Evaluating the Safety and Performance of Electric Micro-Mobility Vehicles

Comparing E-bike, E-scooter and Segway based on Objective and Subjective Data from a Field Experiment

Master's thesis in Systems, Control and Mechatronics

LUCAS BILLSTEIN
CHRISTOFFER SVERNLÖV

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se

Master's thesis 2021:36

Evaluating the Safety and Performance of Electric Micro-Mobility Vehicles

Comparing E-bike, E-scooter and Segway based on Objective and Subjective Data from a Field Experiment

LUCAS BILLSTEIN
CHRISTOFFER SVERNLÖV

Department of Mechanics and Maritime Sciences
Division of Vehicle Safety
Unit of Crash Analysis and Prevention
Chalmers University of Technology
Gothenburg, Sweden 2021

Evaluating the Safety and Performance of Electric Micro-Mobility Vehicles
Comparing E-bike, E-scooter and Segway based on Objective and Subjective Data from a Field Experiment
LUCAS BILLSTEIN
CHRISTOFFER SVERNLÖV

Supervisor: Alexander Rasch, Department of Mechanics and Maritime Sciences
Supervisor: Christian-Nils Åkerberg Boda, Autoliv
Examiner: Marco Dozza, Department of Mechanics and Maritime Sciences

Master's Thesis 2021
Department of Mechanics and Maritime Sciences
Division of Vehicle Safety
Unit of Crash Analysis and Prevention
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: A picture of the e-bike, e-scooter and Segway used in the study.

Typeset in LaTeX
Department of Mechanics and Maritime Sciences
Gothenburg, Sweden 2021

Evaluating the Safety and Performance of Electric Micro-Mobility Vehicles
Comparing E-bike, E-scooter and Segway based on Objective and Subjective Data from a Field Experiment
LUCAS BILLSTEIN
CHRISTOFFER SVERNLÖV
Department of Mechanics and Maritime Sciences
Chalmers University of Technology

Abstract

The rapid increase in popularity of electric micro-mobility vehicles has led to an increasing amount of injuries. A large proportion of injuries are related to the vehicles themselves, therefore, a thorough investigation of their safety is needed. The purpose of this thesis was to collect conclusive evidence for or against the safety level of e-bikes, e-scooters and Segways in terms of stability, maneuverability and rider comfort. A regular bike was used as well to compare with. Rider kinematics data were recorded by sensors mounted on each of the vehicles together with a stationary LIDAR sensor. Thirty-four voluntary participants performed four different tasks with each of the vehicles. Afterwards, they filled in a questionnaire regarding the experienced safety and performance of the vehicles. A set of performance indicators were studied to be able to compare the vehicles and establish the safety of each vehicle.

Results suggest that the e-bike and the e-scooter performed very well in terms of rider comfort and stability. The e-scooter also had good maneuverability, but lacked in safety due to bad braking performance. The least safe vehicle was the Segway which was rated the least safe by the participants and performed the worst according to the performance indicators in high speed scenarios. There were however scenarios at low speed, with the Segway that had comparable results with the other vehicles.

Future studies could include other micro-mobility vehicles or other tasks. Experiments in a more naturalistic settings could provide valuable data to extend the results presented in this thesis. The results from this thesis could be used to help improve the design of electric micro-mobility vehicles and contribute to guidelines for infrastructure design and policy making.

Keywords: safety, performance, micro-mobility, e-scooter, e-bike, Segway

Acknowledgements

Thank you to our supervisor Alexander Rasch for supporting our work with thoughtful insights and recommendations, and for always gladly answering to questions. Your support and positive comments helped us get through stressful periods of this thesis.

Thank you to our supervisor from Autoliv, Christian-Nils Åkerberg Boda for all the help and discussion about technical details such as the orientation estimate. Your humor and positive attitude was always welcome. Thank you Christian-Nils for always thinking one step further and challenging us throughout the whole thesis.

Thank you to Marco Dozza, our examiner, for showing up on our meetings with great insights and ideas. Thank you so much for making this master's thesis possible.

Thank you to all three, Alexander, Christian-Nils and Marco for being very easy to work with.

Thank you to Alessio Violin for giving an introduction to the instrumentation.

Thank you to our opponents, Felicia Österberg and Paula Ek, for their great discussion after our presentation and their detailed feedback on our report.

Thank you to SAFER for advertising our poster that was made to gather participants.

Thank you to all the participants that participated in the field experiment. Without all 34 of you, this thesis would not have turned out the way it did.

Thank you to the kind employees at Autoliv which listened to our "mid-term" presentation and gave great feedback.

We would also like to thank Trafikverket for sponsoring this thesis through the Skyltfonden Project "Characterizing and classifying new e-vehicles for personal mobility (TV 2019/21327)".

Lucas Billstein, Gothenburg, June 2021
Christoffer Svernlöv, Gothenburg, June 2021

Contents

List of Figures

List of Tables

1
Introduction

1.1 Background

In recent years, electric micro-mobility vehicles have increased in popularity drastically [1, 2]. Micro-mobility vehicles refers to small, lightweight vehicles which usually operates at a maximum of 25 km/h. The benefits of these vehicles are their size, maneuverability, affordability and the existence of multiple ride-sharing services. There are several different types of electric micro-mobility vehicles, for example electric bike (e-bike), electric scooter (e-scooter), electric skateboard and Segway.

The e-bike is one of the most common electric micro-mobility vehicles and it still increases in popularity. According to Lee et al., bike makers and sellers are seeing increases in sales of e-bikes [3]. They note that in Germany, e-bike sales in 2018 was up by 36 percent compared to the previous year, which corresponds to nearly one million e-bikes and in the first half of 2019 another million e-bikes were sold.

A different vehicle that has become very popular the last years is the electric scooter. The increase in popularity of e-scooters has also led to more injuries. According to Farley et al., the estimated visits due to e-scooter accidents in emergency departments in the US has increased from 4881 visits in 2014 to 29 628 visits in 2019 [4]. A major factor of the increase in popularity of e-scooters is due to ride-sharing services that distributes the scooters in larger cities. This could be seen by reported accidents in Stockholm where e-scooter companies started to rent out e-scooters in 2018 [5]. In 2018, only four accidents related to e-scooter were reported, while in 2019 (until 19 September), 150 accidents were reported [6].

An electric micro-mobility vehicle that differs a lot from e-scooter and e-bike is the Segway. The Segway was invented in 1999 and was mostly used for tourist tours and law enforcement [7]. However, its price was comparably high, which probably is why the total sales of the original model, the Segway PT, were only 140 000 [8]. The movement of the Segway is controlled only by leaning which differs a lot from for example e-bike and e-scooter [9].

In Sweden, to be classified as bikes, electric micro-mobility vehicles must have a maximum speed of 20 km/h [10]. E-bikes are however an exception and are allowed to assist with motor power up to 25 km/h. The characteristics of electric micro-mobility vehicles are however often very different compared to a regular bike. A regular bike is for example self-stable at some speeds while this is never the case for the e-scooter [1]. Previous participant studies have shown that the e-scooter may be behind conventional bikes in braking capabilities [2, 11]. There is, however, no conclusive evidence from a larger amount of participants.

1.2 Previous Research

This thesis is a continuation of Alessio Violin's thesis from 2020 [11]. Violin developed a data collection and data analysis procedure for comparing the safety of e-bikes, e-scooters and Segways in terms of stability, comfort and maneuverability. The data collection and analysis Violin did, were based on test data from eight different persons. The conclusion drawn from his thesis was that the Segway was easy to maneuver at low speed but increased in difficulty as speed increased based on rider experience. The e-scooter was perceived by the participants almost as safe as the e-bike with a high maneuverability level and high comfort. Poor braking capabilities were the factor that made the e-scooter less safe than the e-bike. The e-bike was the most stable and comfortable in general but struggled a bit with lateral motion and low speed maneuvering. A more extensive testing needs to be performed to validate the results.

The goal of the study done by Garman et al. was to investigate the influence of the rider kinematics and vehicle dynamics on e-scooter stability [2]. They designed a test course to simulate an urban environment which required multiple maneuvers. The maneuvers were turning, slalom, acceleration, deceleration, stopping and unexpected braking. A commercially available e-scooter instrumented with sensors was used to measure acceleration, velocity, steering angle, roll angle and GPS location. Out of the eight participants in the study, seven gave data that could be used for the analysis. The results show that when riding straight on a flat path the e-scooter show high levels of stability. During the low speed turning and slalom maneuver it was noted that the participants had to use counterbalance with their body to stabilize the vehicle. Results needs to be validated on a larger set of participants.

A similar field experiment as the one performed during this thesis has been done before by Kovácsová et al. [12]. They investigated cycling performance of middle-aged versus older participants during tasks where stabilization skills were important. In their study, they specifically looked at and compared conventional bikes and e-bikes. The authors came to the conclusion that cyclists rated themselves to be better than the average cyclists of the same age. Another conclusion that was drawn was that the participants' self-reported cycling skills were different to the actual cycling performance. Participants had a lower roll rate while cycling at low speed with the e-bike than with the conventional bike which might indicate difficulties with stabilizing the vehicle. When participants were to ride at their own pace, they adopted a higher speed on the e-bike than the conventional bike. The participants reached the desired speed faster on the e-bike than on the conventional bike while accelerating. This indicates that they need to exert more force on the conventional bike to accelerate. This indicates a lower comfort for the regular bike than on the e-bike.

Miller et al. conducted an experiment to investigate the rider behavior of 20 Segway operators: ten experienced operators and ten novices[13]. The experiment specifically investigated the approach speed and clearance that Segway devices exhibit on encountering a variety of obstacles on the sidewalk. They concluded that both novice and experienced Segway riders were capable of traveling past the various obstacles. Research containing more parameters regarding the safety of the Segway is required in order to draw any conclusions regarding the general safety of the vehicle.

1.3 Research Question

The research question that was investigated in this thesis is:

> *"How safe, in terms of stability, maneuverability and rider comfort, are e-bikes, e-scooters and Segways based on sensor data and user experience?"*

1.4 Purpose

The purpose of this thesis is to collect evidence for or against the safety level of e-bikes, e-scooters and Segways in terms of stability, maneuverability and rider comfort.

1.5 Scope

There are plenty of electric personal mobility vehicles available, for example e-bikes, e-scooters, Segways, electric skateboards, electric motorcycles and electric trikes just to name a few. In this thesis only the first three, the e-bike, e-scooter and Segway, are used in the evaluation of safety levels.

The participants included in the experiments conducted in this thesis are recruited in the Gothenburg area, Sweden, and have to meet some inclusion criteria.

To ensure the safety of the participants the experiments are performed in an area with little to none traffic and no hazardous tests are performed.

2

Methodology

2.1 Vehicle Selection

Vehicle selection was made with a large influence from last year's thesis by Alessio Violin [11] since the vehicles used in his study were available and mounted with sensors. The vehicles were chosen based on popularity, possibility of mounting sensors and the ease of learning to ride.

2.1.1 E-bike

The chosen e-bike is a Monark Karin 3-VXL, shown in Figure 2.1, which is powered by an EGOING-motor in the front wheel. The EGOING-motor helps the rider reach a maximum speed of 25 km/h. This e-bike was chosen because of its ease of use and it is an common model. Monark Karin 3-VXl has 5 different levels (1-5) of electric assistance from the motor. The higher the level is, the higher the electric assistance is. The e-bike is equipped with a coaster brake for the back wheel and a disc brake for the front wheel.

Figure 2.1: Monark Karin 3-VXL electric bike.

As a reference, the e-bike was also used in the experiment as a conventional bike by turning off the electric assist by setting the assistance mode of the e-bike to 0.

2.1.2 E-scooter

The e-scooter that was used is the Ninebot KickScooter ES2, shown in Figure 2.2. It has a maximum speed of 25 km/h. Although this is higher than 20 km/h which is the highest speed to be classified as a bike in Sweden, it is still a commonly used model. It has two levers on the handlebar, one for acceleration and one for braking. There are three different power modes available on the Ninebot Kickscooter ES2. The three modes are sport mode, standard mode and speed limit mode. The sport mode gives the most power and speed but results in lower range while the speed limit mode gives the least power and speed but results in the longest range. The standard mode is in between the sport and speed limit mode. The e-scooter is equipped with an electric brake for the front wheel and a mechanical brake for the back wheel. The mechanical brake is integrated in the rear fender where the rider steps on it to initiate the brake.

Figure 2.2: Ninebot Kickscooter ES2.

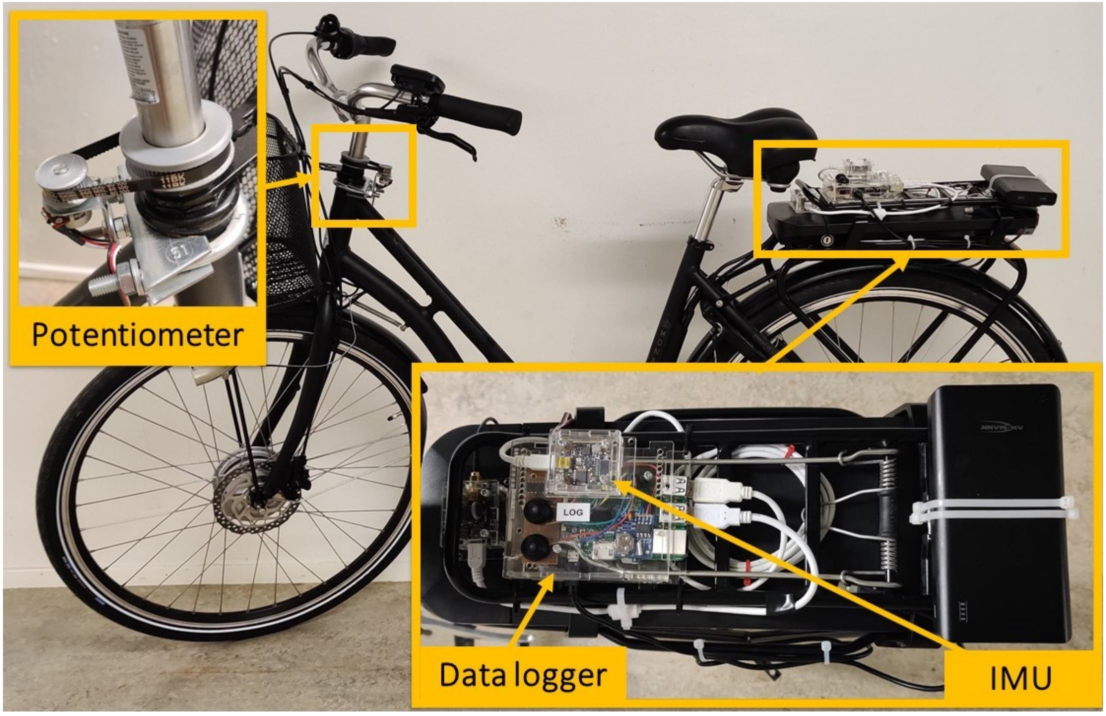
2.1.3 Segway

The last electric micro-mobility vehicle that was examined was the Segway Ninebot S, shown in Figure 2.3. According to Segway's store, it is a smart self-balancing electric transporter which is extremely portable, easy to learn and exciting to ride [14]. It is not so common on the street, but is chosen due to its interesting balancing and steering mechanism. The Segway Ninebot S has three different modes: sports mode, new rider mode and safe mode with speed limits of 19, 10 and 7 km/h respectively. By gently leaning forward and backward one controls the velocity of the Segway Ninebot S. This model of the Segway does not have a handlebar. Instead, the steering bar is located between the legs and to turn, one leans gently left or right against the steering bar.

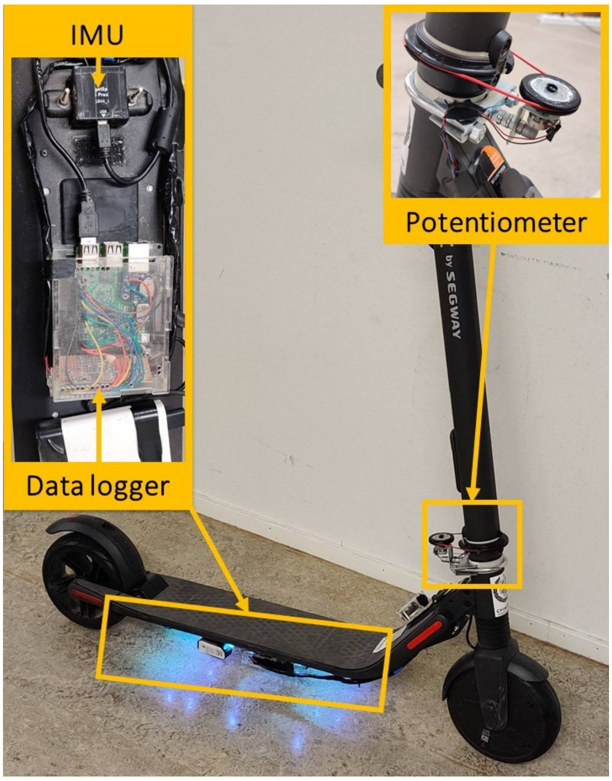
Figure 2.3: Segway Ninebot S.

