke kan gjenskape akselerasjon realistisk, og hvor man også får problemer med simulatorsyke som påvirker resultatene. Om biometriske data kan bli samlet uten bruk av påtrengende metoder, og samtidig kan gi en nøyaktig representasjon av bilsyke, kan data bli samlet billig nok og i stort nok omfang til å tillate bruk av maskinlæring algoritmer for å erstatte dagens matematiske modeller for å forutse bilsyke.

Preface

As part of my study program to become a Master in Mechanical Engineering at NTNU, I have reached out to Audi, where I have written my master thesis during the autumn of 2017. I have been lucky enough to be allowed to write it in the pre-development department for vehicle concepts, which has a large and varied focus with a lot of interesting ongoing projects. As I arrived I was tasked to figure out how I could bring value to the department, and together with my supervisor Thorsten Schrader we decided that motion sickness in autonomous vehicles was an interesting topic. It is no secret that Audi is working on self-driving cars, and it turns out there are a lot of mostly unexplored difficulties as well as opportunities that can be exploited when a car is controlled with computer precision. This thesis is meant to serve as an inspiration for those aiming to design autonomous cars with reduced levels of motion sickness, to addresses different solutions from a technical standpoint, and highlight aspects that needs more research. After getting a understanding of motion sickness, I started realizing that perhaps the more fundamental question that needs answering, before measures are to be developed, is to make data collection more affordable. Coming up with measures that *can* work against motion sickness isn't the root cause, the difficulties lie in how to prove it. Conventional comparative testing as it's done today quickly becomes very expensive and time consuming. I therefore poured effort into rethinking today's experimental paradigm when it comes to motion sickness, and came up with some ideas on how to improve upon them. Developing and collecting measures against motion sickness is naturally still a big part of this thesis, and lastly a good theoretical understanding of what motion sickness is, is required to evaluate the rest of the thesis. The goals of this thesis can therefore be summarized as:

- Compile the current understanding of motion sickness.
- Find and establish measures that can mitigate motion sickness in self-driving cars.
- Develop new methods to evaluate measures against car sickness.

Ingolstadt 23-12-2018 Emil Hjelvik

Acknowledgment

First of all I would like to thank my professor Martin Steinert for supporting my vision to go to Germany to write my Master Thesis. I would also like to thank Thorsten Schrader, my main supervisor at Audi. Mr. Schrader has not only helped guide me through my master thesis, but he has also helped me find housing and otherwise helped me establish myself in Ingolstadt where Audi's headquarter lies. Huge thanks also goes to Bastian Guyot that has co-supervised my master thesis, his experienced insights has helped me steer my focus greatly. Huge thanks also go to EB-12, the department at Audi that welcomed me with open arms and gave me a great work environment.

E.H.

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Acronyms

AV Autonomous Vehicle

CNS Central Nervous System

DOF Degrees of Freedom

FMS Fast Motion Sickness Scale

GIF Gravity Inertial-Force

GVS Galvanic Vestibular Stimulation

HUD Head-up Display

MS Motion Sickness

MSDV Motion Sickness Dose Value

MSI Motion Sickness Index

MSSQ Motion Sickness Susceptibility Questionnaire

MSQ Pensacola Motion Sickness Questionnaire

OKR Optokinetic Reflex

OTO Otolith Organs

PDRS Pensacola Diagnostic Report Scale

SCC Semicircular canals

SSQ Simulator Sickness Questionnaire

VOR Vestibulo-ocular Reflex

VR Virtual Reality

Chapter 1

Introduction

In the near future self-driving cars are predicted to become the new norm[7]. As drivers turn into passengers, travel time will be freed up for recreational purposes or work. The occurrence of car sickness however is predicted to increase as more and more people will take their eyes off the road and instead do activities like reading or watching movies[28]. This paper examines the technical solutions out there capable of mitigating motion sickness, as well as proposes some new measures along with a proposed method to test their efficiency.

1.1 Brief History of Autonomous Driving

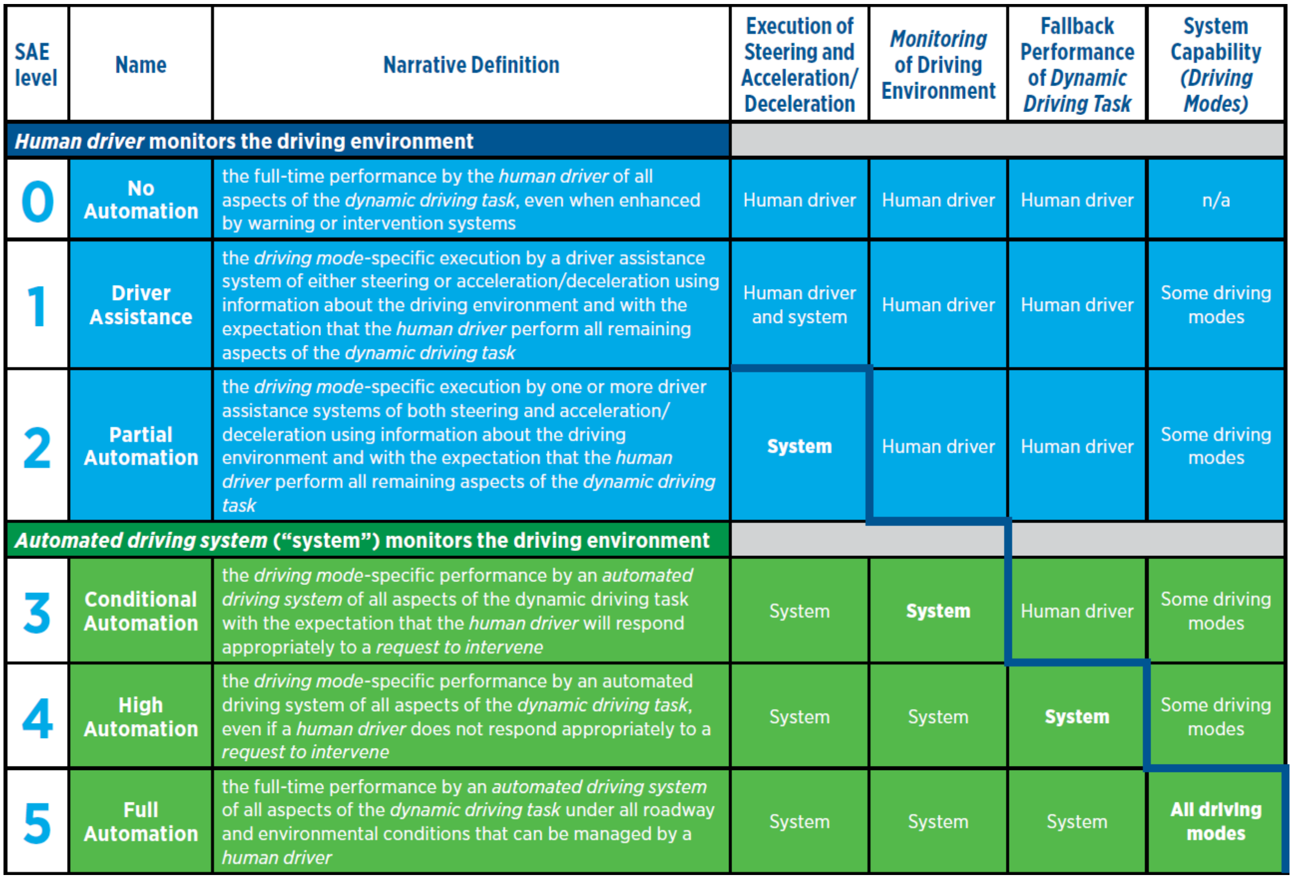
The idea of a self-driving car dates back to at least 1939 when General Motors proposed one in its Futurama Exhibit[101], the technology required however, was far from being developed. As the space race picked up its pace in the 60's, NASA looked at a few different rover designs to drive around on the moon to learn more about it[100]. The rover was to be controlled from earth, which caused difficulties as there is a time delay of about 2,5 seconds to the moon and back, meaning it couldn't be controlled in real time. This predicament was identified with the Stanford Cart in 1961, as the time delay capped its speed to 0,3 km/h to avoid problems. To solve this development of driving assistance computers started. By 1963 path prediction was added to the Stanford Cart, raising it's safe speed to 8 km/h. Development continued, and by 1971 the Stanford Cart could follow a high contrast white line *without human input* at speeds up to 1,3 km/h using video feed[30].

In the following decades more researchers started dedicating their time to the problems associated with autonomous driving. In 1977 a team led by Tsugawa[101] unveiled a car capable of driving fully autonomously at speeds up to 30 km/h in some specific environments[98]. In 1979 the Stanford Cart was capable of successfully navigating a room filled with obstacles by itself, although very slowly[30]. In 1984 the Carnegie Mellon University started researching computer controlled vehicles, and in 1986[49] their first vehicle the Navlab 1 was able to drive mostly by itself using hardware architecture very similar to modern attempts[92]. A year later VaMoR developed at Bundeswehr University Munich drove at speeds of 90 km/h, and in 1995 they demonstrated a new vehicle VaMP, which travelled 1600 km from Munich to Odense in Denmark, reaching speeds of 180 km/h at the Autobahn. An estimated 95% of the distance was covered completely with autopilot.

Fast forward to 2004 and DARPA launched it's Grand Challenge: The first completely self driven car to finish a 228 km race through the Mojave desert would win a prize of 1.000.000$. 15 teams qualified for the starting line, many with huge financial backing, however none of the cars made it further than 11,78 km before coming to a halt[55]. This highlighted the difficulties of going from a laboratory setting to a real life setting, especially when it came to software. In 2005, DARPA relaunched their Grand Challenge. This time 23 teams qualified, and the task was to race through a 281 km track in the Mojave desert. The first one to finish would receive a prize of 2.000.000$. A lot of progress was made in just one year, and out of the 23 participants, five of the cars managed to finish the race. First to finish the race was Stanley, deployed by a Stanford team. Stanley's victory can primarily be contributed to it's improved algorithms for deciding what is drivable[96].

1.2 Present State of Autonomous Driving

Today the hardware required for autonomous driving exists, what automakers and technology companies around the world currently strive for, is perfecting the software to make it safer than human driving, and to make it cheap enough to be commercially feasible. The most comprehensive research into autonomous driving is most likely conducted by Waymo, a rebranding of the Google self-driving car project. In 2015 Waymo had clocked 1.700.000 miles travelled with just 14 minor accidents, all of which were caused by human error as the car either was under human control at the time of the accident, or due to driver errors from other vehicles on the road [80]. Waymo has as of May 2017 clocked more than 3.000.000 autonomous miles travelled on roads in the US [108], they have however stopped publicly releasing accident reports [63]. In fact as of November 2017 Waymo started test driving in Arizona on public roads with no safety driver behind the wheel. The fact that it's on public roads with no safety driver, marks it as the first level 4 vehicle that can safely navigate public space [27].



SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 1.1: The J3016 standard provided by SAE International [89].

As more and more players conduct research into autonomous driving, a few standards have been developed such that researchers can collaborate with a common reference framework. One of these is the SAE International Standard J3016, which defines the different levels of autonomous driving[89]. This standard can be viewed in Figure 1.1 and describes the criteria required to classify a vehicle on a level scale ranging from 0 (no automation) to 5 (full automation).

In California alone, 42 different companies are registered for autonomous car testing[50]. Several international corporations have expressed interest in self-driving vehicle technology, with companies such as Tesla aiming to commercialize level 5 vehicles as early as 2019[65] and BMW as early as 2021[32]. In addition to the auto-industry, great interest comes also from hardware giants such as Intel[57], Nvidia[77] and Samsung[79], which should lower the cost of the hardware required to run the cars. A more complete list of car companies and their timelines can be found in Table 1.1.

Company	Automation Level	By Year
Baidu[85]	4 or 5	2021
BMW[32]	5	2021
Ford[82]	4	2021
GM[51]	4 or 5	2019
Honda[18]	4	2025
Mercedes[56]	5	2020s
Tesla[65]	5	2019
Volkswagen Group[53]	5	2021
Volvo[2]	5	2021

Table 1.1: The timelines of some companies that have gone public about when we can expect them to commercialize autonomous vehicles.

In addition to the technological solutions needed to be developed before the commercialization of autonomous cars, a change in legislation is required for cars to be allowed to drive by themselves. The US is currently leading in this field, where they are working on passing a nationwide law regulating the use of autonomous cars, the bill has already passed the house[70], and the senate is expected to approve the legislation in the beginning of 2018[37]. In California legislation has already been passed, allowing cars to drive on public roads for research purposes, without a human driver as a safety measure behind the wheels, beginning around the middle of 2018[50]. Because of the economic impact autonomous driving will have, nations leading the effort are expected to receive a huge competitive edge in the international market[7], and laggards will most likely have little choice but to follow suit.

1.3 Robo-Taxi

Seba et al.[7] predicts the end of personal car ownership, and makes a a strong case for it. Summarized their strongest argument is that using a robo-taxi service will be much cheaper than personal car ownership. The economics are similar to that of car pooling, and as a robo-taxi service will give everyone quick and easy access to a large pool of cars, which will be at disposal within minutes inside every city. A robo-taxi service can therefore be viewed as the ultimate car pooling service. Seba et al.[7] also argues that the future of cars will be fully electrical, mainly because of reduced maintenance requirements. In today's world cars are parked around 95%[74] of the time, causing problems of it own. Imagine if instead of being parked most of the time, the car only stops to recharge (and simultaneously receives service such as cleaning), and to drop off and pick up passengers. Given a car utilization of 50% compared to the normal 5% utilization today, the price of the car per user drops by a factor of 10. That Uber[20] and Waymo[52] among others have been working towards the goal of deploying robo-taxis for a long time, makes Seba et al.[7]'s prediction much more believable. Waymo is expected to launch its raid hailing service commercially in the suburbs of Phoenix, Arizona early in 2018[52], meaning that robo-taxis might become a common sight within a few years.

