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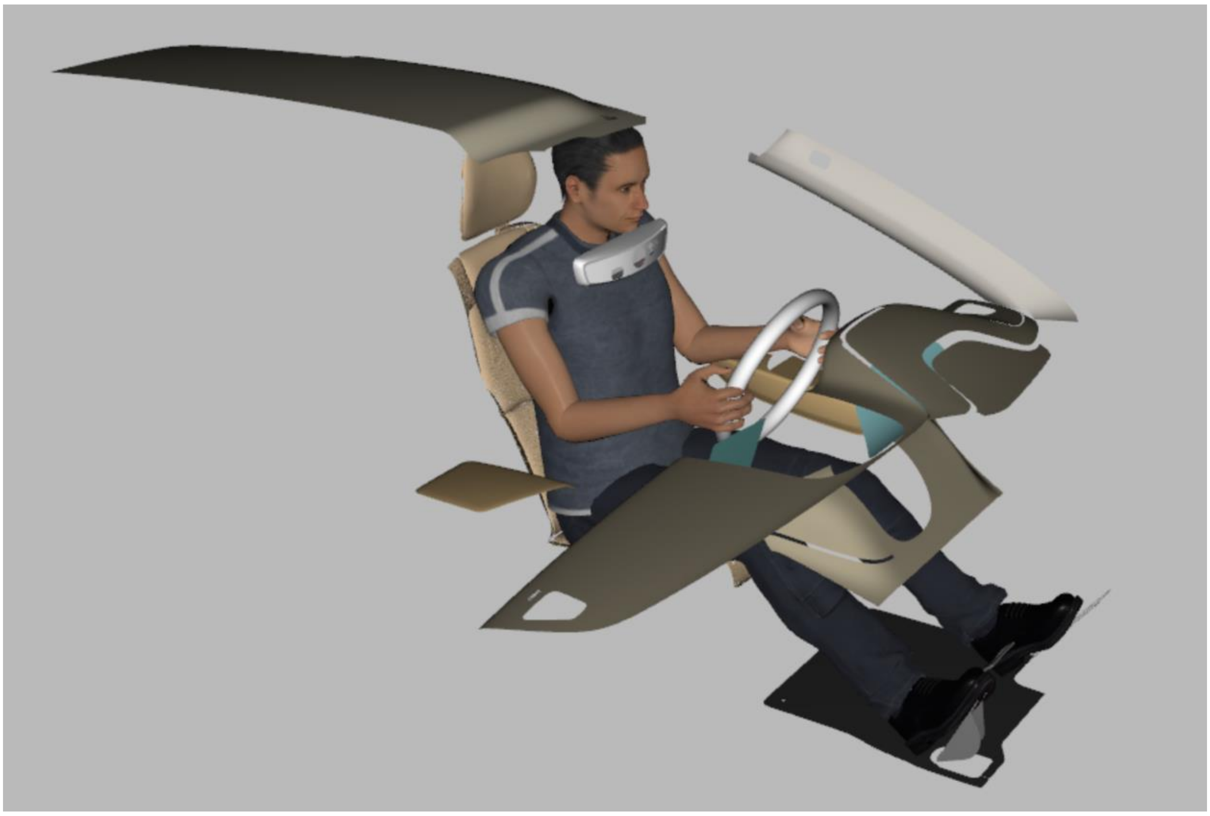

Virtual representation of driver behavior and sitting posture

An investigation on sitting postures and motion patterns during dynamic driving

Master's thesis in Product Development

HANNA SVENSSON
THERESE ULLÉN

DEPARTMENT OF INDUSTRIAL AND MATERIAL SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
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MASTER'S THESIS 2022

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Examiner: Anna-Lisa Osvalder, Department of Industrial and Material Science.

Master's Thesis 2022
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Cover: Visualization in the digital human modeling software IPS IMMA. Manikin positioned in the driver's seat of an XC60.

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Abstract

With the development within computer technology, virtual representation of human models has become a viable tool in ergonomics to simulate and evaluate driving postures and behaviors. It has also become more important since new products are designed and produced in a short time frame, which requires efficient software design tools. One such software is IPS IMMA, developed by researchers at Högskolan i Skövde and Fraunhofer Chalmers. In the future versions of the software, the vision is to be able to simulate automated scenarios of the driver's motion sequence and behavior in different traffic situation. This allows for cost-effective simulations and tests in early design phases and improve ergonomic evaluations. However, there is a need to better understand how dynamic situations affect the driver.

This master's thesis investigates if there are any differences and similarities in sitting postures and motion patterns among drivers in different driving situations, with the aim to suggest generalized driving behaviors that should be considered for the future development of the IPS IMMA software. The work has been performed in collaboration with Volvo Cars and the research project ADOPTIVE.

An experimental, qualitative driver study was conducted with 12 test subjects in a Volvo XC60 car. The dynamic driver study investigated three different situations: city, highway, and highway using Adaptive Cruise Control. Objective and subjective data was collected by video recordings, Xsens motion capture system, and a questionnaire. The objective data was analyzed mainly through annotation in the video recordings.

From the results it could be concluded that it was possible to generalize sitting postures and body motion patterns for the different situations. In general, the sitting posture and motion pattern overlapped for the three driving situations. Significant differences in movements were identified in the city and Adaptive Cruise Control situation. For the city situation, there was a higher frequency of arm and hand movements, and the upper body was leaning forward in certain events, whereas for Adaptive Cruise Control it was the right foot's variety in positions, and the use of both armrests. The finding was formulated into a requirement list, suggesting future implementations in IPS IMMA.

Key words: Vehicle ergonomics, Driver's posture, Driver's behavior, Digital human modeling, Software development.

Acknowledgements

This master's thesis in Product Development was performed in the spring of 2022 at Volvo Cars and Chalmers University of Technology under the Department of Industrial and Material Science. The study was performed as a contribution to the bigger project called ADOPTIVE.

First and foremost, we would like to give our special thanks to our supervisor Sara Alpsten at Volvo Cars, for her continuous support and guidance. She has helped us with everything from settling in at Volvo Cars and getting the right tools to perform our driver studies, to providing valuable input on our methods used and the written report. We would also like to thank our supervisor at Chalmers, Melina Makris from the division of Design & Human Factors, for encouragement and valuable advice during the whole project, and for sharing her knowledge and ideas with us. Finally, we would also like to thank Erik Brolin from the ADOPTIVE project, who taught us how to use IMMA, shared his expertise, and guided us in the process.

We want to extend our gratitude to Pernilla Nurbo at Volvo cars, for sharing her knowledge with us, and to examiner Anna-Lisa Osvalder from the division of Design & Human Factors, for sharing her experience and for giving constructive report consultation.

We also want to express gratitude towards all the employees at the ergonomics department and members of the ADOPTIVE project, that have followed us during the project, listened to presentations, and asked relevant questions for us to reflect upon. A special thank you to Jonas Xu, at the measurement department for helping us prepare the test vehicle for our driver study and to Thiago de Oliveira for helping us with our final testing.

Lastly, we want to thank all participants that contributed to our pilot study and driver study which made it possible for us to develop and perform the tests that were an essential segment to achieve our goals.

Gothenburg, June 2022

Hanna Svensson

Therese Ullén

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List of acronyms and abbreviations

Abbreviation	Description
ACC	Adaptive Cruise Control
ADOPTIVE	Automated Design and Optimization of Vehicle Ergonomics
AHP	Accelerator Heel Point
BSN	Body Sensor Network
CACC	Cooperative Adaptive Cruise Control
DHM	Digital Human Modeling
FCC	Fraunhofer Chalmers
FMEA	Failure Mode and Effects Analysis
G	Earth-fixed reference coordinate system
H-point	The H-point or hip-point simulates the hip joint (from the side view as a hinge point) between the torso and the thighs
H30	The vertical distance from the AHP to the SgRP
HiS	Högskolan i Skövde
IMMA	Intelligently Moving Manikin
IPS	Industrial Path Solutions
ISB	International Society of Biomechanics
NRS	Numeric Rating Scales
OBS	Open Broadcaster Software
P-diagram	Parameter Diagram
PA	Pilot Assist
RQ	Research Question
SAE	Society of Automotive Engineers
SgRP	Seating Reference Point
TP	Test person

Definitions

Bellow follows explanations of terms referred to in the report.

The researchers, the authors, or *thesis workers* refer to the persons who have carried out the master's thesis and written the report, Hanna Svensson and Therese Ullén.

The test leaders refer to the persons who carried out the driver study, which were Hanna Svensson and Therese Ullén.

Test person, *participant*, or *test subject* all refers to the same thing, namely the persons who participated in the driver study carried out during the project.

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1 Introduction

This master's thesis investigates if there are any differences or similarities in sitting postures and motion patterns among drivers in different driving situations. This introductory chapter presents the context of the thesis project including background, research questions, aims, and scope of the study. Lastly, an overview of the thesis outline is provided.

1.1 Background

The car is an important product for many, that allows people to freely move from one place to another. According to Trafikanalys (2022) the number of vehicles in Sweden has grown from just over 4 million in 2001 to about 5 million in 2021, see Figure 1.1. This indicates a continuous need for this product, and hence continued development of the vehicle is highly relevant.

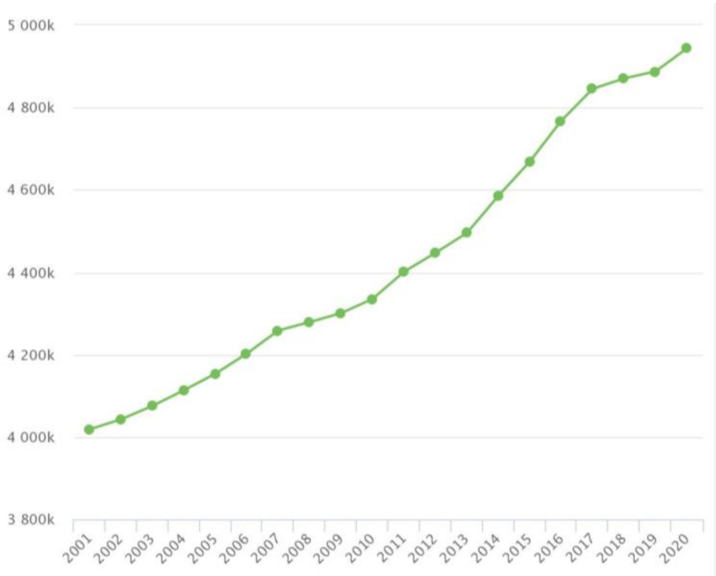


Figure 1.1 Number of vehicles in Sweden over time during 2001-2021 (Trafikanalys, 2022).

One important design aspect of the car is the interaction between the human and the physical vehicle, the field where ergonomics is applied. The user needs the vehicle to be comfortable, convenient, and safe while using it and it is partly the ergonomic engineer's responsibility to ensure that these needs are met (Bhise, 2012). With the development of computer technology and specifically the possibilities to create simulations, virtual representation of human models or so-called digital human model (DHM), has become a viable tool in ergonomics to simulate and evaluate driving postures and behaviors.

Researchers at Högskolan i Skövde (HiS) noticed in the early 00's that existing ergonomic simulation programs lacked essential features, and even though mediating this to the companies behind these software, nothing seemed to change (Högberg, 2022). The problem with existing programs, for example, RAMSIS, was that they could only simulate postures, while the objective for new software was an ability to predict the motion of humans. There was a need for a program that was easy to use and had an inclusive approach in terms of the diversity of people. From this need, the researchers at HiS initiated a collaboration with Fraunhofer Chalmers (FCC) and developed a software called IPS IMMA (Industrial Path Solutions Intelligently Moving Manikin). The project grew into digitally modeling the driver while also seeing the driver as a customer, by looking at the overall picture including passengers, fueling, and so on (Högberg, 2022). In the early versions of the software, the main features were to simulate an assembly process, but later when presented to industrial companies in the vehicle segment, they also requested that the manikins could be seated in the cars for evaluation of the car design. The main users are the people using the software which in general are engineers and developers working with ergonomics and, in the end, the secondary user is the customer using the developed seat and car. The program, that first was called IMMA, expanded by cooperating with FCC and developed into IPS IMMA software (Fraunhofer Chalmers, 2022b).

In the spring of 2021, Volvo Cars started a three-year research project, together with HiS, FCC, Volvo Trucks, and Scania called ADOPTIVE (Automated Design and Optimization of Vehicle Ergonomics), and this thesis work is part of this project. The project aims to further develop the IPS IMMA software and enable virtual representation of the human behavior related to a vehicle's interior sitting area to assess the ergonomic situation in the early phases of product development. The software is developed to comply with seated driving posture and additional in-vehicle activities. The project focuses on developing the software based on four different areas; virtual human models, static posture simulation, task/scenario simulation, and ergonomics evaluation, see Figure 1.2. This thesis project focuses on the task/scenario simulation.

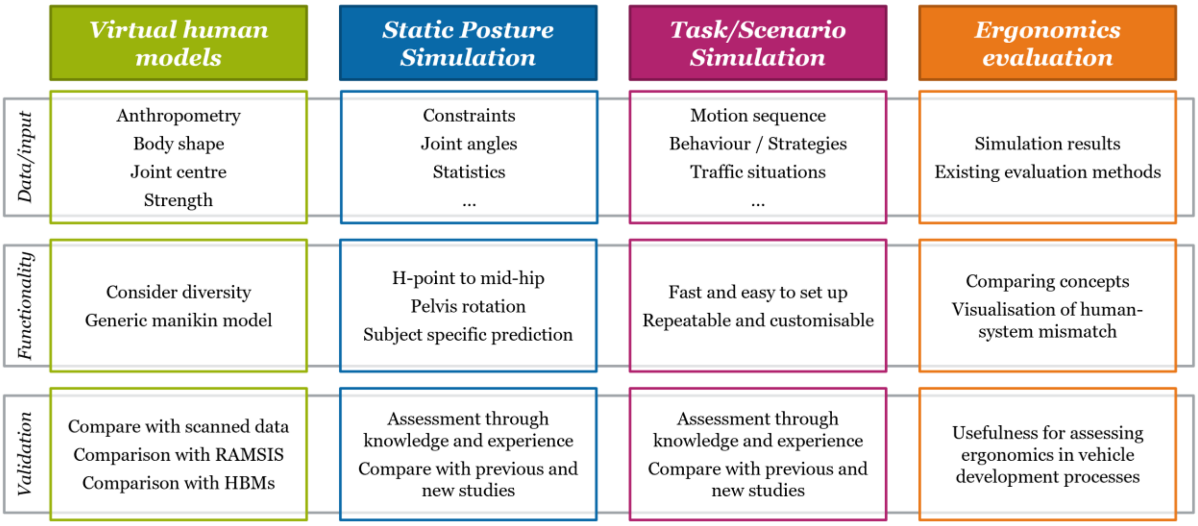


Figure 1.2 Overview of the ADOPTIVE project workplan.

There is currently already a good understanding of static posture simulation, however, the task and scenario simulation is not explored to the same extent, why there is a need to better understand how dynamic situations affect the driver. The task and scenario simulation area includes motion sequence, behavior and strategies performed by the driver, and different traffic situations. This type of information will be the data input for the simulation. Then the software IPS IMMA needs to be developed including certain features and functionalities to make it fast and easy to virtually simulate the input and make it a repeatable and customizable part. With this, simulations can be validated by previous knowledge and compared to other studies in the field to make sure it covers real situations.

This thesis project explores human driving behavior and sitting posture during different dynamic driving situations. The findings from the thesis shed light on the needs from an ergonomics perspective on how to virtually represent motion sequences and driver behavior in the future development of IPS IMMA. This allows for cost-effective simulations and tests in early design phases and improve ergonomic evaluations.

1.2 Research questions

The purpose of the master's thesis is to explore what differences and similarities there are in motion patterns and sitting postures among humans in different dynamic driving situations. The project specifically investigates the three following driving situations: city driving, highway driving and highway driving with the use of Adaptive Cruise Control (ACC). The following two research questions (RQ) have been formulated to fulfil this purpose:

> **RQ1**: What are the differences and similarities in sitting posture of the driver in the following driving situations:
> - S1: city driving
> - S2: highway driving
> - S3: highway driving with the use of ACC

> **RQ2**: What are the differences and similarities in body motion pattern of the driver in the following driving situations:
> - S1: city driving
> - S2: highway driving
> - S3: highway driving with the use of ACC

The two first research questions lead up to the third RQ, which focuses on whether posture and motion pattern can be generalized.

> **RQ3**: If possible, how can sitting postures and body motion patterns be generalized in different driving situations, to formulate suggestions on future software implementations in IPS IMMA?

Finally, it is also of interest to understand why a driver sits in a certain way when driving. Did the person sit as wanted, or were there any limitations that forced the sitting posture in a certain way? The project's fourth and final research question reads:

> **RQ4:** What limitations do drivers experience regarding the sitting posture? If there are any limitations, how do they affect the way drivers are seated?

1.3 Project aims

The aim of the project is to answer the stated RQs and, if possible, suggest generalized driving motion patterns and sitting postures that should be considered for the future development of the IPS IMMA software. The development focuses on the task/scenario simulations area in the ADOPTIVE project, with a long term aim to improve the early product development activities regarding the interior sitting area design of a Volvo vehicle. To reach this, the aim of the project has been divided into the three following parts:

- Identify suitable methods for collecting data to capture driver body motion patterns and sitting posture in dynamic driving situations and identify suitable methods for analyzing the data and visualizing the result.
- Collect and analyze data using the identified methods.
- Suggest what different settings that should be incorporated in the future development of the task/scenario simulations part of the IPS IMMA software. Suggestions should be delivered in the form of a requirement list.

1.4 Objectives

The objectives on how to answer the research aims are the following:

- Identify critical parameters that affects the dynamic driving motion patterns and sitting posture.
- Learn the basics of IPS IMMA and map out the limitations of the software, to understand the limitations of the data collection.
- Identify suitable technology to use for data collection in a dynamic driving situation.
- Collect subjective data from the drivers using a questionnaire.
- Develop a data collection method for the affected parameters.
- Identify suitable methods to analyze and visualize the results.
- Perform studies with a wide range of anthropometric test subjects and collect data for a selected vehicle type.
- Analyze the collected data and visualize the results with the identified methods.
- Present a requirement list of different settings for the future automated position generator IPS IMMA.
- Evaluate the methods used to collect the data.

1.5 Scope

This section covers the scope of the project. It includes related activities, key stakeholders, resources, and limitations.

1.5.1 Project scope

The master's thesis includes a literature review about ergonomics and related relevant areas, learning the basics of IPS IMMA, development of a method to collect data in dynamic driving situations, a driver study with human test subjects to collect objective and subjective data, data analysis of the collected data, and visualization of the results. It also includes presenting a final requirements list on different implementations that should be incorporated in the future development of the IPS IMMA software. Finally, a written essay about the process and results is produced and presented to involved stakeholders. All the activities are conducted by the thesis workers, with support from supervisors and stakeholders.

1.5.2 Key stakeholders

Stakeholders of this project include all partners working on the research project ADOPTIVE which are Volvo Cars, HiS, FCC, Volvo Trucks, and Scania. It also includes the project supervisors from ADOPTIVE which is Sara Alpsten at Volvo Cars who is Senior Analysis Engineer Ergonomics, and Erik Brolin from HiS who is project manager at the ADOPTIVE, and Senior Lecturer in Product Design Engineering. Furthermore, PhD student Melina Makris and Professor Anna-Lisa Osvalder act as supervisor and examiner respectively, from the Chalmers division of Design & Human Factors, Department of Industrial and Materials Science.

1.5.3 Resources

The primary project resources are the two thesis workers that conduct the project. During the spring, they work during the given time frame for this project, which is 30 credits or 20 weeks of full-time studies, corresponding to 800 hours per person. Another resource is the supervisors from whom the project gets feedback, support, and guidance. The project also has a valuable network of competent people at Volvo Cars and Chalmers. Finally, the project has access to tools and devices, such as computers, cameras, software, Xsens, vehicles, material for setting up a test vehicle, and test subjects provided by Volvo Cars.

1.5.4 Limitations

Time and tools available are a resource but also a limitation to the project. The time limit mainly constrains the number of user studies that are conducted. In total 12 driver studies are conducted. This constraint means that the project is of a qualitative character, rather than quantitative. Results that are presented in the report should therefore be seen as propensities, rather than statistically significant results. The time also affects the extent of the data analysis that is performed. Another delimitation regarding time is the knowledge of the software IPS IMMA that needs to be transmitted to the thesis workers to be able to use the software. The time for learning the software is limited to the master's thesis schedule, and therefore, the knowledge about the program is limited and only includes actions related to the project.

The research is conducted in Sweden, Gothenburg. The project aims to collect data, covering the entire anthropometric population based on sitting height in the country Sweden. The study is delimited to ages between 24 and 60 due to the availability of test subjects at Volvo Cars in this period. People outside of this age span are not represented, why this limits to achieve a complete anthropometric variety. Furthermore, the tools and structure of the performed studies follows Volvo Cars guidelines regarding secrecy and therefore only deals with vehicles that Volvo supplies during the project, and not any other brand. The study is limited to a high-seated vehicle, more specifically a XC60. This model is chosen as it is one of Volvo's best-selling cars after S60 and V60 in 2020 (Wagner, 2021). The framework and 3D scans are shared with the ADOPTIVE project, making it possible to use a digital model of the vehicle in IPS IMMA to finalize the research findings. The features in the vehicle are limited to the features available in the test vehicle that is used.

The research is limited to only look at the driver in the driver seat during dynamic driving, and not any other passenger or seat in the car. The study is limited to only examine the three different driving situations city, highway, and highway with ACC, with respect to motion patterns and sitting posture. Other parameters related to the test subjects such as gender and age are not examined further in this project.

1.6 Thesis outline

This section provides an overview of the report structure for the upcoming chapters.

Chapter 2 – Theory
This chapter presents the theoretical framework of the project to provide an understanding of the topic treated in the report. It also helps justify the stated research question in this chapter and the choice of method.

Chapter 3 – Methods
In this chapter, an overview of the methodology is presented, as well as a detailed description and justification for selected methods.

Chapter 4 – Results
This chapter shows all the results obtained during the user tests, the data gathered, and the resulting analysis.

Chapter 5 – Discussion
In this chapter, a discussion regarding the findings and outcomes are pursued as well as a critical and structured analysis of the work performed during the research.

Chapter 6 – Requirement list
This chapter presents the deliverable in form of a requirement list. It also includes a discussion about the requirements and suggestions on implementation and visualization ideas.

Chapter 7 – Recommendation for future work
This chapter presents the authors recommendations for future work.

Chapter 8 – Conclusion
In this chapter, a conclusion of the report with the main findings and results is presented, a short description of how the executed project is performed, as well as a summary of the future recommendations.

2 Theory

This chapter provides a theoretical framework of the project and is the result of the literature review, which is be described in Methods, Chapter 3. It covers an introduction to ergonomics, the essentials of human anatomy relevant to the anthropometric design of a vehicle and sitting, and anthropometrics in general. It also includes theory on sitting posture and seat design considerations, and an overview of current research on dynamic driving. The ACC system and Pilot Assist (PA) in Volvo Cars vehicles are briefly explained. Furthermore, this chapter also goes into the theory on DHM since the deliverable of the project concerns this type of software. Finally, the chapter also introduces the reader to the Xsens equipment used in the study.

2.1 Introduction to ergonomics

The following definition of ergonomics is developed by the International Ergonomics Association and adopted by the Human Factors and Ergonomics Society (2022):

> "Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance. Ergonomists contribute to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people."

The essential goal of ergonomics within the automobile industry is to design equipment that achieves the best possible fit between the user and the vehicle (Bhise, 2012). Ergonomics focuses on designing for a large range of people, to ensure that most users can use and fit the product. An important consideration for the design process from an ergonomic perspective is the human as a system approach. This implies that the design process should have a system-view including the following aspects: the driver, the vehicle, and the environment. The development process should not only consider the properties of the physical object, but also include the human characteristics and needs. Therefore, when designing a vehicle, a thorough understanding of the intended user population and the operating environment that affects the human must be considered.

2.2 Anatomy

Knowledge about the human body is essential in ergonomics because it provides many approaches to solve problems, and it is important to understand when virtually modeling and simulating human and vehicle interactions (Bubb et al., 2021). This section goes through basic anatomy relevant to the anthropometric design of a vehicle and specifically related to sitting.

2.2.1 Musculoskeletal system

The musculoskeletal system is a system consisting of bones, muscles, joints, tendons, ligaments and other connective tissues that gives a human body the ability to move and provide support and stability in resting position, especially sitting (Bubb et al., 2021). This section presents a few of these elements.

Joints

Individual bones are connected through joints. The basic structure of a joint are bone pairings connected with different type of cartilage and connective tissue. There are two structural types of joints; diarthrosis, in which fluid is present, and synarthrosis, in which there is no fluid (MacConaill, 2020). The cartilage gets nutrition from the joint fluid, which is pressed into the cartilage through regular movements. Low mobility of the joints thus restricts the supply of nutrients, which leads to reduced mobility and painful joint movements, especially for elderly people (Bubb et al., 2021). This phenomenon tends to already be observed when driving motor vehicles in a sitting posture for a longer period, approximately two hours.

Spine

The spine forms the connecting and supporting central structure of the skeletal system, stretching from the top, which supports the skull, to the tail, which is tightly linked to the hip bones through the sacrum (Putz & Pabst, 2001). It consists of 24 vertebral bodies, sacrum and coccyx and can be divided into 5 parts: the cervical spine with seven cervical vertebrae, the thoracic spine with 12 thoracic vertebrae, the lumbar spine with 5 lumbar vertebrae, and the sacrum and coccyx, see Figure 2.1 (Bubb et al., 2021).

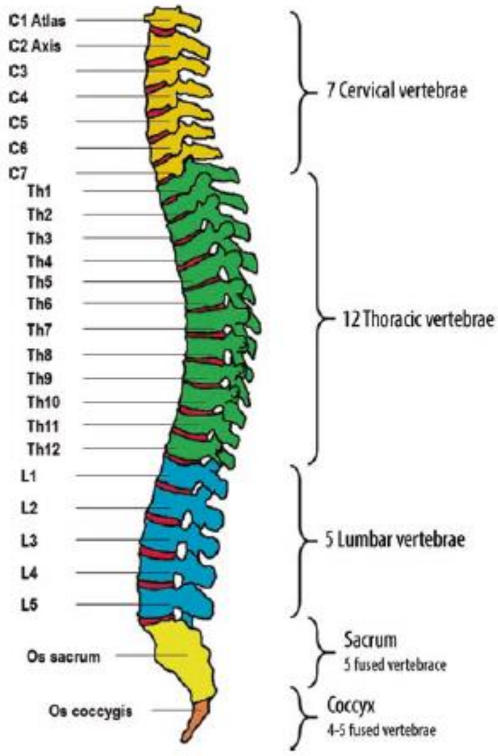


Figure 2.1 The vertebral column (Bubb et al., 2021).

The spine's shape changes depending on posture and body position. When standing upright, the spine has a doubled S-shaped curve. This position is more or less maintained in a seated position. However there could be a tendency to kyphosis, which is a spinal deformity, also in the lumbar spine area after seated for longer periods which can cause stress (Bubb et al., 2021). This can get consequences when driving longer distances.

2.2.2 Individual variability among anthropometric populations

It is important to highlight the individual anatomical variability between humans when considering ergonomics in vehicles since it is a critical aspect. Variations are related to several factors such as gender, age, nationality, and nutrition (Fatollahzadeh, 2006). For example, regarding gender, women generally have less physical strength than men, due to their different muscle volumes (Bishop et al., 1987). Age has a significant impact on the body regarding several aspects of the musculoskeletal characteristics such as muscle and skeletal strength, physical abilities, range of motion, and joint flexibility (Baumgartner et al., 1999). Nationality and nutrition affect the physics and dimensions of humans, such as body height. Significant differences can be seen in a global comparison, see Figure 2.2. According to Figure 2.2, the differences in the average value between Germany and Mexico alone are about 14 centimeters (Bubb et al., 2021).

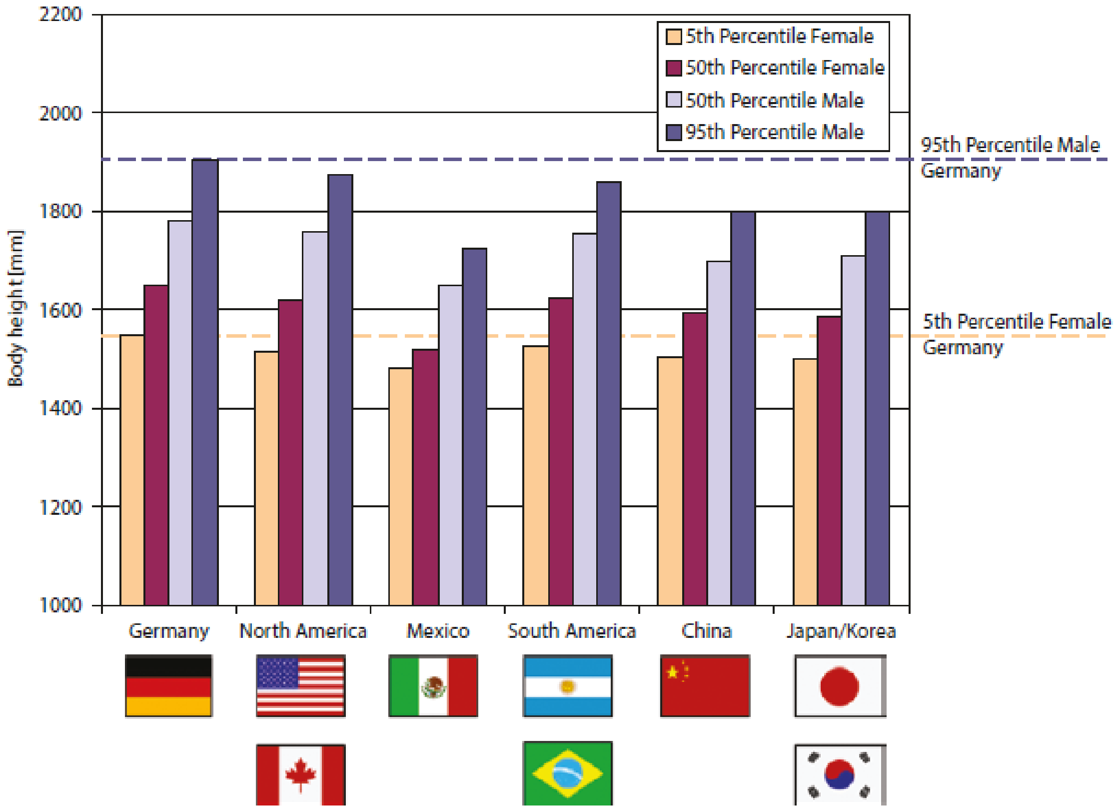


Figure 2.2 Differences in average body height between countries (Bubb et al., 2021).

2.3 Human characteristics and capabilities

Ergonomics includes both human characteristics and capabilities. These can be divided into two classes: *Physical Capabilities* and *Information-Processing Capabilities* (Bhise, 2012). Physical capabilities, as the name implies, can be measured with physical instruments and two different physical aspects can be considered. The first is the *anthropometric characteristics* which simplified can be described as human body dimensions. The second aspect is *biomechanical characteristics* which is the ability to produce a force and body movements. Information-Processing Capabilities are *cognitive capabilities*, involving acquiring and processing information through body senses such as the eyes, and make decisions based on the information. Biomechanics is not clearly related to sitting posture and driver behavior, so the theoretical chapter does not consider this area in any further detail.

2.3.1 Anthropometry

A vehicle is a product that concerns a population of users and therefore needs to be designed for an adequate range of the entire population. To be able to make decisions on how to comprise different design dimensions, one needs to understand the anthropometric characteristics of the intended user population (Pheasant & Haslegrave, 2006). Anthropometry provides the dimensions of the human body and the methods for determining them. It deals with several dimensions of the human body and body segments, such as skeletal dimensions, shapes, volumes, centers of gravity, weights, movement spaces, reaching spaces, and so forth (Bhise, 2012; Bubb et. Al., 2021). Anthropometric measurements can be either of a static or functional dimension. Static dimension is a measurement between different anatomical features in standardized postures when the subject is not moving, while functional measurements are performed when the human is in a work posture and measures range of movement during the activity (Bhise, 2012).

Characterization of body measurements

As mentioned in Section 2.2.2, human bodies vary and so do human body measurements. One common way to describe human variability is through statistical descriptions. The majority of human anthropometrics is normally distributed, which makes the use of percentile values of populations convenient and commonly used. Percentile values are used to evaluate what percentage of the population can fit within a given value of an anthropometric variable. For example, if x is the length of individuals, then the 95th percentile value of x means that only 5% of the individuals in that population would be taller than x. (Bhise, 2012; Pheasant & Haslegrave, 2006).

Terminology

This section defines some anatomical terms of location, that are referred to later in the report. There are three anatomical planes and axes defined as seen in Figure 2.3, perpendicular to each other (Bubb et al., 2021):

1. **Longitudinal axis and Frontal plane (blue):** The longitudinal axis is perpendicular to the standing plane, and the frontal plane divides the body into a front and back.

2. **Transverse axis and Transverse plane (green):** The transverse axis runs from the left to the right half of the body and the plane divides the body into an upper and a lower part**.**

3. **Sagittal axis and Sagittal plane (red):** The sagittal axis runs from the rear to the front half of the body, and the plane divides the body in a right and a left part.

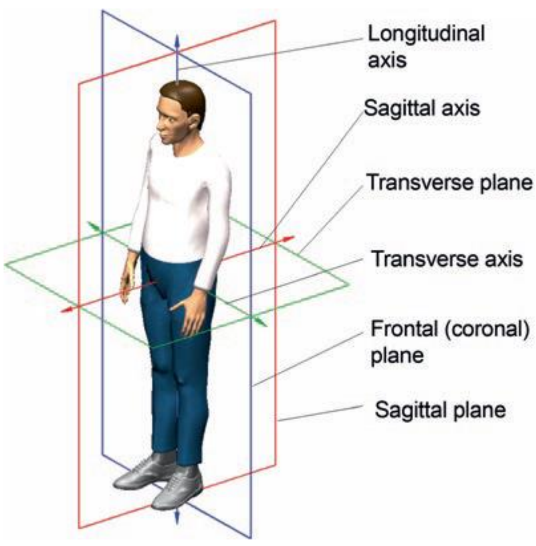


Figure 2.3 Body axes and planes (Bubb et al., 2021).

Anthropometric vehicle design

Vehicle dimensions are standardized according to the Society of Automotive Engineers (SAE). According to SAE J1100, a three-dimensional Cartesian coordinate system is defined for a vehicle as follows: the x-axis runs in the longitudinal direction of the vehicle, the y-axis perpendicular to it in the lateral direction of the vehicle to the right and the z-axis in the vertical direction to the top, and the coordinate origin is located in the middle of the vehicle near the front axle, see Figure 2.4 (SAE, 2009).

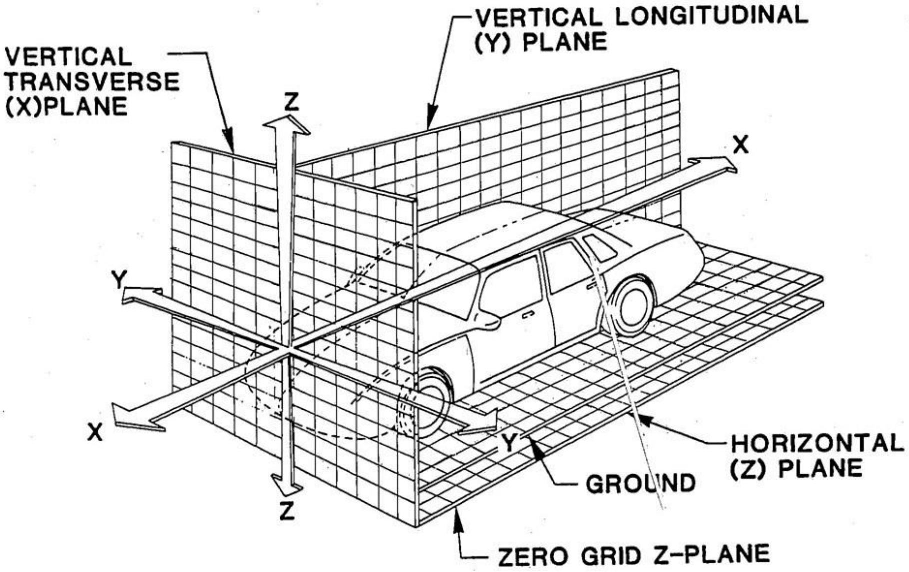


Figure 2.4 Vehicle coordinate system according to SAE (2009).

According to the SAE J1100 standards, all vehicle dimensions are measured in millimeters and use prefixes L, H, and W to denote length, height, and width respectively, and angles are denoted with A and measured in degrees (Bhise, 2012). The two most important dimensions are the Accelerator Heel Point (AHP), which is the point of the driver's shoe that is on the vehicle floor when the driver's foot is in contact with the unpressed accelerator pedal. Furthermore, the Seating Reference Point (SgRP) is the location of a special hip point (H-point) and is a central point for the anthropometric design. An H-point simulates the hip joint (from the side view as a hinge point) between the torso and the thighs, and thus, it provides a reference for locating a seating position. The vertical distance from the AHP to the SgRP is the H30 dimension, which highly influences the driver's sitting posture and therefore determines the vehicle's character (Bubb et al., 2021). The measurements can be seen in Figure 2.5, and Figure 2.6 displays how the H30 measurement gives different vehicle characteristics.

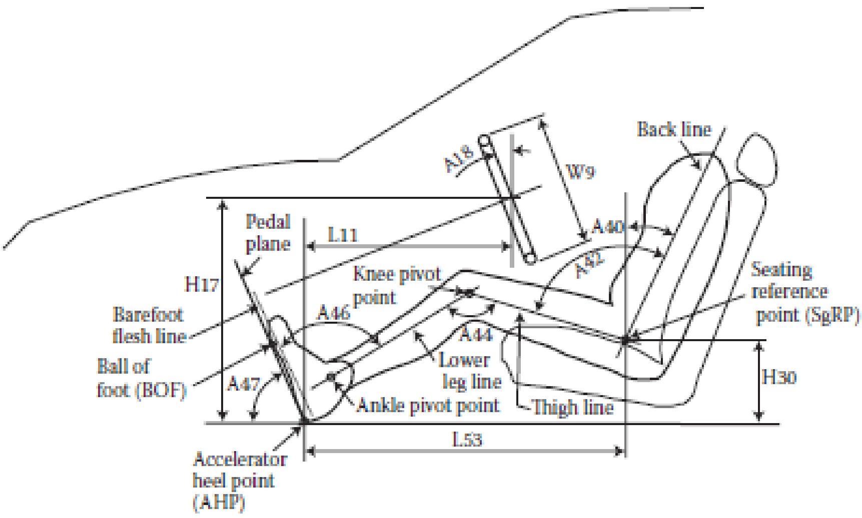


Figure 2.5 Vehicle dimensions and reference points (Bhise, 2012).

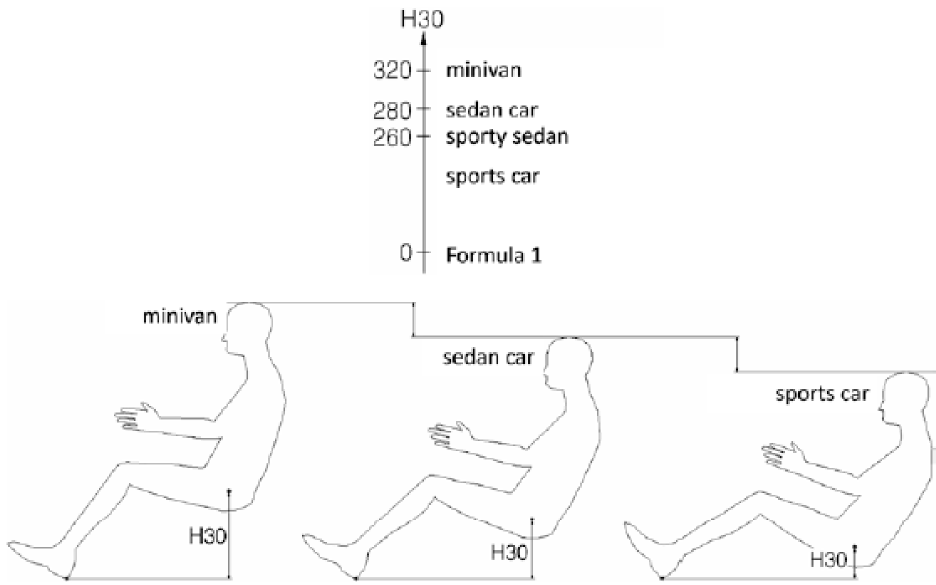


Figure 2.6 Different vehicle characteristics, depending on H30 (Bubb et al., 2021).

2.3.2 Driver behavior

In the Cambridge Dictionary behavior is defined as “the way that a person, an animal, a substance, etc. behaves in a particular situation or under particular conditions” (Cambridge Dictionary, 2022). A person’s driving behavior is consequently something highly complex. Factors influencing driver behaviors can be divided into two segments, internal and external, depending on their origins (Vallet, 2001). The internal factors consist of the functional abilities of the driver on a long-term scale such as age and experience and on a short-term scale such as stress, alertness, fatigue, emotions, and motivation that can be retrieved through a subjective perspective. The internal factors related to cognitive capabilities and how these affect decision-making and driver behavior are not studied further. The external factors that affect the driver could be noise, pollution, discomfort, and attention disturbances, related directly to the driving task itself and the complex road context.

2.4 Comfort in a vehicle

The definition of comfort versus discomfort differs in previous studies. Some studies focus only on one of the aspects, while others include both. Some studies use only subjective assessments or scales. All these various approaches show the difficulties of measuring and quantifying comfort and discomfort (Kyung et al., 2008). In a study made by Kyung et al., a merged model, see Figure 2.7, shows how two previous studies have separated sitting comfort and discomfort. Some descriptive words have a respective opposite while others do not, and some words fall in between (Kyung et al., 2008).

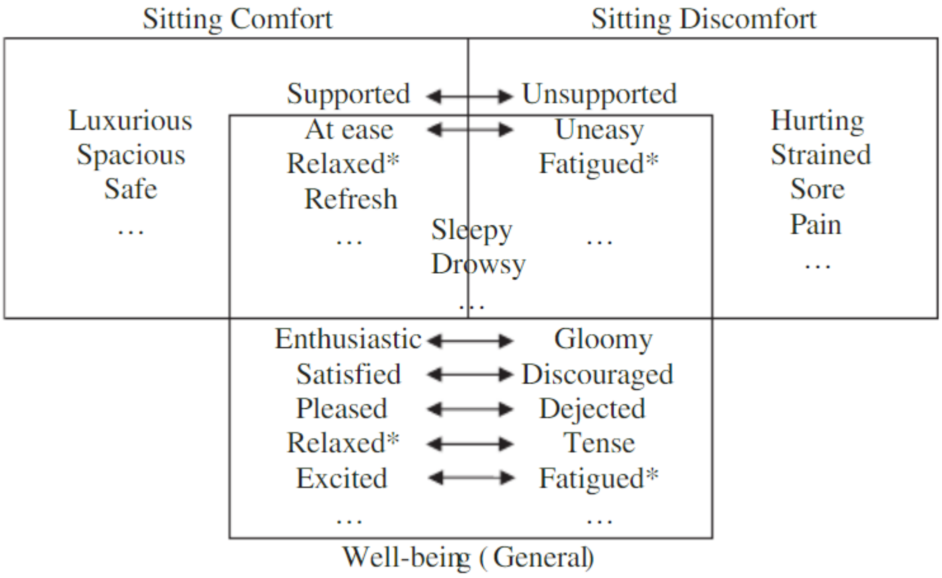


Figure 2.7 A merged model differentiating sitting comfort and discomfort.(Kyung et al., 2008), with previous research from (Andreoni et al., 2002) and (Kahneman et al., 1999).

Experiments made in England regarding comfort between regular car users and traffic police drivers, showed that more time spent in a car increased the frequency of reported discomfort, specifically in the lower back followed by neck pain (Gyi, 1996). Also, buttock discomfort was registered in a higher frequency among the police officers which could be a result of the longtime of being exposed to pressure. Another finding in the study was that people who had driving included in their job had a higher absence of sick leave, compared to other jobs involving sitting. This made Gyi (1996) conclude that comfort and ergonomics in a car do affect a person's health. The study also showed that people that are at the ends of the anthropometric population must compromise their sitting posture to fit properly in the cars, by neglecting the comfort aspect. While seated for a long time, the feeling of what is comfortable can be ergonomically uncomfortable for the body and therefore also be the source to injuries and further symptoms. The comfort and discomfort aspect are factors present in the positioning and body movements among the participants during the dynamic driving.

2.4.1 Studies on forced and preferred sitting positions

Previous studies have also shown to interfere with the preferred sitting posture during user studies by controlling seat angles and other adjustments (Andreoni et al., 2002). A study conducted in 2002 by Andreoni et al, used an optoelectronic system for motion capture as well as matrices for pressure sensors to research the driving postures and identify different behaviors and strategies among users in a static position in the car where the test persons could adjust both seat antero-posterior position and backrest inclination. The findings were that when the test subject had the possibility to adjust the seat to a position where they felt the most comfortable the lumbar flexion angle of 31.6° was almost constant among all participants, see Figure 2.8. Since the angle was chosen by the participant, conclusions were drawn that the lumbar angle could be a parameter that describes what people perceive as comfort in a sitting and driving posture.

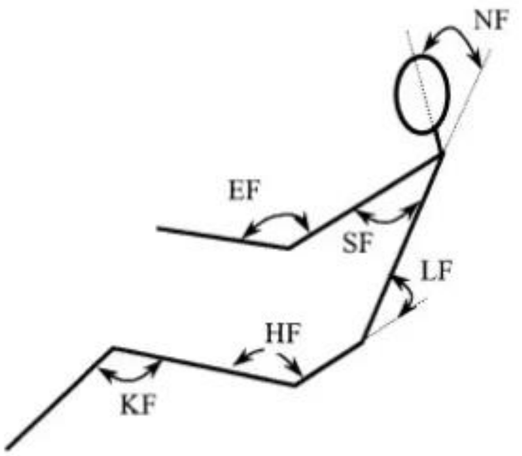


Figure 2.8 LF: Lumbar flexion angle (Andreoni et al., 2002)

2.4.2 Effect of duration on comfort and discomfort

Previous research on driver discomfort has shown a correlation between duration and being seated. Regarding the driver seat specifically, it was observed that there is an increase in discomfort in the back, buttocks and thighs over time, during a 135 min drive (Porter et al., 2003). This was also confirmed in another study, which found that there is an increase in discomfort in the whole body over time when driving a car for 45 min (Na et al., 2005). Accordingly, it was noticed in another study that motion occurred more often with time to alleviate pressure from discomfort (Le et al., 2014). The recommended guideline is that driving trials should have a duration of at least two hours to accurately determine discomfort levels and the performance of a seat (Porter et al., 2003).