2.2 Data Acquisition System

The vehicles were equipped with sensors to collect kinematics data. The sensors mounted on the vehicles are Inertial Measurement Units (IMUs) and potentiometers. The potentiometer was used to measure the steering angle and steering rate. IMUs were used to be able to measure angular velocities and accelerations of the vehicles. It was also used to estimate the orientation of the vehicles. The mounting locations of the sensors can be seen in Figure 2.4. All three vehicles are also equipped with a data logger which is used to record the sensor data.



(a) E-bike/bike



(b) E-scooter

(c) Segway

Figure 2.4: Vehicle instrumentation.

A light detection and ranging sensor (LIDAR) was used to track the planar motion of the vehicles. During the experiments, the LIDAR was static and mounted on a tripod, 80 cm above the ground, to the side of the test area. In order to get the best view with the LIDAR it was placed in the middle of the 100-meter test track.

2.2.1 Data Logger

The data logger is the device logging the data coming from the different sensors. The data logger is a Raspberry Pi 3 model B, which is a single-board computer with a Quad Core 1.2GHz Broadcom BCM2837 64bit CPU and 1GB RAM, using open-source software[1] to save all the data to a USB memory stick. The open source software is written in Python and uses the robotic operating system (ROS).

The data logger has two buttons, one for starting and stopping the recording of data and the other one has two functions. While the data logger is recording data, the second button works as a flag button meaning it gives an output of 1 when pressed and 0 otherwise. The flag feature was used to synchronize the data signals with the LIDAR's data signals. The other function of the second button is to power off the data logger completely which can only be done if the data logger is not recording any data. The data logger can be seen in Figure 2.5.

Figure 2.5: Data logger which is mounted on the e-bike. On top of the data logger is an IMU mounted.

2.2.2 Inertial Measurement Unit

The IMU used in this thesis was the PhidgetSpatial 3/3/3 1044_1B. An IMU is used to measure acceleration, angular rates and magnetic field in three dimensions. Technical specifications for the IMU can be seen in Table 2.1.

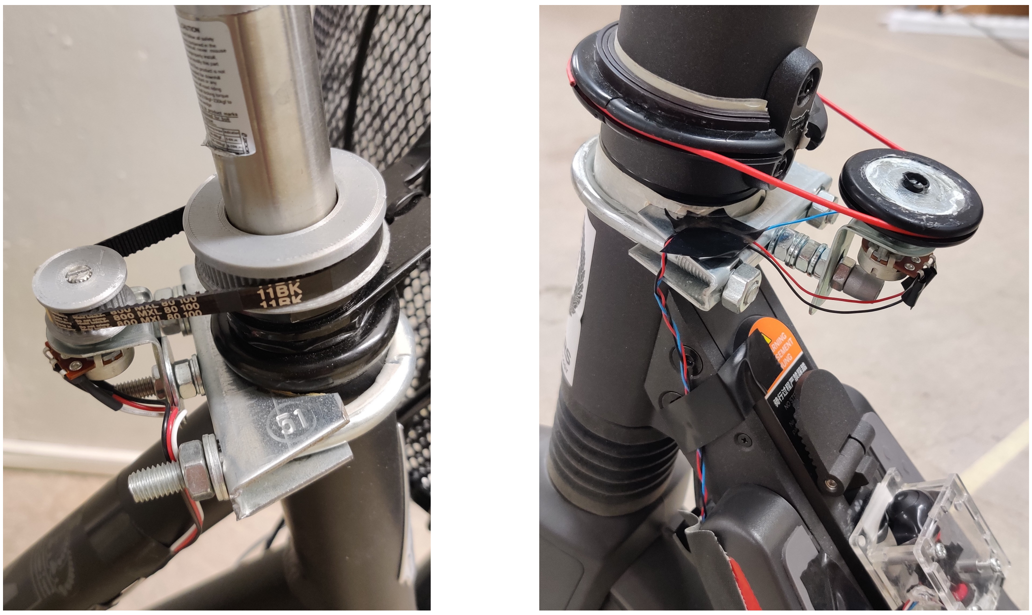
[1] `https://github.com/ruvigroup/div_datalogger`

Accelerometer	
Acceleration measurement maximum range	$\pm 2.5g$
Acceleration measurement resolution	$76\mu g$
Gyroscope	
Gyroscope speed maximum range	$\pm 100°/s$
Gyroscope resolution	$0.0031°/s$
Magnetometer	
Magnetic field maximum range	$\pm 49.2G$
Magnetometer resolution	$1.5mG$
Magnetometer noise	$16mG$

Table 2.1: Technical specifications of PhidgetSpatial 3/3/3 1044_1B.

2.2.3 Steering Angle Sensor

The e-scooter and the e-bike are both instrumented with a steering angle sensor in the form of a potentiometer which can be seen in Figure 2.6. A belt system connected to a wheel mounted on the potentiometer and the handlebar makes the internal resistance of the potentiometer vary depending on the angle of the handlebar. An analog to digital converter (ADC) was used to measure the voltage across the poles of the potentiometer, induced by the varying internal resistance. The voltage is then converted into steering angle by linear fitting. The ADC used was a 10 bit ADC connected to the Raspberry Pi through a serial peripheral interface (SPI) connection.



(a) E-bike **(b)** E-scooter

Figure 2.6: Steering angle sensor mounted on the steering stem of the e-bike and e-scooter.

To convert the voltage from the potentiometer to a steering angle, a calibration recording was made. The voltage was recorded when the handlebar was moved from -30 degrees to 30 degrees in 5-degree steps where 0 degrees are when the handlebar is straight. The linear function from the voltage to the corresponding angles that had the least squared error was then used to convert voltage to degrees. This calibration was made both for the e-scooter and e-bike.

Due to the lack of a handlebar on the Segway, no potentiometer was mounted. On the Segway, the steering angle would compare to the stick inclination angle which was measured using the IMU mounted on the top of the steering stick. The IMU encased in a plastic case can be seen in Figure 2.7.

Figure 2.7: IMU mounted on the top of the steering stick of the Segway.

2.2.4 LIDAR

In order to record the motion of the vehicles, a LIDAR sensor was used. The LIDAR used was the Hokuyo UXM-30LXH-EWA which has a guaranteed detection range of 30 m and a maximum detection range of 120 m. The LIDAR has a scanning angle of 190° and an angular resolution of 0.125°. The logging platform for the LIDAR was run on a Raspberry Pi 3 Model B implemented as a ROS package. The logging software is the same as for the data loggers on the vehicles. A button was connected to the Raspberry Pi which was used to synchronize the data from the LIDAR and the vehicles. The button was also used to indicate when a maneuver started and ended. To start the LIDAR, a web interface is used where you can either visualize the LIDAR data in real time or record the data. The LIDAR mounted on a tripod can be seen in Figure 2.8.

Figure 2.8: LIDAR mounted on a tripod.

2.3 Participant Selection

Participants that met the requirements in the list below were invited to the study.

- Be at least 160 cm tall.
- A maximum weight of 85 kg.
- Be 18-50 years old.
- Be able to ride a bicycle.
- Do not have any physical disabilities.
- Have not suffered from serious traffic accidents.
- No symptoms of Covid-19 in the last two weeks before the study.

The height criteria and the weight criteria were from limitations of the vehicles. The bicycle used was not suited for participants below 160 cm and the Segway had a maximum weight limit of 85 kg. The requirement, *to be able to ride a bicycle*, was set to have a good reference for the electric micro-mobility vehicles and to reduce the training time needed. The two requirements, *not have any physical disabilities* and *not have suffered from serious traffic accidents* were set primarily due to ethical concerns. The age limit was set to reduce the risks of injuries and to limit the number of between-subject factors. Apart from these requirements, a gender balance was desired since both males and females use electric micro-mobility vehicles and could potentially have different riding behaviors.

2.4 Experimental Protocol

All of the experiments with the participants were done on a pier located at Pumpgatan 2 in Gothenburg, Sweden. The pier is a paved road for cyclists and pedestrians with little to no traffic. This section will cover a description of the four tasks the participants performed, how the test track was set up prior to participants arriving at the scene as well as how the experiments were done in detail with each participant.

2.4.1 Description of Tasks

The participants performed four different tasks on each vehicle. The different maneuvers that the participants performed are adapted from work by Kovácsová et al. [12] and Rasch et al. [15].

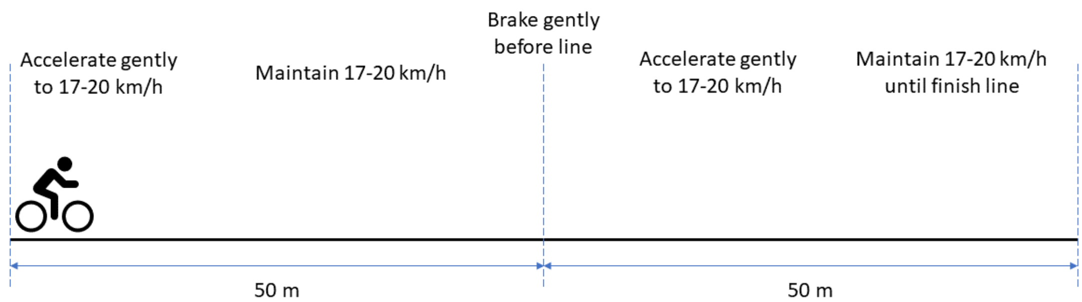


Figure 2.9: The first task which is to study the behavior of constant high speed, comfortable braking and comfortable acceleration.

The first task could be seen in Figure 2.9. It starts with the rider accelerating gently until a speed between 17 km/h to 20 km/h has been reached and then continue in the same speed before braking to stop before a line in a gentle way. Then accelerating gently up to the interval 17-20 km/h again. This task was chosen to indicate how the different vehicles behave in high speed, an expected braking situation and accelerating. This is a common real life scenario when approaching a stop sign. A small speed interval is set to give a fair comparison of the different vehicles, but also make it easy for the rider to complete the task. The risk of setting an absolute speed is that the rider gives a lot of attention to the speed monitor to not deviate from the requested speed.

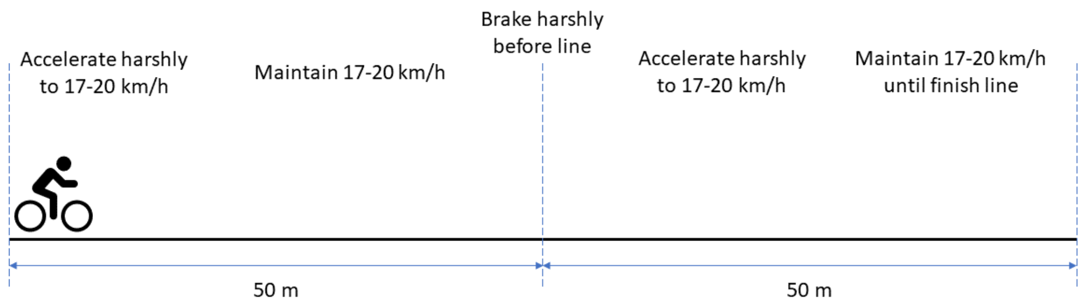


Figure 2.10: The second task which studies the behavior of constant high speed, harsh braking and harsh acceleration.

The second task, which is the harsh maneuver, can be seen in Figure 2.10. It starts with the rider accelerating harshly to 17-20 km/h and maintaining that speed. The rider should then brake harshly and come to a complete stop before a line. Then they should proceed with accelerating harshly up to 17-20 km/h again and maintain that speed until they reach the finish line. In a real life scenario this could represent a person that perceives a stop signal too late due to not being attentive. This task also shows the braking and accelerating capabilities of the different vehicles.

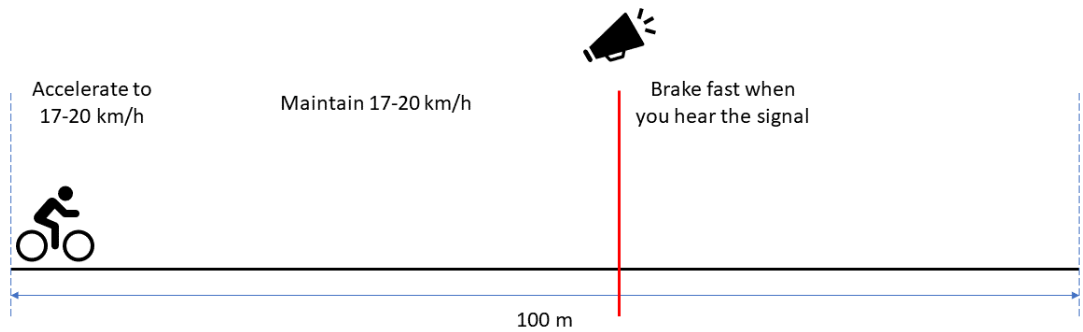


Figure 2.11: The third task which studied the behavior of a harsh acceleration and an unexpected harsh brake.

The third task could be seen in Figure 2.11. It starts with accelerating to the interval 17-20 km/h. The rider then keeps a constant speed until it hears a sound signal, which is that one of the experimenters shouts stop. When the rider hears the sound signal they should brake harshly. This task represents an unexpected stop. In a real life scenario it is important to have a short braking distance to avoid a potential crash, but also that the braking is stable to avoid falling.

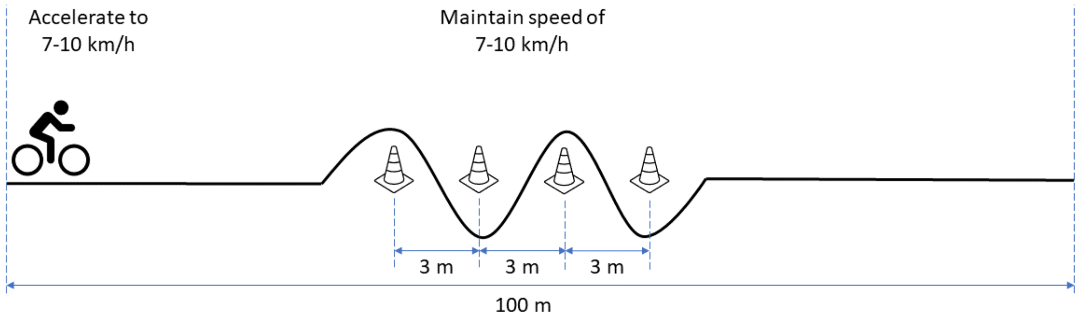


Figure 2.12: The fourth task which studies the behavior during consecutive turns.

The fourth and final task is shown in Figure 2.12. Here the rider should accelerate to 7-10 km/h and try to maintain this speed while completing a slalom course around four cones. Here the performance of the vehicles in turns are studied. This task could represent passing obstacles or pedestrians in a real setting.

2.4.2 Set Up

Three lines were drawn on the ground using chalk to indicate start, brake and finish locations. The start line is where all the tasks were started from and the finish line is the end of the test track. The brake line is the line used in the gentle and harsh maneuver to indicate where the participants should have come to a complete stop. Four small cones were placed 3 meters apart, one by the brake line, two before the brake line and one after the brake line. The LIDAR was positioned parallel to the traffic cones aligned with the brake line to best capture the motion of the vehicles in the most important part of the maneuvers which is acceleration, deceleration and slalom. An illustration of the test area can be seen in Figure 2.13 and a photo of the middle part of the test area can be seen in Figure 2.14.

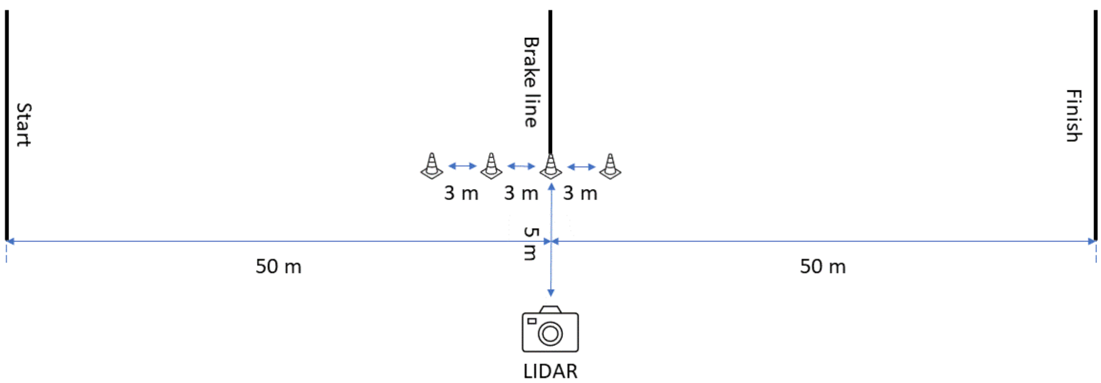


Figure 2.13: Illustration of the test area.

Figure 2.14: Photo of the middle part of the test area.

Before each participant arrived, the LIDAR was tested to see that it was aligned correctly and worked properly. Lamp posts on the pier was used to make sure the LIDAR was parallel to the road using the visualize function of the web application. To reduce the spread of COVID-19 the handlebars of the vehicles and the seat of the bike were disinfected and the experimenters had visors or protective masks.

2.4.3 Main Experiment

When a participant arrived at the test location, a short introduction was given about the experiment. The participant was then asked to read through and sign a consent form. After the consent form was signed, the experimenter and the participant went through the experimental protocol together.