1.4 Motion Sickness in Autonomous Cars

Car sickness has probably been around since the car's invention, and poses a problem for an unlucky minority prone to its effect. As autonomous vehicles are expected to become the new norm[7], the occurrence of motion sickness is expected to increase dramatically[91] [44] [28] . This increase is highlighted by Sivak and Schoettle in their paper "Motion Sickness in Self-Driving Vehicles"[91], where they estimate that 6-10% of Americans riding in level 5 autonomous vehicles will often, usually or always experience symptoms of motion sickness, and that 6-12% of Americans to experience severe motion sickness at some point. How people commute around the world differs, but as commuting by car is by no means unique to the United States, the surge in motion sickness will very much be a global phenomena.

The underlying mechanisms of motion sickness will be discussed further in chapter 2, but its increase in occurrence can according to Sivak and Schoettle primarily be contributed to three factors that occur when those who would normally drive themselves become passengers: First, as more and more people will be doing activities such as reading or watching screens, the eyes will be taken off the road and a visual-vestibular sensory conflict occurs. Secondly the ability to anticipate the direction of motion is hampered, again because attention is no longer necessarily on the road. The third reason is that control over the direction of movement is lost. Passengers are way more likely to develop motion sickness than drivers[88], which is essentially the root of the problem with motion sickness in autonomous vehicles as everybody becomes a passenger. In a survey[71] from 2013 it is revealed that 86% of the American workforce commuted by car to work, and of those 76,4% commuted alone. Multiply those numbers together, and we can estimate that 65,7% of American workers will go from being drivers to being passengers given a fully autonomous vehicle fleet. Potential solutions to the expected motion sickness surge are discussed in chapter 3 and 4.

1.5 Sources of Acceleration

Acceleration is needed to get around, but it can also be viewed as the root cause of motion sickness as will be discussed in chapter 2. For a car the most obvious acceleration sources are accelerating to speed and breaking to stop. Given that any turn can be viewed as a circle segment, cornering introduces a centripetal force towards the center of rotation equal to $a = v^2/r$, and due to inertia this is by passengers experienced as acceleration outwards. Similarly with breaking and acceleration passengers experience the acceleration in the opposite direction of the car due to their inertia. Angular velocity causes additional velocity and acceleration for any point off-set from the center of rotation as illustrated in figure 1.2.

Acceleration in a car occurs where the wheels hit the ground, as the car's center of mass is off-set from this plane, inertia causes the car to roll while cornering and pitch during breaking and acceleration. In addition all sorts of vibrations occur, which are essentially reoccurring acceleration at higher frequencies. The field tasked to control and reduce vibration is known as

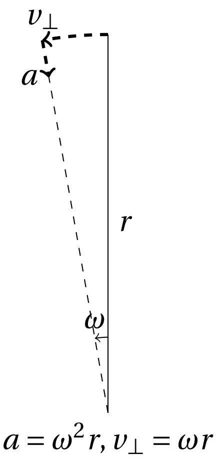


Figure 1.2: Angular velocity about a point will cause velocity and acceleration in the rest of the system.

Noise Vibration Harshness (NVH) engineering, and it concerns itself with every source of vibration in a car, such as from the engine, the road surface etc[48]. NVH states that vibration in the 0-6 Hz range, which covers oscillation known to cause motion sickness[78], can primarily be contributed the car's motion relative to the road[48], an example would be the car following a curvy road.

Chapter 2

Motion Sickness

Nausea as a result of travelling by vehicle has been around as long as vehicles themselves, in fact nausea literally means ship-sickness in ancient Greek[33]. This phenomena is known as car sickness, sea sickness, train sickness, plane sickness, etc. depending on the mode of transport, but overall they are all sub-categories of motion sickness or kinetosis[103] which is the medical term. Motion Sickness (MS) is however not truly a sickness, it is more accurately described as a normal response to an abnormal situation[28]. This chapter tries to summarize the most important findings within the field of motion sickness, such as its prevalence and physiological explanation. In addition various methods concerning its prediction is discussed.

2.1 Symptoms

Motion sickness manifests itself in various ways depending on its severity. The symptoms include sweating, pallor, flatulence, burping, increased salivation, queasiness, apathy, nausea and retching[28]. These symptoms don't necessarily manifest in a particular order, but they typically go from light to more severe symptoms with sustained stimulus. Vomiting is the ultimate manifestation of motion sickness, and where vomiting is usually a good cure for nausea, in the case of kinetosis it is not always helpful. In fact the level at which people vomit varies greatly, some vomit while feeling only mild nausea, which greatly relieves their symptoms. Others vomit under great distress, hardly relieving their nausea, and in extreme cases some are unable to vomit even though they are desperate to do so[64].

2.2 Motion Sickness Susceptibility

Everyone with a working vestibular system is at risk of becoming motion sick, which excludes primarily babies as their balance isn't properly developed, and people with completely damaged balance organs in both ears [41]. Kinetosis is very individual and varies greatly between modes of transport as well as trip duration. For travel by car, about 2/3 of the population have suffered from motion sickness at some point, whereas half of those have vomited [28]. As Golding and Gresty in the Oxford Textbook of Vertigo and Imbalance [41] discuss, gender and age play a huge role in MS susceptibility. Women have a 5:3 higher risk of vomiting traveling by ship, and the menstruation cycle is also shown to have an influence with a peak in susceptibility during menstruation. MS is at its greatest in children that are 9-10 years old, gradually declining into old age. Genetics is although perhaps the biggest influence, shown by high heritability of MS and that some demographics are hyper-susceptible. These differences, along with training, experience [22], fitness and more, causes a variation in the MS susceptibility of the population to be around 1:10.000 [64] i.e. some are 10.000 times more likely to become motion sick than others.

2.3 Spatial Orientation

Our brain builds an image of the world around us, allowing us to interact with it in a safe manner. Our eyes provide us with information about where things are and their relative speed to us, our ears alert us of movement around us, even our smell can provide us information that something is approaching. Taste and touch finalizes the list of the classical senses. The classical list is however somewhat simplified and far from complete, touch for example is part of our somatosensory system, essentially all the nerves allowing us to feel the position of our joints, the strain on our muscles and the pressure on our skin [59]. The somatosensory system allows us to touch our nose with our eyes closed, discern acceleration and gravity through skin pressure and its location, and otherwise to know how our bodies are positioned. For the spatial orientation model our brain constructs, the eyes, the somatosensory system and the balance organ are the most important inputs, and if the brain cannot make a sensible model from these inputs, motion sickness can occur as described in section 2.6.

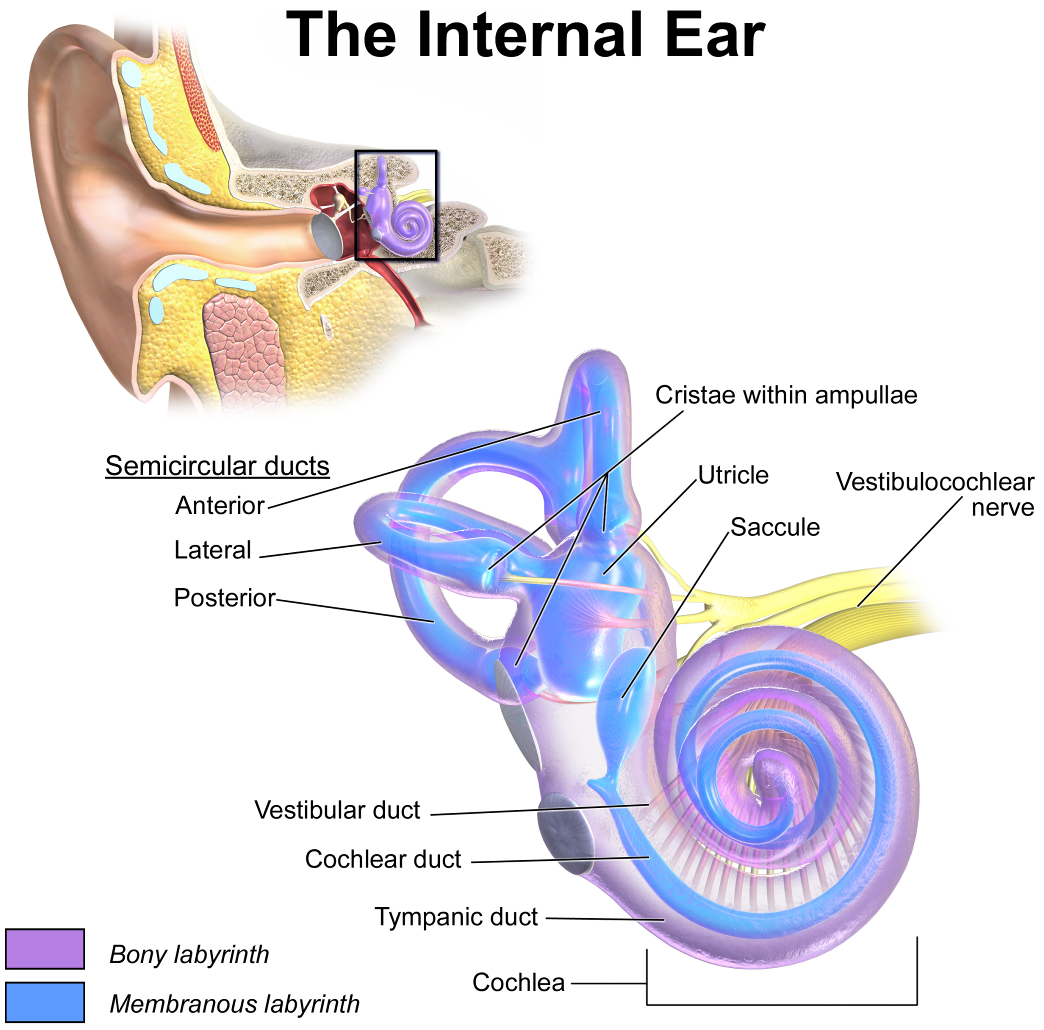


Figure 2.1: Model of the inner ear. The utricle and saccule makes up the otolith organs, and together with the semicircular ducts they make up the balance organ[13].

The balance organ, also known as the vestibular system is shown in figure 2.1. The vestibular system is positioned in the inner ear of both the left and the right ear. Each organ consists of three perpendicular Semicircular Canals (SCC), and two Otolith Organs (OTO), one for vertical acceleration and one for horizontal acceleration[5]. As described by Berotolini et al.[12] the SSC are primarily used for measuring rotational acceleration, but due to its design it cannot measure sustained rotation. The OTO on the other hand measures sustained linear acceleration, which usually gives us the direction of the gravity vector. Vision is often considered the most important sense for humans, and several interactions between the visual and the vestibular systems exists. Two of these have to do with gaze stabilization, one of them is Vestibulo-ocular Reflexes

(VOR)[4], which counter rotates the eyes whenever the head rotates or moves using input from the vestibular system. The second is the Optokinetic Reflex (OKR), which uses visual cues to detect movements that are not otherwise felt. The OKR plays an important role in calibrating the VOR, as the vestibular system changes as a result of growing up, aging or disease[75].

Sense	Input to the brain
The visual system	Position of everything in view
The semicircular canals	Rotational acceleration
The otolith organs	Linear acceleration
The somatosensory system	Pressure and its position

Table 2.1: Senses important for spatial orientation and their inputs to the brain.

The brain utilizes the senses in table 2.1 to build its spatial orientation model, but in addition quite a lot of processing happens in the brain. Change in position of an observed object can be used to calculate speed and acceleration, the rotational acceleration detected by the SCC are compared to each other, to distinguish rotational acceleration from linear acceleration. The somatosensory system indirectly provides knowledge of acceleration through pressure and its location, and the OTO provides linear acceleration directly, especially the direction of gravity is important for every day life. As all sensors, the senses have different domains where they are reliable, and there are various stimuli that will trick the senses into sending wrong information. In the brainstem and cerebellum the inputs are merged and weighed against each other as their inputs often overlap, spatial orientation is therefore the brain's best estimate of how we are positioned in the world around us and which forces are acting upon us[12].

2.4 Habituation

With training the brain is often able to make sense of situations that might have caused spatial disorientation earlier, in a process called habituation. Habituation can be done either intentionally or automatically due to a change in the environment. When done intentionally it is often part of a rehabilitation effort, high dependence on the somatosensory system for example can induce motion sickness as described by Rine et al.[87]. Special training can be conducted to cause a change in the central nervous system such that the vestibular system takes back control of balance, essentially changing the weights the brain assigns to the various inputs to its spatial orientation model.

Habituation can also be due to change in environment, evident by sailors *"getting their sea legs"*. As a sailor embarks on a ship it is difficult to balance until their sea legs are acquired, a process that can take a few minutes or several days depending on the person[93]. Similarly a condition known as *mal de debarquement* happens after the end of a voyage in which a person has obtained their sea legs, it is essentially the opposite effect of getting ones sea legs. Once back on solid ground, mal de debarquement causes people to have difficulties keeping balance, and a they often report that it feels like the ground is swaying as if still on a ship. According to Gordon et al.[72] these are examples of sensorimotor adaption, where the brain adopts new motor patterns for a given stimuli. The duration of mal de debarquement is correlated with the severity of sea sickness during the voyage[93], which indicates that MS susceptibility means that a persons brain is having a harder time to adapt its sensorimotor behavior to a new environment than those who don't suffer from MS. In the study of Gordon et al.[72] 66% of 116 crew members reported that their mal de debarquement became less severe after their first voyages, showing the effects of habituation. Once habituation is obtained, its effects can remain for several weeks, essentially making the brain quicker to adapt. Similar effects also occur on land, where frequent travelers experience less MS[99]. Once habituation is achieved it is stimuli specific, meaning for example that an acquired resistance to sea sickness, doesn't necessarily help against car sickness[90].

2.5 Evolutionary Theory

Why motion sickness occurs is a difficult question to answer, fossils give no indication of when or how or why it manifested itself, so explaining why motion sickness exists can't go far beyond speculating about evolution. There are two hypothesis on the matter worthy of mention however. The oldest one can be credited to Treisman[97], and states that it evolved as a defense mechanism against neurotoxins. Spatial orientation is a finely tuned system with a normally high accuracy, Treisman hypothesized that induced uncertainty in spatial orientation can be used as a detection system against potentially harmful neurotoxins. His hypothesis is supported by the symptoms, vomiting rids the stomach of potential poisonous food. In addition symptoms such as nausea, drowsiness, etc. will make a person want to lay down and relax, slowing down their metabolism and therefore increases their chance of survival should they be poisoned.