2.5 Sitting and seating

Since the project focuses on behavior and posture while seated, this section presents the fundamentals of sitting and some seat design considerations. The purpose of a seat is to provide support to the body in a posture that is comfortable over a period of time and physiologically satisfactory, and that is appropriate to the task or activity in question. Seat comfort, (or discomfort) depends upon the interaction of seat characteristics, user characteristics and task characteristics (Pheasant & Haslegrave, 2006). Examples in each aspect is displayed in Figure 2.9.

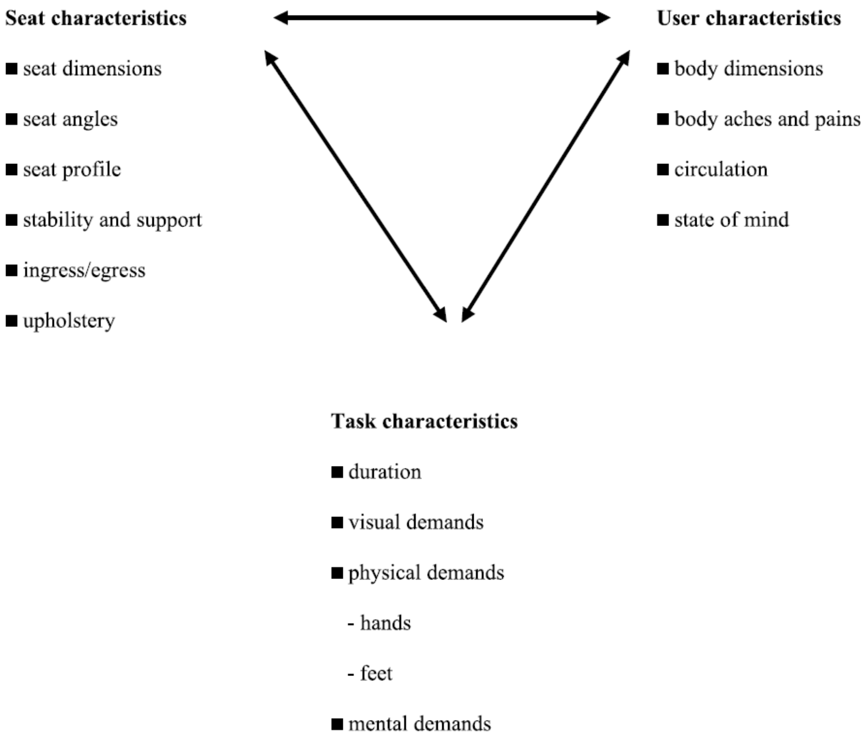


Figure 2.9 Parameters that influence sitting comfort or discomfort (Pheasant & Haslegrave, 2006).

The seat characteristics influence the posture that will or can be adopted. If the body is not adequately supported, the seated person's posture will only be maintained through muscle effort and if the seat profile does not match the person's body shape and size, additional pressure may be imposed on soft tissues that should not be exposed to load-bearing (Pheasant & Haslegrave, 2006). Task characteristics include visual, physical, and mental demands, which have a strong influence on the posture. Consequently, the task demands influence the appropriate seat characteristics that best give support while performing the task. User characteristics can be body dimensions, body ache and pain, and state of mind such as mental stress.

2.5.1 The spine in sitting and standing

The spine's shape changes between standing and sitting posture. Figure 2.10 shows a comparison of the spine curvature when standing (left), where a double S-shape is seen, sitting (middle) where a tendency to kyphosis is observed, especially in the lumbar spine area, and sitting with lumbar support (right) where a beneficial posture is again achieved (Bubb et al., 2021). The design of the driver's seat directly affects the driver's spinal and therefore, the seat design is highly important for comfort. A steeper position of the seat backrest and the use of lumbar support have multiple positive effects and improves the sitting posture significantly.

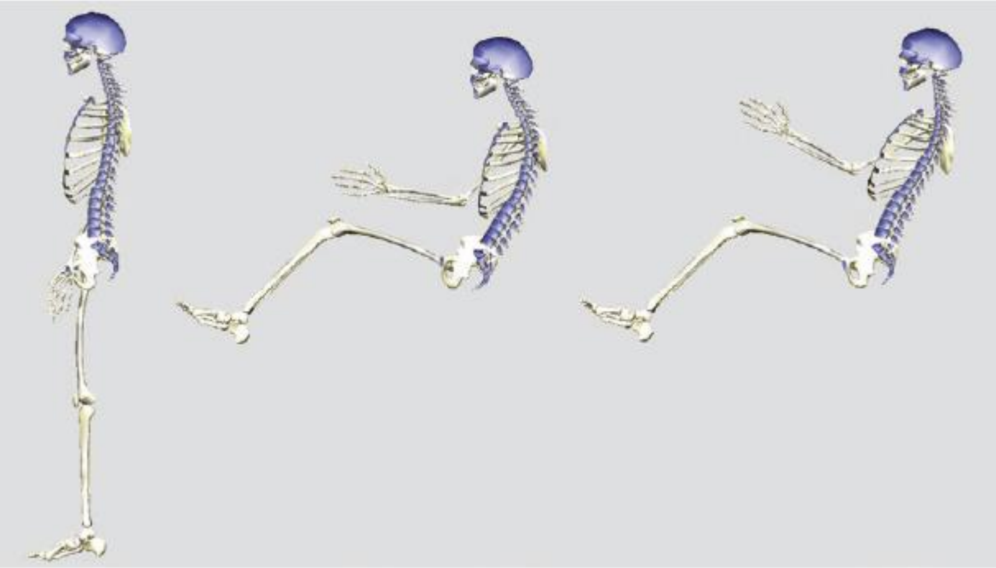


Figure 2.10 Comparison of standing and sitting posture, with and without lumbar support (Bubb et al., 2021).

2.5.2 Slouching

A slouched sitting posture is common for seated persons. Slouching includes a posterior (rearward) pelvis rotation where the back and shoulders sag, see Figure 2.11. There could also appear a more forward position of pelvis which means that the buttocks move forward. Slouching, or changing body position and posture, is a natural way of increasing comfort when seated in a vehicle. When mentioning slouching in this report, it is the posterior tilt slouching that is referred to.

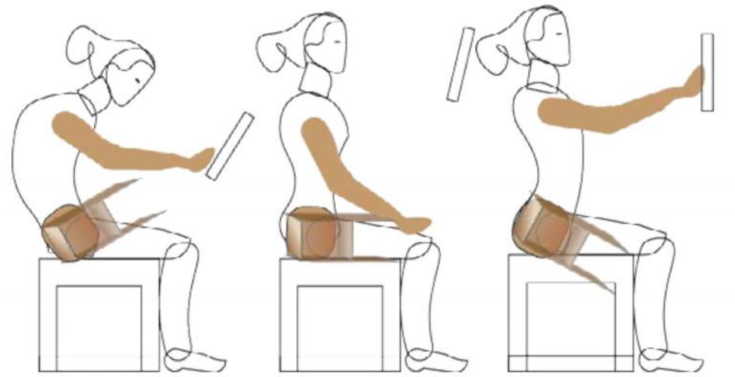


Figure 2.11 Rotation in pelvis creating a slouching position (from left to right): slouching backward, neutral, tilting forward (Zwick, 2022).

2.5.3 Differences in preferred driving position

In a study made by Wolf et al. (2022) looking at preferred driving position, conclusions could be drawn about correlations regarding stature, age, gender and posture (Wolf et al., 2022). The study included 127 participants that were recorded during a short drive, where joint angles were analyzed and where participants answered a questionnaire afterwards on preferred position. The results showed variabilities between the participants, especially for knee flexion. The variability for joint angles were more clearly between individuals than within a person's movement pattern. Also, differences depending on stature, gender and age could be seen between individuals. The most important findings that Wolf et al. (2022) discovered was that the flexion was higher for trunk-thigh angle and less for ankle-hip angle among taller people compared to shorter people. This could be an indication that shorter people position themselves higher for improved visibility. Older people had higher shoulder flexion and less extended arms than younger people. Elbow flexion was something that differed between men and women. This study shows that these parameters do influence the posture while driving, which is relevant as knowledge in this project. However, these are parameters that are not analyzed further during this master's thesis.

The study by Wolf et al. (2022) also included a questionnaire for subjective preferences regarding sitting posture. The questionnaire asked the participant to rate their desired driving posture. The result showed that there were no correlations found for the lower body regarding the participants preferred posture and their actual posture during the test. Therefore, it was not suitable as a method to let the participants estimate their preferred lower body seating. Reasons discussed for obtaining this result was that people have difficulties to assess their own leg posture. For the upper body and arms, the questionnaire gave good correlating results and letting participants estimate their preferred upper body position could be used as a method.

2.6 Volvo Cars Adaptive Cruise Control and Pilot Assist

The ACC in Volvo's vehicles helps the driver to maintain an even speed combined with a pre-selected time interval to the vehicle ahead (Volvo Cars, 2020a). The driver selects a desired settings with controls on the steering wheel. If the vehicle detects a slower vehicle in front of the car, the speed is adapted automatically. When a vehicle is no longer detected, the car accelerates and maintain the speed set by the driver. This means that the driver is only required to steer, however the driver can anytime interfere and accelerate or break at any time if desired.

The PA in Volvo's vehicles can help the driver to drive the car between the lane's side markings using steering assistance as well as to maintain an even speed decided by the driver, combined with a preselected time interval to the vehicle ahead (Volvo Cars, 2020c). The PA function is primarily intended for use on motorways and similar roads. The driver can at any time ignore the PA steering recommendation and steer in another direction, for example, to change lane or avoid an obstruction on the road. For PA to function, the driver's hands must be on the steering wheel. If the system detects that the driver is not holding the steering wheel, the driver is prompted to actively steer the car, via a symbol on the display and a text message.

2.7 Previous studies on dynamic driving

This section goes through previous studies of dynamic driving and behavior in different driving situations.

In their book, Bubb et.al., (2021) refers to a German study conducted by Schweigert in 2003, were he differenced several complex driving classes, and studied how the gaze behavior changed in the different situations. Gaze behavior is one way to understand driver behavior. Low complexity was exemplified as *highway, country road, city with little traffic, and knot-free road*, medium as *city with signposted crossings, traffic lights, bottlenecks and curves, motorway junctions, highway with curves and slopes* and high as *city, signposted junction with waiting motorway junctions*. The result showed that the viewing behavior did differ between the different complex situations and was mainly affected by the road section and the traffic situation. It was seen that more complex route sections had shorter fixation times and more frequent changes of eye gaze focus, since more information per time unit was received in this situation. This implies different driver behavior depending on situation.

Driver upper-extremity postures and activities during driving were researched in a naturalistic driving study by Reed & Ebert-Hamilton, (2016). They manually coded 9856 video frames from 165 drivers in 100 vehicles, with 96 women and 69 men, and where age was estimated from the videos. 65% of participants were estimated to be between 30-60. The study was performed on vehicles of six different brands and seven different models, all sedans. The data were summarized to identify the distribution of behaviors as a function of driver attributes. The results showed the following:

> "Drivers had left, right, and both hands on the steering wheel in 64%, 46%, and 28%, respectively. The driver's left elbow was in contact with the door or armrest in 18% of frames, and the driver's right elbow was contacting the center console armrest in 29% of frames. Men were more likely than women to use both the left and right armrests. Women had approximately the same percentage of armrest use across vehicles, but men's usage differed widely, suggesting that armrest design may influence whether people of different statures can use the armrests comfortably." (Reed, 2016)

Head rotations was studied in another naturalistic driving study focusing on car safety, with the goal to quantify the amplitude and duration of rotated head postures observed in drivers during naturalistic driving (Fice et al., 2018). Interesting results in relation to this project, was that the drivers spent a larger proportion of time in non-neutral postures when the vehicle was stopped (17.5%) compared to moving (8.2%). Drivers also moved their head further from neutral during the movements when the car was stationary compared to moving. This shows evidence that the drivers behave differently in different situations.

Another study investigated the effect of driving environment on sitting posture and developed a system to measure it in a qualitative study (Kim et al., 2003). They performed tests on four male drivers and concluded that "considerable changes in their postures were caused with respect to the driving environment, which implies that not only static optimal postures, but their dynamic changes should be taken into consideration" for interior design.

There have been several studies on driver behavior when using ACC, or Cooperative Adaptive Cruise Control (CACC) which is similar to ACC, but the cars also communicate with each other. Most studies consider more psychological aspects of driver behavior such as feeling of safety, stress, trust in the system and so on, see for example Beggiato and Krems (2013), de Winter et al. (2014), Rudin-Brown and Parker (2004), and Stanton and Young (2005). As an example, the last-mentioned authors Stanton and Young (2005) examined driver behavior using ACC from a psychological perspective. In the study, drivers were asked to drive in a driving simulator under manual and ACC conditions. The authors investigated how the effects of workload as in amount of traffic, and feedback as in degree of information from the ACC system, had on the psychological variables measured. These variables were locus of control, trust, workload, stress, mental models, and situation awareness. The results showed that locus of control and trust were unaffected by ACC, whereas situation awareness, workload and stress were reduced by ACC.

Other studies examined other aspects than only psychological. For example, (Cho et al., 2006) performed a study in a driver simulator, using ACC. They investigated driving behavior in terms of headway-time (duration between vehicles in a transit system measured in time), lateral position of the car and head and eye movement for drivers with different driving styles. The experiment results showed that, when driving with ACC, preferred headway-time was 1.5 seconds regardless of the driving styles, implying consistency in driving speed and safe distance. However, the lane keeping ability reduced, showing larger deviation in vehicle lateral position, which the authors mean shows a behavioral adaptation effect while using ACC. It was also found that the drivers had larger head and eye movement, meaning that they looked around more when using ACC. Another technical report looked at the hurdles of CACC regarding user behavior, and also considered lane position variability, and lane-changing (Jones, 2013).

No papers were found that examined sitting postures while driving with ACC. Search terms such as “posture adaptive cruise control”, “sitting posture adaptive cruise control”, “adaptive cruise control leg room”, was used, but no relevant articles were found on the topic that this project considers.

2.8 Digital human modeling

With the development within computer technology and specifically the possibilities to create simulations, virtual representation of human models has become a viable tool in ergonomics to simulate and evaluate driving postures and behaviors. It also becomes more and more important since new products are designed and produced in a short time frame, and that requires efficient software design tools (Chaffin, 2005). Using DHM for improvement of a physical aspect of a product allows designers and engineers to create digital manikins with specific population attributes, which can then be inserted into their 3D graphic renderings of the proposed design, and the design can be evaluated on several aspects. The following section gives an overview of current available software commonly used. Thereafter, the IPS IMMA software, which this project aims to improve is presented in more detail.

2.8.1 Software overview

There are several software programs available for DHM, developed for different purposes. Figure 2.12 displays the development of the human models used in the automotive industry, and how the development have moved towards more dynamic modeling that serve the construction and evaluation of anthropometric designing (Bubb et al., 2021). According to Bubb et. al., (2021), the most important geometrically oriented human models for vehicle design are RAMSIS, Jack, and Safework. The first two mentioned have also been used at Volvo Cars (Lämkull & Zdrodowski, 2020).

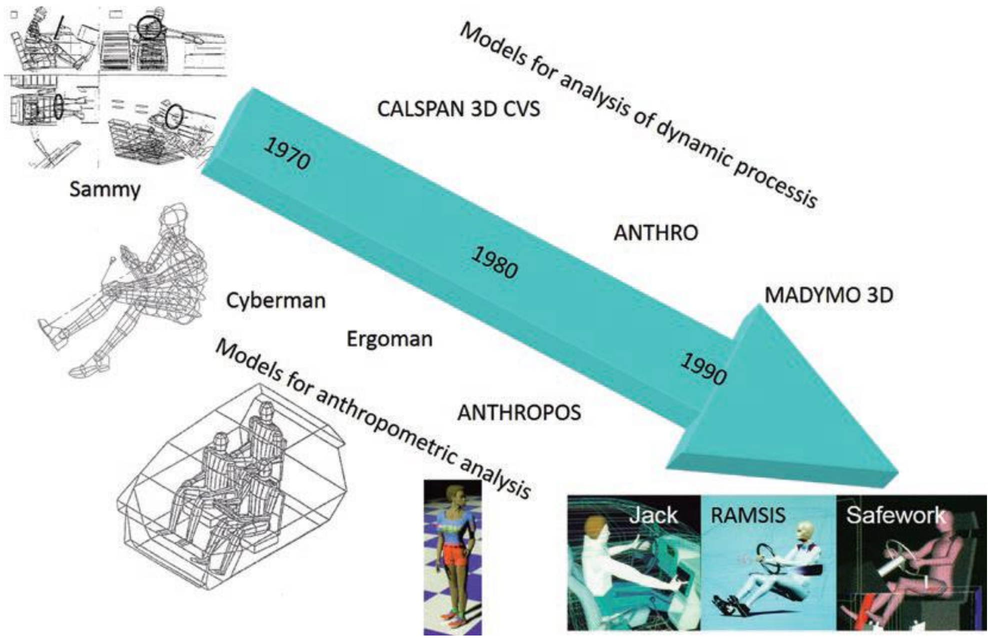


Figure 2.12 Development of digital human models used in the automotive industry (Bubb et. al., 2021).

2.8.2 IPS IMMA

IPS IMMA was initially developed as a tool for DHM combined with path planning for the manufacturing industry (Fraunhofer Chalmers, 2022b). The software was developed to analyze and control biomechanical motions performed by humans during assembly of e.g., cars. Using a virtual environment where analysis of motions can be performed already in the production development phase, minimizes the risk of potential body joint and muscle problems for assembly personnel. This type of computer analysis contributes to a more effective assembly process with a reduced number of injuries and a higher level of quality (Fraunhofer Chalmers, 2022b). Figure 2.13 shows an illustration of an IMMA manikin.

It is already possible to perform ergonomic studies with IMMA in a virtual development stage and the foundation is a biomechanical model that allows fast generation of complex motions that are as comfortable as possible. FCC describes the modeling as follows (Fraunhofer Chalmers, 2022a):

> "Similarly, to a human, it is possible for the IMMA manikin to perform motions with different positioning of the body. The biomechanical model of the IMMA manikin is built as a simplified human skeleton and consists of 82 bone segments that are connected by joints and have, in total, 162 degrees of freedom. A comfort function is used to determine the positions of the manikin that are ergonomically sound. The comfort is based on ergonomic criteria of the biomechanical model and has been formalized to fit the generic mathematical framework of the IMMA manikin. The user instructs the manikin to work in different postures and interact with the environment, and based on the biomechanical model, a motion incorporating the kinematic constraints, balance, contact forces, collision avoidance and comfort is automatically computed." (Fraunhofer Chalmers, 2022a)

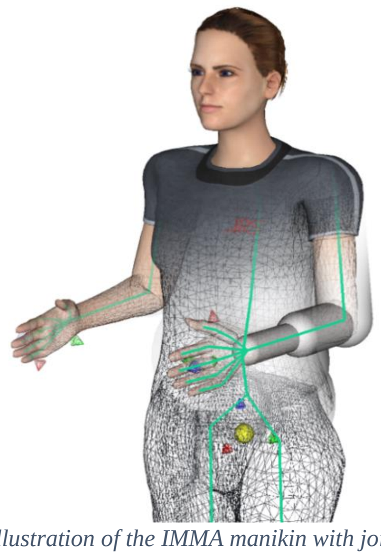


Figure 2.13 Illustration of the IMMA manikin with joints visualized.

When creating manikins in IMMA, one can use predefined anthropometric data, or enter specific data. It is possible to create a full family of manikins to cover an entire range of anthropometrics. The manikins have several predefined control points that allows the user to change the posture and position of the manikin. Figure 2.14 a) and b) shows a male and female manikin sample from a default manikin family, and Figure 2.14 c) shows another representation of the manikin in form of a stick figure which also displays some of the existing control points. These control points can be manipulated to position the manikin into a desired position. There are also some predefined postures in the program, such as “seated car”. It is possible to edit or add more control points through modifying JSON and XML files as well as scripts, however this requires some understanding of the scripting and its commands.

a) *b)* *c)*

Figure 2.14 IPS IMMA manikins: a) male b) female and c) stick figure with some control points displayed.

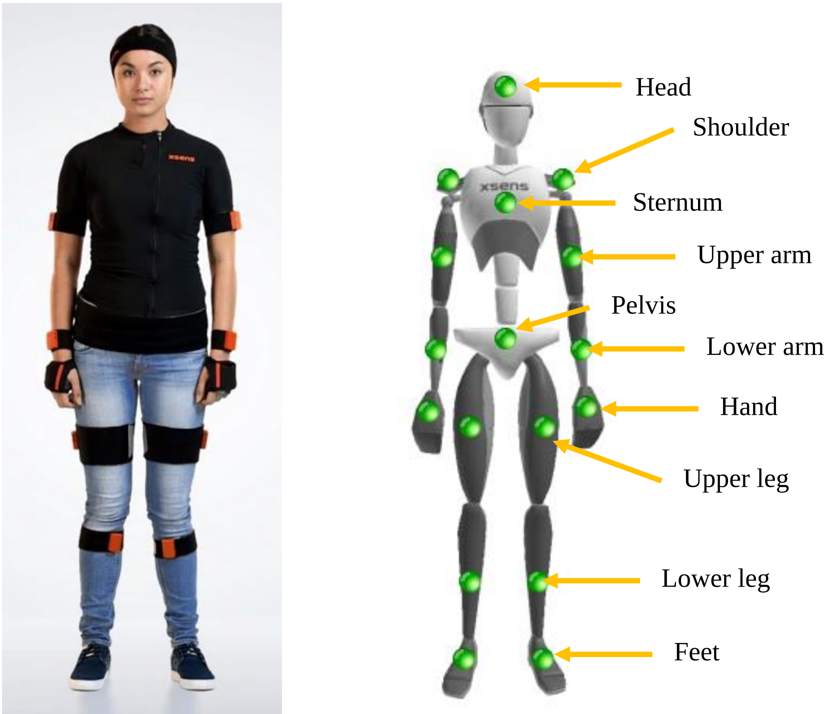
2.9 Xsens

Xsens is a motion tracking solution that allows controlling and detecting movement using sensor technologies. The product used in this project is the MTw Awinda motion tracker. The motion capture system uses wireless inertial-magnetic measurement units that comprise a 3D accelerometer, 3D gyroscope, and 3D magnetometer to acquire high accuracy and robust orientation output for real-time applications (Paulich et al., 2018). Xsens has during recent years put an effort to minimize errors caused by magnetic fields in the surroundings to provide a better user experience and get a more accurate result with less magnetic distortions also claiming full immunity in the MVN Fusion Engine (Xsens, 2021a). The added global navigation satellite system allows for positioning aid and helps reduce the effect of positional drift over time.

Xsens combines several sensors as part of a Body Sensor Network (BSN). Figure 2.15 shows the overall hardware components of the Awinda system, consisting of a) the MTw motion tracker, b) the Awinda station, and c) body straps to attach the sensors. The station is a master system that serves as an interface between an Awinda host, which is a computer using Xsens software, and the MTw’s. The station has a range of 50 meter. The full BSN comprises 17 sensors attached to the body according to Figure 2.16, where a) shows the system mounted on a person and b) shows the sensor location on a Xsens avatar, and an additional property sensor that can be placed on an object, for example, a sword. Furthermore, IPS IMMA is developed to be compatible with Xsens, meaning that its is possible to stream an Xsens recording into IMMA.

a) *b)* *c)*

Figure 2.15 Awinda Hardware comprising a) MTw motion tracker b) Awinda Station, and c) body strap (Paulich et al., 2018).



a) *b)*

Figure 2.16. Xsens motion capture BNS viewing a) mounted on a person and b) sensor locations (Xsens MVN tutorials, 2016).

The MVN system does not have an absolute positioning system. This means that the character can drift regarding an absolute position with respect to the origin. For short recordings, drifting is usually only up to a few centimeters. The position can be reset to origin in between recordings.

The Xsens equipment has a strapdown integration algorithm that improves the performance of estimating the orientations (Xsens, 2021c). Strapdown integration is the process that samples and integrates sensor data to decide changes in location or orientation. Strapdown means that the equipment is strapped on the actual part of which to measure. The combination of the sensors on the actual body parts and a microprocessor eliminates issues that can occur when using other methods for the same purpose. The algorithm computes with high accuracy, the integrated quantities of angular velocity and acceleration with error compensation for coning and sculling. The sensor signals are sampled at 2000 Hz, then passing through calibration, down-sampling, and strapdown integration to the desired output frequency of 100 Hz. All filtering is done by the in-board processor because of the strapdown integration algorithm resulting in integrated higher frequencies in the output signal even when low output frequency is selected.

The sensors have a so-called sensor bias, also called zero-g offset, which gives the output of inertial sensor data a certain offset even when there is no output (Xsens, 2021b). This is due to the gyroscopes and accelerometers in the sensors having physical properties that change over time, which result in different characteristics. Even though calibration and the advanced algorithm are used the physical properties change over time regardless. The on-board filters use sensor fusion combined with gyroscopes, accelerometers, and magnetometers to make it possible to detect and correct sensor biases.

2.9.1 Xsens vehicle scenario

There are several different scenarios one can use in Xsens. This project has used the vehicle scenario where the pelvis is fixed in space and all kinematic quantities are expressed relative to the pelvis. It also has an adjustment to the acceleration divergence monitoring, meaning it can cope better with long and slow accelerations, such as when turning gradual banking in a car (Xsens, 2021a).

2.9.2 Xsens data

Xsens collects several types of data, and this section presents the data that was of interest in the project.

Position

The position and orientation for each body segment is calculated in Xsens with respect to a global earth-fixed reference coordinate system, G (Xsens, 2021a). G is defined by a right-handed Cartesian coordinate system as:

- X positive when pointing to the local magnetic North.
- Y according to right-handed coordinates West.
- Z positive when pointing up.

The Xsens system is aligned with G when a person is standing in T-pose (Xsens, 2021a). T-pose means standing straight with arms out, like a T. After calibration of the system the right heel of the person is positioned at origin (0,0,0), see Figure 2.17, with red arrow in the positive X-direction. However, for vehicle mode, the pelvis is instead fixed at the position (0,0,1.25). The positions are calculated for 23 different segments, Appendix A. However, sensors are not attached to all the 23 segments (Schepers et al., 2018). The movements and position for the segments without a sensor are only estimated by combining information about segments and biomechanical model. The segments are the following: L5, L3, T12, which are locations in the spine, neck, and toes.

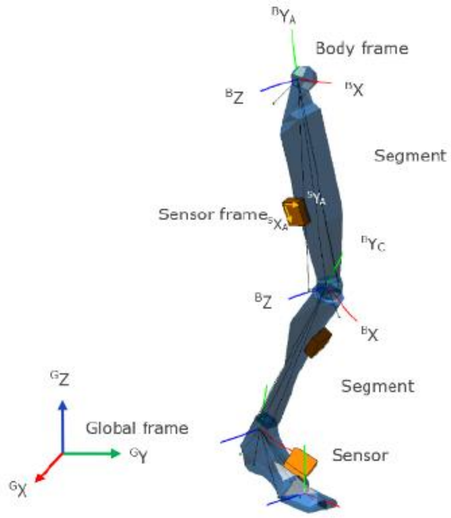


Figure 2.17 Global and local coordinate frames.

Orientation

The orientation is given in a quaternion vector, $q = (q_0, q_1, q_2, q_3)$, which is a mathematical notion for representing spatial rotations in 3D space (Xsens, 2021a). They can be interpreted to represent a rotation α around an arbitrary unit vector $\boldsymbol{n}$. Quaternions can be transformed into rotation matrices according to Equation 2.1.

Equation 2.1 Quaternions transformed into rotation matrix.

$$\mathbf{R} = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2q_1q_2 - 2q_0q_3 & 2q_1q_3 + 2q_0q_2 \\ 2q_1q_2 + 2q_0q_3 & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2q_2q_3 - 2q_0q_1 \\ 2q_1q_3 - 2q_0q_2 & 2q_2q_3 + 2q_0q_1 & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix}$$

$$= \begin{bmatrix} 1 - 2q_2^2 - 2q_3^2 & 2q_1q_2 - 2q_0q_3 & 2q_1q_3 + 2q_0q_2 \\ 2q_1q_2 + 2q_0q_3 & 1 - 2q_1^2 - 2q_3^2 & 2q_2q_3 - 2q_0q_1 \\ 2q_1q_3 - 2q_0q_2 & 2q_2q_3 + 2q_0q_1 & 1 - 2q_1^2 - 2q_2^2 \end{bmatrix}$$

Joint angles

For calculation of joint angles, an extra frame of reference is used for defining body frames, additional to G (Xsens, 2021a):

- Origin: center of rotation
- X forward
- Y up, from joint to joint
- Z pointing right

The origin for each segment is positioned in the proximal joint center, working as functional rotation point and is chosen by Xsens to create a skeleton character see Figure 2.18.

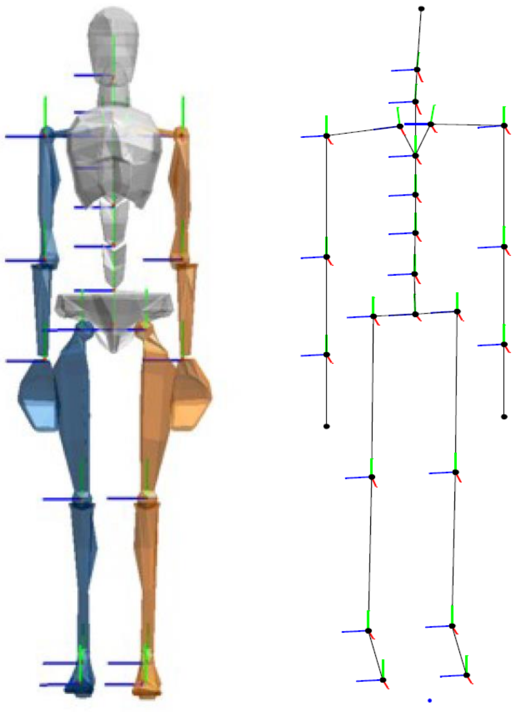


Figure 2.18 Segment coordinate systems for each joint.

The joint rotation that describes the joint angles can be parameterized in different ways but the representations are based on the same quaternions describing orientations, where a standard has been proposed by the International Society of Biomechanics (ISB) (Wu & Cavanagh, 1995). Xsens have chosen to follow the recommendations of ISB and Grood & Suntay (Grood & Suntay, 1983), describing joint angles by joint coordinate system for the angle output. Most of the angles are described by Euler angles extractions where Z defines flexion/extension, X abduction/adduction and Y internal/external rotation, but the definition of the origin for each segment is different since the sensors are placed on the segments of the body and not on bony landmarks. The shoulder joint calculation also differs from the ISB recommendations where Xsens gives three different shoulder angle calculations. The outputs for each joint can be seen in Table 2.1 below.

Table 2.1 Overview of joint angles and their descriptions (Xsens, 2021a).

	Joint Angle	Description (& Euler Sequence)
1	L5S1	Joint between the lumbar spine segment 5 and sacral spine 1 (ZXY)
2	L4L3	Joint between the lumbar spine segment 4 and lumbar spine segment 3 (ZXY)
3	L1T12	Joint between the lumbar spine segment 1 and thoracic spine segment 12 (ZXY)
4	C1Head	Joint between the cervical spine segment 1 and the head segment (ZXY)
Left and Right		
5	C7Shoulder	Joint between cervical spine 7 and the MVN shoulder segment
6	Shoulder ZXY	Shoulder joint angle between the MVN shoulder segment and the upper arm; calculated using the Euler sequence ZXY
7	Shoulder XZY	Shoulder joint angle between the MVN shoulder segment and the upper arm; calculated using the Euler sequence XZY
8	Elbow	Joint between the upper arm and the forearm. (ZXY)
9	Wrist	Joint between the forearm and the hand. (ZXY)
10	Hip	Joint between the pelvis and upper leg. (ZXY)
11	Knee	Joint between the upper leg and lower leg. (ZXY)
12	Ankle	Joint between the lower leg and foot. (ZXY)
13	BallFoot	Joint between the foot and the calculated toe. (ZXY)

n the Xsens data, the joint angles are represented by flexion/extension, abduction/adduction, and internal/external rotation. A visual representation of these types of joint movements for the shoulder and the elbow can be seen in Figure 2.19 (Gopura et al., 2016).

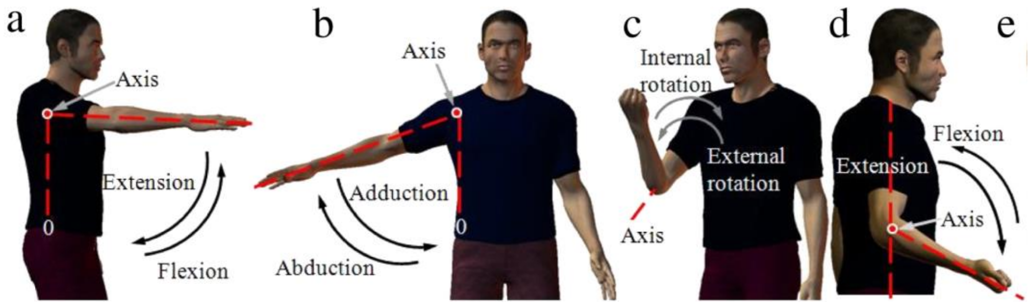


Figure 2.19 Flexion/Extension, Abduction/Adduction and Internal/External rotation for the shoulder and elbow (Gopura et al., 2016).

3 Methods

This chapter covers the methodology used in this project. The first section gives an overview of the overall methodology and activities in the project, and the proceeding sections go more into detail on the specific methods used for every activity. These sections follow the same order as the methodology overview.

3.1 Overview of methodology

The waterfall model was used to structure the overall work. The first publication on the waterfall model is found in an article by Walter Royce's in 1970 (Royce, 1987). The waterfall model is common in product development and is a sequential model for planning, developing, and delivering new products or features. In this project, the development phase is not the design of a product, but rather the development and execution of an experimental test in the early stages of a development process. The development phase focused on developing requirements for the IPS IMMA software through several steps. This model was chosen, as the different activities in the project were defined early on as specific phases and the project had a distinct time frame why a clear plan was needed, and for that the waterfall is a suitable approach (Aha!, 2022). Furthermore, as there was no need to include customer opinions frequently in the process, nor was the project aiming at innovate anything radical, other agile options would not be favorable for this project (Jeff & Hirotaka, 2016). Although the phases have been conducted sequential, there has been iterative approaches within phases when beneficial, for example, to develop testing methods, and define research questions. Figure 3.1 shows an overview of the project and its different steps. Thereafter a brief explanation of the methods used within each step is presented.

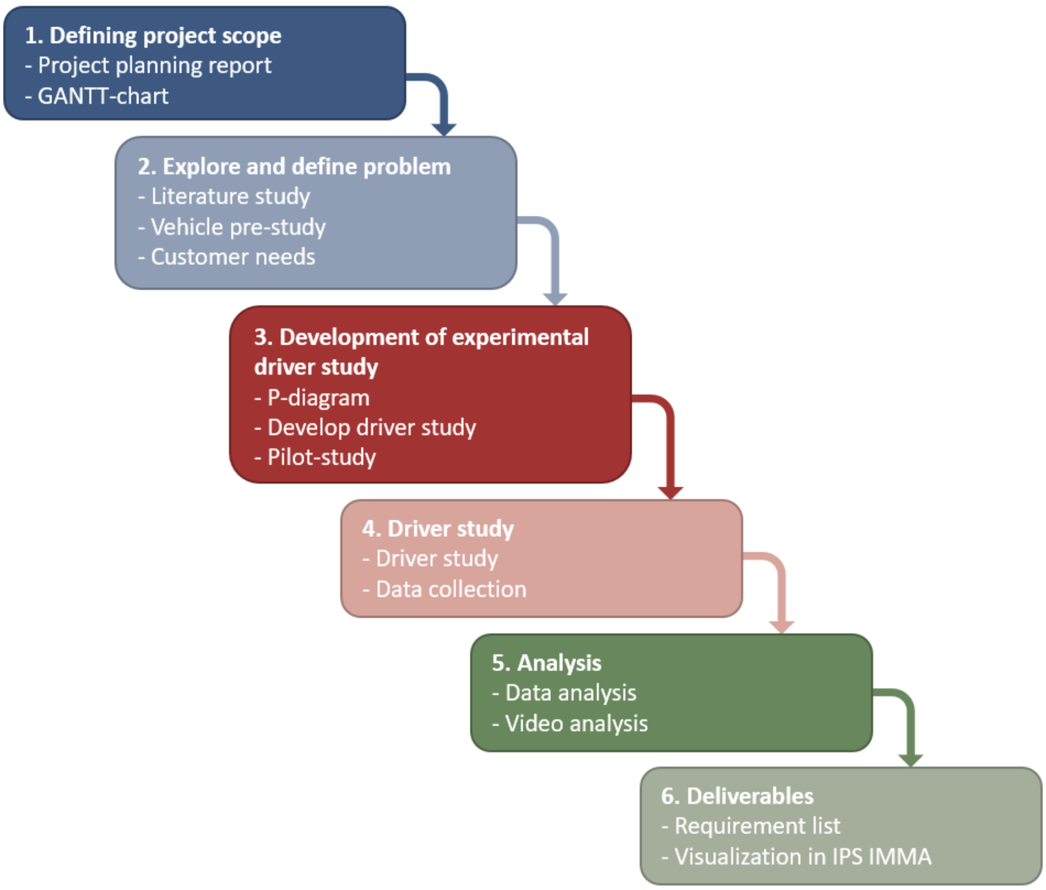


Figure 3.1 Overview of waterfall model with the different steps and activities conducted.

Step 1: Define project scope
The first step of the project included producing a preliminary project planning report and a GANTT-chart covering the entire project, to help plan the upcoming work and define the project scope. The supervisors at both Chalmers and Volvo Cars assisted in these tasks.

Step 2: Explore and define problem
After defining the scope, the next phase focused on understanding and further defining the problem, and included activities such as a literature review, a vehicle pre-study, understanding the customer's needs, and defining the project scope.

Step 3: Development of experimental method
The next step focused on developing an experimental study to answer the stated research questions formulated in the previous step. The work included the development of a Parameter diagram (P-diagram) to identify factors that might impact the driver study, the development of a driver study, and a pilot study to examine the feasibility of the developed driver study.

Step 4: Driver study
The developed driver study was conducted with 12 test subjects making it a qualitative study. The participants were normally distributed regarding both stature and sitting height. Both objective and subjective data was collected.

Step 5: Analysis
The collected data from Xsens, video recordings, questionnaire, and seat measurement were analyzed ongoing. Xsens as a method was also analyzed and evaluated.

Step 6: Deliverables
After analyzing the results and quantifying the findings, a requirement list was produced as a final delivery.

3.2 Explore and define problem

This section presents the activities performed that aimed to further explore and define the problem for this project.

3.2.1 Literature review

The research performed was built on existing knowledge in ergonomics and relating subjects. This knowledge was elicited through a literature review and helped motivate the aim of the study and justify the research questions and hypotheses. A literature review ensured that the project was built upon prior research, and was a valuable starting point for a master's thesis (Höst et al., 2006). The initial aim of the literature review was to build a foundation of knowledge in ergonomics, anthropometrics, comfort, and sitting behavior. Thereafter, the search was narrowed down to more specific topics, hence focusing more on relevant and recent research.

The material used have mainly been peer-reviewed literature from scientific journals, to ensure the trustworthiness of the material, where most papers were retrieved from well-known publishers such as Taylor & Francis, Elsevier, and Springer/Kluwer. To find relevant literature the method presented by Höst, Regnell & Runesson (2006) was used. The process started with a broad search, to get a wide understanding of the problem. Subsequently, the search was narrowed down by a screening of the identified sources, and further investigation of the selected material, followed by a deeper search of specific areas and sources. It was an iterative process, where later described stages were re-iterated as more knowledge was obtained. The literature review was documented in an Excel spreadsheet. For the less renowned publishers, a critical review was done to ensure that the sources were reliable. For example, the people doing peer-review were looked up to ensure that they were qualified, number of citations, or that the article was published on another trusted source.

The review started with an extensive search, using broad search terms such as *vehicle ergonomics, anthropometrics, driver behavior,* and *driver sitting posture.* This led to several textbooks that provided a solid base knowledge, but also articles, where a few of the most relevant was investigated further. From there, further literature sources were found, and other interesting search terms were discovered and explored, such as *sitting comfort, driving environment, digital human modeling,* and so on. The result from the literature review is presented in Theory, Chapter 2.

3.2.2 Pre-study

The pre-study consisted of a static test performed by the researchers to gain knowledge about the different Volvo car models and explore differences and similarities in sitting position between vehicles to be able to identify what car to use during the driver study. Three car models were tested: V90, XC90, and XC60. The V90 is a combi, and the XC models are SUV models. The cars were positioned close to each other which made it possible to easily move from one car to another while remembering the previous experience. This allowed the researcher to clearly notice differences and similarities between car models. Both researchers sat down in each car and adjusted the seat until a comfortable driving position and then photos were taken to do a simple visualization of the differences in seating position. The comparison was made for each researcher by connecting joint parts on the body with lines. The test was performed so that the researcher not sitting in the car took photos and the other altered between the cars. When moving between cars, there was a possibility that the angle and distance altered between each photo. The comparison was therefore an estimation for understanding of differences among the car models. A metal marker in the door opening was used as reference in the photos. A driving test was also conducted by the researchers to try the differences between city driving, highway driving, highway driving with ACC, and highway driving with PA. This was done to further evaluate what type of situations that were interesting to investigate.

3.2.3 Identify customer needs

To elicit and understand customers' needs, unstructured interviews were held frequently with the stakeholders of the ADOPTIVE team, which included the project's supervisors and other relevant people from the ADOPTIVE team. Unstructured interviews are informal conversational interviews in which respondents may not even know they are being interviewed (Patton, 2014). The researchers' questions were brought up during weekly reoccurring meetings where a few very open questions were prepared and then the discussion went on freely, and notes were taken.

A mission statement was formulated to communicate the goal of the ADOPTIVE project and the task definition, between the researchers, supervisors, and stakeholders. According to Ulrich and Eppinger (2019) ”A mission statement summaries the direction to be followed by the development team”. The design of the mission statement followed the guidelines presented by Ulrich and Eppinger (2019).

3.2.4 Define possible outcomes and hypotheses

Possible outcomes to the research questions were stated in an early phase, before testing to activate the researchers minds about what the study could arrive at. Hypothesis to the research questions were formulated as a method to help the project understand what data that needed to be collected in the driver study and how to analyze the data. Hypothesis testing is a scientific method within statistics (Wilcox, 2011). However, the study conducted in this project was of a qualitative character, why statistical measurements did not apply.

Possible outcomes

Possible outcomes to the RQs were identified and presented below. Recall that the research questions were stated as follows:

> **RQ1**: What are the differences and similarities in sitting posture of the driver in the following driving situations:
> - S1: city driving
> - S2: highway driving
> - S3: highway driving with the use of ACC
>
> **RQ2**: What are the differences and similarities in body motion pattern of the driver in the following driving situations:
> - S1: city driving
> - S2: highway driving
> - S3: highway driving with the use of ACC
>
> **RQ3**: If possible, how can sitting postures and body motion patterns be generalized in different driving situations, to formulate suggestions on future software implementations in IPS IMMA?
>
> **RQ4:** What limitations do drivers experience regarding the sitting posture? If there are any limitations, how do they affect the way drivers are seated?

Possible outcomes RQ1

a) No differences in sitting posture between any of the situations.
b) Differences in sitting posture between S1 and S2, and S1 and S3, but no differences between S2 and S3.
c) Differences in sitting posture between S2 and S1, and S2 and S3, but no differences between S1 and S3.
d) Differences in sitting posture between S3 and S1, and S3 and S2, but no differences between S1 and S2.
e) Differences in sitting posture between all situations.
f) None of the above – unpredictable output.

Possible outcomes RQ2

a) No differences in motion pattern between any of the situations.
b) Differences in motion pattern between S1 and S2, and S1 and S3, but no differences between S2 and S3.
c) Differences in motion pattern between S2 and S1, and S2 and S3, but no differences between S1 and S3.
d) Differences in motion pattern between S3 and S1, and S3 and S2, but no differences between S1 and S2.
e) Differences in motion pattern between all situations.
f) None of the above – unpredictable output.

In the next section, the definition of a generalization was defined as something that showed in ≥ 50% of the cases in the user studies. A tendency was defined as something that showed in ≥ 40% to < 50% of the cases in the user studies.

Possible outcomes RQ3

a) Not possible to generalize due to too many differences between drivers.
b) Different generalizations within one or more situations.
c) Different generalizations within one or two situations, while other show tendencies but is not generalizable.
d) Same generalization across two or more situations.
e) Tendencies but no generalizations within a situation or across situations.

Possible outcomes RQ4

Since the exact limitations a driver could experience is very individual, it was not possible to predict all possible outcomes. However, it was believed that aspects regarding the seat and steering wheel configurations, the roominess in the vehicle, reach space, and the car body could limit the driver.

Hypotheses

The project formulated detailed hypotheses regarding RQ1 and RQ2 which are presented in Table 3.1 and Table 3.2 below.

Table 3.1 Hypotheses for RQ1.

Hypotheses RQ1 It is believed that in S1, compared S2 and S3, the following differences show:	
HR1.1	Armrests will not be utilized to the same extent
HR1.2	Both hands placed on the steering wheel to a larger extent
HR1.3	Left foot will be on footrest
It is believed that in S3, compared to S2, the following differences show:	
HR1.4	Right foot heel point will be placed closer to the seat, and away from the accelerator pedal
HR1.5	Larger distance between inner point of knees
HR1.6	Right leg knee angle will be smaller
HR1.7	Increased slouching
HR1.8	Increased arm rest use

Table 3.2 Hypotheses for RQ2.

