Nina Hofset

An exploratory study: Driving comfort in geometric road design and its research potential

Master's thesis in Civil and Environmental Engineering
Supervisor: Kelly Pitera
June 2019

Master's thesis

NTNU
Norwegian University of Science and Technology
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Kunnskap for en bedre verden

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Preface

This master thesis is written by Nina Hofset, marking the end of the 2-year long master's degree program Civil and Environmental Engineering at Norwegian University of Science and Technology (NTNU). The master thesis is written during the spring of 2019 (January-June) as the final work at NTNU, constituting 30 study point.

This thesis is an exploratory study on driving comfort in geometrical design of roads, focusing on the basic parameter vertical acceleration, to see whether there is a research potential for the topic. Any findings or conclusions are based on available literature and a self-developed driving experiment intended to investigate driving comfort and its connection to vertical acceleration.

I would like to express my gratitude to my supervisor from NTNU, Kelly Pitera, for introducing me to this interesting topic and giving guidance, support and suggestions throughout the semester. Also, my gratitude to co-supervisor Giuseppe Marinelli, from Nord University, for the cooperation and assistance on the experiment. Lastly, my gratitude to the those taking time to participate in the driving experiment providing the comfort data necessary for the thesis.

Trondheim, June 11th, 2019

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Summary

This master thesis is about investigating and conducting research on the topic of road planning, where research and development are considered lacking, with the desire to get updated on the newest knowledge. This thesis is an exploratory study regarding research on driving comfort within geometric design of roads, that investigates the basic parameter vertical acceleration. This parameter is given design values in national road standards based on driving comfort and is an important parameter when designing the road's vertical curvature. The aim was to investigate whether there is a research potential for driving comfort in geometric design. The main motivation for this thesis was the lack of documentation for comfort thresholds and how the design values for vertical acceleration were determined. Such research could be used to argue for a re-evaluation of current design values, impacting future geometric road design.

The objective was to get a better understanding of how driving comfort can be defined and measured and try measuring and quantifying driving comfort to determine a comfort threshold. This was used to see whether the current design values should be re-evaluated. The methods that were used were an extensive literature search and a driving experiment, specifically designed for this thesis. As there seems to be a limited amount of literature on driving comfort considered relevant the topic at hand, the thesis starts off by laying a basis in which the thesis is further built on. This basis is about how to define and measure driving comfort with respect to vertical acceleration. Thus, the literature search was used to gather as much information as possible on driving comfort in road design and vertical acceleration (national road standards). The basis is theoretical based and should be tested to confirm whether the definition can be considered valid and whether driving comfort can be measured. The driving experiment was about driving a road section with several sag curves, with different radii, at different speeds based on what vertical acceleration was chosen to test. These accelerations are theoretical as the speed was calculated using the formula for centripetal acceleration. Participants partaking in the experiment would evaluate driving comfort for the different vertical accelerations. The driving experiment was used to test the practicality of the measuring method, in addition to provide comfort measurement that would be used to examine whether driving comfort could be quantified and used to determine a comfort threshold.

The results from the experiment showed that measuring driving comfort was possible. Driving comfort is subjective and evaluating it can give a large variation in description. A systematic way of evaluating the comfort was tested to obtain useable data. The experiment tested a discomfort rating scale, where numbers corresponded to different levels of discomfort. This proved practical as long as the participants understood what the different discomfort levels represented. The comfort measurements (discomfort ratings) are however useless unless connected to vertical accelerations. The data from the experiment showed that there is a large issue in obtaining good acceleration measurements. The measurements were influenced by noise and road surface conditions (e.g. irregularities and bumps), thus making it challenging to obtain vertical accelerations to connect to comfort measurements. Yet, quantify driving comfort was done by using the theoretical vertical acceleration, which was also possible. Based on the participants' input, there was also a possibility to determine a comfort threshold. However, using the theoretical acceleration is not correct as there is an uncertainty what accelerations actually occurred during the experiment. Multiple factors such as uncertainty connected to the accuracy of radii information, the road surface conditions and vehicle suspensions can give a deviation between measured and theoretical acceleration. Without reliable acceleration measurements, making valid conclusion regarding comfort thresholds is not possible.

Based on the comfort measurements and input form the participants, it could suggest that the design values could be re-evaluated. Making a final conclusion whether they should be requires more research. The acceleration measurements need further processing or other measuring methods could be tested (e.g. simulator). It should be created a database with comfort measurements from a large number of individuals (ideal representation of the population) to quantify comfort and determine comfort thresholds, to make a final decision whether a re-evaluation is necessary. The research potential is there, as driving comfort can be measured, and more research is required to continue the work.

Sammendrag

Denne masteroppgaven er handler om å utføre undersøkelser og forskning innenfor vegplanlegging, hvor forskning og utvikling (FoU) betraktes som manglende, med ønske for en oppdatering basert på nyeste kunnskap. Oppgaven er en undersøkende studie for forskning på kjørekomfort i vegutforming ved å ta utgangspunkt i grunnparameteren vertikalakselerasjon. Denne parameteren er gitt dimensjonerende verdier som er basert på kjørekomfort og er en viktig parameter til krav av vegens vertikale linjeføring. Målet har vært å finne ut om kjørekomfort i vegplanlegging har et forskningspotensial. De største argumentene for denne oppgaven er mangel på dokumentasjon for kjørekomfort-grenser og på hvilket grunnlag de dimensjonerende parameter verdiene ble valgt. Slik forskning kan argumentere for en revisjon av de dimensjonerende verdiene, som kan gi betydning for fremtidig dimensjonering av veger.

Hensikten med oppgaven var å få bedre forståelse for hvordan kjørekomfort kan defineres og måles, og bruke dette til å måle og kvantifisere kjørekomfort for å finne en komfortgrense. Dette ble benyttet videre til å se om grunnparameterens nåværende dimensjonerende verdier bør revurderes. Metodene som ble benyttet var et litteratursøk og et kjøreforsøk, spesielt utviklet for denne oppgaven. Siden det ser ut til at det er begrenset med relevant litteratur om kjørekomfort, starter oppgaven med å legge et grunnlag som oppgaven bygges videre på. Dette grunnlaget går ut på definering og målemetoder for kjørekomfort med hensyn på vertikalakselerasjon. Litteratursøket ble dermed brukt til å prøve å hente inn så mye informasjon som mulig om kjørekomfort i vegplanlegging og vertikalakselerasjon (nasjonale vegstandarder). Grunnlaget er i utgangspunktet teoribasert og bør testes for å kunne bekrefte om definisjonen kan anses som gyldig og om kjørekomfort lar seg måle. Kjøreforsøket gikk ut på å kjøre over en vegstrekning med flere lavbrekk, med forskjellige radier, i forskjellige hastigheter beregnet etter hvilke vertikalakselerasjoner som var ønskelig å teste. Disse akselerasjonene er teoretiske da hastigheten ble beregnet ut ifra formelen for sentripetalakselerasjon. Deltakerne som deltok i forsøket skulle vurdere kjørekomforten ut ifra forskjellige vertikalakselerasjoner. Kjøreforsøket ble brukt til å teste om kjørekomfort lar seg måles, i tillegg til å bidra med komfortmålinger som benyttes til å finne ut om kjørekomfort kan kvantifiseres og til å finne komfortgrenser.

Resultatet fra kjøreforsøket viste at det er mulig å måle kjørekomfort. Kjørekomfort er subjektivt og å vurdere kjørekomfort kan gi stor variasjon i beskrivelser. Dermed ble det benyttet en systematisk metode for hvordan målingene utføres, hvordan de skulle vurdere kjørekomforten, for å få brukbare data. Forsøket testet en ubehagsskala hvor tall korresponderte til forskjellige nivåer av ubehag. Dette viste seg å fungere godt, så lenge man hadde forståelse av hva de forskjellige nivåene representerte. Målingene av kjørekomfort (nivå av ubehag) er derimot ubrukbare med mindre de kobles opp mot vertikalakselerasjon. Resultatet fra kjøreforsøket viste at det ligger et større problem i få gode målinger av akselerasjonen. Målingene var utsatt for mye støy og påvirkninger fra vegforholdene (f.eks. ujevnheter og humper), og dermed vanskelig å få ut vertikalakselerasjonsverdier som kan knyttes til komfortmålingene. Kjørekomfort ble likevel forsøkt kvantifisert etter de teoretiske vertikalakselerasjonene. Basert på deltakernes innspill angående kjørekomfort ble det også mulig å finne en komfortgrense. Å benytte de teoretiske akselerasjonene blir ikke riktig, da det er uvisst om hvilke vertikalakselerasjonen ble som ble testet under forsøket. Flere faktorer som usikkerhet knyttet til riktig informasjon om radiene, vegforholdene og bilens dempere kan gi avvik mellom vertikalakselerasjon og de teoretiske. Uten pålitelige akselerasjonsmålinger kan det ikke dras gyldige konklusjoner angående kjørekomfortsgrenser.

Ut ifra komfortmålingene og innspill fra deltakerne kan det antas at de dimensjonerende verdiene for parameteren kan revurderes. For å finne svar om de bør revurderes krever derimot mer forskning. Akselerasjonsmålingene må bearbeides eller andre metoder for å måle kjørekomfort kan testes (f.eks. muligheter for simulering). Det må også utføres samles komfortmålinger fra en større mengde individer (ideell representasjon av populasjonen) for å kvantifisere kjørekomfort og finne komfortgrenser til å ta en avgjørelse om en revurdering er nødvendig. Forskningspotensiale er tilstede, da kjørekomforten kan måles og det kreves mer forskning for å fortsette arbeidet.

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1 Introduction

As of today, it is considered a lack of new research within road planning and there has been limited research and development within the field for many years. This results in the Norwegian national road standards being based on knowledge and methods from the 1950s and 1960s and might be considered outdated. Even if the physical laws and mathematical formulas used in these standards remain the same, there has been a development in both roads and vehicles, as well as the interaction between road-vehicle-driver. This leads to the question whether the requirements for geometric alignment is sufficient for today and future design (NPRA, 2016; NPRA, 2018a).

In 2016, the NPRA initiated a program called Road Design as a part of their ongoing Research and Development program to update themselves on the newest knowledge and best practice. A part of this program consists of a study and assessment of the current basic parameters used for calculating minimum and maximum values for different alignment parameters. This is to determine whether current basic parameters are sufficient for design today and in the future, by looking at the preconditions which the basic parameters are based on (NPRA, 2016). Some of these alignment parameters use driving comfort when describing design criteria, notably vertical acceleration for designing vertical sag curves. The basic parameter is provided with design values in the national road standards that is considered to maintain comfortable driving when navigating such curves. However, there seems to be a lack of documentation as to how comfort threshold for vertical acceleration and how the design values were determined. There is also a lack of definition regarding driving comfort, with respect to vertical acceleration.

Comfort is a parameter that is challenging to both define and measure. Firstly, comfort is a subjective parameter, where feelings and perspective of comfort or discomfort are dependent on individuals and varies between them. Second, the parameter is affected by physical, physiological and psychological factors and lastly, is a result of the interaction between individual and environment (Beggiato et al., 2018; de Looze et al., 2003). Defining and measuring comfort is dependent on what factors influence the driving comfort and in what situation. Geometric road design requires quantitative data to calculate requirements for vertical and horizontal curvature. As driving comfort is a subjective parameter, there is no way of measuring comfort as quantitative data, like speed or acceleration, with any equipment. Yet, there are ways of defining and to measuring driving comfort. For instance, defining and measuring comfort with regards to sitting comfort/discomfort, which is a research field (ergonomics and seat design) that has been given a lot of focus for many years. Research on driving comfort with respect to geometric road design, however, is lacking.

Due to the lack of and desired for new research in road design, this thesis is an exploratory study investigating whether there is a research potential for driving comfort in geometric road design, with respect to vertical acceleration. This is done by studying driving comfort and the basic parameter vertical acceleration, trying to uncover knowledge gaps and providing some answers.

1.1 Background

The main motivation for this thesis was the lack of both research and information regarding parameters that is based on driving comfort in the geometric design of roads. There was a desire to investigate whether there could, or even should, be conducted research on driving comfort. The basic parameter vertical acceleration is given design values in the national road standards to ensure comfortable riding in sag curves, but there is so additional information about how these design values were determined. There was also a desire to investigate whether the current design values are sufficient for today and future design. Without any information on how design values or comfort threshold, with respect to vertical acceleration, were determined also raised the question about the validity of the design values. As mentioned in the introduction, there has been a development in road, vehicle and the interaction between road-vehicle-driver that could have change some of the preconditions the basic parameters are based on.

1.2 Aim and objectives

The primary focus of this thesis is driving comfort and geometric road design. Due to the lack of research and development (as presented in the introduction), the thesis' aim is to investigate whether there is a research potential for driving comfort in geometric road design. Thus, with in this thesis, there is an attempt to find knowledge gaps and investigate the potential and need for research to fill the gaps. Such research could, for example, be used to confirm if the parameter basis is sufficient for current and future design.

Therefore, the objective of the thesis is to better understand how driver comfort can be defined and measured, in order to get insight into whether comfort thresholds for vertical acceleration within road design standards should be re-evaluated given current and future road and vehicle conditions. Three research questions were constructed to help achieving the thesis' objective:

1 **How can driving comfort be defined?**

2 **How can driver comfort be measured?**

3 **Is it possible to quantity driving comfort and find a comfort threshold?**

The third research question is examined through a driving experiment, which would also allow investigating whether there is any indication suggesting that current comfort threshold should be re-evaluated.

1.3 Structure

The report consists of nine chapters as presented below. The first three chapters present the thesis, theory and methodology. The following three chapters are structured based on the thesis' work. First part was looking at how to define and measure driving comfort. The second part was to develop a driving experiment and then lastly performing it. The last three chapters presents the results from the driving experiment, discussion of the thesis' topics, recommendations and a conclusion.

Chapter 1 – Introduction

Introduction presenting the thesis, background and motivation and the aim, objective and research questions.

Chapter 2 – Theory

Basic theory which is fundamental for the topics discussed later in the report. The chapter gives a short presentation on physical forces affecting driving comfort, geometric road design in Norway and autonomous vehicles.

Chapter 3 – Methodology

Description of the methods that were used to gather data and information; why they were chosen, how the data and information was obtained and how they would contribute to the thesis.

Chapter 4 – Defining and measuring driver comfort

This chapter presents the material that was gathered on driving comfort as a design criterion in geometric road design. It also presents some view on how driving comfort can be defined and measured, based on available literature and knowledge gaps. This is also the basis in which the driving experiment was built on.

Chapter 5 – Driving experiment

The chapter gives a detailed description of how the experiment was developed, including information about the equipment, test area and how driving comfort would be measured etc.

Chapter 6 – Executing the driving experiment

This chapter give a short review from when the driving experiment was performed, with a brief presentation of the final experiment procedure.

Chapter 7 – Results, analyzing and discussion

The measurements, comfort and vertical acceleration, from the driving experiment are presented, processed and analyzed. The results are also discussed within this chapter.

Chapter 8 – Discussion

Discussion on the different topics presented in the previous chapters centered round the driving experiment, driving comfort's definition and autonomous vehicle, but also looking at implications and future work.

Chapter 9 – Conclusion

This chapter finishes off the thesis with a short summary and addresses the thesis with respect to the aim and objective.

2 Theory

The primary topics of this thesis are driving comfort and road design. The purpose of this chapter is to give a fundamental understanding for each of these. That includes basic information on physical forces that can influence driving comfort and how roads are geometrically designed in Norway. The information on road design is from the Norwegian Public Road Administration's published road standards and guidelines. The presented material is considered important as it can be used for elaboration and discussion later in the thesis, requiring this basic knowledge. The chapter ends with a short section with general information about the thesis' secondary topic, autonomous vehicles.

2.1 Physical laws

Both driver and passengers in a moving vehicle are under constant influence of forces caused by the vehicle's movements. This section provides some information on acceleration, centripetal force/acceleration and vibration, which can influence driving comfort.

Acceleration/deceleration

Acceleration and deceleration are terms used in everyday life often associated with increase or decrease of speed, whether it's vehicle, bicycles etc. The term speed is the distance travelled per time unit [km/h, m/s], describing how fast an object is moving. Speed is a scalar quantity and is the magnitude of an object's velocity. Velocity is a vector quantity, meaning the movement of an object has a magnitude (the speed) and a direction. Acceleration is the rate of change in the object's velocity, change in speed (magnitude) and/or direction. This rate of change in velocity can occur in the longitudinal (x-axis), lateral (y-axis) and/or vertical (z-axis) direction. This change in speed (and direction) have an impact on driving comfort. Accelerating a vehicle pushes the vehicle occupants back into the seat and decelerating presses the occupants towards the front of the vehicle into the seat belts (see Figure 1). The higher the acceleration/deceleration, the more intense the effects on the occupants (Freedman and Young, 2012).

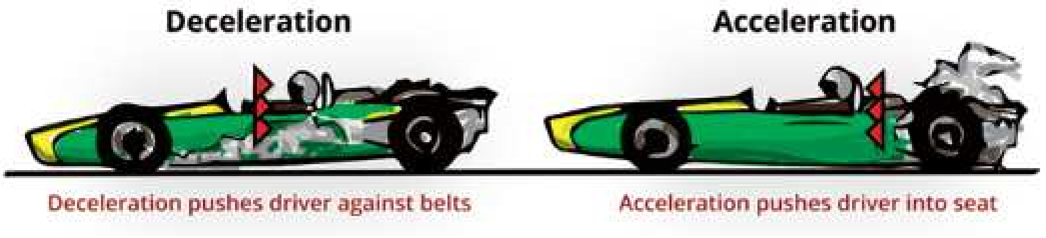


Figure 1: Deceleration and acceleration (longitudinal axis) and how it affects driving comfort (Clip2Art, 2019)

Centripetal force/acceleration

Centripetal force, also called center-seeking force, is a force that allows an object to travel through a curved path. The object will experience an acceleration due to the velocity's change in direction, even if the speed is constant. By looking at a vehicle travelling through a curve at a constant speed, the acceleration works perpendicular to the velocity's direction, towards the center of the curve. This is illustrated in Figure 2 (c) and called a uniform circular motion. A change in the speed will cause an additional acceleration component in the same direction as the velocity, and the acceleration will no longer work towards the curve center. This is illustrated in Figure 2 where a vehicle is (a) speeding up and (b) slowing down. However, even if there is as change in speed, there is still a component of acceleration working towards the center of the curve.

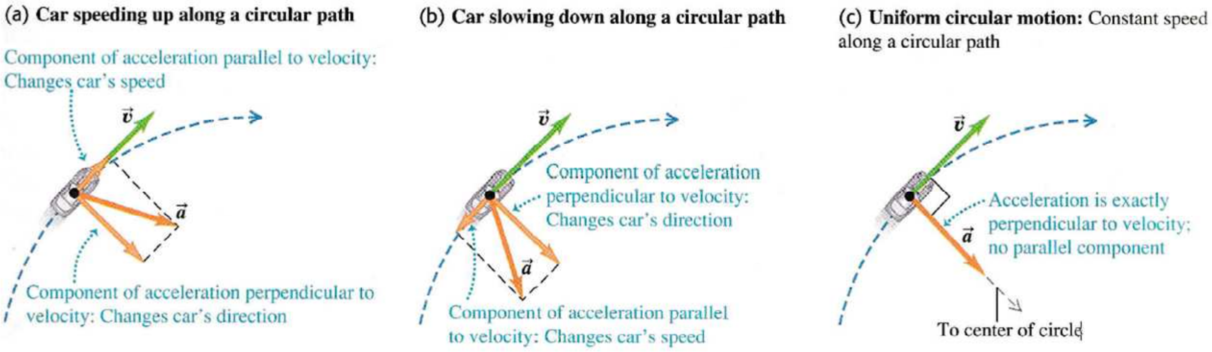


Figure 2: Illustration of acceleration when vehicle is (a) speeding up, (b) braking and (c) at a constant speed (Freedman and Young, 2012, p. 85).

The equation for calculating an object's centripetal acceleration at a constant speed is expressed as (Freedman and Young, 2012, p. 86):

$$a_{centripetal} = \frac{v^2}{R}$$

$a_{centripetal}$ is the centripetal acceleration [m/s^2]
v is the speed of the object [m/s]
R is the curve radius [m]

This acceleration is called centripetal acceleration as it works in the direction of the center of the curve, assuming a uniform circular motion. Centripetal acceleration affects driving comfort as the velocity's direction changes, giving a feeling of being pushed to the side of the vehicle in the opposite direction of the acceleration. The higher the speed and/or smaller the curve radius, the higher acceleration and the effects are intensified.

This centripetal acceleration is a result of the centripetal force. For an object to be able to accelerate, it needs to be subjected to a physical force F (Newton's first law). In order for the vehicle to accelerate towards the center, the force F must also work in the same direction (Newton's second law). This force occurs due to friction and superelevation (see 2.2.4 Basic parameters), causing the centripetal acceleration. Without this force, the vehicle would just continue straight ahead in the velocity's direction ($\vec{v}$) (Freedman and Young, 2012).

Vibration

All occupants inside a vehicle are exposed to some form of vibration, whether it is from the road surface, movement of the vehicle (maneuvering) or in-vehicle sources. Vehicles are relatively rigid, meaning the vibration will transfer to the driver or passenger through the seat or steering wheel. Figure 3 shows some sources of vibration and how it transfers from road/vehicle to driver. Suspensions in vehicles are used as isolation systems to absorb and prevent some of the vibration transferring to the driver or passengers.

Vibration is characterized by magnitude, frequency, direction and duration, and how humans respond to exposure is dependent on those four characteristics. Low magnitude can cause annoyance and be distracting, while higher magnitudes can cause discomfort. Duration is another important factor as longer exposure can lead to more discomfort. In worst cases, vibration can cause health risks like chronic or acute injuries and pains in neck, lower back and shoulders due to longer periods of exposure. Vibrations can occur in longitudinal (x-axis), lateral (y-axis) and vertical (z-axis) direction, and the magnitude can be calculated from acceleration presented in m/s^2 rms (root mean square) (Mansfield, 2012).

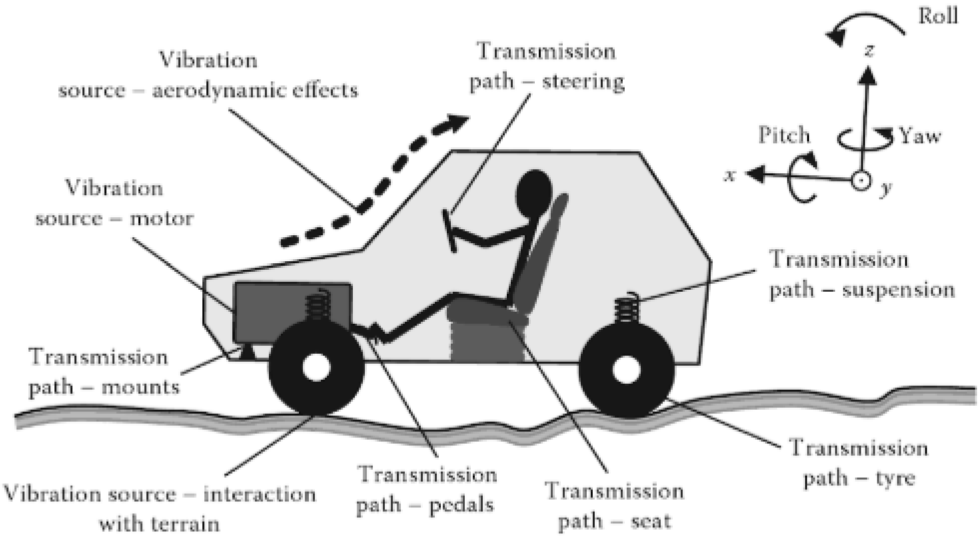


Figure 3: Sources and transmissions of vibration from road/vehicle to driver (Mansfield, 2012, p. 79).

2.2 Road design in Norway

Since the 1960s, transport of timber was carried out with the use of vehicles which resulted in major challenges in terms of bearing capacity, safety and wear on the roads. The need for roads with better bearing capacity increased, and an increase in traffic accidents led to actions aiming to increase the safety by separating the traffic. As the expertise of road design was limited in Norway, new impulses and methods were needed to be able to cope with the new challenges. As a result, road design in Norway was heavily influenced by methods from other countries, e.g. the US (NPRA, 2009).

2.2.1 Handbooks

Road design in Norway are based on handbooks published by the Norwegian Public Road Administration. There are two levels of published handbooks: level 1 which are standards and level 2 which are guidelines. Standards are documents containing information on requirements and the most important handbooks. These standards are based on framework provided by Public Roads Act, Road Traffic act and instructions from Ministry of Transport and Communications and apply to all public roads and streets. Guidelines are standards' supporting documents with source material the standards' requirements are based on (NPRA, 2019a).

In road design, handbook N100 *Road and street design* is an example of a standard, with guidelines such as handbook V120 *Premises on geometric design of road* and handbook V121 *Geometric Design of Road and Street Intersections.* There are also standards for asphalt building (handbook N200), tunnels (handbook N500), operation and maintenance (handbook N600) etc. with accompanying guidelines (NPRA, 2019a). The handbooks most relevant to this thesis are handbooks N100 and V120.

Handbook N100

Handbook N100, *Road and street design*, is a road standard for geometric road design and made from the basis of Ministry of Transport and Communications' regulations by the Public Road Act. The regulations provide a general framework for the road's design and standard, applying to all public roads. The standard consists of five parts of requirements: standard for building and re-building of streets (part B), standard for building new roads (part C), standard for improvement of existing roads (part D), design of intersection, bus stops, solutions for pedestrians and cyclists and lighting for roads and streets (part E) and design basis, e.g. vehicles, pedestrians and cyclist, in road and street design (part F). Figure 4 shows one of a design tables from Part C in N100, with requirement for parameters in both horizontal and vertical curvature (NPRA, 2014a).

In 2018, a new N100 was set to replace the handbook published in 2013. A version was sent to Ministry of Transport and Communications in December 2017 which can be used until the handbook is fully approved, with the exception of some design classes which have not yet been completed (NPRA, 2018b). The handbook will be published along with the other existing handbooks on their publication site when the remaining design classes are completed. The final, completed version of N100 that will replace the 2013 version was released in March of 2019, during the thesis work. Therefore, any figures and data from N100 is gathered from the 2013 version.

Horisontalkurvaturparametre							Vertikalkurvaturparametre					
R_h [1]	Nabokurve		Klotoide	Siktlengde [2]			$R_{v,høy}$	$R_{v,lav}$	Overhøyde	Stigning	Res. fall	
	Min	Maks	Min	Stopp [3]	Δst1	Δst2	Min	Min	e	Maks	Maks	Min
700	700		245	255	-35	55	13600	3400	8,0	6,0	10,0	2
800	700		255	260	-36	56	14100	3500	7,5	6,0	10,0	2
900	700		260	265	-36	57	14600	3500	7,0	6,0	10,0	2
1000	700		265	265	-36	57	14600	3600	6,5	6,0	10,0	2
1200	700		270	270	-37	58	15200	3600	5,6	6,0	10,0	2
1400	700		270	275	-38	59	15800	3700	4,7	6,0	10,0	2
1600	700		270	275	-38	59	15800	3700	3,7	6,0	10,0	2
≥ 1750	700		270	275	-38	59	15800	3700	3,0	6,0	10,0	2

Figure 4: Table C.11, design table for H9, from handbook N100 (NPRA, 2014, p 57).
Horisontalkurvaturparametre – Horizontal curvature parameters
Nabokurve – Neighbour curve
Klotoide – Clothoid
Siktlengde – Sight distance
Vertikalkurvaturparametre – Vertical curvature parameters
$R_{v,høy}$ / $R_{v,lav}$ – Verical curve radius (crest/sag)
Overhøyde – Superelevation
Stigning – Grade
Res.fall – Resulting fall

Handbook V120

Handbook V120, *Premises of geometric road design*, is one of the guidelines for N100. It contains the source material which handbook N100 part C and D is based on, by providing explanation of the formulas and the parameters used in those formulas, giving the max. and min. values presented in the design table from Figure 4. The handbook is divided into chapters with information on basic parameters, alignment, cross-section, sight, design classes, overtaking and tunnels and bridges. The minimum requirements to geometric design are based on the following driving and road conditions: wet road (ice free), daylight and free driving (no queues) (NPRA, 2014b).