The second, newer hypothesis is summarized by Knox[62] and states that motion sickness is a negative reinforcement system meant to end actions leading to spatial disorientation. This hypothesis starts its premise by proposing that moving too far out on a branch to gather food for example, might have fatal consequences. Spatial disorientation can clearly compromise chance of survival, but the theory fails to explain why motion sickness first occurs after spatial orientation has been compromised for some time. Animals already have a much quicker negative reinforcement system in place, namely fear. There are more hypotheses out there, but they are all essentially speculation, and they often fail to explain that motion sickness is so prevalent across species. Cats[25], dogs[107] and rats[73] are some of the species prone to MS on quite different genetic branches. For whatever reason of why MS occurs, motion sickness today serves very little purpose and is more a statement that we as a species have gone beyond what we evolved to be capable of.

2.6 Sensory Mismatch Theory

The most accepted answer to how motion sickness occurs is the sensory mismatch theory[12]. It states that MS is a response to spatial disorientation caused by different sensory organs giving the brain seemingly contradicting signals. The various senses used for spatial orientation all have their weaknesses and are prone to signaling wrong information under some circumstances[12], as can be seen in figure 2.2. As described in section 2.3, the brain integrates several inputs to build up its spatial orientation model. The otolith systems primary function is detecting the gravity vector to determine where down is, but as gravity is indistinguishable from constant acceleration[76] an internal model remembering what's acceleration and what's gravity is constructed. This model is prone to error, if constant acceleration is kept for some time, the brain will recalibrate and assume that the summed acceleration vector is the gravity vector. Similarly the somatosensory system cannot distinguish between gravity and sustained acceleration.

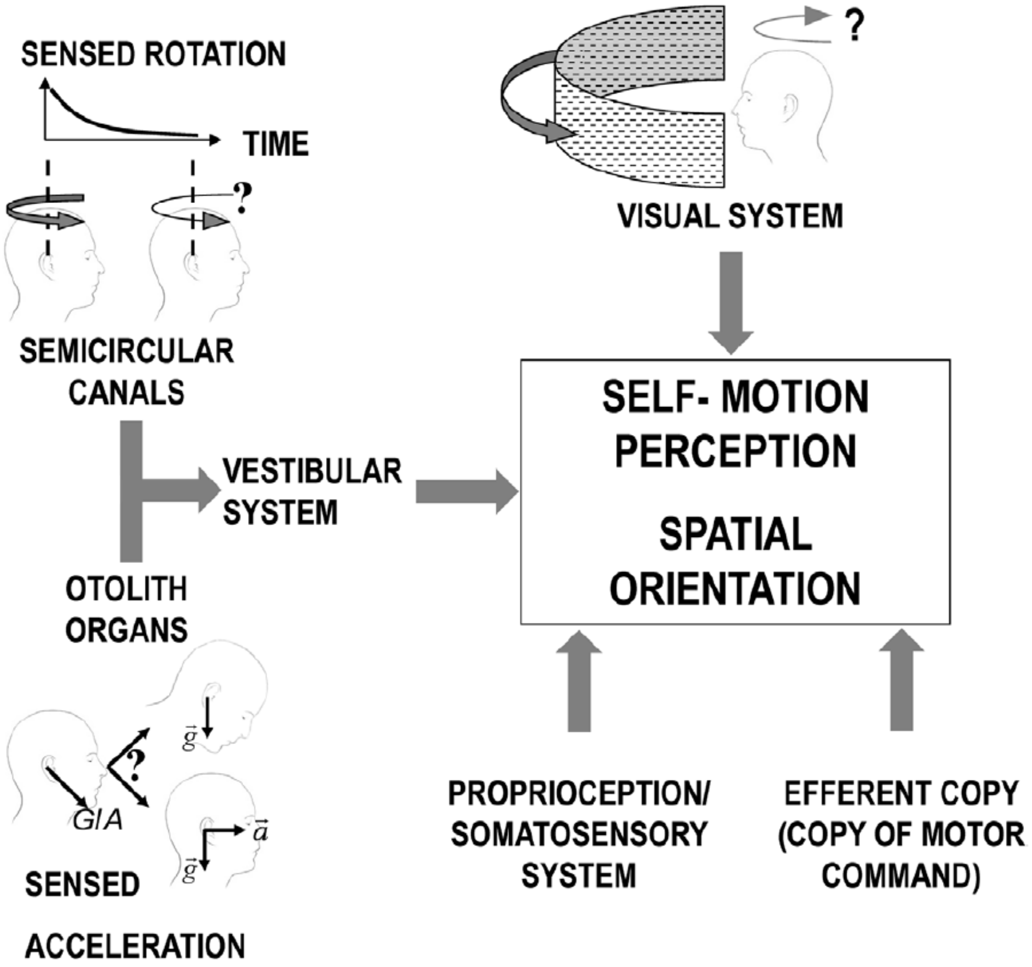


Figure 2.2: The senses responsible for spatial orientation and methods to confuse them[12].

Sustained rotation causes the fluid in the SCC to start rotating along with the head, as a result after 10 to 20 seconds[43] the rotation is no longer felt. If the rotation of the head stops, the fluid in the SCC continuous rotating due to its inertia, causing dizziness as a non existent rotation in the opposite direction is felt. Spatial disorientation contribute to about 5-10% of plane crashes[6] as a pilot with poor visibility and a lack of instruments is essentially flying blind once the spatial orientation model has been compromised. The visual system as well can be tricked as it cannot tell apart being rotated inside a scenery, and the scenery being rotated around one self, the same holds true for translation. The brain takes inputs from the vestibular, the somatosensory and the visual system and does its best making sense of them all by comparing the inputs to past experience, even recalibrating senses if errors are detecting using mechanisms such as the OKR. Even with several fail-safe mechanisms to keep spatial orientation intact, one can easily imagine that watching a movie with fast paced action on a laptop, in the backseat of a car navigating a curvy road will confuse several inputs simultaneously, leading to spatial disorientation.

2.6.1 Translational and Angular Oscillation

Translational sinusoidal oscillation with the frequency of 0,16-0,2 Hz have been found to be by far the most nauseogenic, while the range 0,1-0,5 Hz seems to cover the entire frequency spectre that causes motion sickness[78] [12]. Car travel is known to be nauseogenic, and contrary to the laboratory settings which determined these frequency ranges, oscillation doesn't occur at a fixed frequency. To the author's knowledge, no laboratory experiments using oscillations with continuously changing frequency has been conducted, it is however a well known fact that driving on country roads is more nauseogenic than highway roads[99], strongly indicating that infrequent acceleration is more nauseogenic than the sum of its parts.

The influence of angular oscillation as well is not completely understood, some studies have shown no correlation between angular oscillation and motion sickness while others have[12]. It is generally accepted that angular oscillation with translation acceleration and/or oscillation causes a synergy effect as far as MS is concerned[83]. For a real world example, tilting trains have been studied extensively. They have been around since 1938[84], and allows trains to go at higher speeds in corners, as tilting the car body morphs the experienced lateral forces into vertical forces by tilting the coordinate system of the passengers. This increases comfort for the passengers, but has been found to be nauseogenic. Studies have been conducted showing that it might be due to roll velocity or roll acceleration[36]. Most notably Förstberg[36] has shown that 55% tilt compensation[1] is less nauseogenic than 70% tilt compensation, and he contributes these findings to the fact that less rolling goes on with a lower compensation rate. Another important factor of how nauseogenic a tilt strategy is, is shown to be the time delay of the tilt.

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[1] The percentage of lateral forces morphed into vertical forces by tilting the coordinate system.

Bertolini et al.[11] compared various tilting trains on the market and found a weak correlation between the tilt time delay and MS. To further study this they purposely introduced a 3 second tilt delay on a train run, which increased MS greatly, indicating that tilt delay should be reduced to a minimum.

2.6.2 Motion Sickness Classification

There are several ways for a sensory conflict to occur, Schmäl[90] has therefore proposed a classification scheme which can be seen in table 2.2. There are two categories, category 1 describes the cases where there is conflict between the visual system and the vestibular or somatosensory system, for motion sickness the vestibular system seems to be the important one, as having a non-functional vestibular system makes one immune to motion sickness[41]. The second category concerns conflict within the vestibular system itself, due to stimulus such as spinning on a chair or even the micro-gravity of space.

This paper primarily looks at category 1 type 1 and 3 motion sickness, as they are the one most relevant to autonomous driving where passengers are expected to increasingly read and use screens. Category 1 type 2 MS could arguably be included, as using virtual reality is realistic in an autonomous car setting. The author chose to omit it from this paper however, as simulator sickness is very much a research topic of its own, which a lot of academics are focusing their attention on. It must also be noted that a stimuli doesn't have to fall distinctly within one category, category 1 and 2 can be combined to produce a more potent nauseogenic stimuli.

Category 1 type 1 occurs when both the visual and the vestibular system are picking up movement but are not aligned with each other. An example of this would be looking outside the window of a moving car on a highway going through a forest, little acceleration is felt but the scenery close to the car is moving very quickly. Velocity in itself is not nauseogenic, therefore this indicates that the visual system cannot tell that the speed is static, which wouldn't be surprising as the speeds achievable by car is far beyond anything found in nature. The vestibular system

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[2] Caloric stimulation means in this setting to apply hot and/or cold water to the outer ear, to change the temperature of the inner ear and thus the viscosity of the fluid that resides within the semicircular canals. This causes a sense of movement, and is useful in diagnosing problems with the balance organ.

Type of conflict	Category 1: conflict between visual(A) and vestibular/somatosensory (B) signals	Category 2: conflict between canal (A) and otolith (B) signals
Type 1: Input A and B simultaneously receive contradictory or uncorrelated information	Watching waves over the side of a ship Looking out the side or rear windows of a moving vehicle Making head movements while wearing an optical device that disturbs vision	Head movements made about some axis other than that of bodily rotation - cross-coupled angular acceleration Low-frequency oscillation between 0,1 and 0,3 Hz
Type 2: Input A signals in the absence of the expected B signal	Cinema sickness Operating a fixed-base vehicle simulator with a moving visual display(simulator sickness)	Space motion sickness Caloric stimulation[2] Involuntary eye movement associated with alcohol and heavy water
Type 3: Input B signals in absence of the expected A signal	Reading a map in a moving vehicle Riding in a vehicle without external visual reference Being swung in an enclosed cabin	Rotation about an earth-horizontal axis Any rotation about an off-vertical axis Counter ration

Table 2.2: There are various method to induce motion sickness in a person, depending on the nature of the sensory conflict. The table is modified from Schmäl[90].

is picking up some shaking, turning and some acceleration/breaking depending on the traffic situation, while the visual system is trying to calculate the acceleration required to explain the scenery's behavior outside the window, as these inputs to spatial orientation are vastly different, a sensory conflict occurs.

Category 1 type 3 occurs when the vestibular system is picking up movement while the visual system insists there is none. An example of this would be reading a book while riding the bus, the visual system is fixed on a point static relative to one self, thus no movement is input into spatial orientation. The vestibular system and the somatosensory system on the other hand is signals during every turn, every bus stop and every red light, causing a sensory conflict.

2.7 Mathematical Models

The goal of several researchers have been to develop a mathematical model to predict the onset of motion sickness. Building a complete model however has turned out to be difficult, and is perhaps impossible due to the complexities and individual factors involved. Nonetheless a model can be accurate for a specific type of stimuli, especially if one assumes that no rotational - translation oscillation synergy occurs, as they are poorly understood and behave in non-linear manners which is hard to accurately describe mathematically.

2.7.1 ISO 2361-1

ISO standards are well respected among engineers, and are useful in almost every field. As such ISO Standard 2631-1 [58] proposes a model for calculating how nauseogenic a stimuli is, namely

$$\mathrm{MSDV}_z = \left\{ \int_0^T [a_W(t)]^2 dt \right\}^{\frac{1}{2}}$$

where MSDV is the motion sickness dose value. $a_W(t)$ is the frequency-weighted acceleration in the z direction in m/s^2, and T is the total time domain of the stimuli in seconds. The way this model is used is to measure or predict acceleration in the z direction, combine this with a weighing curve for different frequencies, and calculate the MSDV_z. The percentage of people expected to vomit is then found by $K_m \cdot \mathrm{MSDV}_z$, where $K_m \approx 1/3$ for a mixed adult population.

The ISO-model seems to be based on research conducted by the American Navy during the 70's [78]. As such only the z direction is taken into account, as at sea acceleration is primarily along this axis. This model has been adapted to other directions as well with different weighing curves, for travel by car for example acceleration is primarily in the lateral direction from turning. An observation one can make from this formula is that for $\lim_{t\to\infty}$ a 100% vomit rate is expected, which doesn't correspond with reality. This model has some use in sea travel as the acceleration picture is much simpler, but it doesn't hold up very well on the roads nor is it useful for estimating the response of an individual. As the frequency weighing curves for the z, x and y direction have been developed, they can however be used as a basis to construct more complex models.

2.7.2 Net Dose Model

Kufver and Förstberg[36] propose a very interesting model for motion sickness, which is one of the few models that takes MS leakage into account i.e. MS recovery. The model states that for a time step Δt, a dosage $D_{P\Delta}$ is accumulated, but in addition a leakage factor of $D_{L\Delta}$ proportional to the previously accumulated dosage level $D_n(t)$ is lost, as seen in figure 2.3.

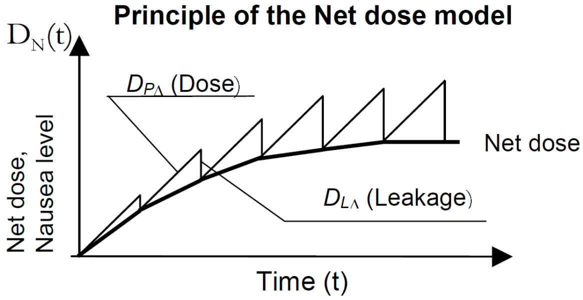

Figure 2.3: The principle of the net dose model. For every time step Δt, a dose $D_{P\Delta}$ is added and a leakage dose $D_{L\Delta}$ is subtracted from the dosage level $D_N(t)$ [36].