When all the required information were given to the participant, they were equipped with a helmet and optional protectors for their knees, elbows and hands. The participants were then asked to try out all four vehicles (bike, e-bike, e-scooter and Segway). If any of the participants did not feel safe or felt uncomfortable riding any of the vehicles, that vehicle was skipped in the experiment. Same goes for the four different tasks. If any of the tasks felt uncomfortable for the participant, the task was skipped.

After the participant had tried out all the vehicles, the main experiment could start. The order in which each of the participants were to ride each vehicle and task was randomized. This was done to reduce any potential learning effect. Before starting the tasks with each vehicle, there were some final set-up steps needed. The recording of the LIDAR and the data logger on the vehicle were started. When the recording of the on-board sensors on the vehicle, through the data logger, was started, the vehicle was kept in a stationary position for a couple of seconds. This was to give the data logger enough time to calibrate the gyroscope. After the calibration was done the flag button was pressed simultaneously on the data logger of the vehicle and on the LIDAR to be able to sync the different sensors.

Before each task, the participant was given oral instructions on how to perform the task which is shown in appendix C. The experimenter operating the LIDAR did a short press on the flag button when the participant started each task and a long press whenever the participant finished the task. For the unexpected task, a button press was also done whenever the signal was given to brake. For the e-bike, a set electric assistance and mechanical gear was used for the different tasks. For the slalom task the electric assistance was set to 2 and the mechanical gear was set to 1. In the other three tasks, the electric assistance was set to 4 and the mechanical gear to 2. The e-scooter and Segway always had the highest power mode on.

After the participant had completed all the tasks with a vehicle, the data logger on the vehicle and the LIDAR was stopped. Then the process restarted with starting the data logger on the next vehicle and so on.

2.4.4 Questionnaire

When the participants were done with the riding tasks, they were asked to fill in a questionnaire about their experience during the riding tasks as well as when they tried out all the vehicles. The questionnaire can be seen in appendix B. It starts with questions regarding the demographics and prior experiences of the participant. It continues with questions about how they felt the different vehicles performed in 11 different scenarios. The questionnaire ends with four questions regarding the overall comfort, maneuverability, stability and safety. All of the questions regarding the performance of the vehicles and the overall questions are questions with a 7-grade scale. The scale can be seen below:

1. Very Poor
2. Poor
3. Fair
4. Good
5. Very Good
6. Excellent
7. Exceptional

After every question there is an optional field for adding comments. If the participant chose not to ride any of the vehicles, the answers related to the skipped vehicles were removed.

2.5 Performance Indicators

Performance indicators (PIs) are information collected at regular intervals to track the performance of a system. In this thesis, a list of different PIs are being measured and calculated in order to assess the safety of the e-vehicles in the dimensions stability, maneuverability and rider comfort. A high stability indicates that the vehicle does not need a lot of correction by the user when riding. A high maneuverability indicates that the vehicle is easy to accelerate, decelerate and turn with. A high comfort indicates that the rider feels comfortable, does not need a lot of physical effort to maneuver the vehicle and is not subject to excessive force. The PIs are parameters that can relate vehicle kinematics to one or more safety dimensions. Each task is split up into smaller segments.

For the gentle and harsh maneuvers, there are three segments: 1) the constant segment, 2) the acceleration segment and 3) the deceleration segment. The constant segment is the part of the task where the rider is trying to maintain a constant speed of 17-20 km/h. The constant segment will occur twice, both before the acceleration segment and after the deceleration segment.

The slalom task is split up into two segments. The first segment is the constant segment where the rider tries to maintain a constant speed of 7-10 km/h which occurs both before and after the slalom segment. The slalom segment is the part of the task where the rider is riding slalom around the traffic cones.

In order to examine the reactions and braking capabilities during the unexpected task, it is split up into three segments. First, there is the constant segment where the rider tries to maintain a constant speed of 17-20 km/h. The second segment is the reaction segment which is from when the signal is given until the rider starts to brake. The third, and final segment, is the deceleration segment which is just like in the gentle and harsh maneuver the segment where the rider decelerates.

The full list of PIs for the bike, e-bike and e-scooter can be seen in Table 2.2. The full list of PIs for the Segway can be seen in Table 2.3.

Signal	Performance Indicator	Segment	Interpretation
Steering angle (deg)	Mean absolute steering angle	Const, Slalom	S,M
Steering rate (deg/s)	Mean absolute steering rate	Const, Slalom	S
Roll angle (deg)	Mean absolute roll angle	Const, Slalom	S
Roll rate (deg/s)	Mean absolute roll rate	Const, Slalom	S
Speed (km/h)	Mean speed	Const, Slalom	M,C
Speed (km/h)	Standard deviation	Const, Slalom	M,C
Time (s)	Time	Acc, Dec, Reaction	M
Longitudinal acceleration (m/s^2)	Mean longitudinal acceleration	Acc, Dec	M,C
Lateral acceleration (m/s^2)	Mean absolute lateral acceleration	Slalom	C
Distance (m)	Braking distance	Dec	M
Steering rate (deg/s), Roll rate (deg/s)	R^2 of linear fit	Slalom	S
Steering rate (deg/s), Roll rate (deg/s)	Time delay between roll rate and steering rate	Slalom	M

Table 2.2: Performance indicators for bike, e-bike and e-scooter. Const, Acc and Dec are abbreviations for constant, acceleration and deceleration. S,M and C are abbreviations for stability, maneuverability and comfort.

Signal	Performance Indicator	Segment	Interpretation
Stick inclination rate (deg/s)	Mean absolute stick inclination rate	Slalom	S,M
Pitch angle (deg)	Mean absolute pitch angle	Const, Slalom	C
Pitch rate (deg/s)	Mean absolute pitch rate	Const, Slalom	S
Speed (km/h)	Mean speed	Const, Slalom	M,C
Speed (km/h)	Standard deviation	Const, Slalom	S,M,C
Time (s)	Time	Acc, Dec, Reaction	M
Longitudinal acceleration (m/s^2)	Mean longitudinal acceleration	Acc, Dec	M,C
Lateral acceleration (m/s^2)	Mean absolute lateral acceleration	Slalom	C
Distance (m)	Braking distance	Dec	M

Table 2.3: Performance indicators for the Segway. Const, Acc and Dec are abbreviations for constant, acceleration and deceleration. S,M and C are abbreviations for stability, maneuverability and comfort.

2.5.1 Speed

The mean speed and the standard deviation of the speed are used as PIs for the constant and slalom segment. A too low mean speed may indicate that the rider is not comfortable enough to ride at a higher speed while a too high speed may indicate that the rider has trouble with maneuvering the vehicle. The standard deviation of the speed is a measurement of both maneuverability and comfort. If the standard deviation of the speed is low it indicates that it is easy to keep a constant speed which indicates a high maneuverability. It also indicates a high comfort since it indicates that the user need to correct the speed less. For the Segway, the standard deviation is also related to stability since trouble with balance will lead to changes in speed.

2.5.2 Braking

The braking distance, the braking time and the mean longitudinal acceleration are used as PIs for the deceleration segment. A short braking distance or time and a high deceleration for the unexpected and harsh brake indicates that it is possible to brake fast which indicates a high maneuverability. A high deceleration may however also indicate less comfort.

The reaction time in the unexpected task is chosen as a PI to indicate maneuverability since a high reaction time indicates that the rider needs more time to initiate the braking.

2.5.3 Acceleration

The acceleration time and the mean longitudinal acceleration are used as PIs for the acceleration segment. A short acceleration time and a high acceleration for the harsh acceleration indicates that it is possible to accelerate fast which indicates a high maneuverability. A high acceleration may however also indicate less comfort.

For the slalom segment the mean absolute lateral acceleration is used as a PI since a high lateral acceleration may indicate less comfort.

2.5.4 Steering and Leaning

2.5.4.1 E-bike, Bike and E-scooter

The mean absolute steering angle, steering rate, roll angle and roll rate are used as PIs for the constant and slalom segment. The peak cross-correlation between steering rate and roll rate and the time delay between steering rate and roll rate are used as PIs for the slalom segment. A high mean absolute steering angle, steering rate, roll angle and roll rate indicates that the rider needs to do a lot of correction to maneuver the vehicle, hence a low stability. For the slalom segment a low steering angle also indicates high maneuverability since less steering is needed to pass the cones. The peak cross-correlation between the steering rate and the roll rate shows how correlated the two control input from the rider are. A high correlation indicates that the user have control of the maneuver and therefore high stability. A low time delay between the roll rate and the steering rate indicates that the vehicle is responsive, hence high maneuverability.

2.5.4.2 Segway

The pitch angle, pitch rate and the stick inclination rate are used as PIs for the constant and slalom segment. The mean absolute pitch angle is related to comfort since it may be less comfortable to lean forward than to stand in a upright position. A high pitch rate may indicate that the rider does not have the stability to stand in a stable way on the Segway. The same reasoning can be done for the standard deviation of the speed. If the speed changes a lot it indicates that the posture also changes a lot which may be a sign that the Segway is not stable. A low stick inclination rate during the slalom may indicate that the rider does not need to do fast correction to go through the slalom course and is therefore a sign of stability.

2.5.5 Box Plot

The PIs will mostly be presented in box charts that represent the distribution of the data. A description of the box chart is shown in Figure 2.15 where the line inside of the box is the sample median. The top and bottom edges of the box are the upper and lower quartiles, respectively. Interquartile range (IQR) is the distance between the upper and lower quartiles. The upper quartile corresponds to the 0.75 quantile and the lower quartile corresponds to the 0.25 quantile. To be classified as an outlier the value has to be more than $1.5 \cdot IQR$ away from the top or bottom of the box. Values that are outside the quartiles but not an outlier are represented by the whiskers which in turn shows the nonoutlier maximum and nonoutlier minimum. The notch is used to see the significance of difference of medians. If notches of two boxes do not overlap, it means that they have different medians at the 5% significance level. The significance level is based on a normal distribution assumption, but can also be used to compare other distributions. If m is the median and n is the number of data points, the notch regions top and bottom edges correspond to $m + (1.57 \cdot IQR)/\sqrt{n}$ and $m - (1.57 \cdot IQR)/\sqrt{n}$, respectively.

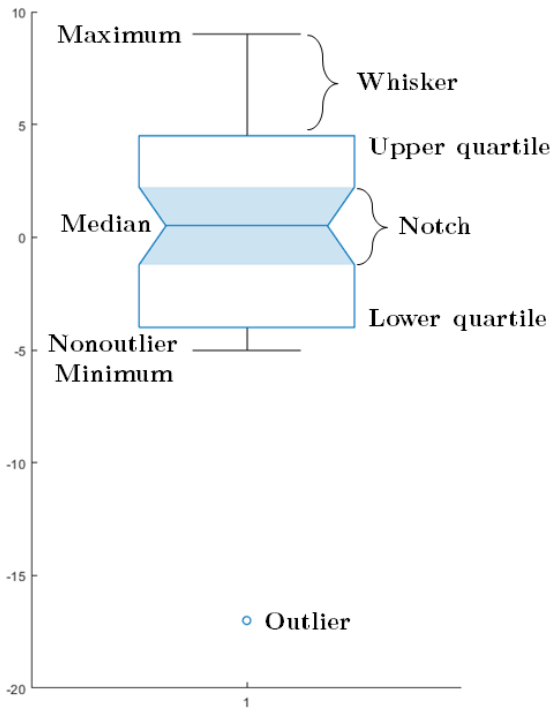


Figure 2.15: Description of a box chart.

2.6 Data Analysis

2.6.1 Calibration

To be able to use the data from the IMUs to compute the PIs, the orientation with respect to the vehicle needs to be known or estimated. The direction of the gravity in the IMU frame is computed by collecting readings from the accelerometer, while the vehicle is set in an upright position with the use of a level. From this a rotation matrix that aligns the z-axis of the IMU with the vehicles vertical axis could be computed by solving Equation (2.1), where g is the gravitational constant, R_1 is the rotation matrix and, a_x, a_y and a_z are the readings from the accelerometer.

$$\begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} = R_1 \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \tag{2.1}$$

The next step is to find the rotation matrix that aligns the x-axis of the IMU with the lateral direction of the vehicle and the y-axis with the longitudinal direction. This was done by leaning the vehicles such that the direction of the gravity is directed only in the lateral and the vertical direction of the vehicle. The second rotation matrix could then be computed from the rotated accelerometer reading by solving Equation (2.2). In this equation k is an arbitrarily constant, R_1 is the rotation matrix from Equation (2.1), R_2 is the second rotation matrix and, a_x and a_y are readings from the accelerometer. By multiplying these two rotation matrices a rotation matrix from the IMU frame to the vehicle frame was estimated. This rotation matrix was then applied to the acceleration readings from the accelerometer and the angular velocity readings from the gyroscope.

$$\begin{bmatrix} 0 \\ k \\ 0 \end{bmatrix} = R_2 R_1 \begin{bmatrix} a_x \\ a_y \\ 0 \end{bmatrix} \tag{2.2}$$

2.6.2 Post Processing

In order to be able to compute the PIs for the vehicles, the data collected during the experiments needed to be processed. This section will cover the filtering methods used, how the tasks were split up into the segments mentioned in Section 2.5, how the orientation of the vehicles were estimated, and how the LIDAR data, together with the IMU data, were used to estimate position and speed. The process of the post processing can be seen in Figure 2.16.

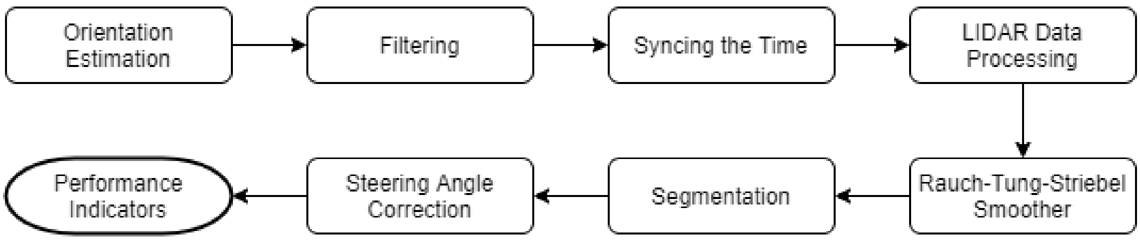


Figure 2.16: Process description for post processing.

2.6.2.1 Syncing the Times

The data logger on the vehicles and the logging device on the LIDAR were instrumented with a real-time clock. The real-time clocks however suffered from drift over time. All the logging devices had a connected flag button. Before starting the tests with a vehicle, the button connected to the vehicle was pressed at the same time as the button connected to the LIDAR.

For some participants, the syncing was not correct due to human errors and hardware problems. The human errors were missing to press a button or not pressing the buttons at the same time. Hardware problems was that the button press was not registered due to loose wire connection. To sync the signals, the longitudinal acceleration of the harsh task was derived from the LIDAR measurements. The time lag between the LIDAR measurements and the IMU measurements was then estimated with the *finddelay* function in MATLAB with the acceleration from the LIDAR and the accelerometer of the IMU. The function finds the delay that gives the highest cross correlation between the two signals.

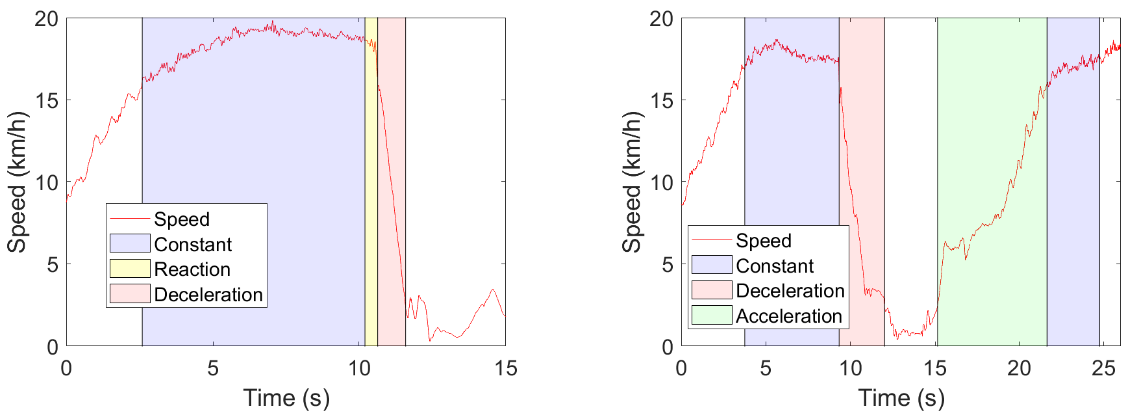
2.6.2.2 Filtering

The steering angle, steering rate, angular velocity and orientation angles were all filtered with a low-pass filter. The low-pass filter used was a zero-phase Butterworth filter [16] with a passband of 0-1 Hz and a stopband of 1-1.5 Hz.

2.6.2.3 Segmentation

The start and end of each maneuver were indicated by a flag button and could therefore easily be extracted. Each maneuver also consists of different segments. These are not indicated by any button press and instead based on the signal data. The first segment of all the maneuvers is the constant segment which started after the first 20 traveled meters, so that the rider had enough time to accelerate to the given speed.