Hypotheses RQ2 We believe that in S1, compared S2 and S3, the following differences show:	
HR2.1	The driver's upper body will move in X-direction to a higher extent
HR2.2	The driver's upper body will move more frequently
HR2.3	Arms will move more
HR2.4	More hand motion when steering
HR2.5	Feet will be more active and use pedals more frequently
We believe that in S3, compared to S2, the following differences show:	
HR2.6	Less leg motion
HR2.7	Larger leg movements when changing lower body position
HR2.8	Feet will be less active and use pedals less frequently

Hypotheses regarding the RQ3 and RQ4 were formulated as follows:

Hypothesis RQ3:
The proposed outcome is believed to be alternative c), Different generalizations within one or two situations, while other shows tendencies but is not generalizable.

Hypothesis RQ4:
It is believed that people with a stature in the outer percentiles of the normal distributed population might feel limited in terms of leg and head space and reach ranges. However, it is also believed that the participants do not feel as limited as if they would not have the possibility to adjust the seat. Also, it is believed that people are used to sit in certain ways and might not have any perception of what a less limited position would feel like for them. To conclude, it is believed that, except for the outer percentiles, people are not limited.

3.3 Development of exploratory driver study

This chapter explains in more detail the methods used to develop the driver study. It includes a description of the overall exploratory approach followed by the objective and subjective data collection methods. The stated hypotheses in the previous section acted as a base for when choosing data collection methods. Thereafter the P-diagram method is described which helped define parameters that could influence the study. Finally, the pilot study, which was conducted for testing, verifying, and revising the study is presented.

3.3.1 Exploratory research – the overall method

In this project, an exploratory research approach was used. Exploratory research is a working approach where researchers are trying to discover something new, not knowing in advance if something comes out of it (Swedberg, 2020). For research topics that do not have conceptual frameworks, exploratory research is needed to identify impacts, outcomes, and variables (Darian-Smith & McCarty, 2017). During exploratory studies, methods like case studies, surveys, and interviews can be used.

The methodology for capturing data during dynamic driving was not set from start, and therefore, exploratory research was a suitable approach for this study. After performing exploratory research, besides the results, a framework should be produced for better understanding of the topic and the development of new theories (Darian-Smith & McCarty, 2017). For this project, evaluation and revision of the methods used for capturing and gathering data during the driver study were a part of the delivery.

Both objective and subjective data were collected. This was done to achieve triangulation, i.e., to use multiple data sources to better understand the user. Triangulation is used mainly for three reasons: to enhance validity, to create a more in-depth picture of a research problem, and to examine different ways of understanding a research problem (Nightingale, 2020). The objective data was argued to help understand how the drivers behaved during the test, in a measurable and quantifiable way. The subjective data is used to understand how the drivers perceived the situation and to help interpret the objective data to answer why they behaved as they did.

3.3.2 Objective data collection

Objective measures can be defined as "measurements that are not affected by the subject performing the tasks or by the researcher observing or recording the subject's performance" (Bhise, 2012). Objective measurements are generally obtained using physical instruments. In this study, available technology at Volvo Cars was utilized to capture objective data on the sitting positions and motion patterns. The Xsens motion capture system and video cameras were used to track the person's posture and motion pattern during the driving. These are described in the following sections.

Xsens

An Xsens video of the manikin's movement was obtained from the recordings with Xsens and was utilized for annotation. The scenario "vehicle scenario", described in Section 2.9.1, was used during the tests.

Video cameras data collection

Data was collected using video cameras. The cameras were connected to a test computer where the software Open Broadcaster Software (OBS) Studio (Jim, 2022) was used to record all video cameras in one frame. Annotation of different sorts were then used to elicit certain frames as data points. The installation and use of video cameras are described in more detail in Section 3.4.1.

Seat and steering wheel measurements

The seat configuration and steering wheel were measured four times: after the initial position, city drive, highway drive, and ACC drive. The seat configuration was measured in pulses but could not be measured continuously due to limitations in the software. The pulse data from the seat was inserted into a converter Excel sheet that transformed the pulses into relevant position coordinates. Those of interest was the seat back inclination and H-point. The steering wheel was mechanically adjustable and measured in Z (vertical) and X (horizontal) changes in mm.

3.3.3 Subjective data collection through a questionnaire

A questionnaire was used to collect subjective data from the test subjects. It is a common and frequently used way to measure qualitative attributes such as behavior (Svensson, 2001). The questionnaire used a mix of numeric scaling questions and open-ended questions where the user could further elaborate. There was also an option to leave an additional comment to the numeric scaling questions to allow the test subject to further explain their ratings. The questionnaire was divided into six parts: Additional information, Initial position, City driving, Highway driving, Highway driving with ACC, and After finishing study. The first part collected additional information about the participants driving habits and experiences. The second to fifth section collected their experience on how it was perceived being seated in the vehicle as well as driving in the different situations. All questions were the same for each part, making a comparison between the situations possible. The last part collected their overall experience about the study. The full questionnaire can be found in Appendix B.

There are several numeric scaling methods to measure a user's subjective experience. One of the more straightforward and easy methods is Numerical Rating Scales (NRS). NRS has a series of numbers in ascending order with a descriptive category anchored at each end to present the best-case and worst-case scenario. A standard format is usually 11 levels, from 0 to 10 with a mid-point being 5 (Brunelli et al., 2010). This method was chosen because it is commonly used in similar studies and easy to understand for the participants.

NRS questions are commonly used in surveys, however, they can easily become biased unintentionally and affect the outcome of the answer (Friedman & Amoo, 1999b). Therefore, several aspects were considered to avoid bias. The first consideration regards the wording of the anchors. Schwarz et al. (1988) found that a scale anchored with "superior" and "terrible" do not produce the same results as when using "very good" and "very bad", which have weaker adjectives, and concluded that respondents seem to a higher extent choose extreme descriptors for their response. The wording of the anchors was chosen carefully, and no extreme wording was used.

Another aspect considered was implicit assumptions of the question, meaning that the phrasing of the question itself is biased (Friedman & Amoo, 1999a). For example, the question "How limited were you by the seat?" assumes that the driver was limited by the seat. By asking, "To what extent could you adjust the seat", or "To what extent did you perceive that you could position your feet?", implicit assumptions were avoided. A final aspect that was considered was the rating scale itself. By having an uneven scale from 0 to 10 and a middle point being 5, a *forced choice* was avoided, and the subject could choose not to take a stance by answering in the middle. By answering in the middle, the participant could express an opinion that was neither high nor low, which could be a disadvantage as it can be difficult to interpret.

3.3.4 P-diagram

A P-diagram was created to identify relevant parameters and understand how they affected the driver study. Figure 3.2 shows a simplified schematic illustration of the P-diagram. A P-diagram takes input signals from a system, while also considering non-controllable outside influences, noise factors, and relates those inputs to desired outputs of a design (The Quality Portal, 2013). The P-diagram was compounded by the following parts (The Quality Portal, 2013; Carlson, 2016):

- **Input signals** were the input to the system and are a description of the sources needed for fulfilling the system functionality.
- **Ideal function** was the primary intended functional output of the system.
- **Error states** were the failure modes, effects of the failure, or other undesirable system outputs as defined by an end-user when using the product.
- **Control parameters** were elements such as design, materials, and processes that the engineer had 'control' over and could change.
- **Noise factors** were things that could influence the ideal function but were not under the control of the engineer. These were piece-to-piece variation, changes over time, customer usage, external environment, and system interactions.

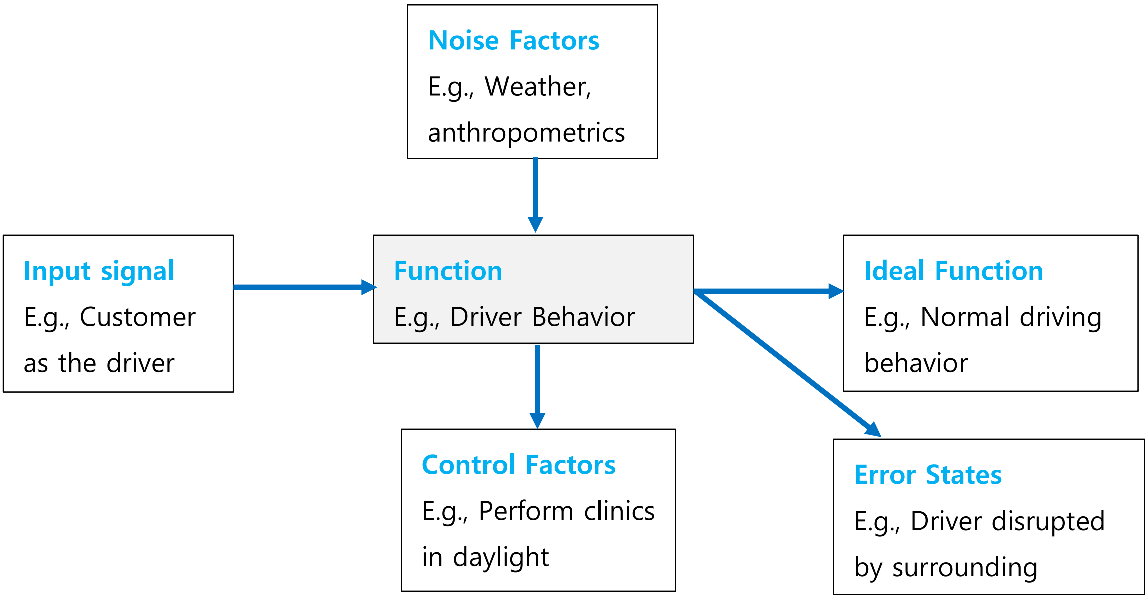


Figure 3.2 Simplified P-diagram

3.3.5 Pilot study

One pilot study was conducted before the large-scale driver study to evaluate the feasibility. It helped to prepare the researchers to ensure repeatability over tests. Invitations were sent out to the ergonomics department and other master's thesis students at Volvo Cars. Three persons participated in total.

Pilot test vehicle

The test vehicle was an XC60 equipped with several measurement tools to collect data which are described next. Three cameras were used at first, but it was later discovered that one camera placed above the seat in the ceiling by the grab handle, which was supposed to capture the legs and knees movement, did not work as desired. No other placement was suitable, and the camera was therefore removed. It was believed that the Xsens data would capture the corresponding information. Regarding the two cameras that were used, one camera was placed under the seat and the second on the passenger seat window frame. Measurement equipment for the steering wheel, floor mat, and seat configurations was decided to be used. However, the test vehicle was not equipped with it since the vehicle was changed between the pilot study and the user study, and the equipment was not ready to use by this time. The measurement equipment is described in the next Section 3.4.

Pilot study test routine

A protocol and manuscript were developed to ensure that all tests were performed in a repeatable way. It included a safety check of the vehicle, preparation of the experimental setup before the test subject arrived, and activities during and after the test. The protocol was cross-checked with supervisors to ensure all relevant aspects were included. A route was planned using Google Maps route planning tool. All of these were evaluated in the pilot study and adjusted for the final driver study and are presented in Section 3.4.2.

FMEA

To evaluate the test routine, a Failure Mode and Effects Analysis (FMEA) was made. The purpose of an FMEA is to determine how processes or items might fail to perform their function, so that any required treatment could be identified and hinder failure (International Electrotechnical Commission, 2018). The FMEA provides a systematic approach for identifying failure modes, their potential cause, and their effect on the system. By considering the failure modes occurrence, severity, and possibility of detection, they can be prioritized to support decisions about treatment. The FMEA was used to evaluate the risks of the test process and identify possible improvements. The goal was to ensure high quality results and a safe test procedure for everyone involved. The analysis evaluated both ethical aspects regarding safety for the test subject, and the test procedure itself. The systematic procedure followed the guidelines presented by (Liu, 2016), and is summarized in Figure 3.3. It was decided that action was required for risk priority numbers of 50 or higher. The actions usually fall into one of the following three categories: eliminating failure modes, increasing failure detectability, and minimizing losses if a failure occurs which was considered as a base for when deciding appropriate actions (Liu, 2016).

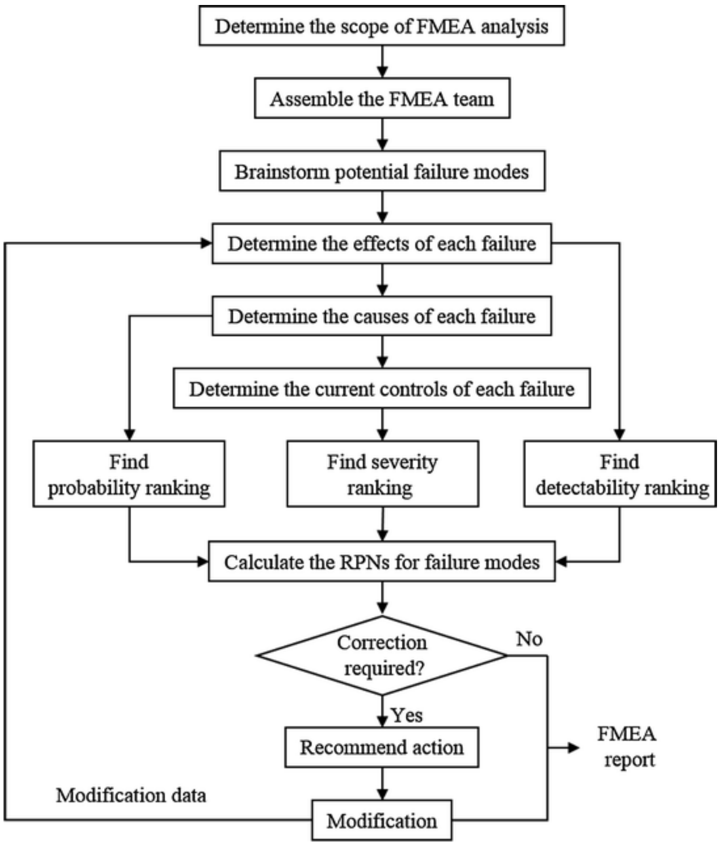


Figure 3.3 Overview of the FMEA process.

3.4 Driver study

This chapter describes the driver study and activities that were performed before executing the user study. A description of how the car was equipped, the route, and how the test subjects were chosen are also presented.

3.4.1 Test vehicle

An XC60 was chosen as the test vehicle. This was decided after testing different models in the pre-study, where a high-seated car was of interest to investigate further, and since the framework and 3D scans are shared with the ADOPTIVE project. This made it possible to use a digital model of the vehicle in IPS IMMA for implementation. This section presents the equipment and measurement tools used in the car.

Video cameras

Two video cameras were attached to the vehicle. One was placed at the passenger seat window frame to capture the sagittal right plane of the driver, and the second was placed under the driver seat to capture foot movements. The camera model was a Logitech web camera, capturing 2D video. Figure 3.4a) and b) shows how the cameras were positioned in the car.

a) *b)*

Figure 3.4 Camera positioned in a) the window frame of the passenger seat, and b) under the driver seat.

Floor Mat

The floor mat was taped with measuring tape, to better see the position of the heel point of the driver's feet in the driver seat camera. Figure 3.5 a) shows what the pattern looked like. Each black or white square is one square centimeter. From this measurement system, the positioning of the drivers' feet could be determined approximately. Figure 3.5 b) shows the floor mat placed in the vehicle.

b) *b)*

Figure 3.5 a) Taped floor mat in, and b) the mat placed in the vehicle.

Seat

To measure the driver's seat adjustments, a software connected to the car's computer through a cable, translated electric signals in terms of engine pulses. The following data was collected: seat height, front height (front edge of seat cushion), cushion extend, slide (position forwards and backward), and seatback inclination.

Steering wheel
The steering wheel configuration was measured by positioning two rulers on the left side so that they covered the whole possible moveable span of the steering wheel, height, and depth as seen in Figure 3.6. The origin was chosen as the position highest up and furthest in, which also was marked with yellow lines, see Figure 3.7. This position was chosen since the steering wheel automatically went back to this position when not fastened.

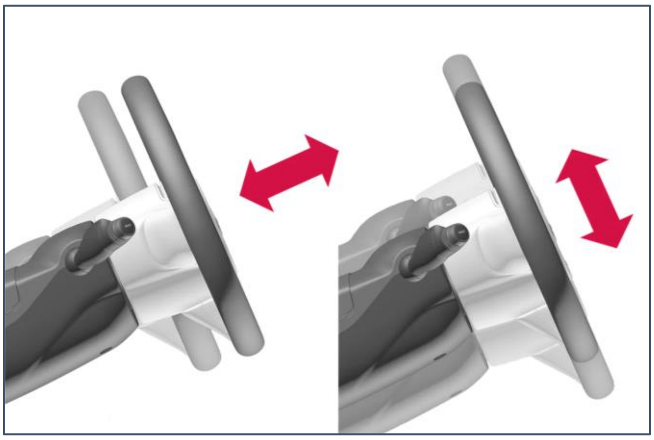


Figure 3.6 Possible steering wheel adjustment: depth and height.(Volvo Cars, 2020b).

Figure 3.7 Steering wheel measurement.

3.4.2 Test protocol and route

The test protocol was divided into four parts: a safety check of the vehicle, and activities before, during, and after the driver study. For each activity, it was stated who should execute what. The protocol was printed on paper and was followed for each test to ensure repeatability. The full test protocol can be found in Appendix C. In the following text, the most important parts of the protocol are presented, and decisions made regarding the test routine are argued for.

When the test subject arrived, the following steps were performed:

1. Test leaders informed about the study, how it would be conducted, and that it was voluntary and could be terminated at any time without having to explain why.
2. The route was shown to the participant.

3. Participant filled in a general data protection regulation consent form and a questionnaire on additional participant information.
4. Measured the test subject’s body to create the manikin in Xsens.
5. Attached the Xsens sensors to their different placements on the test subject’s body.
6. Calibrated the equipment in Xsens.
7. The participant got seated in the driver’s seat and adjusted seat and steering wheel to their preference.
8. One of the test leaders got seated on the second row of the vehicle behind the passenger’s seat.

Important aspects of the first part of the test were that the same test leader did the same task each time. However, the test leader in the vehicle (step 8) varied since it was tiresome for one person to do all the test drives.

The next parts were the actual driving and data collection. The experimental setup was designed so that the test subject was seated in the car from the start to get to know the car and achieve a comfortable situation before the data collection. It was also decided that the test leader and test subject should not communicate with each other during the data collection period, other than the test leader giving directions when needed, to achieve consistency between tests and to simulate naturalistic driving of the driver being alone in the vehicle. The participants had the option of listening to the radio during the drive, to feel more comfortable. A third experimental setup design aspect was that the test subject answered the questionnaire directly after each drive, while seated in the vehicle so that they had the experience in mind, to achieve more accurate answers.

The city drive started in a central part of Gothenburg and passed through many typical city related environments such as round abouts, crossings with a duty to give way, and crossings with bikes, trams, and pedestrians to. The speed limit was in general 50 km/h or lower. The steps in the first part of the driving were the following:

1. The test subject drove out of the Volvo area and parked just outside to answer the questionnaire about their experience of the initial seat position.
2. The test subject drove to Järntorget, the start of the city drive.
3. The test leader announced that the recording started, and no talking was allowed in the vehicle during the data collection. However, road directions were given verbally when needed.
4. The test subject drove from Järntorget to St1 gas station at Heden, see Figure 3.8, and the test leader collected data until Kungsportsavenyn, approximately a 10-minute drive.
5. The test subject answered a questionnaire about the experience from the city driving test while remaining seated in the vehicle.

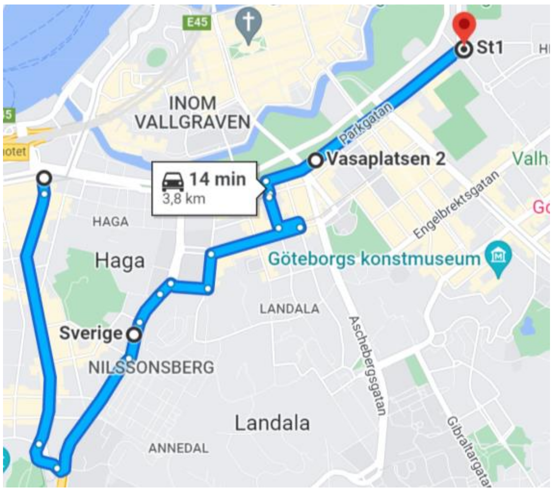


Figure 3.8 City route. Starting at Järntorget and finishing at ST1 at Heden.

The second part of the driving test was highway driving, and the third part was ACC driving. The execution was the same as for the city driving. From St1, the test subject drove onto road 40, and the recordings started at Delsjömotet and were ongoing for approximately 10 minutes until Landvetter Flygplatsmotet, see Figure 3.9. The ACC recording was the same route but in the opposite direction. The highway speed limit was 100-110 km/h, with two or three lanes. It was decided to perform all tests in the same order: city, highway, and ACC, for consistency of the test, making participants experience the same situations during the same time of the day, and to manage the set time frame.

Figure 3.9 Highway and ACC route. From Delsjömotet to Landvetter Flygplatsmotet.

3.4.3 Test subjects

The user study was conducted with 12 participants, all from Volvo Cars, of which 25 percent were women and 75 percent were men. Table 3.3 shows the distribution of the participants' stature. The represented percentile for women ranges from 42,07 to 96,89 regarding stature. The range for men's stature is from 3,05 to 97,11 (Hanson et al., 2009).

Table 3.3 Distribution of stature among participants

Gender	Stature [mm]
Female	1660
Female	1672
Male	1690
Male	1727
Male	1730
Male	1755
Female	1800
Male	1820
Male	1820
Male	1835
Male	1843
Male	1925

However, due to the participants being seated during the test they were selected to fit a normal distribution of a Swedish population based on sitting height, using data from Hansson et al., (2009). The participants sitting height distribution was analyzed in two steps in Minitab to check if it was normally distributed, in accordance with the selected database (Hanson et al., 2009). First, the p-value was calculated and compared to a significant level of 0.05. A p-value ≤ 0,05 means rejecting that the data follow a normal distribution, and values above state that there is no significant variation from the normality (Minitab Express Support, 2022). The p-value for sitting height was p=0.436, see Figure 3.10.

The mean value of the sitting height from the selected database for women was 892,09 mm and for men 944,16 mm (Hanson et al., 2009). The mean value of the sitting height for the participants was 922,00 mm, see Figure 3.10. Since this value is in between the mean value for women and men, it was seen as reasonable. With a mean value in accordance with the selected database and a p-value > 0,05, it was stated that there is no significant variation from normality.

Secondly, to confirm the normality, a visualization to see the fit of the normal distribution was made in a probability plot, see Figure 3.11. Since the data approximately follows along the straight line, a normal distribution could be assumed.

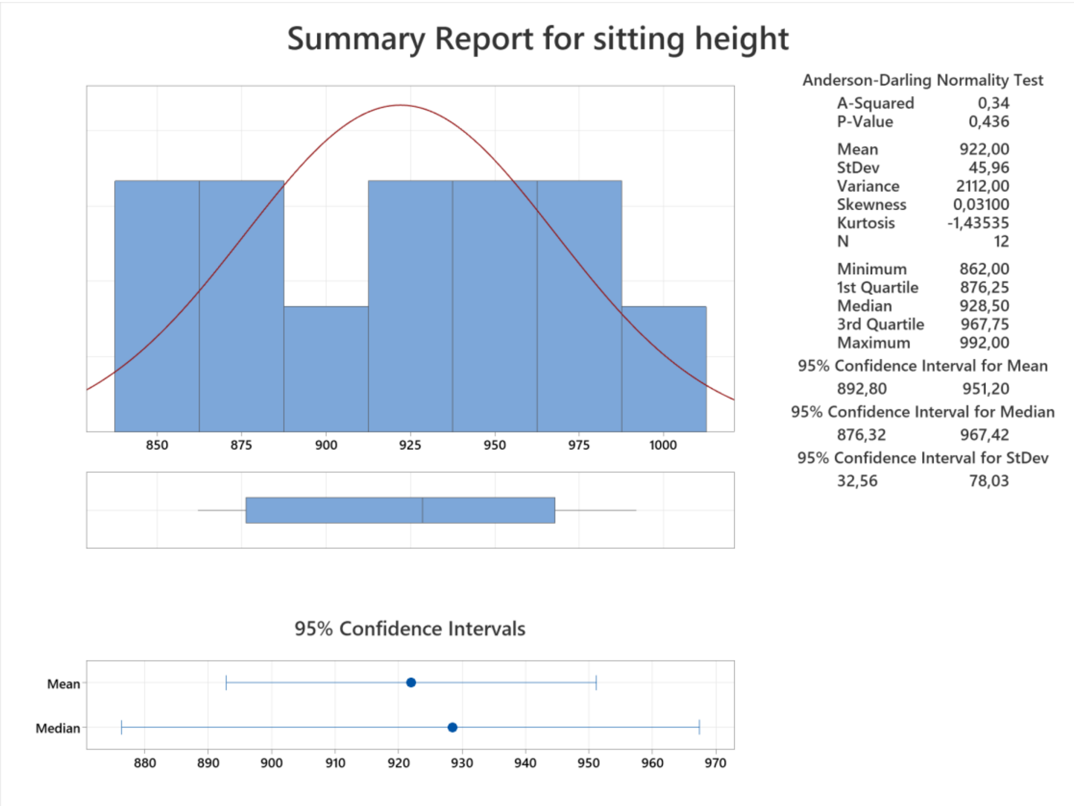


Figure 3.10 The participants' sitting height distribution

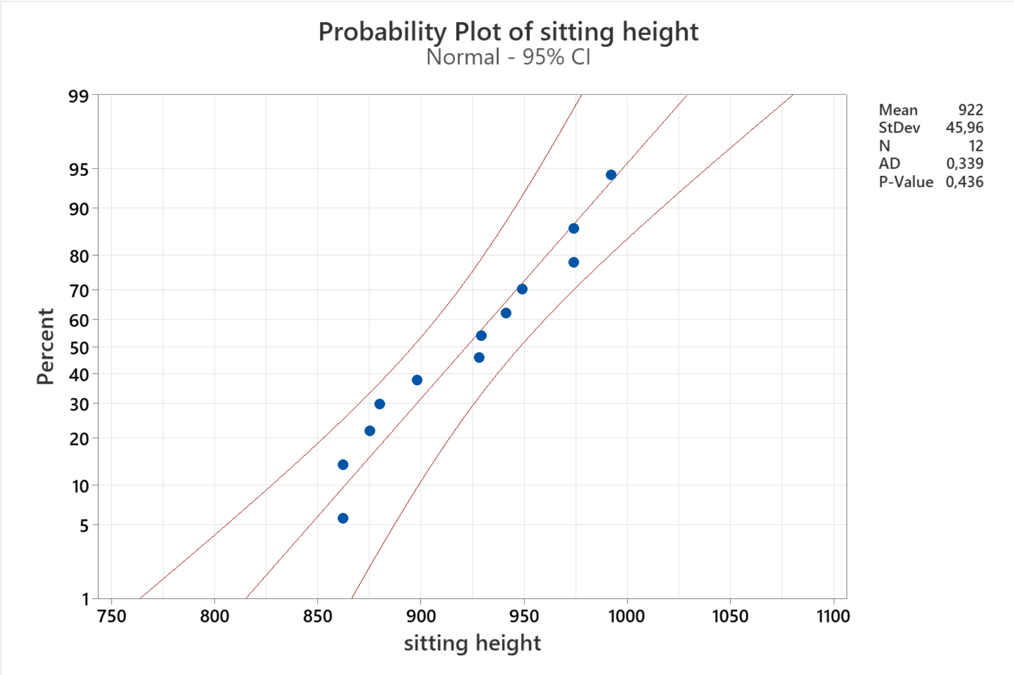


Figure 3.11 Probability plot visualizing the fit of the normal distribution.

3.5 Analysis

This section describes both the methods used for objective and subjective data analysis. The objective analysis focused on the visible movements and positions that was seen from the video recordings. The subjective analysis focused on eliciting the test subjects' subjective experience from the questionnaire answers. The analysis methods were chosen to answer the stated hypotheses described in Section 3.2.4.

3.5.1 Objective data analysis

This section gives a detailed explanation of how the objective analysis was conducted on hands, arms, feet, and posture regarding position and movement. The data was primarily analyzed by annotating from the video recordings, and secondarily by annotating in Xsens for confirmation. The methods used for analysis were based on categorization. Categorization is described as "a major component of qualitative data analysis by which investigators attempt to group patterns observed in the data into meaningful units or categories" (Given, 2008). The categories used were developed by the researchers, based on logical reasoning and through discussions with the supervisor.

Analysis of hand position and motion

An analysis of the hands position on the steering wheel was conducted to answer hypothesis *HR1.2 Both hands placed on the steering wheel to a larger extent* and *HR2.4 More hand motion when steering*. The analysis was based on video annotation and by categorizing the hands positions on the steering wheel. Figure 3.12 shows the categorization which divided the steering wheel in eight parts. In addition, a ninth category was included if the hands were off the steering wheel. The categories were simply called category 1 to 9. Annotation was done for the initial position and each minute, giving in total 11 data points for each test subject. The "base hand position" was considered in the analysis, meaning if the driver was turning the steering wheel in the minute of annotation, the position just after the turning was used as a data point. The left and right hand was coded with different symbols and each minute was coded with a color to understand how the driver had positioned their hands over time, see Figure 3.13.

Each driving situation, city, highway, and ACC was analyzed separately for each test subject. After eliciting all the data from the videos, analysis was performed. For each test subject and each situation, the following was observed: the number of categories that the subject placed their hands in, which categories, and number of changes of base position. What categories that were used indicated whether the driver kept both hands on the steering wheel, to answer hypothesis HR1.2. The number of categories used indicated how many positions the driver had used, and number of switches indicated how much the driver moved their hands. The median values were calculated and used as the unit of analysis to compare the situations. This gave an indication of how the driver moved the hands, answering hypothesis HR2.4. In addition, an analysis of in what situations and for how long the participants had their hands in category 9 was performed and summarized in text in a table.

In addition, to understand if there was a generalized behavior of positioning the hands on the steering wheel, a generalized position was elicited for each test subject, if possible, and summarized for all test subjects. As stated in Section 3.2.4, a generalization was defined as something that is shown in ≥ 50% of the cases in the user studies, and this number was also used for each test subject. Hence, if a person positioned their hands in the same way in at least six of the time frames, it was considered their generalized position. This was summarized for all 12 test persons.

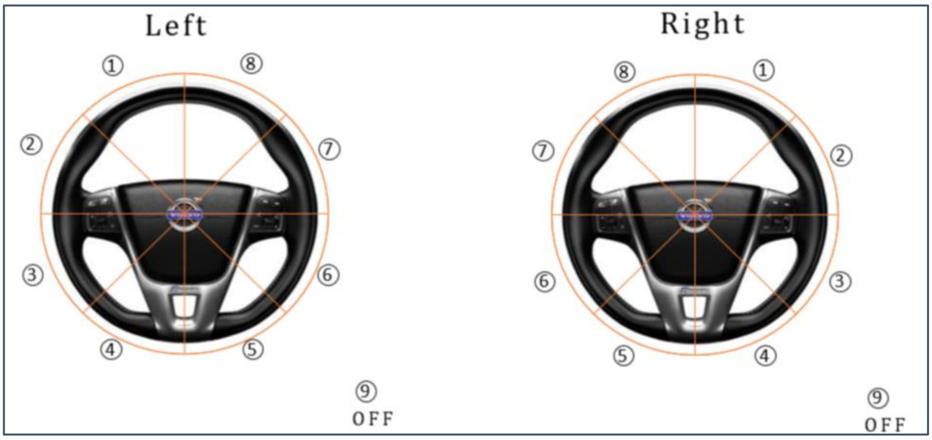


Figure 3.12 Categorization of steering wheel for left and right hand respectively.

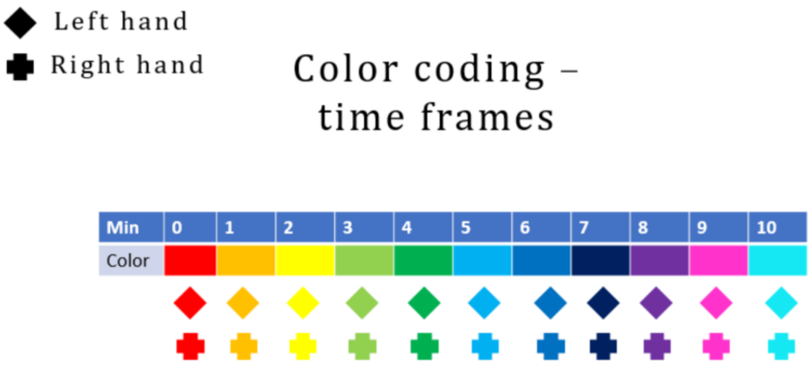


Figure 3.13 Color-coding for each annotation.

Analysis of arm position and behavior

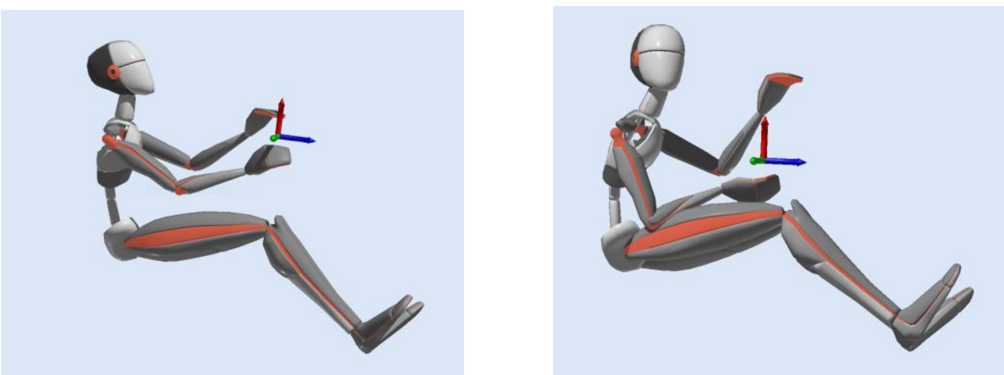
The analysis of the arms behavior and the use of armrests or knee as support was executed to answer hypothesis *HR1.1 Armrests will not be utilized to the same extent, HR1.8 Increased armrest use,* and *HR2.3 Arms will move more*. When analyzing the positioning of the arms, annotations from the video recordings were made. The annotation was performed by fast-forwarding each video of the participant and note down when a change occurred in the arm positioning. The information that was gathered was if the arm were positioned on the armrest or in the knee for left and right respectively to answer hypotheses HR1.1 and HR1.8. The number of times the arm was in this position, and the amount of time in seconds, was noted, to help answering hypotheses HR1.1, HR1.8 and HR2.3. The time was calculated as a percentage of the total recording for each participant and performed test, to overcome differences in recording time. The mean value of percentage was calculated to get the overall summarized result.

The data from all test subjects was inserted in an Excel document and then summarized to get an overview. From the data, it could be concluded which position that was most common for each situation, how many times the participants put the arm in that position and the mean time in seconds the armrest or knee was utilized. The resulting data was categorized to group the participants usage of armrest or knee in low frequency, mid-frequency, or high frequency. A low frequency of usage of either armrest or knee was defined as 1-3 times, mid-frequency as 4-6 times and high frequency as ≥ 7.

Analysis of upper body position and motion

Three hypotheses were stated regarding the upper body's position and body motion. In the city compared to highway and ACC, it was believed that *HR2.1 The driver's upper body will move in X-direction to a higher extent* and *HR2.2 The driver's upper body will move more frequently*. On ACC compared to highway, it was believed that there would be increased slouching, *HR1.7 Increased slouching.*

For city driving, annotation was done for all situations where the test subject made significant movements of their upper body. Any movement was easily detected by fast-forwarding the Xsens video and observing the manikin from the sagittal right plane. Figure 3.14 a) and b) shows an example of how an upper body movement could be detected. The same position was then identified in the video recording. A screenshot was taken of the posture and compared with the initial posture, as well as observing how the person moved and in what situation. These observations were noted down.



a) b)

Figure 3.14 Example of an upper body movement in Xsens where a) shows the initial position and b) a leaned forward position.

For highway and ACC, annotation was instead done every second minute, since it was expected that less motion would be present, and the aim was to see if the test subject over time changed position. In total, data from six frames, including time zero, was obtained for each person. This was done by taking a screenshot of the initial position from the highway and ACC recording respectively, and the other time frames. The pictures were placed on top of the initial frame and were made transparent. If changes in position were identified, the video was viewed to see when and what was changed. Two examples are shown in the figures below, where Figure 3.15

a) shows that the driver has changed from the initial position by changing the seatback angle, and Figure 3.15 b) shows that the driver has not changed position. The results were compiled in PowerPoint and summarized in a table.

a) b)

Figure 3.15 Posture analysis. Example of a) a change in seat back angle and b) no change.

Analysis of feet position and movements

The analysis of the feet, their movements and position were made to answer the following hypotheses:

- *HR1.3 Left foot will be on foot support*
- *HR1.4 Right foot heel point will be placed closer to the seat, and away from the accelerator pedal*
- *HR2.5 Feet will be more active and use pedals more frequently*
- *HR2.6 Less leg motion*
- *HR2.7 Larger leg movements when changing lower body position*
- *HR2.8 Feet will be less active and use pedals less frequently*

The analysis was made by annotating from the video recordings. Hypotheses HR2.6 and HR2.7 were estimated by examining the feet movement. Each video was watched in fast-forward, and when a change in position of the heel point, or movement of the feet was noticed, the video was paused. The change was noted in a PowerPoint document consisting of three pictures of the floor mat, one for each situation, see Figure 3.16. The numbers below each mat describes which position of the left and right foot that were positioned together.

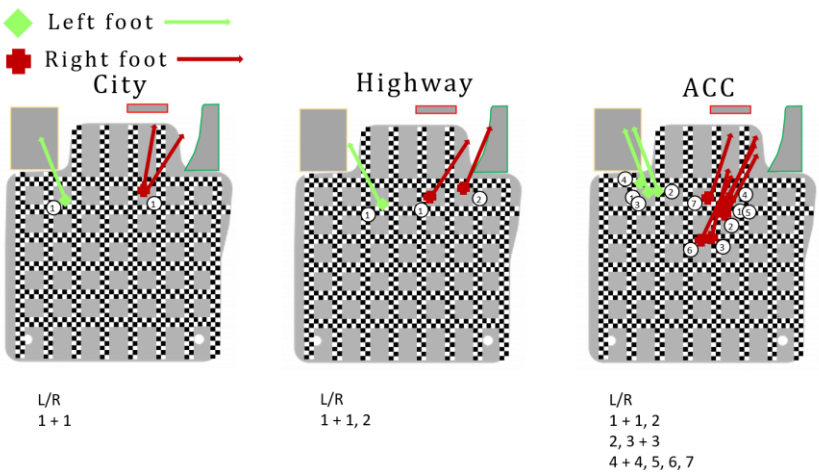


Figure 3.16 Floor mat analysis of feet position and movements for each situation.

Different symbols were used to represent left and right foot, and an arrow showed in which direction the feet were located. The number in a circle showed the order of the position. As seen on the right floor mat describing positions for ACC, there are numbers overlapping, for example, number 1 and 3 for the left foot. These were noted as the same position but another movement; in total 3 different positions, and 3 movements. Consequently, positions and movements were evaluated as two distinct parameters.

The data for each participant, number of positions and movements, were inserted in an Excel document for an overall visualization. The positioning data for the left foot was used to answer HR1.3, while the same for the right foot was used to answer HR1.4. From this information, conclusions could be drawn when looking at all participants together. Both movements and positioning were used together to answer HR2.5 and HR2.8.

The resulting data was categorized to group the participants positioning and movements of the feet in low frequency, mid-frequency, or high frequency. A low frequency of positioning was defined as 1-3 times, mid-frequency as 4-6 times and high frequency as ≥ 7 times. If a person only had the foot in one position, there were no movements, correspondingly low frequency of movements was defined as 0-2 times, mid-frequency as 3-5 times, and high frequency as ≥ 6 times.

When analyzing the preferred placement of the feet among all participants, city, highway, and ACC floor mats were placed together respectively to see if there existed differences or similarities. When similarities were found areas of the floor mat were marked to summarize the results.

Analysis of right knee angle

The analysis of the knee angle was made by looking at the feet positing to answer hypothesis *HR1.9 Right leg knee angle will be smaller*. By estimating if the right foot were placed closer to the seat during ACC driving than highway driving, it was possible to draw conclusions about the knee joint angle, however not the actual angle. This was made for all participants and then summarized.

Analysis of seat and steering wheel

The test subject’s seat configuration was extracted from the vehicle in pulses using a software and transformed in the previous mentioned Excel sheet, to calculate the seatback inclination angle and the x and z position of the H-point. The data was collected four times: for the initial position, after the city driving, after the highway driving, and after driving with ACC. The steering wheel measurement was taken in their initial position, and if the driver had changed the settings between drives.

The analysis considered three aspects. Firstly, to understand if the drivers changed seat configurations between different driving situations, and if so, how. For this, two categories were used, which were either change or no change of seat configuration. Secondly, to understand if the test persons could be representative of a whole population, in addition to the analysis of normal distribution. If all test persons were positioned at an extremity, that would not be particularly representative of a varying population. Thirdly, if the test subjects positioned themselves at any extremities, that could imply that they were limited by the seat, answering RQ four.

3.5.2 Subjective data analysis

The subjective analysis was made by looking at the answers obtained from the questionnaire. The analysis was made to answer RQ4 found in Section 3.2.4.

Since the questionnaire was made in Google Forms, pie charts and bar charts were created automatically. Some of the pie charts and bar charts could be used directly as indicators of the subjective perspective. The analysis of the NRS questions followed the guidelines from Svensson (2001). Svensson states that for NRS it is most appropriate to look at the median value, and use boxplots or bar charts, where the first was chosen for the analysis. If one response stood out from the rest and no comment was written, the participant was contacted afterward to get a better understanding of the answer.

3.5.3 Evaluation of Xsens as a method

Xsens was used to collect objective data on the test subject’s sitting posture and motion pattern. The method was evaluated and revised by investigating different ways of analysis possibilities in MATLAB. An additional final testing of Xsens as a measurement tool was included to perform the evaluation. It was performed as statical driving in a driving simulator. A ten-minute driving on highway and three-minute city driving was simulated, and Xsens data was collected using the vehicle scenario. Two tests were performed by each researcher.

3.6 Deliverables

This section describes the method for creating the deliverables that were done during the final stage of the project.

3.6.1 Development of requirements

A requirement list describing suggestions on implementations in IMMA was composed after analyzing the results, to help support the creation of realistic simulations. A requirement list should describe what functionality is needed, or what is to be done, but not how they are implemented (Paetsch et al., 2003). The requirement list was established by looking at the results individually, but also by attempting to find connections between the different analyzed units to get a fully realistic picture. Desired situations that should be available simulation options and behaviors, motion patterns, and postures that the manikin should realize were described, in terms relating to the software.

When creating a requirement list it is important to analyze the suggested requirements based on necessity (the need for the requirement), consistency (requirements should not be contradictory), completeness (no service or constraint is missing), and feasibility (requirements are feasible for the system development) (Paetsch et al., 2003). To understand these aspects better, the ADPOTIVE team and supervisors were consulted in the development of the requirement list.

4 Results

This chapter presents the results of the master's thesis project. Firstly, insights from the pre-study are shared, followed by the identified customer's needs, and findings from the pilot study. Thereafter, the results from the driver study, followed by a summary of the identified driver behaviors.

4.1 Pre-study

The pre-study, where a XC90, XC60, and V90 were tested, showed that there are experienced differences between the cars. A notifiable difference in height was felt between the V90 model and the XC models where in the first one, a more laid-back posture was experienced. The leg area was experienced wider with more space in the V90. It was also more comfortable to put the left arm on the door armrest in the V90. In the comparison made between the cars it was seen a lower sitting position for both researchers in the V90 car.

Figure 4.1 shows researcher one in the XC90, XC60 and V90 from left. The XC90 is represented in purple, the XC60 in blue and V90 in grey. In Figure 4.2 the comparison can be seen.

Figure 4.1 Researcher one in XC90, XC60, and V90.

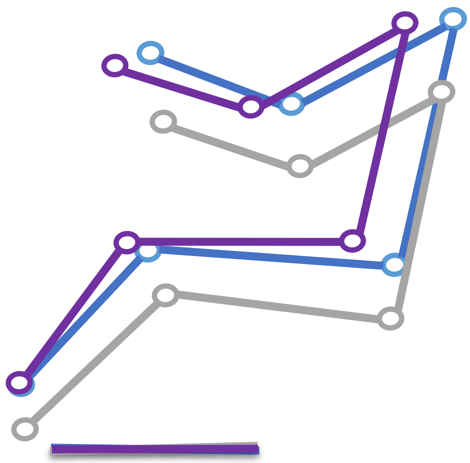


Figure 4.2 Stick figure comparison – researcher one.

For researcher two, XC90 is represented in orange, XC60 in green and V90 in yellow, seen in Figure 4.3. The analysis can be seen in Figure 4.4.

Figure 4.3 Researcher two in XC90, XC60, and V90.

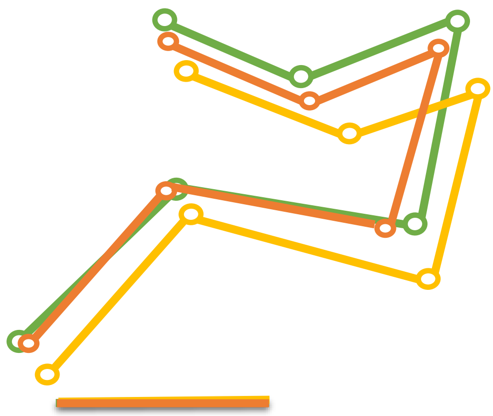


Figure 4.4 Stick figure comparison – researcher two.

The driver test performed by the researchers, showed differences in experience between situations in terms of position and motion pattern. In the city, a more active approach was adopted due to more obstacles during the driving, such as pedestrian crossings, red lights, more traffic, and trams, and the driver was more attentive in general. When driving on the highway, three different "levels" of behaviors was observed. During regular highway driving, both hands, arms, and the right foot were active but stayed statical in position. When turning on ACC, the next level, the feet were experienced as more relaxed and positioned towards the middle of the floor mat, with legs resting on the seat side bolsters. The last level was when turning on PA, where also arms, and hands could be relaxed to a higher extent.