$D_{P\Delta}$ takes the form of $D_{P\Delta} = c_A \cdot A \cdot \Delta t$ and $D_{L\Delta}$ the form of $D_{L\Delta} = c_L \cdot D_n(t) \cdot \Delta t$. A depends on the stimulus, c_A is the individuals sensitivity and c_L is the individuals leakage factor. Combining $D_{P\Delta}$ and $D_{L\Delta}$ yields $D_N(t) = \int_{t_s}^{t} c_A A e^{c_L(\tau - t)} d\tau = \frac{c_A A}{c_L}(1 - e^{-c_L(t-t_s)})$. This gives a few interesting implications, such as that for $\lim_{\Delta t \to \infty}$ we get $D_N = \frac{c_A A}{c_L}$, essentially giving a cap of how motion sick somebody gets for a given stimulus, whereas other models such as the one found in ISO 2361-1 [58] diverges to infinity. Compared to the ISO model, the net dose model is more robust when calculating the expected motion sickness level of a real-life trip - where the stimulus changes over time and pauses can be expected. Kufver and Förstberg have in addition developed the model a bit further, taking into account that MS takes some time to be felt, by proposing a threshold level D_0, such that for $D_N(t) \leq D_0$ no symptoms manifest. It should be noted that the delay of symptoms can be explained by an inherent time delay on MS, as it has been shown that symptoms can manifest 20-30 minutes after ended stimuli [104].

The beauty of the net dose model is not that it can be used to explain the behavior of groups on average, but that it can be fitted to individuals by calculating their c_A, c_L and D_0 as seen in figure 2.4.

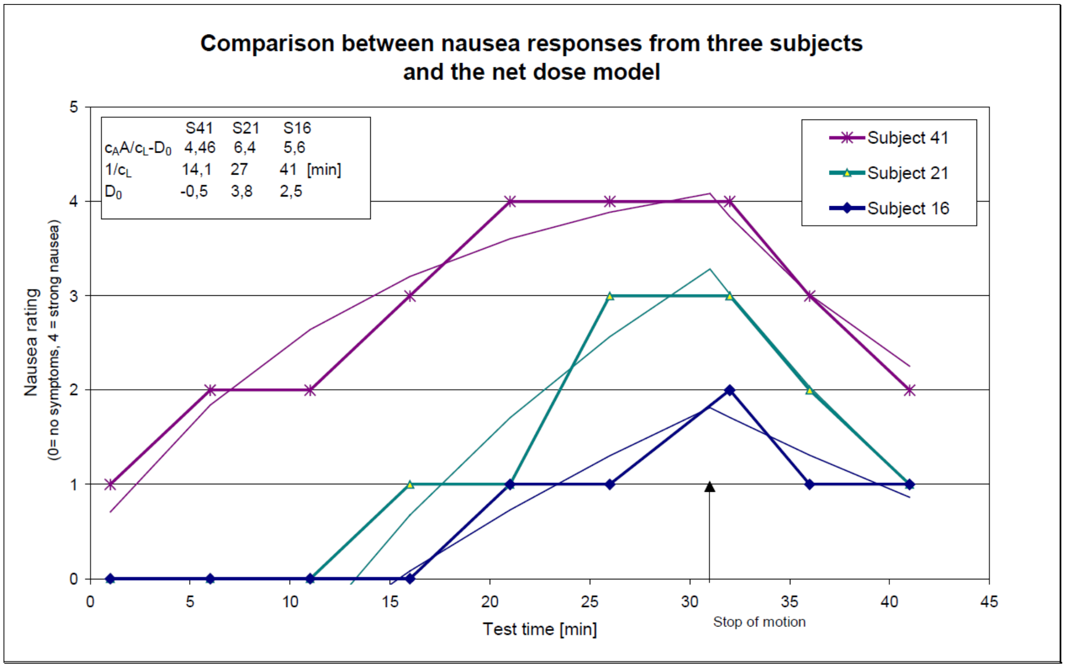

Figure 2.4: Fitting of data from individuals using the net dose model, taken from Förstberg[36].

Lackner[64] has studied MS susceptibility and found that the range of sensitivity as well as adaption rate varies 10 to 1 in the general population, and that the decay constant varies 100 to 1. In Försterbergs model the sensitivity corresponds to c_A and the decay constant to c_L, while adaptation rate is omitted, which might be justified for shorter, varied trips.

2.8 Measuring Motion Sickness

Making objective measurements of MS is difficult, in essence one is trying to measure an abstract phenomena which is not completely understood, using humans as sensors. As stated in section 2.2, motion sickness is incredibly subjective, with individual susceptibility ranging 1:10.000 in severity[64]. Measuring distance with such a sensor would mean that a meter could be measured from anything between 1 cm and 100 m. There are however methods to reduce the variability, the obvious one is to run a good sample size through the same experiment, and hope that the average represents the average human being. Another popular method used in research is to preselect participants such that they are expected to have a similar response. Methods such as the Motion Sickness Susceptibility Questionnaire(MMSQ)[39] have been developed for this goal. Simply asking people if they consider themselves susceptible is an option as well. Another method to work around the susceptibility variance issue it to run the experiment with two different parameters for every person, comparing the stimuli in question. If one chose to use the MMSQ, one can chose a more homogeneous group to run the experiment such that more useful data can be acquired, it can however also introduce bias into the data, such that one can't necessarily generalize the findings to the whole population. Running the experiment with two different parameters introduce higher cost, and is sometimes impractical especially for longer lasting experiments. Simply asking people if they consider themselves susceptible isn't very robust, but if one seeks a sensitive population it is sometimes the easiest method, and it can yield good data if two parameters that don't manifest a response in the average person are to be tested against each other.

2.8.1 Questionnaires

How motion sick somebody feels is best measured by asking them, as it is almost the definition of subjective. The questionnaires all have their pros and cons depending on their application and are typically designed for a given scenario. The questionnaires can generally be divided into two categories depending on if they are administered during or after the experiment, with the former usually being oral and quick to answer, and the latter typically written and more detailed. Below is an incomplete list of the various questionnaires.

- Motion Sickness Index (MSI) [104] is a written questionnaire with a resolution of 0-82.
  MSI tries to score MS objectively, scoring the severity of several known symptoms independently. The symptoms included are sweating, head ache, paleness, increased salivation, nausea and vomiting. Each symptom typically has 3 to 4 levels of severity, and the MSI is derived using a weighted matrix.

- Pensacola Diagnostic Report Scale (PDRS) [94], seemingly also known as the Pensacola Diagnostic Index(PDI) [14] is a written scale with a resolution of 0-62. First 11 symptoms are rated according to their severity, they are then summed using a weighted matrix based on the importance of the symptom. This scale was developed in the 60's and has seen a lot of use.

- Simulator Sickness Questionnaire (SSQ) [14] is a written questionnaire. The questionnaire aims primarily to find correlations between various symptoms and not directly to determine how motion sick someone is. The SSQ can therefore be viewed more as a questionnaire used to understand MS and not to measure it. The questionnaire rates 16 symptoms on a scale of 0-3, and avoids summing them, to instead look at the symptoms independently. This scale is very popular, and versions of it exists where the symptoms are rated from 1 to 9 for increased resolution [38]. SSQ is a shortened version of the Pensacola Motion Sickness Questionnaire (MSQ) designed for use in simulators. MSQ is identical to SSQ except that it rates 28 symptoms instead of 16 [34].
- Fast Motion Sickness Scale (FMS) [61] is an oral questionnaire with a resolution of 0-20. FMS aims to track MS real time in an easy manner. The participant is fist instructed in how the scale should be used, and are asked to focus on nausea, general discomfort and stomach problems. They are then asked to rate their well-being on a 0-20 scale, where 0 means no sickness at all, and 20 means frank sickness. The frequency of FMS is once per minute.

There are several oral scales other than the FMS, rating MS on 3-, 4-, 5-, 7-, 11-point scales [36] [61], with a frequency of up to five minutes. As Keshavarz et al. [61] point out, deciding on the resolution of a scale is a small field of research in itself, with test-retest reliability dropping off until about 5 points where it stabilizes. For MS it is however desirable to have good resolution, as one would like to be able to observe smaller changes.

2.8.2 Biometric Data

Using biometric data as an objective measure of motion sickness has been attempted for quite a while, several changes have been measured in the human body, but an accurate way to interpret this data to match a persons subjective feeling of MS has not beared fruits to the knowledge of the author. However as this is a goal worth pursuing, as once it has been mastered, stimuli can be tested with much higher reliability. A list of measurable biological changes caused by motion sickness can be seen in table 2.3.

Physiological system	Manifestation
Cardiovascular	Changes in pulse rate and/or blood pressure. ↑tone of arterial portion of capillaries in the fingernail bed. ↓diameter of retinal vessels. ↓peripheral circulation, especially in the skin of the head. ↑ muscle blood flow.
Respiratory	Alterations in respiration rate. Sighing or yawning. Air swallowing.
Gastrointestinal	Inhibition of gastric intestinal tone and secretion. Salviation. Gas or belching. Epigastric discomfort or awareness. Sudden relief from symptoms after vomiting.
Blood	Changes in Lactic Dehyorogen ASE concentrations. ↑hemoglobin concentration. ↑pH and ↓ $paCO_2$ levels in arterial blood, presumably from hyperventilation. ↓concentration of eosinophils. ↑17-hydroxycorticosteroids. ↑plasma proteion. ↑ADH. ↓glucose utilization.
Urine	↑17-hydroxycorticosteroids. ↑catecholamines.
Temperature	↓body temperature. Coldness of extremities.
Visual System	Ocular imbalance. Dilated pupils during emesis. Small pupils. Nystagmus.
↑ = increase in value	↓ = decrease in value

Table 2.3: Biometric responses to motion sickness adapted from Kennedy(1985)[60].

A promising method to measure MS using biometric data, might be monitoring brain activity. Lin et al.[67] have found a correlation between activity in certain parts of the brain and motion sickness, and claim they can use this data predict MS with an accuracy of 82%. It should also be mentioned that in the 70's researchers observed reliable, objective biometric data[78] [68], but on a crude binary scale where they only observed if the participants vomited or not (for some parameters they reached 60%).

2.9 Head Tilting

A proposed reason that drivers experience less motion sickness than passengers [88] is that drivers usually tilt their heads into turns as they are actively steering, while passengers usually tilt their head in the opposite direction as a result of the lateral forces [106]. When a person tilts their head into the turn, the summed acceleration vector doesn't change it's angle as much relative to the otolith organs, thus activating them less. There are however other explanations to why drivers experience less MS, the most being that they are in control of the vehicle. Controlling the vehicle makes the accelerations felt expected, and therefore easier to integrate into the spatial orientation model.

Regardless of the cause, actively tilting the head into turns have been shown to reduce the occurrence of MS, this has been shown by an experiment where passenger were tasked to mimic the head movement of the driver. The passengers experienced less MS even though they were not personally in control of the vehicle [105]. In the case of autonomous driving, asking passengers to actively tilt their head is not practical, but given that head tilting is easy to measure it could be used as a way to gather data on how good a ride is, and minimizing it could be a worthy goal of technical solutions aiming to reduce MS.

2.10 Remaining Mysteries

Laboratory setting experiments have isolated quite a few stimuli that are nauseogenic, but a lot of questions remain unanswered. Within the complexities of real life travel for example, it is unreasonable to expect that stimuli is reoccurring, especially for a long enough time for motion sickness to manifest. Combining various stimuli in creative or random ways seems to compromise spatial orientation, which in turn will lead to motion sickness. To the authors knowledge, changing stimuli have received very little research except for indirectly through questionnaires about how a ride was etc. Another believed influence on motion sickness is jerk[3], jerk defines how smooth acceleration feels, and it's been shown to correlate with motion sickness [36] but the research on the topic is very limited.

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[3] The time derivative of acceleration.

2.11 Cause Models

Motion sickness is complex. If one wishes, one can spend years trying to understand the finer mechanisms that goes into it. Luckily cause models have been developed to bring it to a level which is easier to grasp. Below are two such models, one by Griffin[45] seen in figure 2.5 summarizing the inputs and outputs related to MS. The second seen in figure 2.6 is by Benson[10] explaining how the central nervous system processes these inputs.

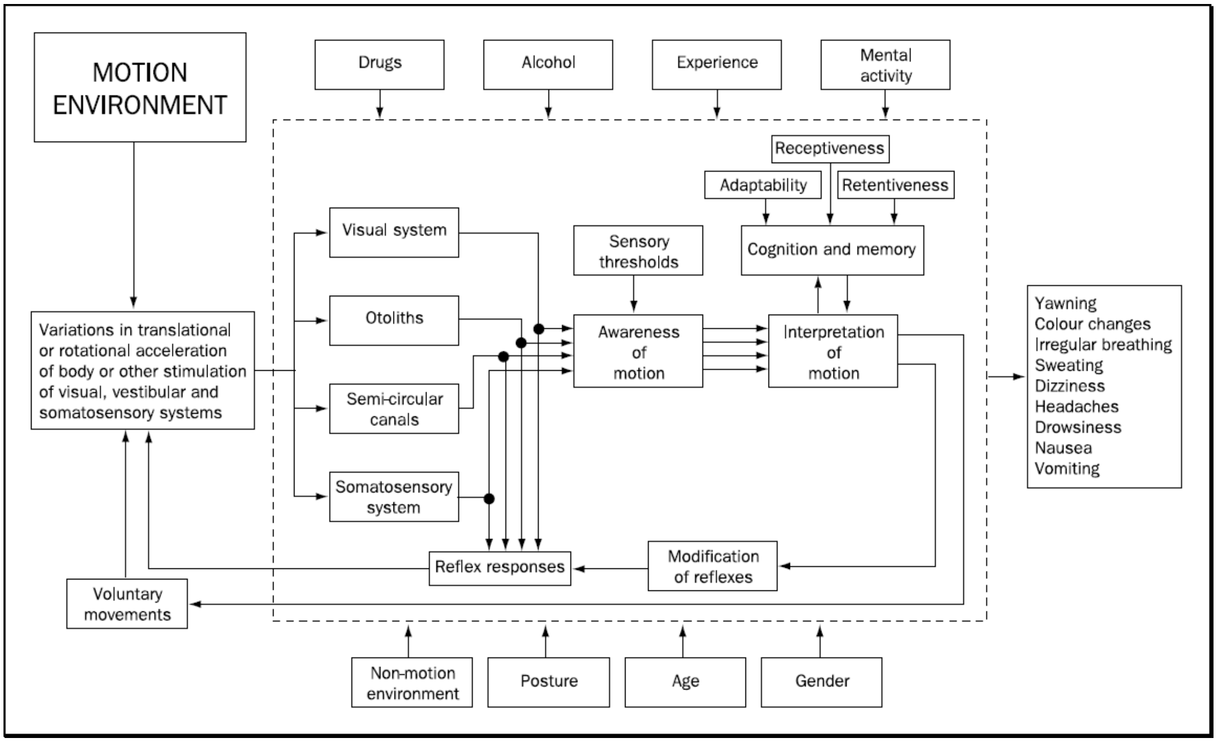

Figure 2.5: Conceptual model including most stimuli believed or shown to influence MS, the various sensory system and their interactions within the brain. From Griffin(1990)[45], figure modified by Försterberg[36].