For the braking tasks, the next segment is the braking segment. It starts when going under 16 km/h the last time before the stop for the bike, e-bike and the e-scooter and ends when the speed is under 2.5 km/h. For the Segway, it starts when the rider is going under 12 km/h the last time before the stop since the participant had a lower speed with the Segway. The unexpected task ends after the stop, but it also has a reaction segment which starts when the signal is shouted. After the vehicle decelerates to a speed that is 1 km/h less than the speed at the time of signal the reaction segment ends. For the gentle and harsh task, the third segment is the acceleration segment which starts when the speed goes above 2.5 km/h and ends at 16 km/h for e-bike, bike, and e-scooter, and 12 km/h for the Segway. After that, a second constant segment starts which ends 10 meters before the finish line to avoid collecting data from braking or steering that some participants did just before the finish line. Examples of the segmentation for the braking tasks is shown in Figure 2.17.



(a) Unexpected task.

(b) Harsh/Gentle task.

Figure 2.17: Example of the segmentation for the braking tasks.

The slalom task is segmented solely based on position. After the first constant segment there is a slalom segment. The slalom segment starts 4 meters in front of the first cone and ends 4 meters after the last cone. The second constant segment starts directly after the slalom segment and ends 10 meter before the finish line. An example of the segmentation for the slalom task is shown in Figure 2.18.

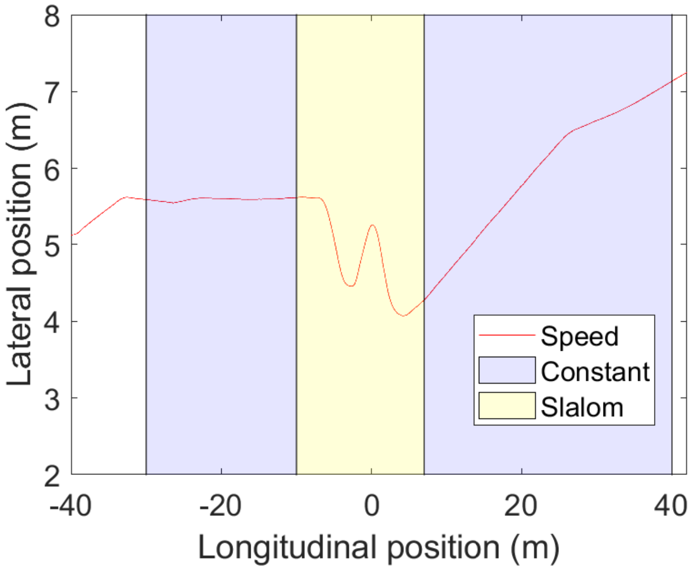


Figure 2.18: An example of the segmentation for the slalom task. The origin is the position of the LIDAR.

2.6.2.4 Steering Angle Correction

A mean correction of the steering angle was made for each maneuver to correct for potential drift. During the constant segment it was assumed that the mean steer angle was zero. The mean steer angle of the constant segment was therefore removed from the steer angle measurements for each task.

2.6.2.5 Orientation Estimation

The orientation of the vehicles was estimated by using a Madgwick filter [17] with the measurements from the gyroscope and accelerometer. The magnetometer values were not used since the values were heavily affected by disturbances, even after calibration. This is probably due to soft iron disturbances from the electronics on the vehicle which is very hard to compensate for. The magnetometer is also mostly used for the yaw angle estimate which could be estimated from the LIDAR measurements instead.

2.6.2.6 LIDAR Data Processing

The LIDAR data consist of a set of 2D points. To extract the position of the vehicle, the LIDAR data were clustered. The detected view was limited to the test area to avoid potential clusters from the environment. The limits were set to ± 50 meters in the longitudinal direction, and between two and nine meters in the lateral direction, where the position of the LIDAR is placed at the origin. The clustering method that was used was DBSCAN which is a clustering algorithm that clusters data based on the density and can discover clusters of arbitrary shape [18]. The center of the cluster representing the vehicle was then interpreted as the center of the vehicle. A first estimate of the speed of the vehicle was then estimated from the LIDAR data by measuring the change of position of the cluster center over time. A better estimation of the speed was then computed by fusing the estimation from the LIDAR with the accelerometer data.

2.6.2.7 Rauch-Tung-Striebel Smoother

The Rauch-Tung-Striebel (RTS) smoother [19] was used to estimate the position and the speed of the rider. For the gentle, harsh and unexpected task, there should be no turning and therefore a one-dimensional model was used. The prediction model is shown in (2.3) where the distance (d) and speed (v) represent the state vector and the longitudinal acceleration (a) from the accelerometer on the vehicle is the input. The sampling period is denoted as T. The measurement model is shown in (2.4) and uses the distance (D_L) and speed (V_L) acquired from the LIDAR measurements.

$$\begin{bmatrix} d_k \\ v_k \end{bmatrix} = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} d_{k-1} \\ v_{k-1} \end{bmatrix} + \begin{bmatrix} \frac{T^2}{2} \\ T \end{bmatrix} a_k + Q_1 \tag{2.3}$$

$$\begin{bmatrix} D_{L,k} \\ V_{L,k} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} d_k \\ v_k \end{bmatrix} + R_1 \tag{2.4}$$

In the slalom task, the rider turns and therefore a two-dimensional model was used. The prediction model for the slalom task is shown in (2.5) where the state vector includes the position (x, y), the linear speed (v) and the heading (ϕ). The position of the LIDAR is set to the origin. The position in the longitudinal direction of the track is described with x. The position in the lateral direction is described with y. The longitudinal acceleration (a) from the accelerometer and the yaw rate (ω) from the gyroscope are treated as inputs. The sampling period is denoted as T. The measurement model for the slalom model is shown in (2.6) and uses the position (X_L, Y_L) and speed (V_L) acquired from the LIDAR measurements.

$$\begin{bmatrix} x_k \\ y_k \\ v_k \\ \phi_k \end{bmatrix} = \begin{bmatrix} 1 & 0 & T\cos(\phi_{k-1}) & -Tv_{k-1}\sin(\phi_{k-1}) \\ 0 & 1 & T\sin(\phi_{k-1}) & Tv_{k-1}\cos(\phi_{k-1}) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ T & 0 \\ 0 & T \end{bmatrix} \begin{bmatrix} a_k \\ \omega_k \end{bmatrix} + Q_2 \tag{2.5}$$

$$\begin{bmatrix} X_{L,k} \\ Y_{L,k} \\ V_{L,k} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_k \\ y_k \\ v_k \\ \phi_k \end{bmatrix} + R_2 \tag{2.6}$$

Q and **R** are matrices that describe the noise. **Q** represents the uncertainty of the prediction model and **R** represents the insecurity of the measurements. These matrices were tuned to give a stable result and are shown in (2.7) and (2.8) where σ was set to 10 for the Segway and 1 for the other vehicles. The sampling period is denoted as T.

$$Q_1 = \sigma \begin{bmatrix} \frac{T^4}{4} & \frac{T^3}{2} \\ \frac{T^3}{2} & T^2 \end{bmatrix} \qquad Q_2 = 10^{-4} \begin{bmatrix} 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 \\ 0 & 0 & 100 & 0 \\ 0 & 0 & 100 & \frac{\pi}{180} \end{bmatrix} \tag{2.7}$$

$$R_1 = \begin{bmatrix} 10 & 0 \\ 0 & 1 \end{bmatrix} \qquad R_2 = \begin{bmatrix} 0.1 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.8}$$

An example of the result of the RTS smoother that was used for the gentle, harsh and unexpected task is shown in Figure 2.19. It shows that by just using the LIDAR measurements, the estimates are very noisy. By simply integrating the longitudinal acceleration from the accelerometer, drift occurs. By combining the LIDAR and the accelerometer, the estimate is much smoother than by just using the LIDAR and with no notable drift as in the case of just using the accelerometer.

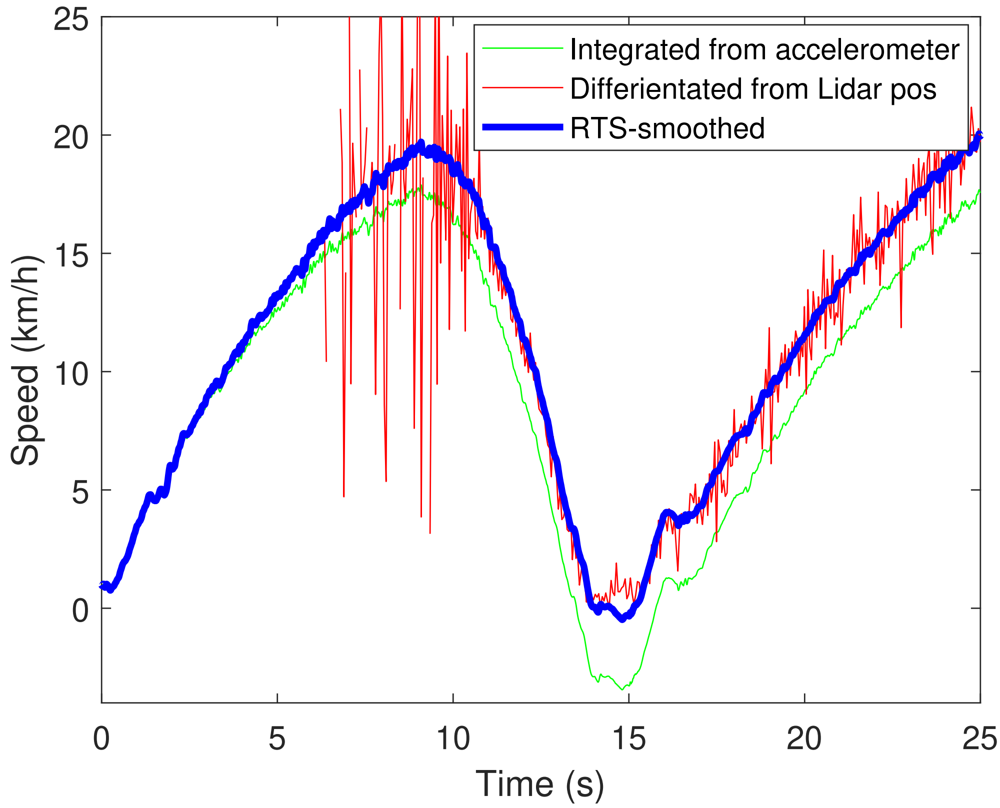


Figure 2.19: A speed estimate from the LIDAR, the accelerometer and the RTS-smoother that uses both the LIDAR and the accelerometer.

3

Results

A total of 34 participants took part in the study and conducted the experiments. The demographics of the participants from the experiments can be seen in Figure 3.1. The mean age of the participants were 25.3, the mean height were 175.1 cm and the mean weight were 71.5kg. There were 25 male participants and 9 female participants.

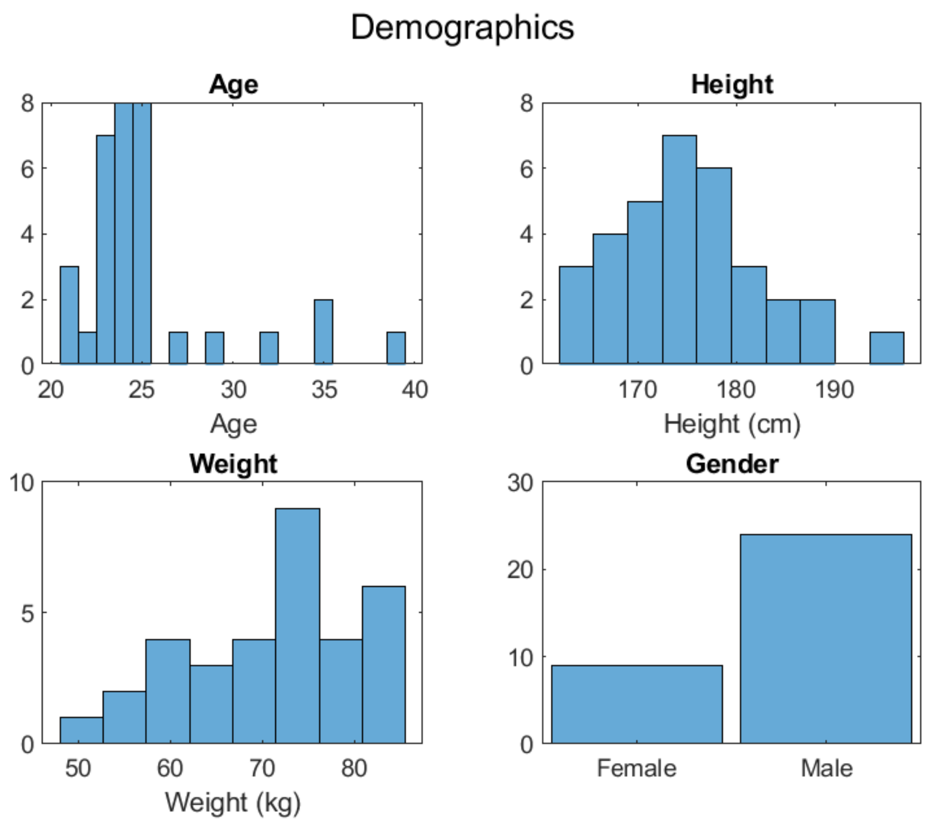


Figure 3.1: The age, height, weight and gender distributions of the participants in the study.

One of the questions in the questionnaire was about the participants prior experience with riding the different vehicles. Specifically the question was how often they used the different vehicles. The results from the prior experience question can be seen in Figure 3.2. For the Segway, it can be seen that all participants, except one, never ride it and 26 participants never ride the e-bike. For the bike, most participants ride it a few days per week but the spread is even through all options except for one participant who never rides a bike. There were 12 participants who never ride an e-scooter and the rest of the participants were split up between the other options.

When there were questionnaire entries related to the Segway and the participant did not ride the Segway during the experiments, those entries were removed. This is the reason why there are fewer participants represented in the Segway prior experience.

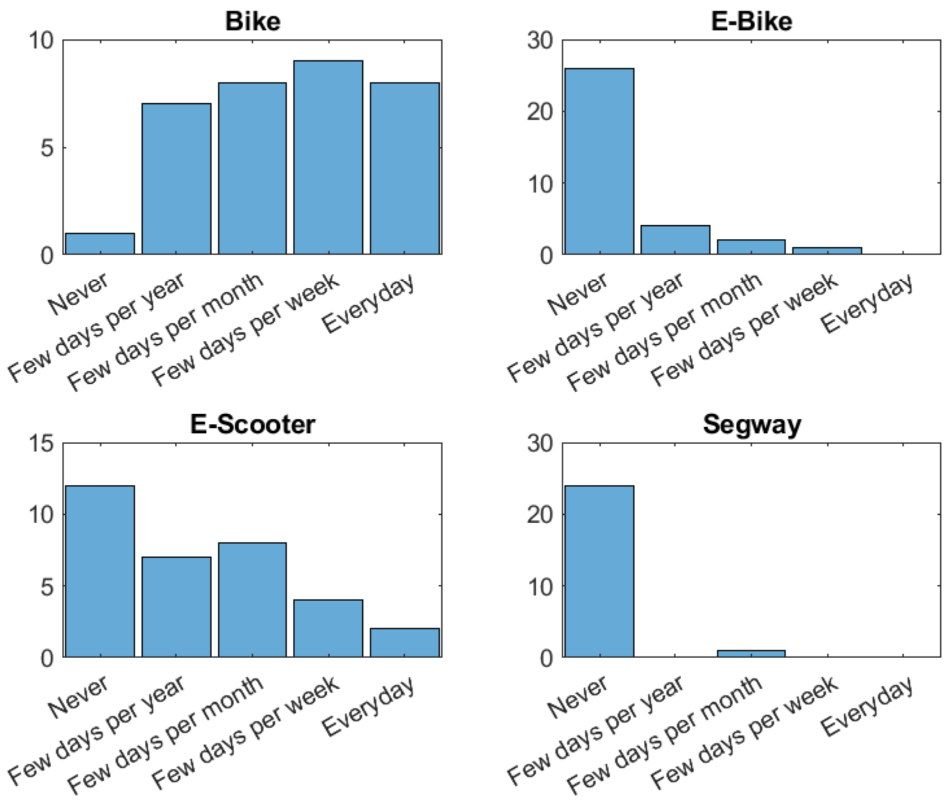


Figure 3.2: Histograms of how often the participants use the different types of vehicles.

3.1 Data Overview

Due to various reasons, some data from the conducted experiments are missing. A list of the data set availability can be seen in Table A.1 in the appendix. There were 9 participants who did not feel comfortable riding the Segway and the questionnaire questions regarding the Segway were therefore skipped for these participants. The data from the other vehicles were however still used for these participants. One of the participants had an accident while riding the first vehicle in the experiments, the regular bike. The experiment was canceled for that participant and that participant did not complete any task with the other three vehicles nor filled in the questionnaire. The number of participants that had useful data for the different performance indicators is shown in Table 3.1. The data that was not useful were data where either the participant did not reach the desired speed, the participant did not come to a complete stop or there were a problem with the potentiometer belt.

	E-bike	**Bike**	**E-scooter**	**Segway**
Longitudinal acceleration				
gentle	26	22	26	13
harsh	26	25	28	13
Deceleration				
gentle	26	18	20	11
harsh	26	25	28	14
unexpected	28	29	28	13
Lateral acceleration	28	29	28	14
Speed constant	28	29	28	14
Braking distance	28	29	28	14
Reaction time	28	29	28	13
Roll/Pitch angle/rate	28	29	28	14
Steering angle/rate	25	25	28	N/A
R^2/Time delay steering-roll	25	25	28	N/A
Stick inclination rate	N/A	N/A	N/A	14

Table 3.1: Number of participants used for the different PIs.