The results from the pre-study helped the researcher to decide upon which situations should be tested and formulate hypotheses. It was decided to focus the research on city driving, highway driving, and highway driving with ACC, since the researchers' experienced differences in positioning and motion patterns between these situations, and it was most likely to find participants comfortable driving in these situations. Even though highway driving with PA was found to have an additional level of relaxation, the feature required much driving experience to generate a natural behavior and it was hard to predetermine the number of people that would have that experience. To make the study more viable it was excluded from further investigation.

4.2 Customer needs

A mission statement was made to visualize the goal for both the master's thesis and the ADOPTIVE project and to satisfy customers' needs. Table 4.1 presents the mission statement that paved the direction for the project. The scope of the mission statement was broader than the project scope, and the contribution from the master's thesis should be seen as a way of taking one step closer to the final goal of creating better and more realistic simulations.

Table 4.1 Mission statement for the ADOPTIVE project in the context of the master's thesis project.

Mission statement: ADOPTIVE development of IPS IMMA	
Product description	The product is a DHM software that can simulate a human's posture, movement pattern, and positioning in the front seat of a car, through a manikin. The simulation can be adjusted and adapted to different dynamic driving situations and tasks.
Benefit proposition	• Realistic human movements • Simulation for ergonomics • Cost-effective to simulate and test in early design phases of vehicle seats and interior
Key business goals	Serve as a simulation of a human's posture, movements, and positioning to make ergonomic improvements in the driver seat, in the early design stages.
Primary market	• Users of IPS IMMA in the field of vehicle ergonomics
Secondary market	• Users of IPS IMMA for all types of vehicle simulations
Assumptions and constraints	• Findings depends on an anthropometric population of Sweden, based on sitting height • Limited to the already existing features in IPS IMMA • Not considering differences between gender • Only considering a Volvo XC60 vehicle
Stakeholders	• Supervisors and the members of the ADOPTIVE project • Secondary users of the IPS IMMA software

4.3 P-diagram

The most important aspects of the driver study that the P-diagram highlighted were to perform the test in the same way each time, measure seat configurations, stay silent during the test to minimize the impact of the test leader, and to have the same conditions for each test. The P-diagram also made the researchers aware of uncontrollable parameters, such as the weather condition. The full P-diagram can be found in Appendix D.

4.4 Pilot study

This section presents results from the pilot study, the FMEA analysis, and evaluation regarding the data collection and the following analysis.

4.4.1 Process considerations

Five key aspects in the driver study were revised based on experience from the pilot study.

Improved structure and protocol

Time could be saved by fully preparing the equipment by mounting the sensors on the straps and connecting the computers to the equipment in the car before the arrival of the test subject.

Also, during the setup, both researchers helped to mount the sensors to speed up the process. A more structured protocol on what steps to perform by whom was written to ensure efficiency and consistency.

Questionnaire

The format of the questionnaire was revised. During the first two tests, a computer was brought in the car with the questionnaire in an Excel document. This resulted in four computers in the car which was a lot to manage for the test leader and a safety issue. It was also cumbersome to hand over a heavy computer to the driver. During the last test, a Google form questionnaire was created that the participant answered using a phone. This resulted in a smoother process and less equipment to manage.

Video camera

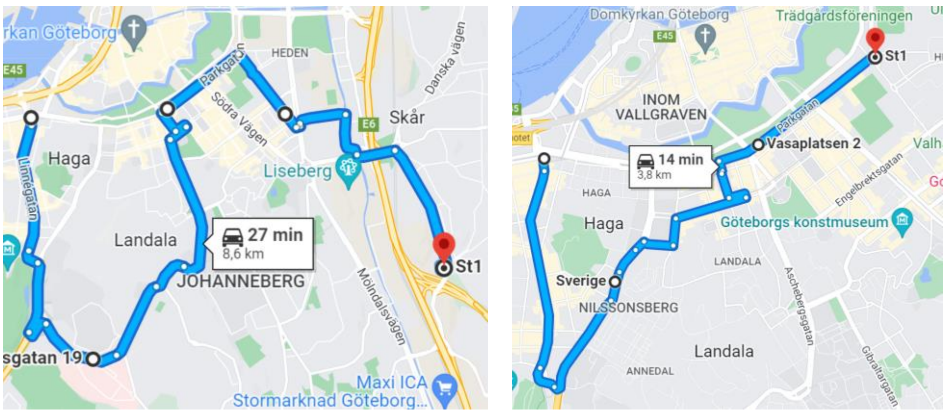
The top camera was placed on the grab handle to capture the legs movement. However, this did not work for very short test subject as their head blocked the camera. From a safety aspect, the camera could cause damage if it was not fastened enough. It was discussed if the camera should be placed elsewhere, however no good location was identified to fulfil the purposes. It was decided that the Xsens data would be sufficient to capture the same information, why the camera was removed. The video quality from the cameras was good, however, the frame from the foot camera was sometimes dark. Position markers placed on the floor mat during the driver study improved the visibility and allowed for easier annotation of the driver's feet position and motion. The video recording tool OBS Studio that was used worked well.

Adding property sensor to Xsens

It was decided to include the property sensor in the vehicle, which helped perform the analysis of the Xsens system.

Improved test route

The results during the first two tests showed that the initial route performance exceeded the set time frame of the test. The city route that originally went from Järntorget, past Sahlgrenska, Vasaplatsen, and ended up at St1 at Sankt Sigfridsgatan, see Figure 4.5 a), was redirected for the driver study to instead go from Järntorget, by Linné, Vasa and to St1 close to Old Ullevi, see Figure 4.5 b). This significantly decreased the duration and distance of the test from 8,6 km to 3,8 km. The highway route was also revised since a natural behavior were obtained already in a shorter distance. The different routes can be seen in Figure 4.6 where the distance changed from 20,5 km to 18,0 km. The new routes saved a lot of time for the complete driving and were decided as testing routes in the driver study.



a) *b)*

Figure 4.5 City routes showing a) initial route and b) redirected route. Time and distance estimations by Google maps

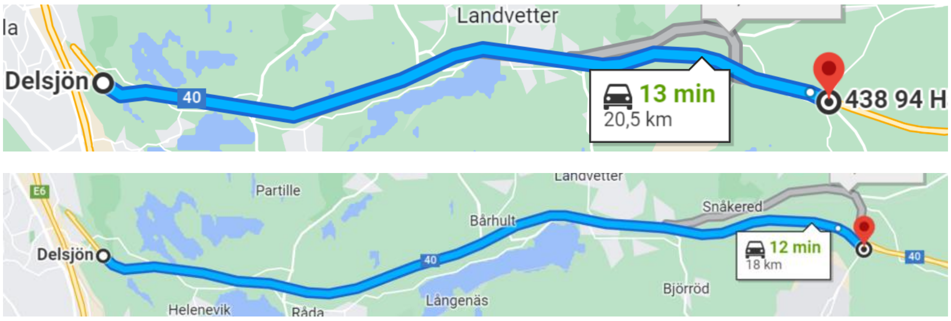


Figure 4.6 Highway routes, upper map showing first route and lower map showing new route. Time and distance estimations by Google maps.

4.4.2 FMEA considerations

The full output of the FMEA on the test process is presented in Appendix E. This section discusses the failure modes where a correction was needed, which was failure modes with a risk priority number of 50 or higher. The taken actions for each of the failure modes are presented next. The headings state the item considered, mode identification number, and failure cause.

Computer - Mode 2 – Runs out of battery

- Started the first test half an hour earlier than originally planned, both because the test took longer time than expected but also to get extra charging time between tests.
- Brought a 12 V charger in the vehicle to charge the computers during tests.
- Used Xsens and video cameras on the same computer if possible. With fewer computers the risk of forgetting to charge between tests was decreased, and the extra charger in the vehicle was only sufficient for one computer.

Xsens – Mode 5 – Poor calibration

- Gave clearly expressed instructions to the test subject on how to hold the N-pose properly to achieve better calibration.

Xsens – Mode 6 – Sensors move during test

- Put on the straps tighter where it was not perceived as uncomfortable (legs, and pelvis).
- Checked that the manikin looked proportional between tests. If not, a recalibration was performed.

Participant – Mode 9 – No-show

- Sent out a reminder to the participant the day before on email or text.

Test leader – Mode 17 – Absence

- Absence due to sickness could not be prevented among both participants and test leaders.
- Absence due to oversleeping was prevented by planning to arrive at least 30 minutes before the test.

Airbags – Mode 24 - Not protecting passengers properly due to equipment in vehicle

- Placed all equipment in a secure location, e.g., on the floor or in the trunk, or fastened properly to the vehicle using straps or similar.
- Top camera was removed as it was placed on the grab handle where it could potentially block the inflatable curtain on the side.

Test equipment – Mode 26 – Cameras blocking the sight

- Inserted a question in the test protocol, asking if the test subject has free sight out of the car, especially at the dead angle. If that was the case, move the camera to a new location.

Test equipment – Mode 27 – Equipment hits persons during hard break/crash

- Placed all equipment in a secure location, e.g., on the floor, or fastened properly to the vehicle using straps or similar. This was especially critical for heavy computers that could seriously injure passengers if the vehicle would overturn.

In addition to this, when performing the FMEA, many failure modes indicated a loss of data. Even though the total score was not that severe, due to immediate detection, actions were taken to prevent this. Transfer of data using an external hard drive was added to the testing protocol to ensure enough storage and not losing data. All recommended actions were considered and accounted for before the final testing.

4.5 Evaluation of Xsens

The data quality from the motion capture system varied in quality. For the first two test persons, the calibration seemed to work well, and the body parts did not seem to drift to any large extent when looking at the manikin in Xsens. However, during the last test, the body part's positions did not coincide with reality, although several recalibrations were made.

In MATLAB, the displacements position of the different segments was plotted in 3D space. However, the vehicle scenario that was used, captured the direction of the vehicle, which made the data points rotate, both around the z-axis when turning, the y-axis when tilting the car uphill or downhill, and around the x-axis. However, the x-axis rotation movements were too small to make a significant difference in the data. By utilizing the property sensor, the rotation of the car could be accounted for and removed from the data. An explanation of how the rotation was performed is explained in Appendix F.

Figure 4.7 shows the data from one of the test drives. All the scenarios were plotted together by colors according to the legend. It was observed that the data points for the feet were much lower positioned for both highway and ACC, compared to city, which was physically impossible as the feet could not move below the floor. Furthermore, no changes to the seat position were made during the drive.

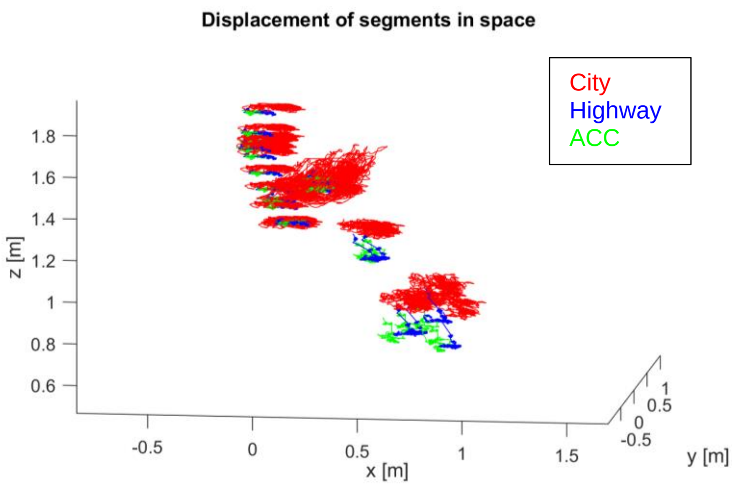


Figure 4.7 Data from all three scenarios: city, highway, and ACC rotated with respect to the pelvis.

When examining the videos from the two scenarios, the posture and position have merely changed. The Xsens manikin was extracted from the software from approximately the same frame as in the video. A simple comparison of the camera posture and the Xsens manikin's posture can be seen in Figure 4.8 a) from the city and in b) from the highway. The Xsens manikin in Figure 4.8 b) does not present reality. When analyzing the Xsens recording from the highway driving, it was observed that the manikin initially had a straighter pose, but during a timeframe of five seconds in the beginning, the manikin's posture shifted into the one seen in Figure 4.8 b), although this was not seen in the video recording. The results showed that the position and joint angle data from Xsens was not accurate or reliable.

a) *b)*

Figure 4.8 Comparison of posture in camera and Xsens from a) city and b) highway.

Furthermore, it was observed in all recordings from the driver study, that the manikin started drifting the longer the system was active, see Figure 4.9 a). For ACC the manikin was sometimes almost straight, in a lying position, which was contradictory to reality. The manikin also moved in positions that was very unnatural in the environment, which could not be seen on the video recordings. See Figure 4.9 b) for a lower body drift.

a) *b)*

Figure 4.9 Visualized drift in Xsens, a) with pictures from city, highway and ACC, and b) the lower body.

The errors that occurred in Xsens affected the analysis and the possible output that the project produced. It was not possible to use the data from Xsens as expected to investigate how specific joint angles changed or analyze slouching over time. Therefore, it was decided to discard the data output from Xsens and focus on annotating the camera video recording, and the Xsens manikin recording as a complement when needed.

4.5.1 Xsens statical driving test

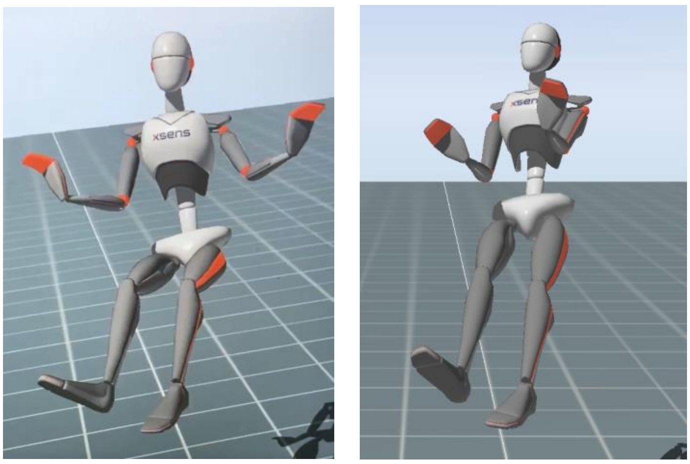
In the additional evaluation that was performed with Xsens, there were different conditions applied for the two researchers. In the first test with researcher one, the seat was reconfigured during the highway drive. For the second test with researcher two, the seat was not reconfigured during or between tests, and recalibration was performed between the driving situations. This was due to the researchers trying to imitate discovered findings and the Xsens manikin's behavior in the software.

Figure 4.10 a) and b) shows a comparison of the posture from the video recording and Xsens manikin posture, from highway for both tests where the hips have been placed to overlap. As seen, none of them correlates well with reality, especially considering the legs for the first test, and the whole posture for the second test. The results showed again, similar to the dynamic driving on the road, that the position or joint angle data from Xsens was not accurate.

a) b)

Figure 4.10 Comparison between initial video posture and Xsens manikin posture from the statical tests on highway, for a) researcher one and b) researcher two.

An issue found with the Xsens software was that during the recording it looked like the manikin or sensors had drifted, but when converting the file into HD quality these issues were gone. Figure 4.11 a) shows a drift of the arms during recording and Figure 4.11 b) shows the same time frame after processing and converting the video to HD quality. However, another issue that then appeared was a change in the knee joint angle, where the legs were almost straight after HD processing.



a) b)

Figure 4.11 Drifting in arms during final test, a) during recording and b) converted into HD quality.

4.6 Driver study

In the following section, the results from the driver study are presented from each analysis made.

4.6.1 Hand position and movement

Table 4.2 presents the result from the hand analysis. Number of categories used, and number of switches are presented in the median value. The results were approximate locations since it was sometimes difficult to find the exact location of the left hand because the right arm was blocking the sight. The result showed that in city compared to highway and ACC, the median number of categories used was three for both left and right hand, compared with two for both highway and ACC. The median number of switches was 6,0 for both left and right hand in city drive, and it was 1,5 and 3,0 for left and right respectively for highway, and 3,5 and 3,0 for ACC. These results implied that the hands do move more during city driving compared to highway and ACC.

Table 4.2 Number of categories and number of switches for each hand

	No. categories L	No. switches L	No. categories R	No. switches R
C, median	3,0	6,0	3,0	6,0
H, median	2,0	1,5	2,0	3,0
ACC, median	2,0	3,5	2,0	3,0

Table 4.3 shows the most common category used amongst participants for left and right hand, with the number of participants specified in the parenthesis. The three most common categories are shown for city, and two most common for highway and ACC to reflect the result above. It also shows the number of participants that has used category 9 (hands off the steering wheel) at least one time.

Table 4.3 Most common category and number of participants that had their hand in category 9 at least once.

	Most common categories L			No. in category 9 L	Most common category R			No. in category 9 R
C	2 (10)	3 (9)	1 (8)	4	3 (12)	2 (10)	1 (7)	4
H	2 (9)	3 (9)		2	2 (10)	3 (9)		3
ACC	2 (11)	3 (10)		2	2 (11)	3 (9)		3

Recall the categories numbering, shown in Figure 4.12, for the results from the generalized positioning. Figure 4.13 shows the result from the generalization of hand positioning on the steering wheel, summarized from the annotation for each person. Each color represents a test subject. The filled in markers shows generalizations, the unfilled markers show tendencies, and in cases where no generalization or tendency was identified the marker was placed above the steering wheel.

In accordance with Table 4.3, categories 2 and 3 were frequently used for all situations and were also many participants' generalized position. However, category 1 for the city drive was not seen as a generalization for any of the participants but was a tendency for one participant's right hand. However, quite contrary to Table 4.3, none of the participants had category 9 as a generalized position in the city, but in both highway and ACC.

Table 4.4 shows the summary of in what situations and for how long the participants used category 9. As seen, the drivers have their hands off for shorter periods, up to one minute, in the city compared to highway, where longer periods of over five minutes was observed at a few instances. Meaning that more participants used category nine in the city but for shorter periods.

To summarize, categories 3 and 2 were concluded to be the generalized used positions for all situations. Fewer people had their hands off the steering wheel on highway and ACC compared to city. However, the participants had their hands off for longer periods for highway and ACC. It was possible to generalize for all situations that drivers do not have their hands off the steering wheel.

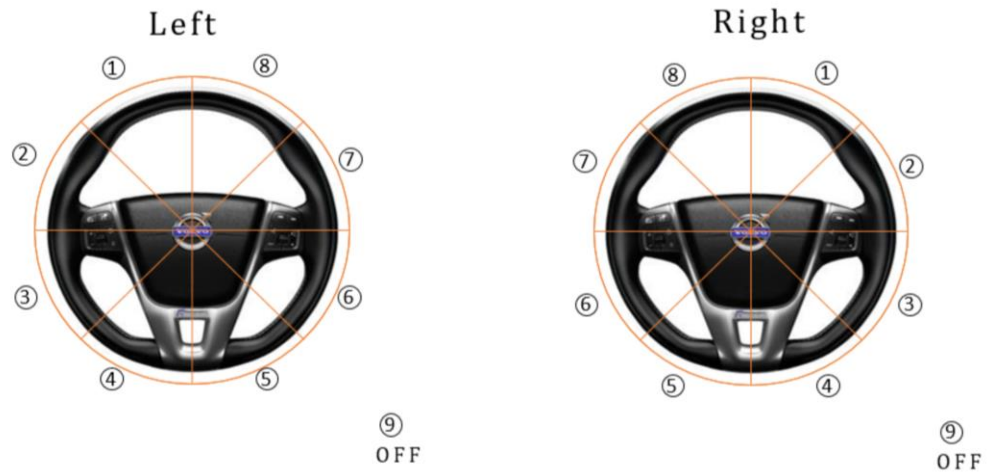


Figure 4.12 Categorization of steering wheel for left and right hand respectively

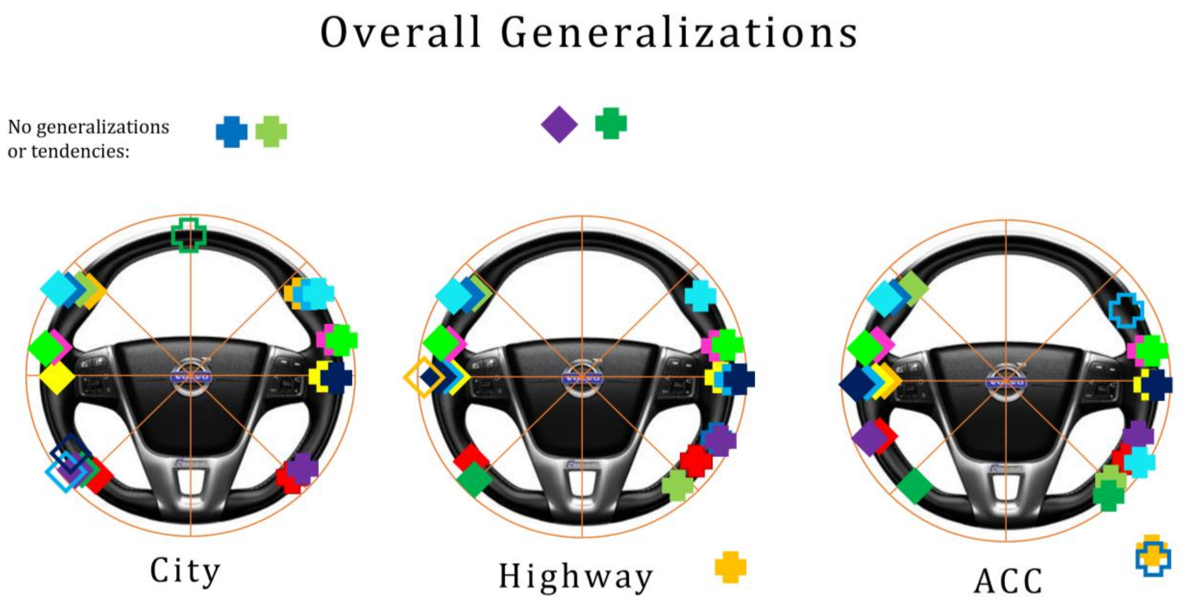


Figure 4.13 Generalized hand position for each test subject. Each color represents a test subject.

Table 4.4 Summary of hand behavior in category 9.

Description of hand in category 9			
TP	**City**	**Highway**	**ACC**
1	-	-	-
2	Had right hand off when driving straight, for shorter periods (< 1 min).	Had left hand off for longer periods (> 5 min).	Had left hand off for longer periods (> 5 min).
3	-	-	-
4	-	-	-
5	Alternated left and right hand, when driving straight and steering in crossings and a roundabout. Shorter periods (< 1 min).	Had left and right hand off, but not at the same time, for shorter periods (< 1 minute).	Had left and right hand off, but not at the same time, for shorter periods (< 1 minute).
6	Had left hand off when driving straight and steering in crossings, for shorter periods (< 1 min).	-	-
7	Alternated left and right hand, when driving and when stopping at red-light. For shorter periods (< 1 min).	Had left and right hand off, but not at the same time, for shorter periods (< 1 minute).	Had left and right hand off, but not at the same time. Mix of mid long periods (between 1-5 minutes) and shorter periods (< 1 minute).
8	Had both hands off during red lights and when stopping. Drove with hand at the bottom of the steering wheel with hand in knee and just a thumb on the steering wheel at periods.	-	-
9	-	-	Had left hand off once for approximately 10 seconds.
10	Had both hands off the steering wheel once when the car was waiting for traffic ahead.	-	-
11	-	-	-
12	-	-	-

Answering hypotheses regarding hands

The first hypothesis regarding the hand position and movement was *HR1.2 Both hands placed on the steering wheel to a larger extent* in the city compared to highway and ACC. The results showed that it was not possible to generalize such a behavior. There were indications that the position "hands off the steering wheel" was used by more drivers in the city. However, none of the drivers had it as their generalized position meaning that this position was kept mainly for shorter periods in the city. The hypothesis was therefore rejected.

The second hypothesis was *HR2.4 More hand motion when steering* in the city compared to highway and ACC. This hypothesis was true since the average number of switches between different positions was higher for city compared to highway and ACC, with five and three switches respectively on average.

4.6.2 Arm position and behavior

In Figure 4.14, a summary of the usage of arm supports among the participants can be seen. The chart was simplified for easier overview, showing the number of participants using each armrest for the respective situation. The results showed that for city, most participants used the left knee, the tunnel armrest, and the right knee. The highway and ACC driving showed very similar results, where only the door armrest is used to a high extent. The tunnel armrest is also used by many participants during ACC but not as much during highway. Considering the frequency level, recall the definition of the frequencies: a low frequency of usage of either armrest or knee was defined as 1-3 times, mid-frequency 4-6 times, and high frequency as ≥ 7. The full frequency analysis can be found in Appendix G. Significantly for city driving, was that there for all supports were one to four participants that used them with a high frequency. For example, four participants used the tunnel armrest in city driving with a high frequency from 9 up to 17 times. For the other situations, a high frequency usage only occurred during ACC driving when one participant used the left knee. Generally, the frequency of usage was more spread during city driving, whereas for both highway and ACC driving, a low frequency, was the prevalent category.

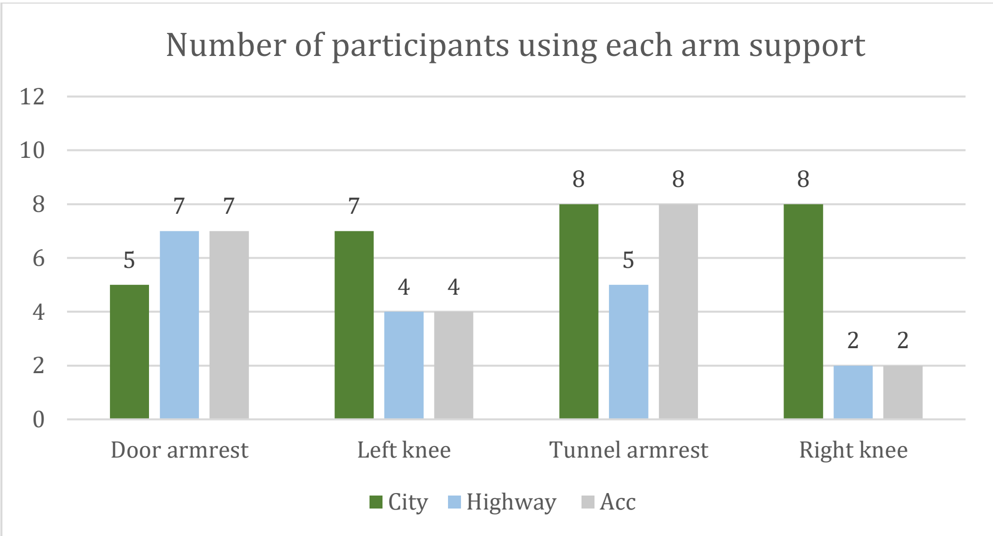


Figure 4.14 Summary of the number of participants using each arm support.

Mean percent values of the time using armrests or knee

The mean values in percentage for each situation among the participants that used the supports are shown in Figure 4.15. Each armrest was used to a higher extent, and similarly in time, during the ACC drive, with 60% for the door armrest and 64% for the tunnel armrest. During city drive, the door armrest was used for 54% and slightly less for the tunnel armrest with 33%. The usage was the opposite during the highway drive where the door armrest was used for 43% and the tunnel armrest for 60%. Both knees as support were scarcely used, with low values from 5 to 9%, except for the right knee during highway which was used 29% of the time.

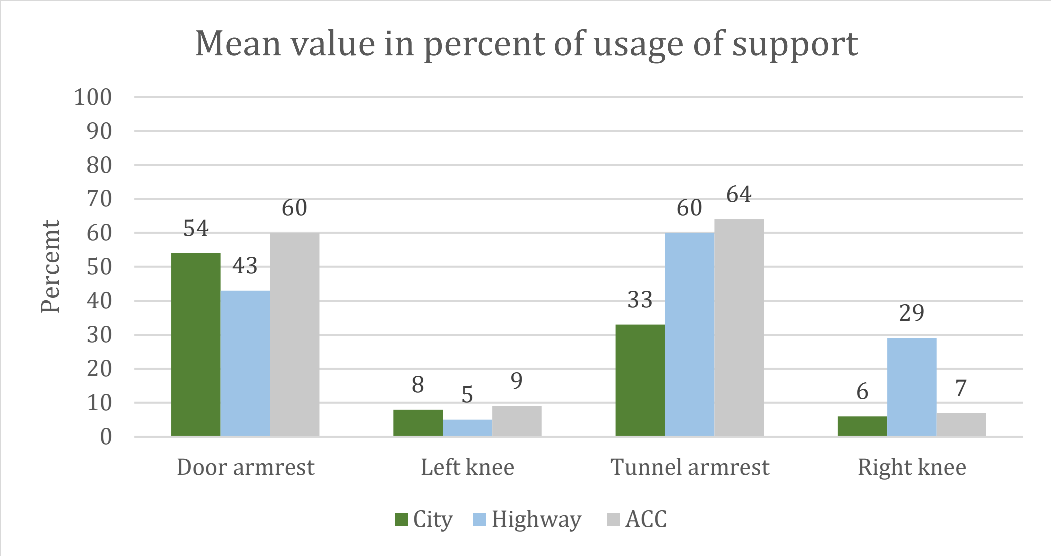


Figure 4.15 Mean values in percent among the participants using each arm support.

Answering hypotheses regarding arms

The first hypothesis stated about the arms was *HR1.1 Armrests will not be utilized to the same extent* in city compared to highway and ACC. This hypothesis was partly true. Regarding frequency, it was a generalized behavior that the door armrest was not used in the city, while it was generalized to be used in the highway and ACC situations, confirming the hypothesis. However, for the tunnel armrest, it was generalized to be used during both city and ACC driving but not during highway. When examining the result of the city driving, it was seen that five of the eight participants that used the tunnel armrest, used it with either mid- or high frequency, see Figure 4.16. Only two of the eight participants used it with mid- or high frequencies during ACC. This result therefore rejected the hypothesis. When the time aspect was included, it showed a somewhat different pattern. Among the seven participants that used the door armrest during highway driving, the average was lower than among the five participants that used it during the city drive, contradictory to the frequency result. It was used during the longest period during ACC. Opposingly the eight participant that used the tunnel armrest during the city driving, used it on average shorter period of times than the five participants that used it during highway driving. The tunnel armrest was also used the longest period during ACC. However, frequency and number of participants counts more for a generalized behavior.

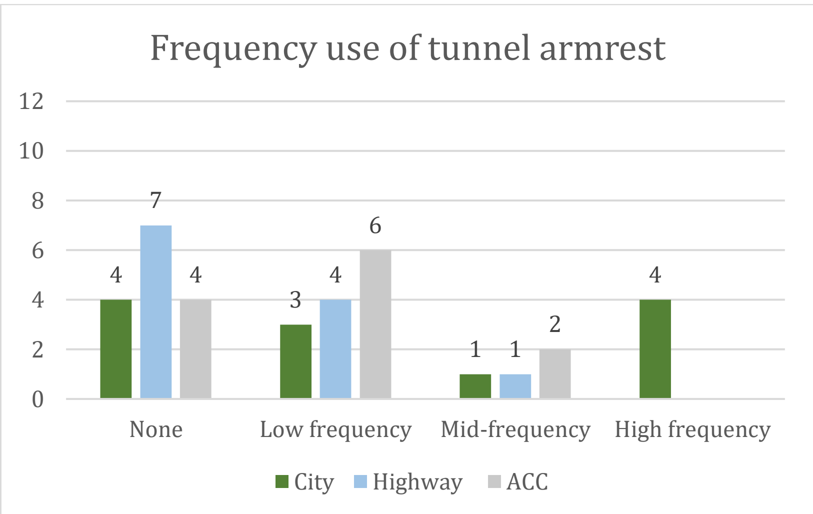


Figure 4.16 Frequency use of tunnel armrest

Hypothesis *HR2.3 Arms will move more* compared city with highway and ACC. Similarly, to HR1.1, the result was based on the frequency. The full frequency analysis can be seen in Appendix G. Even though some supports were generalized to be used more for highway and ACC, it was seen that for all four different supports, there were between 1 to 4 participants that used them with a high frequency in the city. A high frequency usage was only seen in one other situation, during ACC, with one participant using the left knee. However, there were not enough participants during the city situation within high frequency showing this behavior so that it was a generalized behavior, but it indicated more movements during city driving making the hypothesis true.

Hypothesis *HR1.8 Increased armrest use* compared ACC and highway. Figure 4.14 shows that the hypothesis was true. An equal number of participants used the door armrest, but the frequency was higher during ACC. The tunnel armrest is generalized to be used during ACC and not during highway driving. Both armrests were on average used for longer period of times among the participants using them during ACC compared to highway.

4.6.3 Upper body position and motion

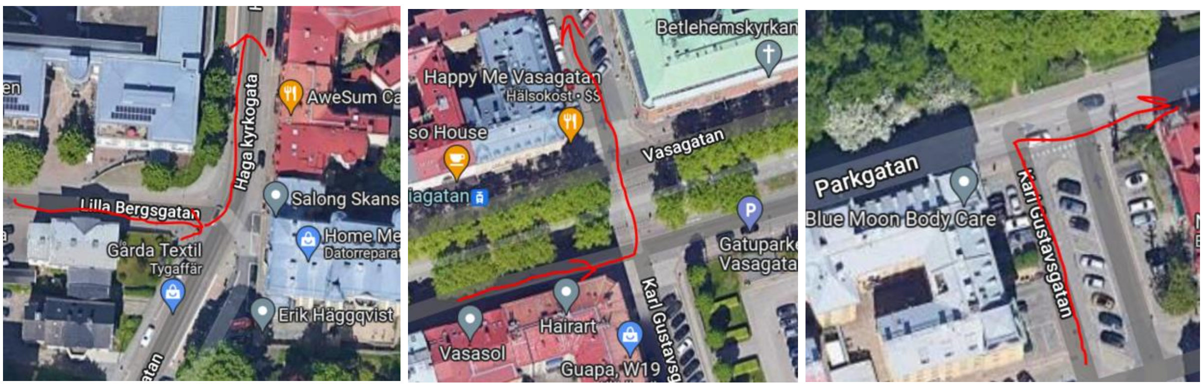
This section goes through the upper body position and motion patterns, starting with city, followed by highway and ACC.

City

Table 4.5 summarizes the notes and comments on the different motions and positions for each test person (TP). The last column also explains if the test person used any means when leaning forward such as the steering wheel or armrest. All drivers leaned forward at least once, but most leaned forward several times. This mainly occurred in three of the busiest crossings on the route. The first was when turning from Lilla Bergsgatan to Haga Kyrkogata, where the road was tilting upwards which gave poor visibility to the right, and there was a lot of traffic with vehicles and trams, see Figure 4.17 a). The second crossing was when turning across Vasa Allén, where a lot of pedestrians and bikes are crossing, see Figure 4.17 b). The third time was when turning to Parkgatan, see Figure 4.17 c). Street views of each crossing can be seen in Appendix H. Nine participants used the steering wheel to lean forward, by pulling themselves forward. An example is seen in Figure 4.18 a). Four used the middle armrest, see an example in Figure 4.18 b). One used the bolster cushion to lean forward. None of the drivers changed their seat configuration during the drive.

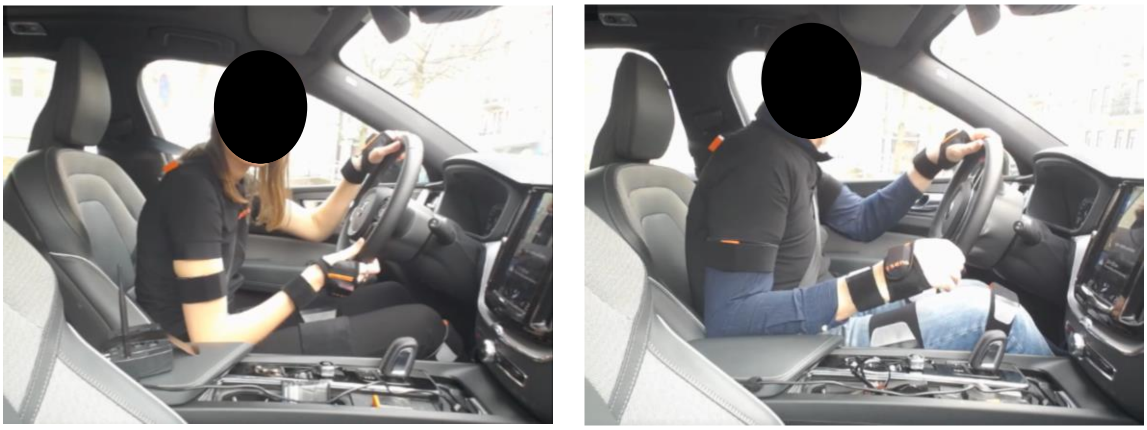
Table 4.5 City upper body movements and means used to lean forward.

TP	Notes/comments upper body movement	Means used to lean forward
1	Leaned body forward/to sides in busy crossings	Armrest
2	Leaned body forward/to sides in busy crossings and roundabout	Steering wheel
3	Leaned body forward/to sides in busy crossings	Nothing clearly
4	Leaned body forward/to sides many times for visibility. Also stayed in up-straight position, away from backrest, throughout crossings compared to other drivers. The person did also comment the need to change position for visibility in the questionnaire.	Mainly steering wheel, partly just leaning forward with body
5	Leaned body forward/to sides in busy crossings	Steering wheel and armrest
6	Leaned body forward/to sides in busy crossings	Mainly steering wheel, partly armrest
7	Leaned body forward/to sides in busy crossings. In Vasa Allén, also looking through the back left passengers window compared to where other drivers look.	Mainly armrest, partly steering wheel
8	Leaned body forward/to sides in busy crossings, but also in other situations for visibility, e.g., when switching lanes. The person also pushed back three times in the seat by "walking backwards" with their hips. The last time, the person did this and stayed up straight (back not in contact with seat) for a longer period, which coincide with the vehicle closing into a crossing.	Steering wheel
9	Leaned body forward/to sides in busy crossings	Steering wheel and bolster cushion
10	Leaned body forward/to sides in busy crossings	Steering wheel
11	Leaned body forward/to sides in busy crossings, leaned longer periods compared to others. Person sat further away from steering wheel than others.	Steering wheel
12	Leaned body forward/to sides in busy crossings	Steering wheel



a) *b)* *c)*

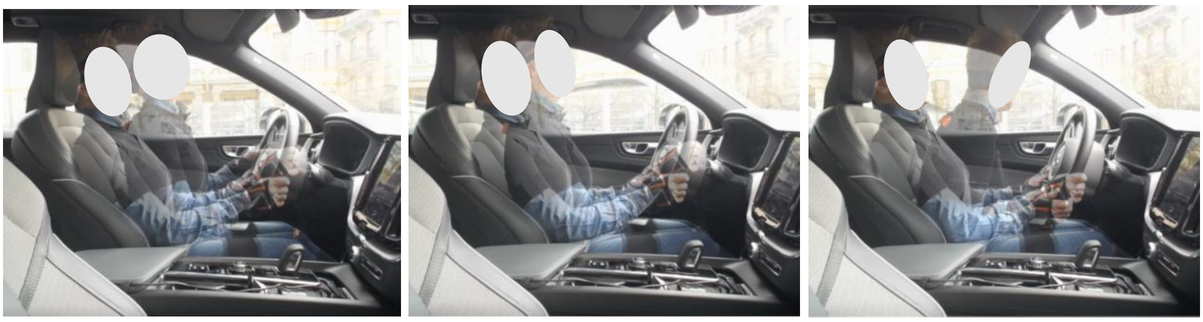
Figure 4.17 Crossings in the city where many drivers leaned forward for visibility: a) the crossing between Lilla Bergsgatan and Haga Kyrkogata, b)the crossing over Vasa Allén and c) when turning to Parkgatan.



a) b)

Figure 4.18 Drivers leaning forward on a) steering wheel and b) mainly on arm support.

Three of the drivers showed deviating behavior, with one aspect in common. They kept an up straight or leaned forward position much longer than others. Two of them also leaned forward in other situations than crossings where others did not. Finally, one person pushed back in the seat three times, to sit more up straight and looked out of the vehicle when doing so. In one instance, this was done while driving into the crossing at Parkgatan. This behavior is seen in Figure 4.19 a), b), and c).



a) b) c)

Figure 4.19 Deviating driver behavior, a) pushing body back at 9.22 min, b) standing up straight at 9.24 mint, and c) going into a crossing at 9.26 min.

Highway and ACC

Table 4.6 shows the summary of the analysis from highway and ACC. Unlike Table 4.5 for the city, Table 4.6only contains comments about the movement since no observation was made where the drivers used any means to change their position. However, other types of adjustments were observed. The result showed a generalized behavior of keeping the initial posture during the entire drive for both highway and ACC, with 75% and 83%. The few test subjects that made major changes in their posture, was either slouching or pushing back their bodies, by “walking” their hips back using their feet to change into a more comfortable position. Only one person changed seat backrest angle to an increased angle.

Table 4.6 Summary of changes in posture on highway and highway with ACC.

TP	Change Highway	Change ACC
1	None	None
2	Slouching	None
3	None	Change comfort position
4	None	None
5	None	Change comfort position
6	Changed seat back angle	None
7	None	None
8	Slouching	None
9	None	None
10	None	None
11	None	None
12	None	None

Answering the hypotheses regarding the upper body

The hypotheses regarding the upper body in city compared to highway and ACC were *HR2.1 The driver's upper body will move in X-direction to a higher extent* and *HR2.2 The driver's upper body will move more frequently*. The first hypothesis HR2.1 was true. When comparing the results from the situations, it was seen that in the city the test persons moved their upper bodies by leaning forward in X-direction and to sides during certain events, which was not observed for highway and ACC. The second hypothesis, HR2.2, was also true. In the city, the participants moved in certain events, such as crossings, and these events were more frequently seen in the city than on the highway, which then naturally led to more frequent movements in the city.

Regarding ACC compared to highway it was believed that there would be increased slouching, *HR1.7 Increased slouching*. This hypothesis was rejected since it was not observed a significant increased slouching between the two situations.

4.6.4 Feet position and movement

The results from the analysis of the feet are presented separately for positions and movements. The full analysis can be found in Appendix I. The categorization of the feet follows the described method in Section 3.5.1, with low frequency as 1-3 times, mid-frequency as 4-6 times, and high frequency ≥ 7. However, for movements, the categories shift with one value, with a low frequency of 0-2, mid-frequency 3-5, and high frequency ≥ 6.

As seen in Figure 4.20, showing the frequency of positions, and Figure 4.21, showing the frequency of movements, the dominant category for the feet in all situations was low frequency. However, a slight difference was seen during the ACC driving where there was a higher representation of both positions and movements in mid-frequency and high frequency compared to city and highway.

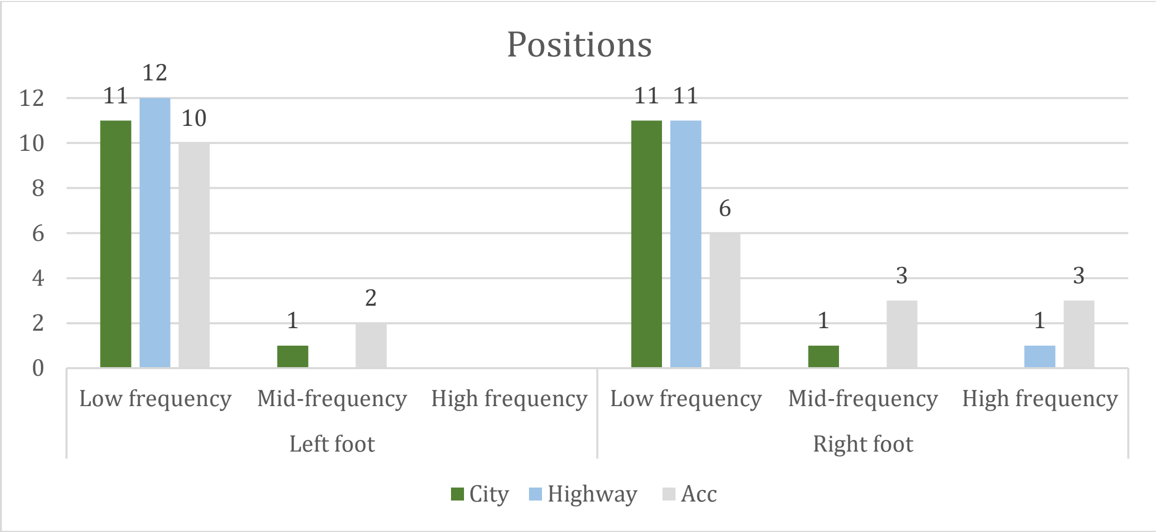


Figure 4.20 Frequency summary of positions

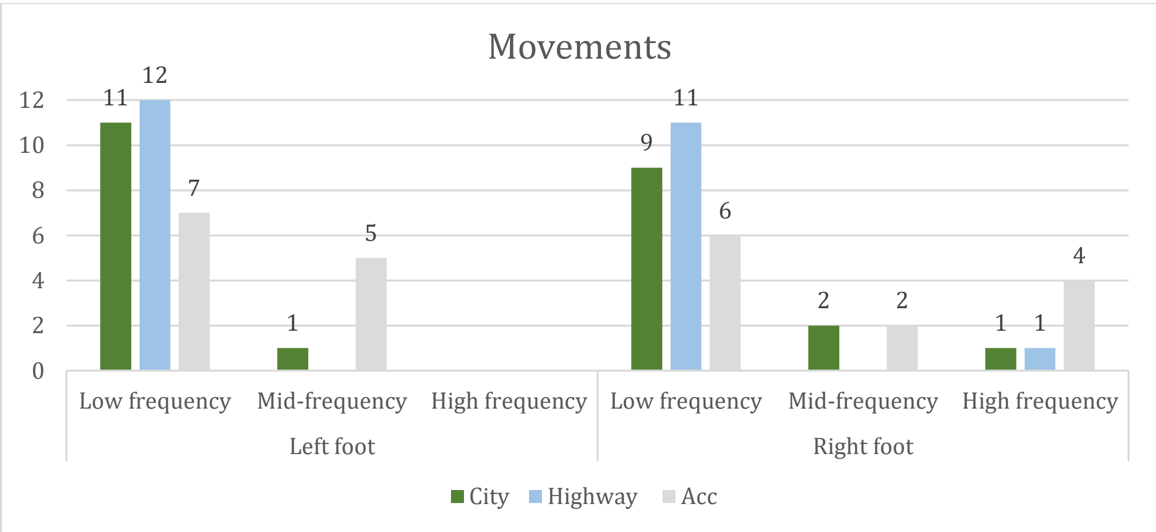


Figure 4.21 Frequency summary of movements

Placement of feet

The analysis of the placement resulted in feet patterns showed among the participants for the different situations. Different color blocks were defined on the floor mat to separate certain areas where people placed their feet more frequently, see Figure 4.22. A full analysis for each participant can be seen in Appendix J.