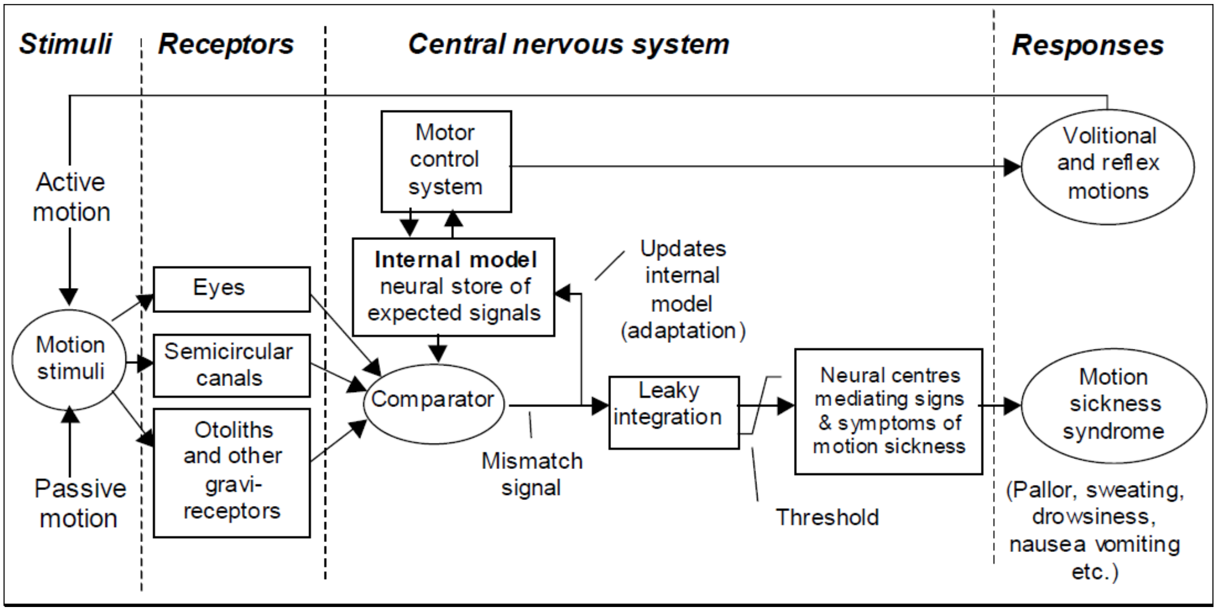

Figure 2.6: Conceptual model explaining how the central nervous system processes spatial orientation input. From Benson(1988) [10], figure modified by Försterberg [36].

Chapter 3

General Measures against Motion Sickness

Methods to mitigate motion sickness that are effective in general, will be applicable in autonomous cars as well. Making sure that the outside of the car remains in the passengers view or peripheral view, is the main focus of car companies in the battle against motion sickness. Researching motion sickness also implied that damping systems and NVH engineering could be a good approach in reducing motion sickness, but sadly the frequency range at which motion sickness occurs primarily lies within the domain the of road construction and traffic planning engineers. This chapter discusses windows and active seats, as well as some medical solutions, both conventional and futuristic.

3.1 Windows

The perhaps oldest and most reliable way to reduce motion sickness in cars is to increase the total window surface area[28], as increased field of vision increases the reliability of the visual system, which in turn reduces sensory conflict. Especially forward facing view is of importance[46], which requires a reduction in the width of the A-pillars if one is seated in the front seat. For clarification on what the A-pillar is, see figure 3.1. The A-pillar is usually of considerable width as it plays an important part in protecting the passengers in case the car should roll over, however as self-driving cars eliminate human error, less protection might be required, allowing for a smaller A-pillar. Otherwise windows are well understood, so it won't become more attention in this paper. It should be noted that a complete field of vision doesn't solve motion sickness, camel riding for example offers complete overview as one is out in the open, nonetheless it's known to be very nauseogenic[40]. Windows plays its part, but should be complemented with additional solutions.

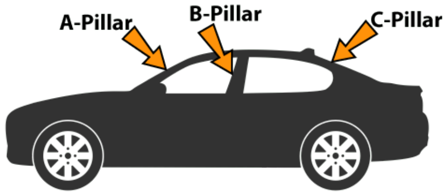

Figure 3.1: The naming convention for the pillars holding up the roof of the car.

3.2 Active Seats

Trailer and bus drivers sometimes use seats with in built dampening as they are subjected to vibrations throughout the day. These seats damp out frequencies above 0,5 Hz, so they are not really helpful against motion sickness, but can aid against other negative effects such as back problems[58]. Some seats also change their shape depending on lateral forces, expanding on one side to push against you as you are pushed outwards, keeping your body position upright, it is however unclear if this effects motion sickness. Section 4.4 discuses tilting of the car body and its consequences. Tilting can also be done individually for each passenger by tilting their respective seat, it should be noted however that this might be impractical as car manufactures strive to make their seat mount as small as possible for unrelated reasons to motion sickness, so fitting such a tilt contraption might be difficult.

3.3 Medication

Some drugs have very good track records of reducing motion sickness or completely hindering its onset. Due to their side effects, one should strive to mitigate MS by other means, but for the most susceptible they offer a reliable solution. Schmäl[90] has compiled a comprehensive list of medications used to treat MS, and states that they do so through three different mechanisms.

- Reducing sensory mismatch, for example by suppressing sensory signals.
- Speeding up adaptation; allow the brain to quicker recalibrate to new stimuli.
- Suppressing the symptoms, for example anti-nauseogenic drugs.

The two most common motion sickness drugs are scopalomine and antihistamines[15].

Scopalomine is the most effective anti motion sickness drug currently on the market, it is believed to suppress the nerve input connecting the vestibular system to the brain, as well as most likely suppressing the brain's vomiting center. Side effects include drowsiness and blurred vision.

Antihistamines treats motion sickness in 70% of patients, they function by increasing the firing rate of the nerves surrounding the semicircular canals. This in turn causes the release of an antagonist numbing the entire vestibular system. Side effects include sedation, which in itself might play a role in reducing MS.

Whereas mitigating motion sickness with technical solutions is realistic, eradicating it is not. Therefore those truly susceptible will have to use medical solutions in the future as well. Medical research does however progress, and in the following sections are two solutions potentially without side effects.

3.4 Galvanic Vestibular Stimulation

Galvanic Vestibular Stimulation (GVS) is the process of stimulating the semicircular canals and the otolith organs with targeted currents[35]. This can be done by placing electrodes behind the ear and pair them up with electrodes placed strategically on the head such that a specific sense of motion can be triggered. GVS is being developed to combat simulator sickness induced by virtual reality[102], but could in theory be used to combat car sickness as well. The technology in this field is under development, if it turns out that accurate control over the vestibular system is possible, GVS can be used to anneal or mask the signals going to the brain. What makes this technology interesting is that it is already under development by the gaming industry[86] [102], and thus it might be marketed as part of an entertainment system instead of an anti-motion sickness device. People might be skeptical of zapping their heads with electrical currents, even if it is safe. If the gaming industry manages to change public opinion, GVS could be adopted by the car industry.

3.5 Electrocortical Therapy

As a functioning vestibular system is a requirement for the development of motion sickness, it has been theorized that suppressing the vestibular system will reduce the onset of motion sickness. This theory has been tried out by a Arshad et al.[8], and has been shown to work. By applying transcranial direct current stimulation they have been able to suppress the left parietal cortex part of the brain, and with it the vestibular system. This stimulation has increased the time before motion sickness symptoms kick in by 40-50%, as well as reduced recovery time. This method is very promising, and has currently no known side effects. It must be noted however that after sufficient time people still become motion sick. As with GVS the willingness of travellers to wear headgear zapping their head with electricity is questionable, but electrocortical therapy will likely see some use by those who currently depend on medicine.

Chapter 4

Unique Opportunities in Self Driving Cars

Computers have shown time and time again that they can do repetitive tasks quicker and with higher precision than what can be expected of a human. In addition computers can control more systems, utilize more sensors, and work with a higher degree of synchronization. Online information is easily accessible by computers and can improve their decision making. This chapter looks at some of the ways one can start to rethink the control system of a car. Depending on the task computers can be very much superhuman, so what are some of the things they can do that we cannot?

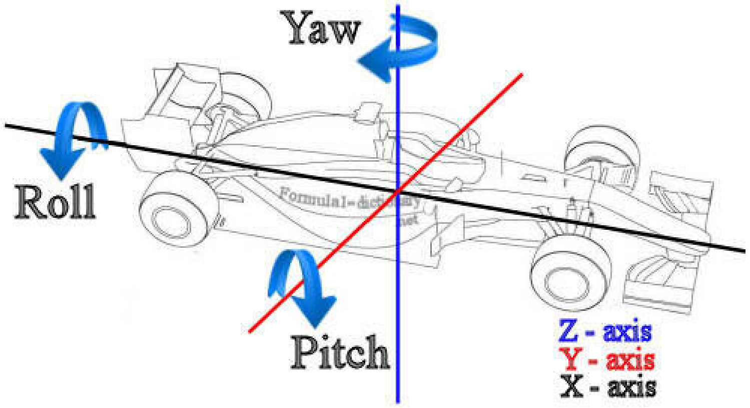

Figure 4.1: The 6 degrees of freedom in three dimensional space.

4.1 Acceleration Manipulation

Acceleration, and possibly jerk[36] in 6 DOF[1] causes motion sickness, a visual explanation on what DOF are can be viewed in figure 4.1. Acceleration in various directions have different weights for how nauseogenic they are, for example acceleration along the Z-axis is shown to be less nauseogenic than in the lateral plane[104]. Cross-coupled stimuli between the 6 DOF are also known to exist, especially when rotation occurs around another axis than the gravity vector[26]. This is known as Coriolis/cross-coupled stimuli and is known to be especially MS inducing[12]. It is not unreasonable to hypothesize that if one can manipulate the perceived acceleration and or jerk in the 6 DOF, one can mitigate motion sickness. Exactly what the ideal way to manipulate the acceleration is, is currently unknown and requires more research, ideas on how this research can be conducted is found in chapter 5. In table 4.1 a summary of the different methods to manipulate acceleration discussed in this paper is found.

Maneuver	Trades	For
Breaking before turning	Y acceleration	Pitch and X acceleration
Rolling while turning	Lateral acceleration	Roll and Z acceleration
Lane Drifting	Yaw	Y acceleration
Pitching during acceleration	X acceleration	Pitch and Z acceleration
Micro-Acceleration	Pitch oscillation	Pitch jerk
Micro-Steering	Yaw oscillation	Yaw jerk
Micro-Steering II	Y oscillation	Y jerk

Table 4.1: Various methods to manipulate perceived acceleration and/or jerk in an autonomous car.

4.2 Computer Reflexes

Average human reaction time during driving is around 2,3 seconds[69], while for a computer sensor system reaction time is measured in milliseconds. Autonomous vehicles (AV) are in addition equipped with sensors greatly outperforming our senses, for example technologies like LIDAR allows the car to precisely measure the speed of the vehicle ahead relative to one self. Where a human might struggle to detect slight changes in speed, an AV can start adjusting its speed to match the car in front of it before a human would even be aware it was necessary. The AV

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[1] Degrees of Freedom

have more time to adjust its speed, thus the acceleration required for the speed adjusted can be distributed over a longer time spectrum, reducing the amplitude of acceleration as well as the jerk experienced by the passengers. Human drivers, especially inexperienced ones, are prone to making minor adjustments where none are required. Matching the speed of the car in front of one selves for example, might require several speed changes, oscillating between a bit too quick and a bit too slow before getting it right. A computer can consistently get it right the first time and therefore reduces break wear and saves energy. As discussed in section 2.6 acceleration activates the vestibular system, so those who were previously passengers themselves can expect a decrease in MS.

Given that AVs becomes the new norm, one can expect to see completely new coordination between cars. Things like lane markings and traffic signs may become obsolete on AV exclusive roads, as coordination becomes superhuman, a lot of the reasons a car needs to stop goes away, and would thus help with travel time, fuel efficiency as well as motion sickness. An example of such superhuman coordination can be found in intersections, where cars can be given a time slot instead of a go signal, allowing cars to pass the intersection from all sides simultaneously[1]. Lastly the driving behavior of the car can be set by defining limits to the amplitude of acceleration which is acceptable i.e. higher limits equals a more aggressive style, and lower limits equals a softer style of driving.

4.3 Route Planning

The greatest influence passenger acceleration is the route that is to be followed[48]. Every turn will give a lateral acceleration according to $a = v^2/r$, and if the turns are spaced with a time difference of 2 to 10 seconds, even nauseogenic oscillation in the 0,1-0,5 Hz range can occur. With autonomous vehicles however, not only can the route can be planned, but also the speed at which it is to be followed. Peak motion sickness occurs at around 0,16-0,2 Hz[78], which is equal to oscillations lasting 5 to 6 seconds. The road stays constant, but the speed the car transverses it is under its control. If the car speeds up or slows down strategically, oscillations from the layout of the road can be pushed out of the 0,16-0,2Hz range, and should thus help reduce motion sickness. The acceleration and breaking required to manipulate lateral acceleration may, however, introduce unwanted fore and aft acceleration, and could also stress the passengers as they may not understand why the car is doing what it does. Route planning today is usually done in an attempt to minimize travel time, and often several routes are proposed with similar arrival times. Detailed maps concerning road layout grouped together with speed limits are readily available, this can be used to calculate the expected lateral acceleration for a given route. By selecting the route that minimizes lateral acceleration, route planning can potentially be used as an efficient method to reduce the occurrence of motion sickness.