2.2.2 Basic terms

The basic parameters in handbook V120 used in the formulas varies depending on three factors, which gives varied requirements for geometric design. Those factors are road function, AADT and speed limit. Information is obtained from Hovd (2014a) and NPRA (2014a; 2014b).

Speed limit

The Norwegian handbooks says the speed limit varies from 30 km/h to 100 km/h for the different design classes presented in handbook N100. Some of the elements on the roads are designed for a speed larger than the speed limit, called *design speed*. There are two additional speeds added to the speed limit, which are then used in the calculations.

Speed addition (NOR. fartstillegg) varies from 0-15 km/h dependent on assessment of risk and consequence (see **Risk** below). *Speed profile addition* (NOR. fartsprofiltillegg) accounts for that the driver, based on experiences, drive at a higher speed with increase road standard. When increasing a horizontal curve radius, people tend to drive at faster. This addition varies from 0 km/h to 5 km/h and are compensated for in the tables in N100.

Road function

Different roads have different functions. In Norway, the different functions can be divided into four different road types:

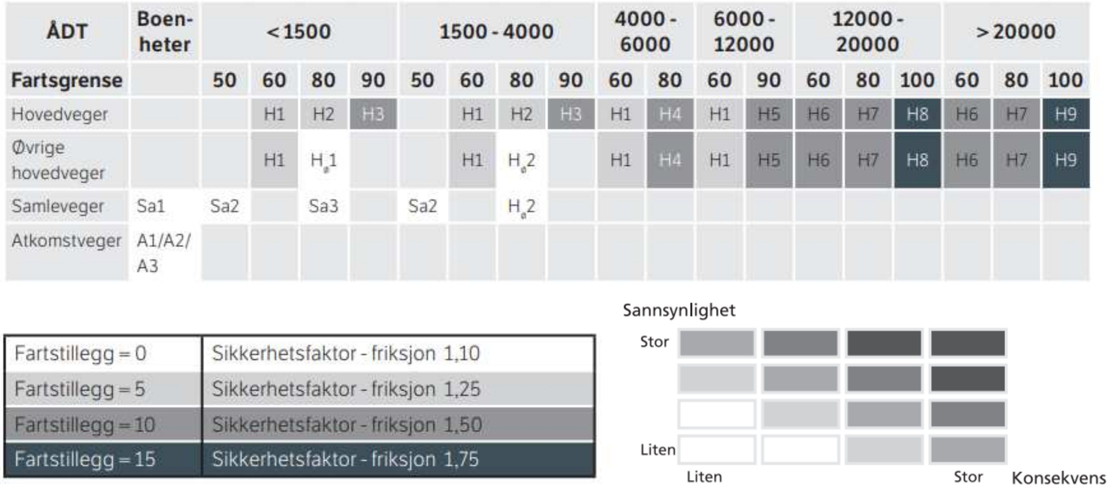
- *Main roads* (NOR. hovedveger) connect different regions, as well as connecting Norway to other countries.
- *Other main roads* (NOR. øvrige hovedveger) connect different districts, cities and city neighborhoods.
- *Collector roads* (NOR. samlerveger) are used as a connection road within districts, between different neighborhoods, and connect access roads to main roads.
- *Access roads* (NOR. adkomstveger) provide access to individual properties, industrial areas, etc.

AADT

Annual average daily traffic (AADT) is a measure of how many vehicles passes a specific point on the road in 24 hours. This is calculated by counting the number of vehicles passing a point on the road all through the year and dividing that number on the number of days within a year.

Risk

Risk analysis is used when looking into road design and is assessed based on probability and consequence. In roads, probability is connected to traffic volumes, while consequence is connected to speed. Higher traffic volumes give a higher chance of an accident occurring, and higher speed leads to more severe consequences, therefore higher the risk. These assessments provide speed addition and a safety factor (for friction) which are used when designing roads. Figure 5 presents the additional speeds and safety factors for the different design classes:



ÅDT	Boenheter	<1500				1500 - 4000				4000 - 6000		6000 - 12000		12000 - 20000			>20000		
Fartsgrense		50	60	80	90	50	60	80	90	60	80	60	90	60	80	100	60	80	100
Hovedveger			H1	H2	H3		H1	H2	H3	H1	H4	H1	H5	H6	H7	H8	H6	H7	H9
Øvrige hovedveger			H1	$H_{ø}1$			H1	$H_{ø}2$		H1	H4	H1	H5	H6	H7	H8	H6	H7	H9
Samleveger	Sa1	Sa2		Sa3		Sa2		$H_{ø}2$											
Atkomstveger	A1/A2/A3																		

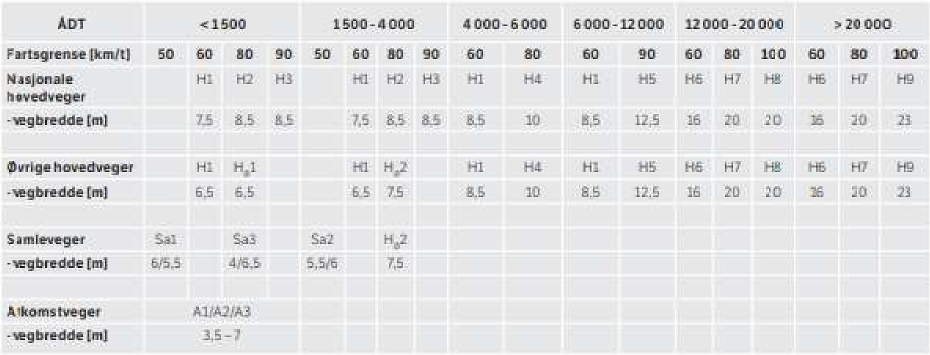
Fartstillegg = 0	Sikkerhetsfaktor - friksjon 1,10
Fartstillegg = 5	Sikkerhetsfaktor - friksjon 1,25
Fartstillegg = 10	Sikkerhetsfaktor - friksjon 1,50
Fartstillegg = 15	Sikkerhetsfaktor - friksjon 1,75

Figure 5: Speed addition and safety factor according to design classes, and risk matrix. The darker the color, the higher the risk (NPRA, 2014b, p. 54).

Hovedveg – Main road
Øvrige hovedveger – Other main roads
Samleveger – Collector roads
Atkomstveger – Access roads
Fartstillegg – Speed addition
Sikkerhetsfaktor – Safety factor
Friksjon – Friction
Sannsynlighet – Probability
Konsekvens – Consequence

Road classes

Roads are divided into different road classes (design classes) dependent on three factors: function, speed limit and AADT. There are nine design classes for main roads (H1-H9), two other main roads (Hø1-Hø2), three collector roads (Sa1-Sa3) and three access roads (A1-A3). Figure 6 show what design class to used dependent on function, speed limit and AADT.



ÅDT	< 1500				1500 - 4 000				4 000 - 6 000		6 000 - 12 000		12 000 - 20 000			> 20 000		
Fartsgrense [km/t]	50	60	80	90	50	60	80	90	60	80	60	90	60	80	100	60	80	100
Nasjonale hovedveger		H1	H2	H3		H1	H2	H3	H1	H4	H1	H5	H6	H7	H8	H6	H7	H9
- vegbredde [m]		7,5	8,5	8,5		7,5	8,5	8,5	8,5	10	8,5	12,5	16	20	20	16	20	23
Øvrige hovedveger		H1	H$_a$1			H1	H$_a$2		H1	H4	H1	H5	H6	H7	H8	H6	H7	H9
- vegbredde [m]		6,5	6,5			6,5	7,5		8,5	10	8,5	12,5	16	20	20	16	20	23
Samleveger	Sa1		Sa3		Sa2		H$_a$2											
- vegbredde [m]	6/5,5		4/6,5		5,5/6		7,5											
Atkomstveger	A1/A2/A3																	
- vegbredde [m]	3,5 – 7																	

Figure 6: Table C1 from N100 showing design classes dependent on function, speed limit and AADT (NPRA, 2014, p. 34).

Nasjonale hovedveger – National main roads
Øvrige hovedveger – Other main roads
Samleveger – Collector roads
Atkomstveger – Access roads
Fartgrense [km/t] – Speed limit [km/h]

2.2.3 Parameters in road design

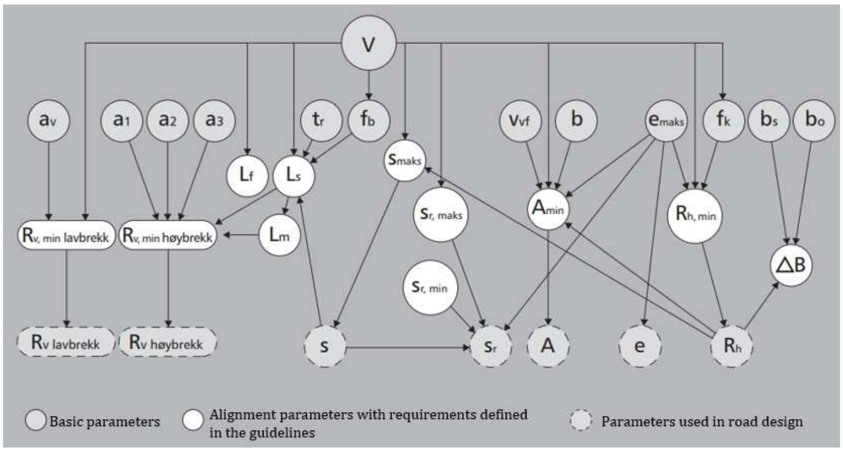


Figure 7: Connection between basic parameters and alignment parameters in road design in handbook V120 (NPRA, 2014b, p. 11)

Figure 7 from handbook V120 shows the different parameters used when designing the road's alignment. There are different sets of parameters. Basic parameters are parameters that serves as variables to determine alignment parameters. Alignment parameters are the guideline parameters (minimum and maximum values) used to design the horizontal and vertical alignment of the road, based on the basic parameters. Then the parameters used in the actual road design (grey circles) are based on the alignment parameters. Figure 7 also shows the connections between basic parameters and alignment parameters. Both the basic and alignment parameters are described below, starting with the alignment parameter to provide context. All information is obtained from NRPA (2014b).

Alignment parameters

The geometric design consists of horizontal and vertical alignments creating a space curve, see Figure 8. Elements in the horizontal alignment consist of straight lines, circles and clothoids, and elements in the vertical curvature consist of grades and vertical curves like circles, parables or clothoids. Values for each of these elements are provided by design tables from N100, as illustrated in Figure 4.

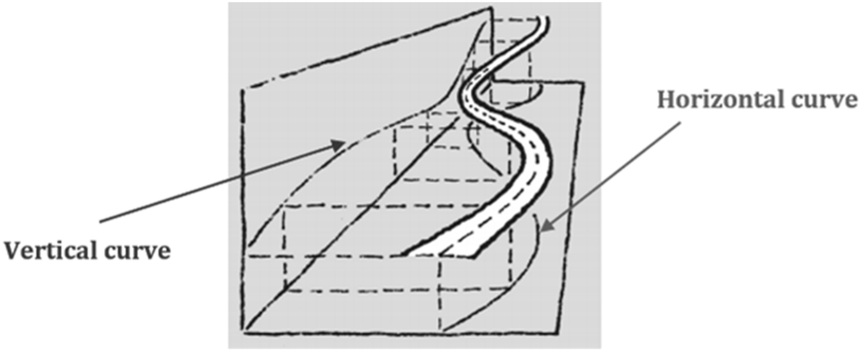


Figure 8: Horizontal and vertical alignment making a space curve (NPRA, 2014b, p. 33).

Horizontal curve radius

Horizontal curves are used as transition between two road sections with different directions. The calculation of minimum radius for horizontal curves is based on the desire for equilibrium between the forces acting on the vehicle: N – normal force, G – gravitational force and F – friction between wheel and road (see Figure 9). The minimum radius is calculated using the following equation (NPRA, 2014b, p. 24):

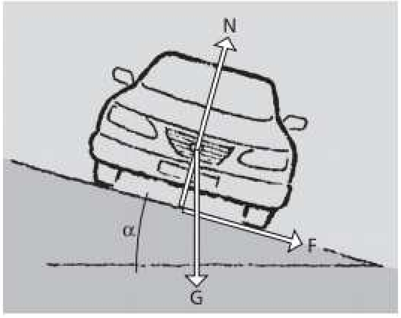


Figure 9: Forces action on a vehicle in a horizontal curve (NPRA, 2014b, p. 24).

$$R_{h,min} = \frac{v^2}{9{,}81 \times (e_{max} + f_k)} = \frac{V^2}{127 \times (e_{max} + f_k)}$$

V [km/h] and v [m/s] is the design speed

e_{max} is the maximum superelevation [m/m]

f_k is the side friction

Clothoid

Clothoids are used to get a smooth transition between a straight line and a horizontal curve or two horizontal curves. Clothoids also provide the build-up of superelevation (see **Basic Parameters**) in a curve, which leads to the parameter to be designed based on requirements for the length of superelevation build-up. Minimum clothoid parameters are calculated by the following equation (NPRA, 2014b, p. 25):

$$A_{min} = \sqrt{R_{h,min} \times L_{0,min}}$$

where minimum length $L_{0,min}$ (see Figure 10) is calculated from:

$$L_{0,min} = \frac{b \times V \times e_{max}}{3{,}6 \times v_{vf}}$$

A_{min} is the minimum clothoid parameter [m]

$R_{h,min}$ is the minimum horizontal curve radius [m]

$L_{0,min}$ is the necessary length to build up superelevation from 0 to e_{max} [m]

b is the axle distance [m]

V is the design speed [km/h]

e_{max} is the max superelevation [m/m]

v_{vf} is the relative vertical speed [m/s]

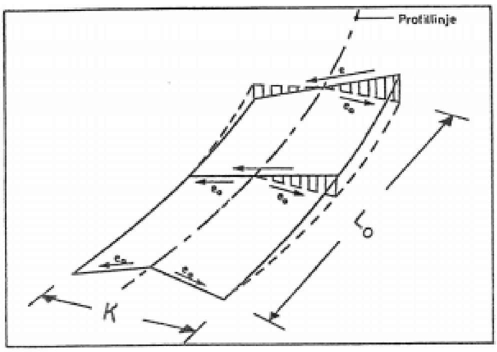


Figure 10: Minimum length for superelevation build up (Hovd, 2014b, p. 7).

Sight distances

There are three types of sight distances: (1) stopping sight distance, (2) meeting sight distance and (3) overtaking distance. The required sight distances are to be met along the entire road and are the design criterion for some of the alignment parameters.

The stopping sight distance is the necessary sight distance for a driver to be able to stop the vehicle when observing an obstacle on the road. The distance consists of two parts, the reaction distance and braking distance. The reaction distance corresponds to the distance driven from the moment the driver observes the obstacle and starts braking. The braking distance is the distance needed for the vehicle to make a full stop.

Reaction distance, L_r (NPRA, 2014b, p. 46):

$$L_r = t_r \times \frac{V}{3{,}6} = 0{,}278 \times t_r \times V$$

L_r is the reaction distance [m]
t_r is the reaction time, fixed value [2 sec]
V is the design speed [km/h]

Braking distance, L_s (NPRA, 2014b, p. 46):

$$L_b = \frac{1}{2} \times \frac{\left(\frac{V}{3{,}6}\right)^2}{9{,}81 \times (f_b + s)} = \frac{V^2}{254{,}3 \times (f_b + s)}$$

L_b is the braking distance [m]
V is the design speed [km/h]
f_b is the braking friction
s is the grade [%]

Stopping sight distance (NPRA, 2014b, p. 46):

$$L_s = L_r + L_b = 0{,}278 \times t_r \times V + \frac{V^2}{254{,}3 \times (f_b + s)}$$

The meeting sight distance is the necessary sight distance for a driver to be able to stop when observing another vehicle in the opposite direction and should be long enough for both of the cars to be able to stop. The meeting distance is two times the stopping distance with a safety margin of 10 meters (NPRA, 2014b, p. 46):

$$L_m = 2L_s + 10$$

L_m is the meeting sight distance [m]
L_s is the stopping sight distance [m]

Overtaking/passing sight distance is the minimum sight distance a driver needs to have to the opposite traffic the moment deciding to perform an overtaking, in a safe and responsible way. The distance is calculated using a calculation model and is provided in handbook N100.

Vertical curve radius

Vertical curves are used as transition between two adjacent slopes. There are two different vertical curves, shown in Figure 11, crest (top) and sag (bottom) curves. The figure also shows crest curve with transition between positive-negative grade and positive-positive grade, and sag curves with negative-positive grade and negative-negative grade.

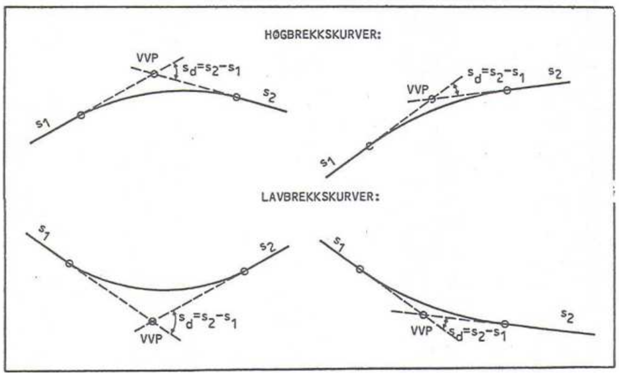


Figure 11: Vertical curvatures: crest curves and sag curves (Hovd, 2014b, p. 11).

Crest curves are convex curves and designed based by requirements for sight distances. The required sight distance is dependent on the design class and calculated as shown above. Roads with one lane are designed based on requirements for meeting sight distance, and roads with two lanes, or more, are designed based on requirements for stopping sight distance. The minimum curve radius is calculated as (NRPA, 2014b, p. 32):

$$R_{h,min} = \frac{1}{2} \times \left(\frac{L_k}{\sqrt{a_1} + \sqrt{a_{2/3}}} \right)^2$$

$R_{v,min}$ is the minimum vertical radius for crest curves [m]
L_k is the requirements for sight distance L_s or L_m [m]
a_1 is the eye height [1,1 m]
a_2 is the height of object, used for stopping distance [0,25 m]
a_3 is the height of vehicle, used for meeting distance [1,25 m]

Sag curves are concave curves and designed based on driving comfort. Sag curves can also be designed by stopping sight distance for headlights, but as roads are designed for daylight driving, driving comfort is the deciding factor (NRPA, 2014b, p. 32):

$$R_{v,min} = \frac{v^2}{a_v} = \frac{\frac{V^2}{3{,}6^2}}{a_v} = \frac{V^2}{12{,}96 \times a_v}$$

$R_{v,min,\ lavbrekk}$ is the minimum radius for sag curves [m]
V is the design speed [km/h]
v is the design speed [m/s]
a_v is the vertical acceleration [m/s^2]

Other alignment parameters

Grades (s) of the road are given maximum values dependent on design class and by considering accessibility for heavy vehicles. Maximum values vary from 5-8% for the different design classes. Road widening (ΔB) is widening of the road in horizontal curves due to vehicles axle properties, particularly to heavy vehicles. Figure 12 illustrates why road widening is important for heavy vehicles like buses and trucks.

Resulting fall ($s_{r,max}$ and $s_{r,min}$) is calculated as the hypotenuse of longitudinal grade and cross fall. The minimum value is to ensure sufficient drainage off the road, while maximum values considers accessibility and vehicles avoid slipping off the road. Maximum resulting fall is set 10% for main roads, and between 9,5-11,3% for other design classes. Minimum value for all design classes is 2%.

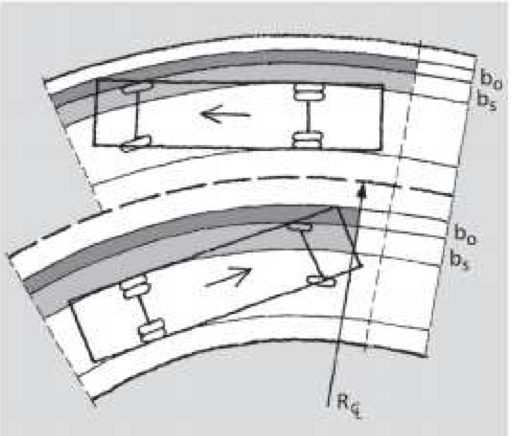


Figure 12: Illustration of road widening in horizontal curves (NPRA, 2014b, p. 44).

Basic Parameters

The basic parameters are parameters that are used in the formulas for calculating the minimum and maximum values. There is a variation of basic parameters where some are constant variables, while others are related to the vehicle, driver and the road.

Design speed

The design speed (V) is used for calculating minimum values for most of the alignment parameters and is the speed limit with the additional speeds. See **Speed limit** (page 13).

Vertical acceleration

Vertical acceleration (a_v) is a parameter used to find the minimum vertical curve radius in sag curves, which takes driving comfort into consideration. Handbook V120 presents fixed values for the vertical acceleration for new road and improvement of existing roads. These values are between 0.3 and 0.5 m/s^2 for new road and 0.5 and 1.0 m/s^2 for improvement of existing roads. The former value applies for main roads and the latter for collector and access roads.

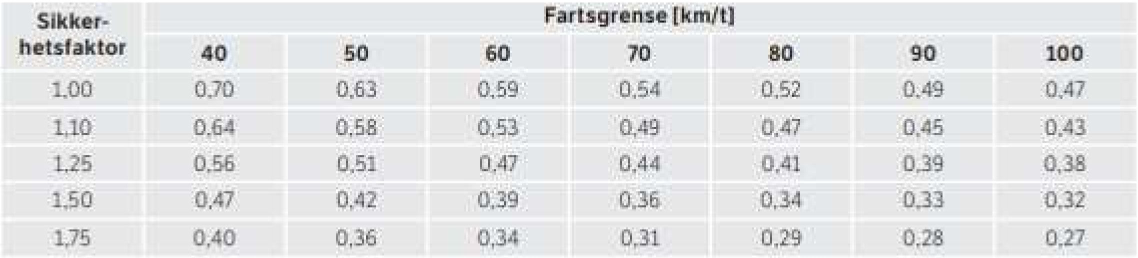
Superelevation

Superelevation (e) is the cross fall of the road in horizontal curves and is one-sided and varies between 3-8%, see Figure 13. Large curve radius requires less superelevation. The highest superelevation is set to 8% so vehicles don't slide off the road in slippery conditions. This max. value is used in calculation of horizontal curve radius.

Figure 13: Superelevation (one-sided cross fall) between 3-8% (NPRA, 2014b, p. 37).

Friction

Friction (f) consists of braking and side friction. Braking friction (f_b) is used to decelerate the vehicle speed or brake the vehicle to a stop. The side friction (f_k) causes the side forces in horizontal curves, allowing the vehicle to travel through the curve. Design values for braking and side friction are dependent on the speed limit and safety factor, provided in V120, as shown in Figure 14.



Sikker-hetsfaktor	Fartsgrense [km/t]						
	40	50	60	70	80	90	100
1,00	0,70	0,63	0,59	0,54	0,52	0,49	0,47
1,10	0,64	0,58	0,53	0,49	0,47	0,45	0,43
1,25	0,56	0,51	0,47	0,44	0,41	0,39	0,38
1,50	0,47	0,42	0,39	0,36	0,34	0,33	0,32
1,75	0,40	0,36	0,34	0,31	0,29	0,28	0,27

Figure 14: Table 2.9 showing braking friction (fb) for different safety factors and speed limits (NPRA, 2014b, p. 20).

Relative vertical speed

This parameter is used when calculating the minimum clothoid parameters, and the distance from cross fall (3%) to superelevation (3-8%). The parameter is defined as the difference in vertical speed for wheels on the same axle. This is due to the lane rotating round the center line when superelevation increase or decrease. Values are chosen based on driving comfort, with 0.05 m/s for main roads and 0.06 m/s for collector and access roads.

Other basic parameters

Table 1: Other basic parameters used as variables when calculating minimum and maximum values for alignment parameters, with short description.

Basic parameter		**Comment**
Reaction time	t_r	See *Stopping sight distance*
Eye height	a_1	See *Horizontal curvature*
Height of object	a_2	See *Horizontal curvature*
Height of vehicle	a_3	See *Horizontal curvature*
Wheel distance	b	Parameters used in calculating min. clothoid parameter
Overhang	b_o	Used to calculate road widening, see Figure 12
Tire track increase	b_s	Used to calculate road widening, see Figure 12

2.3 Autonomous vehicles

Autonomous vehicles, also called automated or driverless vehicles, are vehicle that are able to perform the all the driving tasks themselves without the need of a human driver. Automation of vehicles is divided into six different automation levels defined by the SAE (Society of Automotive Engineers) and referred to as SAE level. The different levels of automation are shown in Figure 15 from “no automation” to “full automation”. A definition of each of the six level are presented below, provided by NHTSA (National Highway Traffic Safety Administration) form the United States Department of Transport.

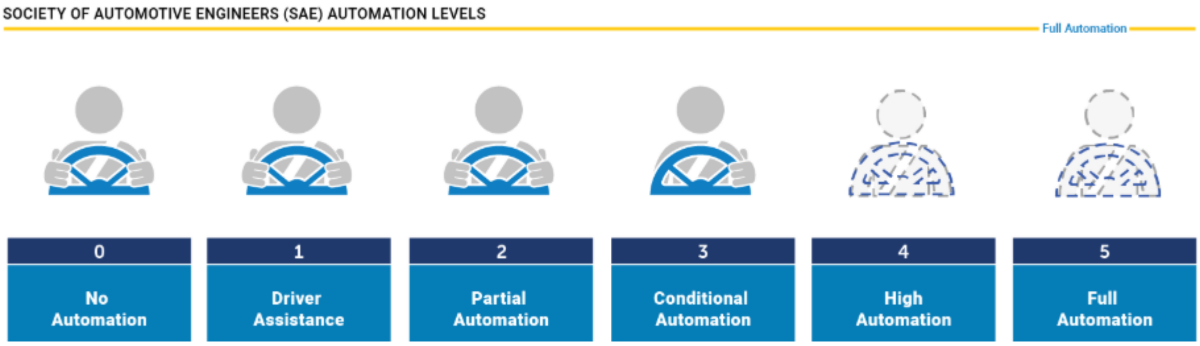


Figure 15: The six levels of automation from No automation to Full automation (NHTSA, 2019).

Level 0 – "*The human driver does all the driving.*" (NHTSA, 2019).

Level 1 – "*An advanced driver assistance system (ADAS) on the vehicle can sometimes assist the human driver with either steering or braking/accelerating, but not both simultaneously.*" (NHTSA, 2019).

Level 2 – "*An advanced driver assistance system (ADAS) on the vehicle can itself actually control both steering and braking/accelerating simultaneously under some circumstances. The human driver must continue to pay full attention ("monitor the driving environment") at all times and perform the rest of the driving task.*" (NHTSA, 2019).