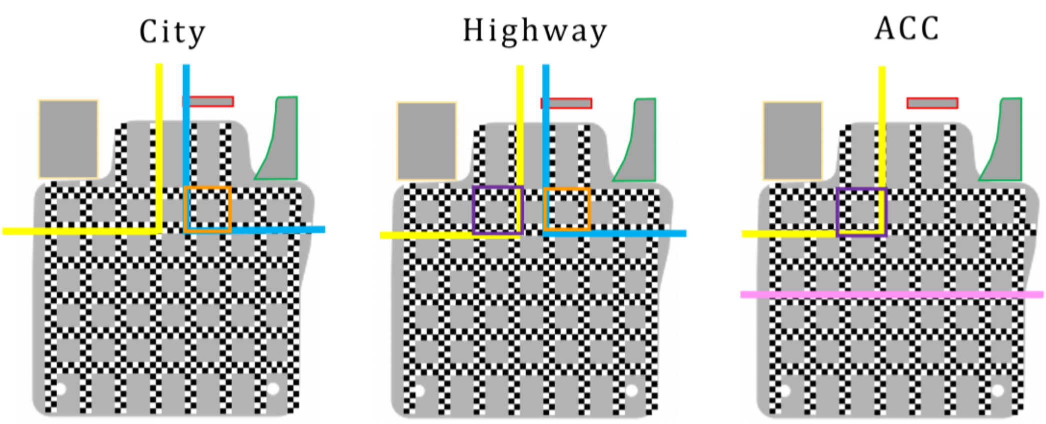


Figure 4.22 Color coding of feet placement for each situation

The yellow area was where the majority of the participants placed their left foot heel-point for all three situations. For highway and ACC, the preferred positioning was narrowed down to placing the left-heel point within the purple box. The footrest was also used during all situations by the majority. On the right floor mat there is a pink line marked. During ACC it was noticed that more participants chose to position the left foot below the line, compared to city and highway driving. However, not enough participants to find a generalized behavior.

The right foot was preferably placed within the blue area for both city and highway driving, and it could be observed that the right heel-point often appeared to a high extent in the orange box. Unlike city and highway, the right foot's placement varied more among the participants during ACC. A full overview of all the right heel-points represented can be seen in Figure 4.23. The purple circles mark the area of the placement of the right heel-point for all participants respectively. It was not possible to generalize a behavior, however, it was noticed that a larger number of the positions were along the turquoise line.

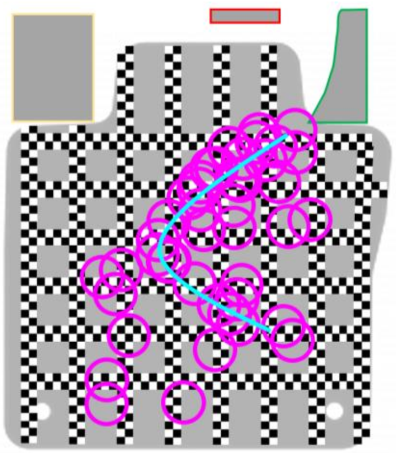


Figure 4.23 Right foot heel-point indications for ACC

Joint angles for knee

The results obtained by analyzing videos of the feet positioning, showed that five participants had the right knee more bent during ACC the whole time compared to highway driving, which was categorized as a tendency. When including having the right knee equally bent during ACC compared to highway, seven participants were represented, categorized as a generalization. For the other participants the majority of their positions of the right foot showed that the knee was more bent but had a larger variety.

Answering hypothesis regarding feet and knee

Hypotheses regarding the feet's positions and movements during city drive compared to highway and ACC was *HR1.3 Left foot will be on footrest* and *HR2.5 Feet will be more active and use pedals more frequently.* It was a generalized behavior to use the footrest for all three situations. HR1.3 was therefore rejected. Hypothesis, HR2.5 was partly true. For both feet a low frequency of positions was generalized for all situations. However, there were a higher number of participants during ACC that had the left foot in the mid-frequency category for both positions and movements compared to city and highway. A higher number of participants also had the right foot in the mid- and high frequency categories during ACC. Being more active during city was therefore partly rejected. However, switching between pedals was observed to a higher extent during the city drive where all twelve participants altered between the accelerator pedal and the brake. For highway this behavior only occurred among six of the participants and for ACC among two participants. This made HR2.5 partly true since the pedals were used more during city driving.

Hypotheses *HR1.4 Right foot heel point will be placed closer to the seat, and away from the accelerator pedal* and *HR1.6 Right leg knee angle will be smaller* compared ACC with highway driving. HR1.4 was confirmed as true since it was generalized that the heel-point was either equally or closer to the seat during ACC compared to highway. It was also a tendency to have the foot placed closer to the seat the whole drive. Hypothesis HR1.6 was true, using the same conclusion as above, even though exact knee joint angles were not measured.

The following hypotheses concerned motion patterns in the situation ACC compared to highway. Hypothesis *HR2.6 Less leg motion*, was rejected. As described for HR2.5 there were a higher number of participants that moved the feet with a mid- and high frequency during ACC than highway. Hypothesis *HR2.7 Larger leg movements when changing lower body position* was stated as true. The small amount of movements that occurred during highway, combined with the placement of the feet, compared to the same parameters during ACC, advocated that there were larger leg movements during ACC. As described previously the feet were more active but used the pedals less frequently during ACC compared to highway driving, making the *HR2.8 Feet will be less active and use pedals less frequently* partly true.

4.6.5 Seat and steering wheel configurations

Only two of the test subjects changed the seat configurations during the tests. The first person moved the seat slide further back, between initial position and the city driving, and the second changed the back inclination during highway driving by 1,6 degrees. Table 4.7 shows the calculated seat back angle, and if changed, the new angle. The angles are in sorted order with short and tall persons marked in yellow and green respectively.

Figure 4.24 illustrates the H-point distribution for the test subjects. The black lines visualize the travel box for the H-point, which was the available adjustment range in x and z coordinates for the seat configurations. As spread was seen among the participants in height, and no participants positioned themselves in the upper or front extremities.

Table 4.7 Seat back angle sorted in ascending order, with color-coding for short and tall persons,

TP	Initial seat back inclination angle [degrees]	Changed seat back inclination angle [degrees]
Short / Tall		
7	24,2	-
6	24,3	25,8
4	24,7	-
10	25,1	-
1	25,3	-
5	26,8	-
3	26,9	-
12	29,4	-
2	30,3	-
11	31,3	-
9	32,7	-
8	33,6	-

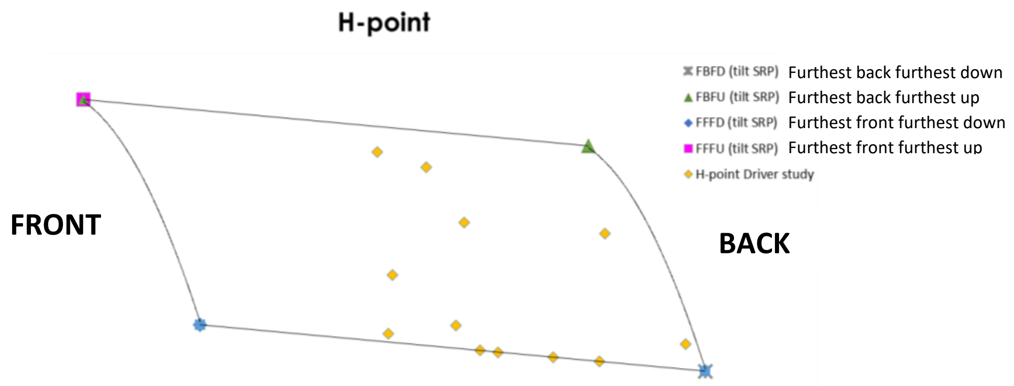


Figure 4.24 H-point for test subjects.

None of the participants changed the steering wheel from their initial configuration. The initial positions are summarized in Table 4.8 and visualized in Figure 4.25. The zero position was furthest up and furthest back for the steering wheel. The travel box for the steering wheel was not measured why the extremities were not known. The positions seen were the measured extremities.

Table 4.8 Steering wheel positions.

TP	Z [mm] (Vertical)	X [mm] (Horizontal)
1	4	10
2	25	40
3	5	4
4	10	55
5	10	58
6	21	55
7	19	56
8	30	50
9	15	37
10	14	32
11	28	54
12	3	8

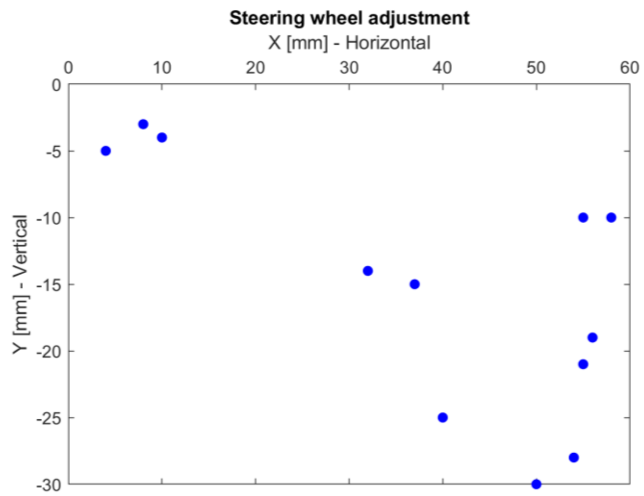
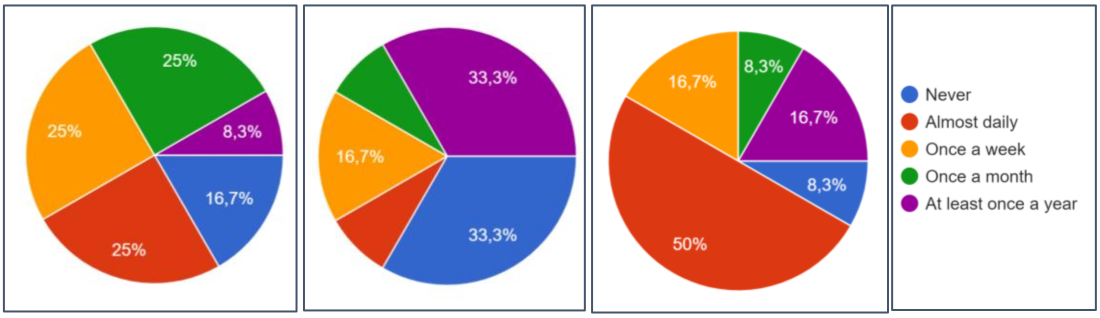


Figure 4.25 Steering wheel positions plotted.

4.6.6 Questionnaire results

The first part of the questionnaire collected additional information about the participants' driver habits. The first question concerned how often the participants drove in Gothenburg city. 50% of the participants were used to driving in the city, doing it daily or once in a week. 25% did it once in a month Figure 4.26 a) displays the full result. The second question asked how often the participants drove a Volvo XC60. A fewer amount was used to driving a XC60 where 25% did it daily or once in a week. Figure 4.26 b) displays the full result. Thirdly, 66,7% were used to driving with ACC, doing it every day or once a week. Figure 4.26 c) displays the full result.



a) *b)* *c)*

Figure 4.26 Distribution of answers of the participants' driver habits.

The second part of the questionnaire considered the participants' initial position. Most questions had the anchor "To a low extent" at zero, and the anchor "To a high extent" at 10 if nothing else is mentioned. All the participants adjusted the steering wheel to their satisfaction with answers ranging from 8-10, and a median of 10. The distribution of the answers can be seen in Figure 4.27. As seen in the figure, the adjustment of the seat showed a similar result with a median of 10 but with answers ranging within 7-10. The person rating a 7 commented that the lumbar support was uncomfortable. The participants felt that they had enough space for both head and legs/feet with a median of 9.5 and 10 respectively.

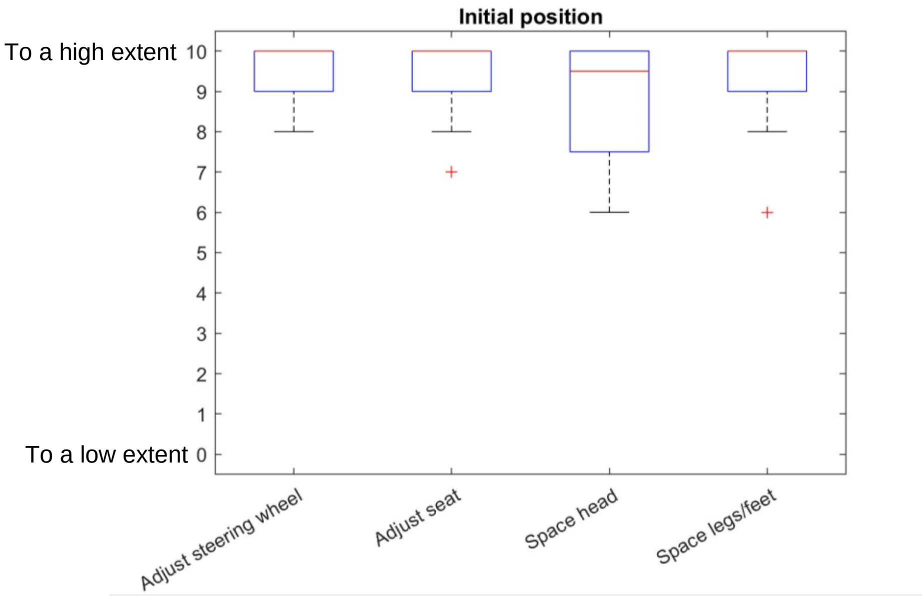
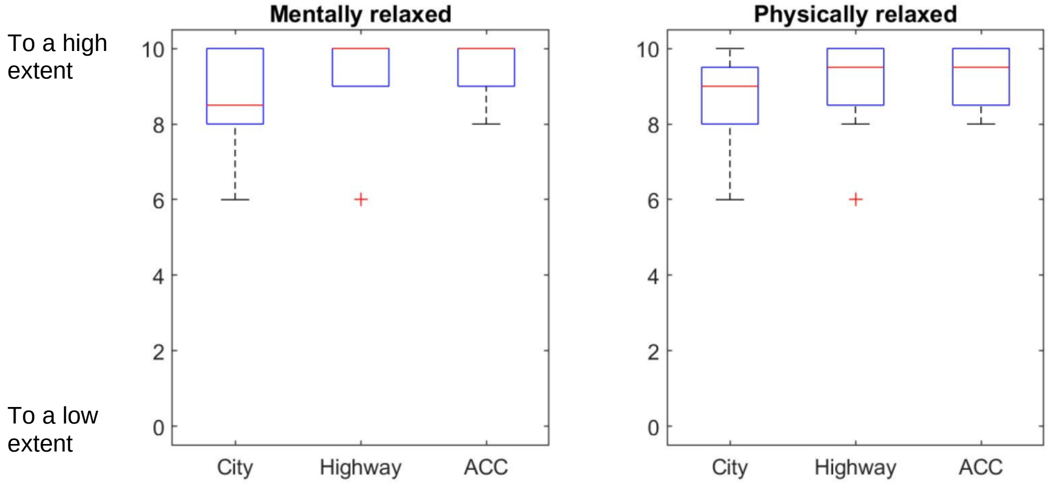


Figure 4.27. Distribution of answers for initial position.

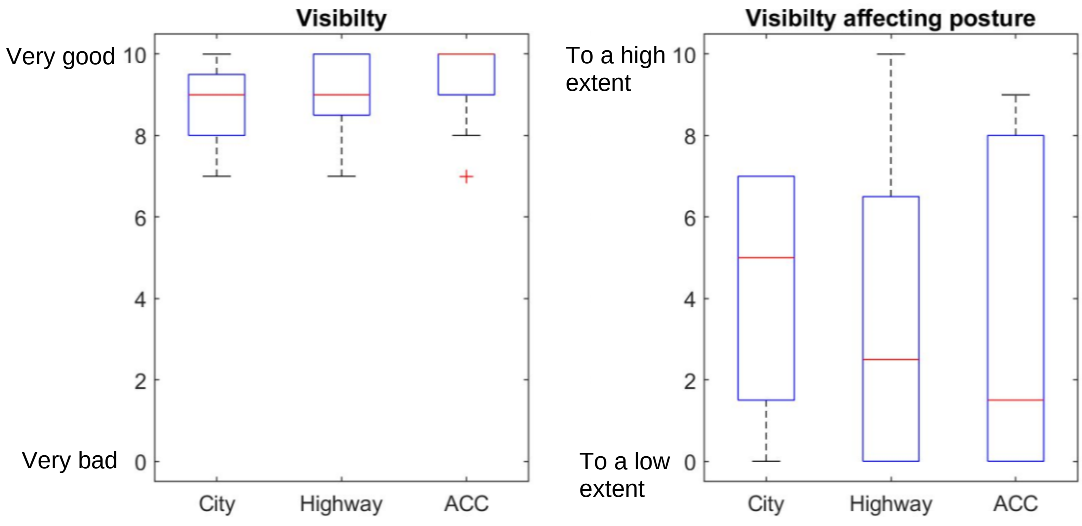
The third to fifth part of the questionnaire asked questions regarding the participants' experiences from the city, highway, and ACC driving. The participants felt more mentally relaxed during highway and ACC. The median for city, highway and ACC were 8.5, 10 and 10 respectively, see Figure 4.28 a). However, for highway there was an outlier at 6. An additional comment from one participant on the city route was that construction sites during the drive were distracting. Regarding being physically relaxed the answers did not differ significantly between situations. The medians were 9, 9.5 and 9.5, see Figure 4.28 b), again, with an outlier of the value 6 for highway. One participant commented that they felt the sensor in the back during the ACC driving.



a) b)

Figure 4.28 a) Mentally relaxed, and b) physically relaxed

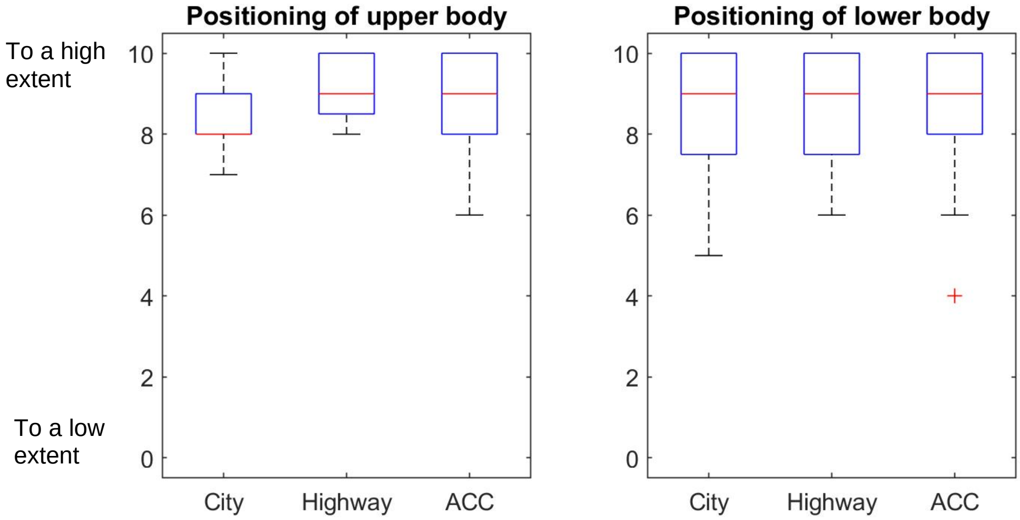
The visibility was experienced similarly for city, highway, and ACC with medians of 9, 9 and 10 respectively, see Figure 4.29 a). Two comments mentioned that the A-pillar was blocking the sight slightly during city driving. One similar comment was also mentioned for the two other situations. How the visibility affected the posture differed between the situations. A low value on the numerical scale meant that the visibility affected the posture to a low extent. For city the median was 5, with a range between 0 and 7. One person added an additional comment that they had to sit high, for all situations, to be able to see well. Another person commented that they needed to lean forward in crossings to have better view forward and to the sides. Median for highway was 2.5 with a range from 0 to 10. Lastly, median for ACC was 1.5 with a range from 0 to 9. The distribution for each situation can be seen in Figure 4.29 b).



a) b)

Figure 4.29 a) Visibility, and b) visibility affecting the posture

The question regarding if the participant were able to position the upper body (back, arms and hands) as wanted resulted in median values of 8, 9 and 9, with the biggest range for ACC from 6 to 10, see Figure 4.30 a). One additional comment during city and highway driving was that one participant felt that the side bolsters were in the way for the arm positioning, especially when keeping hands low on the steering wheel, but also a support at the same time. During ACC drive, one person felt that it was hard to find a comfortable and relaxed position for the arms. Another one said that the arm rest is too far back for its driving position. The participants rated the ability to position the lower body as wanted with a median of 9 for all the three scenarios, ranging from 5 to 10 for city, 6 to 10 for highway and 6 to 10 with an outlier at 4 for ACC, see Figure 4.30 b). One comment added that it would be good to have more space during ACC drive.



a) *b)*

Figure 4.30 a) Positioning of upper body, and b) positioning of lower body.

The overall sitting experience had a median of 9 for all situations. The range for each situation were 7 to 10 for city, 8 to 10 for highway and 8 to 10 for ACC, see Figure 4.31.

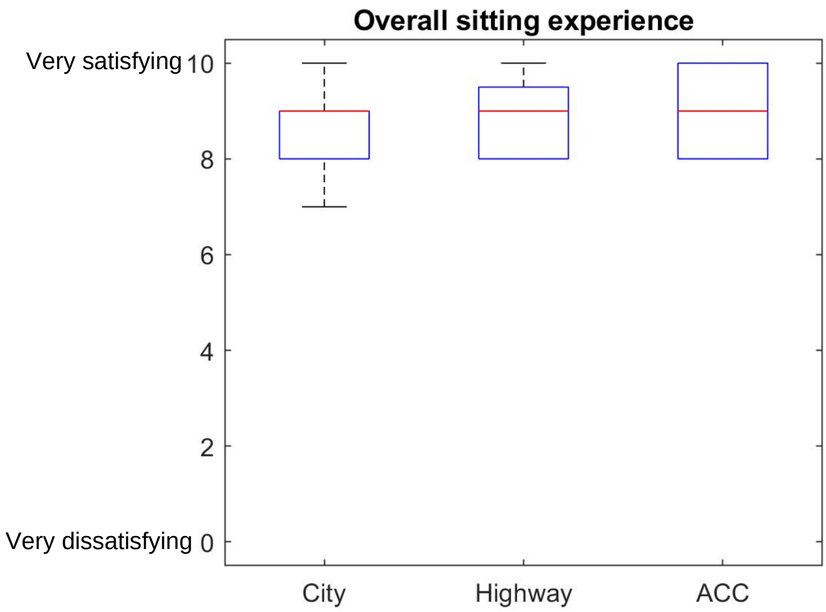


Figure 4.31 Overall sitting experience.

Table 4.9 summarizes all the additional comments made on the initial position, and the three driving situations, connected to each test person number.

Table 4.9 Summary of additional comments from initial position and the three driving situations.

TP	Initial	City	Highway	ACC
1				
2				
3				- The adaptative cruise control didn't leave enough space in front with the leading car in tight situations with trucks around
4		- I needed to lean forward from the backrest every time I was at a crossing and wanted to see better forward and to the sides		- Difficult to find comfortable and relaxed position for the arms
5				
6		- A-pillar blocks sight		
7		- Construction work distracted		
8	- Not OK remove lumbar support			
9		- A-pillar block sight a little - I sit high to get good vision - The bolsters on the sides are in the way for the arm position but at the same time a support	- A-pillar block sight a little - I sit high to get good vision - Side bolsters are in the way when I hold the steering wheel low but at the same time act as a support	- A-pillar block sight a little, but not that bad - I sit high to get good vision
10				
11				- More space for feet would be good
12				- I could feel the sensor on my back - Arm rest is a bit too far back for my driving position

In the final part of the questionnaire, the questions examined how the interaction with the equipment was perceived, and if the test subject were affected by the test leader in the vehicle. The majority were not affected in their driving by the Xsens equipment and video cameras. The median value was 1 and with an outlier with value 7, see Figure 4.32. Comments added was that one person would have leaned the head towards the head rest more if the sensor in the neck were not there. One person's hand got stuck several times with the Velcro tape on the thigh. Another person felt a tense position regarding the shoulders but could relax more when using ACC. Also, the back sensor was uncomfortable over time. How the equipment affected the posture were also to a low extent with a median of value 1 and a range from 0 to 3, see Figure 4.32. Only one person felt that the sensor in the back affected the posture.

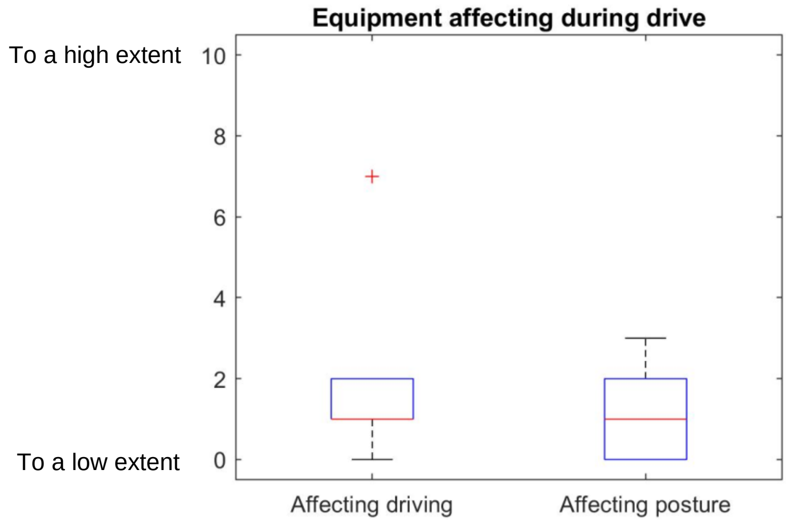


Figure 4.32 Boxplot of the results from question on equipment effecting during drive.

Six of the participants said that the presence of a test leader did not change their driving behavior. Three persons said that they would get more nervous, stressful, and lost without the test leader and that it was nice with the instructions during the drive. One felt a little bit nervous when the recordings started, and one mentioned that the speed would probably be faster in some areas. Two persons were not so familiar with the environment, and one was aware of it being an experiment making that person think about their driving in the beginning. The overall experience of the driving was described as “fun”, “really great”, “interesting and exciting”, “perfect”, and “very positive” and all participants answered that they would like to participate in a similar study again.

4.7 Summary of sitting postures and body movements

This section summarizes all sitting posture and body movement patterns discovered through the results. First, a summary of the representative behavior for each body part within the three different situations is presented in Table 4.10, Table 4.11, and Table 4.12. After the tables, a summary of identified differences and similarities together with explanatory figures to showcase some of the descriptions. Remember that a generalization was defined as something that showed in ≥ 50% of the cases in the user studies. A tendency was defined as something that showed in ≥ 40% to < 50% of the cases in the user studies.

Table 4.10 Descriptive summary of a city driver.

City driver	
Hands	• Moves both hands between three categories. Category 2 and 3 can be seen as generalized categories used, and category 1 as a tendency to use, see Figure 4.33. • Changes base position, between different categories, five times on average.
Body	• In certain event such as crossings, the upper body is leaning forward, and to sides, to get better visibility. Hips and buttocks remain in the same position. The driver is primarily leaning forward with the support of the steering wheel.
Left arm	***Door armrest use:*** • There is a generalization to not use the door armrest. • When the door armrest is used, it is during longer periods of time (54%). ***Use of knee as arm support:*** • The knee is generally used, but it is not possible to generalize or see a tendency of the frequency of usage. The most used frequency is low frequency. There is a tendency to not use the knee. • The knee is used during shorter periods of time (8%).
Right arm	***Tunnel armrest use:*** • The tunnel armrest is generally used, but it is not possible to generalize or see a tendency of the frequency of usage. The most used frequency is high frequency. • The tunnel armrest is used for medium long period of time (33%). ***Use of knee as arm support:*** • The knee is generally used and there is a tendency to use the knee in low frequencies. • Knee is used during shorter periods of time (6%).
Left foot	***Position:*** • There is a generalization of low frequency of positions. There is a generalization for exactly one position. ***Movement:*** • There is a generalization of low frequency of movements. There is a generalization for exactly zero movements. ***Placement:*** • There is a generalization to place the foot within the yellow area, see Figure 4.34. • There is a generalization to use the footrest
Right foot	***Position:*** • There is a generalization of low frequency of positions. There is a tendency of exactly two positions. ***Movement:*** • There is a generalization of low frequency of movements. ***Placement:*** • There is a generalization to place the foot within the blue area, see Figure 4.34. There is a tendency to place the foot within the orange box the whole drive.
Seat	• The driver is not changing seat configurations

Table 4.11 Descriptive summary of a highway driver.

Highway driver	
Hands	• Moves both hands between two categories. Category 2 and 3 can be seen as generalized categories used. • Changes base position, between different categories, two times.
Body	• Upper body posture remains constant from initial position
Left arm	***Door armrest use:*** • There is a generalization to use the door armrest in a low frequency. There is a tendency to not use the armrest. • The door armrest is used during longer periods of time (43%). ***Use of knee as arm support:*** • There is a generalization to not use the knee. • When the knee is used, it is used in shorter periods of time (5%).
Right arm	***Tunnel armrest use:*** • There is a generalization to not use the tunnel armrest. • When the tunnel armrest is used, it is used during longer periods of time (60%). ***Use of knee as arm support:*** • There is a generalization to not use the knee. • When the knee is used it is used for a medium long period of time (29%).
Left foot	***Position:*** • There is a generalization of low frequency of positions. There is a generalization for exactly one position. ***Movement:*** • There is a generalization of low frequency of movements. There is a generalization for exactly zero movements. ***Placement:*** • There is a generalization to place the foot within the purple box. • There is a generalization to use the footrest
Right foot	***Position:*** • There is a generalization of low frequency of positions. There is a generalization for exactly one position. There is a tendency for exactly two positions. ***Movement:*** • There is a generalization of low frequency of movements. There is a generalization for exactly zero positions. There is a tendency for exactly one position. ***Placement:*** • There is a generalization to place the foot within the blue area. There is a tendency to place the foot within the orange box.
Seat	• The driver is not changing seat configurations

Table 4.12 Descriptive summary of an ACC driver.

Highway with ACC driver	
Hands	• Moves both hands between two categories. Category 2 and 3 can be seen as generalized categories used. • Changes base position, between different categories, two times
Body	• Upper body posture remains constant from initial position
Left arm	***Door armrest use:*** • There is a generalization to use the door armrest in a low frequency. There is a tendency to not use the door armrest. • The door armrest is used during longer periods of time (60%). ***Use of knee as arm support:*** • There is a generalization to not use the knee. • When the knee is used, it is used during shorter periods of time (9%).
Right arm	***Tunnel armrest use:*** • There is a generalization to use the tunnel armrest in a low frequency. • The tunnel armrest is used during longer periods of time (64%). ***Use of knee as arm support:*** • There is a generalization to not use the knee. • When the knee is used, it is used during shorter periods of time (7%).
Left foot	***Position:*** • There is a generalization of low frequency of positions. There is a tendency for exactly one position. ***Movement:*** • There is a generalization of low frequency of movements. There is a tendency for exactly zero movements. There is a tendency for mid-frequency of movements. ***Placement:*** • There is a generalization to place the foot within the yellow area. There is a tendency to place the foot in the purple box. • There is a generalization to use the footrest
Right foot	***Position:*** • There is a generalization of low frequency of positions. ***Movement:*** • There is a generalization of low frequency of movements ***Placement:*** • No generalization of area. A lot of placements along turquoise line, see Figure 4.34.
Knee angle	• There is a generalization to have the knee more or equally bent to highway. There is a tendency to have the knee more bent than highway whole drive.
Seat	• The driver is not changing seat configurations

Similarities among all three situations
The similarities between the three driving situations were that all drivers had their hands placed in category 2 and 3 as a generalization, seen in Figure 4.33. The hip point and buttocks did not move significantly for any of the situations. Both feet had a low frequency of positions and movements as generalization. For the left foot the yellow area was a generalized placement, whereas for highway and ACC it was further narrowed down to the purple box within the yellow area, see Figure 4.34 which shows a CAD visualization of the XC60 in IMMA. For the right foot, similarities were seen between city and highway where it was placed in the blue area and preferably in the orange box, see Figure 4.34.

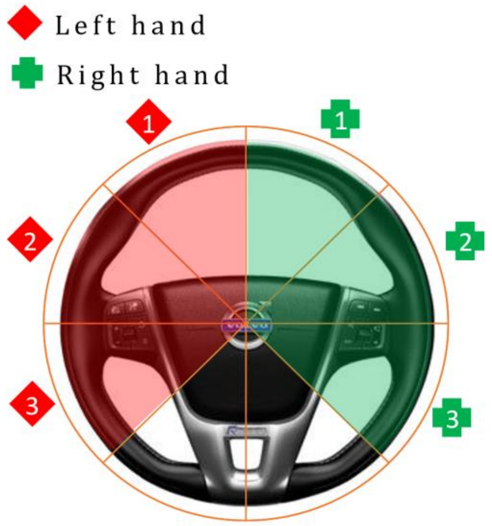


Figure 4.33 Most used categories, showing left hand position in red and right in green.

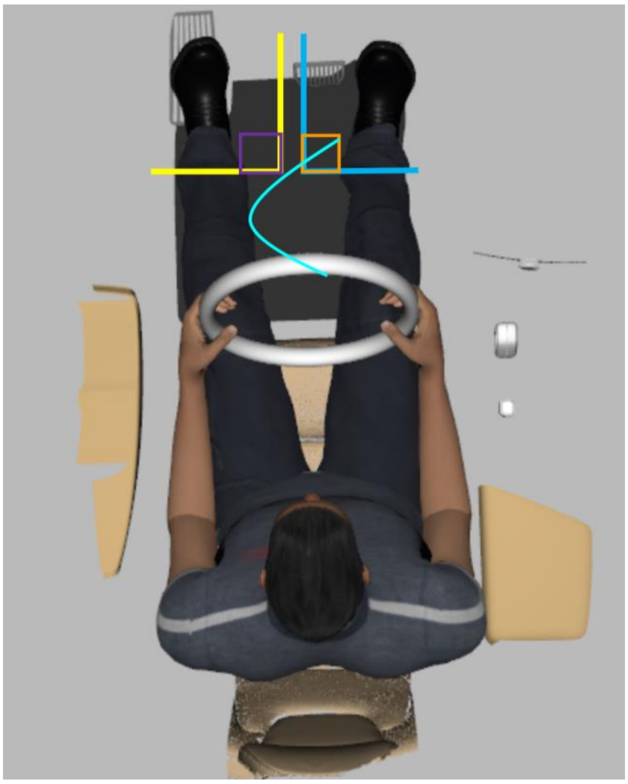


Figure 4.34 Visualization of the feet position from a top view of a driver in IMMA. The left foot heel point is in the yellow area for city and in the purple box for highway and ACC. The right foot heel point is in the blue area for city and highway and preferably in the orange box. For ACC a lot of positions along the turquoise line.

Similarities between highway and ACC only

The similarities between highway and ACC specifically, were that the upper body remained still and that the door armrest was used whereas the left knee was not used, see Figure 4.35.

Differences between the three situations

The differences showing was that the hands moved more between positions in the city than they did on highway and ACC. The upper body leaned forward in certain events with obstacles in the city where it remained still for the other two situations. The left door armrest was generalized to not be used in the city while the opposite in highway and ACC, see Figure 4.35.

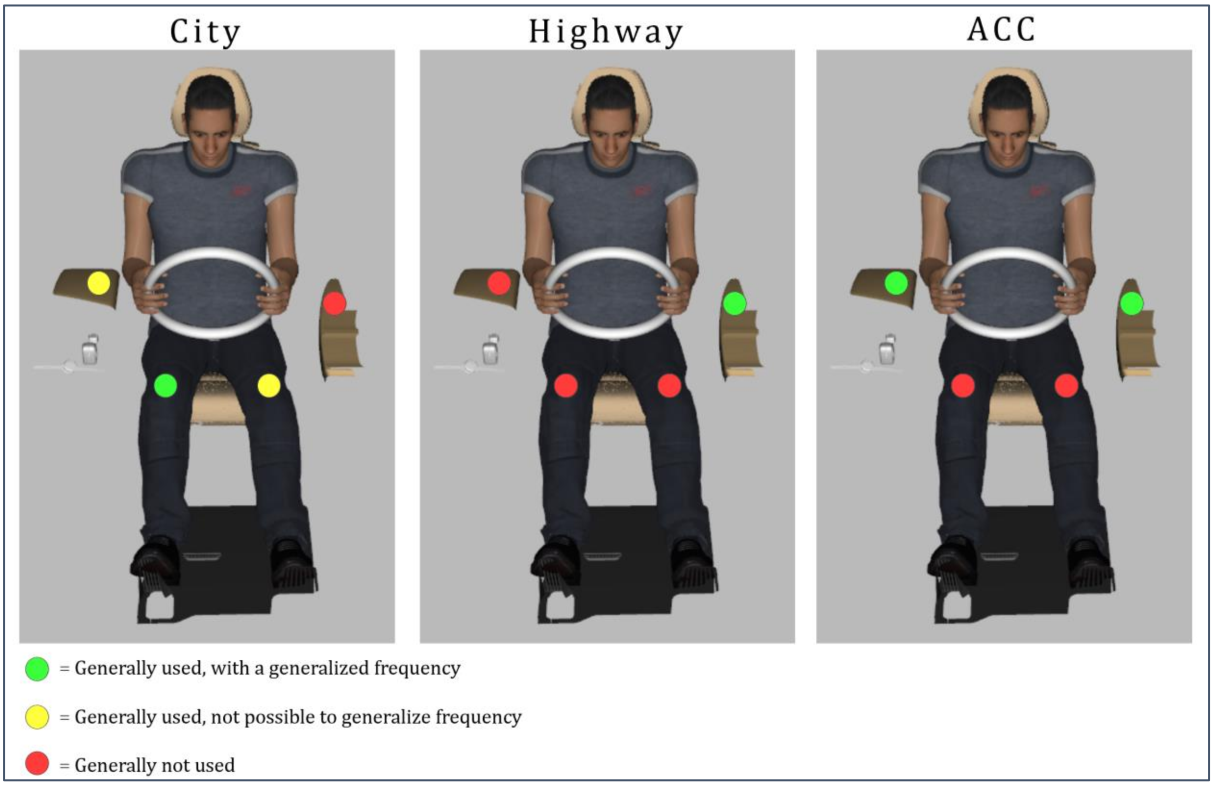


Figure 4.35 Visualization of the use of armrests and the knee as an arm support for the different situations.

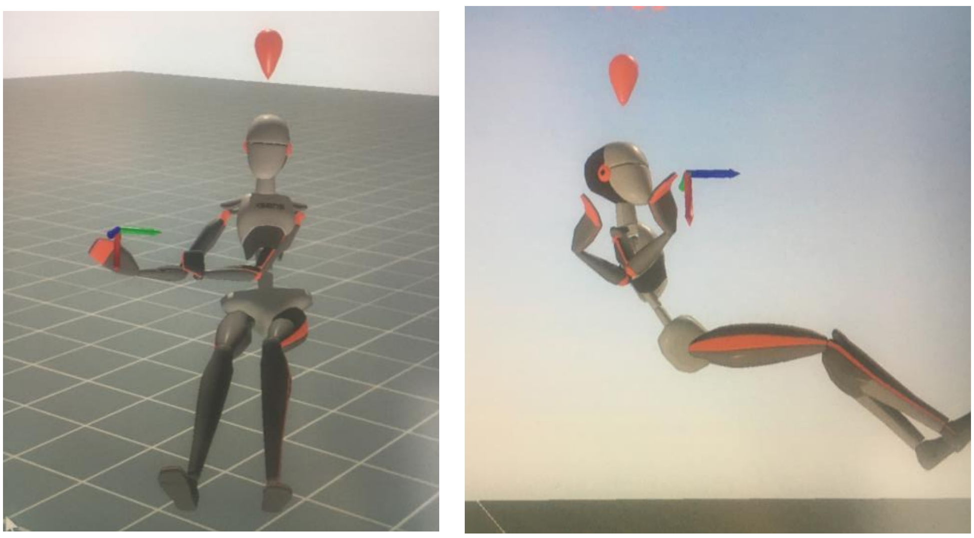
5 Discussion

This chapter covers the discussion about the motion capture system Xsens, the used methods, ethical considerations, and the results. Lastly a discussion of the summarized result for implementation in IMMA is presented.

5.1 Discussion of Xsens

The use of the body motion capture system Xsens for dynamic driving tests shows to be problematic. The sensors and the system seemed to work accurately from the beginning and a lot of effort was put into learning the system, understanding the produced data, and do calculations. Nevertheless, several issues are detected which makes the system unreliable. The first issue is that the manikin's posture does not coincide with reality, although several recalibrations are performed. It is unclear why this is the case, but one reason can be due to a poorly performed N-pose during calibration. The second issue is that the manikin changes position over time, often to a more laid down posture. Again, it is not certain why the manikin changes position, but reasonable causes can be either due to sensors drifting or sensors moving or sliding on the test subject. Due to these issues, all data analysis using Xsens is discarded. This also affects the hypotheses, since there are some of them that cannot be tested. For example, it is of interest to see how the upper body moves in y-direction, the heads side movements, and the angles on the knees, back and hip. This is information that must be collected through Xsens since there was no other solution available for capturing these movements or data. Therefore, these points of interest are discarded after performing the driver study.

Another problem that appears while using Xsens is the reliability in the software while annotating. When examining one of the test subject's Xsens recording it is found that the manikin moves the arms in a very unrealistic way, see Figure 5.1a), assuming they are drifting. In Figure 5.1 b), it is demonstrated that the left arm is behind the back, straight out to the right side, which is physically impossible. This is interpreted as a recording of bad quality to use in the test. However, when the same file is reopened, this does not occur. The manikin's arm does not behave in the same way as when looking at the file the first time. This makes it difficult to rely on the Xsens software and the data representing the movements, since it is difficult to judge whether the data is correct and represents reality.



a) *b)*

Figure 5.1 Capture of manikin with arms drifting

5.1.1 Evaluation of Xsens as measurement tool

The results from the evaluation show that Xsens is not reliable in static simulator driving. One issue is that the posture does not comply with reality, especially the legs. Another is that the data is lagging, which shifts both the posture and position of joints. Furthermore, when using the vehicle scenario, the pelvis is locked in one position, why all points move around this point in the plot. This is found to be misleading. For example, if the driver is slouching, the movements are not reflected in the displacement data for the hip point, and neither is the change of seat height. Hence, other scenarios to capture the accurate hip behavior in the static driver simulator can probably show a more accurate result However, the other problems mentioned above is still expected to appear for other scenarios.

A final issue is that the sensors still drift with time, which completely shifts the posture of the manikin. In addition, as is seen in Figure 4.11, a strange drifting in the arms is observed during the data recording in Xsens, which changes after processing to HD quality. Due to this, it is very difficult to know if the manikin is calibrated correctly and if it is necessary to recalibrate during the recording. This creates insecurity while using the software since it cannot be predicted what the finished data and video produce. After processing, the legs also change and show a different position, not accurate to reality. Hence, the researchers conclude that Xsens as a tool for dynamic ergonomic analysis in vehicles is not reliable and needs to be improved by the retailer before it should be used for further testing.

5.2 Discussion of methods used

This section discusses the methods used and what implications the choice of method has on the study and results.

5.2.1 Choice of route

The route as such is argued to be suitable for the purpose of the study. Performing all the tests in the same order is considered suitable since a changed order would impose a time-consuming detour for the already long driving route. Performing the tests in the same order might impact the results. When the highway driving starts, the participants have been driving for approximately 35 minutes, and when the ACC drive starts, they have been driving for 50 minutes. As stated in the Theory, Section 2.4.2, discomfort increases over time when seated for longer periods, and studies with durations of 45 minutes already sees a change in comfort. Therefore, it is expected that the drivers in this study experience a decrease in comfort over time and that affects how they move and position themselves. The fact that the studies are performed in the same order means that it is difficult to verify if the drivers move in the way they do due to the situation only, or due to discomfort, especially for the last two situations. For example, do the drivers move their feet back during the ACC recordings, only because the possibility exists, due to discomfort in the lower body, or the combination of them?

5.2.2 Layout of the test

The test is performed so that it is always the same test leader who does the same task for each test. This is decided so that the human errors that might occur are equal for each test person. The participants can adjust the seat and steering wheel to their satisfaction. This approach is used to reflect a natural behavior. Previous studies use an experimental setup where participants are forced into a position, for evaluation of comfort and sitting postures (Andreoni et al., 2002). These studies create an unnatural seating situation in the car that might never exist if the drivers can decide for themselves. Therefore, it is of interest to have an approach where the user has more control and that has not been examined to a large extent.

During the driver study, the test leader that goes with the car is altered. Each test lasts for approximately 1,5 hours depending on the smoothness of the execution. The reason for changing test leaders is due to the duration and exhaustion of performing each test and for each test leader to get a reasonable break. The drawbacks of changing test leaders are that there might be a difference in instructions during the driving, which could have affected the drivers differently, but to avoid this, the same protocol is followed. The ability to verify the accuracy of the measurement tools during the whole drive can also differ which might result in less reliable data.

One drawback of the execution of the driver study is the decision of whether to drive for exactly ten minutes or have a certain recording stop point regardless of the time. This is executed differently between the test leaders, where one stops the recording after ten minutes even though the complete route is not fulfilled, whereas the other stops at the same place irrespective of the recorded time. What can be affected by this is the annotation analysis. Since the length varies, not all events are the same for all recordings, which can give extra information on a longer recording. The consequence for the city driving is the last turn to Parkgatan is not captured for all test subjects. However, since other crossings are included, the upper body behavior in crossings is captured in the other instances. For highway and ACC, the last few seconds that are not recorded, do probably not change the overall analysis of the findings. Overall, the drawback is not seen as a major error during the execution of the test but is something that can be improved in future tests for consistency of the execution.