3.2 Performance Indicators

In this section, the results of the PIs are shown. The results for the constant segment on the gentle, harsh and unexpected tasks were very similar. The results for the constant segment are therefore limited to the constant segment on the harsh task and on the slalom task and will be referred to as *high speed* and *low speed*.

3.2.1 Speed

In Figure 3.3, it could be seen that the e-bike has the highest mean speed on the high-speed constant segment. The Segway which did not have a speedometer and a speed limit at 19 km/h has a considerably lower mean speed than the other vehicles in the high speed segment. It also has a lower mean speed in the low speed segment and slalom segment. It could also be seen that the mean speed of all vehicles is lower in the slalom segment than on the low speed segment, even if the participants were instructed to keep the same speed in these segments.

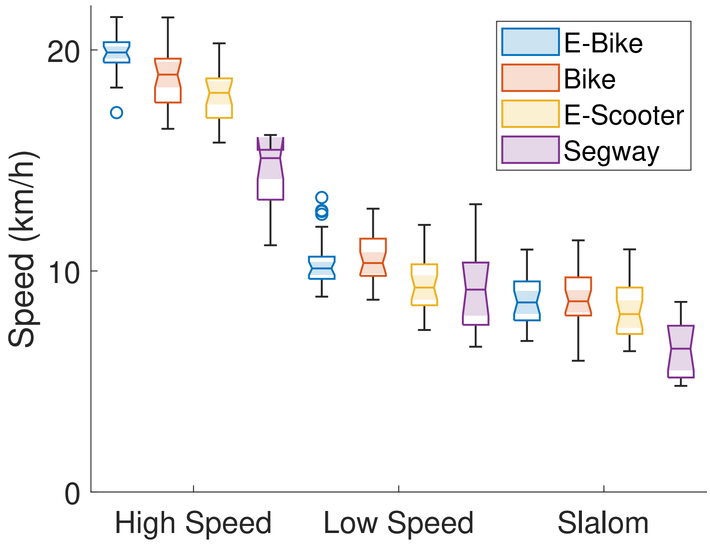


Figure 3.3: A box chart showing the distributions of the participants average speed in different segments where they were instructed to keep a constant speed.

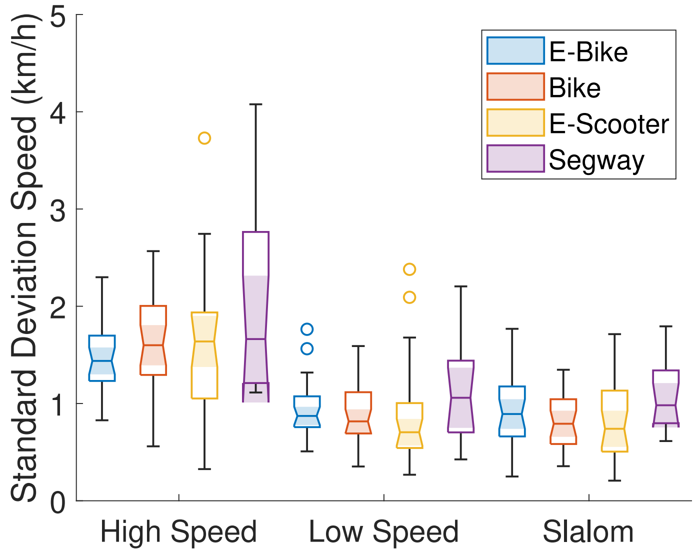
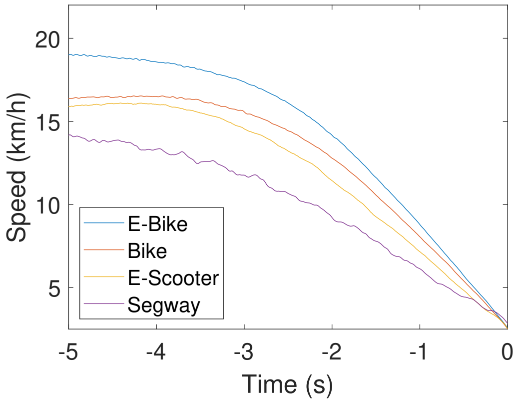


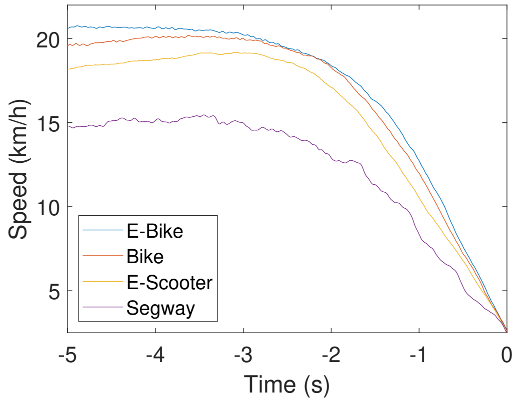
Figure 3.4: A box chart showing the distributions of the participants standard deviation of the speed in different segments where they were instructed to keep a constant speed.

Figure 3.4 shows the standard deviation of the speed when the participants were instructed to keep a constant speed. The results can not show with 95 % certainty that there is any difference in the median between the vehicles. The median is however higher on the Segway than on the other vehicles, but the confidence interval is also very large. The standard deviation however decreases with speed for the e-bike, bike and e-scooter. It also seems to decrease for the Segway, but this is not verified with a 95 % confidence interval. The standard deviation for the Segway has the largest spread meaning that the participants managed to keep a constant speed differently from each other.

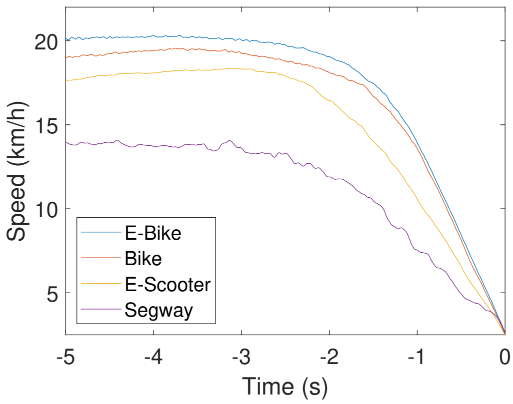
3.2.2 Braking



(a) Average speed during gentle braking.



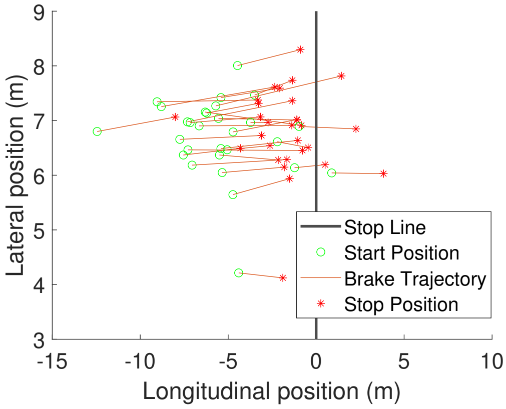
(b) Average speed during harsh braking.



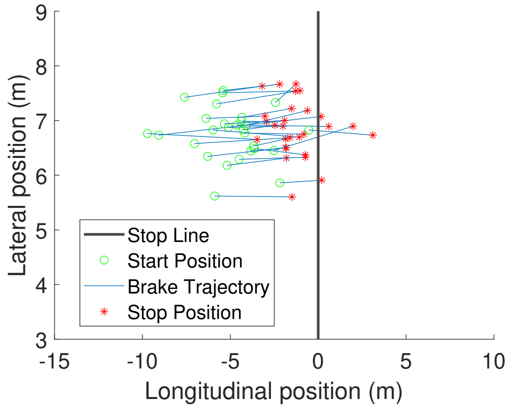
(c) Average speed during unexpected braking.

Figure 3.5: Average speed across participants during gentle braking, harsh braking and unexpected braking with the four different vehicles.

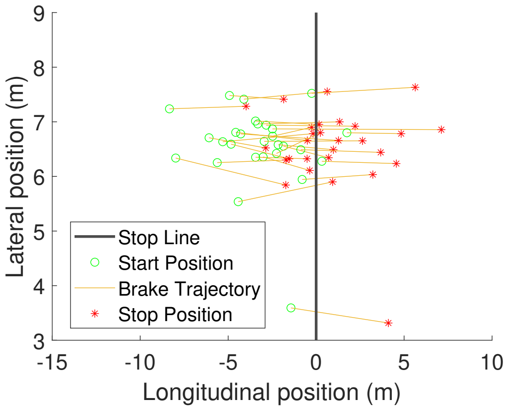
In Figure 3.5, the average speed across participants during the gentle braking, harsh braking and the unexpected braking are shown. The Segway has the slowest braking of the four vehicles followed by the e-scooter. The bike and e-bike have similar braking, but the initial speed is higher on the e-bike, especially during gentle braking.



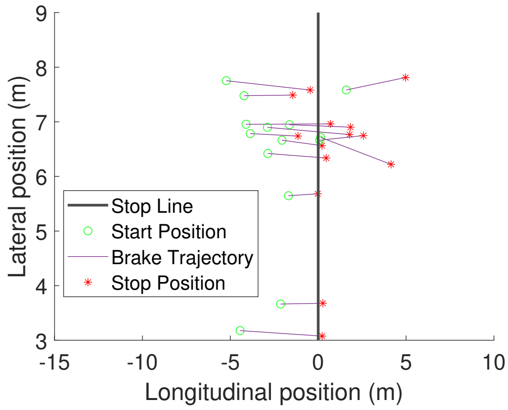
(a) Braking trajectories for the bike.



(b) Braking trajectories for the e-bike.



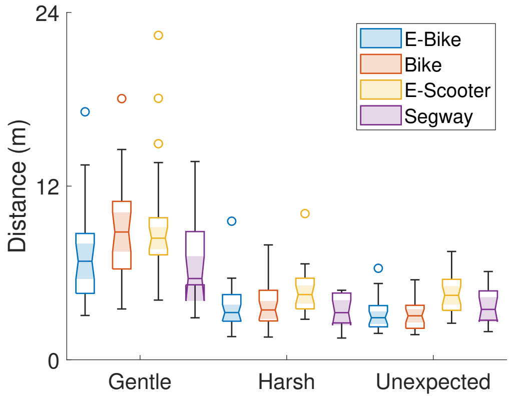
(c) Braking trajectories for the e-scooter.



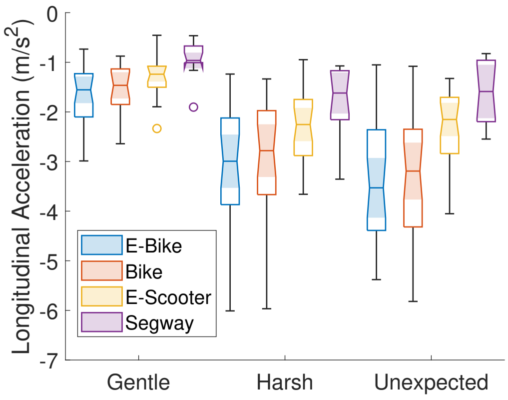
(d) Braking trajectories for the Segway.

Figure 3.6: The braking trajectories for the harsh brake with the four different vehicles. The origin is placed at the position of the LIDAR.

When performing the harsh brake, a lot of participant passed the stop line before reaching a complete stop with the e-scooter which could be seen in Figure 3.6c. This was also the case for a large proportion of the harsh brake with the Segway which is shown in Figure 3.6d. For the e-bike and bike, there were however only a few participants that passed the line before stopping which is seen in Figure 3.6a and 3.6b.



(a) A box chart showing the distributions of the participants braking distance for the gentle, harsh and unexpected brake.

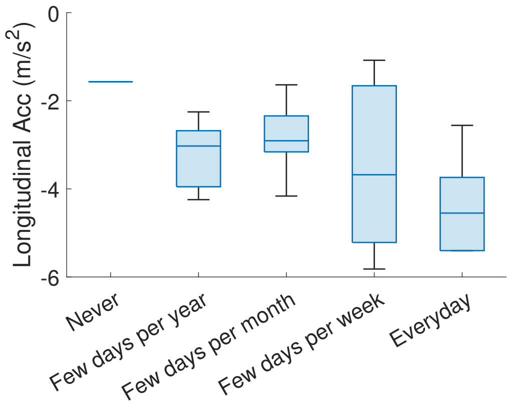


(b) A box chart showing the distributions of the participants mean longitudinal acceleration for the gentle, harsh and unexpected brake.

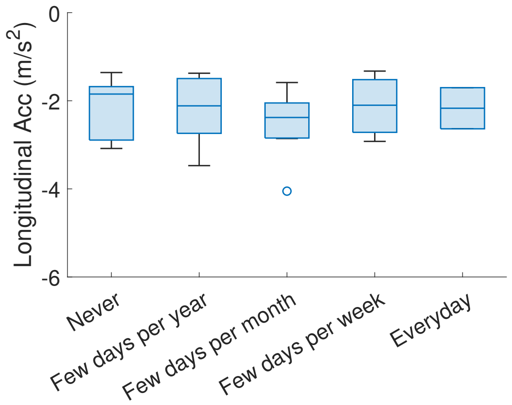
Figure 3.7: The distributions for the mean braking distance and the mean longitudinal acceleration for the braking segments.

In Figure 3.7a, the braking distance distributions between the different participants are shown for the gentle, harsh and unexpected brake. It could be seen that the e-bike and bike, that have the same brakes, have similar distributions for the harsh and the unexpected brake. The e-scooter has a longer braking distance than both the e-bike and the bike. The Segway starts braking from a considerably lower speed, but still has a similar braking distance as the other vehicles on the harsh and unexpected brake. For the gentle brake, the Segway has a shorter braking distance than the e-scooter and the bike. The e-bike seems to have a shorter braking distance than the bike and the e-scooter, but this is not verified with a 95 % certainty.

The e-bike and the bike have very similar deceleration values, which is shown in Figure 3.7b. They are also the vehicles on which the participants braked the hardest in the gentle, harsh and unexpected brake. The braking however differ a lot between the participants, especially for the harsh and the unexpected brake. By sorting the participants by how often they use a bike, it could be seen that the participant that bikes often, brakes harder. This is shown with the box charts in Figure 3.8a. There is however no clear trend between experience and braking deceleration with the e-scooter, which is shown in Figure 3.8b. The braking of the e-scooter was slower than the e-bike and the bike, but faster than with the Segway. The harsh and the unexpected brake distributions are very similar.



(a) Unexpected brake bike.



(b) Unexpected brake e-scooter.

Figure 3.8: Box charts showing the distributions of the participants mean longitudinal acceleration on the unexpected brake with the e-scooter and the bike based on their experience.

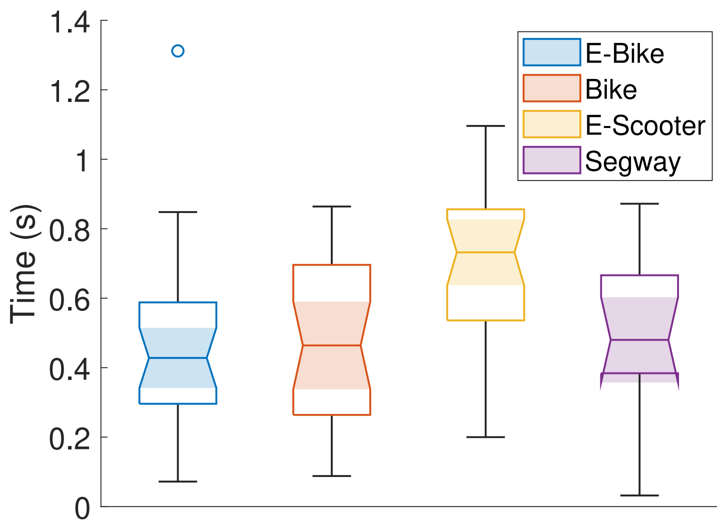
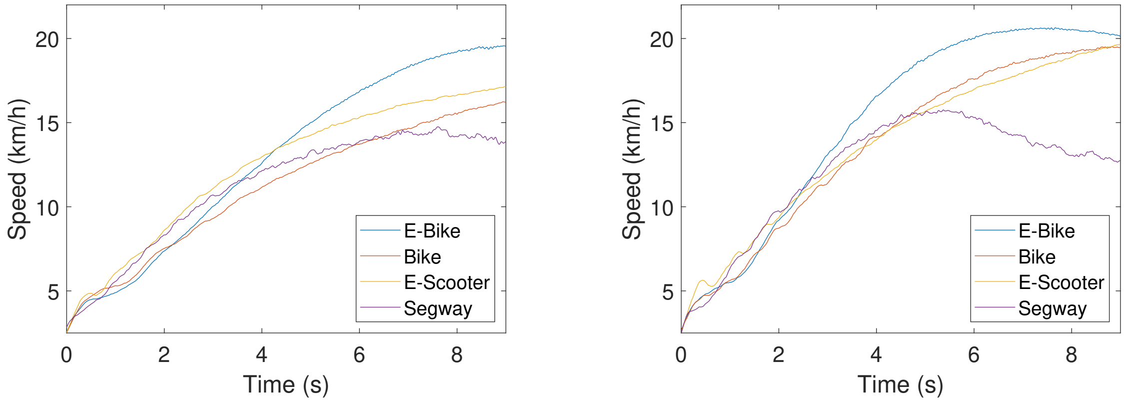


Figure 3.9: Box chart showing the distributions of the participants reaction time in the unexpected task.