4.4 Active Tilting

Similar to active tilting trains discussed in section 2.6, some of the more luxurious cars today, such as the Audi A8[3] and the Mercedes S-Class[47], can tilt inwards in turns. The reason active tilting falls within unique opportunities for autonomous vehicles however, is because it has been shown that tilt delay is nauseogenic[11]. In an AV the driving algorithm can tell the tilting mechanism to activate synchronized with turning, as the actions of the car is planned ahead in time. Also as mentioned in section 2.6, tilting trains have been shown to be more nauseogenic than non-tilting trains, so one could expect tilting cars cause motion sickness instead of reducing it. In cars there's also the option of pitching the car backwards while breaking, and forwards during acceleration, again to minimize the perceived lateral forces. Experiments on pitch tilting do not exists to the authors knowledge, but as the only difference from a physics standpoint to roll tilting is the orientation of the vestibular system, similar results should be expected. Factors such as how long a turn last, the amplitude of the lateral forces, roll velocity and jerk rate of the tilt might play a crucial role in how its perceived. Tilting would also influence head bobbing as discussed in section 2.9. How to tilt involves many different parameters, and it is possible that tilting can be used as a countermeasure against motion sickness if the correct parameters are found, but quite a bit of research would be required to tell for sure.

4.5 Habituation to Vehicle Fleet

Developing autonomous car algorithms is currently extremely expensive. One can therefore expect that the same algorithms will power the self-driving capabilities of a manufacturers entire vehicle fleet, or even that several car manufacturers share a common software platform. The driving behavior of such a fleet will be very similar across vehicles and most likely identical for a given car model. As discussed in section 2.4, habituation occurs when a person learns to quickly adapt to a given stimuli through repeated exposure. Exactly how stimulus specific habituation is, is currently unknown. If it turns out to be specific enough that habituation can occur for a distinct driving style, habituation will reduce motion sickness for all cars sharing the same software platform. Brand loyalty might become more than a matter of taste, instead becoming a matter of a habituated brand causing a person the least motion sickness.

4.6 Lane Drifting

Four wheel steering is used in more luxurious cars as it can increase handling, and reduce the turning radius of the car[9]. However, there is a very important opportunity with four wheel steering that cannot be unlocked by a steering wheel, namely drifting. There are two methods to change a lane, the classical one where one turns the steering wheel, the car changes direction for a brief moment before the direction is changed back to follow the lane. The second method is drifting as illustrated in figure 4.2, where all four wheels are turned simultaneously, causing no turning of the car but nonetheless the same feat is achieved. The reason this can't be done with a steering wheel is simply because the car wouldn't know if a turn or a drift is the desired result. With autonomous driving however, the car would know if a turn or a drift is the desired result, and thus drifting can possibly be useful against motion sickness or for increased comfort. Drifting will essentially remove the rotational acceleration required for a lane change, but will introduce higher lateral forces.

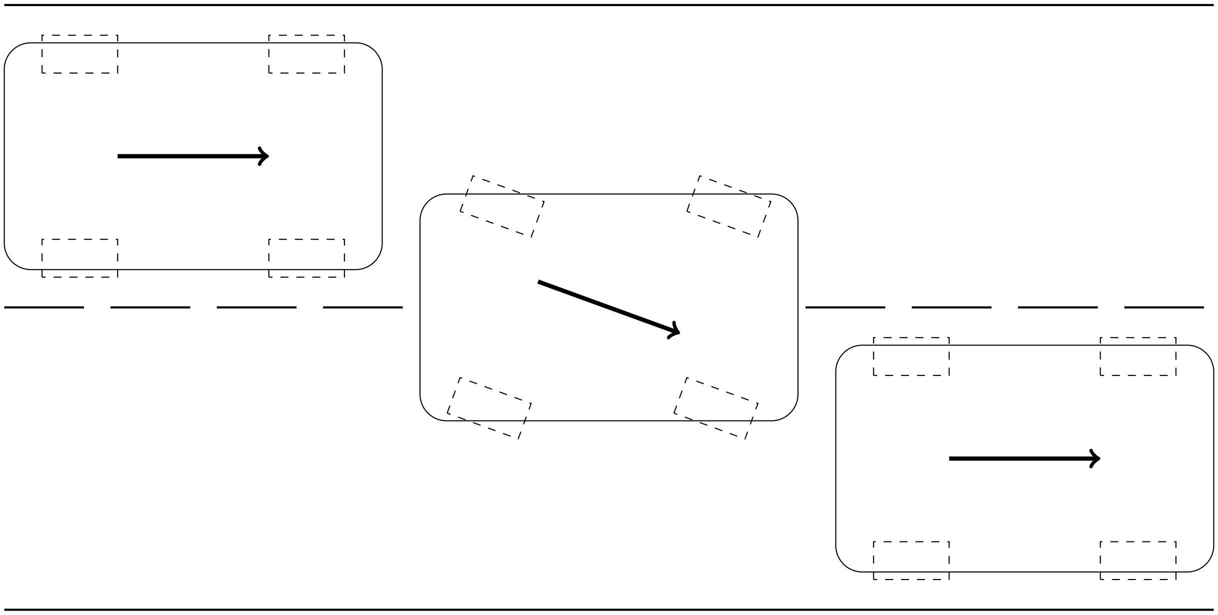

Figure 4.2: Four wheel steering can be used to drift into a new lane without turning the vehicle.

4.7 Micro-Maneuvering

Oscillations and vibrations of a car is primarily countered by the use of dampeners, both active and passive. Active dampers are usually better at the job as they can damp out vibrations faster and more smoothly, they are however more expensive. Micro-Maneuvering is essentially a proposed software solution to use the steering of a vehicle in such a manner that it can mimic the effects of an active damping system if none is present, or synergize with a present one. Micro-maneuvering work on the premise that the impulse given is big enough to cancel out oscillation, but small enough not to change the direction or speed of the vehicle significantly. How this will affect motion sickness, if at all, is unknown as to the authors knowledge as the concept of micro-maneuvering is introduced in this paper and therefore lacks empirical data.

4.7.1 Micro-Acceleration

Accelerating a car tips the car body backwards, as does breaking tip it forward. Micro-acceleration takes advantage of this by precise timing of acceleration or breaking. If the car body for whatever reason is bobbing back and forth, rotating about it's center of mass, correct timing of acceleration or breaking can cause it to tilt in the opposite direction, canceling out the bobbing.

4.7.2 Micro-Steering

Turning the wheels of a car will cause the car to turn, followed by some yaw oscillation as the car body continues rotating due to inertia. If the car body is experiencing yaw oscillation, using a short turning session timed 180°off phase with the one experienced, will allow the oscillation to cancel itself out.

4.7.3 Micro-Steering II

Four wheel steering can be used for lane drifting, but it can also be used to give the car an impulse in the Y-direction. If the car body is oscillating in the Y-direction, a short impulse timed correctly can be used to cancel it out.

4.8 Green Wave

When dealing with traffic, green wave refers to coordinated traffic lights timed such that a road can be traversed without the need for breaking[31]. This is achieved by timing the traffic lights such that the next traffic light on the route turns green as it is reached for a given speed. Traffic lights are either dynamic or static. Dynamic traffic lights recognize the current traffic situation using sensors, and uses algorithms to try to resolve it in an optimal way, whereas static traffic lights uses set timers[23]. Especially in the case of static traffic lights, its rules can easily be predicted by enough observation data. In the case of self-driving cars, data is gathered every time a car using the same platform passed by the traffic light, and given a large enough fleet of cars, every static traffic light could thus have a digital copy stored alongside the fleets map service. Given traffic light data, the idea of a green wave can be used by individual cars, instead of simply being a traffic flow strategy.

Dynamic traffic lights are however more unpredictable, as they are dependent upon the current traffic picture, be it an intersection or a more complete picture of several intersections. Their sensor data and algorithms cannot easily be duplicated digitally, however some dynamic traffic lights are currently communicating with buses electronically[110], and others give emergency vehicles priority over other vehicles[17]. If such a line of communication can be established between autonomous vehicles and the traffic infrastructure, the autonomous vehicle will be able to get a glimpse into the inner workings of the juncture and will thus be able to make an informed decision about what the ideal speed is. If traffic light data is released online by the city, the information can simply be downloaded. As traffic lights are a major source of acceleration during city driving, using this information wisely should mitigate motion sickness.

4.9 Projected Trajectory

Diels et al.[28] argues that the reason windows reduce the occurrence of motion sickness is because the brain uses vision of the road ahead to anticipate the movement of the car, and is thus not surprised by the following acceleration. The addition of an horizon is beneficial as shown in ship experiments[95], but anticipation probably plays an important role as well. An interesting approach to increase anticipation is the use of monitors, HUD[2] or VR to show the planned trajectory. If proven useful, the planned trajectory can then be implemented into games or other in-car entertainment systems to reduce the motion sickness level of whomever is using it.

4.9.1 Sound

Spatial orientation is subconscious. It is known that the brain is very good at adapting to new circumstances, so even though it’s not directly supported by our current understanding of motion sickness, there is a chance that the brain can be taught to use sound as an indication on whether the car is going to steer left or right. A person put in an experiment where two different beep sound would cause a rotation to either the left or the right, would soon be able to build a connection between the sound and rotation consciously, and could thus anticipate the movement. If the frequency or amplitude of the sound indicate the level of turning, a person could learn to predict the turn ahead with decent accuracy. According to classical conditioning[42], responses can be taught to the subconsciousness, implying that sound can be added to our spatial orientation model. If it’s proven that brain can adopt sound to its spatial orientation model, the goal becomes to create the least intruding sound image such that it is not deemed annoying.

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[2] Head-up Display

Chapter 5

Streamlining Motion Sickness Testing

As discussed in chapter 3 and 4 there are more than a dozen measures against motion sickness, some known to work but not exactly to which degree, and several that *might* work. The list of measures in chapter 3 and 4 isn't complete, as there are always more undiscovered ideas out there. As discussed in section 5.5.2 several of the measures have tweakable parameters going over a continuous range and many of the measures most likely influence each others results. The end effect is that hundreds, if not thousands of experiment setups should be tested to find the ideal way to construct and drive an AV to minimize motion sickness. With the current experiment paradigm in motion sickness this would be terribly expensive, this chapter focuses on streamlining car sickness testing, such that it can be conducted cheaper, more accurate and in a realistic setting.

5.1 Current Paradigm

Motion sickness testing is primarily done in three ways today.

- Absolute testing, for a given stimuli it is observed to what degree people get motion sick. Examples of this are studies conducted in the 70's identifying which frequency range is the most nauseogenic by measuring the percentage of people puking [78], and in modern days where they measure how nauseogenic rotation is, differing in that researchers today stop when the participants feel miserable [26].

- Comparative testing, two or more stimuli or measures are tested against each other, as various motion sickness levels can be observed for the different scenarios, one scenario can be identified as the better one. An example of this is Förstbergs[36] experiment showing that a 55% tilt compensation is less nauseogenic than 70% tilt compensation in trains.
- Real world studies, for a given commuter line for example one can ask how motion sick the passengers are and measure for example the acceleration experienced. This is a relatively cheap method of testing as one tests people doing what they normally do. It does however introduce bias as passengers have developed habituation to their commuter line, and because those really struggling with motion sickness might have changed mode of transport. An example of this kind of study is one by Turner[99] showing among other things that backward facing seats are more nauseogenic than forward facing seats.

These methods all have their strengths, weaknesses and applications. The biggest differences lie however in cost and control, where absolute and comparative testing are expensive but offer high levels of control, and real world studies are relatively cheap but more loose. In all studies motion sickness is usually measured using questionnaires, both oral or written, as discussed in section 2.8.

5.2 Autonomous Paradigm

Self-driving cars allows for real world scenario testing with the same control of parameters as in a laboratory setting. An AV driving on a closed track can drive in exactly the same manner between test runs as it is controlled with computer precision. The absence of a human driver also cuts costs down, tape recorders and voice recognition programs can be used to record the MS levels of the participants, further reducing the cost of the experiments.

5.3 Participant Preselection

As discussed in section 2.2 motion sickness susceptibility varies among people by a factor of 1:10.000. By using tests such as the MSSQ mentioned in section 2.8 one can do a preselection of subjects such that one can be fairly certain that they are either susceptible, "normal", or not-susceptible. This narrows the variance in the results across people. Additionally genetic testings might tell you how susceptible a person is. A gene has been identified related to MS[62], there are two variants, one 6,3Kb big while the other is 6,7Kb. People with the 6,3Kb variant are 60% more likely to be susceptible to MS. The most reliable method to test how susceptible someone is, would however be to have them do a physical standardized test concerning motion sickness susceptibility. To the authors knowledge no such test has been developed, probably because it is quite a bit more expensive than a questionnaire. In section 5.5 the author proposes a way to include such a test within another experiment such that cost can be kept low.

5.3.1 Animal Testing

Selective breeding or genetic modification is used in for example cancer research to produce mice prone to cancer[81], such that the efficiency of a treatment is easier to discern. If 50% of the mice normally get cancer, a much smaller sample size is needed than if 0,1% of the mice gets cancer. Similarly animals can be used for motion sickness testing, and with selective breeding and/or genetic modification a very homogeneous group of animals can be bred as far as motion sickness susceptibility is concerned. Rats and mice can be used for MS studies[109], rodents lack the capability to vomit, but their MS manifest in other measurable ways. Dogs[24] and cats[54] experience motion sickness in a more similar way to humans as they too are capable of vomiting. Dogs have in fact been used for motion sickness studies for a long time as their response is similar to that of humans[64]. Animal testing can possibly be done cheaper and quicker than with humans, and with the addition of selective breeding and/or genetic modification a very homogeneous group can be tested. As animals lack language however, their motion sickness level is more difficult to discern. If animal testing is preferable to human testing, requires deeper analysis, but it most certainly have some perks.