5.2.3 Recruitment of participants

As seen in Section 3.4.3, the participants are normally distributed in terms of sitting height, which, by judging their anthropometrics would represent the population in Sweden. The only weak aspect to mention is that the lower limit for women with regards to sitting height is the 42-percentile, meaning that women in percentiles below this are not well represented. Furthermore, it is seen in the seat analysis that there is a spread in how the participants position themselves. This is based on the H-point, the seatback inclination, and how they position the steering wheel. Since the test persons varied relatively much in how they are seated, it is argued that the test group is representative of the population.

5.2.4 Choice of vehicle

The choice of using a high-seated XC60 affects how the drivers are seated. For example, the behavior of leaning forward could vary for different car models due to a difference in visibility. As described in Section 2.3.1, the difference in H30 leads to different knee joint angles and different space and room for the legs and feet, which could affect how one places the feet. The H30 might also affect how the driver is positioned compared to the steering wheel, how the hands are placed on the steering wheel, and how the use of arm support looks like. The armrest’s design could also differ which can affect the behavior. It is therefore expected that a different vehicle may show other behaviors than presented in the result.

5.2.5 Data collection

The data collection methods are discussed in this section.

Unstructured interviews

The unstructured interviews with supervisors and ADOPTIVE representatives are argued to be appropriate for the purpose of understanding the aims of the ADOPTIVE project and their needs as customers and stakeholders of this project. Since the study is exploratory, it is desired to get creative responses in a broad spectrum. Therefore, unstructured interviews are argued to be appropriate as they yield the most captivating responses, compared to other interview types.

The possible drawback with this method is that the answers given might have low reliability. It was generally the supervisors from Volvo and the project manager from ADOPTIVE that were included in the interviews, making it difficult to completely rely on the information extracted. For example, it is not evident if ideas that are discussed are possible to implement in the IMMA software since the system developers' thoughts are not included. This can affect the requirement list's content. An improvement can be to achieve triangulation of the interviews, by interviewing several people involved in the development of IMMA to better understand the full context and increase the credibility. However, the resulting customer needs' output, is not the most critical result in the master's thesis, why it should not affect the major findings and conclusions.

Video recording

The video recordings as a method to capture the participants' natural behavior, works well and is a straightforward technology to use, understand, and equip the car with. From the recordings it is easy to observe the participants' behavior and posture and it is relatively quick to analyze. However, during the pilot study, it was realized that it was difficult to position a top view camera in an appropriate way. The positioning or the camera needs to change for the top view camera to capture the knees' movement as desired.

The disadvantages of using video recordings in the analysis are that there is no clear procedure to do the analysis, and it is difficult to convert video material into text or quantifiable units. An improvement is to use landmarks on the participants and in the car during recordings to better be able to quantify how much participants move. The current analysis focuses more on if and how they move in a descriptive way, rather than in a quantifiable way. Furthermore, the video recordings are a method intended to objectively observe the behavior, however, during the ride it was sometimes necessary to give road directions, making the test leaders partake in the recording. This method is therefore a mixture of the test leaders observing and participating. The results of the test leader being a part of the activity caused some additional movements among the participants that would not be present if they are driving alone for real. These gestures are mainly pointing on the road or looking in the rear-view mirror, which has insignificant impact on the results. The cameras can also affect the driver as they might feel observed and therefore behave in an unnatural way. However, the participants do not express any issues with the equipment in the questionnaire, why it is believed to not have an impact on the test.

Questionnaire

The questionnaire combines NRS questions and open-ended questions. The advantages of this are that it increases the depth of the study. However, the disadvantages are that it is more difficult to interpret the results and more parameters to consider in the analysis. The NRS offers several benefits including ease of administration and scoring, easiness to understand as a user, multiple response options and no reported age-related difficulties in using it (Brunelli et al., 2010; Goldberg & Smith, 2013). The downside with NRS is that, statistically, it does not have ratio qualities. This means that numerically equal intervals on the scale, e.g., 1-3 and 7-9, may not represent equivalent intervals in terms of the respondents subjective experience (Lazaridou et al., 2018). This means that rating scales response data indicate only an ordered structure and not a numerical value in a mathematical sense, which have an effect on how the analysis of the result should be performed (Svensson, 2001). Since the analysis in this project is not statistically significant due to the qualitative character of the study, it is decided that the advantages with NRS overweigh the disadvantages.

It is chosen to have a rating scale ranging from 0 to 10, which allows the participant to be neutral by choosing a 5. This choice of method has both pros and cons. The advantage is that it can capture a third neutral opinion, while the disadvantage is that if the participants choose this neutral option, it is difficult to interpret such an answer. However, since this scale is the most commonly used, as discussed in Methods, Chapter 3, and since the researcher think the advantage of being able to capture a third opinion is valuable, it is the chosen structure.

Regarding the format of the questionnaire, it is perceived by the researchers to work well. It has a good balance between both amount of and types of questions, and the result supports answering RQ4 in an appropriate way. Many of the received answers are of high value ranging from 8-10. This can imply a questionnaire design with a too narrow rating scale where another type of scale might give a better accuracy among the answer. Also modifying how the questions are expressed may showed different results. For example, one question seems to be interpreted in the wrong way. This is discussed further in Section 5.3.5.

Seat and steering wheel configuration

The seat and steering wheel configuration are measured initially and after each situation: city, highway, and ACC. Hence, it is not measured continuously and, therefore, not capturing if several changes are made during the tests and when. This is due to the limitation in the software that could only measure discrete data and since the steering wheel measure is done manually. Nevertheless, a test leader is in the vehicle during the drive and can note down how many times the driver changes the seat to better understand the full behavior. The goal with the seat measuring is threefold, and described in Methods, Section 3.5.1. For these causes, the measurement technique used is considered to be adequate for the study.

5.2.6 Definitions and categorizations

During the development of methods for analyzing the data, categorizations and other definitions are made by the authors. The chosen categories, frequencies, and other parameters of time are defined to make the analysis convenient for a future requirement list for IMMA implementation. However, this also affects the results and outcomes. For this project it is believed to be suitable, since in this stage of the ADOPTIVE project, a common generalized behavior is what is desired to implement. It is of importance to find a behavior that can be implemented that represents the population as a first step. Even though, some individual behaviors are found, which are interesting to examine further, the goal is to investigate the possibility to find distinct, descriptive generalizations. For future improvements, it is desired to include the most extreme behaviors, where categories and other parameters might need to be redefined to appropriately cover the scope. However, at this stage of this qualitative, exploratory study, it is considered a suitable method to answer the research questions.

The categories and methods for analyzing different body parts are established by the researchers, from their understanding of the problem and based on the hypotheses. Therefore, there is a risk that the categories and analysis are created in a way that mainly supports the hypotheses and leaves out other important information or parameters. An example could be that for the analysis of the arms, the focus is on how much the arms moved, but not the situation in which they move. For instance, one might also discover that the arms rest on the arm supports only when the vehicle is not moving. The creation of the analysis does indeed affect the results, and one should be aware that the analyses performed do affect the stated conclusions.

5.3 Discussion of the results

This section discusses the results. The results in this thesis are interpreted from the data that is collected. The risk with interpretations is that the researchers draw conclusions based on what made the strongest impression or overlooks information that does not confirm the researchers' pre-assumptions. This is avoided through triangulation and by using multiple data sources to better understand the driver. By combining objective data, mainly from video annotation, with the subjective data from the questionnaire, it is easier to make accurate interpretations. However, in some instances, it is still difficult to interpret the driver's behavior. Some participants behave in a distinguishing way, and despite including the questionnaire result, it is difficult to understand why. Even though triangulation is a useful tool, the risk of different types of biases is always present and can influence the result of the study. In the following, the results from each body part analyzed are discussed. A discussion about what works well and what should be improved for further studies is also included.

5.3.1 Hands

The result shows that it is quite individual how and in what situations the participants have their hands off the steering wheel. In the city it is mainly when driving, both on straight roads and when turning. Two participants, test person 8 and 10, have their hands off only when standing still in red lights or when the traffic stands still. This can indicate that they want to rest their arms, but are not able to do so while driving, and therefore only do so when stopping. The test persons are in the short category, and it is expected that the shorter persons might not be able to reach the armrest in a comfortable way, which this behavior confirms. Regarding how they have their hands off, the drivers either have left or right hand off, alter between them, or as seen in a few instances at a red-light, has both hands off.

Furthermore, the result shows that more participants have their hands in category 9 in the city. However, for highway and ACC, one driver has the right hand off the steering wheel as their generalized position, and one has it as a tendency, and in the summary in Table 4.4, it is also seen that the drivers have their hands off for longer periods for highway and ACC. This means that although the result shows that a fewer number of people have their hands off the steering wheel for highway and ACC, they have it for longer periods.

In addition, an observation made is that it is difficult to generalize one specific position as the most common, looking at Figure 4.13. Although category 2 and 3 are the most common ones, within each of these categories, the participants tend to position their hands quite differently. Also, when looking at each individual behavior, the hand behavior seems to vary from person to person. Some participants hold one position the entire time, and others move their hands very frequently. The full detailed annotation can be found in Appendix L for the interested reader. A conclusion drawn based on this is that it is difficult to generalize a very specific hand behavior and that it is rather a personal preference on how to position and move one's hands.

Improvements for future analysis is to put markers on the steering wheel and the participants to be able to define the placement of the hands correctly. It is also difficult to see where the left hand is in the camera frame when the right arm is blocking the sight. An additional camera can solve that problem, or possibly, other technologies. It would also be interesting to see how the hand and arm behave in relationship to each other. This would probably be easy to do in Xsens, should the data be more accurate, but is cumbersome to do in video analysis.

5.3.2 Arms

The results regarding arm behavior and use of arm support differ in several ways. There is a high number of people that put the arms in the knee during city driving compared to the other two situations. However, the average time of using the knee is very low. This indicates that the knee as a support is used only during short moments, where the armrest may not be conveniently close as support in the complex situations in the city where the arms move a lot. The reason to why the knees as support are barely used during the less complex situations during highway and ACC, may be that the arms find a comfortable position that can be kept during longer periods of time without having to move. The result regarding the average time use of armrests among the participants is interesting, since there is a clear need for the armrests to be comfortable among the people that use them since they are used during longer periods. The difference among individuals also points towards that the use of arm support is a personal preference.

The findings from this master's thesis project regarding the usage in time of each support correlates bad with the study on upper posture activities described in Section 2.7. The study consists of 9856 video frames where the usage of armrests is calculated in percent of frames. In the study the left elbow is placed on the door armrest 18% of frames, and the right elbow on the tunnel armrest 29% of frames. It is also found a difference between women and men, where women have the same percentage of armrest use regardless of the vehicle, but where men's usage differ extensively. The result in this project shows that the participants using the door armrest uses it between 43% to 60%, depending on situation, and the tunnel armrest between 33% to 64%. There is a significant difference between the results obtained in this project and the results of the study. One reason can be the fact that the study investigates the behavior in 100 different vehicles of six different brands, and seven different models, where the usage becomes dependent on which participant using a certain car. It would be interesting to see if the results would be similar to the ones obtained for this project, if all the participants use the same car. Another reason for a difference in the results can be the amount of people participating and the distribution between men and women. In the study, 165 drivers participated, with 96 women and 69 men and of ages estimated between 30-60. In this project it is only twelve participants with an opposite distribution for gender, and age span between 24 and 60 years. A larger number of participants might acquire a result where individual preferences show to a higher extent, creating a more fluctuant behavior among the participants. Finally, the difference in the experimental setup might also affect the outcome. In the study, no test leader is seated in the vehicle during the driving, whereas other passengers instead can be present.

The analysis that is made by annotating from the videos works relatively well. A problem that occurs is that the right arm sometimes covers the left arm. This makes it hard to see exactly in which position the left arm is placed. However, it is possible to do complementary annotation from the Xsens recording, which is used to confirm an estimated distance of the arm to the body, and a position correlating with using the door armrest. With the two annotation possibilities the analysis can be done easily, but still by a human with the possible occurrence of errors. The analysis is probably more convenient to perform if it would be possible to use data from Xsens. Then, the data for the armrest position can be compiled in more detail. The analysis focuses on noticing how many times a certain support is used and the period using it. These two focus areas are enough to answer the hypotheses, but for a deeper understanding it would be interesting to also see, especially for city, in which situations they are used. While annotating, it is observed that many participants use supports to a high extent while waiting at a traffic light. However, it is not examined further if there exist correlations, but this can be a future point of interest. A correlation between hand positions and armrest use can also be seen where the hands are either in the lower position of the steering well, namely categories 3 or 4, or off the steering wheel.

5.3.3 Upper body

An observation made during the driver study regarding seat position, is that the participants do not position the seat in a certain way for certain situations but instead move and adjust their upper bodies when a situation requires them to. There is a pattern to do so, particularly in busy crossings, where the participants need to observe surrounding traffic to the sides before driving into the crossing. Only one participant changes seat back rest angle during the highway driving, and from the recording it looks like it is done to increase the comfort and not due to the change in task.

Two participants, 4 and 8, have deviating behavior that is worth discussing. They lean forward for longer periods and move their bodies more than other participants and in other situations. Test person 4 does comment on the question "To what extent did the visibility affect your sitting posture?" that "I needed to lean forward from the backrest every time I was at a crossing and wanted to see better forward and to the sides", why this participant seems to be aware of its own increased upper body movement, and the visibility might explain why the participant moves more than others. The participant does not articulate that the visibility has affected the positioning in the seat in a way to better see, but rather that the upper body is adapted to get better vision. This correlates with the behavior seen amongst the other participants which is described initially, however, this participant does it in an extreme way. Furthermore, when looking at the participant's rating, the overall position is rated as 10, space for the head as 7, and space for legs as 10. The participant does seemingly experience less space for the head, compared to other body parts. This can indicate that the participant's behavior partly can be due to limitations in the car design.

Test person 8 does, in addition to move more than others, also push back in the seat several times. The participant has commented "Not OK lumbar support", which can be interpreted as a perceived discomfort in the lower back. Hence, the participant's movement can be due to discomfort from the lumbar support. However, the participant only does these larger movements in the city driving. On the highway the person slouched once, but these larger movements are not observed. Therefore, it seems unlikely that the behavior in the city is only due to discomfort. As discussed in the result, when looking at the video it seems more like the person pushes back and at the same time lifts their sight to get better visibility. There is possibly a combination of poor visibility and comfort that results in this behavior.

When it comes to ACC and highway, the participants do not move their upper bodies particularly much or change position, and it is no significant difference between the two situations. In addition, a majority of the test persons remain with their initial seat configuration. The changes in body posture that do occur is either slouching or pushing back in the seat by using their feet and pushing down on the floor and at the same time "walking" backwards with their hips. Both movements are a change of position to increase comfort. This confirms what is discussed previously, that it is expected to see increased movement due to comfort with time since the driving is at least 50 minutes. Important to consider is, therefore, the time frame of the test. As mentioned previously, it is recommended that studies should be at least two hours to properly examine comfort as a parameter (Porter et al., 2003). Therefore, it is expected to see more of these movement, should the test have been longer. However, comfort is not included in the scope of this study. This fact should be considered by the ADOPTIVE team for future software development. A longer driver route may lead to other generalized motion patterns and postures. Therefore, if it is desired to simulate motion due to long time seating, further investigation is recommended.

Seeing that most drivers do not change seat configurations between situations can indicate that drivers have a preferred seat back rest angle that they maintain during the different driving situations investigated. Reflecting back on the theory in Section 2.4.1 on preferred sitting postures, and the joint angles described in Section 2.5.3, it would be interesting to see if the angles are the same in this study as in theirs. However, this cannot be measured in this study.

The performed analysis works well for the purpose of the study - generalizing driver behavior and sitting posture. However, the analysis does lacks depth in terms of more detailed descriptions of joint movements where the Xsens data would give more precise and quantifiable data. As mentioned above, landmarks in the vehicle would allow for quantifiable measures which can improve the analysis. The annotation in highway and ACC recordings is performed for every second minute, which can be perceived as a too low frequency. However, it is believed that if the participants change into a position such as slouching, they remain in it to the next annotation frame, and therefore it is argued to be enough data points. However, regarding the deviating behavior of test person 8, more movements might be identified on highway and ACC if annotation is performed more frequently. This should be considered for the conclusions connected to test person 8.

5.3.4 Feet and knee

The feet are generalized to a low frequency of positions and movements for all situations. However, it is a somewhat higher frequency seen during the ACC. There can be various reasons for this behavior. As discussed in Section 5.2.1, the movement of the right foot during ACC can be the result of two circumstances. Firstly, the task has changed from city and highway driving, where ACC allows the driver to perform the task of driving without having the foot on the accelerator pedal. Secondly, the movement can relate to discomfort which can be related to two things. To the task itself, where it is more comfortable to place the feet further back while using ACC, or due to that the driver has been seated for about 50 minutes with the foot constantly on the accelerator pedal. The left foot, however, is free to move during all situations. Even so, the participants keep it in the same area of placement, indicating no discomfort when keeping the left foot and leg in the same position during the whole test. This indicates that the movement of the foot during ACC is due to the task rather than discomfort after driving for 50 minutes.

However, one question that appears with this reasoning is why the participants do move their right foot backwards, since the left foot is still most of the time. It is possible that there is no comfortable or suitable placement similar to the left footrest for the right foot when the leg is stretched, and therefore it becomes more convenient to position the foot closer to the seat. In the questionnaire, one participant commented “More space for feet would be good” during ACC. This indicates that this could be the case and that there can be a latent need of more foot space that would increase the overall perceived comfort. However, it does not seem like the participants are dissatisfied with the current space either according to the questionnaire answers. An alternative reason for moving the right foot more during ACC can be that the foot previously is restricted but when ACC enables movement, participants mentally feel a freedom that did not exist before, so they move it just because it is now possible.

The analysis that is made by annotating from the video recording of the feet works well. The floor mat that is taped with measurement tape made it easier to observe and detect any change in feet position. What can be improved is to install a light that keeps the area visible all the time. In certain situations, for example in tunnels, or in darker areas, the video recording is very dark and for a few seconds it is hard to notice changes. However, this needs to be done so it does not affect the driver in any way. Too much light can distract the driver and create an unnatural driving experience. In the annotations that are made during this project this is not seen as a problem, since these dark periods of time are short, and the feet did not appear to move that much. If they move, the position can be retrieved when the light comes back again. However, if the test is performed in another environment this is an aspect that can have a big impact.

Another improvement can be to install an additional camera filming from another direction. Sometimes the position needs to be estimated when the participants move their feet far back and close to the seat, and the heel-point ends up outside of the camera's frame. This can be avoided with the additional camera. The analysis is made by gathering positions, movements, and directions of the feet. This information is enough to answer the hypotheses but can be more exact if the time in each position also is documented. Certain positions where a participant places their feet for only a few seconds might be considered as not relevant for the overall evaluation and can be excluded. In this study, all positions are included, even the ones that are held for short moments, to recognize the whole space that is used and the complete motion pattern.

5.3.5 Questionnaire

The researchers perceive the questionnaire to be easy to understand and use, and this perception seems to be shared amongst the participants as they did not need help to understand the questions during the driver study. However, for the question "To what extent did the visibility affect your sitting posture?", a variety among the answers is seen that cannot be seen for the other questions. During the drive, both authors noticed that the participants had a hard time understanding this question, asking how to interpret the anchored extremities. In addition to this, it is noticed that many participants answer the question before "How was the visibility forward when driving?" as good, see the results in Section 4.6.6. However, when answering the following question regarding visibility affecting the posture, it is a spread among the participants answers between "To a high extent" and "To a low extent".

The spread in the participants answer can be interpreted as that the participants got confused that the positive anchor where for the second question switched to the left, whereas on the previous question the positive anchor was on the right. It is noticed that some participants thought that answering the far right, "To a high extent" means that the visibility did not affect the posture, but in fact it means that it did affect the posture. One of the test leaders had to explain to one of the participants several times what is meant with the question due to this confusion. Therefore, this question should have been formulated differently to make it easier for the participants to understand. Another interpretation can be that the visibility is very good, but to obtain that good visibility, the sitting posture is affected. However, this is not what the authors believe to be true due to the experience in the car with the participants and since most participants did not leave comments pointing out this as a problem or limitation. Also, it can be reasoned that if the visibility affects the sitting posture to such an extent, other limitations and discontents should show in the questionnaire as well.

One specific comment that is interesting to reconnect to is from the shorter participant, test person 9, who comments in the questionnaire that “I sit high to get good vision”. This can be compared with what is stated in the theory Section 2.5.3. The study by Wolf et al. (2022) discovered that the flexion is higher for trunk-thigh angle and less for ankle-hip angle among taller people compared to shorter people, and this can be an indication that shorter people position themselves higher for improved visibility. Although only one person comments on this, it coincides with the statement from the study.

A relatively similar result for each situation is obtained for all the other questions. The results can therefore be interpreted as that the participants feel comfortable and satisfied with both the driving and their positions, and that they did not feel limited by the car, the roominess in the car, or the interface with the interior design. However, since the comments section after each question is optional, most participants do not further describe their perception and the opinions on what features that made them feel satisfied cannot be stated either. Therefore, it is of importance to have the objective measurements from video, seat, and steering wheel to connect their responses to how they position themselves and from that draw conclusions about perceived comfortable space, for example. One change that can give more value to the answers is to make the comments sections compulsory. If doings so, it is necessary to evaluate the advantages and disadvantages. One advantage is that more detailed explanations of the participants experience can be obtained. However, there can be a reluctancy among participants to take the time to answer the questions properly and create an annoyance to fill in the questionnaire. Performing an interview after the completion of the questionnaire, could also be a complement, to be able to ask in more detail about deviating answers and why participants answered like they did.

5.4 Transforming the summarized results to IMMA requirements

The summary of the sitting postures in Section 4.7, presents similarities and differences for the different situation. This section discusses how these findings can be interpreted and how that in turn can be implemented in IPS IMMA.

The main differences between city and highway are that the driver, overall, moves their upper body, defined as hands, arms, shoulders, head, and back, more. The movements are more connected to certain events in the city, and not constant. What is similar for the situations is that the seat remains in the same configuration between situations, and the hips and buttocks remain in the same position to a large extent. Therefore, in a future simulation, this position can remain the same between different situations. Furthermore, the lower body behaves quite similar for all situations. The left foot has a low frequency of positions and movements for all situations, and similar placement. The right foot has a low frequency of position and motion for all situations, but a deviating placement for ACC. Hence, there is no clear need to simulate the left legs differently for the different situations. An adaptation of the right leg is suggested to be implemented for the ACC situation, while the other two situation can remain with the base position.

Regarding use of armrest and positioning of hands, some preferred positions are identified for the different situations. The suggestions in the requirement list are based on these findings, however, the authors recommend that further investigations should be conducted on a larger scale since other types of motion patterns and positions are seen as well, however not as generalizable behaviors.

It is suggested to have a base seat position that includes the most common or similar behavior of the driver, and then specify additional motion patterns and positions for each of the situations. These should be added on to simulate different simulations.

5.5 Ethical considerations

There are a few ethical considerations, such as used methods, integrity of participants, anthropometrics, humans as test subjects, and environmental aspects, that needs to be discussed. The selection of participants is limited to Volvo employers, which results in an uneven distribution of men and women, and a lack of people outside the age span of 24 to 60 years old. Due to lack of response on invitations it is not possible during the time frame to even out the difference. Specifically, there is a poor representation of shorter women which can result in that their behavior is not represented in the study. The implementation of the findings in the software IMMA can therefore lack the preferences of this population group. The ergonomic changes in design based on the findings might then interfere with what is healthy and suitable for shorter women, or people outside the age span, creating a seating situation that could be the opposite. However, this is something that the researchers try to actively avoid by sending out invitations to new test subjects within this participant group three times. Future additions to this study can focus on the groups that are not represented well. A societal aspect of implementing the findings in the software IMMA is that the future development by the ergonomics department contributes to a positive impact on people’s health and complications related to sitting, as a result of this study.

Another ethical consideration is the participation of human test subjects. The study is of an observational character and non-medical. It is always a risk of accidents occurring when driving, but by performing an FMEA, the most important aspects is found and accounted for. For example, the seat belt is always used, the car is examined before the tests, and the cameras are placed to not hinder the sight of the driver which is also confirmed with the participant. The computers that are used for data collection in the car are placed behind the driver’s seat on the floor, or fastened, so in case of a crash, it minimizes the risk of seriously injuring the passengers.

Sensitive information about the participants is gathered, such as name, gender, age, weight, and body measurements. The participants are video recorded during the driver study, and information about the participants during conversations in the car ride is shared. All participants must give their consent to let the researchers collect this information by signing a GDPR document, where it is stated that the information is only used during the study, in compliance with Chalmers guidelines on how to handle personal data (Chalmers Student Portal, 2022). All sensitive information about the participants is anonymized in the report to protect the integrity and privacy of the test subjects and is deleted after finishing the study.

The sustainable aspect considered during this master’s thesis is that the car used has a direct impact on the environment, due to the diesel fuel used. However, seeing this study in a larger context, the emissions caused during the driver study, is not considered as having a major impact on the environment compared to the total amount of daily emissions. The study consists of twelve driver tests, and with some preparational activities made by the researchers, which can be seen as a small study. The assembled material gives a deeper understanding of human behavior to design cars in the future in a more sustainable and efficient way. In addition, the values, and goals that Volvo as a company strives for regarding sustainability, with a transformation towards zero emissions, gives the researchers confidence that this project is performed in collaboration with a company working for a sustainable future.

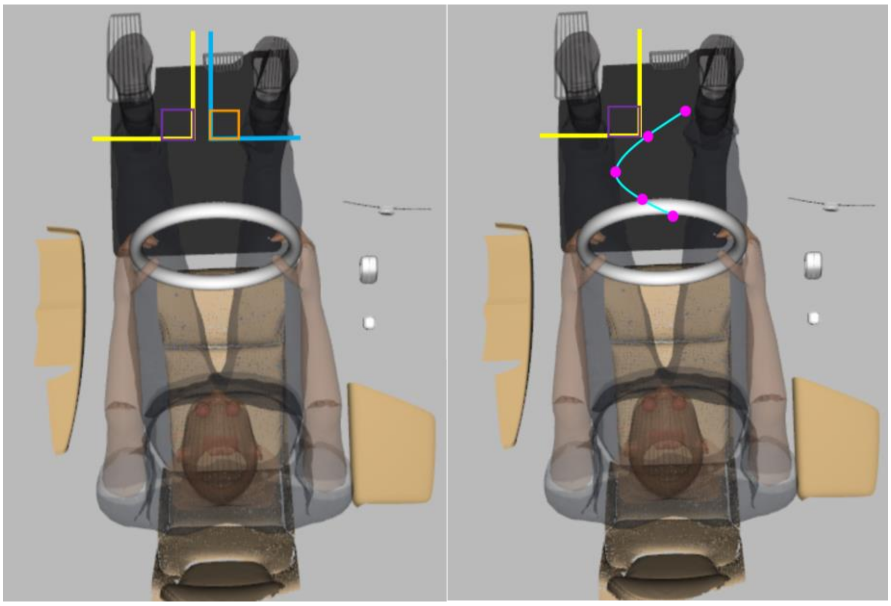
6 Requirement list

The requirement list, exhibited in Table 6.1, is a recommended product implementation of the results from the driver study to the software IPS IMMA. It is developed with inputs from the experts in the ADOPTIVE project team and supervisors. The assumption made for the requirement list is that the simulation lasts ten minutes for each situation. All adaptations are built upon the base position, specified in Table 6.1. If a change of body part is not mentioned, it is supposed to stay in the base position.

Table 6.1 Requirement list for IPS IMMA software development.

Requirement list			
No.	*Function*	*Requirement*	*Constraints*
1	Base position	Body is placed in a predefined posture *"Driving car"*, as it is currently implemented in IMMA	• XC60 car
2	Base position	Left hand is placed in category 2, with cylindrical power grip	-
3	Base position	Left elbow is in the air	-
4	Base position	Right hand is placed in category 2, with cylindrical power grip	-
5	Base position	Right elbow is in the air	-
6	Base position	Left ball of foot is on footrest and left heel point is in the middle of the purple box, see Figure 6.1 a)	-
7	Base position	Right ball of foot is on accelerator pedal and right heel point is in the middle of the orange box, see Figure 6.1 a)	-
8	Base position	Back is against back rest	-
9	City adaptation	Control point T6T7 is moved forward within a pre-defined box	• In crossings and roundabouts • Hands on steering wheel
10	City adaptation	Left hand moves between category 1, 2 and 3, with a cylindrical power grip. Category 1 10% of the time, category 2 60% of the time, and category 3 30% of the time	-
11	City adaptation	The left-hand position switches six times	-
12	City adaptation	Left elbow is on knee 5%	• Left hand in category 3
13	City adaptation	Right hand moves between category 1, 2 and 3, with a cylindrical power grip. Category 1 10% of the time, category 2 60% of the time, and category 3 30% of the time	-
14	City adaptation	The right-hand position switches six times	-
15	City adaptation	Right elbow is on knee 10% of the time, and on tunnel armrest 10% of the time	• Right hand in category 3

16	Highway adaptation	Left hand moves between category 2 and 3, with a cylindrical power grip. Category 2 50% of the time, category 3 50% of the time	-
17	Highway adaptation	The left-hand position switches two times	-
18	Highway adaptation	Left elbow is on door armrest 40% of the time	• Left hand in category 3
19	Highway adaptation	Right hand moves between category 2 and 3, with a cylindrical power grip. Category 2 60% of the time, category 3 30% of the time	-
20	Highway adaptation	The right-hand position switches three times	-
21	ACC adaptation	Left hand moves between category 2 and 3, with a cylindrical power grip. Category 2 40% of the time, category 3 60% of the time	-
22	ACC adaptation	The left-hand position switches four times	-
23	ACC adaptation	Left elbow is on door armrest 60% of the time	• Left hand in category 3
24	ACC adaptation	Right hand moves between category 2 and 3, with a cylindrical power grip. Category 2 40% of the time, category 3 60% of the time.	-
25	ACC adaptation	The right-hand position switches three times	-
26	ACC adaptation	Right elbow is on tunnel armrest 60% of the time	• Right hand in category 3
27	ACC adaptation	The right foot heel point moves between five positions, every second minute, along the turquoise, for the extremities and between them, see Figure 6.1 b)	-



a) *b)*

Figure 6.1 Visualization of right foot position constraints during a) base position and for b) ACC. The pink dots show the suggested placement of the foot.

6.1 Requirement list discussion

The requirement list is produced based on the findings from the driver study. The most common behavior is defined for the different body parts. Additionally, some extreme situations for the right foot's ACC placement are included to cover the full behavior. However, the recommended implementation forms a summarized behavior seen by most of the participants. There is a risk that behavior occurring among the anthropometric population outer percentiles is omitted, where some recommendations might be physically difficult to perform by these manikins. For example, a short woman that position the seat very close to the steering wheel, might not even have the physical possibility to place the right arm on the tunnel armrest and the hand in a certain category on the steering wheel at the same time. The requirement list as a whole is realistic and in compliance with the findings, but it is possible that these inconvenient situations can occur. A future consideration is to further examine the behavior of people in the outer percentiles and to add constraints to the simulations based on anthropometric limitations.

6.2 Further visualization ideas

If Xsens would have worked as expected, the idea would be to use representative recordings from the driver study, or do new recordings with the researchers acting, and directly implement these in the software IPS IMMA. The software reads Xsens files, so simple visualizations would have been easier to produce. Also, it was of interest to plot the data points in a volume, defining movement boxes to be implemented in IMMA. For example, the box in requirement nine could be defined accurately in this way.

One solution that could be implemented, if further investigated, would be to allow the driver to position their arms and hands, on all types of arm supports (door armrest, tunnel armrest, and knees) and on several types of categories on the steering wheel, and then let the simulation randomly place the hands and arms, but weighted towards the most used positions, and with constraints on impossible combinations. Since this study is only conducted on few participants, not sufficient data has been collected to verify such a rank or order on how the positions would be prioritized.

7 Recommendations for future work

Future work on the topic would be to perform a study on a larger scale to be able to statistically prove the generalized behaviors presented in this study. Then it would also be possible to conclude whether other parameters such as gender and age also affect the driver's behavior.

Furthermore, it would also be of interest to examine other car models, especially lower seated cars as were tested during the pre-study. It is not evident that the driver behaves the same way in another vehicle, and it would be interesting to see the differences or similarities. This result would be valuable for the ADOPTIVE project, since either the requirement list suggested for simulation in this project could be sufficient to use as a standard or the behavior is strictly dependent on the car model. If the latter, then it might not be of interest to implement such specific behaviors as suggested here.

Another interesting aspect is the behavior of the right leg during ACC. Many drivers positioned their right feet further to the back when using ACC, while the left foot remained on the left footrest. It would be interesting to further investigate this behavior and understand why drivers position themselves in this way. There could possibly be a latent need for more leg space that would improve the comfort for the user. A further expansion of the study through examining PA could also result in other leg roominess requirements of interest for future development.

A final recommendation would be to further analyze the position and placement of the knees in more detail. It is still not explored if and how people use the tunnel as support for the knee when driving. From the video recording, it was seen that amongst the taller men, some did indeed lean their right leg towards the tunnel. However, for others, this was hard to see due to dark clothing and camera angle, so it is not possible to draw any conclusions. The knee placement is of interest to further understand what roominess or support that is required for future designs.

8 Conclusion

This master's thesis investigates if there are any differences and similarities in sitting postures and motion patterns among drivers in different driving situations, with the aim to suggest generalized driving behavior that should be considered for the future development of the IPS IMMA software. The results from the conducted driver study shows that it is possible to generalize sitting postures and body motion patterns for the different situations: city, highway, and highway with ACC.

In general, the sitting posture and motion pattern overlaps for the three situations. Significant differences in movements are identified in the city and ACC situation. For the city, these are a higher frequency of arm and hand movements, and that the upper body is leaning forward in certain events, whereas for ACC it is the right foot's variety in positions and the use of both armrests. The findings are formulated into a requirement list, suggesting future implementations in IPS IMMA.

It is investigated if the Xsens motion capture system is a relevant tool to collect and analyze body motion patterns and positions with. Using Xsens as a method for dynamic driving evaluation of ergonomics is concluded to be an inappropriate method, due to poor data quality and unreliable software. This affects the choice of method used in the master's thesis which have relied on video annotation.

By answering the project's four research questions, the aim of the project can be achieved. In the following, the research questions are revisited and answered.

> **RQ1**: What are the differences and similarities in sitting posture of the driver in the following driving situations:
> - S1: city driving
> - S2: highway driving
> - S3: highway driving with the use of ACC

The similarities in sitting posture are that hands are placed in the same categories on the steering wheel, the left foot's positions are placed in the same area for all situations, and the footrest is generally used. For highway and ACC driving, the left foot's placement is further narrowed down to an even smaller preferred area. The behavior of the right foot shows similarities for city and highway driving where it is placed in the same preferred area. The door armrest is used to a higher extent during highway and ACC driving. The tunnel armrest is used to a higher extent for city and ACC. The seat position remains the same from the original seat configuration for all situations, therefore their sitting posture generally remains constant. Identified differences are that in the city there is a tendency to also use an additional category for the hands, and the right foot during ACC does not show a certain generalized placement as for the other situations.

> **RQ2**: What are the differences and similarities in body motion pattern of the driver in the following driving situations:
> - S1: city driving
> - S2: highway driving
> - S3: highway driving with the use of ACC

The identified similarities and differences between the situations are that the feet move with low frequencies as a generalization. The upper body tends to be very still during highway and ACC driving, whereas for the city it is observed that at certain events the upper body leans forward to a higher extent. However, the hip-point and buttocks do not move significantly in any situation. A higher frequency of putting the arm on any of the arm supports or the knee occurred during the city drive, however, it is not generalizable. Hands also move between positions to a higher extent during the city drive.

> **RQ3**: If possible, how can sitting postures and body motion patterns be generalized in different driving situations, to formulate suggestions on future software implementations in IPS IMMA?

It is possible to generalize sitting postures and body motion patterns. In general, the sitting postures and motion patterns overlap for the three situations, with some significant movements during city and ACC that are prominent. For city these are the higher frequency of arm movements, and leaning forward in certain events, whereas for ACC it is the right foot's variety in positions. These findings make it possible to give suggestions for future implementations in IPS IMMA, which are concluded in a requirement list.

> **RQ4:** What limitations do drivers experience regarding the sitting posture? If there are any limitations, how do they affect the way drivers are seated?

In general, the participants do not experience any limitations regarding the sitting posture. One participant needs to sit high for better visibility, and two that leans forward in a deviating way, to get better vision. Otherwise, the participants rate that they have enough space for both lower and upper body and are satisfied with their positioning and overall sitting experience.

Recommended future work on the topic can be to perform a study on a larger scale to be able to statistically prove the generalized behaviors presented in this study. It would also allow for drawing conclusions on the effect of other parameters such as gender and age. Furthermore, it can be of interest to examine other vehicle models, especially lower seated cars. Therefore, it is recommended to perform a similar study with a lower seated vehicle. A final recommendation is to further analyze the position and placement of the knees in more detail. The knee placement is of interest to further understand what roominess or support that is required for future designs.

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Appendix A: Segments in Xsens

Table A.1 explains the different segments in Xsens.

Table A.1 The 23 different segments (Xsens, 2021).

Number	Segment Label	Tracker	Joint
1	Pelvis	Pelvis	jL5S1
2	L5	T8	jL4L3
3	L3	Head	jL1T12
4	T12	RightShoulder	jT9T8
5	T8	RightUpperArm	jT1C7
6	Neck	RightForeArm	jC1Head
7	Head	RightHand	jRightC7Shoulder
8	Right Shoulder	LeftShoulder	jRightShoulder
9	Right Upper Arm	LeftUpperArm	jRightElbow
10	Right Forearm	LeftForeArm	jRightWrist
11	Right Hand	LeftHand	jLeftC7Shoulder
12	Left Shoulder	RightUpperLeg	jLeftShoulder
13	Left Upper Arm	RightLowerLeg	jLeftElbow
14	Left Forearm	RightFoot	jLeftWrist
15	Left Hand	LeftUpperLeg	jRightHip
16	Right Upper Leg	LeftLowerLeg	jRightKnee
17	Right Lower Leg	LeftFoot	jRightAnkle
18	Right Foot		jRightBallFoot
19	Right Toe		jLeftHip
20	Left Upper Leg		jLeftKnee
21	Left Lower Leg		jLeftAnkle
22	Left Foot		jLeftBallFoot
23	Left Toe		

Appendix B: Questionnaire

Google form was used to collect answers in the questionnaire. After each question, there was an option saying “Additional comments: “, where participants could clarify or explain their subjective opinion. However, for simplicity, this question has not been added in the appendix.

Additional Participant Info

Welcome to the study "Virtual representation of driver behavior and sitting posture". You will fill in six different questionnaires. When each page is finished, please hand over the phone to the leader of this study. Do not hesitate to ask the test leader if you have any questions. Thank you for participating!

Fill in this questionnaire (3 questions) and afterwards hand over the phone to the leader of this study.

1. How often do you drive in Gothenburg City? (City is defined as within the road tolls) *

- ◯ Never
- ◯ Almost daily
- ◯ Once a week
- ◯ Once a month
- ◯ At least once a year

2. How often you to drive Volvo XC60? *

- ◯ Never
- ◯ Almost daily
- ◯ Once a week
- ◯ Once a month
- ◯ At least once a year

3. How often do you drive with Adaptive Cruise Control? *

- ◯ Never
- ◯ Almost daily
- ◯ Once a week
- ◯ Once a month
- ◯ At least once a year

Initial Position

Fill in this questionnaire (4 questions) and hand over the phone to the leader of this study afterwards.

1. To what extent were you able to adjust the steering wheel according to your preferences? *

	0	1	2	3	4	5	6	7	8	9	10	
To a low extent	○	○	○	○	○	○	○	○	○	○	○	To a high extent

2. To what extent were you able to adjust the seat according to your preferences? *

	0	1	2	3	4	5	6	7	8	9	10	
To a low extent	○	○	○	○	○	○	○	○	○	○	○	To a high extent

3. To what extent did you feel that you had enough space for your head? *

	0	1	2	3	4	5	6	7	8	9	10	
To a low extent	○	○	○	○	○	○	○	○	○	○	○	To a high extent

4. To what extent did you feel that you had enough space for your legs and feet? *

	0	1	2	3	4	5	6	7	8	9	10	
To a low extent	○	○	○	○	○	○	○	○	○	○	○	To a high extent

City Driving

Fill in this questionnaire (7 questions) and hand over the phone to the leader of this study afterwards.

1. To what extent did you feel mentally relaxed during the drive? *

	0	1	2	3	4	5	6	7	8	9	10	
To a low extent	○	○	○	○	○	○	○	○	○	○	○	To a high extent

2. To what extent did you feel physically relaxed during the drive? *

	0	1	2	3	4	5	6	7	8	9	10	
To a low extent	○	○	○	○	○	○	○	○	○	○	○	To a high extent

3. How was the visibility forward when driving? *

	0	1	2	3	4	5	6	7	8	9	10	
Very bad	○	○	○	○	○	○	○	○	○	○	○	Very good

4. To what extent did the visibility affect your sitting posture? *

	0	1	2	3	4	5	6	7	8	9	10	
To a low extent	○	○	○	○	○	○	○	○	○	○	○	To a high extent

5. To what extent were you able to position your upper body as you wanted? *
(Back, arms and hands)

	0	1	2	3	4	5	6	7	8	9	10	
To a low extent	○	○	○	○	○	○	○	○	○	○	○	To a high extent

6. To what extent were you able to position your lower body as you wanted? *
(Legs and feet)

	0	1	2	3	4	5	6	7	8	9	10	
To a low extent	○	○	○	○	○	○	○	○	○	○	○	To a high extent

7. Overall, how did you experience your seating position? *

	0	1	2	3	4	5	6	7	8	9	10	
Very dissatisfying	○	○	○	○	○	○	○	○	○	○	○	Very satisfying

Highway Driving

Fill in this questionnaire (7 questions) and hand over the phone to the leader of this study afterwards.

< Same questions as for city repeated>

Highway Driving with Adaptive Cruise Control

Fill in this questionnaire (7 questions) and hand over the phone to the leader of this study afterwards.

< Same questions as for city repeated>

After finishing study

Fill in this questionnaire (5 questions) and afterwards leave the phone to the leader of this study.

1. To what extent did the measurement equipment affect your driving? *

	0	1	2	3	4	5	6	7	8	9	10	
To a low extent	○	○	○	○	○	○	○	○	○	○	○	To a high extent

2. To what extent did the measurement equipment affect your sitting posture/position or body motions? *

	0	1	2	3	4	5	6	7	8	9	10	
To a low extent	○	○	○	○	○	○	○	○	○	○	○	To a high extent

3. What other aspect affected your driving? (E.g., tired, stressed, nervous, felt observed) *

Your answer

4. How would your driving have changed if the test leader was not in the vehicle? *

Your answer

5. What is your overall experience of participating in this driving study? *

Ditt svar

6. Would you like to participate in a similar study again? *

○ Yes

○ No

Appendix C: Test protocol driver study

This list presents the protocol used during the driver study.

Safety Checklist – before all tests

- ☐ Check all lamps, turn signals, and break signals (Therese)
- ☐ Oil level (Hanna)
- ☐ Brakes (Hanna)
- ☐ Tires (line depth) (Therese)

Protocol Checklist

- ☐ Name and Phone number to Participant (Therese)
- ☐ Inform about the study (Therese):
  - This is a study about driving behavior in different traffic situations for visual representation. We will do a drive during 1,5 h in three different situations, city, highway, and highway with ACC, where we will record and gather data. The study does not test you as a person, only the interaction with the system and therefore you should drive as you usually do, and you can't do anything wrong.
  - This is voluntarily so you can interrupt the study anytime you want without any explications.
  - The answers in the questionnaire will not be linked to you as a person and is used only for study purposes so please be as honest as possible when answering.
  - We will start by taking measurements, put on the Xsens equipment and then you will fill in some additional information.
  - There will be only one test leader in the car during the drive. Before, between and after the recordings we can talk, but during the recordings the test leader will stay silent and only give road directions, but music will be played in the car.
  - We will use automatic driving
- ☐ Fill in GDPR paper if it hasn't been done before/Do you have any questions regarding GDPR (Hanna)
- ☐ Show the road map, tell where recordings will start and end for each phase, and where stops will be (ST1 Ullevi, OKQ8 Flygmotet, BK Kallebäcksmotet) (Hanna)
- ☐ Take body measurements, always from back (Hanna)
  Fill in measurements in Xsens (Therese)
- ☐ Turn on and put on Xsens straps, check that it feels comfortable with the participant that we do it. (Both)
- ☐ Calibrate Xsens (Hanna)
- ☐ Let participant fill in body part comfort scale (Inhouse) and additional participant info (Car-rider)
- ☐ Check that equipment is comfortable or if they want to change anything? (Therese)
- ☐ Let passenger adjust to initial position
- ☐ Let passenger fill in the Initial seat position questionnaire (Car-rider)
- ☐ Check calibration in the car, hands straight forward, feet together then wide (Car-rider)
- ☐ Take a picture of steering wheel position (Inhouse)
- ☐ Record 5 seconds to collect initial position (Car-rider)
- ☐ Check seat values and quick recording of few seconds for base position (Car-rider)
- ☐ Check fastening equipment of computers (Car-rider)

Driving test

☐ Check that participant has their Volvo card (Inhouse)
☐ Check that participant can see clearly to this side, dead angle (Car-rider)
☐ Start recording in Xsens and video cameras at Järntorget until St1 Ullevi (Car-rider)
☐ Let passenger fill in questionnaire city drive and check seat values (Car-rider)
☐ Check that calibration looks good (Car-rider)
☐ Start recording in Xsens and video cameras at BK-motet until Flygplatsmotet (Car-rider)
☐ Let passenger fill in questionnaire highway drive and check seat values (Car-rider)
☐ Check that calibration looks good (Car-rider)
☐ Inform the participant to use ACC as much as possible now (Car-rider)
☐ Start recording in Xsens and video cameras at Flygplatsmotet until BK-motet (Car-rider)
☐ Let passenger fill in questionnaire highway with ACC and check seat values (Car-rider)

After driving test

☐ Take off all Xsens equipment and put them in charger (Both)
☐ Clean chair with disinfectant wipes and check hand-disinfectant in PVF (Car-rider)
☐ Check gas-status and refill if necessary (Car-rider)
☐ Load files from computer to hard drive (Inhouse)

Appendix D: P-diagram

The parameter diagram is seen in Table D.1.

Table D.1: Parameter diagram

Noise Factors:

Piece to Piece Variation (P)	Changes Over Time (C)	Customer Usage (U)	External Environment (E)	System Interaction (S)
P1: H-point tolerance	C1: Change of seat comfort experience over time (longer journeys)	U1: Front seat position Z and X(adjustable)	E1: Vehicle sideway G forces	S1: Seat position (Legroom) - Samma utrymme
P2: Seat upholstery material	C2: Seat ventilation	U2: Front backrest seat angle (adjustable)	E2: Other vehicles lights	S2: Heel kick position x-pos (Foot room rearwards)
P3: Seat stitching/split lines (mostly cushion)	C3: Normal slouching (slouch down, then up again)	U3: Seat belt adjustment	E3: Day or night	S3: Tunnel (Foot/leg room) SURVEY
P4: Customer anthropometrics	C4: Belt fit when slouching up and down	U4: Lumbar support adjustment	E4: Vehicle vibrations	S4: Foot support
P5: Customer body shape	C5: Getting tired over time	U5: Bolster adjustment	E5: Cold/hot temperatur from pano roof or windows	S5: Roof height (head room) SURVEY
P6: Clothes (Jacket, coat, skirt, dress, silk clothes, bare skin, jewellry)	C6: Getting used to new features	U6: Adjusting steering wheel position	E6: Sun shining into the car (sun glare)	S6: Arm support
P7: Shoes (High heel or boots etc.)		U7: Cushion Extension	E7: Weather conditions (Snow, fog, rain, etc.)	S7: A/B-pillar trim
P8: Physical Health issues		U8: Usage of seat heat	E8: Road condition (Ice, water, snow, road surface etc.)	S8: Grab handle
P9: Motion sickness		U9: Massage function on/off	E9: Obstacles (Animals, Pedestrians, disturbing objects etc.)	S9: Beltline-height
P10: Feeling of safety		U10: Usage and interaction with buttons and displays	E10: Rush hour/ fluctuation in traffic	S12: Belt retractor force (active)
P11: Age		U11: Customer vision		S13: Mirrors
P12: Customer vision		U12: Using seat belt or not		S14: Sun shades
		U13: Arms on arm support in different positions		S15: Xsens and cameras
		U14: Feet on/off pedals and in different positions		S16: Body shape car
		U15: Seat comfort accessories (pillow, clothes)		
		U16: Sideways body position in seat (angle from x plane)		
		U17: Sitting preferences (market/cultural)		
		U18: Person in seat behind you		
		U19: Interaction with other passengers		
		U20: Other person in car (without interaction)		
		U21: Activites in car when seated (music, calling, games, phone, eating, drinking, GPS etc.)		
		U22: Usage of grab handle		
		U23 Male or Female (behaviour, eg. "man-spread")		
		U24: Use of AC		
		U25: Manual driving/Automatic		
		U26: Individual factors (Stress, sleep, workinghours, mood etc.)		


Input signal
Customer as a driver sitting in driver's seat
Body Motion Pattern & Sitting Posture
Ideal function
- Driver sits as he/she wish, and is not limited by the car
- 100% normal driving Body Motion Pattern & Sitting Posture
Error state
- Disturbed by equipment (Xsens and cameras)
- Disturbed by other person in car
Control parameters
(P6, P7) Ask participandts to wear tight clothes, take of jacket while driving and flat shoes
(P1, P2, P3) Same test vehicle
(P4, P5, P11, P12) Try to get different test subjects, normlly distributed based on height
(U17) Only test subjects in Swedish population
(P8, P9, P10, U26) Ask in a survey before/after
(U4, U5, U8, U9, U15) Turned off/ not allowed to use
(U1, U2, U6, U7, U13, U14, U16, U22, U23, S1, S2, S6, S8, S17) Measure
(C6) Participants used to adaptive cruise control
(U15) Not allowed to use comfort accessoaries
(U18) Test leader sits in the rear right passenger seat
(U19) No talking with test subject
(U21) No other activites allowed while driving
(U12) Mandatory use of seat belt
(U24, E5) AC set to 22 degrees and not allowed to change.
(U25) Automatic driving only
(E2,E3) Test during day in daylight
(E5) Windows and panos closed during drive
(E7, E8) No tests in extreme weather
(E8) Same route each test
(E10) Test performed outside of rush hour
(S15) Make person as comfortable as possible wearing Xsens

Appendix E: FMEA

Table E.1 and E.2 shows the FMEA worksheet and Tables E.3-E.5 shows the rating scales used to quantify occurrence (O), severity (S) and detection (D).

Table E.1 FMEA part 1.

FMEA - Driver Study Test Procedure											
Item name	**Item description**	**Mode id.**	**Failure mode**	**Failure cause**	**Local effect**	**Next effect**	**End effect**	**O**	**S**	**D**	**RPN**
Computers	Test computer to collect data and monitor test	Mode 1	Stop working	Hardware or software stop working	Loss of test data	Extra studies needs to be performed	Tight schedule, poor quality results	5	7	1	35
		Mode 2	Runs out of battery	Not charged enough prior to test or not charged during vehicle ride	Loss of test data, unable to collect all data	Extra studies needs to be performed	Cramped schedule, poor quality results	7	8	4	224
Seat measurement	Tool comprising of several cables, devices and a computer.	Mode 3	Not measuring correctly	Software error	Faulty data or loss of data	Not able to control	Poor quality results	2	2	8	32
		Mode 4	No contact to software	Software or hardware error, cables lose connection	Loss of test data	Extra studies needs to be performed	Thight schedule, poor quality results	9	2	1	18
Xsens	Motion capture system, comprising 17 sensors, straps, headband, gloves, t-shirt and a dongle conected to a computer.	Mode 5	Poor calibration	Calibration not working properly, due to hardware/software/ noise factors	Poor quality data gathered	Wrong outcomes during analysis	Invalid results	10	6	1	60
		Mode 6	Sensors move during test	Moved out of position by participant or surroundings	Incorrect data positions	Wrong outcomes during analysis	Invalid results	5	4	8	160
		Mode 7	Sensors runs out of battery	Not charged enough prior to test	Sensors will lose connection	Data loss	No result	2	7	3	42
		Mode 8	Software crash	Software problems, data overload	Program not answering	Data loss	No result	6	7	1	42
Participant	Test subject, driving the vehicle.	Mode 9	No-show	Participant doesn't show up	Test not performed	No data	Extra work finding new participant, tight schedule	8	8	2	128
		Mode 10	Interruption of test	Participant want to quit during test	Testdata can't be used	No data	Extra work finding new participant	1	8	1	8
		Mode 11	Not following directions	Distracted by test leader, or environment	Wrong driving route	Other situations than other participants	Test not homogenous	2	3	1	6
		Mode 12	Vehicle accident	Driver error or external factor, e.g., other driver	Injuries on vehicle and particpants	Stop test, go to hospital	No data, no vehicle, long term sickleave, potentially death	1	10	1	10

Table E.2 FMEA part 2.

Route	Route driven during test.	Mode 13	Delay during first or second drive	Test person is late, rush hour traffic or other obstacles	Too little time to charge sensors, interferance with rush hour	Sensors not fully charged during next test, test time prolonged	Sensors dying on second test. Dissatisfied participent stuck in traffic	7	4	1	28
		Mode 14	Rush hour	Test delayed	Longer test times	Dissatisfied participant	Dissatisfied participant, might delay test	8	2	1	16
		Mode 15	Not able to drive	Unpredicted drive conditions due to weather	Test not possible to perform	Find a new time for participant if possible	Test not performed at all or later, thight schedule	3	7	2	42
		Mode 16	Blocked/road work	Road work not known beforehand	Confusion while giving directions	Other route than decided	Test not homogenous	3	3	2	18
Test leader	Person leading the test.	Mode 17	Absence	Sickness among test leaders, over sleeping, running late	Test can't be performed	Tests need do be done by one person or be moved	One person will have a lot of work, or risk of not get all tests done	6	7	2	84
		Mode 18	Interrupt test	Motion sickness due to computer handling	Test leader can't engage in test as expected	Important steps can be missed	Failure in test	1	7	1	7
		Mode 19	Giving faulty road direction	Distracted by driver/ environment	Wrong driving route	Other situations than other participants	Test not homogenous	6	4	2	48
		Mode 20	Forgets protocol	Distracted	Important steps can be missed	Failure in test	Data can't be used	4	7	5	140
Lights	Lights on the vehicle	Mode 21	Stop working	Hardware error	No light on the road from vehicle	Bad sight and it is illegal	Could get a fine and could affect the drivers sight	1	2	4	8
Tires	Vehicle tires (four)	Mode 22	Worn out	Too old tires	Poor grip to ground	Vehicle goes off road	Car accidents and injuries	1	9	1	9
		Mode 23	Flat tire	Sharp item puncture tire	Not able to drive, interrupt tets	Need to switch tier or need help, test subject affected	Need to perform a new test	1	7	1	7
Air bags	Airbags in vehicle	Mode 24	Not protecting passengers properly due to equipment in vehicle	Equipment comes in between airbag and person.	Airbags safety function is lost	Person gets injured	Could in worse case lead to deadly injuries	1	10	10	100
Battery	Battery in vehicle	Mode 25	Runs out of battery	Computers draws to much energy	Car is not able to start	Test is delayed and need external support	Unessecary time spent, test delayed, dissatisfied test subject	1	8	5	40
Test equipment	All external test equipment brought in the vehicle: Cameras, computers, Xsens, devices.	Mode 26	Cameras block sight	Bad position of cameras	Driver get distracted or do not see external objects	Driver feel un-comfortable, could block dead angle	Driver feels stressed, injuries on vehicle/persons	5	9	7	315
		Mode 27	Equipment hits persons during hard break/crash	Bad fastening solutions of equipment	The equipment could get damaged, and persons in the vehicle could get hit by lose equipment	Perons could get injured	Could in worse case lead to deadly injuries	1	10	8	80

Table E.3 Occurrence scale

Probability of occurrance		
Probability	**Frequence**	**Factor**
Very Low	< 1 in 100	1
		2
Med Low	1 in 50	3
		4
Medium	1 in 20	5
		6
Med High	1 in 10	7
		8
High	1 in 5	9
	> 1 in 5	10

Table E.4 Severity scale

Severity if failure occurre		
Probability	**Consequence**	**Factor**
Effects hardly noticable	The failure has no impact on the test or test procedure. Test subject is unlikely to notice.	1
Failure is not important	The failure has little effect on the test or test procedure.	2 - 3
Resonably serious failure	The failure can result in impared quality of the test and the test procedure. Test subject will notice.	4 - 6
Serious failure	The failure can cause invalid test result.	7 - 8
Faliour with large negative effects	The failure may cayse injury and cause invalid test results.	9 - 10

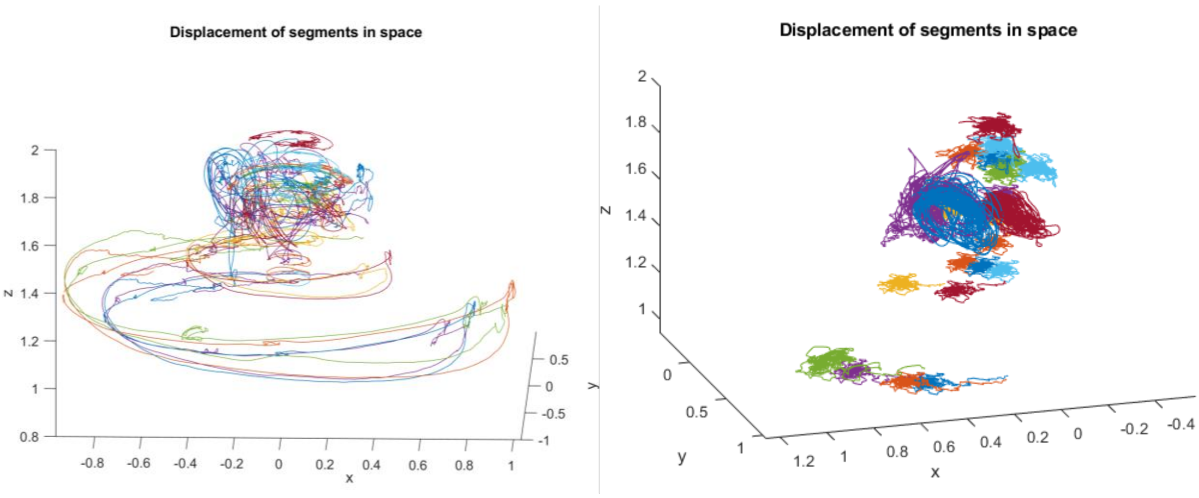
Table E.5 Detection scale

Failure detection likelihood		
Detection	**Probability**	**Rating**
Almost certain	Potential cause and subsequent FM will be detected	1
Very high	Very high chance of detecting caue and subsequent FM	2
High	High chance of detecting caue and subsequent FM	3
Moderately high	Moderately high chance of detecting caue and subsequent FM	4
Moderate	Moderate chance of detecting caue and subsequent FM	5
Low	Low chance of detecting caue and subsequent FM	6
Very low	Very low chance of detecting caue and subsequent FM	7
Remote	Remote chance of detecting caue and subsequent FM	8
Very remote	Very remote chance of detecting caue and subsequent FM	9
Absolute Uncertainty	Potential cause and subsequent FM cannot be detected	10

Appendix F: Xsens data rotation procedure

The reference frame for the orientation of the data points was given in the global frame, why the manikin rotated with the orientation of the car. It was desired to get the manikins position with respect to the car's frame, without including the motion of the car. This was accounted for by including the additional property sensor in the vehicle and using its frame as a reference frame instead. Through transformation matrix calculations in MATLAB, the coordinates could be rotated from the global frame to the property sensor frame, meaning the cars frame. The transformation is described next.

The coordinates in Xsens are given in the global frame, which means that the manikin rotates with the vehicle. When plotting the data, it looks like as in Figure F.1 a). It is desired to rotate the positions into a vehicle reference frame, to make the data look like Figure F.1 b).



a) b)

Figure F.1 a) Position data of displacement of segments in space, and b) rotated position data from Xsens.

To do this rotation matrices was used. Quaternions were transformed to rotation matrices according to Equation 2.1. A rotation matrix transforms coordinates in the following way, see Equation F.1, where p1 and p2 are two different positions.

Equation F.1 Transformation to rotation matrix

$$\begin{bmatrix} x1 & y1 & z1 \\ x2 & y2 & z2 \\ x3 & y3 & z3 \end{bmatrix} \begin{bmatrix} x_{p1} \\ y_{p1} \\ z_{p1} \end{bmatrix} = \begin{bmatrix} x_{p2} \\ y_{p2} \\ z_{p2} \end{bmatrix}$$

What the 3x3 matrix does in simple words is to perform three rotations around, x, y, and z-axis respectively, see Figure F.3.

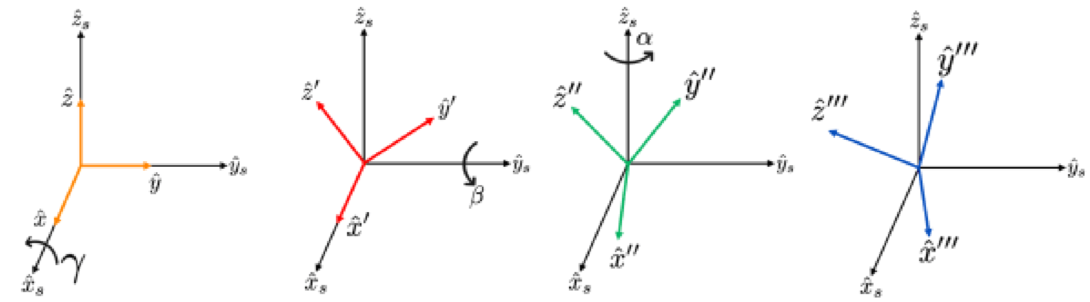


Figure F.3 Rotation in 3D space around x, y, and z-axis (Mecharithm, 2022).

For each point, we have the points orientation in terms of such a rotation matrix. By taking the inverse of that rotation matrix, for each time frame, and multiply that with all other positions in the plot from the same time, one can rotate back the points to that first points initial coordinate frame. And in this case, that coordinate frame is the property sensors coordinate frame that represents the vehicles coordinate frame. Mathematically, we can describe this as follows:

- The property sensors coordinate system at time, $t = 0$ is denoted S_0, and at time $t = i$ is denoted S_i. This coordinate system is given in terms of quaternions from Xsens, and the transformation matrix can simply be converted as described.
- The manikin's different segments position at time $t = i$ is denoted $M_{a,i}$ in the global frame, which is given in the Xsens data.
- The manikin's different segments position at time $t = i$ is denoted $m_{a,i}$ in the property frame, and this is the position we would like to calculate.

Given that the global position equals the property sensors orientation times the position in the property sensor frame:

$$M_{a,0} = S_0 \cdot m_{a,0}$$

The position in the property sensor frame can be calculated by taking the inverse orientation, or here, rotation matrix, by right multiplying it with the position in the global frame:

$$S_0^{-1} \cdot M_{a,0} = m_{a,0}$$

And this can be done for each time frame, i :

$$S_i^{-1} \cdot M_{a,i} = m_{a,i}$$

However, assume that at $t = 0$ the car would be standing in a very tilting slope. That would mean that, visually when plotting, the manikin would look very tilted. Therefore, as a final step, all the points were rotated back to the original global frame, by multiplying both sides with S_0:

$$S_0 \cdot S_i^{-1} \cdot M_{a,i} = S_0 \cdot m_{a,i}$$

Appendix G: Arm support frequency analysis in detail

The results from the arm analysis are described for each situation. A color-coding scheme is used to describe the different categories described in Section 3.5.1, and can be seen in Figure G.1. For the high frequency bar, the exact number is given in parenthesis and with a change of color if varieties exist.

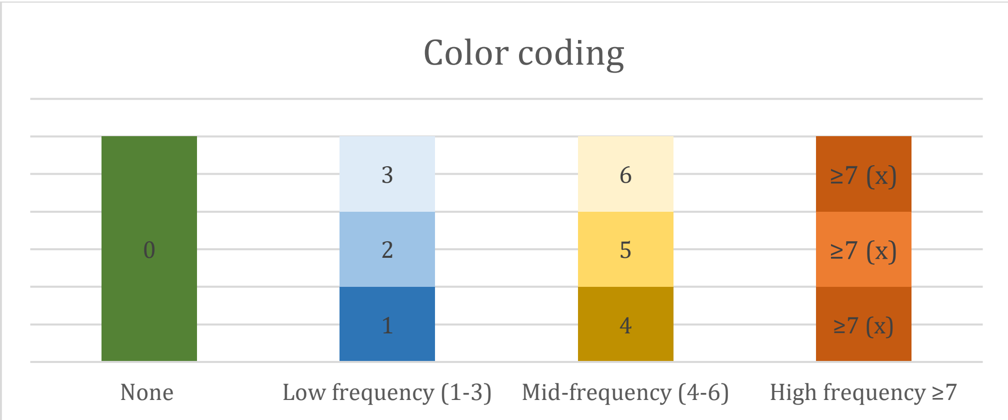
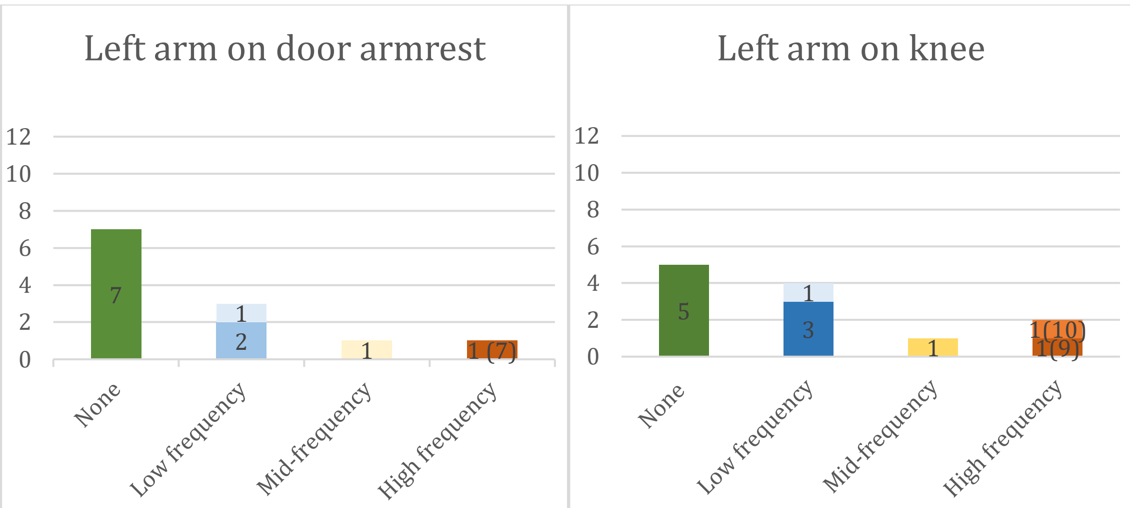


Figure G.1 Color coding of categories

City driving

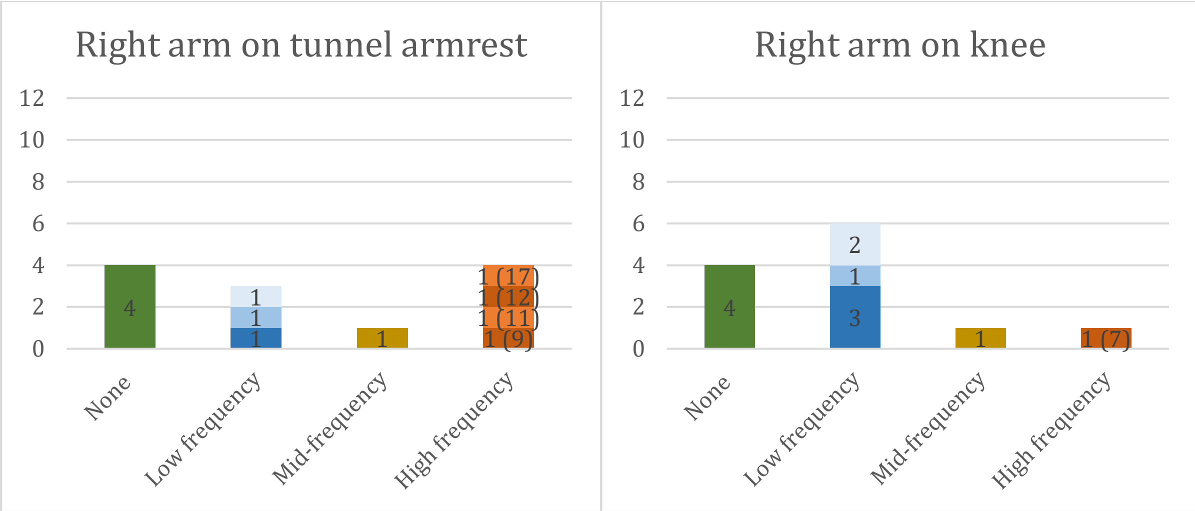
The result from the city driving shows that 7/12 do not use the left arm on the door armrest. Of the five participants that uses the armrest, three uses it in a low frequency, one in mid frequency and one in high frequency, see Figure G.2 a). 7/12 put the left arm in the knee, however, there is a tendency for not using the knee. For the frequency using the knee among participants, see Figure G.2 b).



a) *b)*

Figure G.2 Frequency among participants of using the left arm on the door armrest or knee for city.

The use of the tunnel armrest differs among the participants. 8/12 use it but the amount and time varies a lot. The frequency of usage of tunnel armrest can be seen in Figure G.3 a). 8/12 put the arm in the knee at least one time, meaning a low frequency can be generalized. The frequency distribution can be seen in Figure G.3 b).

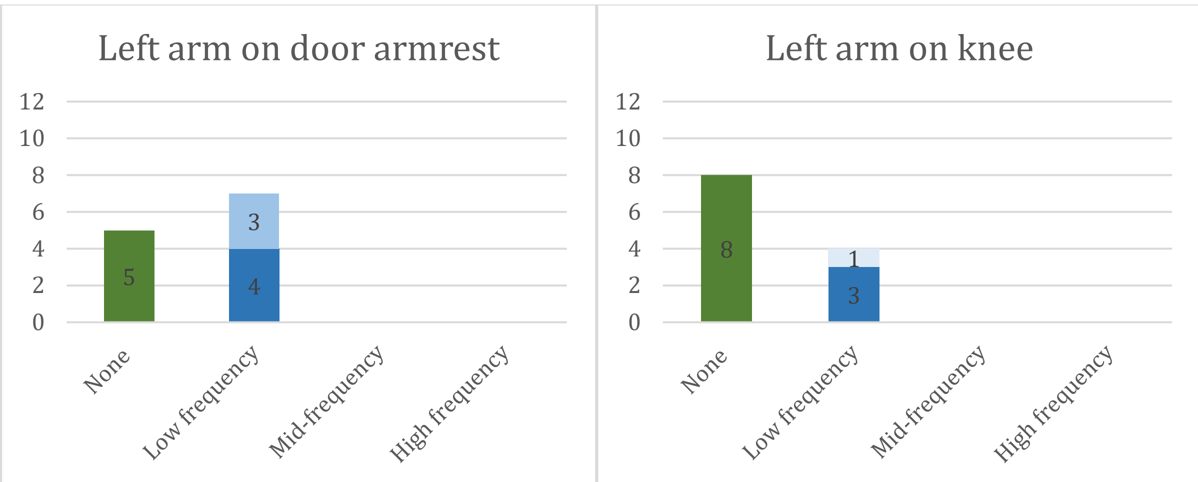


a) *b)*

Figure G.3 Frequency among participants of using right arm on the tunnel armrest or knee for city.

Highway driving

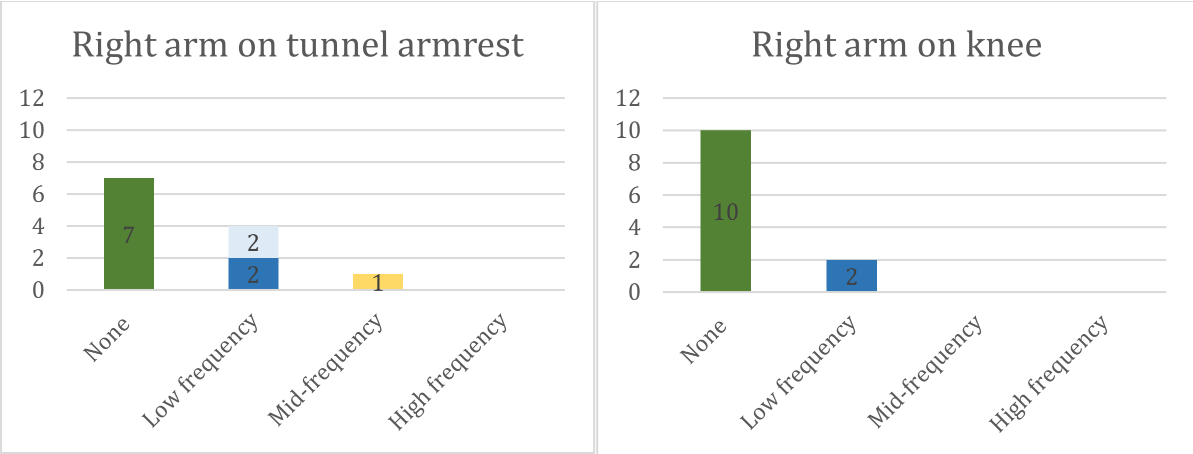
The highway drive shows that 7/12 use the left arm on the door armrest in a low frequency, see Figure G.4 a). However, 5/12 do not use the door armrest, which is seen as a tendency. One participant also used the window frame as support, however only during 4% of the ride. 4/12 of the participants put the left arm in the knee. However, 8/12 do not put the left arm in the knee and can be seen as a generalization, see Figure G.4 b).



a) *b)*

Figure G.4 Frequency among participants of using the left arm on the door armrest or knee for highway.

For the tunnel armrest, 7/12 do not use it, making it a generalization and the frequency distribution can be seen in Figure G.5 a). Regarding putting the right arm in the knee, 10/12 do not do it, see Figure G.5 b).

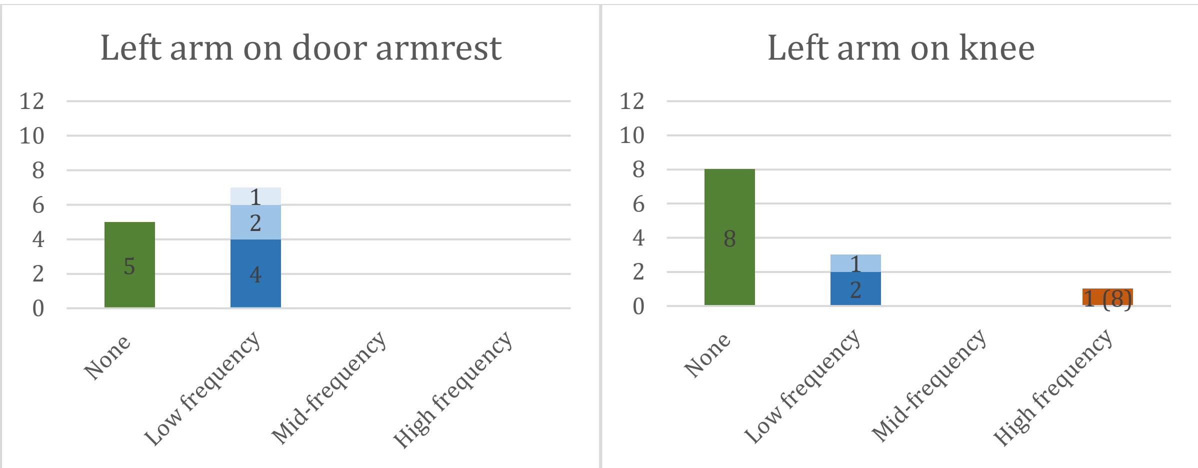


a) *b)*

Figure G.5 Frequency among participants of using right arm on the tunnel armrest or knee for highway.

ACC driving

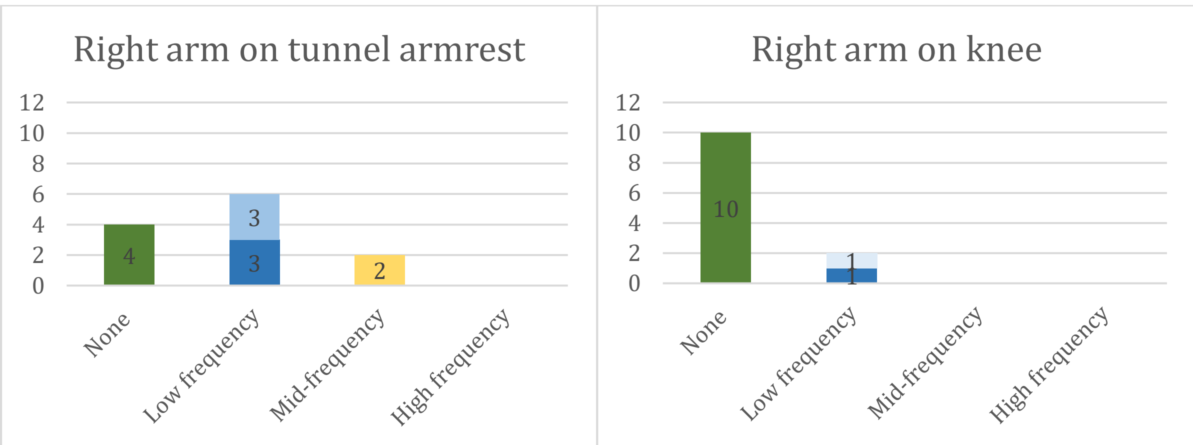
The results from the ACC driving shows that 7/12 use the door armrest in a low frequency, see Figure G.6 a). The rest, 5/12 do not use the door armrest indicating a tendency. 8/12 do not put the left arm in the knee, see Figure G.6 b).



a) *b)*

Figure G.6 Frequency among participants of using the left arm on the door armrest or knee for ACC

The tunnel armrest is used by 6/12, indicating a generalization of low frequency, see Figure G.7 a). A total of 10/12 does not put down the arm in the knee during ACC, see Figure G.7 b).



a) *b)*

Figure G.7 Frequency among participants of using right arm on the tunnel armrest or knee for ACC

Appendix H: Street views of crossings in the city

Street view of crossing between Lilla Bergsgatan and Haga Kyrkogata.

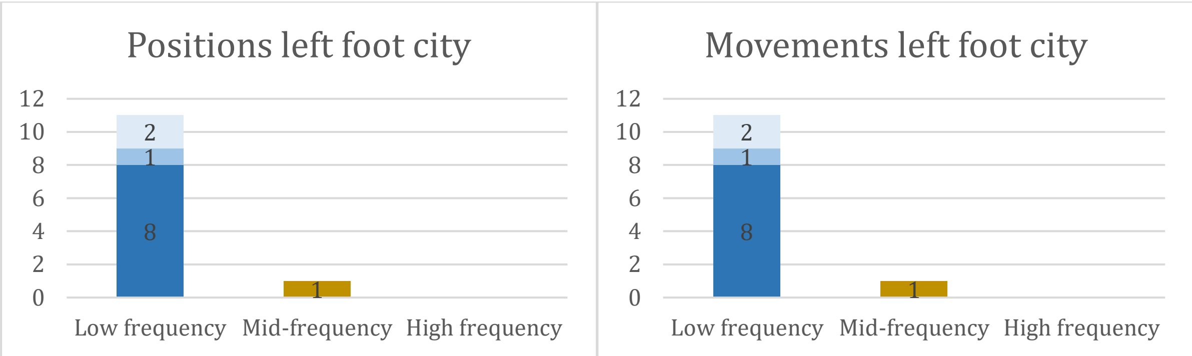
Street view of Vasagatan, viewing the crossing over Vasa Allén.

Street view of crossing between Karl Gustavsgatan and Parkgatan.

Appendix I: Feet frequency analysis for positions and movements in detail

City driving

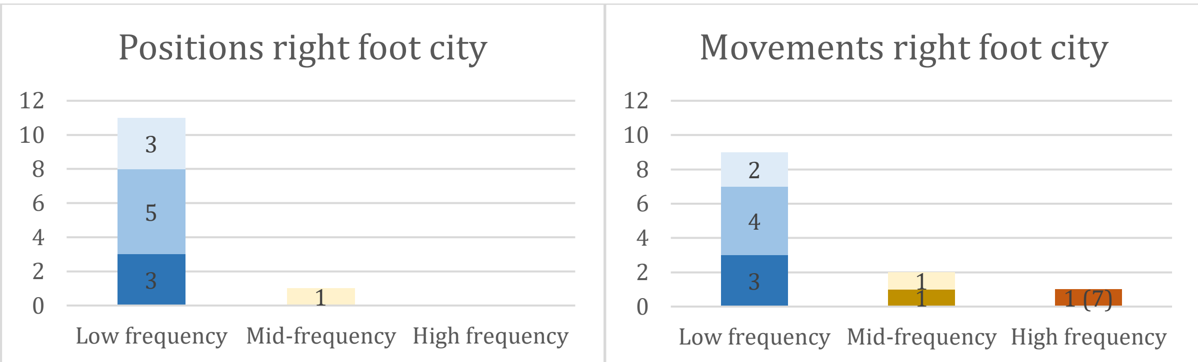
The city driving shows that for low frequency positions and movements 11/12 are represented. 8/12 have the left foot in exactly one position and with zero movements which can be seen as generalizations, see Figure I.1 a) and b).



a) *b)*

Figure I.1 Frequencies for left foot in city, a) positions and b) movements.

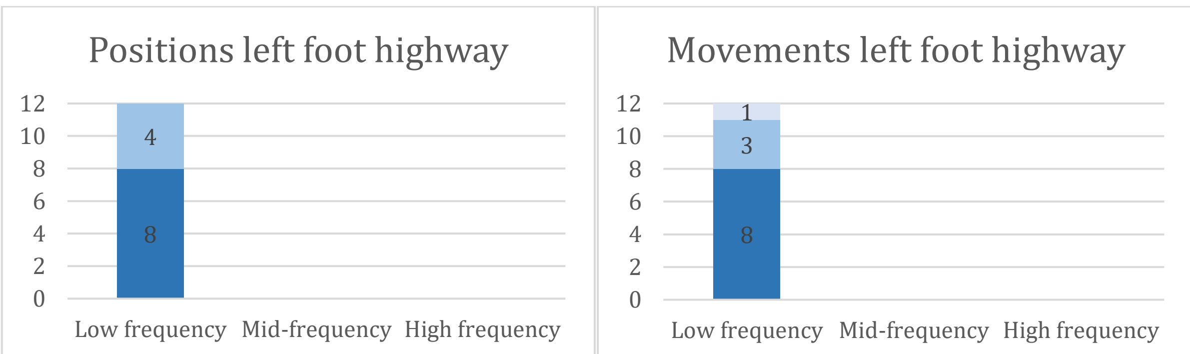
11/12 have the right foot in a low frequency of positions making it a generalization, see Figure I.2 a). 5/12 has the foot in exactly two positions which can be seen as a tendency. 9/12 of the participants move the right foot in a low frequency as a generalization, see Figure I.2 b).



a) *b)*

Figure I.2 Frequencies for right foot in city, a) positions and b) movements.

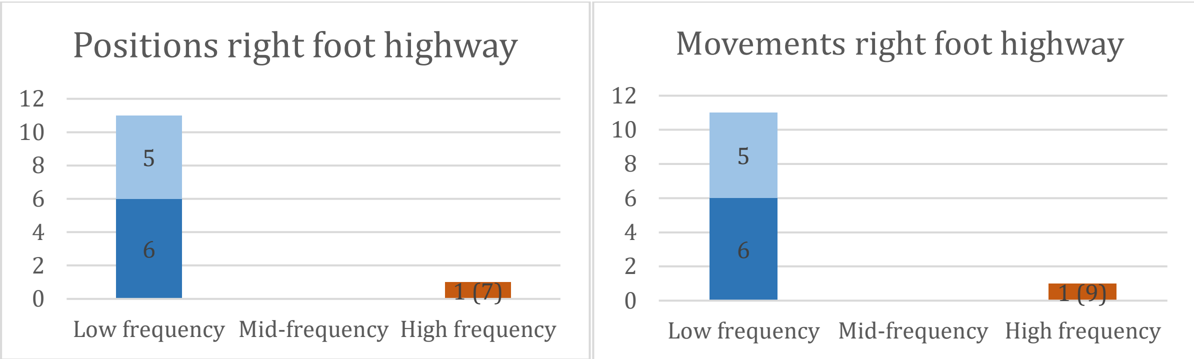
For highway driving, 12/12 has the left foot in a low frequency of positions and movements, see Figure I.3 a) and b). The foot was in exactly one position with zero movements among 8/12 participants which is a generalization.



a) *b)*

Figure I.3 Frequencies for left foot on highway, a) positions and b) movements

The right foot is positioned in a low frequency among 11/12 participants. The foot is in exactly one position among six of the participants making it a generalization. Five had the foot in exactly two positions making it a tendency, see Figure I.4 a). The movements follow the same pattern, see Figure I.4 b).

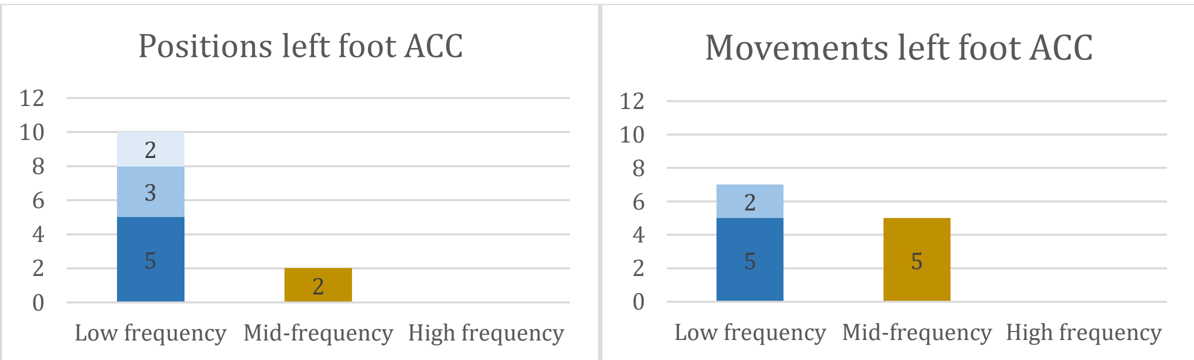


a) *b)*

Figure I.4 Frequencies for right foot on highway, a) positions and b) movements

ACC driving

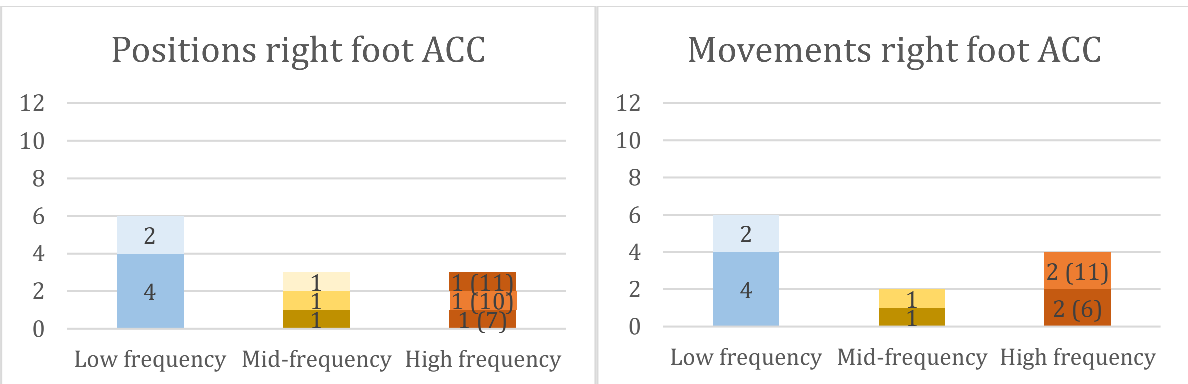
During the ACC driving a low frequency is represented by 10/12 which is a generalization, see Figure I.5 a). It is seen that 5/12 has the left foot in exactly one position which can be seen as a tendency. 7/12 move the left foot zero or one times representing a low frequency, where zero movements show a tendency, see Figure I.5 b). The rest moves it three times which also is a tendency.



a) *b)*

Figure I.5 Frequencies for left foot on highway with acc, a) positions and b) movements

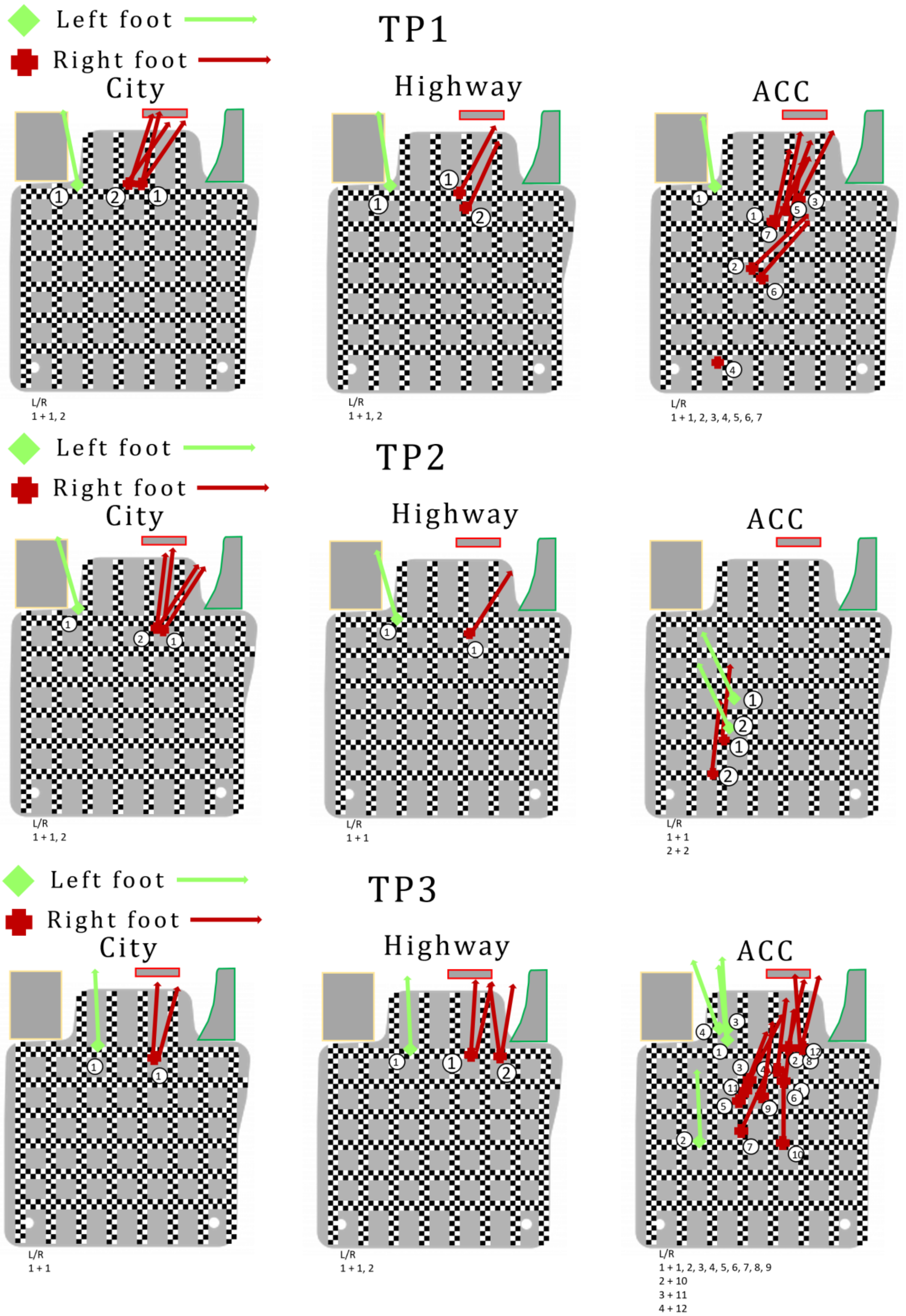
None of the participants have the right foot in only one position. 6/12 has the foot in a low frequency of positions see Figure I.6 a). There are equally number of participants having the foot in mid-frequency as high frequency of positions. Six participants, move the feet in a low frequency, see Figure I.6 b). However, four participants move the right foot in a high frequency.