The reaction time of the participants during the unexpected brake are very similar for the e-bike, bike and the Segway which is shown in Figure 3.9. The participants however have a significantly higher median reaction time with the e-scooter than with the other vehicles.

3.2.3 Accelerating



(a) Average speed during gentle acceleration.

(b) Average speed during harsh acceleration.

Figure 3.10: Average speed during gentle acceleration and harsh acceleration with the four different vehicles.

From Figure 3.10, it could be seen that the bike and the e-bike accelerate very similarly in the beginning, but after a while, the e-bike accelerates faster than the bike, both in the gentle acceleration and the harsh acceleration. The e-scooter and the Segway have the fastest acceleration in the beginning, but after a few seconds, the e-bike accelerates faster. This leads to that the e-bike have the highest speed after 4.3 seconds for the gentle acceleration and after 2.5 seconds for the harsh task.

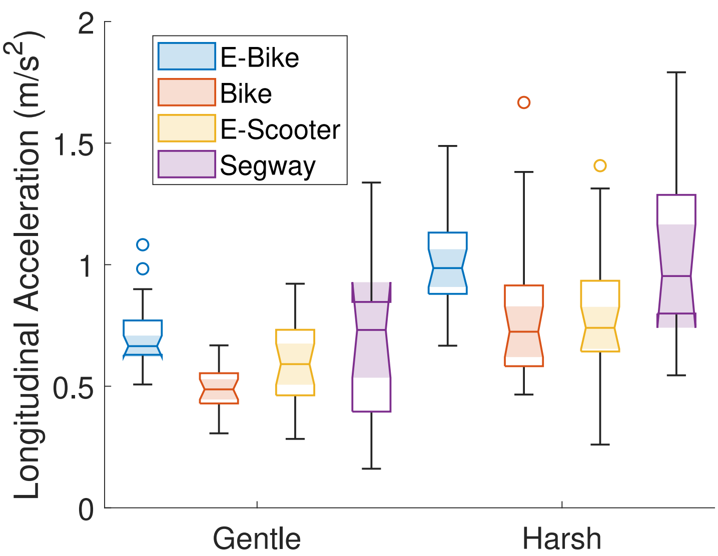


Figure 3.11: A box chart showing the distributions of the participants mean longitudinal acceleration for the gentle, and harsh acceleration.

In Figure 3.11, the distributions of the mean longitudinal acceleration when accelerating are shown. Both the Segway and the e-bike have a median of around 1 m/s^2 during the harsh acceleration. The Segway however has a large interval which shows that the participants accelerated very differently with it. The e-scooter and the bike have a smaller median acceleration than the e-bike for the harsh task. For the gentle task, the bike has a smaller mean acceleration than both the e-bike and the Segway.

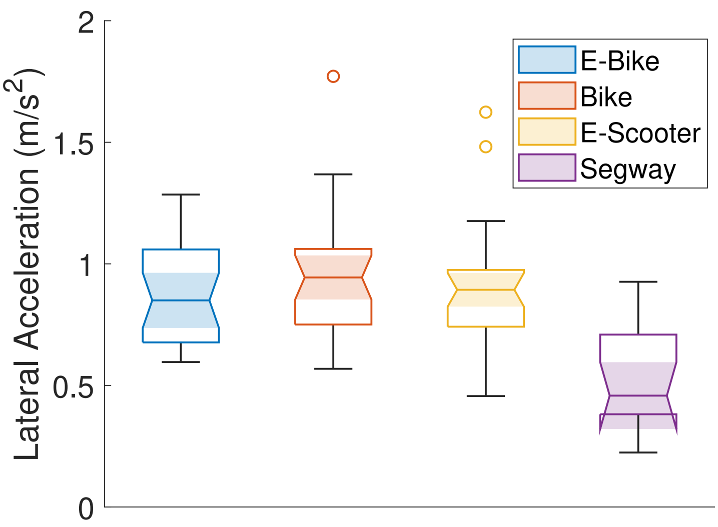
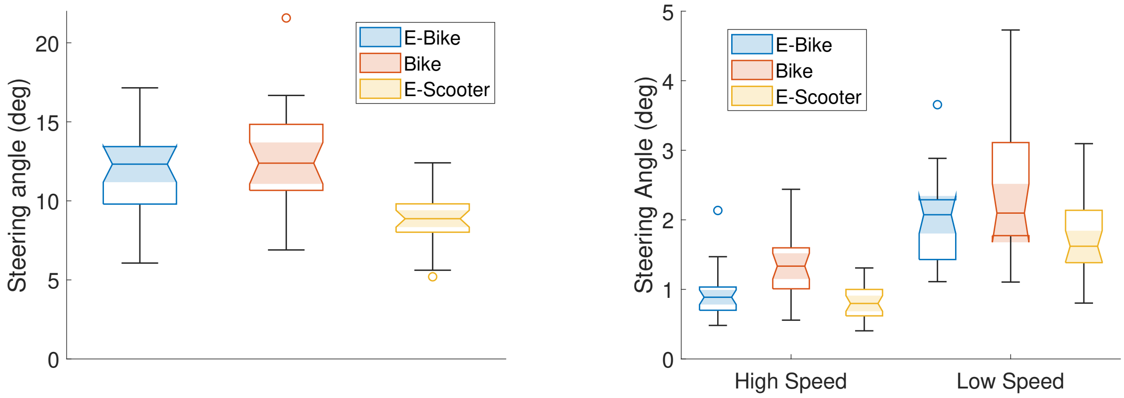


Figure 3.12: A box chart showing the distributions of the participants mean absolute lateral acceleration during the slalom segment.

In Figure 3.12, the distributions of the mean absolute lateral acceleration during the slalom segment, are shown. From the figure it is shown that the Segway has a significantly lower lateral acceleration than the other vehicles. There is no significant difference in lateral acceleration between the e-bike, the bike and the e-scooter.

3.2.4 Steering and Leaning

3.2.4.1 E-bike, Bike and E-scooter

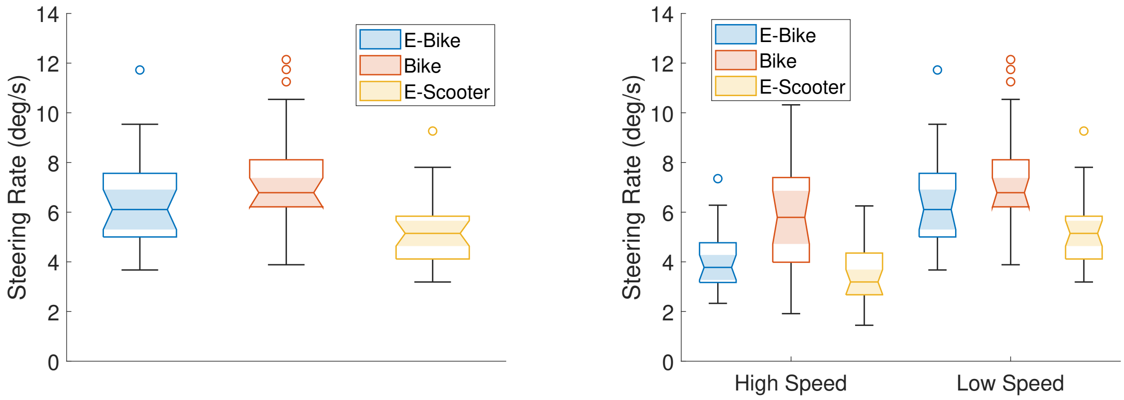


(a) Mean absolute steering angle during slalom.

(b) Mean absolute steering angle when riding straight.

Figure 3.13: Distributions of the mean absolute steering angle.

In Figure 3.13, the distributions of the mean absolute steering angle is shown. It could be seen that the median of the e-scooter is significantly lower than both the e-bike and the bike in the slalom segment. In the high speed segment, the e-bike and the e-scooter have a significantly lower median than the bike. In the low speed segment, there is no significant difference of the median between the vehicles even if it indicates that it is lower for the e-scooter. The mean absolute steering angles for the low speed segment is significantly larger compared to the high speed.

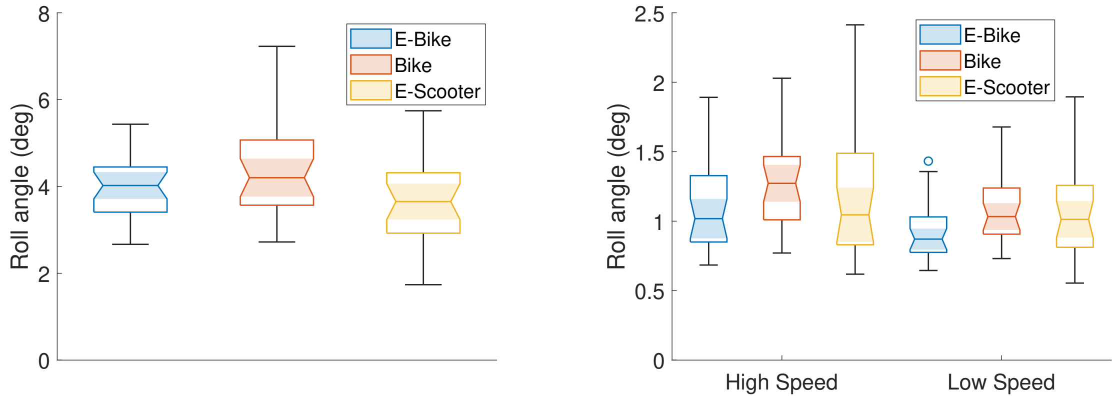


(a) Mean absolute steering rate during slalom.

(b) Mean absolute steering rate when riding straight.

Figure 3.14: Distributions of the mean absolute steering rate.

The average absolute steering rate distributions are shown in Figure 3.14 where the e-scooter has a significantly smaller median than the bike in all three segments. A significant difference in median is also shown in the high speed segment between the e-bike and the bike where the e-bike has a lower steering rate than the bike.

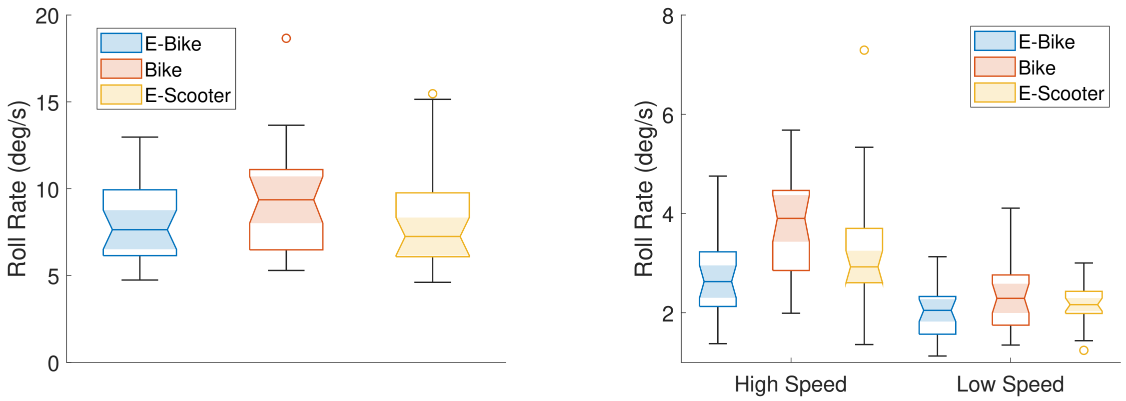


(a) The mean absolute roll angle during slalom.

(b) The mean absolute roll angle when riding straight.

Figure 3.15: Distributions of the mean absolute roll angle.

The distributions of the mean absolute roll angle are shown in Figure 3.15. There is no significant difference in the median between the vehicles, but the results indicate that the median absolute roll angle is the lowest for the e-scooter during the slalom maneuver and the lowest for the e-bike when riding straight at a low speed. There is also no significant difference in the median when riding straight at high speed and low speed.

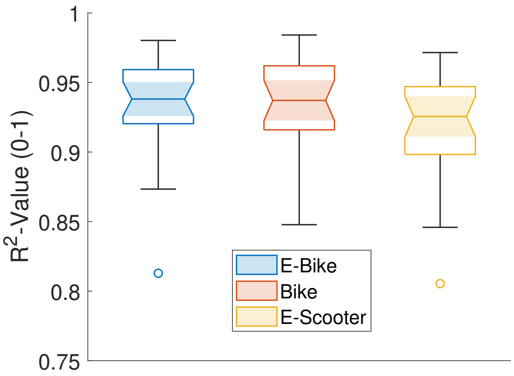


(a) The mean absolute roll rate during slalom.

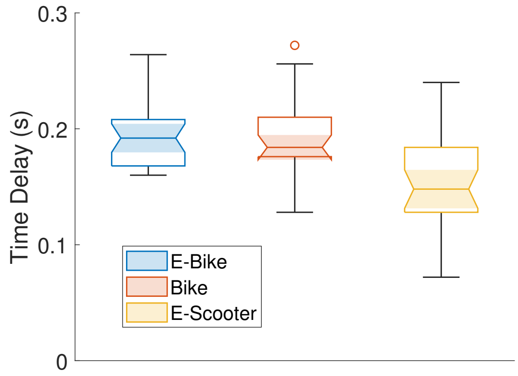
(b) The mean absolute roll rate when riding straight.

Figure 3.16: Distributions of the mean absolute roll rate.

The distributions of the mean absolute roll rate are shown in Figure 3.16. The median absolute roll rate is significantly lower for the e-scooter and the e-bike than the bike during the high speed segment. Another result that is shown is that the roll rate is significantly lower when riding straight in a low speed than in a high speed. For the slalom segment there is no significant difference of the median roll rate between the vehicles but the results indicate that it is higher for the bike.



(a) Linear fit between roll rate and steering rate.

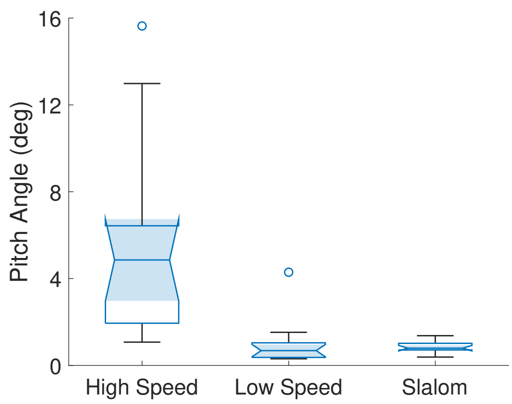


(b) Time delay between roll rate and steering rate.

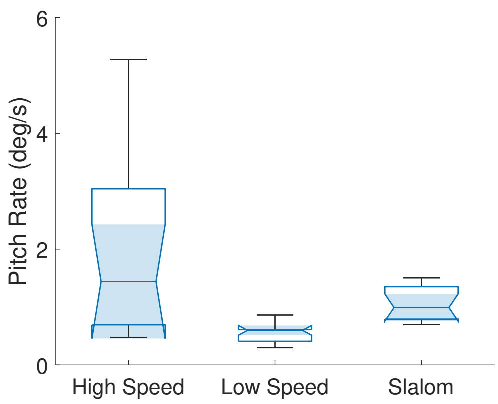
Figure 3.17: Distributions of the correlations between roll rate and steering rate in terms of linear fit and time delay.

The three vehicles have a similar linear fit between roll rate and steering rate during slalom since they have similar R^2-values which is shown in Figure 3.17a. The median time delay between the roll rate and the steering rate is significantly lower for the e-scooter than the e-bike and the bike which is shown in Figure 3.17b.

3.2.4.2 Segway



(a) Average absolute pitch angle at high speed, low speed and slalom with the Segway.



(b) Average absolute pitch rate at high speed, low speed and slalom with Segway.

Figure 3.18: Average absolute pitch angle and pitch rate at high speed, low speed and slalom with the Segway.

The pitch angle of the Segway is significantly lower when riding at low speed than at high speed, which is shown in Figure 3.18a. The average absolute pitch rate was very different between the participants at the high speed segment, which can be seen in Figure 3.18b. The results from the figure also indicates that the pitch rate is lower when going straight at low speed than at high speed and slalom.

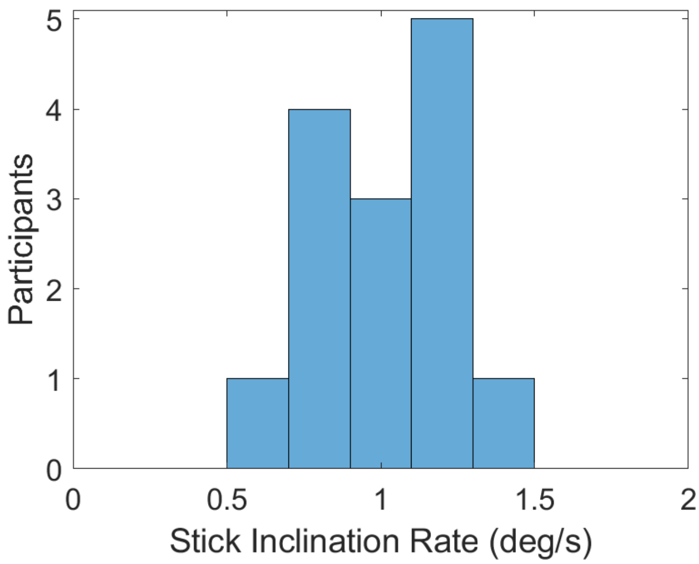


Figure 3.19: Distribution of the mean absolute stick inclination rate with the Segway during slalom.