Level 3 – "*An Automated Driving System (ADS) on the vehicle can itself perform all aspects of the driving task under some circumstances. In those circumstances, the human driver must be ready to take back control at any time when the ADS request the human driver to do so. In all other circumstances, the human driver performs the driving tasks.*" (NHTSA, 2019).

Level 4 – "*An Automated Driving System (ADS) on the vehicle can itself perform all driving tasks and monitor the driving environment – essentially, do all the driving – in certain circumstances. The human need not pay attention in those circumstances.*" (NHTSA, 2019).

Level 5 – "*An Automated Driving System (ADS) on the vehicles can do all the driving in all circumstances. The human occupants are just passengers and need never be involved in driving.*" (NHTSA, 2019).

3 Methodology

The first two research questions are about looking at how driving comfort can be defined and measured, with respect to vertical acceleration. Finding answers to these questions require obtaining information about driving comfort and vertical acceleration. The last research question asks about the possibility of quantifying driving comfort and determine any comfort threshold. Obtaining such information requires to measure driving comfort. Based on this, two different methods were chosen for this thesis. A literature search was the first method that was chosen, to obtain information on how driving comfort can be defined and measured. This information would be of high importance to the second method, which was a self-developed driving experiment where driving comfort would be measured.

This chapter gives a presentation of these two methods, giving a brief description of the methods, strengths and weaknesses, how data and information would be collected and used and how these methods would contribute to the thesis' objective.

3.1 Literature search

A literature search is a good method for gathering useful information, with a wide selection of scientific research papers and other reliable materials. A few different search engines were used to find relevant research or literature, such as Google Scholar, ResearchGate and TRID (Transportation Research Board). These search engines have access to an enormous amount of scientific papers. The challenges are finding the relevant literature, where trying to find the appropriate keyword can be challenging. For instance, when searching "DRIVING COMFORT", Google Scholar's search engine presents all papers including the words "DRIVING" and "COMFORT", in either the title or in the paper. Papers where driving comfort is briefly mentioned but not the topic of the paper, appears as well. Trying to add more keywords might not have the desired effect of trying to narrow the search or find specific papers related to the thesis' topic. One of the keywords could be the paper's topic (e.g. driving comfort), while the remaining keywords were only mentioned once in the paper (vertical alignment), without any connection between the driving comfort and vertical alignment.

This next part gives a brief description of the literature that was included in this thesis, why it was included and how this information would be used.

3.1.1 Driving comfort

Searching for literature on driving comfort, with respect to vertical acceleration or even geometric road design, resulted in limited information that could contribute to the thesis' research questions. This proved that there are a lot of knowledge gaps on the topic. As there were not information to gather, the literature search was taken in a different direction where available information had to be used in a different manner. The literature search became about gathering information on driving comfort on general level to see what has been previously said about the topic. This resulted in many research papers about driving comfort in regard to sitting comfort/discomfort, vibrations and even autonomous vehicles (driving behavior). These papers were examined to see how driving comfort has been defined in those studies and how it has been measured. The literature search was used as inspiration and suggestion when working on a definition and measuring method, as it could not provide direct useful information. For instance, some of the studies were used to see if there could be some similarities. Could something from measuring sitting discomfort be applied when trying to measure driving comfort under the influence of vertical acceleration? In what way did they differ? The literature also provided a better understanding and knowledge of driving comfort in general, that became a good starting point. For instance, what should be considered when looking at driving comfort, regardless of the factors affecting it.

Due to the limited literature on driving comfort and vertical acceleration (parameter), the literature search on the next topic became important.

3.1.2 Road design

A number of different national road design standards, from different countries, were examined to gather what information they had on driving comfort as a design criterion and the basic parameter vertical acceleration. The standards and guidelines that were used are from the countries and publishers presented in Table 2:

Table 2: Standards used in this thesis, with country, year and publisher.

Standard	**Country**	**Year**	**Publisher**
V120 Premises of geometric road design	Norway	2014	Norwegian Public Road Administration
Road and Streets – Terms and values	Sweden	2015	The Swedish Transportation Administration
Alignment in Open Land	Denmark	2018	The Danish Road Directorate
A Policy on Geometric Design of Highways and Streets (6th edition)	USA	2011	American Association of State Highway and Transportation Officials
Guide to Road design Part 3: Geometric Design	Australia	2016	Austroads

Norway

The Norwegian handbook V120 *Premises for geometric design of roads* (NOR. Premisser for geometrisk utforming av veger) was used to provide information on vertical acceleration and sag curves and published by the Norwegian Public Road Administration (NPRA). The NRPA consists of the Road Directorate and five regions, providing advice to the politicians and implements the projects on behalf of the state and counties when politicians have made the decision on what and where to build. All the guidelines and standards are available at NPRA's website. The edition used for this thesis is dated as 2014, though the content and publishing year was 2013. A new version of V120 was published in May 2019, during the final stage of the work, and any information from V120 is from the 2014 version (NPRA, 2018c).

Sweden

The Swedish guideline that was used to gather information on vertical acceleration was *Road and Streets Design – Terms and Values*, (SWE. Vägars och gators utforming – Begrepp och grundvärden) from 2015 published by the Swedish Transportation Administration . The Swedish Transportation Administration has the responsibility for long-term planning of the transport system (road, rail, water and air traffic) and for building, operating and maintaining the public roads and rail roads. The standard is an older version and therefore available on the Swedish Transportation Administration's website (The Swedish Transportation Administration, 2018).

Denmark

The Danish guideline *Alignment in Open Land* (DK. Tracéring i åbent land) provided the information on vertical acceleration and sag curves. The guideline is published by the Danish Road Directorate and the version that was used was from 2018. The Danish Road Directorate has the responsibility for the public road network with planning, design and operation, and traffic engineering/management. This guideline, among other standard/guideline publications, is available on the Danish Road Directorate's website (Danish Road Directorate, 2016).

USA

The American standard *A Policy on Geometric Design of Highways and Streets* published by the American Association of State Highways and Transportation Officials (AASHTO) was used to find information on vertical acceleration and sag curves. AASHTO is a non-governmental association representing highways and transportation in the 50 states. The association represents other transportation mode such as air, rail, water and public transport. AASHTO issues also standards, e.g. for design and construction of highways. The version that was used was the 6th edition from 2011, borrowed by a professor at NTNU (AASHTO, 2019).

Australia

The Australian standard *Guide to Road Design Part 3: Geometric Design* was published by Austroads in 2016. Austroad is an organization of road transport and traffic agencies in Australia and New Zealand. The organization conducts research helping road agencies with current and emerging issues and publishes guidelines to promote universal design, maintenance and operation of the Australian road network. The standard is also available on their webpage but required to register an account and state the purpose for needing access. It provided the information on vertical acceleration and sag curves (Austroad, 2019).

All the information gathered from the literature search was used to give a basis on how driving comfort could be defined and measure and is given a separate chapter: 4 Defining and measuring driving comfort.

3.2 Driving experiment

The choice for performing a driving experiment was based on several reasons. The intention was to test whether driving comfort under the influence of vertical acceleration could be measured. Any information presented for defining and measuring driving comfort is theoretical based, which must be tested to confirm its practicality. The third research question is about quantifying driving comfort and finding a comfort threshold. Doing this requires measurement on driving comfort which could be obtained by performing a driving experiment. Thus, the driving experiment would provide comfort and acceleration measurements that would be used to find answers to the third research question, about whether it is possible to quantify comfort and find indication whether current comfort threshold should be re-evaluated.

The driving experiment would be a self-developed experiment for the purpose of this thesis, built from the basis for how driving comfort can be defined and measured, with respect to vertical acceleration. As is had to be developed, time became a limitation for the driving experiment. The work required to be able to do the experiment can be divided into four processed, each time-demanding: preparatory work (how to define and measure driving comfort), developing the experiment and procedure, performing the experiment and lastly, analyzing the measurements. This resulted in the experiment being simplified and scaled down.

Sections 4.2 and 4.3 gives the basis for defining and measuring in which the driving experiment was based on. A separate chapter is dedicated to the development of the driving comfort. This is chapter 5 (Driving experiment) which gives a detailed description about the road section (test area), equipment, planning the procedure, and how to make the measurements for driving comfort.

4 Defining and measuring driving comfort

Performing an extensive literature review was required to find information in order to address the first two research questions about defining and measuring driving comfort. Thus, the first part of working on the thesis consisted of a literature search to gather information and to uncover any knowledge gaps. The function of this chapter is to present this information about driving comfort with regards to vertical acceleration and sag curve that were considered most relevant for further work. The information, and also the lack of, is used to map out what is known and what is missing to give a basis for how driving comfort can be defined and measured. This is also the basis when constructing and developing the driving experiment.

This chapter is divided into three separate sections. The first presents the relevant information about vertical acceleration and its comfort thresholds in geometric road design. The last two sections try giving answers of how to define and measure driving comfort. Any knowledge gaps considered relevant for further work is also included.

4.1 Driving comfort in road design

The minimum sag curve radius ($R_{v,min}$) and minimum clothoid parameter (A_{min}) are the two alignment parameters in the Norwegian standard that are designed with regards to driving comfort. The parameters vertical acceleration (a_v) and relative vertical speed (v_{vf}) are basic parameters for these two design parameters as highlighted in Figure 16, which are given predetermined design values based on ensuring satisfactory driving comfort (see section 2.2.3, page 20-21). In addition, the minimum sag curve radius is designed based on a comfort criterion.

Minimum clothoid parameter in other standards also considers driving comfort in its design, but the parameter that is based on driving comfort address a maximum allowed change in lateral acceleration (jerk). For instance, the American standard mentions a maximum change in lateral acceleration of 1.2 m/s^3, while the Danish standard jerk should not exceed 0.5 m/s^3. Driving comfort is also considered for other parameters in geometric design. In the American and Danish standard, the maximum side friction value used when calculating the minimum horizontal curve radius considers driving comfort. The maximum side friction used in the design should "*... be that portion of the maximum available side friction that can be used with comfort...*" (AASHTO, 2011, p. 3-21). Another key consideration is to select a maximum side friction that causes a driver to experience discomfort due to lateral (centripetal) acceleration and react instinctively to avoid high speeds (AASHTO, 2011).

This section presents the literature and information that was found on vertical acceleration (and sag curves) with regards to driving comfort. A number of standard and guidelines from different countries were used to gather as much information as possible. In addition to the Norwegian standard, the American, Australian, Danish and Swedish were used for the purpose of gathering information.

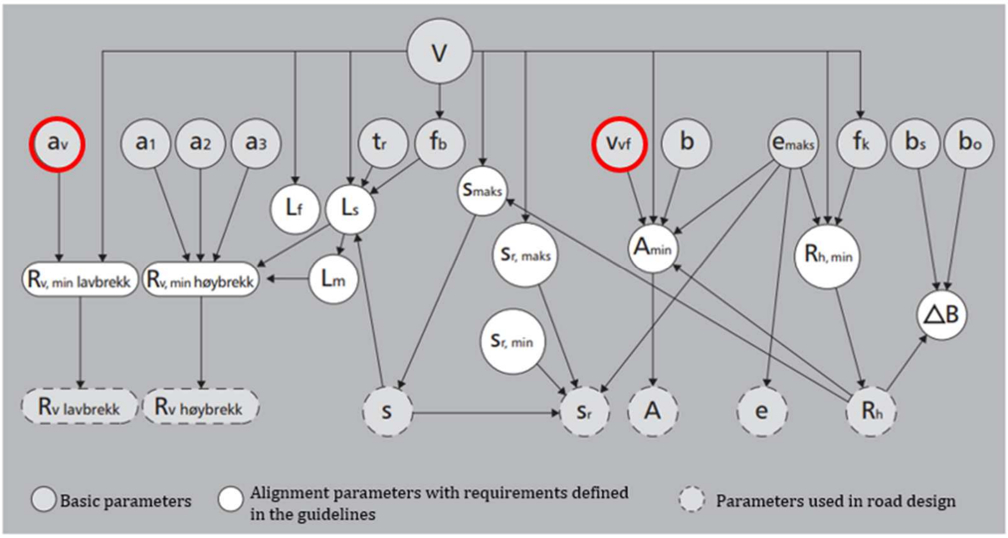


Figure 16: Basic parameters which are based on driving comfort are those marked with red circles (NPRA, 2014b, p. 11).

4.1.1 Vertical acceleration and sag curves

A vertical curve is the transition between two adjacent slopes. As mentioned in section 2.1, a centripetal acceleration is generated when an object or body follows a curved path. As a vertical curve also is a curved path, a vertical centripetal acceleration is generated when a vehicle travels through vertical curves. This centripetal vertical acceleration affects driving comfort. A person that is subjected to a rapid change in vertical direction (acceleration) may experience discomfort (Austroad, 2017). The effects of the vertical centripetal acceleration work in the same direction as the acceleration due to gravity and will generate a feeling of being pushed down into the seat. In crest curves, the effects of vertical acceleration and acceleration due to gravity work in different direction generating a feeling of being lifted of the seat. The intensity of these effects is dependent on the vertical acceleration magnitude. The Danish standard use the requirement of not exceeding a vertical acceleration of 0.5 m/s^2 in both crest and sag curves. However, requirements for stopping sight distance in crest cures are stricter than a comfort requirement would be. There are no stopping sight distance issues with sag curves. The American and Australian standards do consider headlights distance as a design criterion for sag curve, but the Norwegian roads are design for daylight driving.

The vertical acceleration a vehicle experience when driving in a sag cure is the same as centripetal acceleration presented in section 2.1. The magnitude of the acceleration (a) is dependent on the vehicle's (v) speed and the curve's radius (R).

$$a = \frac{v^2}{R}$$

Rearranging the formula and changing speed unit from [m/s] to [km/h] gives the equation presented below, which is the same equation for the minimum sag curve radius presented in section 2.2.3.

$$R = \frac{V^2}{12.96 \times a}$$

a is the vertical acceleration [m/s^2]
v is the design speed [km/h]
R is the radius of the curve [m]

4.1.2 Parameters and design values

Returning to driving comfort, vertical acceleration is the parameter that affects driving comfort by causing discomfort. Thus, to ensure riding in a sag curve is not uncomfortable, the curve radius should be large enough to prevent generating vertical acceleration that causes discomfort. This is done by determining a comfort threshold and assigning predetermined design values to the parameter (a), ensuring that satisfactory comfort is maintained. This section of the chapter presents how the different standards and guidelines ensure comfortable driving in sag curves.

Norwegian design

The Norwegian design is based on driving in daylight, only considering driving comfort as a design criterion in V120. The formula for minimum curve radius is as presented above (and in section 2.2.3), with the following design values for vertical acceleration (see Table 3) maintaining a desired level of driving comfort (NPRA, 2014b, p. 32).

Table 3: Design values of vertical acceleration in Norwegian road design (NPRA, 2014b, p. 16).

Road standard	**Main roads**	**Collector and access roads**
New Roads	0.3 m/s^2	0.5 m/s^2
Improvement of existing roads	0.5 m/s^2	1.0 m/s^2

Swedish design

The Swedish handbook, called *Road and street design – Terms and values* (Swedish Transport Administration, 2015) also uses vertical acceleration as a basis with regard to driver and passenger's comfort when designing vertical curve radii. The standard provides a table showing the vertical accelerations that can be generated in sag curves, dependent on the road standard, and provides some additional comments regarding discomfort due to vertical acceleration, as seen in Table 4 (Swedish Transport Administration, 2015, p. 67).

Table 4: Vertical acceleration values provided by The Swedish Transport Administration (STA), dependent on road standard (SNRA, 2015, p.67).

Standard	**Vertical acceleration**	**Comment**
Good	0-0.5 m/s^2	No discomfort
Less good	0.5-1.0 m/s^2	Slight discomfort

American design

The American standard *A Policy on Geometric Design of Highways and Streets* (AASTHO, 2011) lists a few different approaches when designing sag curves. There are different criteria to design by, such as sight of headlights, driving comfort, drainage and general aesthetics. The formula for vertical curvature using driving comfort as a design criterion calculates the minimum length of the sag curve, and is given as (AASTHO, 2011, p. 3-160):

$$L = \frac{AV^2}{395}$$

L is the length of the sag curve [m]
A is the algebraic difference in grades [%]
V is the design speed [m/s]

The American standard uses length rather than a radius to design vertical curvature, and the formula includes a vertical acceleration values of 0.3 m/s^2, provided by the standards, that is considered to ensure comfortable riding in a sag vertical curve (AASTHO, 2011).

Australian design

Austroad's *Guide to Road Design Part 3: Geometric Design* (2016) states that vertical sag curves are design based on appearances, comfort and headlight sight distance. The Australian standard states that the vertical acceleration generated on a vertical curve is usually limited to a value less than 0.05g to minimize discomfort. The value of 0.05g corresponds to an acceleration of 0,49 m/s^2. The Australian standard, like the American, determines a minimum length of a sag curve and the equation for comfort criteria is given as (Austroad, 2016, p. 217, eq. 20):

$$K = \frac{V^2}{1296 \times a}$$

K is the length of vertical curvature for 1% change in grade [m]
a is the vertical acceleration set as 0,05g (max) [m/s^2]
V is the design speed [km/h]
g is the gravitational acceleration [9,81 m/s^2]

Danish design

The Danish handbook *Alignment in open land* (2018) provides information on minimum sag curve radius and vertical acceleration. The minimum vertical curve radius is, like the other countries' road standards, based on comfort, headlights distance, sight under bridges and consideration to aesthetics. In order to accommodate for comfort, the standard states that the vertical acceleration should not exceed 0,5 m/s^2, to ensure that driving in vertical curves in not uncomfortable. The formula for finding minimum curve radius is listed below, and also applies for crest curves (The Danish Road Directorate, 2018, p. 44).

$$\frac{{v_p}^2}{R_v} \leq 0{,}5 \;\Rightarrow R_{v,min} = 2 \times {v_p}^2$$

$R_{v,min}$ is the minimum radius [m]
v_p is the speed [m/s]

4.2 Defining driving comfort

The information that is presented in section 4.1 provided some useful information about what factors affect the driving comfort and why it is affected. To quickly summarize, the driving comfort is affected by the vertical acceleration that is generated due to change in vertical direction when riding a curve. The curve radius and speed determine the vertical acceleration, which can cause discomfort to anyone inside the vehicle if the acceleration is high enough. The standards generally agree on a comfort threshold of 0.5 m/s^2, a boundary where accelerations above this value inflict discomfort on those inside the vehicle. As long as vertical curve radii are large enough to generate vertical acceleration below that threshold, riding a sag curve eliminates or minimize discomfort, maintaining a comfortable riding. However, finding the information about 0.5 m/s^2 being considered as a boundary could not have been found from either the Norwegian or American standards alone. The American road standard provides information about one certain value that ensures comfortable riding, but no information about discomfort with respect to the acceleration. The Norwegian standard also provides several vertical accelerations between 0.3-1.0 m/s^2, and states that sag curves are design based on a desired level for driving comfort. There is no information about these vertical accelerations with respect to discomfort. Based on the wording of a desired level of driving comfort, along with several design values, knowing which accelerations cause discomfort, or even if they do, can be challenging. The Australian, Danish and Swedish standards provide specific information about discomfort, by saying that a vertical acceleration value of 0.5 m/s^2 or above generates discomfort.

The standards and guidelines provide information concerning what factors affects the driving comfort, why is affect it and how driving comfort is maintain when designing the vertical curves. What is missing is a description of how driving comfort/discomfort affects humans. The only information to get from the standards is that vertical acceleration can cause discomfort, but what kind of discomfort and how does it affect those subjected to it? Like comfort, the term discomfort is equally challenging to provide definition for. Discomfort can be physical, physiological or psychological and should be explained in terms of the situation and factors that affects driving comfort. Without information about what kind of discomfort is inflicted on those exposed to the vertical acceleration and how it affects them, led to some questions regarding the design values themselves. This concerns how this comfort threshold was determined and the reasoning for choosing those particular design values in section 4.1.2. This part of the chapter takes a closer look into this point.

4.2.1 Subjective parameter: Finding comfort threshold

Driving comfort is a subjective parameter that is not impartial and is dependent on feelings, opinions, thoughts and perspectives. This is also a point that makes the term challenging to define. In addition, feelings, perspectives etc. can influence how discomfort, both physical and physiological, is perceived by the individuals. Thus, there is a psychological part that results in different comfort thresholds dependent on each individual, even with physical and physiological discomfort.

The literature search on driving comfort showed that research focuses a lot on seat design and ergonomics, due to health risks. Best sitting posture and how the discomfort is perceived varies between individuals. Yet, there is a threshold, a body tolerance for how much the body can handle such strain before affecting human health. Duration is important, as often exposure for long-term driving in a static posture (e.g. profession as a driver) without sufficient support can lead to health issues to the musculoskeletal system and fatigue (Recovre, 2019). Thus, a short investigation on human physical tolerance to vertical acceleration was performed, uncovering that the human body can sustain high accelerations. During accelerations in the head-to-toe direction, blood is driven away from the brain and towards the feet. At the extreme, with increasing g-forces, the body will experience challenges providing the brain with blood, resulting in a lack of oxygen. Measuring tolerance to acceleration is not easy, as it depends on the magnitude, duration, direction etc., but a typical person would be able to sustain 5g (49 m/s^2) without losing consciousness. Fighter pilots use special compressed suits can endure forces up to 8 or 9g (78-88 $m/^2$). Unassisted tolerance for acceleration in the toe-to-head direction is less, as 2 or 3g (20-29 $m/^2$) can lead to unconsciousness due to too much blood rushing to the brain (Venosa, 2016; Tyson, 2007; Wikipedia, 2019).

The design values are mainly set somewhere between 0.3-0.5 m/s^2, corresponding to only 0.03-0.05 g-forces. Thus, discomfort from vertical acceleration due to driving through sag curves are not limited by any human body limits. This means that each individual's comfort threshold is purely based on their feelings and opinions about the discomfort they experience. Duration can be a factor that affect how discomfort is perceived, but vertical acceleration exposure in a sag curves are also quite low, merely a few seconds. Neither duration nor magnitude is an issue for vertical acceleration in when riding sag curves.

4.2.2 Determining threshold and design value

The design values, or comfort threshold, seen in the various design standards had no referencing to any documentation that support or argue for the decision of those values. No other literature or papers with input on comfort threshold for vertical centripetal acceleration were identified. The American standard stated briefly that limited attempts of measuring vertical acceleration gave a broad conclusion of a centripetal acceleration of 0.3 m/s^2 was considered comfortable. This then led to the question of how the comfort thresholds were determined, and the reasoning for chosen those particular design values.

This section looks into some options and suggestions how to move forward obtaining that information.

Determining comfort threshold (and design values)

It is the comfort threshold that sets the limit for allowed vertical acceleration, and based on the standards, it is connected to the absence of discomfort. Comfort threshold can vary between individuals and could, in this case, be described as what individuals feel comfortable with, even if there is a presence of discomfort. It is possible that small about of discomfort is still able to ensure comfortable riding for drivers and/or passengers. This all depends on the amount of discomfort that is generated, which also goes back to how individual perceives and experience that discomfort. It is the individuals, those driving or riding along the road, that should determine what *level* of driving comfort maintains what they consider comfortable or even acceptable when riding in a sag curve. These *levels* are connected to vertical accelerations which sets a comfort threshold in terms of quantitative data.

Comfort varies between individuals and determining one comfort threshold therefore needs input from a large number of individuals, ideally representative for the population. The more input is gathered, the more valid and reliable the comfort threshold will be. This comfort threshold could be decided on by an 85th percentile, where comfort threshold is the vertical acceleration where 85% of the individuals' comfort threshold are equal to or below that value. It could also be taken a consideration whether to use the comfort threshold as a design values or use a value below. The American and Norwegian uses design values below 0.5 m/s^2, which is interpreted as comfort threshold by the three other road standards. However, it is not always easy, possible or even favorable to account for every individual. As an example, a similar approach was used for determining a deceleration rate when calculating braking distance in the American standard. The standard mentions that most drivers brake with a deceleration rate larger than 4.5 m/s^2, while 90% of all drivers brakes with a deceleration rate larger than 3,4 m/s^2. The latter value is used in designing for braking distances (AASHTO, 2011, s. 3-3).

Measured or theoretical acceleration

The American standard mentions that acceleration "*… due to change in vertical direction is not easily measured because it is affected appreciably by vehicle body suspension, vehicle body weight, tire flexibility and other factors. Limited attempts at such measurements have led to the broad conclusion that riding is comfortable on sag vertical curves when the centripetal acceleration does not exceed 0.3 m/s^2.*" (AASHTO, 2011, p. 3-160). Vehicles, suspensions and tires have developed throughout the years. The same centripetal acceleration is generated by the curve, but how that centripetal (vertical) acceleration affects those inside the vehicle today can be different compared to older vehicles.

The design criterion for sag curves and comfort threshold (design values) are based on a theoretical centripetal acceleration, based on the formula in section 2.1. As mentioned above, while measuring the centripetal acceleration is challenging, there could be a possibility to base the comfort threshold on measured vertical acceleration in real-life driving conditions. However, these measurements will not only include centripetal acceleration, but also other factors that influence vertical acceleration, like the vehicle conditions (weight, tires and suspension). Investigating and comparing both accelerations (theoretical and measured) could open a discussion what the comfort threshold should be based on, and what is most practical considering obtaining measurements.

4.3 Measuring driving comfort

Measurements can either be objective or subjective. Subjective measurements are based on individual's own judgement, feelings and perceptions, and can be criticized as they are open to interpretation and not easily defined. Objective measurements are the types of measures that that are impartial and usually measured by equipment, e.g. measuring time with a stopwatch. Road design uses physics laws and mathematical formulas in their design basis, requiring quantitative data, like vertical acceleration. Measuring driving comfort is about quantifying it into such quantitative data, which can be challenging. This section of the chapter looks into some suggestions how driving comfort can be measured.

Driving comfort when designing sag curves have been quantified, to some degree in the standards, by expressing driving comfort using vertical acceleration. Different vertical accelerations are described as either providing comfortable riding or generating discomfort. The Swedish standard have also categorized vertical acceleration based on what discomfort they generate (Table 4). Being able to measure driving comfort requires both subjective (what is comfortable) and objective measuring methods (what is the vertical acceleration).

Measuring driving comfort requires subjective measurement, consisting of individuals' evaluation, assessment or impression of driving comfort. Obtaining such measurements are relatively easy. Individuals who are subjected to vertical acceleration can easily describe how the experience was. However, asking people to describe their experiences can give many different descriptions, making it difficult to process that information and use it to quantify driving comfort. There is a need for a systematic way of evaluating the driving comfort, providing data that is easy to structure, process and analyze. For instance, a discomfort rating scale where individuals rate the amount of discomfort they experience from no discomfort to high, based on numbers. Numbers are easy to work with but need to be clearly defined what they represent so that individuals will know how to rate discomfort and make the measurements comparable. The final step for quantifying (measuring) driving comfort is to connect the subjective measurements (feeling of discomfort) to the objective ones (vertical acceleration).

Measuring and quantifying driving comfort can consist of having participants being exposed to different vertical accelerations where they provide subjective measurement through their evaluation of driving comfort (discomfort). Connecting those measurements to the vertical accelerations that were tested would provide information about how much discomfort they felt for the different accelerations. This could be used to categorize vertical acceleration based on amount of discomfort, like the Swedish standard (Table 4).

Evaluating or rating discomfort can however be challenging, and there could be other methods that could provide additional information. Electromyography is an objective method used when researching sitting comfort (driver comfort), that measured muscle activity (Kyung and Nussbaum, 2007). When a body is exposed to (physical) discomfort, the muscles can tense. For instance, in a horizontal curve with high speed and a small curve radius generates a centripetal acceleration and an impulse would be to fight this forced movement. This method could be used to test if people are able to relax. Another method could be to record or monitor people's reaction, e.g. body language and facial expression, to see how they respond to the acceleration.

5 Driving experiment

This driving experiment had two functions. Firstly, it is a way of testing the practicalities of measuring driving comfort (and vertical acceleration) and is based on the ideas for defining and measuring driving comfort presented in section 4.2 (Defining driving comfort) and 4.3 (Measuring driving comfort). Additionally, it was considered as a good opportunity to gather additional information about discomfort and general view on driving comfort, with respect to vertical acceleration.

The driving experiment was about testing driving comfort and vertical acceleration measurements in an attempt to see whether vertical acceleration could be connected to feelings of discomfort experienced by subjects riding inside a vehicle. The driving comfort and acceleration measurements would be based on different speeds on a road section with several sag curves. The driving experiment was simplified and scaled down (real driving conditions, procedure, participants number etc.), due to limited time and resources, which was favorable as this driving experiment was about testing the method to determine how well it works.

Any data from the experiment would be used to see if quantify driving comfort is possible to find a comfort threshold and see whether there is any indication suggesting that current comfort threshold should be re-evaluated.

This chapter give a description of important aspects of the experiment and how it was developed. The chapter is divided into sections as listed below:

- **5.1 Road section**: Information on the road section where the driving experiment would be performed, and arguments as to why this road section was considered favorable to be used in this experiment.

- **5.2 Equipment**: Description of the vehicle that was used in the experiment, automation level and systems, and the sensor used for measuring vertical acceleration.

- **5.3 Developing the procedure**: Explanation and description of how the procedure was composed, e.g. selecting vertical accelerations the participants would be exposed to.

- **5.4 Subjective measurements:** Description of how the measurements would be done and collected, and a brief description of the participant's role in the experiment.

5.1 Road section

The location chosen to perform the experiment was a 250-300 meters long road section, about 15 kilometers from Orkanger city in Orkdal municipally, direction west. The location is about 60 kilometers from Trondheim city and takes about an hour to get there by car. Figure 17 and Figure 18 shows the location of the area compared to Trondheim and a closer look at the road section itself, marked with the orange box. This area was quickly chosen without considering other sections, based on personal experience and knowledge for reason further described within this section.

Until autumn 2015, this road section was a part of E39 in Trøndelag between Orkanger and Vinjeøra (Hemne municipally) that continues west towards Kristiansund and Molde in Møre and Romsdal county. It was downgraded to a county road (Fv 463) when a new E39 opened between Orkanger and Vinjeøra. Both the old and new E39 are shown in Figure 17. Prior to the opening of the new E39, this road was the main connection between urban areas in Trondheim and the coast, with an AADT of about 1800 vehicles and 14% heavy vehicles. Road Fv463 (old E39) now consist of an AADT of 300 vehicles and no registered heavy vehicle percentage (NPRA, 2018c). This is a two-lane road with a speed limit of 80 km/h.

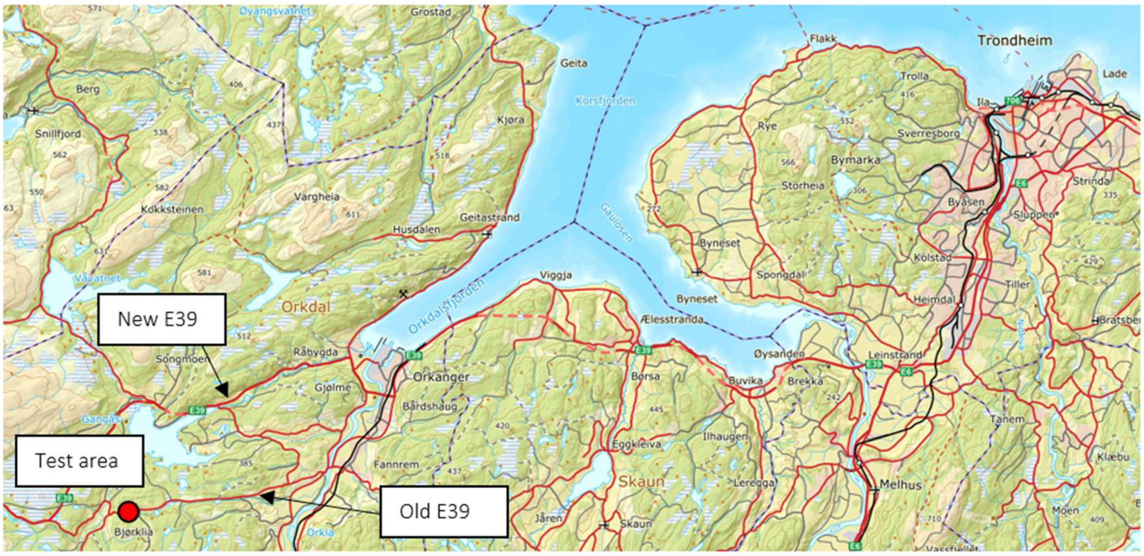


Figure 17: Picture showing the location of test area compared to Trondheim city. The area is in Orkanger municipally. Screenshot taken from map service Kartverket (2019).

This road section is about 200-250 meters above sea level, and close to mountainous terrain, restricting the placement of the road's alignment. Therefore, the road (Fv463) consists of tight curves in both the horizontal and vertical alignment. As a main road (*hovedveg*) with speed limit of 80 km/h, the minimum vertical curve radius is 1900-2100 meters, dependent on the road class.

Figure 18: Picture showing the road section where the experiment would take place. Screenshot from map service Finn kart (2019).

Table 5 present information about the vertical sag curves that were used for the experiment. All information on the sag curves are obtained from "*Vegkart*", a website provided by the NPRA where it is possible to search for data from the National Road Data Bank on speed limits, traffic volumes, equipment etc. (NPRA, 2018c). Figure 19Figure 19 shows the vertical alignment (section within the box in Figure 18) based on information on height, distances and lowest points from *Vegkart.* The first concave alignment consists a compound of sag curves with different radii (79<x<124 in Figure 19). The sag curve located between 109<x<124 has the sharpest radius and was used when developing the driving experiment. Figure 20 shows the location of each of the curves on the map.

Table 5: Information of the sag curves on the road section. Information obtained from Vegkart (NPRA, 2018c).

Curve no.	Radius [m]	Reference in Vegkart	Distance [m]	x- values in Figure 19	Lowest point [m]
1	-155	FV6484 HP1 m9425-9440	15	109<x<214	215.0
2	-449	FV6484 HP1 m9485-9536	51	169<x<220	216.4
3	-252	FV6486 HP2 m47-85	38	300<x<338	215.0

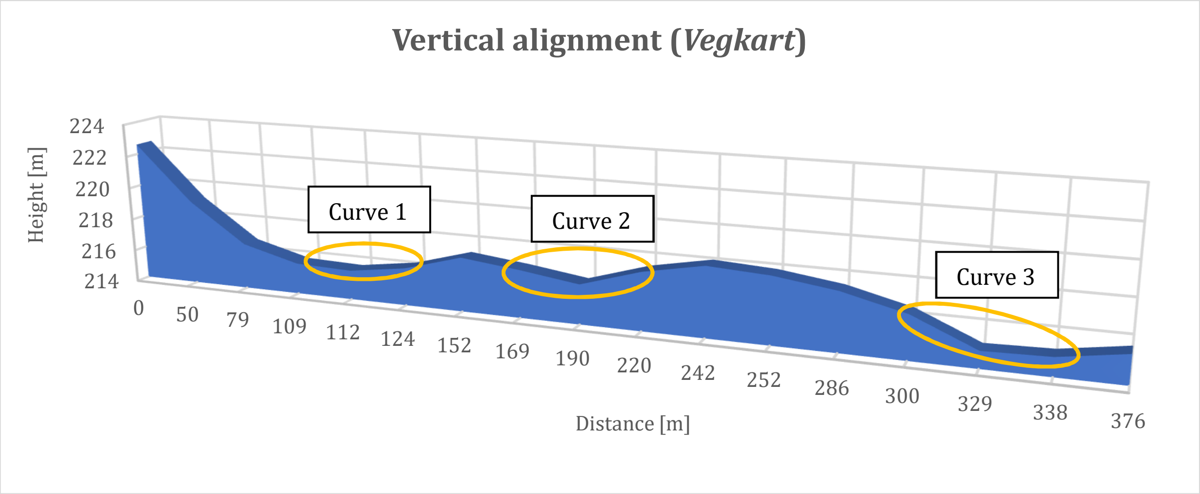


Figure 19: Sketch of the vertical alignment, based on information from Vegkart (NPRA, 2018c).

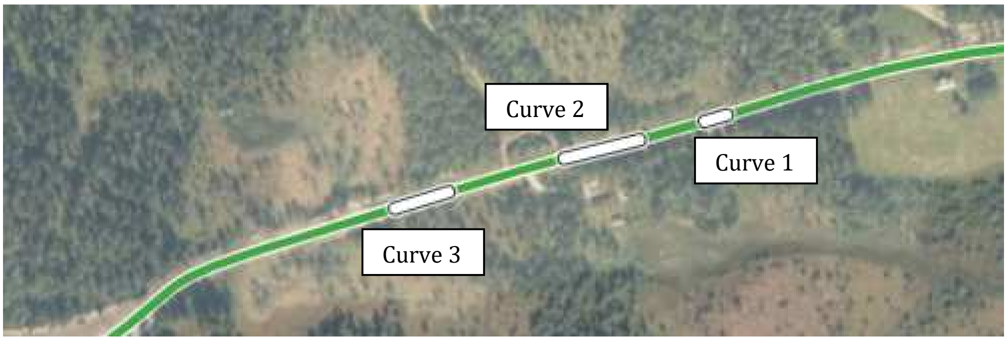


Figure 20: Location of the sag curves on the roadway section. Picture and information from Vegkart (NPRA, 2018c).

The main reason for choosing this section was due to the curve radii. The best ones for this experiment were those with small radii, giving the possibility to test both low and high vertical accelerations. The smallest vertical curve has a radius of 155 meter, which corresponds to a theoretical centripetal acceleration of 3,19 m/s^2 when driving the speed limit. This would give the opportunity to test driving comfort with a wide range of vertical accelerations without having to drive with too high speeds, jeopardizing the safety of both driver and passengers. Due to the demotion from E39 to Fv643, the road section has experienced a significant reduction in traffic, as mentioned. This is beneficial as the experiment could be carried out without interrupting or being interrupted by ongoing traffic when testing speeds below the limit.

Given the desired to isolate the comfort effect of sag curves and vertical acceleration, it was important that the roadway section had a straight horizontal alignment. Centripetal acceleration in the horizontal plane (lateral axis) occurs in horizontal curves, which also have an effect on driving comfort and might make it harder to distinguish the effects caused by the sag curves. Additionally, the pavement condition was also of concern. The section is located near mountainous terrain where snow and cold temperature tend to linger into spring seasons, and the effect of e.g. frost heave can affect driving comfort. As the road was downgraded, the road maintenance is not as prioritized and bumps and cracking within the pavement are evident, which also can affect driving comfort.

5.2 Equipment

The main equipment required for the driving experiment were a vehicle and a sensor that could measure vertical acceleration. This section gives a description of the vehicle and the sensor that were used.

5.2.1 Vehicle and automation level

The vehicle used in the experiment was a Nissan Qashqai (see Figure 21), a crossover SUV from 2015. As is seen within vehicle advancement, most vehicles on the road network have some degree of assisted driving system. For the vehicle used within the experiment, this includes cruise control, lane departure warning and forward collision warning. Only cruise control was utilized in the experiment, to keep the speed at a constant and the driving behavior as similar as possible throughout the experiment to get comparable data.

Figure 21: The vehicle used in the driving experiment, a Nissan Qashqai Crossover SUV.

5.2.2 Measuring vertical acceleration

The objective of the experiment was to test if driving comfort can be measured, considering a metric vertical acceleration. There are several ways of determining the vertical acceleration, as described below:

Simple calculation

The easiest way to find the vertical acceleration is to calculate the value based on the vehicle speed and the radius of the vertical curve. Given a specific curve radius, this method can be used to determine the speed that is required to obtain certain vertical acceleration or determine the vertical acceleration using the speed. However, these accelerations are theoretical centripetal accelerations, based on uniform circular motion. Any deviations from the theoretical value cannot be accounted for. Additionally, this method requires knowledge of the curve radius. Vegkart can give curve radius data (Table 5), although this data is a representation of the curve radius based on mobile measurements and its accuracy is not known. However, this method was used to find the speed needed to obtain vertical accelerations that were desirable to test (see section 5.3 for more).

Sensors

The most reliable option for this experiment was sensors that can measure acceleration. The following sensors were considered:

Human Activity Monitor (HAM)

A small and compact sensor from Gulf Coast Data Concepts (GCDC). The data is saved onto a microSD card and can easily be connected to a personal computer, without any need of special software to process the data. The data is stored as a simple txt. file which can be imported to Excel. There are three variants of this sensors: HAM-x16, HAM-IMU and HAM-UMI+Alt all of them featured with a 3-axis accelerometer and selectable sample rates varying from 12 to 400 Hz. This sensor was best aimed for measurements for bicycles but could be applied to vehicles as well (GCDC, 2019).

VBOX

Sensors from Racelogic have three models which could be used. These sensors are primarily aimed for motorsport and driving instructors. VBOX Sport is a small, lightweight data logger equipped with battery and GPS antenna, and can used for measurements with vehicles without any cables. The model can be used for measurements of velocity, position and acceleration. VBOX Mini is a model with an extern antenna that should be placed on the roof of the vehicle and connected to a power outlet. Video VBOX Pro is the most advanced model combining a 20 Hz GPS data logger and video camera system, allowing videotaping during logging. The model logs measurements for velocity, distance, position and acceleration. A software is used to open and look at the measurements from test runs (VBOX, 2019a; VBOX, 2019b; VBOX, 2019c).

Xsens MTi-G-710

The MTi-G-710 from Xsens is GNSS-aided, IMU (Inertial Measurement Unit)-enhanced GNSS (Global Navigation Satellite Systems)/INS (Inertial Navigation System) and AHRS (Attitude and Heading Reference System) that provides high quality data for velocity, position, orientation and acceleration. The sensor has a sampling frequency of 60 kS/s. Figure 22 show a picture of sensors from Xsens. The MTi-G-710 sensor was selected due to a cooperation with Nord University on the driving experiment, and their desire to test this sensor.

Figure 22: MTi-sensors; MTi 10-series (left), MTi 100-series (middle) and MTi-G-710 (right) (Xsens, 2019c).

The MTi-G-710 comes with an additional outlet to be connected to a GPS antenna, as shown in Figure 22 (sensor to the right). The other outlet is for a power cable that can be connected to any computer through an USB port. Once the sensor is connected, it starts measuring. A software called Xsens MT Manager is used to record the measurements from the sensor, with the possibility to look at the measurement while it is recording. This was not possible for the other investigated sensors. The software is free to download and can also be used to open previously recorded files. The sensor has its own orientation of the axes, as shown in Figure 23, and should be placed so that the x-axis is in the same direction as travel direction (Xsens, 2019a; Xsens, 2019c).

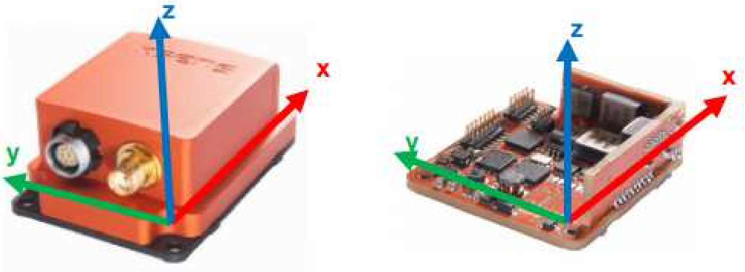


Figure 23: Orientation of the three axes: x, y and z (Xsens, 2019c, p. 24).

5.3 Developing the procedure

This experiment was about testing different vertical accelerations and seeing the amount of discomfort they generate. For this experiment, it was desirable to try obtaining a good coverage of vertical accelerations, where the values were handpicked. This section presents which vertical accelerations were chosen and why. Each "round" of the experiment consisted of driving the three sag curves, with different radii, at a constant speed, thus expanding the range of acceleration tested. The third curve ($R_{V,3}$ = 252 m) was used as the basis when selecting speeds and accelerations. The speeds and vertical accelerations are based on the calculated theoretical values using vertical radius information from *Vegkart*.

Table 6 give a summary of all the vertical acceleration design values form the different national road standards and guidelines:

Table 6: Vertical acceleration design values from national standards and guidelines.

Country	**Standard/guideline**	**a_v req. [m/s^2]**
Norway	V120 Premises of Geometric Road Design Main roads	0,3 m/s^2 (0,5 m/s^2) [1]
	V120 Premises of Geometric Road Design Collector and access roads	0,5 m/s^2 (1,0 m/s^2) [1]
Sweden	Roads and Streets – Terms and Values Good standard	0-0,5 m/s^2 [2]
	Roads and Streets – Terms and Values Less good standard	0,5-1,0 m/s^2 [3]
Denmark	Alignment in Open Land	0,5 m/s^2
US	A Policy on Geometric Design of Highways and Streets	0,3 m/s^2
Australia	Guide to Road Design Part 3: Geometric Design	0,05g ≈ 0,5 m/s^2 [4]

[1] *Requirement for improvement of roads*

[2] *Vertical accelerations should stay within the range, no discomfort*

[3] *Vertical acceleration can stay within the range, cause slight discomfort*

[4] *0,05g=0,49 m/s^2*

These design values became the starting point when choosing which vertical accelerations to test within the experiment. Based on the information presented in section 4.1 (summed up in Table 6), it can be assumed that vertical acceleration values below 0.5 m/s^2 do not cause discomfort. There was a desire to test this, leading to both 0.3 m/s^2 and 0.5 m/s^2 being included. The Swedish guidelines also states that vertical acceleration between 0.5-1.0 m/s^2 cause slight discomfort. Therefore, two additional accelerations that were desirable to test were 1.0 m/s^2 and a value in that range (0.7 m/s^2). For these accelerations, the theoretical speed was calculated using the equation shown below, corresponding to round with speed of 31, 40, 48 and 57 km/h:

$$V = \sqrt{\mathrm{a_v} \times 12{,}96 \ \times \mathrm{R}}$$

V [km/h] is the theoretical speed to obtain theoretical acceleration

R [m] is the radius provided by Road Map (NRPA, 2019)

a_v [m/s^2] is the theoretical vertical acceleration

The speed limit is 80 km/h which made it desirable to test driving comfort under those driving conditions, meaning a theoretical vertical acceleration more than 10 times the design values (in V120) for curve one. An additional round with a speed of 90 km/h was included to test more *extreme* conditions. These accelerations were calculated using the equations for centripetal acceleration presented in section 2.1 (a reformulation of the formulas above).

$$a_v = \frac{V^2}{12{,}96\ \times R}$$

The coverage of vertical acceleration within of 0-1.0 m/s² were considered good (see Figure 24). However, there was a desired to include more accelerations between 2.0-3.0 m/s². Of the three curves, only one vertical acceleration could be targeted each round, giving two fixed accelerations. That made it challenging to choose accelerations while making sure that the same accelerations did not recur too often. Two additional rounds with 2.3 and 2.7 m/s² were considered the best option. The smallest curve was used as a basis for calculating the required speed, resulting in 68 and 74 km/h.

This led to the driving experiment consisting of eight rounds with different speed each time, testing a total of 24 vertical accelerations. Figure 24 presents all the vertical accelerations that would be included in the experiment.

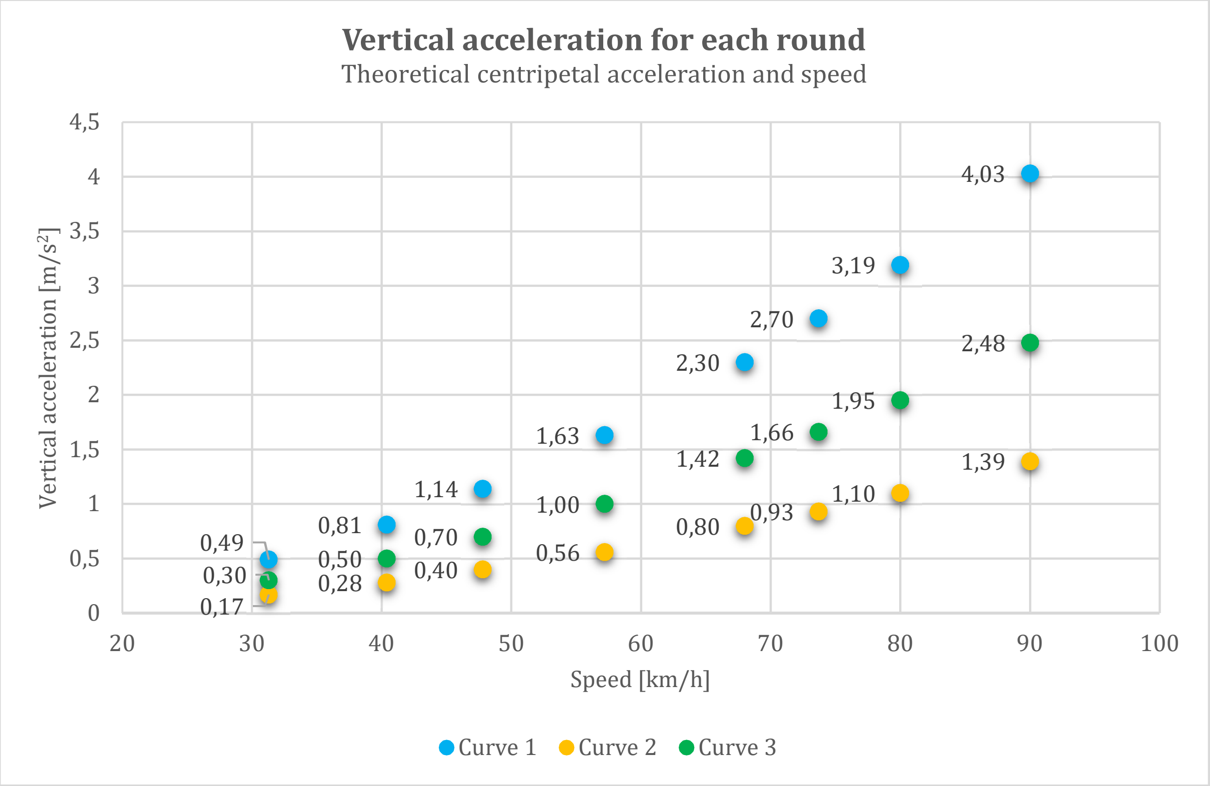


Figure 24: Diagram showing the vertical acceleration values for all three curves.

5.4 Subjective measurements

Measuring driving comfort requires vertical accelerations (objective) and driving comfort (subjective) measurements. Subjective measurements are based on individuals' feelings, options, etc. resulting in a large variation of how it can be described and how comfort/discomfort is perceived. Thus, participants were crucial part of the driving experiment. Although relatively easy to obtain, having comfort measurements that is easy to structure, process and analyze requires a systematic way of describing the comfort (as mentioned in chapter 4.3). A rating system based on a discomfort scale was arranged for the participants to use to express the discomfort they experienced. The discomfort scale was divided into different discomfort levels that corresponded to a number between 0-10.

The rating system were given reference points, or guidelines, to assist rating the discomfort. This was considered important as two individuals exposed to the same vertical acceleration can experience discomfort differently. The rating system was given seven discomfort levels. Level 0 corresponded to not feeling any discomfort, and level 10 corresponds to the highest amount of discomfort. Level 5 was set as the tipping point where discomfort goes from being insignificant to uncomfortable. Numbers below 5 were discomfort that is negligible, meaning that the participants were not bothered or negatively affect by the presence of discomfort. Discomfort levels above 5 corresponds to discomfort being uncomfortable and having a negative effect where the participants are no longer able to fully relax. The full rating scale with description is shown in Table 7.

Table 7: Description of discomfort levels and their corresponding rating number.

Level of discomfort	**No.**	**Comment**
None	0	No discomfort detected.
Slight	1-2	Small amount of noticeable effect, insignificant.
Moderate	3-4	Noticeable effect, but still insignificant.
Tipping point	5	Starts to become uncomfortable.
Significant	6-7	Discomfort is uncomfortable.
High	8-9	Very uncomfortable, unable to fully relax.
Very high	10	The highest level of discomfort you'll expose yourself to.

The measurements (discomfort ratings) were collected using a questionnaire that was produced for this experiment. A blank copy is presented in the Appendix A, attachment A.1. By using a questionnaire, the participants would be able to rate discomfort based on their initial impression while riding the curves. It was considered a very simple and efficient way of making and collecting the measurements.

The driving experiment also gave the opportunity to gather additional information on driving comfort (as mention in this chapter's introduction). The questionnaire was therefore divided into two parts. The first part consisted of a table that provided empty columns where the participants would write down their discomfort ratings for each curve. The table also contained two questions regarding whether they felt any apparent discomfort and if so, what kind, based on the first round (80 km/h) testing high accelerations. Additionally, two questions regarding their view of the term driving comfort and its relation to road design would be answered before starting the experiment. The second part of the questionnaire was a short assessment session about some of the topics from chapter 4.2. For instance, their thoughts on the discomfort they felt, what they considered with the term "desired level of driving comfort" and what speed they would drive themselves on this section. This would be done orally and recorded, instead of writing a few sentences, in order to create discussion within the group and make it easier for the participants to answer. The last page of the questionnaire would allow the participants to give some feedback on the experiment itself.

Participants' role

The participants were a crucial part of the experiment, as they would provide the subjective measurements. Each of the participants would rate discomfort for the three curves, all eight rounds. The more participants taking part in the experiment, the more reliable and valid the results become. However, due to limited time to perform the experiment (access to sensor) and having enough time to process the data, the number of participants were limited to about 10-15 people.

The participants would be passengers instead of driving themselves. A driver has many tasks to focus on when driving, but as passengers, the participants could focus on the effects of the sag curves. Having the participants drive themselves would also be time-consuming and require a driver’s license. All participants would be seated in the back, giving the same conditions as there is a possibility of a difference in driving comfort due to different design of front and back seats. Testing difference in driving comfort dependent on placement inside the vehicle could be an option by having one participant in the front and one in the back. However, that would lead to two sets of data, with fewer measurements each, that is based on different condition and would not be comparable.

6 Executing the driving experiment

The previous chapter presented aspects of constructing and developing the driving experiment. This chapter gives a brief insight into aspects important to be able to carry out the experiment. The sensor that was used belongs to Nord University and required attendance from the university when performing the experiment, limiting the number of days where the experiment could be carried out. As getting to the test site required one-hour travel time and a desire to include as many participants as possible, the execution required planning and preparation. The chapter addresses this issue, and also gives a brief description of the final experiment procedure and a review from the days the driving experiment was performed.

- **6.1 Planning and preparing**: Brief summary how the overall execution of the experiment was planned.

- **6.2 Procedure**: A brief summary describing the experiment's procedure.