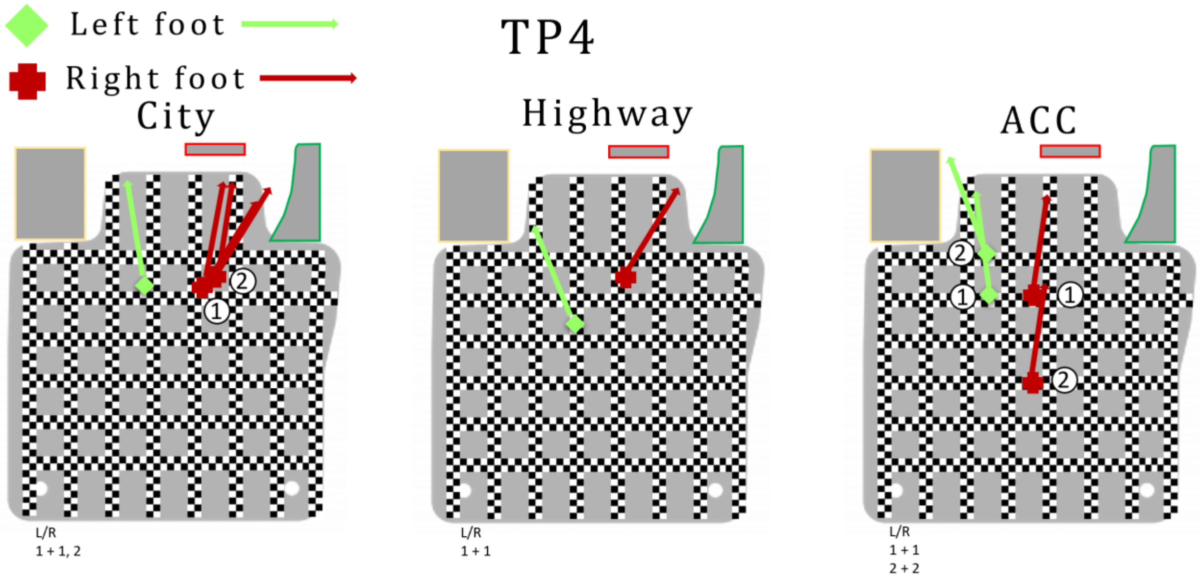


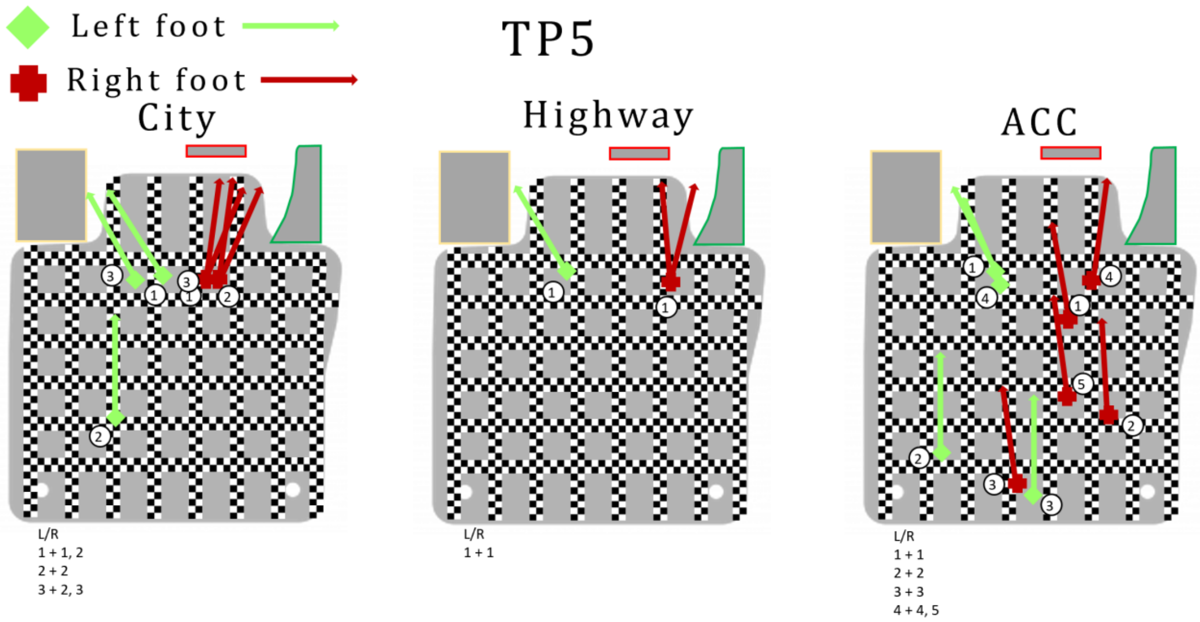
a) *b)*

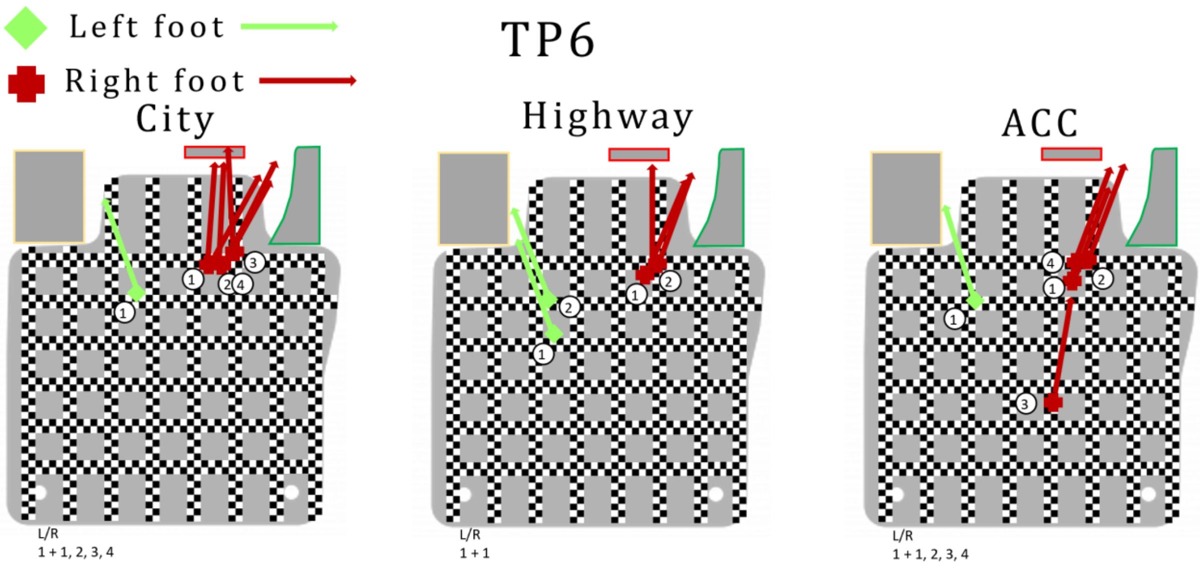
Figure H.11 Frequencies for right foot on highway with acc, a) positions and b) movement

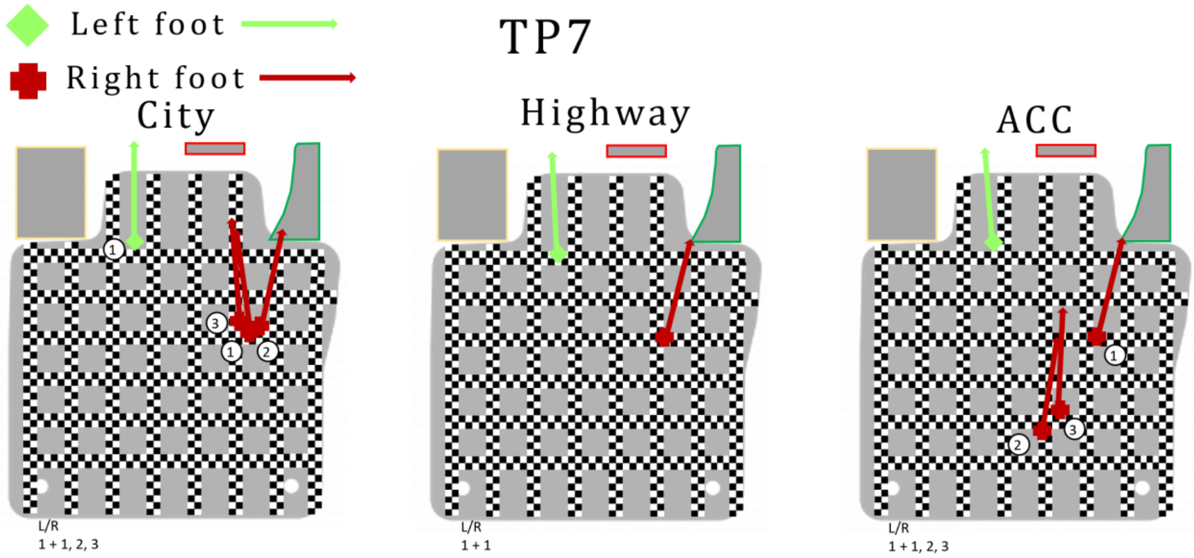
Appendix J: Full analysis of feet position and movement

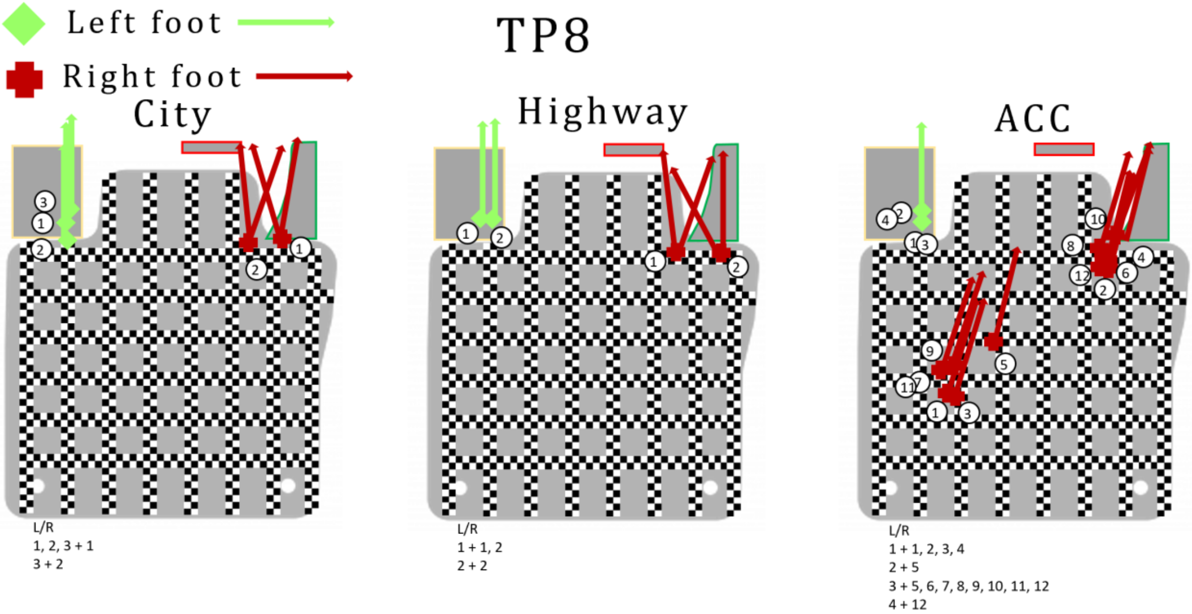


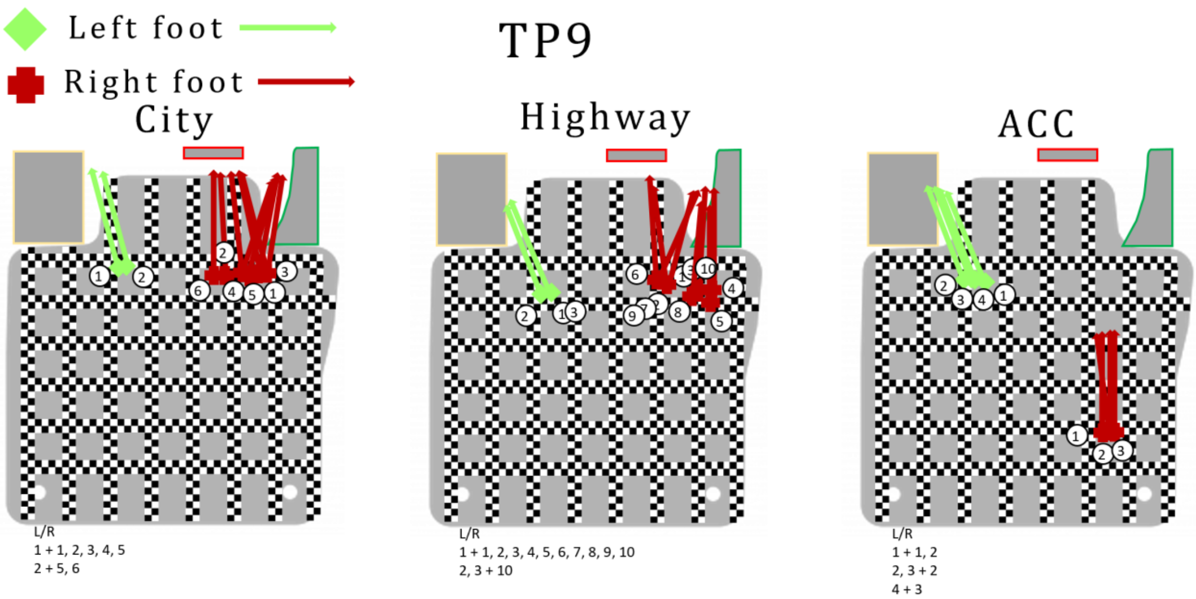

Left foot
Right foot
TP4
City
Highway
ACC
L/R
1 + 1, 2
L/R
1 + 1
L/R
1 + 1
2 + 2

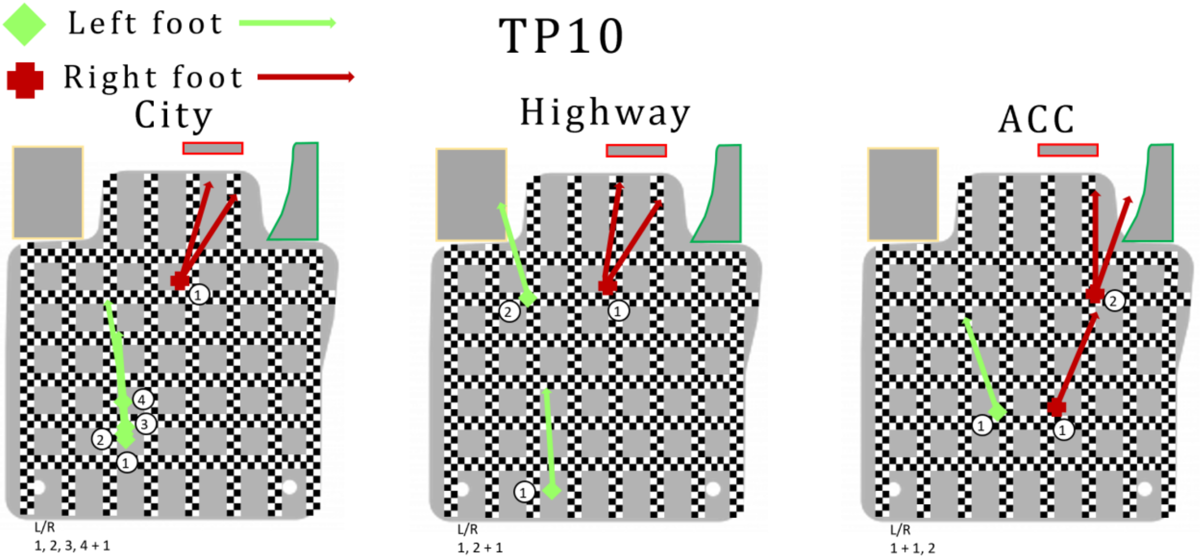

Left foot
Right foot
TP5
City
Highway
ACC
L/R
1 + 1, 2
2 + 2
3 + 2, 3
L/R
1 + 1
L/R
1 + 1
2 + 2
3 + 3
4 + 4, 5

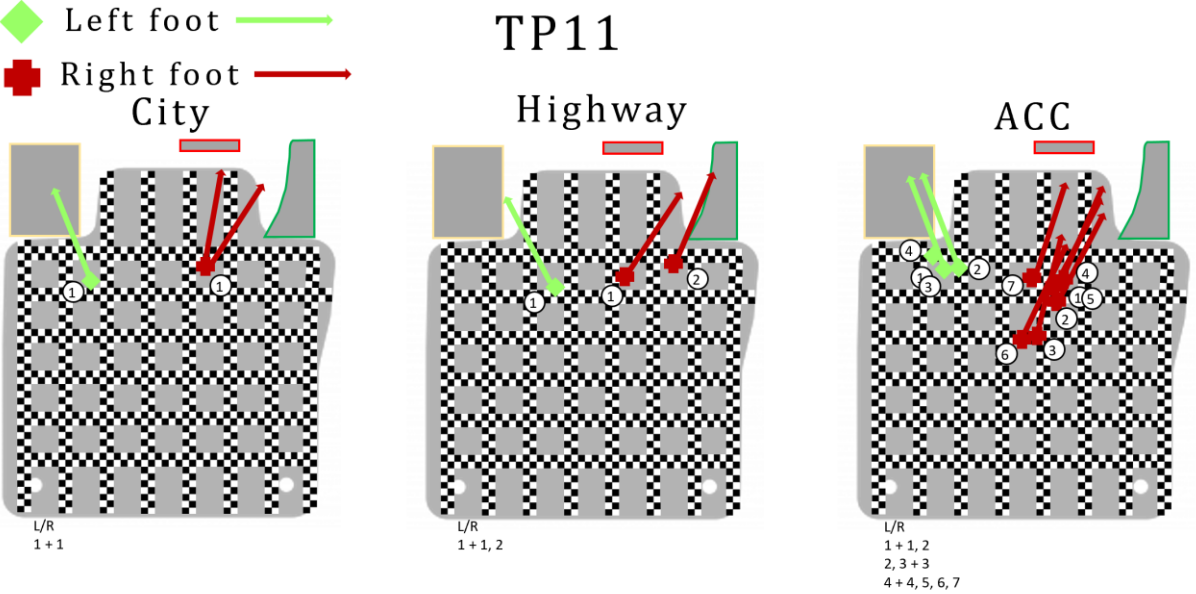

Left foot
Right foot
TP6
City
Highway
ACC
L/R
1 + 1, 2, 3, 4
L/R
1 + 1
L/R
1 + 1, 2, 3, 4

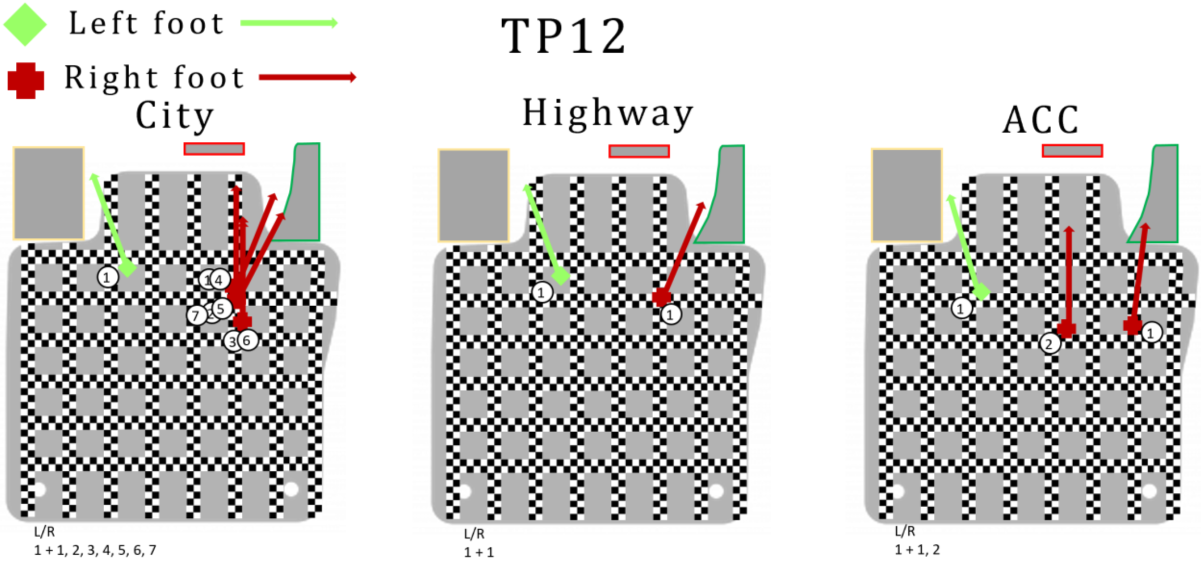

Left foot
Right foot
TP7
City
Highway
ACC
L/R
1 + 1, 2, 3
L/R
1 + 1
L/R
1 + 1, 2, 3


Left foot
Right foot
TP8
City
Highway
ACC
L/R
1, 2, 3 + 1
3 + 2
L/R
1 + 1, 2
2 + 2
L/R
1 + 1, 2, 3, 4
2 + 5
3 + 5, 6, 7, 8, 9, 10, 11, 12
4 + 12


Left foot
Right foot
TP9
City
Highway
ACC
L/R
1 + 1, 2, 3, 4, 5
2 + 5, 6
L/R
1 + 1, 2, 3, 4, 5, 6, 7, 8, 9, 10
2, 3 + 10
L/R
1 + 1, 2
2, 3 + 2
4 + 3


Left foot
Right foot
TP10
City
Highway
ACC
L/R
1, 2, 3, 4 + 1
L/R
1, 2 + 1
L/R
1 + 1, 2


Left foot
Right foot
TP11
City
Highway
ACC
L/R
1 + 1
L/R
1 + 1, 2
L/R
1 + 1, 2
2, 3 + 3
4 + 4, 5, 6, 7


Left foot
Right foot
TP12
City
Highway
ACC
L/R
1 + 1, 2, 3, 4, 5, 6, 7
L/R
1 + 1
L/R
1 + 1, 2

Appendix K: Summary of differences and similarities

Similarities among all three situations

- All drivers have a generalized hand position in category 2 and 3, seen in Figure 4.33.
- Hip point and buttocks do not move significantly in general for any of the situations.
- Left foot position: Low frequency (1-3 positions).
- Left foot movement: Low frequency (1-3 movements).
- Left foot placement: Generally, uses footrest, within yellow for all situations, and further refinements as within purple area for highway and ACC.
- Right foot position: Low frequency.
- Right foot movement: Low frequency.
- Right foot placement: In city and highway – within blue area with orange box as a preferred placement.

Similarities between highway and ACC only

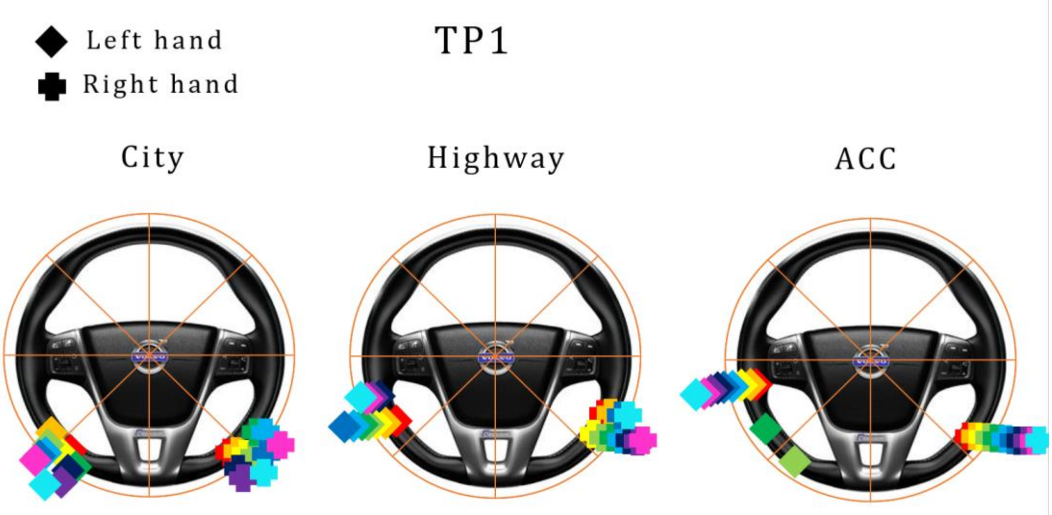
- Upper body remains still
- Left door armrest is used
- Left knee is not used as arm support

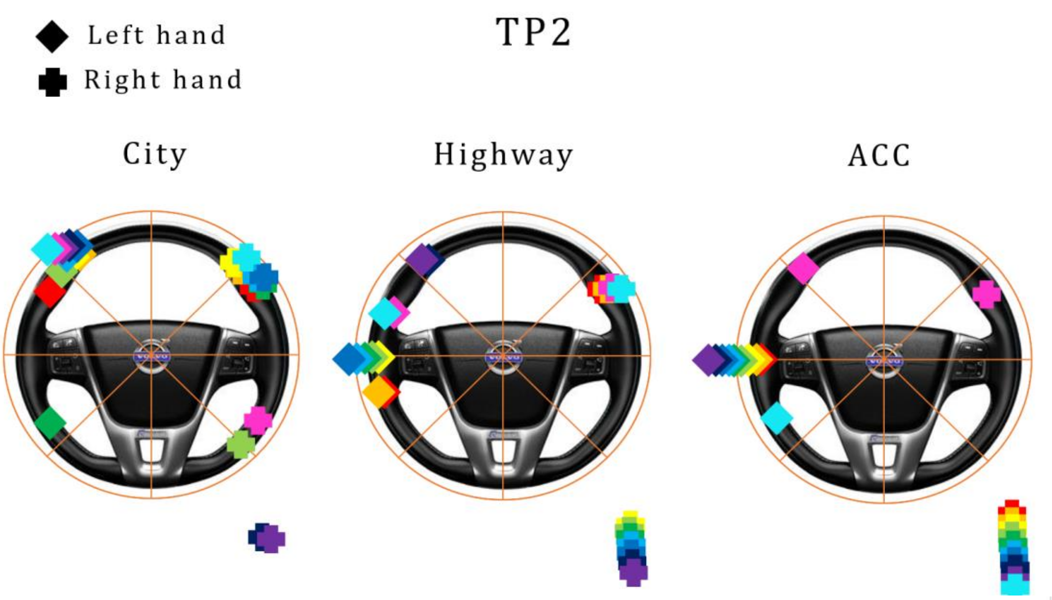
Differences between the three situations

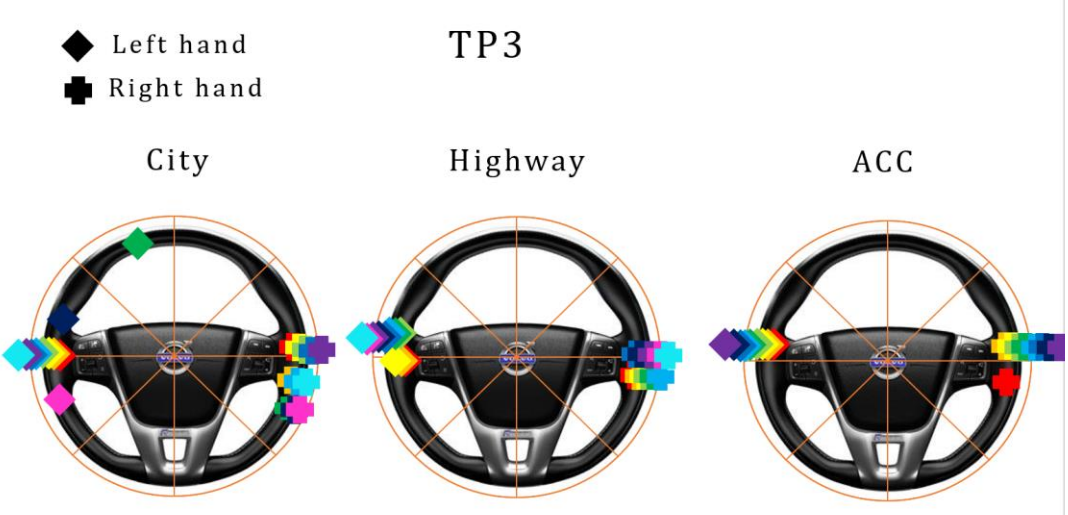
- Hands move more between positions in the city than in highway and ACC.
- City has an additional position determined as a tendency, which is category 1, seen in Figure 4.33.
- Upper body is leaning forward in certain events in city but not in highway and ACC.
- Left door armrest is not used in city, but in highway and ACC.
- Left knee as arm support is used in city, but not in highway or ACC.
- Right tunnel armrest is used more in city and ACC, but for shorter periods in the city.
- Right knee is only used in the city, and is generally not used on highway or ACC.
- Right foot placement: Not possible to generalize a position for ACC – but as a suggestion along the turquoise line.

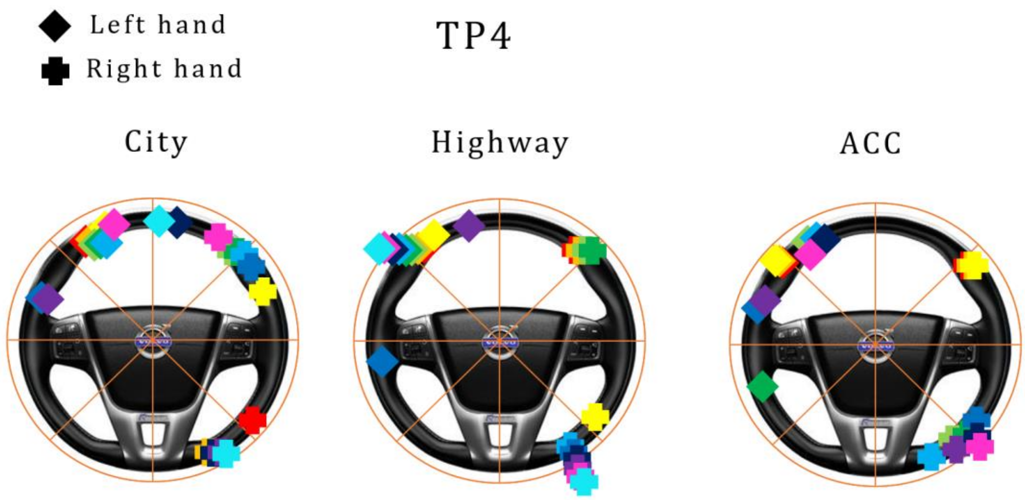
Appendix L: Full analysis of hand position

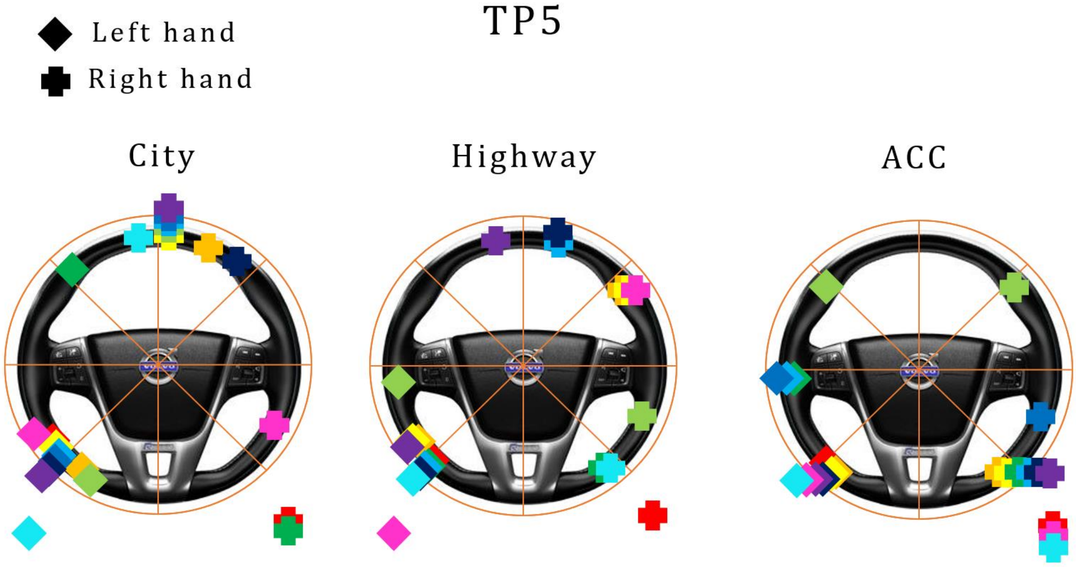
The following figures shows the full hand annotation, described in Section 3.5.1.

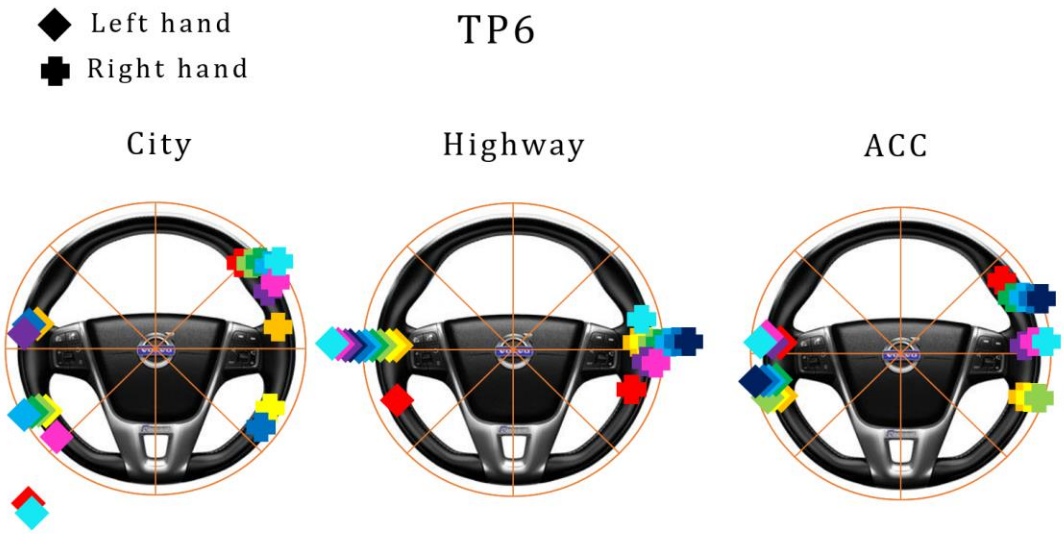




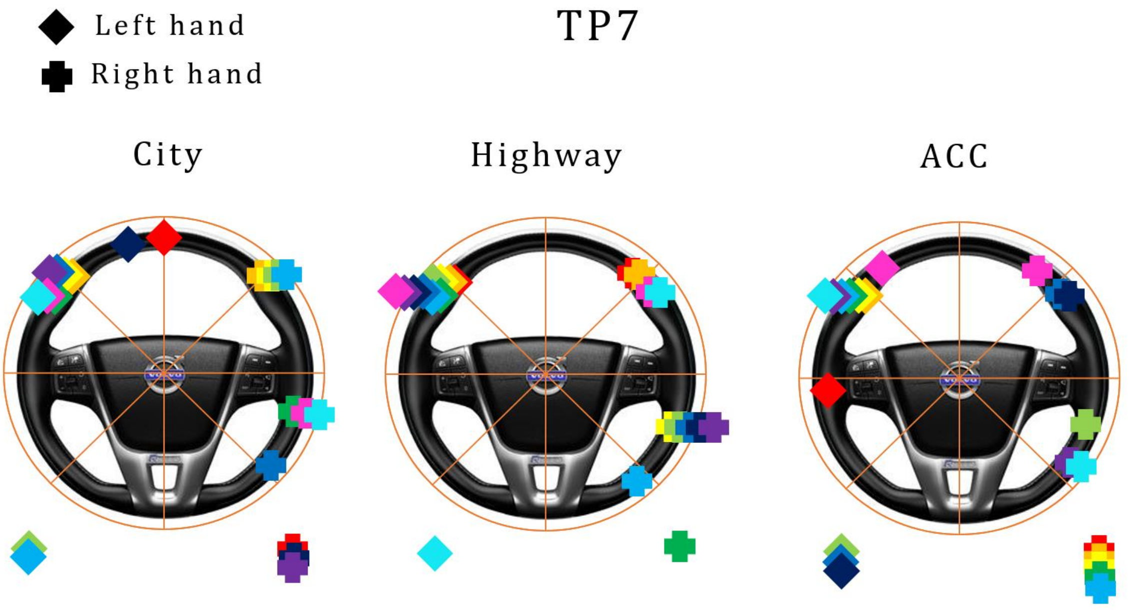



Left hand
Right hand
TP4
City
Highway
ACC

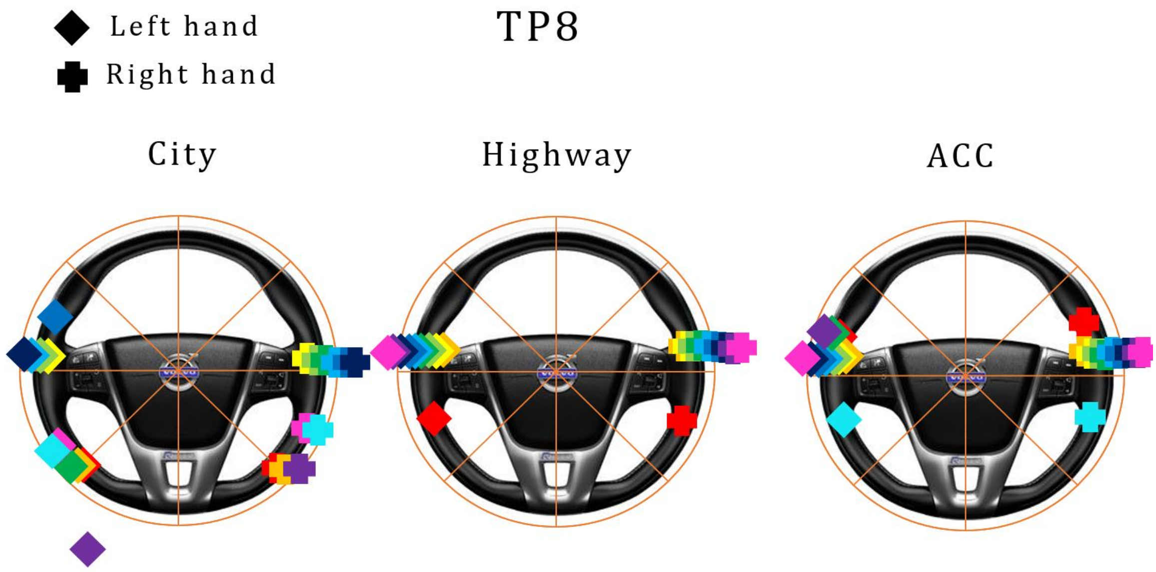

Left hand
Right hand
TP5
City
Highway
ACC


Left hand
Right hand
TP6
City
Highway
ACC

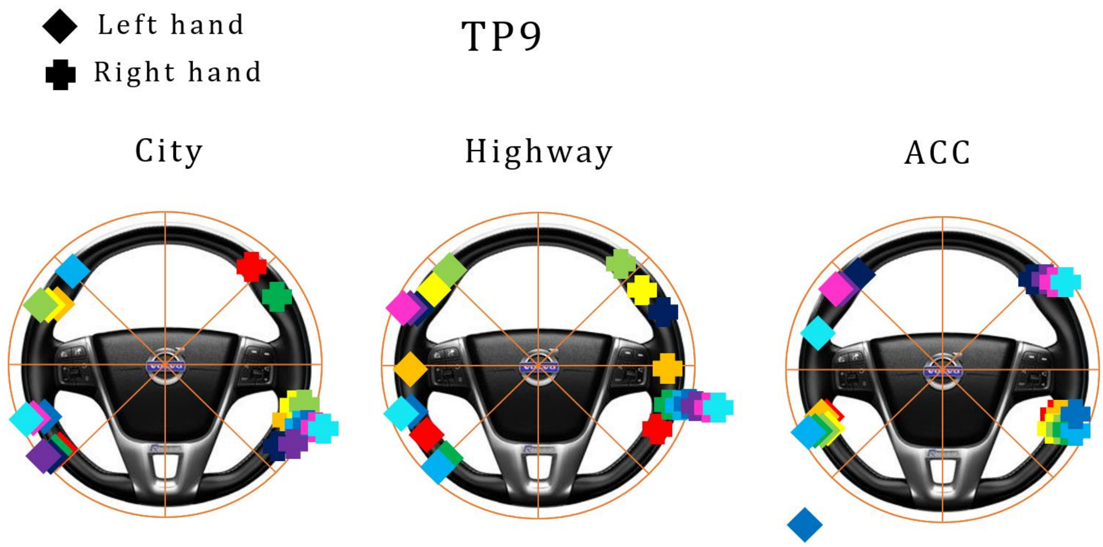
TP7


Left hand
Right hand
City
Highway
ACC

TP8

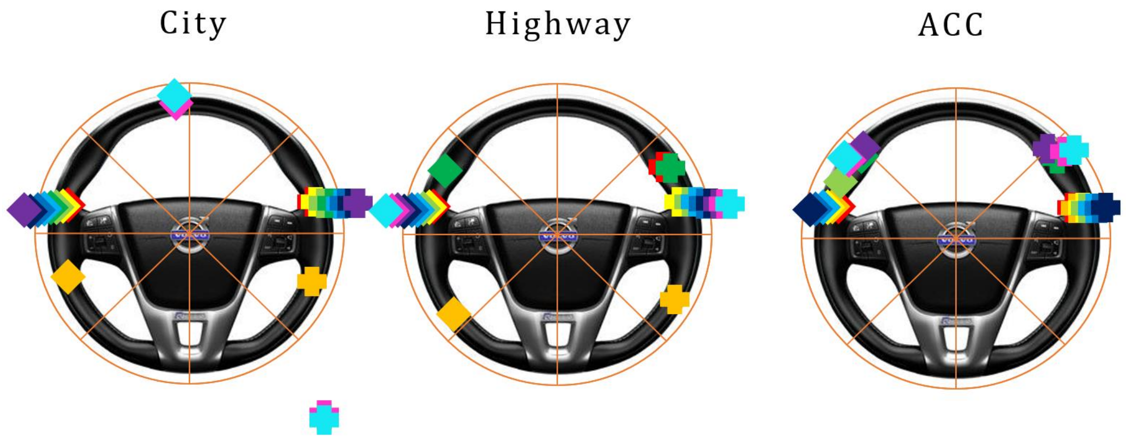

Left hand
Right hand
City
Highway
ACC

TP9


Left hand
Right hand
City
Highway
ACC

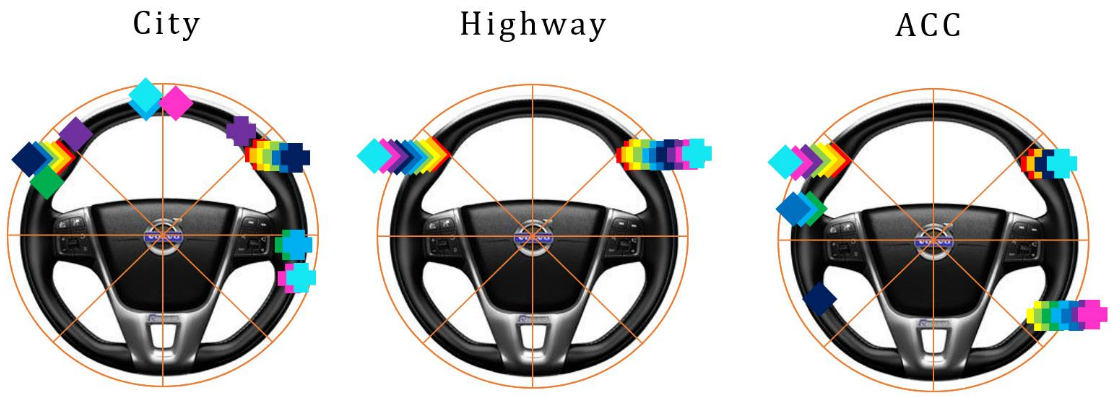
◆ Left hand
✚ Right hand

TP10



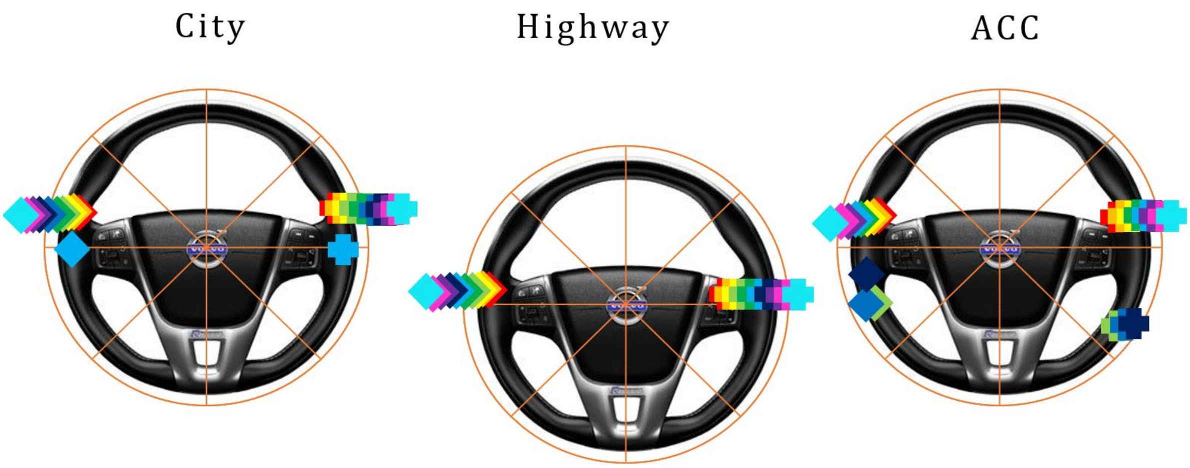
◆ Left hand
✚ Right hand

TP11



◆ Left hand
✚ Right hand

TP12



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