A histogram of the mean absolute stick inclination rate for the Segway is shown in Figure 3.19, where the interval is between 0.5 and 1.5 degrees per second with the most participants between 1.1 and 1.3 degrees per second.

3.3 Questionnaire

The mean of the questionnaire results from the 11 different scenarios for each vehicle can be seen in the spider plot in Figure 3.20. It can be seen that the Segway generally is rated the lowest on the different scenarios. The e-bike closely followed by the bike is generally rated the highest in the different scenarios. There are, however, a few questions that differ from this.

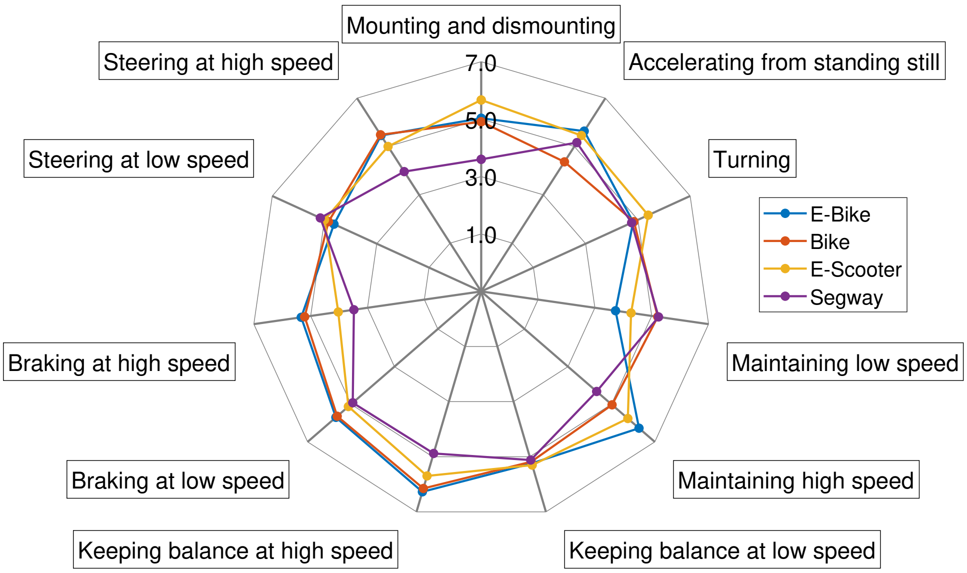


Figure 3.20: A spider plot of the result of the questions about how the vehicles performed when riding. The scale is converted from very poor, poor, fair, good, very good, excellent and exceptional to 1-7 where 1 corresponds to very poor and 7 to exceptional.

3.3.1 Mounting and Dismounting

The lower score on the Segway is reflected in the comments given by seven of the participants saying they were having trouble mounting and dismounting the vehicle. There were two participants commenting on the mounting and dismounting of the bike and e-bike. One of the participants was 164 cm tall and commented that the bike was a bit too large for them, which resulted in troubles getting on and off. The other participant said that they were used to a bike where they could turn the pedals backwards to get a good starting position of the pedals. This is not possible on the bike used in this experiment because of the coaster brake.

3.3.2 Accelerating from Standing Still

The accelerating from standing still question resulted in a fairly similar result across the four vehicles with the regular bike being a bit lower. There were some comments about the e-scooter acceleration. One participant commented that they had some problems with the accelerate button. To accelerate with the e-scooter, a small push manually is needed, before it is possible to accelerate with the electric motor. There were three participants who said the e-bike had the best acceleration. There were however one of them saying that the acceleration was a bit too high which made it difficult to keep a steady speed after acceleration. There was another participant who noted similar difficulties when accelerating with the e-scooter. This other participant said that it was hard to accelerate gently without sudden changes of speed.

3.3.3 Turning

The question regarding turning was not specifically about the experience during the tasks but also the experience the participant had when trying out all the vehicles as well. For this question, it can be seen that the e-scooter is on top and the bike, e-bike and Segway have very similar score. Two comments mentioned that the e-scooter simply was the easiest vehicle to turn with. Another comment mentioned that the Segway had similar turning performance as the e-scooter. Three participants disliked turning with the e-bike since they felt the electric assist kick in during a sharp turn resulting in a larger turn radius.

3.3.4 Maintaining Low Speed

The only question where the e-bike got the lowest score was the question about maintaining a low speed. There were multiple comments saying that it was hard to maintain a low speed with the e-bike since the motor would kick in a bit too much. Two participants said that they periodically had to brake to not go over the desired speed. It can be seen that the e-scooter also has a lower score at maintaining a low speed which also was reflected in the comments. There were three comments saying the throttle for the e-scooter was very sensitive to small movements. This meant that they always had to do small adjustments on the throttle to maintain a low speed. Contradictory to these three comments were one participant who said that it was easy to keep the throttle in a set position and easily maintain the low speed.

3.3.5 Maintaining High Speed

One of the highest average score of the questionnaire is the e-bikes score on maintaining a high speed. The Segway has the lowest score, which is also reflected by multiple participants who felt uncomfortable riding fast with it. There was one participant who noted that it was exhausting for the legs to ride the Segway fast. The bike had a relatively low score compared to the e-scooter and e-bike. This is also reflected in a comment saying that it was very difficult to maintain a high speed with the regular bike.

3.3.6 Keeping Balance

All four vehicles had an average of "Very Good" for how the vehicles perform at keeping balance at low speed. One participant complained about the regular bike being heavy, due to the electric motor and battery, which made it hard to keep the bike upright.

The Segway has the lowest score on keeping balance at high speed followed by the e-scooter then the e-bike and bike. There were two comments saying that balance with the Segway is an experience and practice problem. They said that more experience with the Segway would make it feel more stable and easy to keep balance at high speed.

3.3.7 Braking

In both braking at high speed and braking at low speed, the bike and e-bike have the highest and very similar score. The e-scooter and the Segway have similar scores at braking at low speed but when it comes to braking at high speed, the Segway has a lower score than the e-scooter. The e-scooter, compared to the e-bike and bike has a low score. There were participants who complained about the poor brakes on the e-scooter and that it was hard to judge when to initiate the brake. As for the Segway, there were participants who said that if they had more experience riding it they would feel safer with it and be able to brake better. The general score for braking at low speed is higher than braking at high speed.

3.3.8 Steering at Low Speed

The Segway has the highest score for steering at low speed and the e-bike has the lowest score. The difference between the scores of all four vehicles are however very small. One of the participants said that while pedaling with the regular bike and steering at the same time resulted in poor balance. Another participants once again said that the heavy weight of the regular bike resulted in bad maneuverability at low speed.

3.3.9 Steering at High Speed

Steering at high speed gave scores similar to other questions like the ones about braking and keeping balance. The Segway has the lowest score while the e-bike and bike have similar scores in the top and the e-scooter has a slightly lower score.

3.3.10 Overall

The mean of the results of the four questions regarding the overall comfort, maneuverability, stability and safety can be seen in Figure 3.21. It is clear to see in the graph that the Segway has a lower score on all four overall questions and the e-bike has the highest score in general on the different questions. One can however see that the regular bike is slightly higher rated on the overall safety. The Segway however has a comparable mean score on the overall maneuverability to the other vehicles.

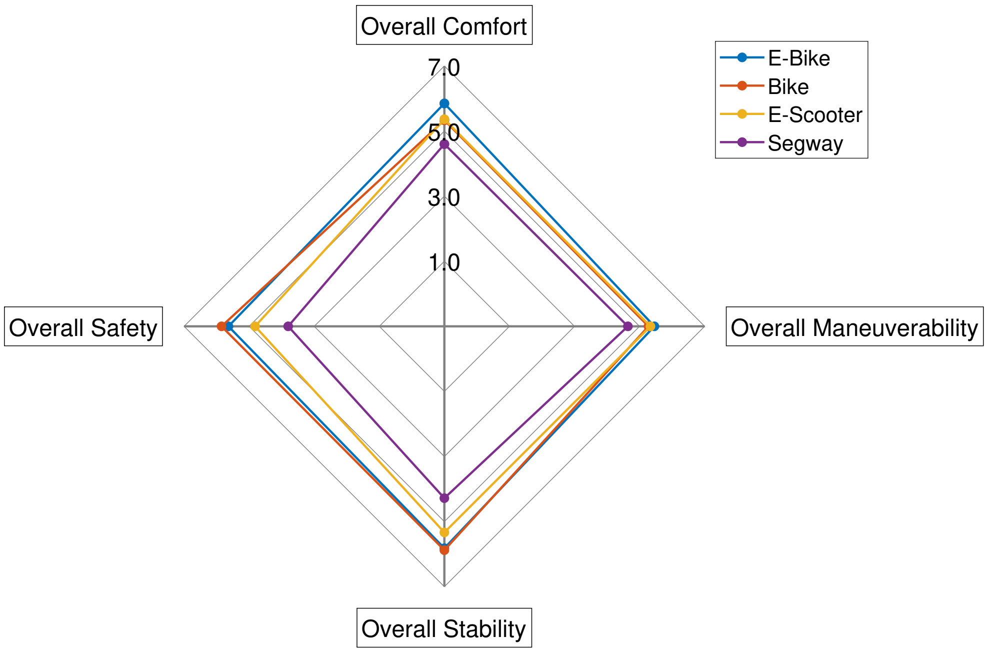


Figure 3.21: A spider plot of the overall questions of the vehicles performance. The scale is converted from very poor, poor, fair, good, very good, excellent and exceptional to 1-7 where 1 corresponds to very poor and 7 to exceptional.

4 Discussion

4.1 Data Analysis

4.1.1 Speed

The mean speed of the vehicles are similar to the study by Violin [11] especially the difference between the vehicles. For the high speed segment the mean speed is generally 1-2 km/h higher in his study which may be since the segmentation was done differently. If the constant segment is started when the participants were still accelerating, the mean speed would be lower. Participants generally had a lower speed with the Segway during the slalom segment which indicate that a lower speed was need to comfortably complete the slalom course. This indicate a lower maneuverability with the Segway compared to the other vehicle, but could also be due to that the Segway did not have a speedometer.

The standard deviation of the speed when the participants were instructed to keep a constant speed is a factor of stability. A low standard deviation indicates that the vehicle is easy to maintain a constant speed with and a high standard deviation indicates that it is hard to keep a constant speed with the vehicle. From the results it could be seen that the Segway is the hardest vehicle to maintain a constant speed with, followed by the e-scooter. The e-bike is harder to maintain a constant speed with than the bike at low speed, but similar at high speed. The reason for this is that the e-bike sometimes gives more power than intended by the user at low speed.

The perceived performance by the participants is different to the actual performance when discussing the speed. Like mentioned before, the Segway was rated one of the best vehicles to maintain a low speed with but the results indicate otherwise. The difference may be due to the participants not being able to see their speed while riding the Segway.

4.1.2 Braking

The mean deceleration is very similar between the harsh brake and unexpected brake. Since the participants however were prepared that they would do an unexpected brake, the result could be different compared to a real unexpected situation. The correlation between how often the participants use the bike and the deceleration with the bike indicates that more experienced cyclists brake harder. Both when braking gently and harshly. The e-scooter however does not have a clear correlation between braking acceleration and experience. A reason for this may be that even if the participants had a high experience with the e-scooter, it is not sure that they were used to the foot brake. The smaller range however also indicates that the rider has less influence on how fast the vehicle brakes with the e-scooter than the bike and e-bike. The results therefore show that the e-scooter has worse braking capabilities than the e-bike and bike which also corresponds well with the study by Violin [11]. The braking distances for the unexpected brake is also in a similar interval as in the study by Garman et al. [2]. The median braking distance were however lower in that study due to that the participants generally had a lower speed with a mean of 13.7 km/h. That the e-scooter has worse braking capabilities than the e-bike and bike is also indicated by the questionnaire results were braking at high speed were ranked the lowest with e-scooter. The Segway clearly has the lowest deceleration which is a negative aspect in both maneuverability and safety aspects.

An alarming result with the e-scooter is that a lot of people passed the stop line before stopping which could be very dangerous in a real setting. Some of these start to brake around the stop line and these participants may have misunderstood or forgotten that they should come to a complete stop before the line and instead believed they should start braking at the line. However since there only was a few cases where the stop line was crossed with the e-bike and the bike, it is fair to say that several participants overestimated the brakes of the e-scooter. This is also the case for some of the riders with the Segway.

The braking results are probably affected by which brakes the participants used. Some of the participants used both brakes on the bike, e-bike and e-scooter and some only used one of them. This was not something that was looked at in detail but something that was noticed during the experiments.

4.1.3 Acceleration

A high acceleration indicates a high maneuverability. A higher acceleration however also makes it harder to estimate the behavior of the vehicle by other persons in a real setting which is a negative safety aspect. From the acceleration results, it could be seen that the Segway and the e-scooter were the vehicles that could accelerate the fastest in the beginning. It however also has the broadest range of mean accelerations which shows that the acceleration behavior differed a lot between participants. All the electric vehicles accelerate faster than the bike, even if the difference between the e-scooter and the bike is small when the participants where told to accelerate fast. The result of the acceleration corresponds well with the results from the study by Violin [11].

From the questionnaire it could be seen that the participants' perceived performance of the vehicles while accelerating are similar to their actual acceleration performance. The comment regarding the accelerate button on the e-scooter not activating could be the reason for the outlier and long whiskers during the harsh acceleration.

4.1.4 Steering and Leaning

The steering angle was generally lower when riding with the e-scooter than with the bike and the e-bike. For the slalom task, this may indicate that the maneuverability is higher for the e-scooter. For the straight maneuvers, it may indicate a higher stability. Another reason for the lower steering angle could be the smaller wheel base of the e-scooter compared to the bike. The steering angle for the e-bike, bike, and e-scooter are generally lower than in the study by Violin [11]. This may be due to that the segmentation was done differently. The mean absolute steering angle will be considerably higher if a turn or part of a turn is captured. It has also been shown in an earlier study by Kovácsová et al. that the mean absolute steering angle for the bike and the e-bike is considerably higher during acceleration than during straight riding at a constant speed [12]. From the study by Kovácsová et al., it has been shown that the steering angle decreases when the speed increases for e-bikes and bikes [12]. In the study the average mean absolute steering angle were 2.5 degrees when the average mean speed were 7.6 km/h and 1.8 degrees when the average mean speed were 13 km/h for the middle aged participants with the bike. This corresponds well with the results from the bike in this study where the median mean absolute steering angle were 2.0 degrees, when the median mean speed was 10 km/h with the bike. The results were similar for the e-bike. From the results in this study it could be seen that the steering angle also decreases for the e-scooter when the speed increases. The steering rate is lower on the e-scooter which also indicates a higher stability. It is however worth to take into consideration that the pedaling on the e-bike and the bike lead to a motion that affects both the roll motion and the steering motion. This could be a reason that the bike has a significantly higher roll rate and steering rate than the e-scooter and the e-bike at high speed.

The stick inclination rate for the Segway is hard to compare with the other vehicles since the vehicles are controlled in such different ways. From the questionnaire, however, it can be seen that the participants rated the Segway the highest for steering at low speeds which would indicate that the Segway is very maneuverable at low speeds. For steering at high speed the Segway was rated relatively low indicating low levels of maneuverability during high speeds.

The perceived steering capabilities of the e-bike, bike and e-scooter were very similar. This indicates that the participants feel that the bike was just as stable as the other two even though there is a small difference in the actual results.

The peak cross correlation between the steering rate and the roll rate is very high for the three segments. The cross correlation was only calculated at the slalom task where the speed was low. In a study by Cain, it was shown that the cross correlation generally is high for both competitive cyclists and regular cyclists at a low speed [20]. This also holds for the e-bike and the e-scooter according to the results from this experiment. The cross correlation values in this study are however much higher than the results from Violin [11] and Kovácsová et al. [12]. In the study by Violin [11] this could depend on how the filtering is done on the steering rate. If the signal contains a lot of noise the correlation will be lower. In this study the peak cross-correlation is estimated during the slalom segment, while it is measured during straight riding in the study by Kovácsová et al. [12]. During the slalom segment, the steering rate and roll rate comes from the turning of the slalom course. When the rider is riding straight, the steering rate and roll rate are inputs done by the rider to stabilize the vehicle. This may be a reason that the peak cross correlation is different. The time delay between the steering rate and roll rate is lower for the e-scooter which indicates a higher maneuverability at a low speed than the bike and the e-bike. The time delay of the bike and the e-bike are similar to the study by Kovácsová et al. [12]. The time delay for the e-bike, bike and e-scooter are similar compared to the earlier study by Violin [11].