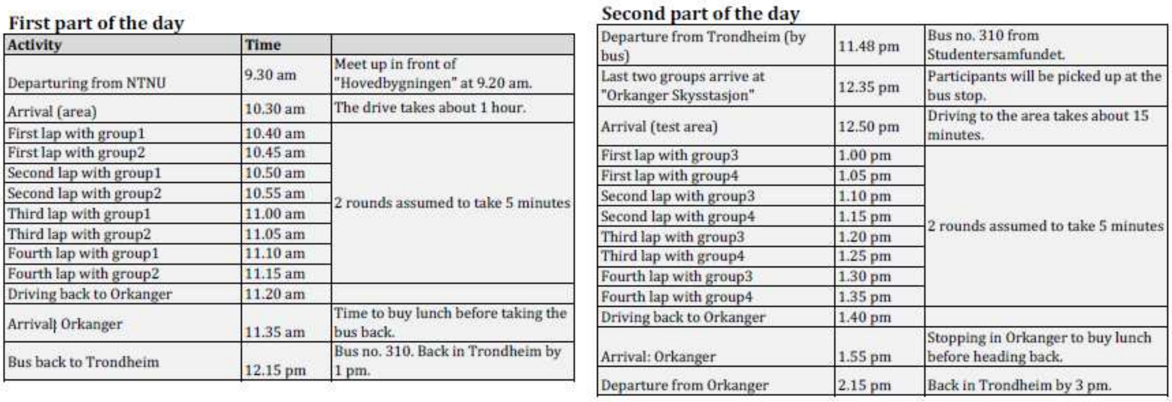
- **6.3 Review of test days**: Review from the test days with additional pictures and comments.

6.1 Planning and preparing

As mentioned in this chapter's introduction, the sensor belongs to Nord University and required someone from the university to be present, which limited the options when to perform the driving experiment. It was desirable to do the experiment as soon as possible to get enough time to process the measurements. Thus, the experiment had to be compacted into two days, Thursday and Friday in week 18. The sensor needed someone to make the recordings, limiting the number of participants in the test vehicle. Thus, it was decided to use groups of two. The experiment would also be performed with two groups at once, switching between them after every second round to give them a break as driving eight rounds all at once can be tedious.

A large number of participants were favorable and getting as many as possible to participate these two days required a solution for transportation. Travelling from Trondheim to/from Orkanger is simple through public transport, but the participants would have to be transported the last 15 km to the test site. A second vehicle would be needed to assist transporting the participants between the test site and Orkanger. The vehicle would be present during the experiment providing shelter for the participants, in case of bad weather, or a place to stay when waiting for their turn. The second vehicle would bring the first two groups in the morning, as the test vehicle would have to drive ahead to mount and prepare the equipment. The two groups would after the experiment be driven back to Orkanger and then go back to Trondheim. In the meantime, two new groups would arrive to Orkanger at the same time and be driven to the test site. Having two groups at a time like this made for a more efficient transport solution.

This gave a capacity of eight participants each day. A total of 16 participants were considered good for the experiment. Figure 25 (next page) shows the final schedule for both Thursday 2nd and Friday 3rd of May.



First part of the day

Activity	Time	
Departuring from NTNU	9.30 am	Meet up in front of "Hovedbygningen" at 9.20 am.
Arrival (area)	10.30 am	The drive takes about 1 hour.
First lap with group1	10.40 am	2 rounds assumed to take 5 minutes
First lap with group2	10.45 am	
Second lap with group1	10.50 am	
Second lap with group2	10.55 am	
Third lap with group1	11.00 am	
Third lap with group2	11.05 am	
Fourth lap with group1	11.10 am	
Fourth lap with group2	11.15 am	
Driving back to Orkanger	11.20 am	
Arrival} Orkanger	11.35 am	Time to buy lunch before taking the bus back.
Bus back to Trondheim	12.15 pm	Bus no. 310. Back in Trondheim by 1 pm.

Second part of the day

Departure from Trondheim (by bus)	11.48 pm	Bus no. 310 from Studentersamfundet.
Last two groups arrive at "Orkanger Skysstasjon"	12.35 pm	Participants will be picked up at the bus stop.
Arrival (test area)	12.50 pm	Driving to the area takes about 15 minutes.
First lap with group3	1.00 pm	2 rounds assumed to take 5 minutes
First lap with group4	1.05 pm	
Second lap with group3	1.10 pm	
Second lap with group4	1.15 pm	
Third lap with group3	1.20 pm	
Third lap with group4	1.25 pm	
Fourth lap with group3	1.30 pm	
Fourth lap with group4	1.35 pm	
Driving back to Orkanger	1.40 pm	
Arrival: Orkanger	1.55 pm	Stopping in Orkanger to buy lunch before heading back.
Departure from Orkanger	2.15 pm	Back in Trondheim by 3 pm.

Figure 25: Timetable for performing the driving experiment for both days (May 2nd and 3rd).

6.2 Procedure

The experiment procedure was a relatively simple one and not assumed to be particularly time demanding. Figure 26 shows the test area and the roadway section where the curves are located (blue box). This section would be driven eight times for each group, four times each direction. Odd numbered rounds (1, 3, 5 and 7) were driven in the south-west direction and even numbered rounds (2, 4, 6 and 8) in the north-east direction, as illustrated in Figure 26.

Figure 26: Picture showing the road section

The two groups would switch between themselves when returning to the starting point, doing two rounds at a time. Figure 26 also shows some areas where turning the vehicle could be done in a safe manner. The turning point was chosen dependent on the speed for each round, as the speed would have to been reach before entering the road section and set to cruise control. The speeds for each round are summarized in Table 8. Measurements from the sensor would be recorded for each round, giving eight measurements for each group. Each measurement would be coded with LX-GY-Z (X – the round, Y – groups number, Z – speed)

Table 8: Theoretical speed for each round.

Round	1	2	3	4	5	6	7	8
Speed [km/h]	80	31	40	48	57	68	74	90

The participants would answer the first part of the questionnaire (discomfort rating table, see attachment A.1, page 2) during the experiment. When turning the vehicle, each group would be given some time to write down their discomfort ratings before continuing with the next round. Completing two rounds were assumed to take five minutes, where one run-through with two groups was assumed to take about 45 minutes.

6.3 Review of test days

There were some challenges getting 16 participants, as the experiment was performed during two weekdays, during work hours and took about 3-4 hours in total. The main focus was to promote the experiment to students at NTNU. Within two weeks, eight participants signed up to partake in the experiment. These were divided into four groups, with two groups participating on May 2nd and the last two on May 3rd, between 9.30 am to 1.00 pm.

The day started with departure from NTNU's campus Gløshaugen at 9.30 am. The participants were given a short description of what was going to happen and time to get familiar with the questionnaire before reaching the test area. The test vehicle drove one hour before to set up the sensor and do some test runs, making sure the sensors had GPS signal and were measuring properly. Driving the eight rounds for both groups went very well. The theoretical speed was reached each time, and there was no need to repeat any of the rounds. Two rounds took about five minutes, as assumed, and the experiment was finished within the hour with both groups. The participants were asked if they wanted to try an extra round with a higher speed of 100 km/h, just to test more extreme conditions. Figure 27 shows a picture of the road section in the south-west direction right before the first sag curve.

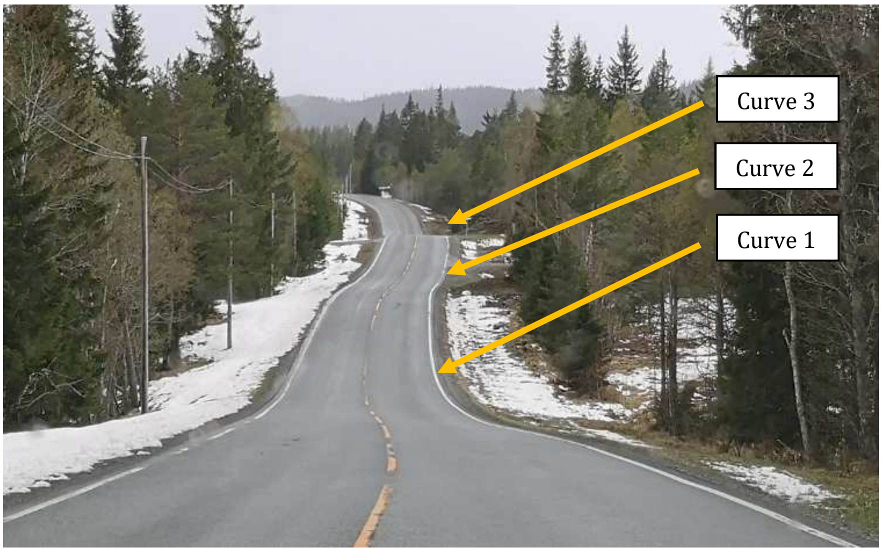


Figure 27: The road section showing the alignment (south-west direction). The picture shows curve 1 and curve 2, with curve 3 behind the second crest curve.

Road and traffic conditions

The main concern about performing the driving experiment on real road condition was the surface conditions and the alignment. It did not pose a challenge for executing the experiment but was considered to have an impact on driving comfort. This will be discussed in chapters 7 and 8. The road surface condition consisted of some cracking and unevenness (e.g. irregularities, bumps and settlement) along the section. The road conditions can also affect the acceleration measurements as bumps, settlements and vibration due to irregularities influence acceleration measurements. Since the road was demoted from Europe road to county road, maintenance is no longer as prioritized. Some pictures showing the conditions are given in Appendix B. The traffic during those day were quite low, and the experiment was performed without any interruptions.

Sensor and measurements

The sensor Xsens MTi-G-710 was used to make the measurements and a computer with the software MT Manager was used to record them. To make the measurements easier to interpret and use, the sensor should be placed on a stable surface with its x-axis in the direction of travel (see section 5.2.2). Nord University constructed a box where the sensor would be placed inside. Figure 28 shows the finale result. The sensor and its antenna are placed inside the box, with levelling meters, to ensure that the sensor's z-axis is upwards and x- and y-axis is horizontal. This box was placed on a suction cup, fixing it to a chosen surface. The sensor was originally to be placed on the vehicle roof but was, due to large noise interference, placed inside the vehicle as shown in Figure 29. A cable goes through the box connecting the sensors to the computer. Additional pictures from the experiment are presented in Appendix B.

Figure 28: The box with sensors, GPS antenna and leveling meter.

Figure 29: Placement of the sensor inside the vehicle.

7 Results, analyzing and discussion

All data and measurements obtained from the experiment are presented within this chapter. The first part of the chapter presents the raw data for both discomfort and acceleration measurements, with additional input on the discomfort itself. The last part of the chapter takes the raw data through a short and simple analysis process to determine any potential usage. Discussion about the results are presented within this chapter as well.

7.1 Discomfort ratings

This section presents the discomfort rating (comfort measurements) obtained through the driving experiment, with additional input on driving comfort, and a short discussion at the end.

7.1.1 Raw driving comfort data

The comfort measurements were obtained using the questionnaire presented in chapter 5.4. The measurements consisted of discomfort ratings where the participants assigned a number that best described the discomfort they were feeling (see Table 7 in section 5.4). Appendix A shows the discomfort rating from the questionnaires. Tables 9 and 10 summarize the ratings for all participants, each round for the three curves. The ratings are also presented in diagrams, in Figures 30-37, showing the share for each discomfort level, all participants combined, with the theoretical vertical accelerations.

The term *Curve 1* in the questionnaire represent the first curve driven in both directions, meaning that *Curve 1* in odd numbered rounds is curve R_{sag_1} and curve R_{sag_3} in even numbered rounds. This is accounted for in both Tables 9 and 10.

Table 9: Presentation of all the discomfort ratings for all three curves on the first, second, third and fourth round, for each participant.

		Subjective evaluation of discomfort											
	Rounds	**R1**			**R2**			**R3**			**R4**		
	Curve	**C1**	**C2**	**C3**	**C1**	**C2**	**C3**	**C1**	**C2**	**C3**	**C1**	**C2**	**C3**
Participant	*G1-P1*	3-4	6-7	1-2	1-2	1-2	1-2	1-2	2-3	1-2	1-2	1-2	1-2
	G1-P2	0	1-2	3-4	0	0	0	0	0	1-2	0	1-2	0
	G2-P1	3	6	0	0	0	0	0	1-2	0	0	1-2	1-2
	G2-P2	3-4	4	3-4	0	0	0	1-2	2	2	0	0	2
	G3-P1	1-2	3-4	1-2	0	0	0	0	0	0	0	0	0
	G3-P2	3-4	1-2	6	1-2	0	1-2	0	0	1	0	0	1
	G4-P1	0	0	4	3	0	0	1	0	0	2	0	0
	G4-P2	1[1]	4[1]	1[1]	0	0	0	0	0	0	0	0	0

[1] Participant commented "not sure" in the questionnaire (deviates from rest of the ratings)

Table 10: Presentation of all the discomfort ratings made for all three curves on the fifth, sixth, seventh and eighth round, for each participant.

		Subjective evaluation of discomfort											
	Rounds	**R5**			**R6**			**R7**			**R8**		
	Curve	**C1**	**C2**	**C3**	**C1**	**C2**	**C3**	**C1**	**C2**	**C3**	**C1**	**C2**	**C3**
Participant	*G1-P1*	2-3	3-4	2-3	1-2	1-2	3-4	1-2	5	1-2	1-2	5	1-2
	G1-P2	0	0	1-2	1-2	0	0	0	1-2	3-4	1-2	3-4	0
	G2-P1	0	1-2	1-2	0	1-2	1-2	1-2	1-2	3-4	2	3	5
	G2-P2	0	1	2-3	0	1	2-3	1	2-3	3-4	2	3	4
	G3-P1	1-2	3-4	0	3-4	1-2	1-2	3-4	3-4	1-2	3-4	3-4	5
	G3-P2	2-3	1	3-4	1-2	0	2-3	3-4	1	1-2	3	4-5	4
	G4-P1	0	0	1	1	0	0	0	0	3	0	0	0
	G4-P2	0	0	0	0	0	1	0	0	1	0	0	0

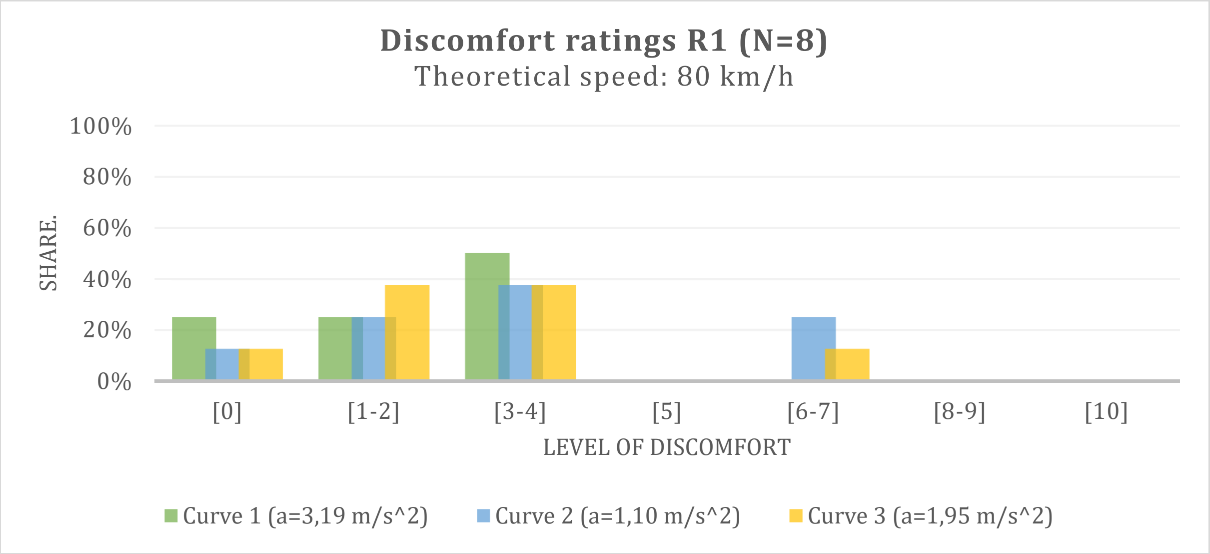


Figure 30: Discomfort ratings for the first round (R1).

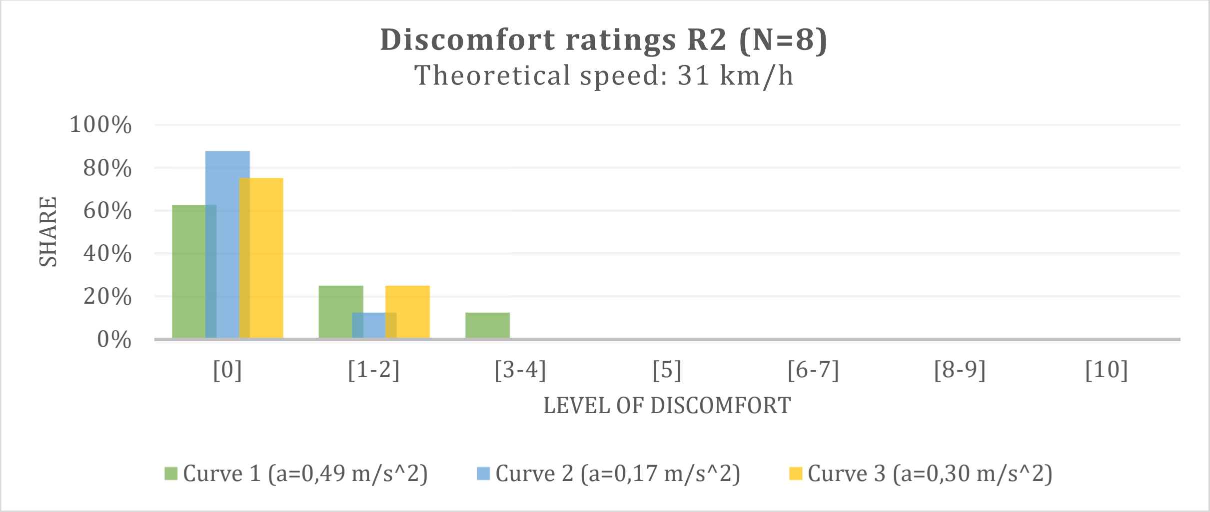


Figure 31: Discomfort ratings for the second round (R2).

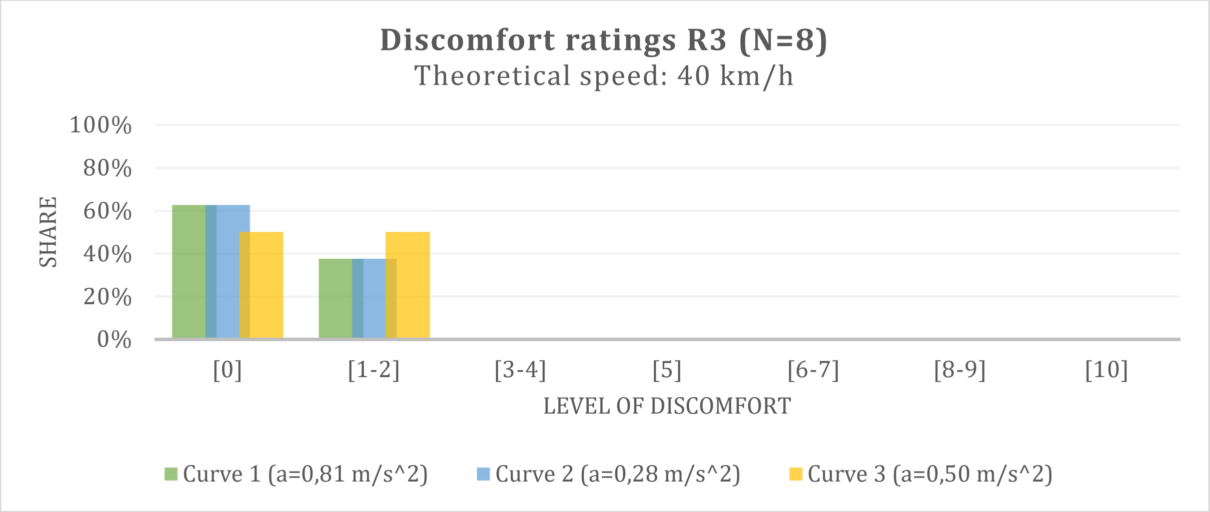


Figure 32: Discomfort ratings for the third round (R3).

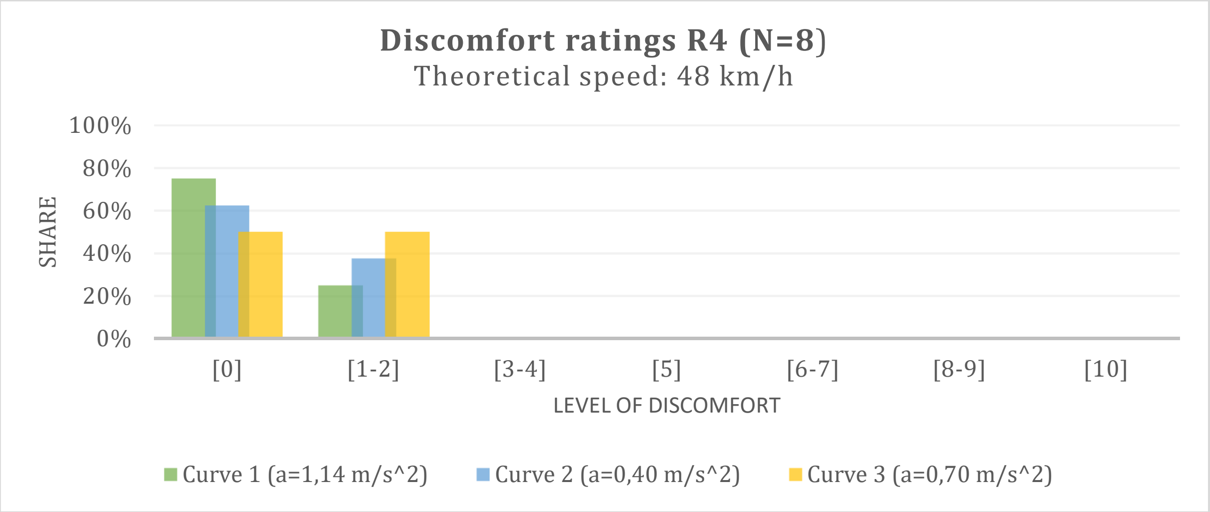


Figure 33: Discomfort ratings for the fourth round (R4).

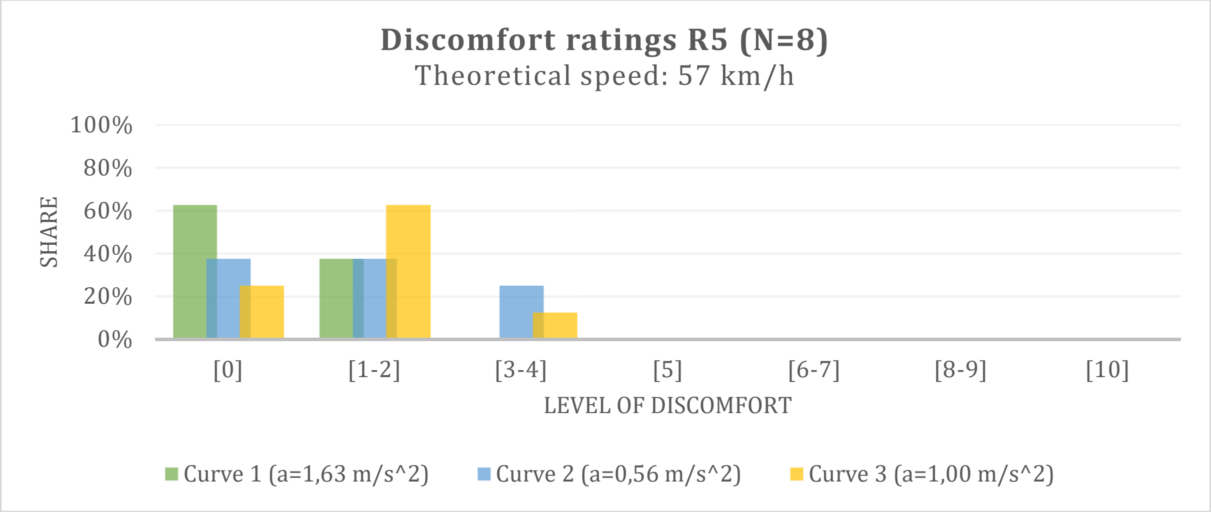


Figure 34: Discomfort ratings for the fifth round (R5).

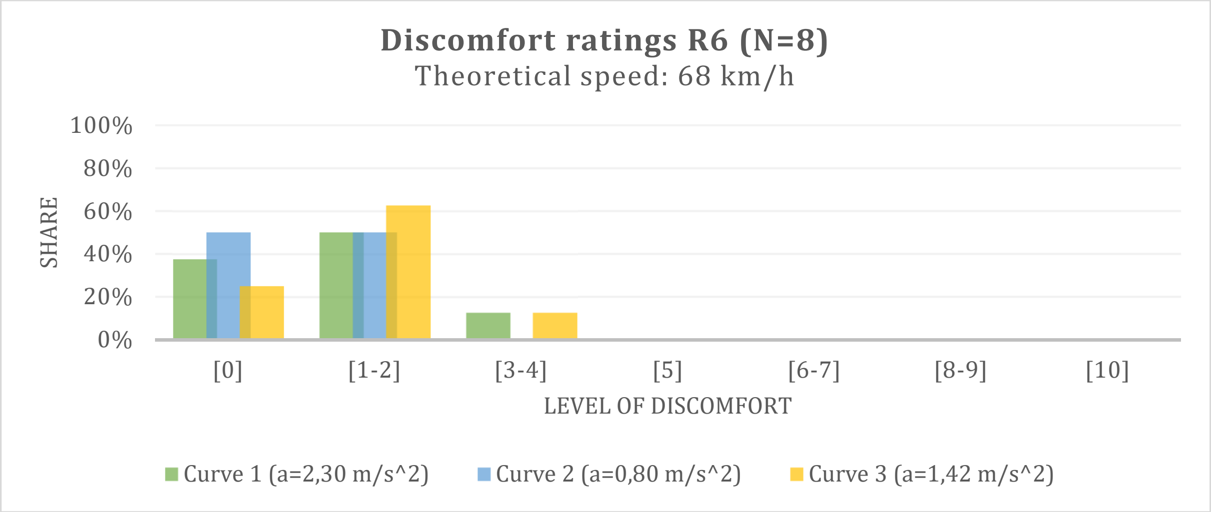


Figure 35: Discomfort ratings for the sixth round (R6).

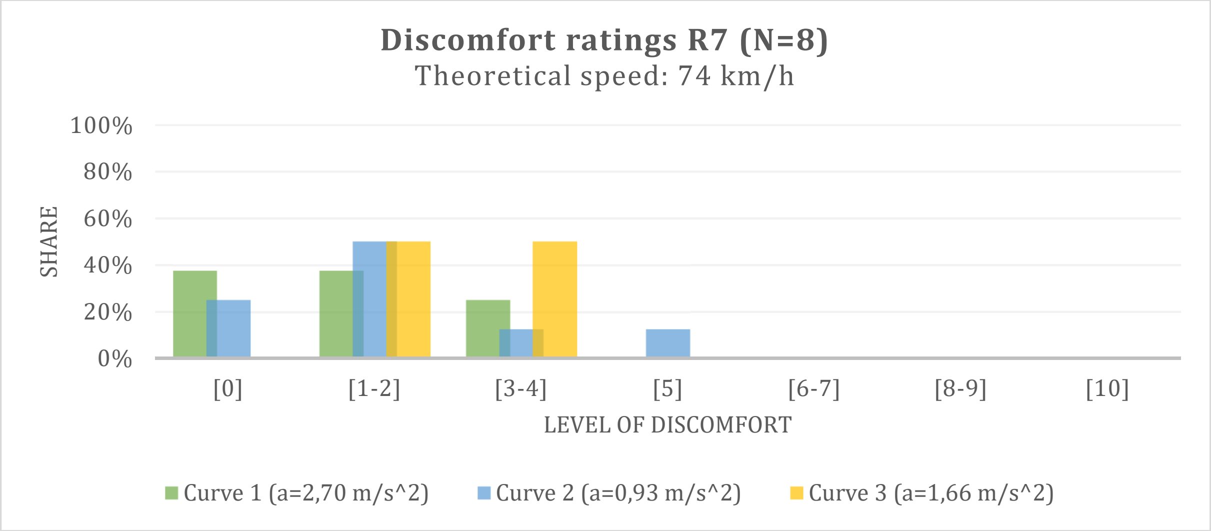


Figure 36: Discomfort ratings for the seventh round (R7).

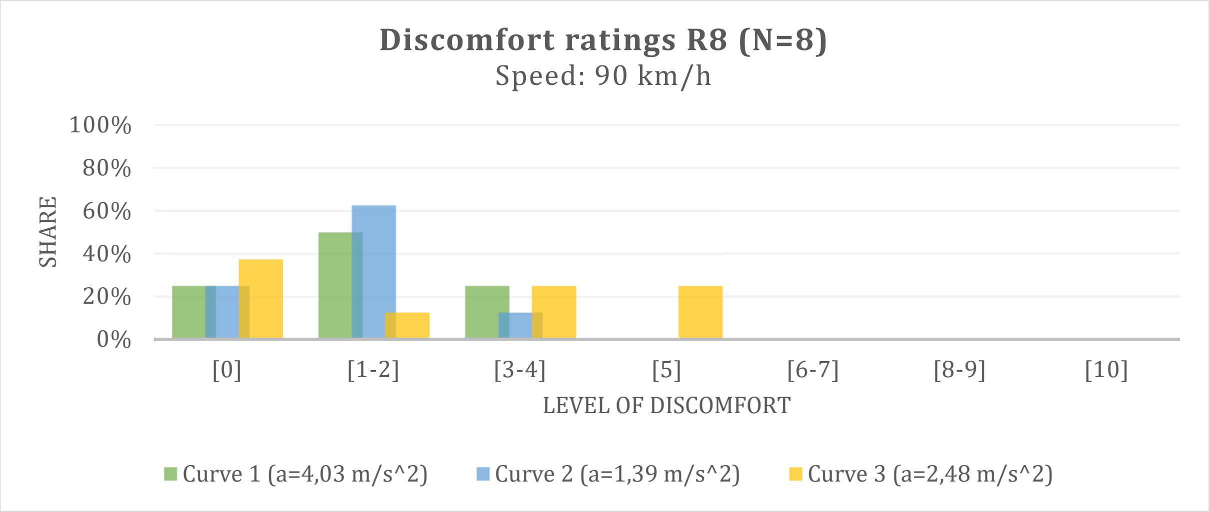


Figure 37: Discomfort ratings for the eighth round (R8).

Figures 30-37 emphasize on how the share for the different discomfort levels change throughout the rounds. The data can also be presented as shown in Figures 38-40, which emphasize on the trends for each discomfort level. The diagrams are given for each curve with increasing speed.

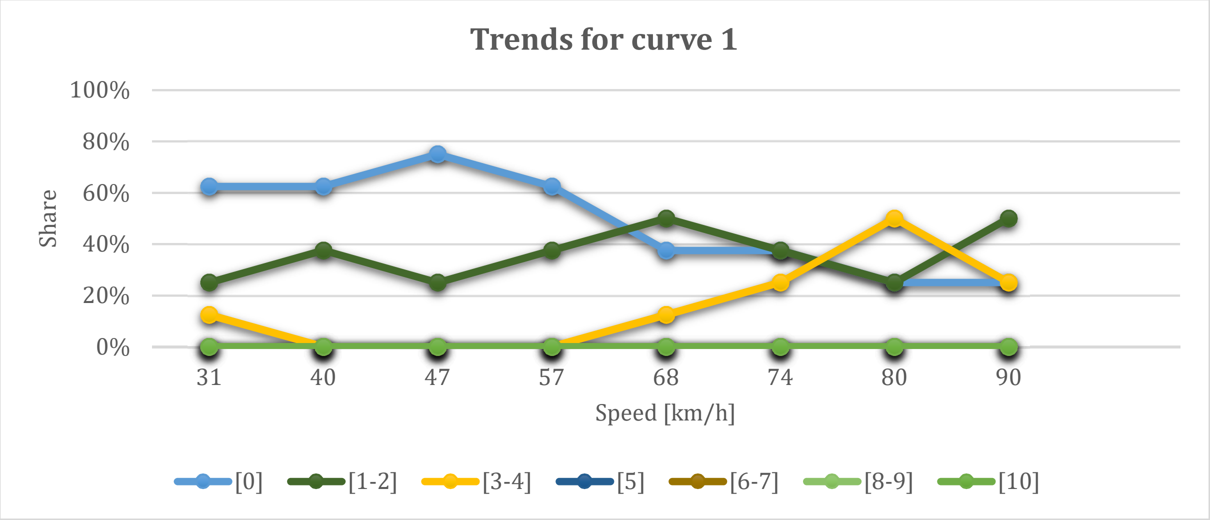


Figure 38: Diagram highlighting the trends for each discomfort level for the first curve.

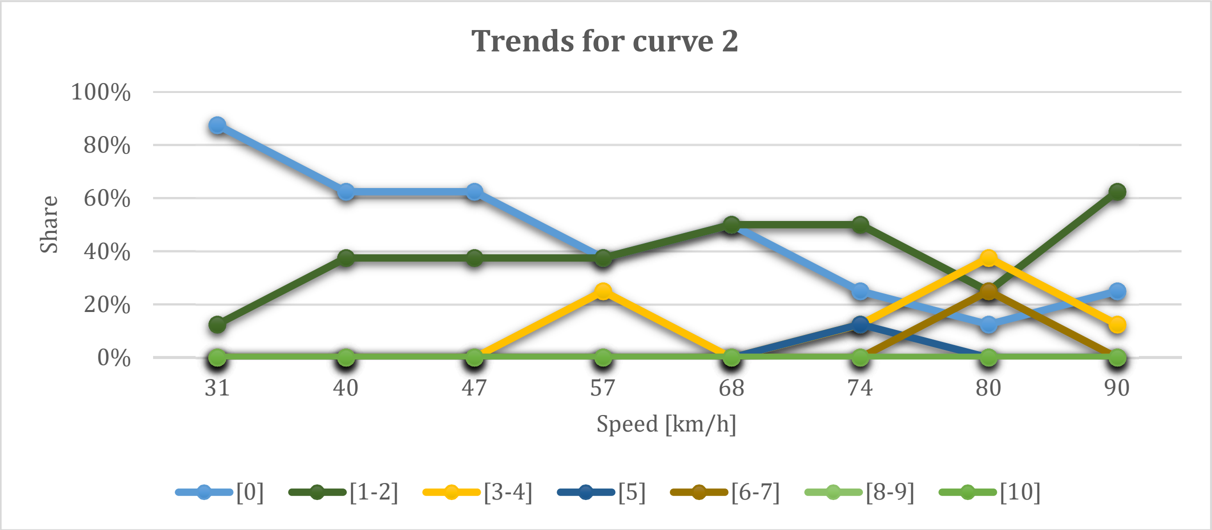


Figure 39: Diagram highlighting the trends for each discomfort level for the second curve.

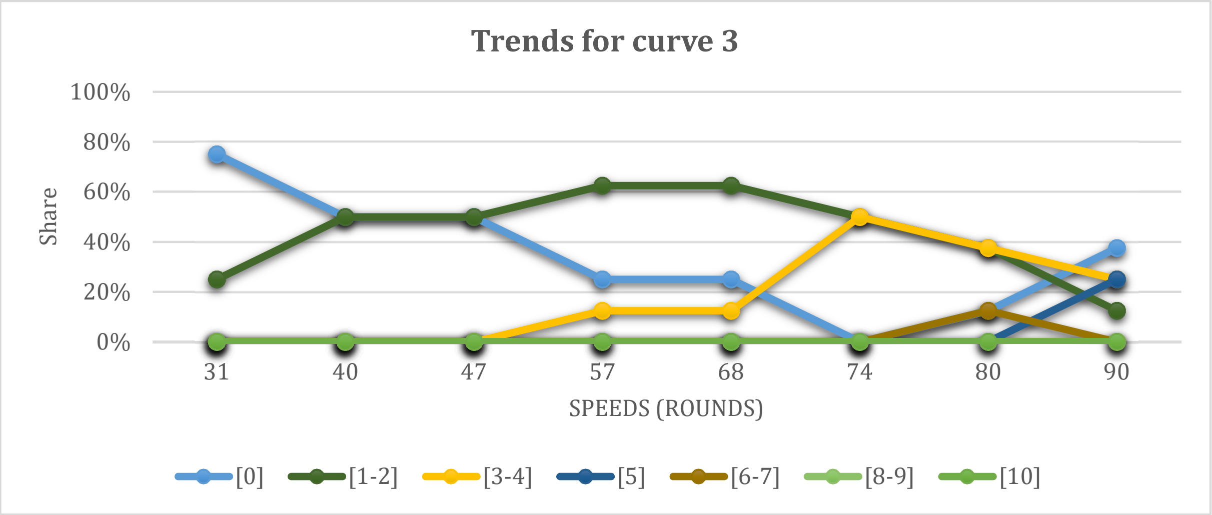


Figure 40: Diagram highlighting the trends for each discomfort level for the third curve.

7.1.2 Additional input on discomfort

This section presents some of the additional input on discomfort, based on the second part of the questionnaire. This included some description of the actual discomfort that was experienced, and some views on the participants considers comfortable. The section gives a short summary of the answers, which will also be further discussed in section 8.2).

The experiment exposed the participants to different vertical acceleration values (see section 5.3), both *extreme* conditions (high acceleration) and *normal* conditions (design values), to get their input on the discomfort itself. When subjected to relative *extreme* conditions (accelerations associated with travelling at the speed limit and above) the participants were asked if they felt any apparent discomfort. Of all the participants 75% said YES and 25% said NO. In addition, they were asked to describe what kind of discomfort they felt. About 50% of those saying YES to feeling discomfort commented on a *ticklish* feeling in the stomach and 20% had a feeling of falling. Answers can be seen in Appendix A. While some felt uncomfortable with the discomfort, some were barely bothered by it. When asked about their thoughts on the discomfort, about 87.5 % said they did not mind the discomfort even with the highest speeds tested.

When asked what they considered a desired level of driving comfort, 100% of the participants considered a discomfort of level 1-2 (slight discomfort, see Table 7) as comfortable, while 75-85% also considered discomfort of level 3-4 acceptable (moderate discomfort, see Table 7), as the discomfort neither bothered nor affect them in a negative way. Most of the participants said they would likely drive the speed limit, or maybe a little slower due to not being familiar with the alignment and area. There were also those who would not mind driving faster, and some who were more affected by the acceleration and would reduce the speed to 40-50 km/h.

7.1.3 Discussion on discomfort ratings

The discomfort ratings illustrate how different the discomfort can be perceived by individuals. Some could feel uncomfortable at the highest speeds, while other still were not bothered by the effects of acceleration. The differences in perceptions between individuals did not start showing until the higher speeds were tested, as illustrated in Figures 30-37.

There are some interesting points to comment on from the discomfort ratings. Firstly, there is a pattern throughout the rounds, Figures 30-37, where an increase in speed (vertical acceleration) results in the ratings moving towards higher discomfort levels. Yet, the ratings rarely cross the tipping point where the *discomfort* starts having a negative effect causing an uncomfortable situation, even at very high speeds. About 2,6 % of the discomfort measurements are ratings of level 5 or above. This was reflected in the feedback from the participants were the common impression of being exposed to vertical acceleration was that they would not directly consider the effect as discomfort or uncomfortable. Only a few did, but that occurred at the highest speeds. Second, the ratings from the first and last rounds shows some interesting inconsistencies. The first round was rated as one with the highest amount of discomfort and the last round, which is driven with higher speed, has discomfort ratings that are considerably lower than the first. The participants could have grown accustomed and familiar with the effects of vertical acceleration throughout the driving experiment. In Figures 38-40, it can also be seen that the ratings at 80 km/h for the higher discomfort levels decreased and the lower discomfort levels increases when reaching 90 km/h. This was also commented by the participants. Some stated that the effects of vertical acceleration did not feel uncomfortable as they were used to driving on roads like this, while one of the participants stated that driving in such a vertical alignment was new and could be uncomfortable when following the speed limit. Another point to mention is that no one knew what to expect when performing the first round, and the effect could be a result of surprise, that impacted the results of the first round. Lastly, it seems that the surrounding alignment of the curves could play a part as to how the effects were perceived. In theory, curve one (R=155 meters) should be the curve with the highest discomfort ratings and curve two (R=449 meters) with the lowest. The general impression from the ratings is that curve one is the one with the lowest discomfort ratings and curve two has relative high ratings, able to match the ratings for curve three. Studying the alignment in Figure 19 (page 46) shows that the transition between the curve are different. Curve one is located between another sag curve with a larger radius (>1400 meters) and crest curve, while curve two is located between two crest curves, both with small radii. The transition between the crest and second sag curve could intensify discomfort, as this transition is a quick and sharp (due to small radii), while a smoother transition for curve one could diminish the discomfort.

7.2 Acceleration measurements

The driving comfort measurements are useless for geometric road design purposes if not connected to vertical accelerations. The method used to obtain the vertical accelerations was using a sensor that measures accelerations (x-, y-, and z-direction). Figure 41 shows one of the acceleration measurements made during the second day of the experiment. The measurements only present the vertical (z-direction) acceleration.

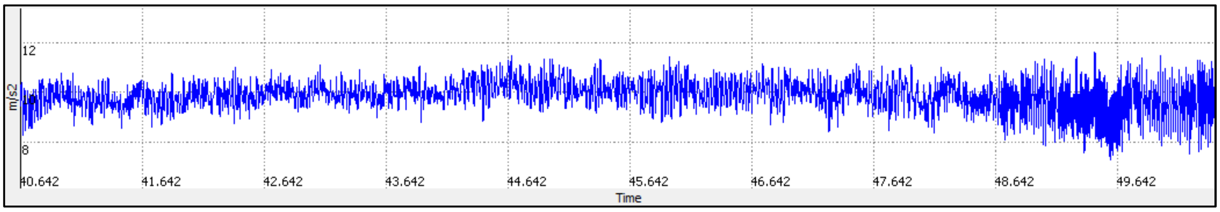


Figure 41: Vertical acceleration measurements for the third round with the third group (L3-G3: 40 km/h)

The measurements in Figure 41 show a lot of variations of the measured vertical acceleration, due to noise, irregularities and other road damages. Noise and other interruptions in the acceleration seem to vary between 1-2 m/s^2 in average. The acceleration measurements are presented for all groups, each round and all curves in Appendix C, along with measurements of elevation. Elevation measurements were used to locate the curves. Figure 42 shows an example of an elevation measurement.

The MT Manager software was used to re-play the recordings. The software only displayed the measurements (acceleration and elevation) within a 10 second time frame, as illustrated in Figures 41 and 42.

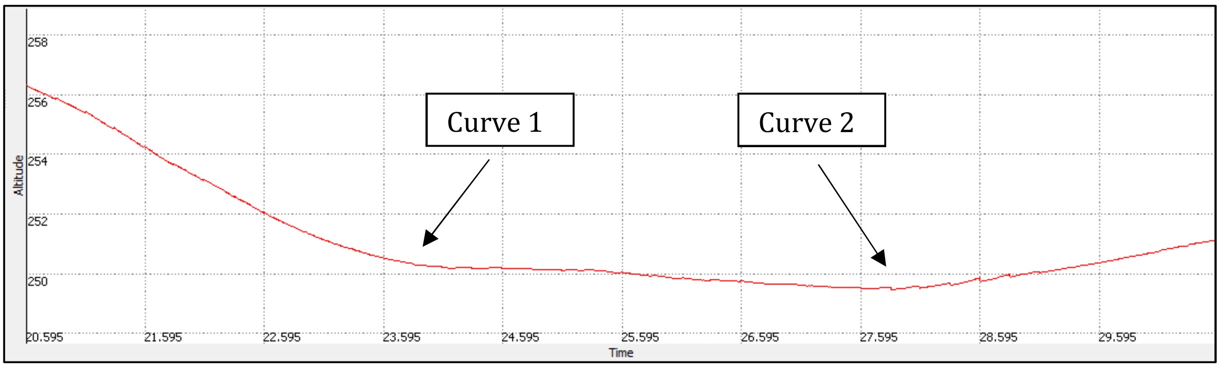


Figure 42: Elevation measurements for the seventh round with the fourth groups, showing curves one and two (L7-G4: 74 km/h).

7.3 Processing the measurement

Gathering the raw data was relatively easy to do. The question that remains is whether these measurements can be used for their intended purpose. This chapter takes the raw data through a processing and analyzing procedure to investigate what can be done with the measurements and suggesting how they can be used.

7.3.1 Subjective measurements

Table 11 presents all the ratings from all the participants in the order of increasing vertical acceleration. All the discomfort ratings were used to find a final discomfort level (overall impression), based on the concept of 85th percentile. However, the final discomfort level was chosen by selecting a level where at least 75% of ratings were that level or below (due to low participant number). For example, the second data row in Table 11: discomfort level *none* has 62.5% of ratings of that level and below, *slight* has 87.5% and *moderate* has 100%, thus the final discomfort level can be categorized as slight discomfort.

Table 11: Discomfort levels for each participant for every predetermine accelerations with the final discomfort level.

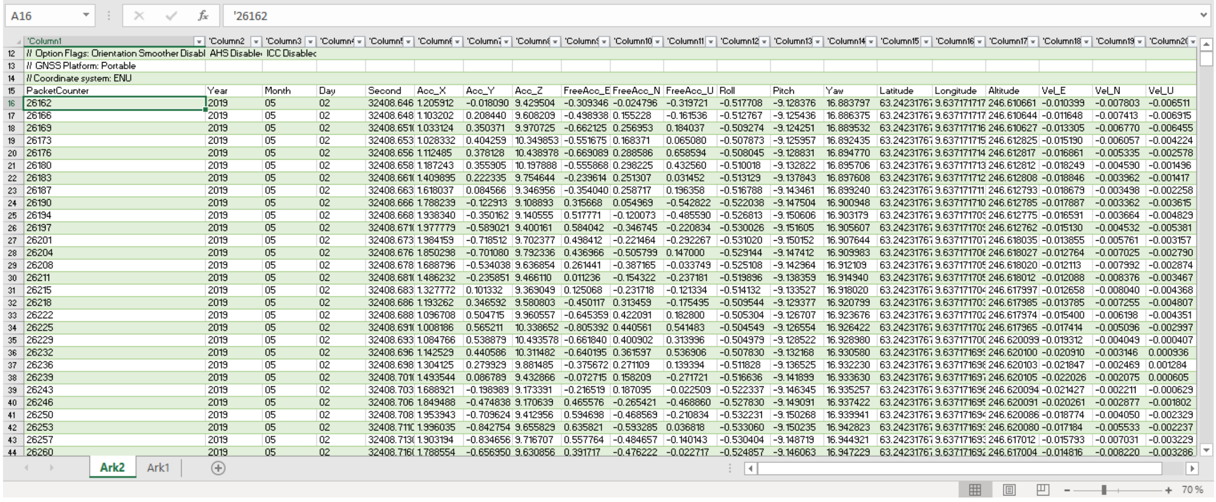
Round /curve	**[m/s^2]**	**G1-P1**	**G1-P2**	**G2-P1**	**G2-P2**	**G3-P1**	**G3-P2**	**G4-P1**	**G4-P2**	**Final discomfort level**
2_2	**0,17**	Slight	None	None	None	None	None	None	None	***None***
3_2	**0,28**	Slight	None	Slight	Slight	None	None	None	None	***Slight***
2_3	**0,30**	Slight	None	None	None	None	Slight	None	None	***None***
4_2	**0,40**	Slight	Slight	Slight	None	None	None	None	None	***Slight***
2_1	**0,49**	Slight	None	None	None	None	Slight	Moderate	None	***Slight***
3_3	**0,5**	Slight	Slight	None	Slight	None	Slight	None	None	***Slight***
5_2	**0,56**	Moderate	None	Slight	Slight	Moderate	Slight	None	None	***Slight***
4_3	**0,70**	Slight	None	Slight	Slight	None	Slight	None	None	***Slight***
6_2	**0,80**	Slight	None	Slight	Slight	Slight	None	None	None	***Slight***
3_1	**0,81**	Slight	None	None	Slight	None	None	Slight	None	***Slight***
7_2	**0,93**	Tipping point	Slight	Slight	Slight	Moderate	Slight	None	None	***Slight***
5_3	**1,0**	Slight	Slight	Slight	Sight	None	Moderate	Slight	None	***Slight***
1_2	**1,10**	Significant	Slight	Significant	Moderate	Moderate	Slight	None	Moderate	***Moderate***
4_1	**1,14**	Slight	None	None	None	None	Slight	None	None	***None***
8_2	**1,39**	Tipping point	Moderate	Moderate	Moderate	Moderate	Moderate	None	None	***Moderate***
6_1	**1,42**	Slight	Slight	None	None	Moderate	Slight	Slight	None	***Slight***
5_1	**1,63**	Slight	None	None	None	Slight	Slight	None	None	***Slight***
7_3	**1,66**	Slight	Moderate	Moderate	Moderate	Slight	Slight	Moderate	Slight	***Moderate***
1_3	**1,96**	Slight	Moderate	None	Moderate	Slight	Significant	Moderate	Slight	***Moderate***
6_1	**2,30**	Slight	Slight	None	None	Moderate	Slight	Slight	None	***Slight***
8_3	**2,48**	Slight	None	Significant	Moderate	Significant	Moderate	None	None	***Moderate***
7_1	**2,70**	Slight	None	Slight	Slight	Moderate	Moderate	None	None	***Slight***
1_1	**3,19**	Moderate	None	Moderate	Moderate	Slight	Moderate	None	Slight	***Moderate***
8_1	**4,03**	Slight	Slight	Slight	Slight	Moderate	Moderate	None	None	***Slight***

7.3.2 Objective measurements

The files were exported from Xsens MT Manager (software) into a txt. file and used in Excel. The data that was exported are presented in Table 12. The Excel file, as shown in Figure 43, showed that the sensor took a measurement every 0.0025 second, resulting in 400 measurements in one second. Each file contained about 20 000-25 000 measurements in total. Xsens MT Manager allowed export of different data.

Table 12: The data that was exported into txt. and Excel (Xsens, 2019b, p. 70-72).

Date and time	Year, month and day. Second measurements are expressed as seconds after midnight.
Acceleration	Acceleration in the sensor's orientational axes (x, y and z).
Free Acceleration	Acceleration in the local frame and the local gravity is deducted. Acceleration in the directions east (E), north (N) and up (U)
Euler Angles	Orientation (roll, pitch and yaw) of the body in the three axes (x, y and z).
Position	Position is measured in latitude, longitude and elevation.
Velocity	Velocity is measured in directions east (E), north (N) and up (U).



	'Column1	'Column2	'Column3	'Column	'Column	'Column	'Column	'Column	'Column	'Column10	'Column11	'Column12	'Column13	'Column14	'Column15	'Column16	'Column17	'Column18	'Column19	'Column2
12	// Option Flags: Orientation Smoother Disabl	AHS Disable	ICC Disable																	
13	// GNSS Platform: Portable																			
14	// Coordinate system: ENU																			
15	PacketCounter	Year	Month	Day	Second	Acc_X	Acc_Y	Acc_Z	FreeAcc_E	FreeAcc_N	FreeAcc_U	Roll	Pitch	Yaw	Latitude	Longitude	Altitude	Vel_E	Vel_N	Vel_U
16	26162	2019	05	02	32408.646	1.205912	-0.018090	9.429504	-0.309346	-0.024796	-0.319721	-0.517708	-9.128376	16.883797	63.24231767	9.637171717	246.610661	-0.010399	-0.007803	-0.006511
17	26166	2019	05	02	32408.648	1.103202	0.208440	9.608209	-0.498938	0.155228	-0.161536	-0.512767	-9.125436	16.886375	63.24231767	9.637171717	246.610644	-0.011648	-0.007413	-0.006915
18	26169	2019	05	02	32408.651	1.033124	0.350371	9.970725	-0.662125	0.256953	0.184037	-0.509274	-9.124251	16.889532	63.24231767	9.637171716	246.610627	-0.013305	-0.006770	-0.006455
19	26173	2019	05	02	32408.653	1.028332	0.404259	10.349853	-0.551675	0.168371	0.065080	-0.507873	-9.125957	16.892435	63.24231767	9.637171715	246.612825	-0.015190	-0.006057	-0.004224
20	26176	2019	05	02	32408.656	1.112485	0.378128	10.438978	-0.669089	0.288586	0.658594	-0.508045	-9.128831	16.894770	63.24231767	9.637171714	246.612817	-0.016861	-0.005335	-0.002578
21	26180	2019	05	02	32408.658	1.187243	0.355905	10.197888	-0.555868	0.298225	0.432560	-0.510018	-9.132822	16.895706	63.24231767	9.637171713	246.612812	-0.018249	-0.004590	-0.001496
22	26183	2019	05	02	32408.661	1.409895	0.222335	9.754644	-0.239614	0.251307	0.031452	-0.513129	-9.137843	16.897608	63.24231767	9.637171712	246.612808	-0.018846	-0.003962	-0.001417
23	26187	2019	05	02	32408.663	1.618037	0.084566	9.346956	-0.354040	0.258717	0.196358	-0.516788	-9.143461	16.899240	63.24231767	9.637171711	246.612793	-0.018679	-0.003498	-0.002258
24	26190	2019	05	02	32408.666	1.788239	-0.122913	9.108893	0.315668	0.054969	-0.542822	-0.522038	-9.147504	16.900948	63.24231767	9.637171710	246.612785	-0.017887	-0.003362	-0.003615
25	26194	2019	05	02	32408.668	1.938340	-0.350162	9.140555	0.517771	-0.120073	-0.485590	-0.526813	-9.150606	16.903179	63.24231767	9.63717170	246.612775	-0.016591	-0.003664	-0.004829
26	26197	2019	05	02	32408.671	1.977779	-0.589021	9.400161	0.584042	-0.346745	-0.220834	-0.530026	-9.151605	16.905607	63.24231767	9.63717170	246.612762	-0.015130	-0.004532	-0.005381
27	26201	2019	05	02	32408.673	1.984159	-0.718512	9.702377	0.498412	-0.221464	-0.292267	-0.531020	-9.150152	16.907644	63.24231767	9.63717170	246.618035	-0.013855	-0.005761	-0.003157
28	26204	2019	05	02	32408.676	1.850298	-0.701080	9.792336	0.436966	-0.505799	0.147000	-0.529144	-9.147412	16.909983	63.24231767	9.63717170	246.618027	-0.012764	-0.007025	-0.002790
29	26208	2019	05	02	32408.678	1.688796	-0.534038	9.636854	0.261441	-0.387165	-0.033749	-0.525108	-9.142964	16.912109	63.24231767	9.63717170	246.618020	-0.012113	-0.007992	-0.002874
30	26211	2019	05	02	32408.681	1.486232	-0.235851	9.466110	0.011236	-0.154322	-0.237181	-0.519896	-9.138359	16.914940	63.24231767	9.63717170	246.618012	-0.012088	-0.008376	-0.003467
31	26215	2019	05	02	32408.683	1.327772	0.101332	9.369049	0.125068	-0.231718	-0.121334	-0.514132	-9.133527	16.918020	63.24231767	9.63717170	246.617997	-0.012658	-0.008040	-0.004368
32	26218	2019	05	02	32408.686	1.193262	0.346592	9.580803	-0.450117	0.313459	-0.175495	-0.509544	-9.129377	16.920799	63.24231767	9.63717170	246.617985	-0.013785	-0.007255	-0.004807
33	26222	2019	05	02	32408.688	1.096708	0.504715	9.960557	-0.645359	0.422091	0.182800	-0.505304	-9.126707	16.923676	63.24231767	9.63717170	246.617974	-0.015400	-0.006198	-0.004351
34	26225	2019	05	02	32408.691	1.008186	0.565211	10.338652	-0.805392	0.440561	0.541483	-0.504549	-9.126554	16.926422	63.24231767	9.63717170	246.617965	-0.017414	-0.005096	-0.002997
35	26229	2019	05	02	32408.693	1.084766	0.538879	10.493578	-0.661840	0.400902	0.313996	-0.504979	-9.128522	16.928980	63.24231767	9.63717170	246.620099	-0.019312	-0.004049	-0.000407
36	26232	2019	05	02	32408.696	1.142529	0.440586	10.311482	-0.640195	0.361597	0.536906	-0.507830	-9.132168	16.930580	63.24231767	9.63717169	246.620100	-0.020910	-0.003146	0.000936
37	26236	2019	05	02	32408.698	1.304125	0.279929	9.881485	-0.375672	0.271109	0.139394	-0.511828	-9.136525	16.932230	63.24231767	9.63717169	246.620103	-0.021847	-0.002469	0.001284
38	26239	2019	05	02	32408.701	1.493544	0.086789	9.432866	-0.072715	0.158209	-0.271721	-0.516636	-9.141899	16.933630	63.24231767	9.63717169	246.620105	-0.022026	-0.002075	0.000605
39	26243	2019	05	02	32408.703	1.688921	-0.198989	9.173391	-0.216519	0.187095	-0.022509	-0.522337	-9.146345	16.935257	63.24231767	9.63717169	246.620094	-0.021427	-0.002211	-0.000629
40	26246	2019	05	02	32408.706	1.849488	-0.474838	9.170639	0.465576	-0.265421	-0.468860	-0.527830	-9.149091	16.937422	63.24231767	9.63717169	246.620091	-0.020261	-0.002877	-0.001802
41	26250	2019	05	02	32408.708	1.953943	-0.709624	9.412956	0.594698	-0.468569	-0.210834	-0.532231	-9.150268	16.939941	63.24231767	9.63717169	246.620086	-0.018774	-0.004050	-0.002329
42	26253	2019	05	02	32408.711	1.996035	-0.842754	9.655829	0.635821	-0.593285	0.036818	-0.533060	-9.150235	16.942823	63.24231767	9.63717169	246.620080	-0.017184	-0.005533	-0.002237
43	26257	2019	05	02	32408.713	1.903194	-0.834656	9.716707	0.557764	-0.484657	-0.140143	-0.530404	-9.148719	16.944921	63.24231767	9.63717169	246.617012	-0.015793	-0.007031	-0.003229
44	26260	2019	05	02	32408.716	1.788554	-0.656950	9.630856	0.391717	-0.476222	-0.022717	-0.524857	-9.146063	16.947229	63.24231767	9.63717169	246.617004	-0.014816	-0.008220	-0.003286

Figure 43: Screenshot of Excel with the data (Table 12) from G2-L1.

There are a lot of possibilities when processing this data but can be very time-consuming, due to the size of the dataset. The focus when processing the data was obtaining the vertical acceleration in the curves and taking a closer look at the measured speed. "Free Acceleration (FreeAcc_U)" gave the acceleration in vertical direction where gravity is subtracted, making it easier to work with. Only the round with 80 km/h was analyzed, due to limited time and experimental nature of this study.

To locate the sections of the recording where the curves occurred, a time interval, $t_{n,1}$-$t_{n,2}$, (see Figure 44, n is the group number) was determined using the elevation measurements from Appendix C. The time interval and corresponding "second"-measurements (see Table 12) are presented in Table 13. The rest of the data was removed. Locating the curve could be challenging (e.g. Appendix C.8 and C.16). Thus, the interval for the curves are approximate values with a safety margin (+1-2 seconds), making sure the whole curves were included.

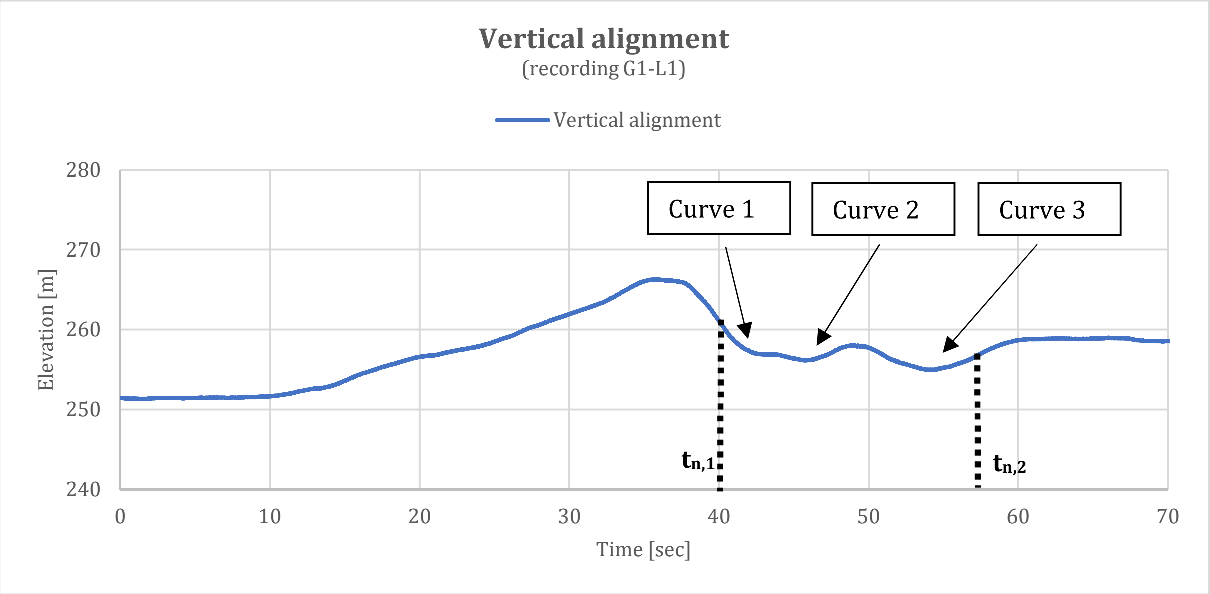


Figure 44: Elevation measurement (L1-G1) from MT Manager (elevation-time) converted into Excel. Time interval was determined using MT Manager (Appendix C).

Table 13: Time interval of the section with the three curves, and their corresponding "second" measurement in Excel.

Recording no.	Time interval (elevation measurements)	In Excel (second measurements)
L1-G1	$t_{1,1}$-$t_{1,2}$: 40-58	31643,7680 – 31661,7680
L1-G2	$t_{2,1}$-$t_{2,2}$: 36-52	32444,6230 – 32460,7210
L1-G3	$t_{3,1}$-$t_{3,2}$: 36-45	31039,6200 – 31058,6200
L1-G4	$t_{4,1}$-$t_{4,2}$: 22-38	32008,9590 – 32025,0790

Latitude and longitude measurements were converted to E- and N-coordinates and used to calculate the distance from $t_{n,1}$-$t_{n,2}$ for each recording. Distance at $t_{n,1}$ is set at x=0. The acceleration measurements (rounds testing 80 km/h) are presented in Figures 45-48 together with the vertical alignment (elevation measurements). Figures 49-52 also presents the measured speed for each round with alignment, calculated using Vel_E and Vel_N (see Figure 43) given as [m/s].

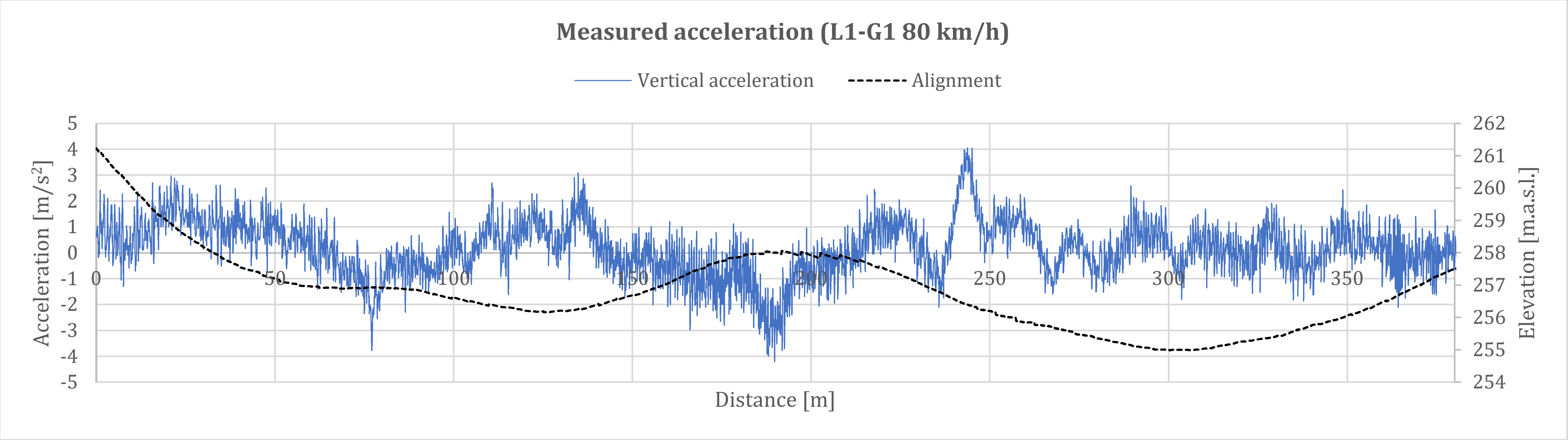


Figure 45: Vertical acceleration measurements, recording L1-G1 (80 km/h) with vertical alignment.

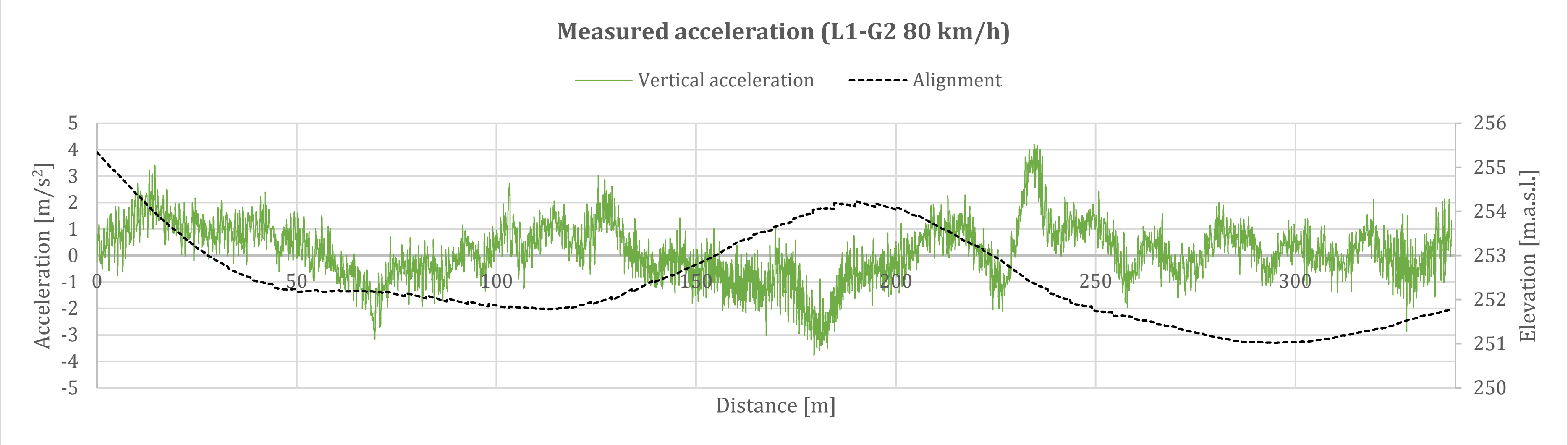


Figure 46: Vertical acceleration measurements, recording L1-G2 (80 km/h) with vertical alignment.

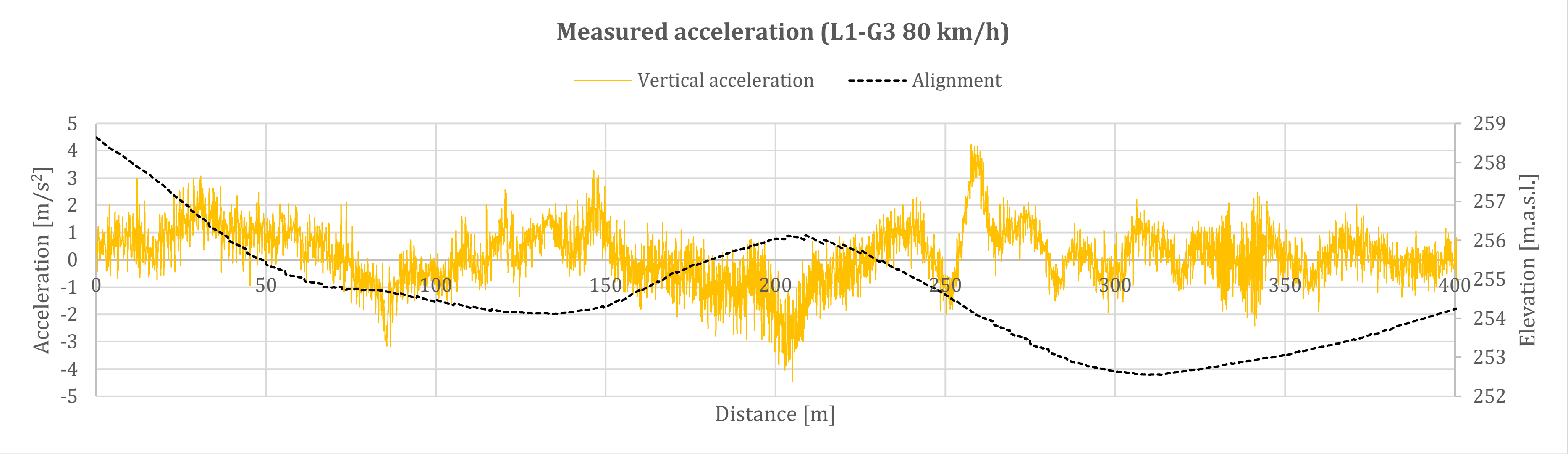


Figure 47: Vertical acceleration measurement, recording L1-G3 (80 km/h) with vertical alignment.

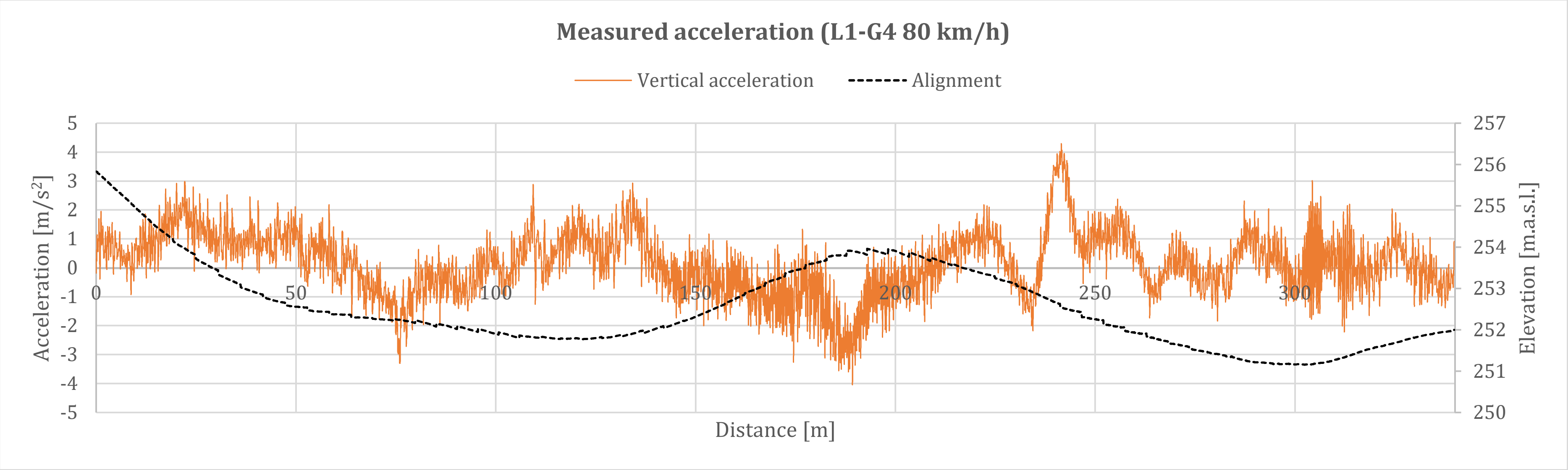


Figure 48: Vertical acceleration measurement, recording L1-G4 (80km/h) with vertical alignment.

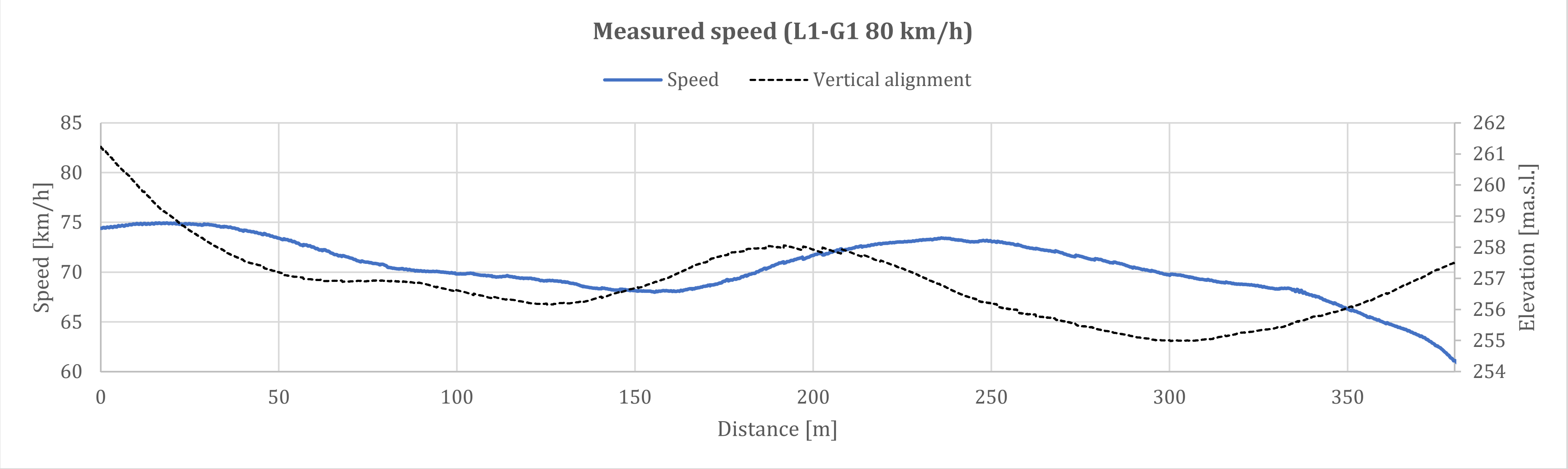


Figure 49: Speed measured for recording L1-G1 (cruise control at 80 km/h) with vertical alignment.

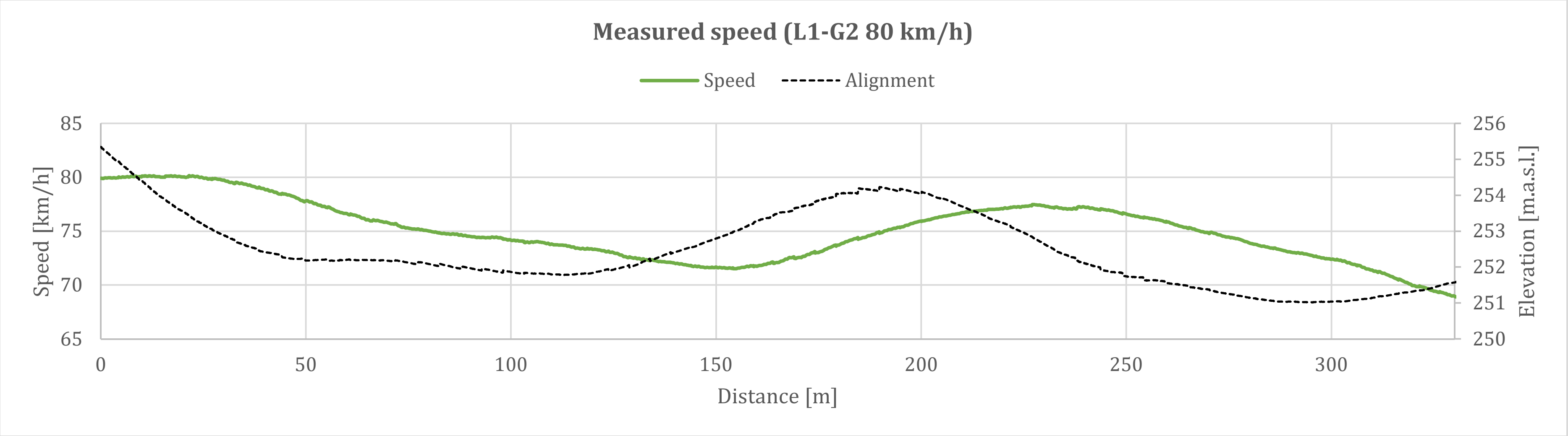


Figure 50: Speed measured for recording L1-G2 (cruise control at 80 km/h) with vertical alignment.

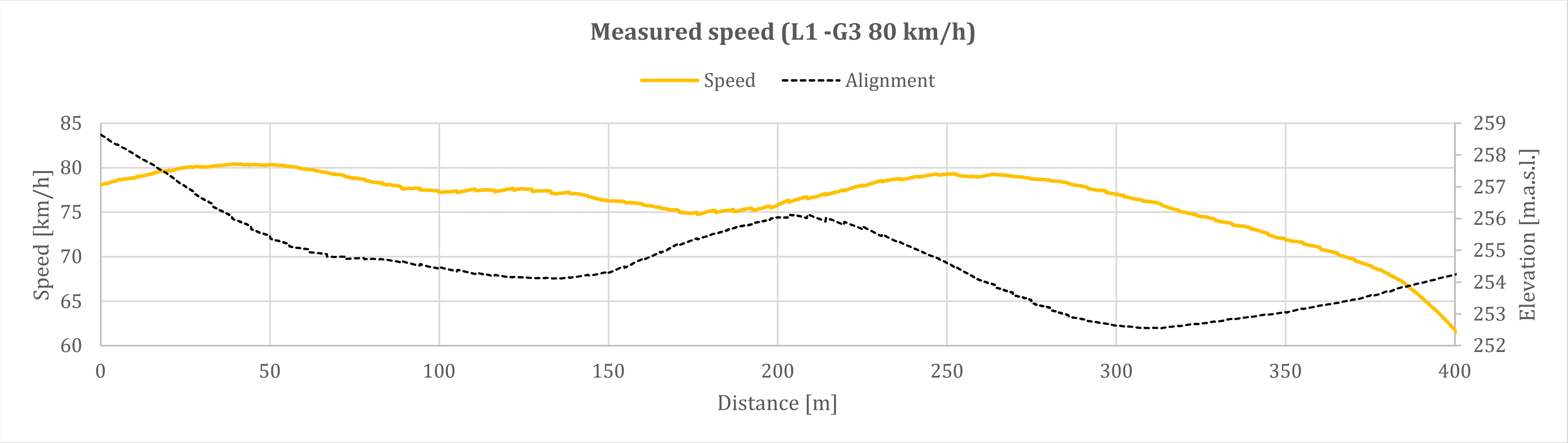


Figure 51: Speed measured for recording L1-G3 (cruise control at 80 km/h) with vertical acceleration.

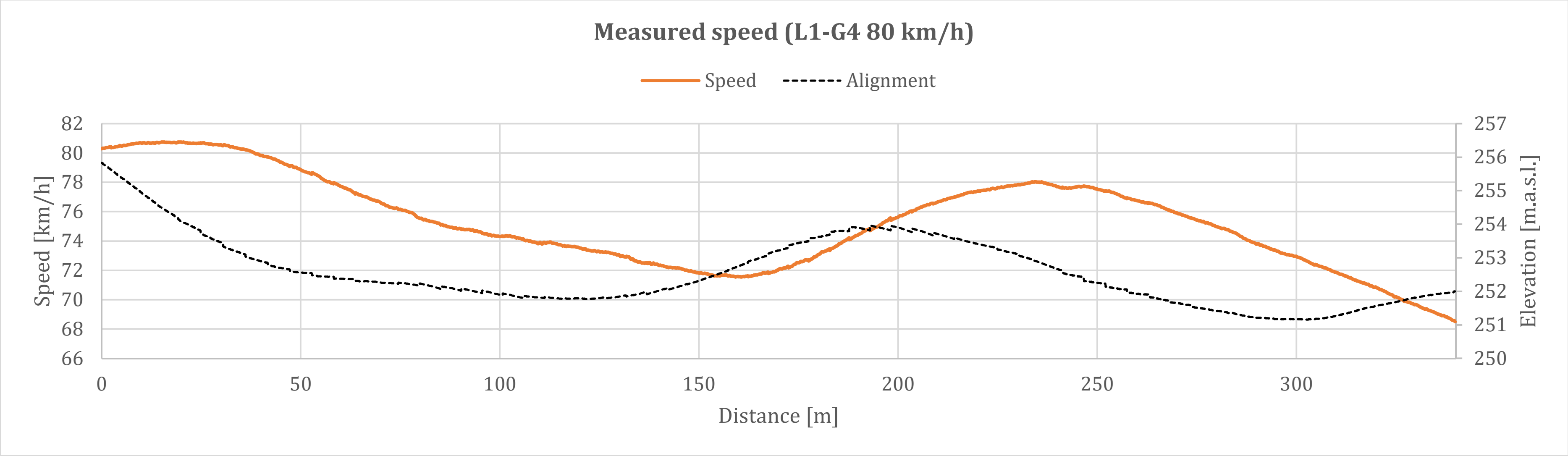


Figure 52: Speed measured for recording L1-G4 (cruise control at 80 km/h) with vertical acceleration.

7.3.3 Discussion on processed data

This section takes a closer look at the processed data for both subjective (driving comfort) and objective (vertical acceleration) measurements and makes a few comments how the measurements could be used.

Subjective measurements

The raw comfort data in Table 11 was used to see how discomfort progressed with increasing vertical acceleration. Usually an 85th percentile would be used, but as the measurements were quite susceptible to even small variations between the participants due to the small sample, a lower percentile (75th) was used for processing this data set. For instance, the seventh (0.56 m/s^2) and thirteenth (1.10 m/s^2) data row would be changed to moderate and significant respectively, if one more of the participants rated moderate or higher in the seventh row and significant or higher in the thirteenth row, removing the trend that can be seen.

Using the data, it was possible to try quantifying driving comfort, which was the final step in measuring driving comfort and could lead to a result as presented in Table 14. As this experiment is just an attempt to see how driving comfort can be quantified, the information presented in Table 14 is only an example to how this procedure could work, based on the limited data in this experiment. Table 11 and Table 14 are based on the theoretical centripetal acceleration that was used when developing the experiment procedure and should be connected to the actual vertical acceleration (see section **Objective measurements** below).

Table 14: An example how driving comfort, with respect to vertical acceleration, can be quantified.

Driving comfort (level of discomfort)	Vertical acceleration
No discomfort	0-0.50 m/s^2
Slight discomfort	0.50-1.10 (1.60) m/s^2
Moderate discomfort	> 1.10 (1.60) m/s^2

Some aspects of the experiment should be given further consideration with respect to quantifying driving comfort, as in Table 14. For instance, looking at individual ratings, which curves and the order of the rounds, as well as the final discomfort level. This is something that can be done with this small data set, giving the opportunity to investigate and understand the driving comfort more, e.g. factors that can impact driving comfort.

There are some accelerations that are rated as slight in the range of 0-0.5 m/s^2, but the common impression seems to be no discomfort. Results based on a larger data collection would be able to give more validity to the assumption of 0-0.50 m/s^2 resulting in no discomfort. The small variations will not be as influential as they are with this data set.

The *limit* between slight and moderate were a bit challenging to determine. The final discomfort level for vertical accelerations of 1.10-4.03 m/s^2 shifts between slight and moderate discomfort, not displaying a clear transition between the two levels. There are five slight discomfort ratings in-between moderate discomfort ratings (final discomfort level) in the range of 1.10-4.03 m/s^2. These ratings are connected to the first curve with the smallest radius and should in theory have the highest discomfort ratings. This was shown not to be the case based on the comfort data above (Tables 9-11 and Figures 30-37). The discomfort rating for curve one is also considered *none* discomfort in the fourth round (a=1,14 m/s^2), where the final discomfort level starts shifting between slight and moderate. In the last round, curve three have a higher discomfort rating than curve one. As stated previously, curve one follows a larger sag curve (>1400 meters, not included in the analysis), see Figure 19 (page 46). This could indicate that the large sag curve impacts how the adjacent small curve (curve one) is perceived, as the change in direction might not be as easily noticed as e.g. curve two that is located between two (small) crest curves, such as curve two.

Table 15: Overall discomfort ratings based on increased vertical acceleration for each curve.

	Curve 1		***Curve 2***		***Curve 3***	
Round	*m/s^2*	*Rating*	*m/s^2*	*Rating*	*m/s^2*	*Rating*
2	0,49	Slight	0,17	None	0,30	None
3	0,81	Slight	0,28	Slight	0,50	Slight
4	1,14	None	0,40	Slight	0,70	Slight
5	1,63	Slight	0,56	Slight	1,00	Slight
6	2,30	Slight	0,80	Slight	1,42	Slight
7	2,70	Slight	0,93	Slight	1,66	Moderate
1	3,19	Moderate	1,10	Moderate	1,96	Moderate
8	4,03	Slight	1,39	Moderate	2,48	Moderate

Table 15Table 15 shows the final discomfort levels with increasing vertical acceleration for each of the curves. Curve one is more inconsistent in its ratings but seems to cause slight discomfort with every acceleration. Curve two and three shows clear change between the discomfort levels, but the limits are reached faster in curve two compared to curve three. This could also indicate that the surrounding alignment can impact discomfort, as curve three is located between a crest curve and an even slope. A value in the range of 1.10-1.60 m/s^2 could be a limit between slight and moderate discomfort. Section 7.1.3 mentioned that the participants could get accustomed to the effects of vertical acceleration, which could indicate or argue that 1.10 m/s^2 could be a limit, as this acceleration was tested in the first round, being the first encounter with the discomfort. Most accelerations above 1.10 m/s^2 was tested on the four last rounds and the participants commented on becoming a bit familiar with the effect after performing some rounds, perceiving the effects as less uncomfortable.

Based on these results, there is a possibility to quantify driving comfort and even suggest a comfort threshold based on feedback from the participants. When asked about where to set the comfort threshold (in terms of what they feel comfortable with), all of the participants agreed on that slight discomfort (discomfort level 1-2, see Table 7) could be set as a comfort threshold, even if some would accept moderate discomfort and higher accelerations. This particular driving experiment could make a suggestion of 1.0-1.10 m/s^2 as a comfort threshold (the value of the vertical accelerations to be used to determine the vertical radius). This is a value higher than what the standards use as a design value, mainly due to the fact that vertical (centripetal) acceleration do not generate a type of discomfort that generally have a negative effect, physically (e.g. pain) or psychologically (e.g. feeling unsafe). The majority did not even consider the effects as discomfort. However, a large database of discomfort ratings and acceleration would provide more reliable and valid quantification of driving comfort and comfort threshold, based on an 85th percentile, where the variations are less influential. Yet, investigating the raw data and processed data in this thesis gave a lot of interesting views on driving comfort and some input on how to do and process driving comfort measurements.

Objective measurements

The vertical acceleration is presented with the vertical alignment based on distance in Figures 45-48 for each groups' first round (80 km/h).

The measurements required further processing to be able to use them when connecting vertical acceleration to driving comfort. There is a lot of noise that should be filtered out to see if it could be easier to read of acceleration values. Even the first rows of "FreeAcc_U" in Figure 43 (column 11, from row 16) shows a large variation in accelerations when the speed is 0 km/h (column 18 and 19), thus noise. An option could be to place the measurements from the different runs of the same speed over each other and see if there are some similar peaks and other patterns where the curves are located. However, a closer look at the data showed that the position (latitude, longitude and elevation) measurements did not match across the four datafiles. Finding a common starting point based on position was therefore challenging, which is why a time interval based on alignment (elevation measurements) were used instead. The elevation measurements also show this in Figures 45-58. The measurement would have to calibrated for this option.

The speed measurements, as presented in Figures 49-52, were also considered further. The speed could be used to find the centripetal acceleration based on an average speed value for each curve. However, this acceleration would be theoretical as the curve radius would have to be the value obtained from *Vegkart*. It could be investigated whether curve radius could be determined from the position measurements. However, the position measurements, for different rounds and groups, have some differences that could results in different radii. Also, the first concave alignment is a compound of curves (including cure one) and separating the two curves are challenging. There was also the issue of locating curve two (e.g. attachment C.8), where there is no hint of a curve. The measurements for the rounds with the highest speed (90 km/h) also become more turbulent (e.g. attachment C.32). The data also illustrates that the vehicle was not able to keep the speed at a constant throughout the curved section, due to the variation in the alignment and operations of the vehicle, resulting in a deviation from the pre-determined acceleration. Table 16 shows the measured speed for each group.

The measured speeds compared to the selected speeds are expected to be lower as there are some deviations between what the speedometer shows and what the actual speed is. The measured speed could be used to correct the theoretical centripetal acceleration to a value more similar to the actual vertical acceleration. However, there are at least three different speeds and accelerations, as shown in Table 16, and it would just be easier to categorize them as the pre-determined acceleration, even if the actual acceleration is lower. This might be a bit of a controversial way of doing it as the discomfort applies to the actual acceleration and not the theoretical. The main issue with this approach it that the discomfort ratings are not made based on the theoretical, but the measured vertical acceleration. The best option would therefore be to obtain the measured vertical acceleration, which requires further work to get good and reliable measurements.

Table 16: Measured (average) speed and deviation from pre-determined vertical acceleration.

Curve	Rec.	Measured speed [average]	m/s^2 (based on measured speed)	m/s^2 (pre-determined)	Deviation
1	*L1-G1*	73	2.65	3.19	-5-15%
	L1-G2	78	3.03		
	L1-G3	80	3.19		
	L1-G4	78	3.03		
2	*L1-G1*	68	0.79	1.10	-10-30%
	L1-G2	73	0.92		
	L1-G3	76	0.99		
	L1-G4	73	0.92		
3	*L1-G1*	70	1.50	1.95	-10-25%
	L1-G2	73	1.63		
	L1-G3	76	1.77		
	L1-G4	73	1.63		

There are however some other minor issues related to the measurements that need to be handled. The American standard mentioned that measuring the change in vertical direction is influenced by factors such as vehicle weight, vehicle suspension and tire flexibility. Using the measured vertical acceleration might be a bit controversial as well, as sag curves are designed based on the centripetal acceleration formula (see section 2.1). The discomfort ratings were based on the acceleration (change in vertical direction) which is influenced by factors such as the vehicle properties, rather than the theoretical acceleration of an object or body along a curved path. Using measured acceleration would be more representable for the comfort measurements as it is based on real driving and vehicle conditions and would be easier to obtain. It is also the issue of how representative the measurements are for the driver and passengers experiencing the effects of the sag curves. The sensor was fixed to the inside of the vehicle as shown in Figure 29 (page 61), measuring the change in direction of that surface inside the vehicle and not the individuals. Placing a sensor on the individual would require them to stay completely still. Another option could be to place a sensor on the headrest, as this is more similar to what the individual might experience.

One final point to give some thoughts to is the vehicle conditions that gave these driving comfort and vertical acceleration measurements. The vehicle that was used is of a newer model (2015) where vehicle weight, suspension and tires can have an effect on driving comfort, in respect to vertical acceleration. This might the reason why the effects were not considered uncomfortable. When investigating the road section used in the experiment, an older vehicle from 2005 was used, and the effect, or discomfort, of the sag curve were more evident. There are both old and new vehicles on the road network and using the theoretical centripetal acceleration could account for this. However, comfort has become an important trait and ensuring comfort makes the vehicle manufacturers' products competitive, and future vehicle properties will ensure good comfort. Using measured acceleration might be a good option as it could account for the vehicle properties, and since centripetal acceleration seems challenging to measure.

Summary

Two of the research questions asked about how driving comfort could be measured and if it was possible to measure it within the driving experiment. Working on the experiment and the results showed that it is possible, the main issue is obtaining good and reliable acceleration measurements to be able to draw valid conclusions. The last two research questions asked whether the measurements could be used to quantify driving comfort, determine any comfort threshold and find any indication that design values could or should be re-evaluated. The data from this driving experiment could be used to quantify driving comfort and showed that the design values could be re-evaluated. Whether they should be re-evaluated also depends on other factors further discussed in chapter 8.3 and 8.4.

8 Discussion

This chapter makes some finale comments on the thesis. The chapter is divided into five sections, each focusing on a topic considered both relevant to the research questions and important to give thoughts on. The main topics are the driving experiment, driving comfort's definition, implications, autonomous vehicles and future steps.

8.1 Driving experiment

The driving experiment was developed as a part of the thesis, built on both available literature and on knowledge gaps presented in chapter 4. Developing the experimental method with limited data on driving comfort and vertical acceleration led to it being constructed in a way to gather data and information, to fill knowledge gaps, that was most desirable and also achievable at this early stage. The general feedback from the participants of the driving experiment was positive, saying it was a good and interesting experiment. The feedback also included a comment about the importance of investigating driving comfort in geometric road design.

Uncovering potential improvements to the method were necessary and expected. It starts of as a trial-and-error experiment, finding out what does or does not work or what needs improvement and how to achieve it. The method, and research, shape itself as new ideas are being tested. There are a few insights regarding how the driving comfort measurements were made, the procedure and test conditions, as discussed below.

There were eight rounds in total, where 24 vertical accelerations were tested. Without having any ideas on how discomfort would develop with increasing acceleration, there was an uncertainty whether testing this wide range (0-4.0 m/s^2) was necessary, or even productive. There were comments from the participants about that there could be less rounds and more testing of extreme conditions (high speed). Half of the tested accelerations stayed within the range of 0-1.0 m/s^2, which had very low discomfort ratings, while the other half ranged between 1.0-4.0 m/s^2. Testing just 0.3, 0.5 and 1.0 m/s^2 would have been enough, as the discomfort ratings below 1.0 m/s^2 were generally the same and not providing any interesting views on driving comfort, with respect to vertical acceleration. Testing the three mentioned acceleration would have given the same conclusion as the 12 acceleration that were tested. However, the section had three sag curves with small, varying radii, and this was taken advantage of to consider more accelerations. All three curves would have had to be driven, nonetheless. The experiment allowed to map out how much discomfort the different accelerations generated, so that further experiments can focus on a narrower acceleration range. The most interesting would be to test high speeds where there could be more signs of uncomfortable situations. Having eight rounds could also lead to the participants becoming more familiar with the discomfort as mentioned in section 7.1.3. The rounds were also listed by increasing speed, except for the first round. Driving the speed limit was chosen to be performed first to get the participants impression of what discomfort vertical acceleration can generate, which required high speeds. A random order of the speeds could give more real first impression, instead of having the discomfort gradually increasing each round.

The discomfort ratings system and the questionnaire were easy to use. Yet, there could be some adjustment to the system, based on a few comments from the participants and the information obtain on discomfort. Level 5, which represented the tipping point between discomfort being acceptable to uncomfortable, should have just been a limit rather than a rating. It is not easy to interpret, and the ratings should be either comfortable/acceptable or uncomfortable. Another point was that all the levels were defined as discomfort. As also presented in section 7.1.3, most of the participants would not consider the effect of vertical acceleration as discomfort. Some commented during the experiment that they did not quite know which discomfort rating to use as it was not discomfort, but they still felt some effect form the acceleration. An option could be to have a level for no discomfort (level 0) and one or two levels for comfortable or acceptable driving comfort (noticeable effects). When having two level, it is possible to give an indication whether they are reaching an acceleration that they consider uncomfortable. The rest of the levels would be discomfort where the effects have a negative impact and is uncomfortable, going from slight to high.

Another topic to discuss is the test conditions. Some aspects are already mentioned, like how alignment might influence driving comfort and cruise control lead to different accelerations in the curves. There were some bumps and irregularities along the road surface that can affect both driving comfort and the vertical acceleration measurements. There was also a comment from a participant about the curves being too close together, making it more difficult to remember how each of the three curves felt and rate discomfort. The section was also driven in both directions. The most ideal would have been to test the same curve with different acceleration, but in real driving conditions, this is not as efficient with the amount of accelerations that were tested. It could have been with an experiment focusing on with fewer vertical accelerations, as mentioned above. The driving experiment was used to test the method of how to measure driving comfort and did not require ideal testing conditions to do so with this kind of investigation. Thus, this road section was a good choice for this experiment, as it was possible to test several accelerations on very small radii very efficiently and obtaining good and interesting information on driving comfort, with respect to vertical acceleration.

8.2 Driving comfort's definition

The driving experiment provided useful and insightful input regarding driving comfort when exposed to vertical acceleration, allowing to add or alter some of the points presented in chapter 4. The experiment was performed in real-life driving conditions, where ratings and feedbacks on driving comfort are based on the actual vertical acceleration which considered to be affected by the vehicle and road conditions. There is a possibility to argue for basing design values on measured vertical acceleration as it represents the actual conditions of an individual riding a sag curve inside a vehicle, compared to theoretical centripetal acceleration which only considers the acceleration of an object or body that follows a curved path (as mentioned in chapter 7.3.3).

Within the experiment, the participants were asked to describe what kind of discomfort they experienced. This feedback was based on the first round with a speed resulting in (theoretical) a centripetal acceleration ten times higher than Norwegian design values for curve one, and 3-7 time higher for curves two and three. The description was related to physical effects such as a ticklish feeling in the stomach or a slight feeling of falling, but relative high accelerations were required to obtain these effects. However, none of the participants express any form of physical pain or strain. When asked about their thoughts on the effect, the common response was that they did not consider the effects of vertical acceleration uncomfortable. As mentioned in section 7.1.3, only 2.6% of the driving comfort ratings were above the limit (level 5) where the effects of vertical acceleration start becoming uncomfortable. This shows that there were a few participants who did find it uncomfortable. Yet, high acceleration values were required to create this uncomfortable situation. The information about driving comfort and vertical acceleration from the standards assume that vertical acceleration above the 0.5 m/s^2 threshold causes discomfort. As mentioned above, the general response was that they would not describe acceleration above this level as uncomfortable. Based on the measurements form the experiment, values up to 1.0 m/s^2 where considered comfortable, even if the participants could experience some effects from vertical acceleration.

The participants were also asked what they consider their desired level of driving comfort, to find out what is their comfort threshold. All the participants said that they did feel comfortable with the discomfort level 1-2 (slight discomfort, see Table 7, page 52). A few even stated they would feel comfortable with discomfort level 3-4 (moderate discomfort, but still negligible). Even if all the participants were comfortable with discomfort level 1-2, there is a difference is where this comfort threshold is with respect to vertical acceleration. For instance, say the comfort threshold is discomfort level 1-2, the comfort threshold for participant G1-P1 could be somewhere about 1.0 m/s^2 (theoretical value), while the comfort threshold for participants G4-P1 and G4-P2 could be somewhere about 3.0 m/s^2 or even higher. This shows that each individual's comfort threshold can be different, which is why an 85th percentile can be a good method to determine a comfort threshold for all when determining design values.

To summarize, the general impression of vertical acceleration was that it was not considered as discomfort by the participants, even if some extreme conditions (high speed) could be uncomfortable for a few. The Swedish, Danish and Australian standards' description of vertical acceleration and discomfort gave a misinterpretation of the its actual effects, as something could be uncomfortable, but not necessarily discomfort.

Acceleration above 0.5 m/s^2 causing discomfort seems like an oversimplification and not really describing the real situation, as this driving comfort seems to be a bit more complex than that discomfort or no discomfort. The term used in the Norwegian guideline, *desired level of driving comfort*, seems like an appropriate description. However, without any information what that term entails, its meaning could be up for interpretation.

8.3 Implications

It is important to look into the implications this research on driving comfort in geometric road design can result in. It can establish any importance and need for further research. Researching driving comfort could lead to a re-evaluation of the basic parameter vertical acceleration, where the biggest outcome would be an update to the current design values. These values might not be up to date with current development of roads and vehicles, and it is not easy to verify such as there is no previous documentation to use for confirmation or comparison.

An update of the acceleration parameter can have a large impact on how sag vertical curves are design. Vertical acceleration is one of two parameters that decides the minimum curve radius. Looking at different situation can give a better understanding the impact a small change in the parameter can have on the road's vertical alignment. Table 17 presents three different design speeds and how an increase in vertical acceleration can affect the minimum curve radius. For this example, design speed is based on an AADT of less than 4000 and additional speed from Figure 5 (page 13).

Table 17: Impact on sag curve requirements due to change in design values.

Design speed [km/h]	Vertical acceleration [m/s^2]	Minimum curve radius [m]
85	0.3	≈ 1900
85	0.5	≈ 1200
65	0.3	≈ 1100
65	0.5	≈ 700
100	0.3	≈ 2600
100	0.5	≈ 1600

Adopting the 0.5 m/s^2 values from other standards would lead to a 700 meters reduction in minimum curve radius. The smallest difference for design speed 65 km/h is 400 meters, while a design speed of 100 has a difference of 1000 meters. An increase in design value from 0.3 to 0.5 m/s^2, for new roads, has a large impact on the minimum sag curve radius.

A positive outcome of allowing higher vertical acceleration in sag curves is that it makes it easier to adapt the road to challenging terrains. Large radii can easily make the road dominate such terrain and require more disturbances to nature with cuts and fillings. However, there is the issue of how often the minimum sag curve radius is used. Alignment of new roads usually consists of large radii, like the new (few and large curves) and old (many and small curves) E39 from the driving experiment.

A revision of the basic parameter would require some work and would, based on the experiment results, likely lead to the conclusion that current values are sufficient or that higher accelerations can be considered comfortable, or acceptable, when designing sag curve. Whatever the outcome, one would have design values that is supported and based on documented research.

8.4 Autonomous vehicles

It can be important to consider driving comfort for autonomous vehicles when the time comes for them to take over the road network. It is not easy knowing what to expect from implementing autonomous vehicle, as the vehicle have yet to be developed. However, there are some aspects that can be addressed. Driving comfort is one of the important factors when it comes to accepting autonomous vehicles. If the users do not feel comfortable, or safe, with the vehicle, no one is going to use them. There are some factors with autonomous vehicle that can affect driving comfort. The major change with autonomous vehicle is that the human role in a vehicle goes from an active driver to a passenger (Beggiato et al., 2018). Any design value should be based on individuals as passengers. As a driver, one is constantly looking at the road and environment, which can provide the driver with information of what comes next. For instance, with a tight curve, the driver will know what to expect and can either endure the effect of the curve or adjust speed to minimize the effects. SAE level 5 vehicles will not require any input from the vehicle occupants and the passengers might not pay attention and obtain this information the alignment can give. The effects of such curves could be intensified if it comes as a surprise (as indicated from the experiment).

The road's alignment should be designed to assist in providing a safe and comfortable ride. As autonomous vehicles are assumed to improve traffic safety, the vehicles can drive at higher speeds and reduce travel time (Jordbakke et al., 2018). Increasing the speed has as impact on all the alignment parameters. The minimum radius for sag curves would increase. New roads are not likely to have any issues of maintaining driving comfort, but there might be a question about existing roads. Higher speeds results in higher vertical acceleration. Take for instance the road section used in the driving experiment. If an autonomous vehicle were to drive this section with a higher speed, or even the speed limit, the vertical acceleration would be high and exceed the current comfort threshold. There are about 42 000 sag curves with a radius lower than 1600 meters in the mid-Norway area (Vegkart, 2019). A lot of roads in Norway consist of tight and small curves due to challenging terrain in mountainous and coastal areas. Autonomous vehicle could be able to obtain information about the alignment and adjust the speed when needed (Jordbakke et al., 2018) but knowing how to adjust the speed would require information about comfort threshold (or design values). Either way, knowing this comfort threshold to vertical acceleration (as a passenger) can be important to ensure comfortable riding whether it is for the vehicle's driving behavior or the geometric road design. The method for measuring driving comfort would be the same, it is just the data would be used for different purposes.

8.5 Future steps

Working with the topic and the experiment proved that there is a potential to conduct further research on driving comfort, in geometric road design. There is still some work to be done in order to make any final decision on comfort threshold and re-evaluation of the design values. This section mentions three areas as next steps: the vertical acceleration measurements, creating a driving comfort database and looking into possibility to create a simulator study.

Vertical acceleration measurements

In order to continue with the experimental method tested in this thesis, it will require better and more reliable vertical acceleration measurements. There are for instance three issues to consider. Firstly, the sensor measurements alone were not enough to find any vertical acceleration values. The noise interruption was too high. Secondly, obtaining the centripetal acceleration is challenging (see chapter 4.2.2, page 39) and would require research on how to obtain this acceleration, if chosen to be used instead of measured acceleration. Lastly is finding the best placement for the sensor, giving the most reliable and valid measurements for driver and passenger(s).

Database for driving comfort

Quantifying driving comfort and finding comfort threshold require establishing a database containing comfort measurements with vertical acceleration and what individuals' comfort threshold is (e.g. acceleration that starts to become uncomfortable). The measurements are easy to do but require work to be obtained. For instance, gathering comfort measurements for a large number of individuals, and a sensor measuring vertical acceleration. Creating a database could also be used to update the data on a regular basis to either revise or argue for revision, if there were any developments in the future. A database would also be a documentation supporting design values decisions, both current and potential future ones.

Simulator

The test conditions, as presented in section 8.1, might not have been the ideal for these types of research, due to real road and driving conditions. This causes challenges working with vertical acceleration (as previously presented). Looking into making a simulator could be another option. The issues with acceleration measurement would be eliminated and it would be possible to test vertical acceleration that is close to the theoretical pre-determined values. The discomfort ratings would also be more based on the centripetal acceleration, and not the vertical acceleration from the alignment and vehicle condition. However, there is the question whether this or real-life driving tests would be the most practical method.

9 Conclusion

The aim of the thesis was to investigate whether there is a research potential for driving comfort, attempting to find knowledge gaps and fill them. Such research could be used to determine if the parameter basis is sufficient for current and future road design. The parameter in focus was the vertical acceleration, where literature with respect to driving comfort was lacking. Thus, the objective of the thesis was to investigate driving comfort and the parameter to get a better understanding of how driving comfort could be defined and measured, and to see if driving comfort could be quantified to determine a comfort threshold.

The methods for the thesis was an extensive literature search and driving experiment. The literature search was used to find relevant information and uncovered knowledge gaps regarding driving comfort in road design. The literature was used to look at how driving comfort could be both defined and measured, becoming the basis when developing the driving experiment. The experiment's purpose was to test the practicalities of measuring driving comfort, and to provide comfort and acceleration measurements, which would be assessed to see whether they could be used to quantify driving comfort. This, along with additional input on driving comfort form the experiment, were used to determine any comfort threshold and to investigate if there was any indication whether the current design values should be re-evaluated

The experiment provided raw comfort and accelerations data that needed to be process and analyzed in order quantify driving comfort (connecting feelings of discomfort to vertical acceleration). A final discomfort level for each of the vertical accelerations that were tested were decided based on a 75th percentile, instead of 85th percentile, as the comfort data were quite susceptible to even small variations in the participants' ratings due to the small sample. The final discomfort levels and the (theoretical) vertical acceleration were analyzed to locate limits between the different discomfort levels, and lastly, comfort threshold was determined based on input form the participants. Obtaining the raw comfort measurements and quantifying driving comfort seemed to work quite well. There were however some issues. It was not possible to use the vertical acceleration measurements, as they need more processing and analyzing to give acceleration values to be connected to the comfort measurements, e.g. due to noise. Thus, quantifying driving comfort was done with the predetermined theoretical centripetal acceleration as an example to test if it was possible. In order to make a final assessment on whether current design values should be re-evaluated will require a larger sample of comfort measurements and good, reliable acceleration measurements, to determine a comfort threshold design values should be based from. However, based on the discomfort ratings, and the additional input on driving comfort from the participants, it could be interpreted that there is something suggesting that the comfort threshold could be re-evaluated.

There are several possibilities to continue forward with the research to make a final decision for a re-evaluation of current design values. As mentioned in the last section of the previous chapter: improved acceleration measurements, look into simulator opportunities or start creating a comfort database could be next steps in this research. The conclusion is that there is a potential for research within this field. Whether the design values should be re-evaluated need to consider other factors. The re-evaluation would not result in a stricter requirement to ensure comfortable riding but allow smaller minimum curves radii and higher acceleration, while maintaining comfortable riding. There is also the question of how often these minimum curve radii would be used. Whatever the outcome, either keeping or updating current design values, they would be supported and based on new and documented research.

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Appendixes

The appendixes are divided into three parts, consisting of a total of 48 attachments containing additional data and picture for the report.

Appendix A: Questionnaires with discomfort ratings
- A.1: Blank questionnaire
- A.2-A.9: Discomfort ratings

Appendix B: Additional picture from the experiment
- B.1: Equipment (sensor MTi-G-710)
- B.2: Road alignment
- B.3: Road conditions

Appendix C: Measurement for elevation and vertical acceleration: Screenshots of the recordings as presented in the MT Manager software
- C.1-C.8: Measurements for G1, L1-8
- C.9-C.16: Measurements for G2, L1-8
- C.17-C.24: Measurements for G3, L1-8
- C.25-C.32: Measurements for G4, L1-8
- C.33-C.36: Measurements for *bonus round* (100 km/h)

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