5.4 Motion Sickness Estimation

According to Förstbergs[36] Net Dose Model described in section 2.7.2, three variables are sufficient to model a persons motion sickness response to a given stimulus. These variables are the individuals susceptibility c_A, MS leakage factor or recovery factor c_L and lastly their threshold dosage D_0 required for symptoms to set in. Following a scale with MS resolution of 0 to 5, and time steps of 5 minutes, this model have given quite good results. As argued in section 2.8 the FMS scale with a MS resolution of 0 to 20 and time steps of 1 minute should allow for more accurate results.

Running an experiment to calculate a person's c_A, c_L and D_0 should yield a much more accurate assessment of their MS susceptibility compared to that which is acquirable through questionnaires, as it is derived through data and not personal assessment. Using this data we should be able to make accurate predictions of their response, at least for the stimuli that yielded the data in the first place. Lets say we develop a standardized MS test, lasting one hour, consisting of 40 minutes of test track autonomous car driving, 5 minutes break time, followed by 15 minutes of continued driving. Firstly this should push the person above their threshold dosage D_0 such that their c_A can be measured, while the break allows their MS level to drop somewhat. The readings in this period might be heavily biased as the relief felt is probably based on that they feel much better than previously, and can therefore be expected to drop below their MS level if they were comparing it with the 0 point. Continuing for another 15 minutes should then make the person nauseous again, allowing us to see how much relief the 5 minute break actually gave, giving an accurate reading of their c_L. Once a persons c_A, c_L and D_0 is calculated, we should be able to accurately estimate their MS level if the same test track autonomous driving exercise continue for another hour. The accuracy of this hypothesis must of course be determined through experimental data, but given that the hypothesis holds true with reasonable accuracy, the following experiment paradigm is feasible.

5.5 Standardized Test

Given that the hypothesis in the previous section is true, one can do a sort of two-in-one experiment. Firstly every test person will be run through an identical experiment consisting of one hour of autonomous driving with a five minute break starting at the 40 minutes mark. After the first hour passes, change some parameter of how the car drives or behaves, be it tilting, driving pattern, or other parameters of interest. Then compare the MS response of the individual with their projected MS response if the stimuli would have remained the same. If the projection has been proven to be accurate, the influence of the parameter tweak should be easily discerned. The main two reasons behind doing a comparative test in one experiment instead of two separate ones are firstly that it will reduce cost, the second reason is that it eliminates the influence of daily mood changes, as comparative testing is usually conducted on separate days.

5.5.1 Isolating the Stimuli Variable

Assuming that motion sickness level M is some sort of product of the stimuli S and the individual experiencing the stimuli I we get $M = S \times I$. For an AV I is outside its control, but S can be minimized. Both S and I consists of many variables themselves, an incomplete list can be found in table 5.1. For a controlled experiment of limited duration most of these factors can be viewed as constant. Nocebo, placebo and other human factors will introduce some uncertainty into any motion sickness model, but hopefully to an acceptable degree. In the I section there are several time dependant variables, but for shorter experiments only adaptation and fatigue is of interest. Adaptation makes a stimuli less nauseogenic with time, and fatigue has the opposite effect. Fatigue has no apparent effect on vibration comfort for experiments lasting less than two hours [66], assuming this holds true for motion sickness as well, fatigue can be neglected for experiments lasting up to two hours. Adaptation has been shown to play a major role in very repetitive stimuli, such as those of waves or oscillating chairs, the author finds it however reasonable to question its importance in a car scenario where the stimuli is primarily governed by road layout and traffic, which causes infrequent forces upon the passengers. Assuming this reasoning is correct, adaptation can be neglected.

Factors influencing MS susceptibility I	
Activity[91]	Adaptation[72]
Age[41]	Electrocortical Therapy[8]
Experience/Habituation[90]	Fatigue[29] [66]
Gender[41]	Genes[62]
Health	Medication[90]
Menstrual cycle[41]	Placebo/Nocebo
Sleep deprivation[29]	Mood*
GVS**[section 3.4]	
Factors influencing MS stimuli S	
Outside view[28]	Route[99]
Tilting[36]	Air quality*[21]
Car suspension*	Driving behavior*[section 4.2]
Projected Trajectory*[28]	Active seats**[section 3.2]
Lane drifting**[section 4.6]	Micro-maneuvering**[section 4.7]
Sound**[section 4.9.1]	

*Probable but not properly documented influence.
**Untested ideas.

Table 5.1: Some factors influencing car sickness.

As S is within the control of the car while I is not, S must be minimized to minimize the motion sickness response M. S equals 0 for no stimuli at all, for example when the car is standing still. Developing a scale for S is beneficial as it makes data and measures easier to compare. An arbitrary choice of $S = 100$ for when the stimuli equals that of no change to driving pattern gives us such a scale.

5.5.2 Parameter Breakdown

To arrive at the estimate that hundreds, possibly thousands of experiments are required to find the ideal way of driving a car to battle motion sickness, the following assumptions were made:

- For parameters with a discrete number of possibilities, all possibilities should be carried out.
- Parameters with a continuous range $[A, B]$ of options, bisection should be carried out, i.e. find the influence of the extremes A, B and the middle point C. Then redefine the range to

$[A, C]$ if $A + C < C + B$, if $C + B < A + C$ then redefine the range to $[C, B]$. Repeat this process until $A \approx C$.

If we limit the experiments down to those that have to do with car behavior, the measures requiring testing, described in this paper, are;

- Driving behavior, continuous variable ranging from an aggressive to a soft driving style.
- Active tilting, continuous variable ranging from 0% to 100% tilt compensation. Due to inertia cars naturally rolls outwards in curves, which might set the lower limit to some negative number. It is also possible that instead of looking at a limit to tilt compensation, one should rather be looking at limiting roll in degrees, roll velocity or some other parameter.
- Route planning, discrete variable containing the most reasonable routes to the destination.
- Projected trajectory, discrete variable containing various methods to visualize the trajectory ahead.
- Lane drifting, continuous variable ranging from 100% steering to 100% drifting.
- Sound, if proven to have influence, it is a discrete variable to find the least intruding sound that still works. If it doesn't work, it's a single experiment.
- Active seats, discrete, possibly continuous variable containing various strategies for how the seats should behave while cornering.
- Micro-maneuvering, contains three measures which all range from 0% to 100% compensation.

It is difficult to estimate how many experiment setups are required for each parameter, as for many of them there exists no data. Given an estimate of five experiments for each parameter however, we get 50 experiment setups. This does however greatly increase in number as acceleration manipulation especially is very likely to influence the results of each other. The ones dealing with acceleration manipulation are driving behavior, active tilting, active seats, lane drifting and micro-maneuvering, which itself contains three different variables. Finding the ideal combination of these requires n^7 experiments, where n is the number of parameters to be tested for each measure in question. For $n = 3$, which might turn out to be low, this leads to 2187 permutations. Given that some of the measures probably show no effect, this number drops. With more advanced statistics this number can likely be further lowered, but it proves the point that finding the ideal car behavior is tremendously expensive using today's methods.

5.5.3 Experiment Setup

To develop a high quality standard several iterations are required, here are the authors proposals for the first iteration.

- **Closed Test Track** - To ensure that traffic doesn't interfere with the experiment it is important that the track is closed off. If the experiment is to become a standard, it is also important that a track which have similar tracks around the world is picked such that it can be reproduced at other locations. If another kind of track must be used, calibration runs can be conducted to see how the track compares to the agreed upon standard track.
- **Autonomous Driving** - Reproducing the same run time and time again is essential to keep parameters constant between tests. Machines excel at repetitive tasks, making this a task best left for an AV. A professional driver might arguably be able to reproduce a driving pattern down to an acceptable margin of error, but hiring such a driver would increase the cost of the experiment significantly.
- **Time Control** - As the time of an experiment increases so does its cost and difficulty in finding participants. Motion sickness is in addition time dependant on several different levels, with symptoms manifesting only after prolonged stimuli. Increasing the time of the experiment should yield higher accuracy up to the two hour mark after which fatigue no longer should be neglected. The proposed experiment of two hours is however a bit arbitrary, and can be expected to change as the standard iteratively improves. Especially the second part of the experiment where stimuli are compared to each other, might prove to require less than one hour to yield results.

- **FMS** - The Fast Motion Sickness Scale described in section 2.8 is deemed to be the best scale currently available by the author, simply because it excels in resolution compared to other scales widely used in MS research. Giving a MS resolution of 0 to 20, and a time resolution of 1 minute, it is the authors recommendation for the standard.

- **Preselection** - People with low MS susceptibility are not expected to become car sick in less than two hours, if their FMS score remains at zero throughout the first part of the experiment, their D_0, c_L and c_A cannot be calculated. If their susceptibility is too high the experiment must likely be aborted. In both cases no usable data can be gathered from the experiment. It is therefore important that a preselection occurs using MSSQ or by other means, to ensure that the experiment produces valuable results.

- **Outside View** - A parameter that can cause a lot of variability in the results depend on where the participants gaze is. It is therefore of importance to control this in some manner. As gaze influence is difficult to quantify, the author recommends using opaque windows on the car such that outside view is completely eliminated, resulting in identical gaze influence between the test runs. This comes with the additional "benefit" of increasing the participants susceptibility as described by the sensory mismatch theory in section 2.6. As the participants susceptibility increase, the time duration of the experiment can essentially be lowered, saving money.

- **Activity** - According to Sivak et al.[91] watching movies and reading greatly increases MS susceptibility, with reading being the most nauseogenic of the two. As increased susceptibility is a good thing in such an experiment, requiring the participant to read a book seems like a good idea. However a short experiment conducted by the author deems this impractical as FMS impairs the reading experience. Watching a movie however seems to be compatible with the FMS, and is therefore the authors recommendation for activity to be conducted in the car. The results of the experiment can be found in Appendix A. In addition to increasing susceptibility, having an activity in the car is required to lower the risk of participants getting sleepy which can greatly impair the results.

- **Recorded Questions** - Putting another person in the car to question the participant introduces human inaccuracy into the experiment, be it inaccurate timing of the question, influence of the mood of the supervisor or otherwise. It also increases the cost of the experiment as supervisors cost money. Having a device automatically ask the participant of their FMS level each minute is therefore the authors recommendation.

- **Voice Recognition** - Using the FMS means that once a minute the participant is required to score their MS level. Audio recording in the car is sufficient to document their answers, to reduce cost of human labor, voice recognition can be used to automate the process of writing down the data points. If the FMS level reaches 15 or higher, the participant should be prompted if he or she would like to end the experiment. Ending the experiment can for example be done with a simple abort button present within arms reach of the participant.

- **Flexibility** - The usability of a standardized experiment depends on it being applicable for a great number of inquiries. Changing the parameters of the car with software is essentially how to ensure this, requiring of course hardware capabilities in the car for whichever parameter that is to be tested.

- **Indoor Climate** - Temperature, lighting and air quality should be kept constant throughout the experiment unless they are the parameters that are in question. Preheating the car and keeping air flow constant should be enough to ensure this. As opaque windows are recommended, lighting should be sufficient to ensure that the participant doesn't grow sleepy.

- **Other Measurements** - Conducting various measurements isn't required to discern if a parameter change is helpful, it might however turn out to be valuable data required to for example develop better mathematical models for motion sickness. Cross referencing acceleration, jerk and rotation with how nauseogenic the stimuli is such an example.

5.5.4 Shared Data

A vast number of experiment runs might be required to find the ideal settings to mitigate MS. In the academic community findings are usually shared, but corporations are known to be more secretive about their research as to keep their competitive edge. If auto manufacturers agree on a standard as well as collaborating on the common goal of mitigating motion sickness, the cost of this research can be split. The competitive edge with such an approach will be dulled, but considering the amount of data required it might be a worthy sacrifice to satisfy the customers.

5.6 Big Data Approach

An unanswered question within the field of motion sickness is if biometric data can be used to accurately assess MS. More information on using biometric data on measuring motion sickness can be found in section 2.8.2, this section will focus on the possibilities that become available if such a method gets developed.

Oral scales such as the FMS are prone to personal bias, requiring some training/explanation before the scale can be viewed as accurate. As biometric data is separate from opinion it can give more objective MS measurements. There are two ways big data can be collected using biometric data, depending on the method which gets developed.

- **Active Measurement** - The user is required to wear a measuring device, but is otherwise free to do whatever he or she wants to during the ride. Measuring devices of this sort might for example take the form of a earpiece[19]. Every car in the fleet would then have to be equipped with such a device, making most sense in the robo-taxi scenario described in section 1.3. Subsidizing passengers by for example lowering the fare price would prompt people to wear the accessory, and given that the service is popular enough, a lot of data can be collected cheaply. This data would of course have to be coupled with accelerometer data from the car, as well as the given parameters used for the ride. Some problems with this approach would be questions about how hygienic it is to share a wearable with other passengers, as well as passengers forgetting to return the accessory to the car before leaving the vehicle. Lastly there might be some bias introduced in the data as only a certain type of person might be willing to wear such a device.

- **Passive Measurement** - This approach assumes that a measuring method which requires no interaction from the passenger is developed, be it advanced camera recognition algorithms or something completely different. The obvious disadvantage of such a measuring device compared to that of active measuring, is that it is further from being developed, and it's unclear if such a technology is at all feasible. Nonetheless, the opportunities that become available with this such a device makes it worthwhile to mention. For every car equipped with such a technology, every single ride will yield data points, for a personal AV this would mean about 70 minutes[74] of data every day, and in the robot taxi scenario it would mean several hours of data every single day.

5.6.1 Self Improving Algorithm

Given a continuous stream of motion sickness data from the passengers of a car, the car itself can start to tweak its parameters until motion sickness reaches a minimum. It must although be noted that due to habituation described in section 2.4, it is likely that people become less motion sick from older parameters which they are already adapted to. To work around the habituation problem, one must therefore be aware of whom is riding in the car and take their car driving history into account before making any judgments. Some methods to do this in a practical sense would be:

- Run different parameters in different cities for say a month, and compare the data between cities. The bias introduced by the cities must of course be accounted for.
- Change the parameters so often that habituation doesn't occur, this will however cause more motion sickness during the phase where the correct parameters haven't yet been established.
- Run the same parameters for every individual for a given number of times, and compare the influence of parameters in chunks. This might cause difficulties with ride sharing where various people in the car could be supposed to have different settings.

As motion sickness varies greatly between people, it makes sense to have the car adapt to its passengers. Given automated data collection, this can be done by calculating the passengers susceptibility, and changing the driving behavior of the car accordingly. In practice this would mean that less susceptible people would experience a faster driving style with higher levels of acceleration, and susceptible passengers would arrive somewhat slower to their target location but with a lower chance of experiencing motion sickness.

5.6.2 Machine Learning

Developing a mathematical model for motion sickness is to create a map that translates a given stimuli to its corresponding MS level. If acceleration, jerk[1], rotational velocity and rotational acceleration is to be part of such a map, we would get the following equation

$$D_{P\Delta} = c_i(t) \sum_n c_{w_n} A_n(h,t) \qquad n \in \{\ddot{x}, \ddot{y}, \ddot{z}, \dot{\phi}, \dot{\theta}, \dot{\psi}, \dddot{x}, \dddot{y}, \dddot{z}, \ddot{\phi}, \ddot{\theta}, \ddot{\psi}\} \quad h \in [0.1\text{Hz}, 0.5\text{Hz}]$$

where $D_{P\Delta}$ is the MS dosage for a given time step, $c_i(t)$ is a product of the individuals MS sensitivity, adaptation rate, and fatigue, and c_{w_n} are the weight curves for the various frequencies in A_n. This formula is complex, but manageable, however it completely ignores factors such as gaze and cross-coupling between the various stimuli which has been proven to be nauseogenic[64]. It is possible that human researchers can construct an accurate model given enough data, but as the way machine learning works is to construct mathematical maps until it finds a good fit[16], it might be the cost-efficient way to go given that big data becomes collectable.

Motion sickness would in this case have about a couple dozen inputs, such as acceleration amplitudes over time, rotation, gaze direction, air quality, parameter control over for example tilting and so on. Its only output would be the motion sickness level. If such a model is developed and it's accurate, it can be used in simulating expected motion sickness levels in the development phase of a new car or a road layout, and would be a very valuable tool in combating motion sickness.

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[1] Time derivative of acceleration

Chapter 6

Conclusion

As an ancient ailment, motion sickness has received a lot of attention over the course of human history. Due to its complex nature however, research into the field is still trying to understand its root causes, as the tools required to do so have only been developed in the later years. Research on how to mitigate motion sickness have been limited for specific modes of transport, although valuable findings have been found. A limitation to such research seems to be the reproducibility of a given stimuli, forcing researchers to instead focus their time and resources on experiments conducted in unrealistic settings. With the invention of autonomous vehicles, the reproducibility of more natural experiments is no longer a hindrance, allowing for a new paradigm in car sickness research.

The most recognized theory of why motion sickness occurs is currently the sensory mismatch theory. The senses primarily responsible for motion sickness are the eyes and the vestibular system, itself consisting of the semicircular canals and the otolith organs. As acceleration is required to trigger the vestibular system, it can be viewed as the source of motion sickness. Several measures can reduce the amount of acceleration required during transport, and more measures can manipulate how the acceleration is perceived by the passengers. The first category mitigates motion sickness according to the current understanding of how it occurs, while the second category involves uncharted territory and requires experimental data before the measures can be judged as helpful or harmful. The measures discussed in this paper are listed in table 6.1.

Measures helpful against MS according to the sensory mismatch theory
Outside view, section 3.1
Medication, section 3.3
Electrocortical Therapy, section 3.5
Driving behavior, section 4.2
Route planning, section 4.3
Habituation, section 4.5
Green Wave, section 4.8
Measures with an unknown influence on motion sickness
Active seats, section 3.2
GVS, section 3.4
Tilting, section 4.4
Lane drifting, section 4.6
Micro-maneuvering, section 4.7
Projected Trajectory, section 4.9
Sound, section 4.9.1

Table 6.1: The measures against motion sickness discussed in this paper.

The fundamental reason behind streamlining a process or developing a standard is to lower cost and/or increase quality. The current experiment paradigm for motion sickness testing is deemed too costly and time consuming by the author for sufficient progress to be made within the field. A proposition for how this can be streamlined is thus made, based on that an autonomous car can drive in the same manner repeatedly. The cars characteristics can be changed in real time using software, also in a repeatable fashion, allowing for comparative testing. If the Net Dose Model developed by Förstberg et al.[36] is assumed to be true, an individuals motion sickness response can be accurately estimated for a given stimuli. A two-part experiment is proposed. The first part is designed to determine the factors which defines the individuals response characteristics. In the second part of the experiment, the persons end motion sickness level is projected using the data collected in the first part. Additionally the stimuli is changed compared to the baseline stimuli, and the difference between the measured motion sickness level and the projected one thus gives data on how beneficial/harmful the parameter change is. The assumptions and consequences of such an experiment paradigm is further discussed in this paper.

Autonomous vehicles are expected to become common within a decade, and among the other changes this will bring, is an expected increase of motion sickness symptoms in the population. As people often seek comfort and health, developing a self-driving car that mitigates motion sickness can therefore be seen as not only a humanitarian goal to reduce suffering, but also as a race to get an competitive edge.

Chapter 7

Recommendations for Further Work

A lot of information exists about motion sickness, but much knowledge is still missing. Many experiments are recommended throughout this paper, below are however the authors recommendations for experimental setups that should be tried, as they are deemed the most important for mitigating motion sickness.

7.1 Motion Sickness Projection

The premise of the proposed standard in section 5.5 is that the Net Dose Model in section 2.7.2 is accurate enough to calculate a persons MS level in the future. To test this hypothesis an experiment must be conducted. Using a test track and a specially equipped autonomous car, first avoid the influence of as many variables as possible. Have the car drive in the exact same manner for every test run, preheat the car to same temperature every time and keep it constant throughout the run, have opaque windows to block out the influence weather and outside view might have, as well as conduct other measures as their need becomes apparent. Have the person watch a movie to increase their MS susceptibility and to keep them occupied, and have them rate their FMS score, as described in section 2.8 once a minute.

First conduct 40 minutes of driving to determine the persons threshold dosage D_0, if the individuals thresholds dosage is not breached within the first 40 minutes, he or she is too resilient against motion sickness to give any valuable data and the experiment can be terminated. If the threshold dosage is breached, do a 5 minute break, followed by another 15 minutes of driving, then calculate their accumulation factor c_A and their leakage factor c_L. Continue for another hour driving in the same manner as previously. If the measured motion sickness level at the end of the experiment corresponds well to the extrapolated MS level, the hypothesis holds true.

7.2 Jerk Influence

The influence of jerk[1] on motion sickness is poorly understood, and should be fairly simple to measure using a simulator setup. To square a sine curve, terms are added according to $sin(x) + \frac{1}{3}sin(3x) + \frac{1}{2n+1}sin(2n+1)$. A square curve is similar to a sine curve in amplitude, but a square curve differs greatly in that its derivative spikes towards infinity when it oscillates. Having acceleration follow a square curve thus causes jerk (its derivative) to spike towards infinity, by scaling the curves to have equal $\int \sqrt{A^2}$, A being the amplitude of the curve, the influence of jerk should be easily discernible by a comparative trial. As an infinite jerk rate might be difficult to obtain due to practical reasons, a finite number of $\frac{1}{2n+1}sin(2n+x)$ terms can be used as its derivative show that jerk would equal the number of terms n times that of the first sine.

7.3 Single turn Influence

Oscillation in the 0,1-0,5 Hz is known to be motion sickness inducing[78], but how this relates to cars is unclear as turns aren't normally periodically spaced. A full oscillation in this spectrum lasts 2 to 10 seconds, whereas the lateral forces from a turn can be viewed as half an oscillation. One hypothesis of the author is thus that if a turn lasts 1 to 5 seconds it's nauseogenic. The 0,16-0,2 Hz range is the most nauseogenic[78], by the same logic a turn lasting 2,5-3 seconds is therefore expected to be the most nauseogenic. Empirical evidence to support this hypothesis would justify using speed control, as discussed in section 4.3 to avoid the most nauseogenic turning duration. A setup to test this hypothesis is to have a car do infrequent turns to the left and the right with straight segments between them.

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[1] The time derivative of acceleration.

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Appendix A

FMS Compatibility

A small experiment with three participants was conducted. The goal of the experiment was to determine the practicability of using the Fast Motion Sickness scale in conjunction with reading or watching a movie. The experiment was conducted using an Audi A8L, and lasted around one hour. Each participant had their own use case, participant A and B were required to read Die Verwandlung by Franz Kafka, while participant C was required to watch the movie Das Experiment by Oliver Hirschbiegel. All the participants were asked to sit in the right back seat of the car, and asked to keep the book or laptop positioned in the lap to limit the view of the outside. Limiting the view of the outside increases the chance of motion sickness as the visual system no longer feeds reliable information to the brains spatial orientation model as described in Chapter 2. As the majority of people wouldn't feel any considerable nausea after one hour of driving, reading or watching movies thus increases the spread in the data, as time required for MS to set in is reduced. Additionally reading and watching movies are realistic activities during autonomous driving. The scale used to measure motion sickness was a German translation of the FMS scale, which ranges from 0-20, but due to a small blunder the one used in the experiment ranged from 1-20. The participants were instructed to report their motion sickness symptoms using this scale, and were told that 1 means they feel good, 5 means they recognize some symptoms, 10 means they don't feel good, 15 means they feel bad and 20 meaning that they have to vomit. The recorded FMS for the participants can be viewed in figure A.1.

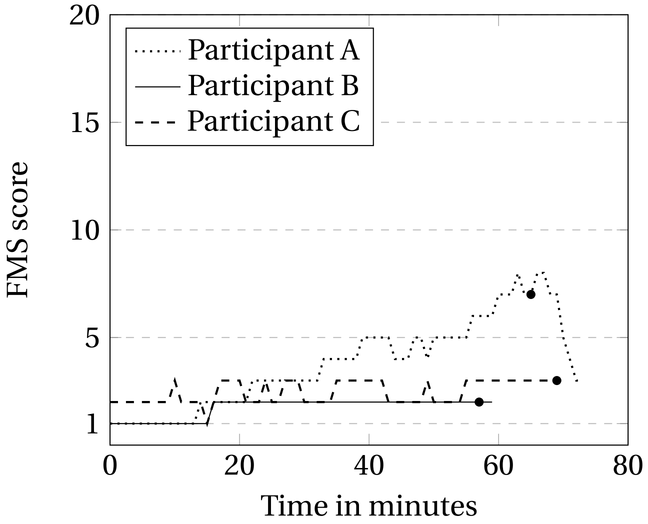

Figure A.1: FMS scores of the participants. The circles represents the end of the test drive. FMS explanation: 1-Feels good; 5-Feel some symptoms; 10-Don't feel good; 15-Feel bad; 20-About to vomit.

Participant A

Participant A was female in her early 20's and experienced motion sickness from the ride, peaking at an 8 at the end of the experiment. Her task was to read Die Verwandlung, and once a minute to report her FMS score as well as which page and line number she was currently reading. This turned out to be very disturbing to her reading experience and somewhat stressful, especially as her motion sickness started kicking in. Line number and page were recorded to track her reading speed. There are two reasons reading speed was of interest, first as a detection system to see if she was following her task, and secondly to see if there were any changes as motion sickness manifested. Reading speed is related to working efficiency, and is therefore something one would be interested in optimizing for autonomous cars. Her reading speed remained about constant throughout the experiment, even as she started losing concentration at the end of the experiment, briefly looking out the windows of the car. This indicates that reading speed in itself is a bad indicator of working efficiency, as it doesn't say anything about how well the content was processed.

Participant B

Participant B was male in his late 20's, and was tasked to read Die Verwandlung and to report his FMS score once a minute, but contrary to participant A he didn't have to report his page and line number except for at the end of the experiment. Not having to check his page and line number once a minute turned out to be less distracting to the reading experience, but he still found having to report his FMS score once a minute a nuisance. After the experiment he was asked how he used the scale, and it turned out his score represented feeling annoyed from the questions and otherwise being tired. No motion sickness was experienced by participant B.

Participant C

Participant C was male in his 50's, and was tasked to watch Das Experiment and simultaneously report his FMS score once a minute. FMS scoring didn't seem to influence the movie experience very much, probably as a lower level of concentration is required to follow a movie. Participant C did not experience motion sickness at all, with his score of 2 reflecting he wanted coffee. Additionally he was the only one that enjoyed the experiment.

Discussion

In addition to the change of parameters discussed in the previous sections, there were two additional changes between the one of participant A and those of B and C. With participant A she was asked once a minute how motion sick she feels, and she was able to answer quite precisely using the scale, perhaps underscoring her symptoms somewhat. The wording "How motion sick are you?" can although induce an nocebo effect, so with participant B and C the wording was changed to "How do you feel?". Although they were instructed to report their FMS score, the participants misunderstood this wording somewhat and their scores represent feeling sleepy and not any MS symptoms. In addition the car has partial autonomous driving capabilities, such as adaptive cruise control and automatic steering while driving on a marked road. The driver was a normal male driver in his mid 20's, and with participant A he was driving the route himself, while with participant B and C he made all the decisions driving, but allowed the auto pilot to take control where applicable. As the author was sitting in the backseat taking notes, he can say that the autopilot was a more comfortable driver than the human. Acceleration, breaking and curving all felt smoother. A question that might arise is if participant A was feeling symptoms due to a combination of poorer driving and nocebo, and the answer is maybe, but most likely it's due to the huge variance in motion sickness susceptibility as discussed in section 2.2.

Conclusion

FMS scoring is not compatible with reading, answering a question once a minute is too disturbing to the reading experience as it requires a high level of concentration. People are capable of doing both simultaneously, but it no longer leads to a realistic reading experience, and the stress induced can affect the scoring itself. FMS scoring is however compatible with watching movies, it can possibly be a bit distracting, but not enough to compromise the experience.