Another aspect of steering and leaning is keeping balance which is directly connected to stability. From the questionnaire the participant rated the four vehicles similarly to the questions about steering. The Segway is rated similar at keeping balance at high and low speeds where the other three vehicles were rated higher at keeping balance at high speed than low speed. The reason why the bike and e-bike is rated higher on the high speed is probably due to that a bike is self-stable at high speeds [1].

4.1.5 Mounting and Dismounting

Troubles mounting and dismounting in real traffic could cause problems when, for example, stopping and starting from a traffic light. By not being able to dismount the vehicle after coming to a stop could result in a fall. Not being able to mount the vehicle again after coming to a stop could result in delaying traffic. Mounting and dismounting could be seen as both stability and comfort aspect. If it is difficult to mount and dismount a vehicle it might be because the vehicle is unstable. During the experiments and try-out session, nearly all of the participants needed help with getting on and off the Segway. This together with the questionnaire results indicates that the Segway has the lowest levels of stability and comfort during mounting and dismounting.

4.2 Limitations

4.2.1 Data Sets Availability

During the testing there were some problems that led to missing or corrupted data. The reason for missing LIDAR data was caused by either the 12 V battery running out of charge or due to the power cables braking. Missing vehicle data was due to some different reasons. There are some missing data from the Segway due to malfunction of the USB memory stick, which was used to store the data from the data logger. The broken memory stick made it so no data was saved at all with that memory stick. The other reason for missing vehicle data was a problem with the buttons on the different vehicles. Sometimes the button would not light up (indicating it was recording data), which made it so that there were no way of seeing if it was recording or not. Another problem with the button was that the button simply did not register a button press sometimes. This was a problem when the data recording was to be turned off because if the data logger loses power while recording a file, the file can not be used. A final problem with the buttons was their mounted position on the Segway and e-scooter. It was possible to accidentally press the record button with the feet while mounting and dismounting the vehicles. This resulted in incomplete files.

4.2.2 Potentiometer

The belt connected to the potentiometer and the steering stem of the e-bike had some problems in the beginning. The potentiometer system was set up similarly to the e-scooter, with a small cable and two rubber rings with groves. The cable on the e-bike snapped off multiple times because of high tension, when turning the handlebar too far. This resulted in faulty data for steering angle and was fixed after participant 11 into a better system with a toothed belt and 3D-printed wheels.

4.2.3 Measurement Uncertainty

As stated in Section 2.2, both the IMU and the LIDAR are affected by measurement noise. These are however very small compared to vibrations, uncertainties in the orientation estimate and error from the clustering method.

The orientation estimate that was used was the Madgwick filter. This works very well when an object is not subject to accelerations, but when the vehicles changes speed or turns, the IMU is subject to longitudinal or lateral accelerations. This leads to some error in the pitch and roll angle estimate.

The position from the LIDAR was given by taking the mean of the cluster representing the vehicle. The points will however not be evenly spread out at the vehicle and will change when moving. For example, there will be more points at the front when moving towards the LIDAR and more points on the back when moving away from the LIDAR. The cluster mean will therefore be at different positions of the vehicle over time. This will therefore affect both the position and the speed estimate. These errors are however somewhat compensated for with the RTS smoother that fuses the information from the accelerometer with the LIDAR measurements.

4.2.4 Biases

The results that have been presented may suffer from some biases. During all experiments, there is a risk for selection bias. Because the vehicles had different height and weight limits and to minimize the risks, there were requirements on the participants. There were also mostly young people and more males than females in the study. The participants however represent the main user group fairly well. For example, young males are the largest user group of micro mobility vehicles in the US [21]. There are also several types of models of bikes, e-bikes, e-scooters and Segways available. Many people were not used to the foot brake on the bike and e-bike. Regarding the e-scooter some participants said that the brake on the e-scooter was very bad compared to models they were used to.

There is one participant that entered "Never" for how often they use a regular bike in the questionnaire. This could be interpreted as they have never ridden a bike before, even though one of the inclusion criterion was that they had to be able to ride a bike. Since the question was how often they use the vehicle on a scale from never to everyday there is no way of expressing that the participant had been riding the vehicles in the past or not.

4.3 Future Work

In this study only three electric micro-mobility vehicles were studied. There are a lot of different models of these vehicles and also a lot of other electric micro-mobility vehicles that would be interesting to study. To validate the results of the Segway more data need to be collected since the data from only 14 participants could be analyzed for this vehicle.

The experimental protocol could be extended to include more tasks, such as signaling for a turn and riding over a bump. It is also needed to do naturalistic testing with the vehicles to investigate the safety of the vehicles in a real traffic situation. This could for example be the braking behavior at a crossing where the results could be compared to the braking performance in this study.

5 Conclusion

The Segway was the vehicle that was rated the worst in the questionnaire. It also performed the worst in the performance indicators at high speed, that were comparable between the other vehicles, and included braking deceleration and speed standard deviation. There were also 9 participants out of 34 that did not feel comfortable enough to ride the Segway. The Segway was however comparable with the other vehicles at low speed. For example, the Segway enabled a faster increase in speed from standing still than the bike and the e-bike and was comparable with the e-scooter. The Segway was also rated well in *Steering at low speed*, *Accelerating from standing still*, and *Keeping balance at low speed*. The results therefore indicate that the Segway has a high level of safety at a lower speed in terms of stability, comfort and maneuverability, but a low safety at a higher speed. This suggests that the Segway should have a lower speed limit than the e-scooter, e-bike and bike to be allowed in traffic.

The e-scooter had good stability and comfort at both high speed and low speed. The e-scooter had a significantly lower steering rate than the bike at both low and high speed indicating high stability performance. The e-scooter also performed well in terms of maneuverability since it needs a smaller steering angle than the e-bike and the bike to perform the slalom course. The e-scooter acceleration was lower than the e-bike, but comparable with the bike. A negative performance with the e-scooter is the braking performance. The braking distance with the e-scooter was the longest of all the vehicles at the harsh and unexpected task. Many participants also passed the stop line at the harsh brake which may indicate that the brakes on the e-scooter are worse than what the participants expected. Since the braking performance is an important factor of safety, the poor braking performance of the e-scooter indicates a lower safety compared to the bike and e-bike. The e-scooter may need some more development regarding the braking performance if it should be treated as a bike and be allowed to be ridden at the same speed.

The e-bike performed very well in terms of comfort. The e-bike was the fastest vehicle to accelerate to a high speed with and needs less effort to maintain a high speed with than the regular bike. In terms of maneuverability, the e-bike also performs well with comparable results of roll angle and steer angle on the slalom course as the regular bike. The e-bike also had the same braking performance as the regular bike and better than the Segway and e-scooter. A negative aspect however in terms of safety is that the participants rated *maintaining a low speed* the worst with the e-bike and many participants had a higher mean speed with the e-bike than what was instructed. The results with the e-bike may indicate that the speed of the e-bike would be the highest in a naturalistic setting giving less time to react to sudden obstacles. Overall, the e-bike has a similar safety level as the regular bike and the same policies and infrastructure for bikes would probably be a good solution for e-bikes as well.

The results can be used to help improve the design of electric micro-mobility vehicles and contribute to guidelines for infrastructure design and policy making. For example the results indicated that people are comfortable with the different vehicles at different speeds. An example of infrastructure design could therefore be wider bike paths to make overtaking easier. Examples of policy making could be to restrict electric micro mobility vehicles to different speeds and clearly define where they are allowed to be ridden.

The results could also be used as a baseline for future studies of different electric micro-mobility vehicles and more naturalistic testing.

Bibliography

[1] D. García-Vallejo, W. Schiehlen, and A. García-Agúndez, “Dynamics, Control and Stability of Motion of Electric Scooters,” *Lecture Notes in Mechanical Engineering*, vol. 1, pp. 1199–1209, 2020.

[2] C. Garman, S. G. Como, I. C. Campbell, J. Wishart, K. O’Brien, and S. McLean, “Micro-Mobility Vehicle Dynamics and Rider Kinematics during Electric Scooter Riding,” *SAE Technical Papers*, vol. 2020-April, no. April, pp. 1–15, 2020.

[3] P. Lee, J. Loucks, D. Stewart, D. Jarvis, and C. Arkenberg, “Cycling’s technological transformation,” *Technology,Media, and Telecommunications Predictions 2020*, pp. 118–126, 2019. [Online]. Available: https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/technology-media-telecommunications/deloitte-cn-tmt-prediction-full-report-2020-en-200217.pdf

[4] K. X. Farley, M. Aizpuru, J. M. Wilson, C. A. Daly, J. Xerogeanes, M. B. Gottschalk, and E. R. Wagner, “Estimated Incidence of Electric Scooter Injuries in the US From 2014 to 2019,” *JAMA network open*, vol. 3, no. 8, p. e2014500, 2020.

[5] H. Stigson, “Kartläggning av olyckor med elsparkcyklar och hur olyckorna kan förhindras.”

[6] Idesign, “Risker och möjligheter med nya elfordonskoncept,” 2020.

[7] J. Diaz, “Segway to End Production of Its Original Personal Transporter - The New York Times,” 2020. [Online]. Available: https://www.nytimes.com/2020/06/24/business/segway-pt-discontinued.html

[8] R. Sandler, “Segway Will Stop Making Its Iconic Scooter And Lay Off 21 Employees,” 2020. [Online]. Available: https://www.forbes.com/sites/rachelsandler/2020/06/23/segway-will-stop-making-its-iconic-scooter-and-lay-off-21-employees/?sh=5271af4839db

[9] Ninebot (Changzhou) Tech Co. Ltd., “Ninebot S User Manual,” 2018.

[10] “Utredning behov av förenklade regler för eldrivna enpersonsfordon Delrapport ett - redovisning av dagens regelverk,” 2019.

[11] A. Violin, "Development of an experimental protocol for testing new electric personal mobility vehicles," Chalmers Unviersity of Technology, Tech. Rep., 2020.

[12] N. Kovácsová, J. C. de Winter, A. L. Schwab, M. Christoph, D. A. Twisk, and M. P. Hagenzieker, "Riding performance on a conventional bicycle and a pedelec in low speed exercises: Objective and subjective evaluation of middle-aged and older persons," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 42, pp. 28–43, 2016.

[13] S. Miller, J. A. Molino, J. F. Kennedy, A. K. Emo, and A. Do, "Segway rider behavior: Speed and clearance distance in passing sidewalk objects," *Transportation Research Record*, no. 2073, pp. 125–132, 2008.

[14] "Ninebot S by Segway| Smart Self Balancing Transporter." [Online]. Available: https://store.segway.com/segway-ninebot-s-self-balancing-hoverboard

[15] A. Rasch, M. Dozza, and Y. Håland, "Evaluation of a new narrow and tiltable electric tricycle (e-trike) concept," pp. 1–29, 2016. [Online]. Available: https://research.chalmers.se/en/publication/243873

[16] S. Butterworth, "On_the_Theory_of_Filter_Amplifiers - Experimental Wireless - 1930," pp. 536–541, 1930.

[17] S. O. Madgwick, "An efficient orientation filter for inertial and inertial/magnetic sensor arrays," Tech. Rep., 2010.

[18] M. Ester, H.-P. Krigel, J. Sander, and X. Xu, "A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise," in *Proceedings of 2nd International Conference on Knowledge Discovery and Data Mining (KDD-96)*, 1996.

[19] H. E. RAUCH, F. TUNG, and C. T. STRIEBEL, "Maximum likelihood estimates of linear dynamic systems," *AIAA Journal*, vol. 3, no. 8, pp. 1445–1450, 8 1965. [Online]. Available: https://arc.aiaa.org/doi/10.2514/3.3166

[20] S. M. Cain, "An Experimental Investigation of Human/Bicycle Dynamics and Rider Skill in Children and Adults." Ph.D. dissertation, 2013. [Online]. Available: http://deepblue.lib.umich.edu/handle/2027.42/98003

[21] K. J. Krizek and N. McGuckin, "Shedding NHTS Light on the Use of "Little Vehicles" in Urban Areas," *Findings*, 2019.

A

Data Set Availability

Participant ID	**Bike**	**E-bike**	**E-scooter**	**Segway**
1	N2	N2	N2	N2
2	Y	Y	Y	N1
3	Y	Y	Y	N1
4	Y	Y	N3	Y
5	Y	Y	Y	Y
6	Y	Y	Y	Y
7	N2	N2	N2	N2
8	Y	Y	Y	Y
9	Y	N2	Y	Y
10	Y	Y	Y	N3
11	Y	Y	Y	Y
12	Y	Y	Y	N1
13	Y	Y	Y	N1
14	N2	N2	N2	N2
15	Y	Y	Y	Y
16	Y	Y	Y	N3
17	Y	Y	Y	N3
18	Y	Y	Y	N3
19	Y	Y	Y	Y
20	Y	Y	Y	N3
21	Y	Y	Y	N3
22	Y	Y	Y	N3
23	Y	Y	Y	N3
24	N3	N1	N1	N1
25	Y	Y	Y	Y
26	Y	Y	Y	Y
27	Y	Y	Y	Y
28	Y	Y	Y	N1
29	Y	Y	Y	Y
30	Y	Y	Y	N1
31	Y	Y	Y	Y
32	Y	Y	Y	N1
33	N2	N2	N2	N1
34	Y	Y	Y	Y
% of data	85,29%	82,35%	82,35%	41,18%

Table A.1: Data sets availability. Y indicating that the data is available and NX means that the data is missing with problem ID X. N1 means that the participant didn't ride the vehicle, N2 means that LIDAR data is missing for that vehicle and N3 means that the vehicle data is missing for that vehicle.

B
Questionnaire

Questionnaire nr:________

Please fill out the following questionnaire subjectively with your background and experience during the tests. All information will be stored anonymously.

Background information

Age		Height [cm]		Weight [kg]		Gender	Female ☐ Male ☐ Prefer not to say ☐ Other ☐

	Everyday	Few days per week	Few days per month	Few days per year	Never
How often do you use a Bike?	☐	☐	☐	☐	☐
How often do you use an e-Bike?	☐	☐	☐	☐	☐
How often do you use an E-Scooter?	☐	☐	☐	☐	☐
How often do you use a Segway?	☐	☐	☐	☐	☐

Experience during tests

How did the three e-PMVs you tried out perform?

Mounting and dismounting	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Comments							
Accelerating from still stand	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Comments							
Turning (incl. experience in the try out session)	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Comments							

Keeping balance at low speed	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Comments							

Keeping balance at high speed	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Comments							

Maintaining a low speed	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Comments							

Maintaining a high speed	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Comments							

Braking at low speed	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Comments							

Braking at high speed	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Comments							
Steering at low speed	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Comments							
Steering at high speed	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Comments							

Overall evaluation of the e-PMVs

How was your overall experience with the e-PMVs?

Overall comfort	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Overall maneuverability	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Overall stability	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐
Overall safety	Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
Bike	☐	☐	☐	☐	☐	☐	☐
E-Bike	☐	☐	☐	☐	☐	☐	☐
E-Scooter	☐	☐	☐	☐	☐	☐	☐
Segway	☐	☐	☐	☐	☐	☐	☐

Further comments:

C

Task Description Scripts

C.1 Script for E-bike, Bike and E-scooter

Gentle Maneuver

Now it is time for the gentle maneuver. Start from the start line and accelerate gently to a speed of 17 to 20 kilometers per hour. You should start braking gently to come to a complete stop before the line in the middle. After you have stopped you should accelerate gently again to a speed of 17 to 20 kilometers per hour and then keep this speed until you reach the finish line.

Harsh Maneuver

Now it is time for the harsh maneuver. Start from the start line and accelerate harshly to a speed of 17 to 20 kilometers per hour. You should start braking harshly to come to a complete stop before the line in the middle. After you have stopped you should accelerate harshly to a speed of 17 to 20 kilometers per hour and then keep this speed until you reach the finish line.

Slalom Maneuver

Now it is time for the slalom task. Start from the start line and accelerate to a speed of 7 to 10 kilometers per hour. Go slalom through the cones and keep a speed of 7 to 10 kilometers per hour until the finish line. Please start the slalom by going to the left of the first cone.

Unexpected Maneuver

Now it is time for the unexpected task. Start from the start line and accelerate to a speed of 17 to 20 kilometers per hour. When “STOP” is shouted, you should brake harshly until you come to a complete stop.

C.2 Script for Segway

Gentle Maneuver

Now it is time for the gentle maneuver. Start from the start line and accelerate gently to a high speed. You should start braking gently to come to a complete stop before the line in the middle. After you have stopped you should accelerate gently again to a high speed and then keep this speed until you reach the finish.

Harsh Maneuver

Now it is time for the harsh maneuver. Start from the start line and accelerate to a high speed. You should start braking harshly to come to a complete stop before the line in the middle. After you have stopped you should accelerate harshly to a high speed and then keep this speed until you reach the finish line.

Slalom Maneuver

Now it is time for the slalom maneuver. Start from the start line and accelerate to a low speed of approximately 7 to 10 kilometers per hour. Go slalom through the cones and keep a low speed of approximately 7 to 10 kilometers per hour until the finish line. Please start the slalom by going to the left of the first cone.

Unexpected Maneuver

Now it is time for the unexpected maneuver. Start from the start line and accelerate to a high speed. When “STOP” is shouted, you should brake harshly until you come to a complete stop.

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY