CHALMERS
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Development of an experimental protocol for testing new electric personal mobility vehicles

Vehicle instrumentation, data collection procedure, data processing and analysis, and performance indicators computation

Master’s thesis in Automotive Engineering

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Abstract

The growing trend toward electric personal mobility vehicles introduces new participants in the world of mobility, giving new challenges and new potential hazards to traditional road users. This fast growth has also given hard times to road regulators to follow the trend which generated a lack of rules, especially due to a lack of knowledge on the behavior of these vehicles and their users.
The goal of this thesis was to develop a data collection and data analysis procedure to objectively compare these vehicles.
Four vehicles were chosen to be tested: a conventional bike, an e-bike, an e-scooter, and a segway. A set of four different maneuvers was developed to simulate real-world riding scenarios: 1) a "gentle" and 2) a "harsh" maneuver to evaluate the longitudinal behavior of these vehicles, 3) a "slalom" maneuver to evaluate the lateral motion and 4) an "unexpected" maneuver to evaluate the rider's reaction after an unpredicted event. Performance indicators of stability, maneuverability, and comfort, that were to be analyzed for the four vehicles, were defined. In order to record the performance indicators, motion, steering, and speed sensors were mounted on the vehicles, while an external LIDAR sensor recorded the vehicles' trajectories. An experimental procedure capable of collecting the data for the analysis was developed. The procedure consisted of a briefing with the participant, a test phase in which the participant completed the four tasks on each of the four vehicles, and a questionnaire to be filled at the end regarding the experience during the test phase. Two pilot tests were organized in order to assess the procedure and to collect data from nine participants. The experimental procedure has demonstrated to be solid and ready for future data collections. Some guidelines have been defined after the pilot tests for what concerns the analysis of the vehicles' behavior. The segway demonstrated to be the most difficult to be used by the participants as it required longer training time and was graded as the least safe in the questionnaire. A long brake reaction time and low braking capabilities confirmed this observation. For the e-scooter, instead, high maneuverability in the slalom and fast acceleration from standing still are counterposed to low braking capabilities. Bike and e-bike, instead, were mainly graded the same according to safety. Riders exhibited excellent braking capabilities for both bicycles, that proved to be very stable and maneuverable in the longitudinal direction, while less maneuverable in the lateral direction. The short brake reaction times for both bikes resulted in a high level of maneuverability and safety.

Keywords: personal mobility vehicle, bike, e-bike, e-scooter, segway, safety, stability, maneuverability, comfort, riding performances.

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Alessio Violin, Gothenburg, June, 2020

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Introduction

1.1 Background

Electric personal mobility vehicles (e-PMVs) such as e-bikes and e-scooters, are a fast-growing trend nowadays. This growth has introduced new participants in the world of mobility giving new challenges and new potential hazards to traditional road users [1].
The fast advent of these new vehicles has also given hard times to road regulators to follow this trend, generating a lack of rules that can increase the danger for road users. At the time of writing, there is a lack of information regarding where these vehicles are allowed to ride and what are the rules that they should follow. Moreover, e-PMVs are generally treated as bikes even if several studies on e-bikes [3, 8] and e-scooters [6, 4] have demonstrated that they behave differently from them, introducing the needs of new and more appropriate rules.
One of the main problems related to these vehicles is that they generally ride in areas in which other types of vehicles travel with different speeds and behaviors. As previously cited it is not clear where these vehicles can ride, and every city has its own rules regarding this [2], which means that it is possible to find them in pedestrian areas, bike lanes and roadways where they can interact with pedestrian, bikes and cars. In most of the cities there is a speed limit for these vehicles (approximately 20 kph) and it is recommended from either the producers or the rental companies to wear a helmet while riding the vehicles. Despite the recommendation to wear a helmet, e-vehicles riders tend to avoid the use of it and according to a study performed in Los Angeles on the behavior of e-scooter riders, less than 11% of the riders wear a helmet [17].

A study on electric scooters performed by Garman *et al.* [5] shows that these vehicles have limited braking capabilities. On asphalt, the average braking deceleration for this type of vehicles is in between 0.30-0.35 g (2.94-3.43 m/s^2) which is significantly lower than other personal mobility vehicles.
On the other hand, e-scooters showed good stability while riding straight. The same study showed that while riding on a straight line, steering and roll angles were close to zero. This means that the vehicle does not require much input from the rider in order to travel on a straight line.

Opposed to bikes and e-bikes, most of the e-vehicles are highly affected by the body posture and interaction with the vehicle which can highly affect the behavior of these. An example of this is a study conducted on e-scooter dynamics by Garman *et al.* [5], which observes the high impact of the position and the reaction motion

of the body in balancing the e-scooter, especially in low speed maneuvers where generally a high control of the inputs (for example steering input from the rider) is required.
Another example of this is a study conducted by Garcia-Vallejo *et al.* [4] which shows that the position of the feet on the e-scooter base affects the comfort of the rider.

These aspects generate the needs of a better understanding of the behavior of these vehicles, in order to increase the safety level for both traditional and "new" road users. Moreover, a better understanding of new e-vehicles can be beneficial also for other purposes such as autonomous driving and the development of safety features in traditional vehicles.

1.2 Scope

Due to the previously cited reasons, the initial goal of this thesis was to analyze the behavior of some new e-PMVs and compare them with more traditional bicycles in order to assess their safety. The assessment of safety has been divided into three macro areas: Stability, Maneuverability and Comfort in order to position the vehicles in a Safety matrix, as previously performed for a traditional bike, an e-bike, and an e-trike [15].
Initially, a larger data collection with participants was planned for this thesis. However, due to the spread of COVID-19 at the time of collection, this experiment was postponed in order to limit the spread of the virus. The scope of this thesis was therefore changed. The new goal was to prepare a complete procedure for the data collection and develop an analysis software capable of automatically analyzing new data (that will be available once the larger data collection happens and will greatly facilitate analysis).

2

Methodology

In Figure 2.1 it is possible to observe a schematic overview of the whole process.

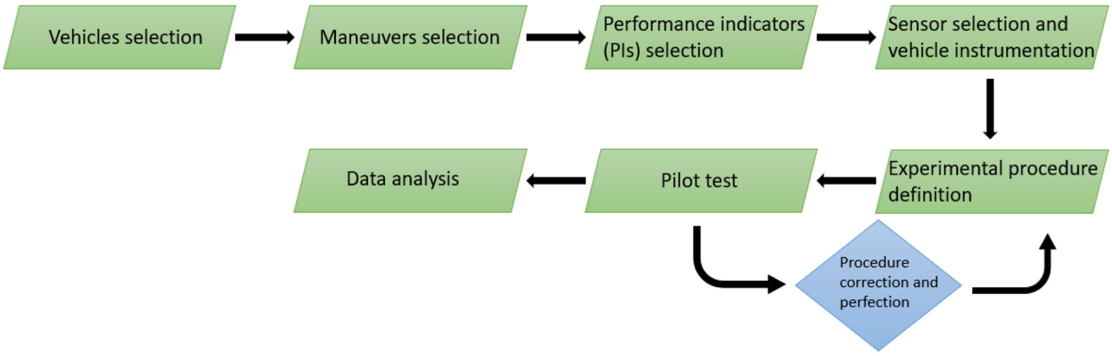


Figure 2.1: Process description

2.1 Vehicles selection

The first operation that has been done was the selection of the vehicles for the test. The selection started with an analysis of the current e-vehicles available in the market and a subsequent analysis of them in order to choose among all the possibilities. The main characteristics that have been analyzed are:

- Popularity.
- Possibility of mounting sensors.
- Easiness in learning how to use them in order to avoid vehicles which cannot be learned to ride in a short amount of time.

In Table 2.1 it is possible to observe which vehicles have been chosen, the maximum speed that they can reach and some comments on them, including the reason why they have been chosen.

Vehicle	Max speed (km/h)	Comments
Bike (Fig: 2.2a)	40	Used as reference since already studied in depth and considered as a traditional PMV
E-bike (Fig: 2.2a)	30	Similar to a traditional bike and already studied in depth, good to be compared with other vehicles
E-scooter (Fig: 2.2b)	25	Already present in the streets due to some sharing companies and therefore quite popular. The model has been chosen in order to be similar to the ones in the streets
Segway (Fig: 2.2c)	16	Not so popular on the street but of increasing popularity, very interesting due to the different balancing direction and steering mechanism

Table 2.1: Chosen vehicles and technical comments

More details regarding the vehicle under study are presented in Appendix A.

Figure 2.2 shows the selected vehicles. As it can be noticed, only one vehicle has been used as traditional and electric bike, in which the electric motor was turned off and on, respectively.

(a) Bike/E-bike

(b) E-scooter

(c) Segway

Figure 2.2: Selected vehicles

Before proceeding with the description of the maneuvers, in Figure 2.3 it is possible to observe the reference system used for the vehicles and the names associated to the angles and directions. It has been decided to use the same reference system and names commonly used in vehicles dynamic. The picture has been taken from [7].

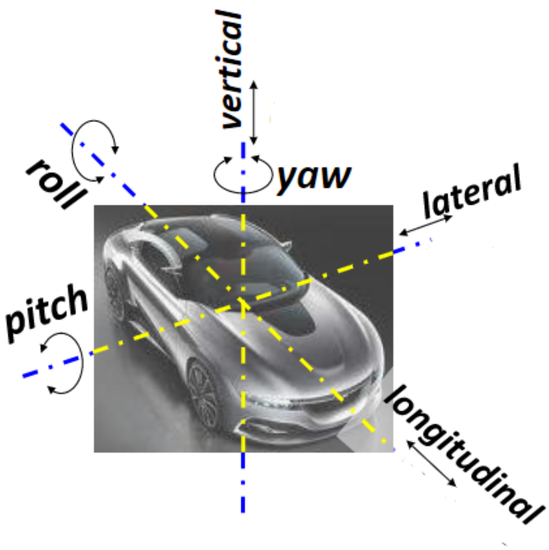


Figure 2.3: Reference system for the vehicles and directions names

2.2 Maneuvers selection

The second step of the process was to choose tasks for the participants to perform. Those should be representative of real-life riding situations. Furthermore, the tasks should be similar to the ones in previous studies in order to allow result comparison. Thus, task 2 has been chosen to be equivalent to task 2 in Kovacsova et al. [8], while task 1 and 3 were chosen to be equivalent to task 1 and 4 in Rasch et al. [15].
In the following sub-sections, the different tasks will be described in detail.

2.2.1 "Gentle" maneuver - Task 1

The "gentle" maneuver consisted of the following steps:

1. Accelerate in a comfortable manner and stay above 17 km/h. For what concerns the segway, considering that an odometer is not present and so a constant speed cannot be maintained, was decided to ride at the maximum speed allowed by the vehicle.
2. Maintain the speed.
3. Brake in a comfortable way in order to come to a stop before the line.
4. Accelerate again in a comfortable manner and stay above 17 km/h (or the maximum for the segway).
5. Maintain the speed until the end of the test area.

This maneuver was intended to be a simulation of a rider approaching a stop line (for instance due to a red light) and a subsequent acceleration to start again the ride.
The maneuver is summarized in Figure 2.4:

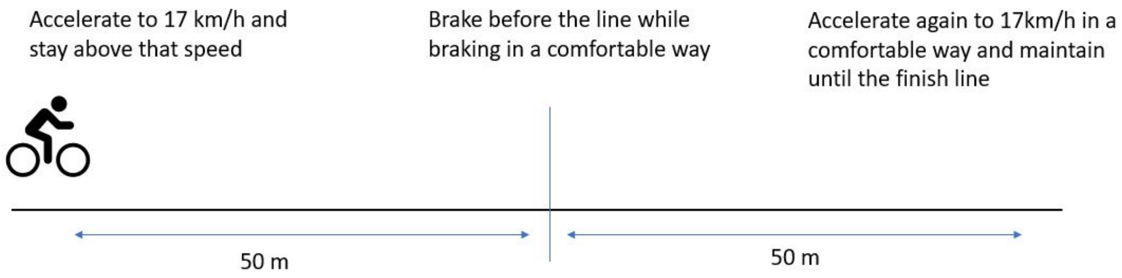


Figure 2.4: "Gentle" maneuver

2.2.2 "Harsh" maneuver - Task 2

The "harsh" maneuver is similar to the gentle one with the difference that the braking and acceleration phases are performed not in a comfortable way but in a harsh way. This maneuver is intended to be the same simulation as before but with the increased harshness due for example to a late perceived stop signal due to inattention. This maneuver is also interesting to compare the different vehicles braking and accelerating phase when is requested to brake and accelerate not in a comfortable way but using the respective maximum capabilities of the vehicles.
The maneuver is summarized in Figure 2.5.

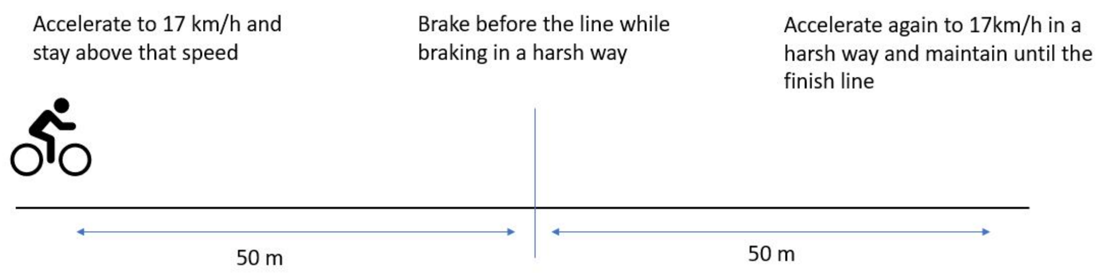


Figure 2.5: "Harsh" maneuver

2.2.3 "Slalom" maneuver - Task 3

The "slalom" is a maneuver intended to evaluate the lateral dynamics of the vehicles and the dynamic of the vehicles at a lower speed compared to the one previously tested. It consists of reaching and maintaining a speed between 7 and 10 km/h, approaching and performing a slalom maneuver and reaching the end of the test area while always keeping the speed. To perform this procedure with the segway it is necessary to limit the maximum speed of the vehicle to 10 km/h using the phone app and then ride at maximum speed. The cones are positioned at distances of 3m between each other, and are four in total.
This maneuver simulates the rider intended to avoid some obstacles, which can be for example some pedestrian walking in the pedestrian area or some obstacles in the street.
The maneuver is summarized in Figure 2.6.

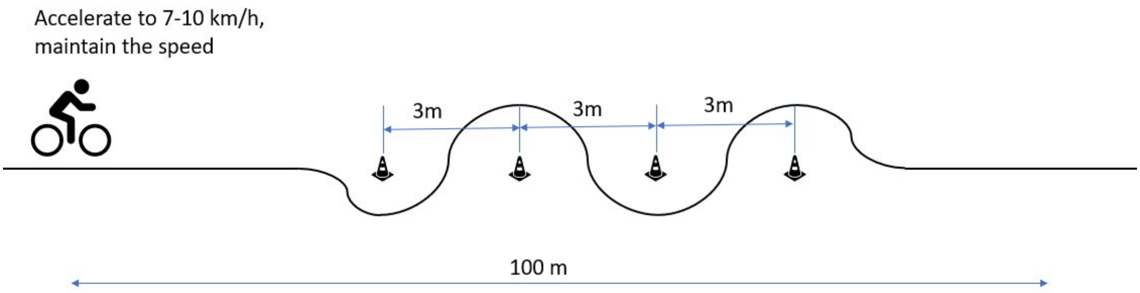


Figure 2.6: "Slalom" maneuver

2.2.4 "Unexpected" maneuver - Task 4

The "unexpected" maneuver is intended to simulate a situation in which the rider reacts to a surprising event. It is quite common that while riding, an unexpected situation can occur, for example an unseen car that honks at the rider in order to warn of its presence.
With this maneuver, it is possible to evaluate the different reactions of the riders using different vehicles and their kinematics when critical situations are involved.
In order to create the unexpected event, a sound signal is emitted to which the rider has to react by braking as fast as he can.
The maneuver is summarized in Figure 2.7.

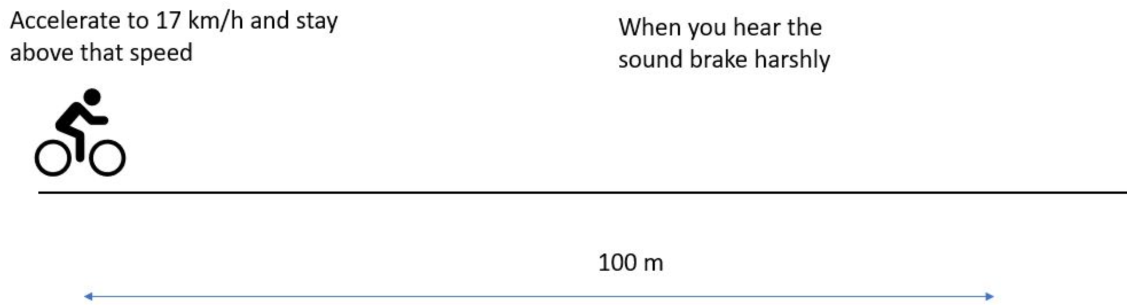


Figure 2.7: "Unexpected" maneuver

2.3 Performance indicators (PIs) selection

The performance indicators (PIs) are the tool needed to assess the level of safety of the vehicles. These parameters describe some aspect of the vehicle kinematics and relate them to one or more safety dimensions of the matrix (stability, maneuverability and comfort). The PIs, taken from [8, 15] and adapted to this study, are summarized in Table 2.2 and 2.3.
Before proceeding with the description of the PIs, the following pictures are needed in order to understand the division of the segments in the task and their name.
In Figure 2.8, it is possible to observe the segment division in task 1 and 2. The

tasks are characterized by a "const17" phase (constant speed of 17 km/h), "dec" phase (braking until standing still) and "acc" phase (accelerate up to 17km/h).

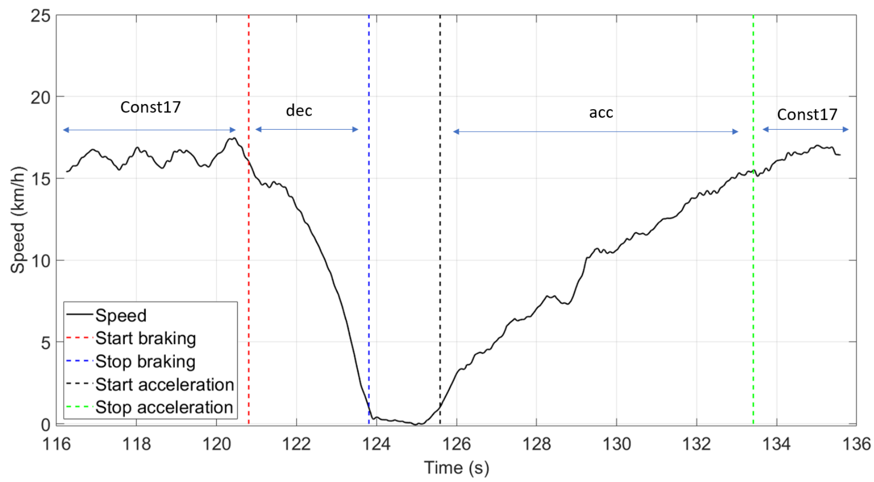


Figure 2.8: Segment subdivision in task 1 and 2

For task 3, the segment division is summarized in Figure 2.9. It is possible to observe two different phases: a "const7" phase (constant speed of 7 km/h and a "slalom" phase (phase in which the slalom was performed).

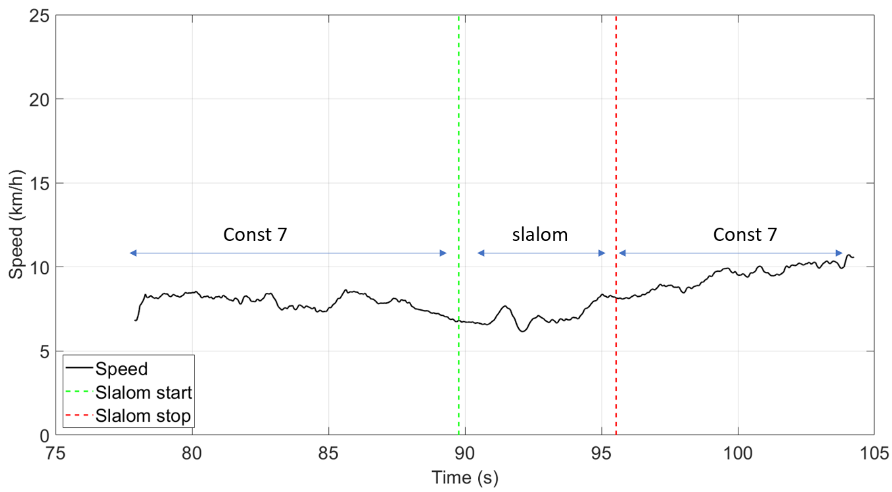


Figure 2.9: Segment subdivision in task 3

For the unexpected task, the subdivision is shown in Figure 2.10. It is possible to observe three different phases: a "const17" phase (constant speed of 17 km/h), a "reaction" phase (phase in which the rider reacts to the sound) and the "dec" phase (braking until standing still).

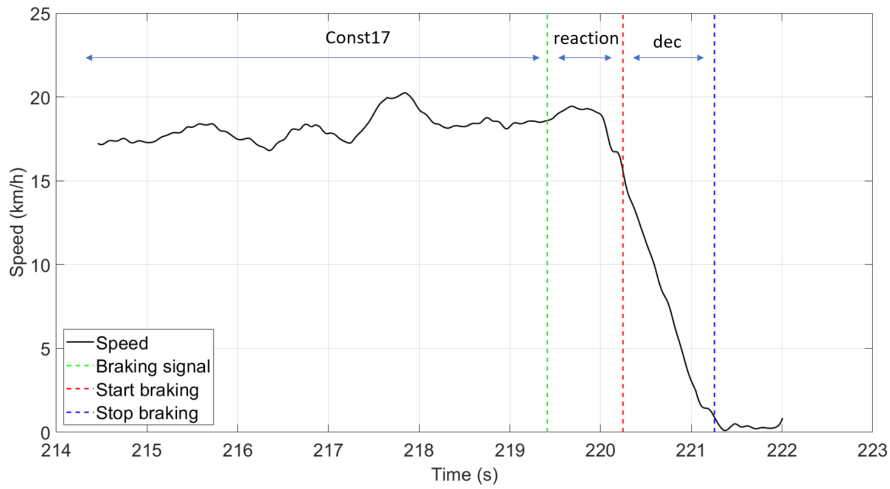


Figure 2.10: Segment subdivision in task 4

Now, the PIs are here described and summarized in the following Tables. The needed sensor will be described in detail in paragraph 2.4.

The steering angle is an indicator of the maneuverability of the vehicle in turning conditions, while of stability and comfort in straight riding. The roll rate mainly describes the stability of the vehicle. A large value of this parameter might indicate difficulties in controlling and stabilizing the vehicle while riding [8]. Steering rate and roll rate are correlated in a vehicle with the handlebars (in the same way the stick inclination and the yaw rate in the segway), the R^2 of the linear fit and the time delay describe how much these parameters are correlated. An R^2 value close to 1 means high correlation and so the possibility of steering by tilting the vehicle. The time delay describes how much later the steer signal follows the roll of the vehicle (or yaw for the segway). The time and the distance covered from when the sound signal has been emitted until when the participant starts to brake in task 4 describe the time and the space needed to start the braking maneuver after an unexpected signal. The higher these values, the lower the maneuverability of the vehicle. For the segway, the pitch rate signal describes the "shaky" behavior of the vehicle. The higher this value, the more unstable the behavior of the vehicle and the higher the risk for the rider to lose balance and fall.

The needs of choosing different PIs for the segway is because it has a very different shape and configuration compared to the other vehicles so, it would be impossible to use the same parameters.

Bike, E-bike, E-scooter					
	Data segment	Signal	PI	Meaning	Sensor needed
Task 1,2,3	Const17, Const7, Slalom	Steering angle (deg)	Mean abs. steering angle	S,M,C	Potentiometer
	Const17, Const7, Slalom	Roll rate (deg/s)	Mean abs. roll rate	S	IMU
	Const17, Const7, Slalom	Steering rate (deg/s), Roll rate (deg/s)	R^2 of linear fit	S,M,C	Potentiometer, IMU
	Const17, Const7, Slalom	Steering rate (deg/s), Roll rate (deg/s)	Time delay between roll rate and steering rate (s)	S,M,C	Potentiometer, IMU
	Const17, Const7, Slalom	Speed (km/h)	Mean speed, std. deviation	S,M,C	Lidar, DC motor (if present)
	Acc, Dec, Slalom	Time(s)	Time (s)	M,C	any
	Acc, Dec	Longitudinal acc. (m/s^2)	Mean abs. longitudinal acc.	M,C	IMU
Task 4	Reaction, dec	Time (s)	Time (s)	S,M	any
	Reaction, dec	Distance (m)	Reaction and braking dist. (m)	S,M	Lidar
	Const17	Speed (km/h)	Mean speed, std. deviation	S,M,C	Lidar, DC motor (if present)
	Dec	Longitudinal acc. (m/s^2)	Mean abs. longitudinal acc.	M,C	IMU

S= stability, M= maneuverability, C= comfort

Table 2.2: Performance indicators for bike, E-bike, E-scooter

Segway					
	Data segment	Signal	PI	Meaning	Sensor needed
Task 1,2,3	Const17, Const7	Pitch rate (deg/s)	Mean abs. pitch rate, std. deviation	S,M,C	IMU
	Const17, Const7, Slalom	Speed (km/h)	Mean speed, std. deviation	S,M,C	Lidar
	Slalom	Stick inclination rate (deg/s), Yaw rate (deg/s)	R^2 of linear fit	S,M,C	IMU
	Slalom	Stick inclination rate (deg/s), Yaw rate (deg/s)	Time delay between stick incl rate and yaw rate(s)	S,M,C	IMU
	Slalom	Stick inclination (deg)	Mean abs. stick angle	S,M,C	IMU
	Acc, Dec, Slalom	Pitch rate (deg/s)	Mean abs. pitch rate (s)	S,M	IMU
	Acc, Dec, Slalom	Time(s)	Time (s)	M,C	any
	Acc, Dec	Longitudinal acc. (m/s^2)	Mean abs. longitudinal acc.	M,C	IMU
Task 4	Reaction, dec	Time (s)	Time (s)	S,M	any
	Reaction, dec	Distance (m)	Reaction and braking dist. (m)	S,M	Lidar
	Const17	Speed (km/h)	Mean speed, std. deviation	S,M,C	Lidar
	Dec	Longitudinal acc. (m/s^2)	Mean abs. longitudinal acc.	M,C	IMU
	Dec	Pitch rate (deg/s)	Mean abs. pitch rate (s)	S,M	IMU

S= stability, M= maneuverability, C= comfort

Table 2.3: Performance indicators for segway

2.4 Vehicle instrumentation and sensors description

After having defined the parameters to analyze, it was possible to proceed to the next step of the procedure.
In order to measure the kinematics of the vehicles and then later analyze the performance indicators (PI) described in section 2.3, the vehicles need to be equipped with some sensors. These, will be described in detail in the next sections of this paragraph.
Before proceeding with the description of these, all the sensors attached to each vehicle are summarized in Table 2.4.

Vehicle	Sensor	Sampl. f (Hz)	Position
Bike/E-bike	IMU	125	On the rack of the bike
	Potentiometer	20	Attached to steer
	DC motor	20	In contact with the wheel
E-scooter	IMU	125	Below the base for the feet
	Potentiometer	20	Attached to steer
Segway	IMU	125	Below the base for the feet
	IMU	125	On the steering stick

Table 2.4: Sensors attached to each vehicle

In addition to all the sensors, a device called data logger has been added to each of the vehicles. This device is needed to log all the sensor data and save them on a memory device.

In order to track the horizontal motion of the vehicles, a light detection and ranging (Lidar) sensor has been positioned in the test area. As opposed to the other, this sensor was static during the trials and positioned on a tripod.
Now, all the sensors and the data logger will be described in detail.

2.4.1 Data logger

As previously stated, a data logger is needed in order to connect all the sensors, read the measurements and save these in a USB device. This was done with a Raspberry Pi 3 model B and the open source data logger obtained from [16]. The software, written in Python and based on the robotic operating system (ROS), was modified in order to allow the use of multiple IMUs and to meet the requirements in sampling frequency for the different sensors.
A real time clock (RTC) has been added to the board in order to have a timestamp to name the file and to easily recognize and analyze the files during the data analysis.
In order to supply the energy for the whole system, a power bank with an output of 5V and 2A has been connected to the Raspberry Pi and fixed to the vehicle.
The data logging is started and stopped thanks to two buttons installed on each vehicle. One button is needed to start and stop the data logging, the other one has two different functions:

1. When the data logging is on, it works as a flag button, it gives as output 1 when pressed and 0 when not. This is needed to synchronize the signals coming from the vehicle and the Lidar.

2. When data logging is off, it works as a shut off button.

In Figure 2.11, it is possible to observe the data logger device and the two buttons needed to use it.

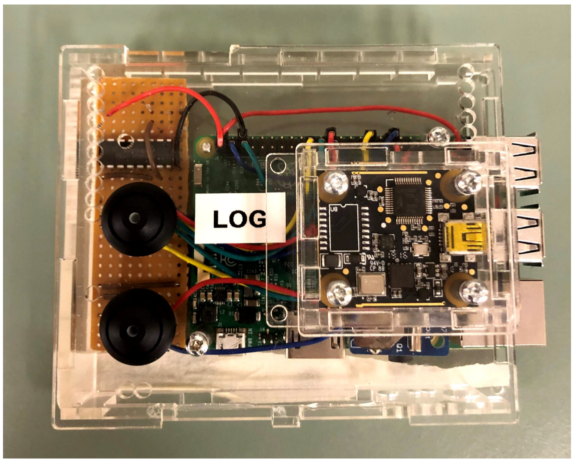


Figure 2.11: Data logger device

2.4.2 Inertial measurement unit (IMU)

The inertial measurement unit (IMU) is a sensor needed to sample acceleration and gyroscope data in three dimensions each. The used model is a "PhidgetSpatial 3/3/3 1044" which has the following technical specifications:

- Acceleration measurement max: $\pm$ 2.5 g
- Acceleration measurement resolution: 76 μg
- Gyroscope speed max: $\pm$100 °/s
- Gyroscope resolution: 0.0031 °/s

This sensor is needed in order to compute the longitudinal and lateral acceleration as well as the roll and pitch rate.
In Figure 2.12 it is possible to observe the IMU, mounted on the rack of the bike.

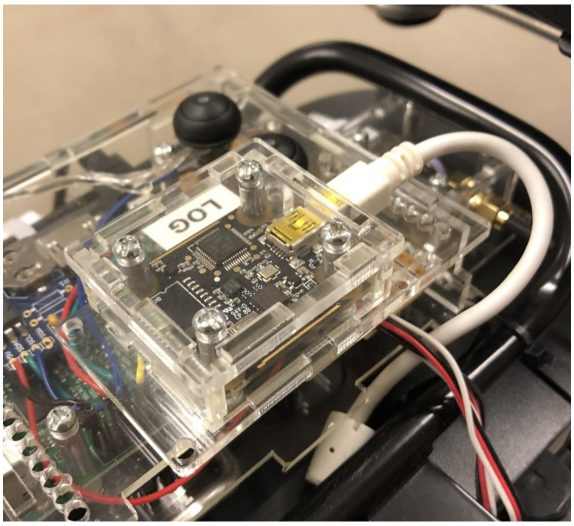


Figure 2.12: IMU sensor mounted on the rack of the bike

2.4.3 Steering angle sensor

In order to evaluate the steering angle of the vehicles, a potentiometer has been used. The potentiometer is a device capable of varying its internal resistance due to a movable wheel mounted on it. Connecting this wheel with a belt system to the handlebar (Figure 2.13) and measuring the variation in the voltage across the poles of this device (induced by the variation of the internal resistance), it is possible to measure the steering angle. In order to do so, an analog to digital converter (ADC) was needed. The ADC used for this study is an 10 bit ADC connected to the Raspberry Pi via an serial peripheral interface (SPI) connection.
It must be noticed that this sensor has not been mounted on the segway due to the absence of a handlebar.

Figure 2.13: Steering angle sensor made with a potentiometer and a belt system

In order to calibrate this device, a step variation of 20° from -60° to 60° has been made while measuring the output from the ADC (which can distinguish 2^{10}=1024 discrete values). Then, by linearly interpolating the angles and the outcome from the ADC, it was possible to obtain a function needed to convert the output of the sensor in degrees. This procedure has been repeated for both vehicles.

2.4.4 DC motor

The DC motor was used to compute the speed of the bike. For simplicity, it has been positioned inside the dynamo of the bike (Figure 2.14) and it is connected to the Raspberry Pi by means of the previously described ADC.

Figure 2.14: DC motor placed inside the bike's dynamo and used as speed sensor

In order calibrate the sensor, the output of the DC motor has been measured due to a variation of speed from 5 to 20 km/h with 5 km/h step variations. Then, as for the potentiometer, the values from the ADC and the speed have been linearly interpolated in order to obtain the calibrating function to convert the output of the DC motor into the speed in km/h.

2.4.5 Lidar

The Lidar sensor was used to track the horizontal motion of the vehicles during the experiments. The model used during the experiments was a "Hokuyo UXM-30LXH-EWA", which is characterized by the following technical specifications:

- Guaranteed detection range: 30 m
- Maximum detection range: 120 m
- Scanning angle: 190°
- Angle step: 0.125°

In order to log the data coming from the Lidar, a Raspberry Pi 3 model B has been used as data logger as for the vehicles. To this has also been attached a button which is needed to synchronize the files coming from both the Lidar and the vehicles and to divide the different maneuvers during the experiments.
The sampling frequency for this sensor has been set to 20 Hz.

Figure 2.15: Lidar sensor

2.5 Experimental procedure

In this section the whole procedure for the data collection will be described. It is mainly characterized by three different phases, a pre-test phase, in which the test area is prepared and the participant is instructed regarding the procedure, a test phase, in which the participant performs the test and data are collected and a post-test phase, in which the participant is asked to fill a questionnaire and debriefed.

2.5.1 Pre-test phase

The pre-test phase is the phase that precedes the data collection.
The procedure starts with the set up of the test area and a trial of the vehicles in order to verify their functioning status. In Figure 2.16 it is possible to observe a schematic layout of the test area.

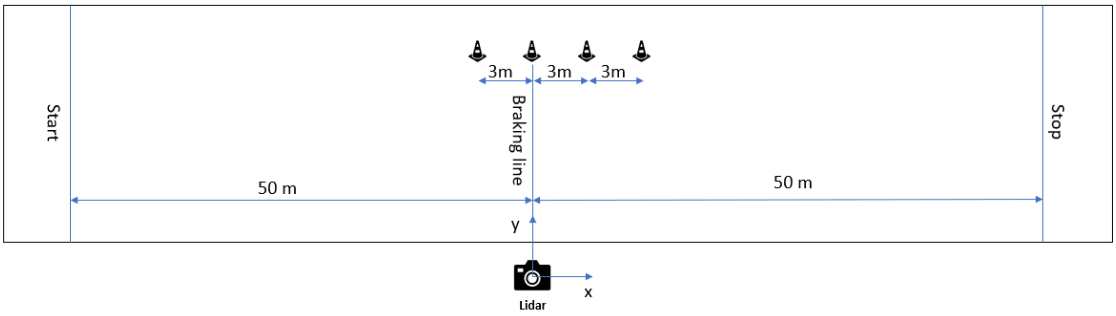


Figure 2.16: Scheme of the test area

After having verified that everything worked, it is possible to start the briefing with the participant.
The briefing starts with the description of the test procedure to the participant, describing the scope of the test, the task that he is going to perform and its rights during and after the test. After this, a consent form is furnished to the participant, in order to have its approval to use the data for the analysis and to declare that he understood all the procedure previously illustrated.
The next step is to furnish all the needed safety equipment to the participant, in order to allow him/her to familiarize with the vehicles. To facilitate this, two training procedures (one for the segway and one for the e-scooter) have been developed and can be observed in Appendix B. These, taking inspiration from [14, 13], are designed to cover all the possible situations that can occur during the test.

Finally, once the rider feels ready to start the procedure, it is possible to start the data collection.

2.5.2 Test phase

Figure 2.17: Test area

During the test phase, the participant performs all the required tasks on each vehicle. In order to avoid possible biases in the data, the task order and the vehicle order have been randomized so that every participant performs the test in a different order.

Now, the procedure to collect the data is described in detail:

1. Start recording from the Lidar and the vehicle. Wait a couple of seconds before moving the vehicle since two seconds are needed for the IMU to calibrate.
2. Simultaneously press the flag button on the vehicle and the lidar data logger in order to synchronize the files.
3. Now, the participant can proceed to the start line to begin with the first maneuver.
4. In order to segment the data set for the different maneuvers, the following technique has been used: a short press of the lidar flag button means that the maneuver has started, a long press means that the maneuver has finished.
5. Once performed all the maneuvers, stop the recording in the lidar and in the vehicle.
6. Change vehicle and repeat the same procedure here described until all the vehicles have been tested.

Once all the vehicles have been tested it is possible to proceed to the post-test phase.

2.5.3 Post-test phase

When the participant has performed all the required tasks, a questionnaire to fill regarding the experience is furnished. This questionnaire, observable in Appendix C and adapted from [15], is needed to have a subjective overview of the vehicles from each of the participant. The first part of the questionnaire consists of several questions regarding the participant's feeling when different aspects of the maneuvers are taken into account and is asked to answer considering a scale from 1 (very poor) to 7 (exceptional). The second part, instead, is a generic overview of the vehicles considering stability, maneuverability, comfort and safety.

Once finished answering to the questionnaire, the participant can leave the test area and it is possible to start again the procedure with another participant.

2.6 Pilot test

Due to the limitations caused by COVID-19 at the moment of writing this thesis, it was impossible to collect data from many participants, as initially planned.

In order to still be able to develop the analysis process, a pilot test with some members of this project and some volunteers has been performed. This test was also meant to try the whole procedure in order to verify its functionality and adjust it in case of any potential problems.

The pilot test took place two different days in April 2020 and nine people participated in total. The location for the test was in front of the SVT building at

Pumpgatan 2, Gothenburg (Figure 2.18).

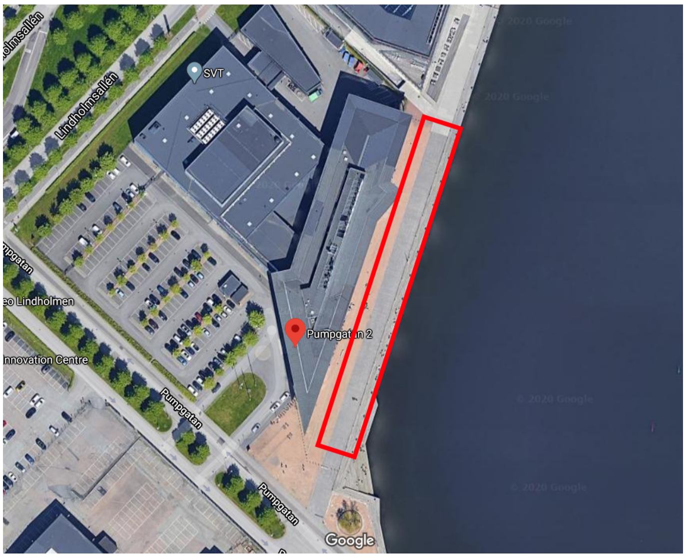


Figure 2.18: Test location

In the following Table, it is possible to observe some background information regarding the participants.

	Average	St. deviation	Max	Min
Age (y)	30.55	10.12	55	23
Height (cm)	178.56	8.31	188	161
Weight (kg)	72.11	7.60	80	60
Gender	M= 7, F= 2			
How often do you use a bike?	3.55	1.34	5	1
How often do you use an e-bike?	1.56	0.83	3	1
How often do you use a segway?	1.33	0.47	2	1
How often do you use an e-scooter?	1.89	0.87	3	1
Was the training time enough?	Yes= 9, No= 0			

For the questions "How often": 1=never, 2= few days per year, 3= few days per month, 4= few days per week, 5= everyday

Table 2.5: Background information of the participants

2.7 Data analysis

Once having performed the data collection, it is possible to analyze the obtained data. In the following sections the data analysis procedure is explained in detail. The software used for the analysis is Matlab©.

2.7.1 Time synchronization of the signals and maneuvers division

As previously described in sections 2.4.1 and 2.4.5, the lidar and the vehicles have a flag button needed to synchronize the data. The flag button creates a signal equal to 1 in the data set, when pressed, and 0 otherwise. By letting the time signal begin with the moment in which both the lidar and the vehicle have a 1 in the button signal, it is possible to obtain a synchronization in the data sets.
The flag button in the lidar is also used to divide the maneuver slots in the data files. The procedure described in 2.5.2 allows to easily divide the data set by knowing that if the 1 signal is short means that the maneuver is started, while if the 1 signal is long means that the maneuver is finished.

2.7.2 Signal calibration

The calibration procedure starts by obtaining the converting functions as described in section 2.4.3 and 2.4.4. With these functions, it is possible to convert the raw data coming from the sensors into values that are congruent with the measured parameter (e.g. steering angle in degrees).

For what concerns the IMU in the segway, a different type of calibration is needed. It must be noticed that in this type of vehicle the variation in pitch cannot be neglected. This means that the acceleration measured by the IMU is highly affected by the gravitational acceleration acting not only on the vertical axis but also in the longitudinal by means of this variation in pitch. In order to solve this problem, the reference system of the segway (and so of the IMU) must be changed using a rotation matrix and the pitch angle as a rotating value. The pitch angle is directly obtained from the IMU in which there is a pre-built Madgwick filter [10], capable of obtaining the inclination by fusing acceleration, gyroscope and magnetometer data. With this procedure it is possible to obtain the pure longitudinal acceleration of the vehicle needed to evaluate its dynamic behavior.

2.7.3 Lidar data analysis - data clustering and tracking of the vehicle

The procedure to analyze the data coming from the Lidar sensor starts by converting them from a polar reference system to a cartesian one. With this conversion, it was easier to analyze the results in the next steps.
The data to be analyzed has then been limited considering the geometry of the test area. All the points detected by the Lidar have to be included in a limit of ± 55 m in x direction and from 1 to 6m in y direction (considering the axis defined in Figure 2.16).

Once having extracted only the points included in the actual test area, a clustering procedure has been performed by means of the "Density-based spatial clustering of applications with noise" (DBSCAN) algorithm in Matlab. This algorithm compares all the points on each time-stamp and divides them in different groups (called clus-

ters) according to some specifications. The input needed for this algorithm were two: ϵ (radius of a neighborhood with respect to some point) and minPts (the minimum number of points required to form a dense region) [19]. For this analysis the used values were respectively: $\epsilon = 1.1$ m, minPts=2.
It should be noticed that ideally there should be only one cluster recognized by the function for each time-stamp. If this was not the case (maybe because of the presence of someone else in the test area), a selection of the cluster has been performed by defining that for each time stamp the position with respect to the previous one cannot be larger than 1 meter.
Chosen the cluster that represents the vehicle it was possible to proceed.

The last step was to compute the centroid of the cluster of the vehicle, by computing the average in x and y direction of all the point in the cluster.
With this procedure, it was possible to track the vehicle in the ground plane and obtain its position in time during the experiments.

2.7.4 Signal filtering

The signals have been filtered in two different methods:

- For what concerns the speed signal, a Rauch-Tung-Striebel (RTS) smoother [18] has been used with a constant acceleration model for task 1,2,4 and a constant turn rate model for task 3 in which the lateral motion is relevant for the study. In the first case the input measurements are the acceleration coming from the IMU, the position coming from the lidar and the speed obtained by discrete time derivative of the position from the lidar. In the second case, the inputs were the longitudinal and lateral speed derived from the lidar position signal, the longitudinal and lateral acceleration coming from the IMU and the position in the two directions coming from the lidar.
- For all the other signals, a low pass filter has been used. The applied filter is a Butterworth low pass filter with a pass band frequency of 7.5 Hz and a stop band frequency of 9Hz.

2.7.5 Maneuvers segmentation

The maneuver segmentation is the process in which the maneuvers are divided into the segments previously described in section 2.3. This procedure is performed in different ways according to the different task and is summarized in the following sections.

2.7.5.1 Task 1 and 2

For the gentle and the harsh maneuver, the segmentation is performed with the speed signal, previously smoothed with the RTS smoother. The steps to follow are the following:

1. The process starts by defining the end of the braking phase. The condition that defines this, is when the speed reaches a value below 1 km/h.

2. Now, it is possible to define the starting point of the braking maneuver. This condition is reached when the speed is below 16 km/h (14 km/h for the segway due to the limitations in maximum reachable speed). In order to solve situations in which an oscillating behavior of the speed during the const17 phase occurred, one more condition has been added: the beginning of the maneuver has to occur in a range from 3 to 0 s before the end of the braking phase for the gentle maneuver and 1.5 to 0 s for the harsh maneuver (for the segway 3 to 0 s for the gentle and 2 to 0 s for the harsh due to some difficulties in braking found by some participants). These two conditions have shown a good response in dividing the maneuvers and with the actual data sets no further conditions are needed.
3. The start of the acceleration maneuver can be easily computed with the same technique used for the end of the braking but in the opposite way. the last point of the speed signal that is lower than 1 km/h is the starting time of the acceleration. This method can also fix some situations in which the participants started accelerating for some centimeters and stopped again before actually starting the acceleration phase.
4. The end of the acceleration is reached when the speed overcomes the value of 16 km/h. The condition for the time to be greater than the acceleration starting time is needed to set the end of the acceleration phase after the beginning of it.

The simple conditions previously described performed well with the actual data sets and so no further conditions are needed.

2.7.5.2 Task 3

For the slalom task, due to the constantly kept speed during this maneuver, the previously described conditions cannot be used and so, a different approach has been adopted.
This segmentation is performed by using the horizontal position of the vehicle obtained with the Lidar and imposing a limit of 1m before the first cone and 1m after the last cone. This was possible because the cone positions are know due to a specific way of positioning them during the set up of the test area.

2.7.5.3 Task 4

The conditions for the task 4 are very similar to the ones for task 1 and 2. The end of the braking phase is set in the same way, while the start of it is defined in the same way as of tasks 1 and 2 but changing the range in which it should occur. In this case, there is the unexpected signal whose time is known from the flag button, and so the braking start phase should occur in the range starting from the unexpected signal to the end of the braking phase.
This definition of the starting point of the braking phase also marks the end of the reaction phase which starts with the unexpected signal.

2.7.6 Performance indicators computation and analysis

The PIs are computed by analyzing the signals in the different segments and computing the values defined in Tables 2.2 and 2.3.
The analysis of the PIs starts by computing the different values for every vehicle and for every maneuver and successively analyzing the results in order to understand the behavior of the vehicles under test. All the results can be observed in section 3.2.

3 Results

The results obtained during this study are here summarized.

3.1 Data set description

Due to some technical issues with the lidar and some problem occurred with the vehicles' data loggers, not all the data sets are available for being analyzed. In the following Table, it is possible to observe which data sets are available, which not and the problem that occurred.

	ID participant									
Vehicle	1	2	3	4	5	6	7	8	9	Missing (%)
Bike	Y	N,1	Y	N,1	Y	Y	Y	Y	Y	22.2
E-bike	Y	N,1	Y	N,1	Y	Y	Y	Y	Y	22.2
E-scooter	Y	N,2	Y	Y	Y	Y	Y	Y	Y	11.1
Segway	Y	N,3	Y	Y	Y	N,1	Y	Y	Y	22.2
Missing (%)	0	100	0	50	0	25	0	0	0	

Y= yes, N,*= no, problem id

Table 3.1: Data sets availability

The problems that occurred are here summarized:

- 1: Problem related to the lidar data logger: shut off of the logger while recording.
- 2: Problem related to the scooter power supply due to a fall of the vehicle caused by strong wind: interruption of power supply while recording.
- 3: Problem related to the segway data logger: shut off of the logger while recording.

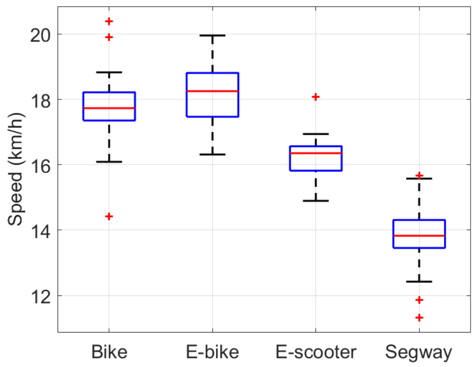
3.2 Experiment results

3.2.1 Constant 17, constant 7 segments

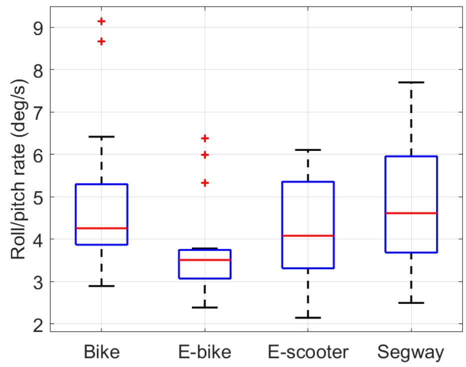
In Figure 3.1, it is possible to observe the comparison between the time-averaged PIs from the const17 segment for the different vehicles.

As it can be noticed, the segway has the lowest speed during the const17 segment while the e-scooter has the lowest spread of values across the participants with a

median value lower than the required speed of 17 km/h.
In Figure 3.1b, the mean absolute roll rate averaged across the participants for the bike, e-bike and e-scooter and the mean absolute pitch rate for the segway are shown. It is possible to observe that the e-bike has the lowest value, followed by the e-scooter and the conventional bike.



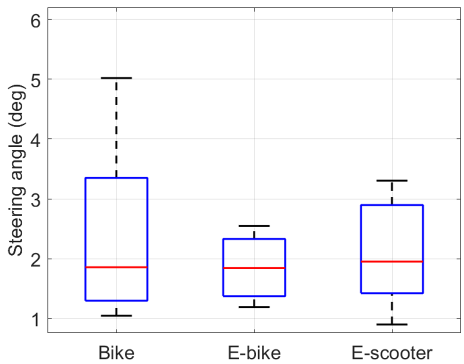
(a) Mean speed



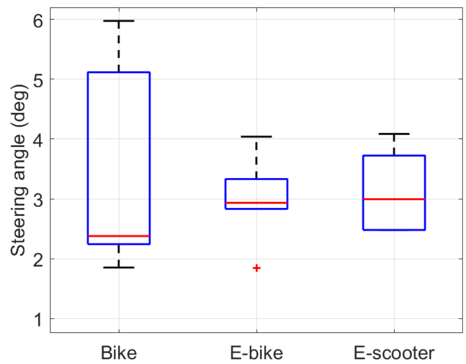
(b) Mean abs. roll/pitch rate

Figure 3.1: Const17 phase, comparison between vehicles

In Figure 3.2, it is possible to observe a comparison of the mean absolute steering angle between the const17 and const7 segments.
It can be observed that in the const17 segment, the median steering angle is lower compared to the const7 segment. Moreover, the vehicles show a similar average behavior in the const17 segment while, the conventional bike has the lowest average (but also the widest distribution) in the const7 segment.



(a) Steering angle const17 segment

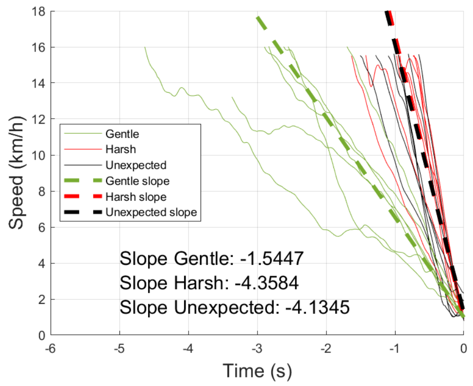


(b) Steering angle const7 segment

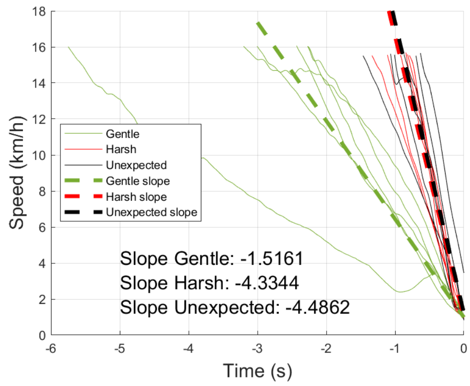
Figure 3.2: Mean absolute steering angle comparison between const17 and const7 segments

3.2.2 Deceleration segment

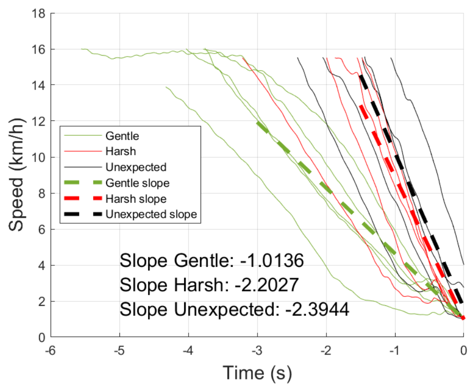
In order to compare the different braking segments, in Figure 3.3, it is possible to observe, for each vehicle, a comparison among the braking phases from task 1, 2 and 4. In each of the graphs has also been added the value of the slope averaged across all the participants for each of the braking types (dashed lines).
As it can be noticed, the "gentle" braking maneuver does not only have the lowest slope (and therefor the lowest acceleration), but also the most spread among all vehicles. Moreover, for the e-bike and the e-scooter, the unexpected maneuver is the one with the steepest slope, which means the highest negative acceleration. Another observation is that for the segway and the e-scooter the difference between the slopes, especially between the gentle and the other two, is smaller with respect to the bikes.



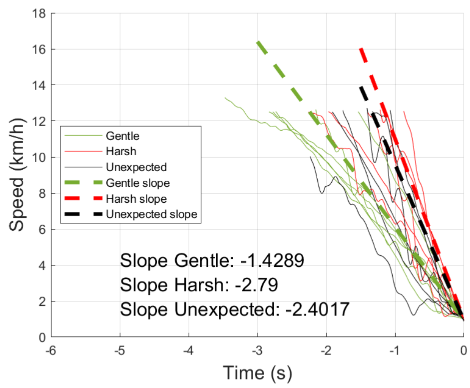
(a) Bike



(b) E-bike



(c) E-scooter



(d) Segway

Figure 3.3: Braking phase comparison for tasks 1 (gentle), 2 (harsh) and 4 (unexpected)

In Figure 3.4, it is possible to observe the mean absolute pitch rate of the segway during the braking phase of the maneuver in tasks 1, 2 and 4.
It can be noticed that during the gentle maneuver the lowest values were observed, followed by the unexpected and the harsh, in which the highest median value among the participants has been registered.

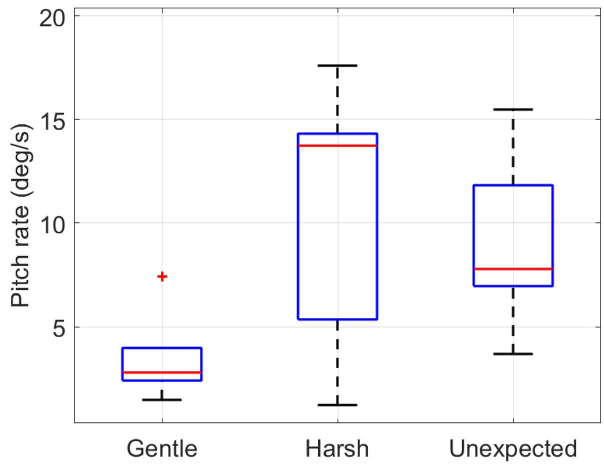
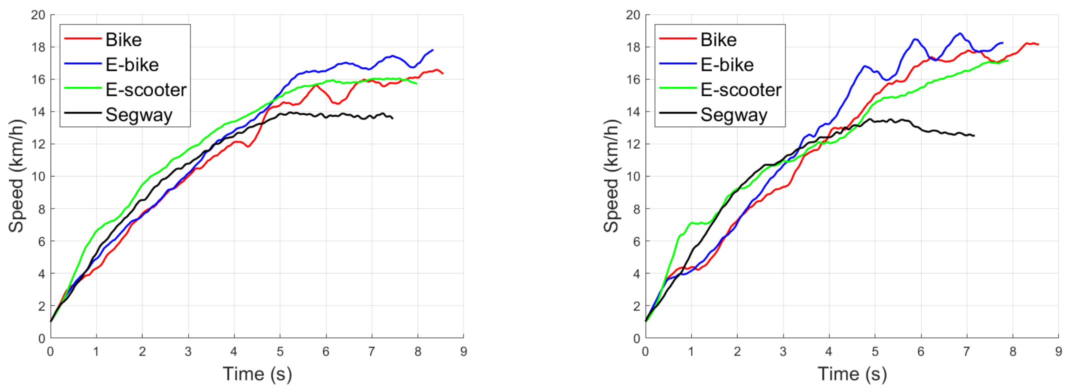


Figure 3.4: Mean absolute pitch rate of the segway, comparison between tasks 1 (gentle), 2 (harsh) and 4 (unexpected)

3.2.3 Acceleration segment

In order to compare the different behaviors during the acceleration phase in tasks 1 and 2, the mean average speed from the acceleration instant until the last visible point by the lidar is presented in Figure 3.5.
It can be noticed that both the e-scooter and the segway, in the first part of the acceleration phase, present a higher speed than the other two vehicles. By the end of the segment at t $\approx$ 5 s, it can be noticed the lower speed reached by the segway (which never overcomes 14 km/h) and the e-bike speed that reaches higher values than the other vehicles.



(a) Task 1 (gentle) **(b)** Task 2 (harsh)

Figure 3.5: Task 1 (gentle) and 2 (harsh) acceleration segment comparison, showing the mean speed across the participants

3.2.4 Constant 7, slalom segments

For what concerns the slalom maneuver (task 3), in Figure 3.6 and 3.7, it is possible to observe the results of the time-averaged PIs.
In Figure 3.6, the time-averaged mean speed during the different segments in the maneuver is shown. It is possible to notice that for every vehicle during the slalom segment, the speed is lower with respect to the const7 segment, especially for the segway in which this difference is bigger.

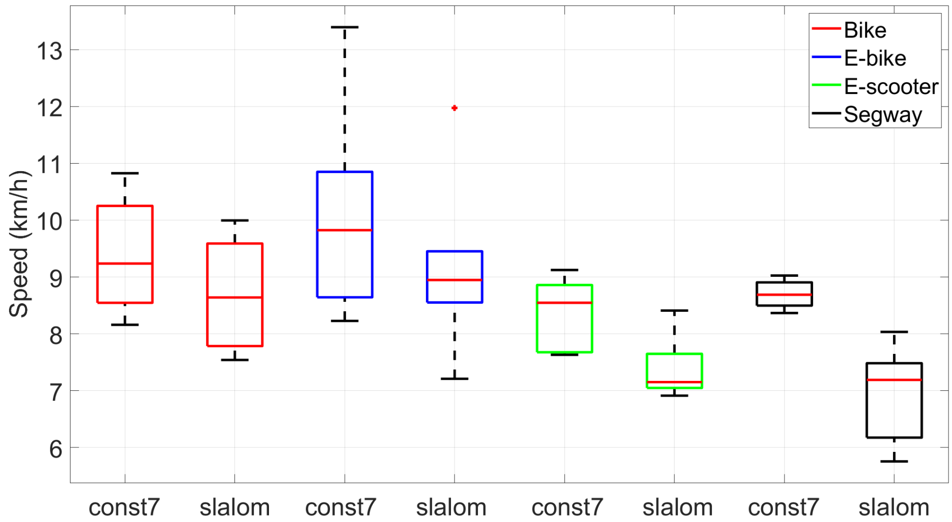
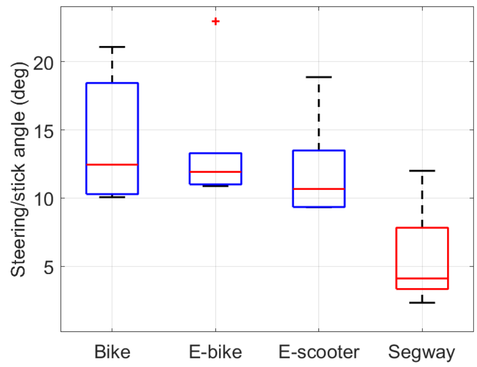
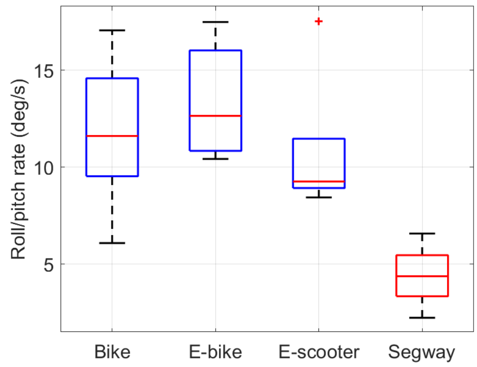


Figure 3.6: Mean speed comparison in task 3 (slalom) for different segments

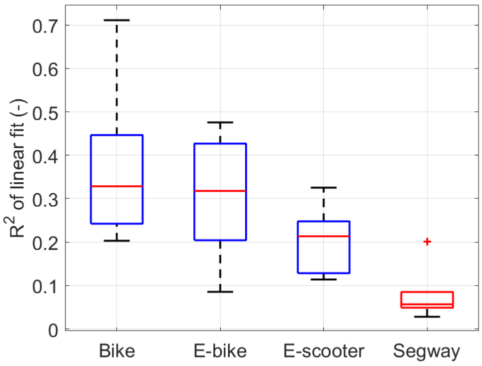
In Figure 3.7a, the mean absolute steering/stick angle is shown, measured during the slalom segment. It is possible to observe that the scooter presents a lower median value compared to the bike and the e-bike. For what concerns the segway, the inclination of the stick required to complete the slalom maneuver is lower compared to the required steering angle for the other three vehicles.
The mean absolute roll rate for bike, e-bike and e-scooter can be observed in Figure 3.7b. As it can be noticed, the e-bike has the highest value, while the e-scooter has the lowest.
Regarding the time delay and the R^2 plots in Figure 3.7d and 3.7c, respectively, it is possible to notice that the segway has a very low R^2 value (low correlation between stick inclination rate and yaw rate), and higher time delay between the signals. The highest R^2 value has been obtained with the bike and e-bike which have similar values while the e-scooter has the lowest time delay between the signals.



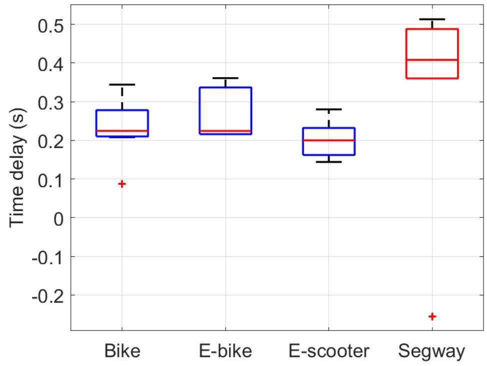
(a) Mean abs. steering/stick angle comparison during slalom segment



(b) Mean abs. roll/pitch rate comparison during slalom segment



(c) R^2 of linear fit steering and roll rate/stick inclination and yaw rate during slalom segment



(d) Time delay steering and roll rate/-stick inclination and yaw rate during slalom segment

Figure 3.7: Task 3 (slalom), Performance indicator comparison. Note that the segway boxes refer to different values

3.2.5 Reaction segment

In Figure 3.8, it is possible to observe the time between the sound signal and the start of the braking section (reaction time) during task 4.
It can be noticed that the segway has a longer reaction time compared to the other vehicles while the others show a very similar behavior considering the median value. Moreover, it is possible to observe that the e-scooter has the less spread distribution compared to the other vehicles.

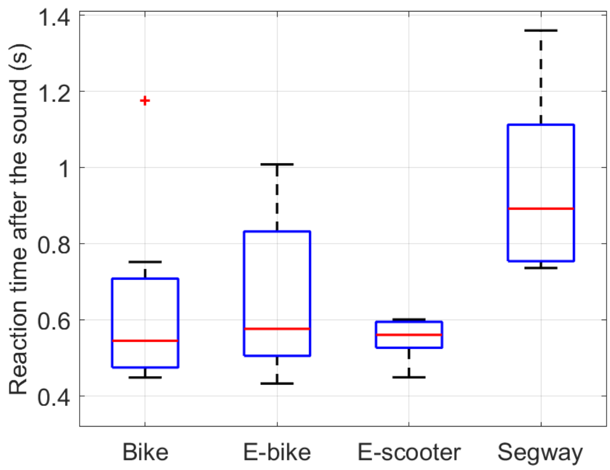


Figure 3.8: Reaction time comparison between different vehicles in task 4 (unexpected)

3.3 Questionnaire results

Before proceeding with the presentation of the questionnaire results, the levels for each of the questions are here summarized:

- 1= Very poor
- 2= Poor
- 3= Fair
- 4= Good
- 5= Very good
- 6= Excellent
- 7= Exceptional

All radar plots have been made using the Matlab function "spider_plot", created by [12].

3.3.1 Experience during test

In Figure 3.9, it is possible to observe a radar plot of the questionnaire results regarding the experience during the tests.

In general, the segway has been appreciated by the participants in the maneuvers requiring low speed (steering, keeping balance and maintaining the speed). The e-scooter has been rated high for what concerns accelerating from standing still, steering at low speed, mounting and dismounting, and maintaining high and low speed.

For what concerns the bike and the e-bike, the results are very similar. The highest ratings for these vehicles have been given for the braking at high speed, keeping balance at high speed and in the mounting and dismounting. The difference between the two bikes can be observed in the accelerating from standing still.

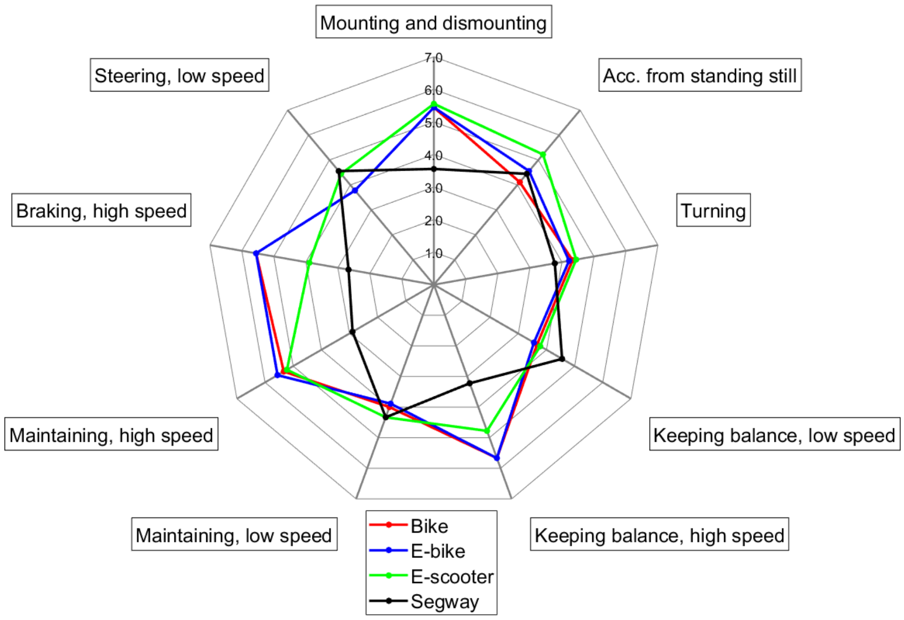


Figure 3.9: Radar plot of the questionnaire results "Experience during tests"

3.3.2 Overall evaluation of the vehicles

In Figure 3.10 and 3.11, it is possible to observe the results of the questionnaire regarding the overall evaluation of the vehicles from the participants.
Bike, e-bike and e-scooter have been rated almost the same except for the overall safety in which the scooter has been graded worse.
The segway, instead, has been graded worse than the other three vehicles in all the aspects except in maneuverability in which has been graded similarly.

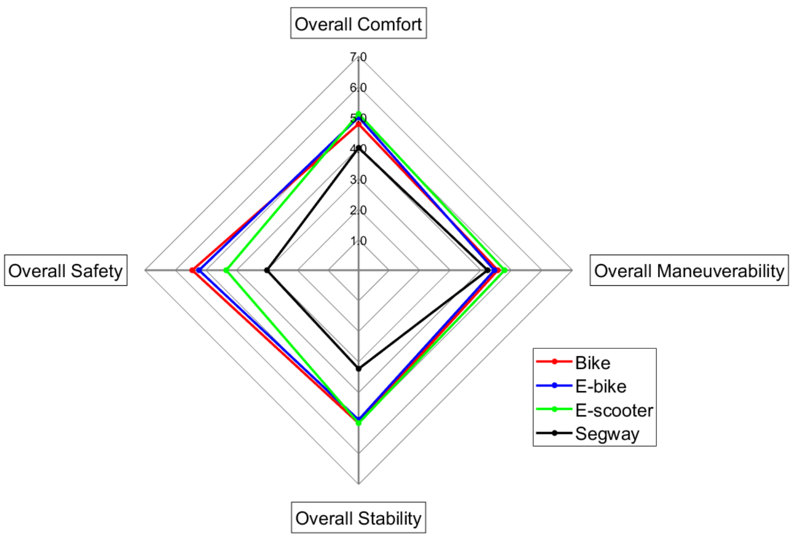
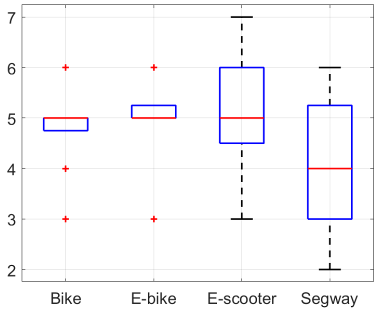
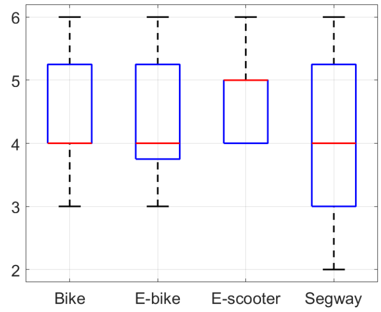


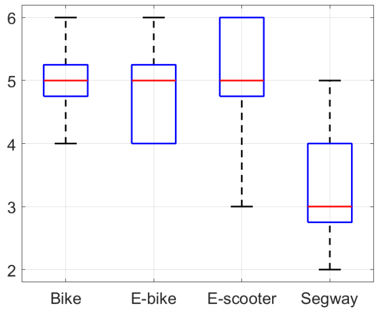
Figure 3.10: Radar plot of the questionnaire results "Overall evaluation of the e-PMVs"



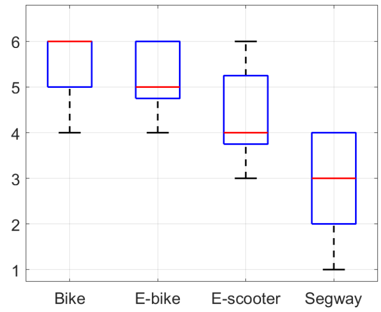
(a) Overall comfort



(b) Overall maneuverability



(c) Overall stability



(d) Overall safety

Figure 3.11: Overall evaluation of the vehicles

3.3.3 Relevant comments from the participants

- "The e-bike was poor in the *turning* and *keeping balance* at low speed and small turning radius due to sudden acceleration".
- "The speed limiter of the segway is very disturbing and tends to destabilize".
- Regarding the question "Was enough the training time?" some of the participants, referring to segway and e-scooter, answered: "yes, but not enough to act as experienced".
- "Braking at high speed doesn't feel safe with the segway".
- "The bike is very heavy"

4
Discussion

As previously stated, the spread of COVID-19 at the time of writing the thesis limited the possibility to perform the large data collection that was initially planned. For this reason, the focus has been moved to the definition of a solid procedure needed to collect and analyze the data that will simplify this procedure when the larger data collection will take place.
In order to verify the whole procedure and to start collecting some data, a pilot test has been performed with a limited number of participants, nine in total, which took place during the month of April 2020. Due to the limited number of participants, the presented results of the data are just some observed possible trend and must be verified when the larger data collection will take place.

4.1 Vehicles selection

4.1.1 Bike

The conventional bike (or simply bike) has been chosen to be the benchmark for this study since it is a widespread vehicle that has already been studied in depth in previous research. It is the simplest one, no electric motors that can affect the behavior and it is purely controlled by the rider.
In general, it worked well, no problems were encountered in installing the sensors (since there is a lot of space for placing them), and no problems occurred during the data collection.
As previously stated in the methodology chapter, the vehicle is the same used for the e-bike in which the electric motor was turned off. This choice, made for the sake of simplicity, was not appreciated by some participants who commented that the bike was very heavy due to the presence of the battery pack and the electric motor which are not usually present in a conventional bike. Moreover, the coaster brake was a new feature for some of the participants and some of them felt uncomfortable with it.

4.1.2 E-bike

Also for the e-bike, the choice was mainly made for its wide spread and the high level of knowledge of its behavior due to several studies already performed.
The comments related to it were the same as for the bike for what concerns the coaster brake while the presence of the support, given by the electric motor, eliminated the problems related to the weight of the bike.

An interesting observation given by one participant is that it was difficult to control the e-bike at low speed due to the sudden acceleration given by the electric motor while maneuvering. This on-off mechanism of the e-bike is related to the lack of controlling the power furnished by the motor in a continuous way. Its control is limited to five different levels of speed at which the vehicle can travel without acting on the brakes to stop it or pedaling more to accelerate it.

4.1.3 E-scooter

The e-scooter was chosen for its growing popularity and responsibility for the rise of micro-mobility worldwide. It is very small, light and intuitive to use, as some participants commented.
Except for a problem that occurred during the first pilot test, in which the presence of strong wind overturned the vehicle and broke the power supply of the data logger, it worked well during the collections.
Due to the limited space, all the instrumentation has been placed below the vehicle. This positioning prohibited the possibility of riding it on an uneven road or, for instance, over speed bumps.

4.1.4 Segway

The segway was the vehicle that divided the participants of this study into two groups. On one side, some participants really liked it and found it very fun to use. On the other side, some participants found it very unsafe and they felt almost uncomfortable to perform some maneuvers.
For what concerns the positioning of the equipment, also in this case the instrumentation has been placed below the foot base and, therefore, the same riding limitations as for the e-scooter applied.
One problem encountered with the segway during the data collection was that the battery of the vehicle was not sufficient to perform more than 5 data collections without being recharged. Moreover, the control system of the vehicle limits the maximum speed reachable when low levels of charge are reached.

4.2 Experimental procedure

The procedure for the data collection, tested during the two pilot tests with participants either inside or outside the research group, has demonstrated to be very solid. The introduction of the training procedure to simplify the learning process has been appreciated, especially by the less experienced participants, and has been followed by most of them. Moreover, no problems have been encountered during the data collections that can be attributed to the procedure itself. This demonstrates the solidity of it and its readiness for future data collections.

For what concerns the data analysis procedure, the created software to analyze the data demonstrated to be very efficient. It allows analyzing the recorded data starting from the extraction of the data sets from the raw files until the analysis of the performance indicators in a very simplified and automatic way. Moreover, the chosen files synchronization procedure (flag buttons), the chosen filtering and smoothing techniques and the chosen criteria to segment the maneuver demonstrated to properly work in analyzing the data and allowing a fast and easy analysis of the PIs.

4.3 Data analysis

4.3.1 Constant 17, constant 7 segments

Considering the mean speed reached by the vehicles during the const17 phase, the segway registered the lowest speeds compared to the other vehicles. This is not only a consequence of the maximum speed reachable by the vehicle but also of the speed limiter that induces the participant to brake by tilting the feet base. Moreover, if also the outliers were considered (in Figure 3.1a), the bike has the most spread distribution of average velocities maintained by the participants. This spread can probably be a consequence of the absence of an electric motor that complicates the task of keeping a constant speed.
The highest mean absolute roll rate has been measured for the bike. This can be explained considering that the absence of the electric motor forces the rider to cycle more and this could induce a higher roll rate as a consequence of the cycling motion.

Comparing the steering angle in the constant speed segments, it is possible to observe that the mean absolute value is lower if the speed is higher. For what concerns the bike and e-bike, this result can be a consequence of the self-stabilizing mechanism of these two vehicles when overcoming the speed of 15 km/h, as demonstrated by Meijaard J. P. *et al.* in [11]. The obtained results are in line with [8, 15], in which similar steering angle values were recorded. For what concerns the e-scooter, instead, the trend is the same as for the bikes even if the self-stabilizing mechanism is not present in this type of vehicle, as demonstrated by Garcia-Vallejo *et al.* in [4].

4.3.2 Deceleration segment

The deceleration segment is present in three different tasks (1, 2 and 4) and for each of these, it is performed in a different way.
It can be noticed that the slope of the gentle maneuver is always the smaller in magnitude (which means slower deceleration) and the more spread in distribution. This can be attributed to the impact of the participants' perception and what each of them felt comfortable while braking.
The lower accelerations measured for the e-scooter and the segway during the harsh/unexpected maneuver in comparison to the two bicycles indicate that the braking performances of these vehicles are lower and so their safety and maneuverability levels are lower. While the acceleration values registered for the bike and e-bike during the gentle maneuver are in line with [9], the accelerations registered for the e-scooter are a bit lower if compared to the study by Garman *et al.* [5]. This result can be a consequence of the different e-scooter model used for the tests.
It must also be considered that the speed reached by the segway is lower in comparison to the other vehicles and so the acceleration might be affected by this. Moreover,

the braking mechanism of the segway is related to a movement that might be scary for some participants (inclining the body backward might induce the feeling of falling off) and so the registered accelerations might be lower than the actual capabilities of the vehicle.

The pitch rate of the segway during the braking phase is an indicator of how harshly the participants activate the brakes. This value is lower for the gentle maneuver which indicates a more cautious behavior from the participants while is higher if the harshness of the maneuver is increased.

4.3.3 Acceleration segment

The acceleration segment is only present in tasks 1 and 2.
As previously described, the e-scooter and the segway are the vehicles that have a higher acceleration in the first part of the segment. This can be a consequence of the lower weight of the vehicles, which allows them to be faster in the first 3,4 seconds. After this first period, the segway reaches its maximum speed limit and so it stops accelerating while the e-scooter decreases its acceleration (probably because of the limit in its acceleration capabilities).
Overall, the e-bike has the higher average acceleration (becomes faster than the e-scooter after the first instants) and the highest measured speed, results that are in line with [15] when a comparison with the conventional bike is made.

4.3.4 Constant 7, slalom segments

Starting by analyzing the speed in the different segments of the third maneuver, it can be noticed that the average speed is lower during the slalom segment compared to the const7. This is probably a consequence of the higher caution of the participants during the slalom segment when compared to the less dynamic constant speed segment.

During the slalom segment, a smaller steering angle is needed by the e-scooter to perform the maneuver. This is an indicator of a higher maneuverability compared to the bicycles and is probably a consequence of the smaller dimensions of the wheels and the vehicle itself. Moreover, it also registered lower roll rate if compared to the bikes. Also this is an indicator of a higher maneuverability of the e-scooter.
Regarding the correlation between the signals, the segway measured low values for the R^2 and high values of time delay. This low correlation assign low levels of stability and maneuverability since there is a low correlation between the speed of steering (stick inclination rate) and the speed of turning (yaw rate). On the other hand, the three other vehicles measured higher values for the R^2 (especially the conventional bike) and lower time delays (even if a lower R^2 value and a longer time delay has been obtained when compared to [15]), indicating a higher correlation between the signals. This indicates a better balancing skill and allows to steer by tilting, giving higher levels of stability, maneuverability and comfort.

4.3.5 Reaction segment

The reaction segment describes the time interval between the sound signal and the start of the brake and is only present in task 4.
Analyzing the reaction time, it is possible to observe that the segway is the vehicle in which the participants took a longer time to start braking after the signal had been given. This behavior characterizes a low level of maneuverability and in turn safety, which can represent an important weakness of this type of vehicle. The longer the reaction time, the longer the time to react to a dangerous situation, the higher the risk for the rider to get involved in a crash.

4.3.6 Questionnaire results

The results from the questionnaire have added a subjective evaluation of the vehicles according to the participants' feelings.
It is important to notice that the e-scooter and the segway have generally been graded better than the bicycles for what concerns the low-speed tasks while for the high-speed tasks, the trend is the opposite.
For what concerns the overall evaluation of the vehicles, the segway has received the lowest grades for stability, comfort and safety while almost the same results for maneuverability. This result is in line with the comments from the participants who evaluated its behavior positively at low speed (a perception that changes completely for the high-speed characteristics).
The e-scooter, instead, reached very similar results with respect to the bikes for maneuverability, comfort and stability while a lower level of overall safety has been perceived.
The overall perception of the bikes has been graded almost the same. This can be a consequence of the usage of the same bike for both vehicles.

4.4 Limitations

The scope of this project was to develop a solid procedure in order to successively collect data from a larger amount of participants. In order to do so, some limitations need to be mentioned:

- Limited amount of participants in order to limit the spread of COVID-19.
- No naturalistic data were recorded, the study is limited to experimental procedures performed in a controlled test area.
- Due to a time constraints, the number of vehicles and the number of maneuvers/tasks had to be limited.
- The vehicle selection has been performed while paying attention to avoid vehicles that were difficult to maneuver (but may be relevant in traffic).
- In order to reduce the risk of injuries during the analysis, no hazardous maneuvers have been chosen.

4.5 Future work

The limitations, as described in section 4.4, represent the starting point for a more in depth analysis of these vehicles.
First of all, a larger data collection is needed to validate the previously described results and to find new characterizing aspects in order to better classify these vehicles under the safety profile.
Then, a variety of new different tasks can be studied, considering other possible riding situations not taken into account in this study. For example, a very common situation that can happen while riding in the city is to ride over a bump.
A wider selection of e-PMVs may be chosen, considering more sophisticated and less common vehicles that were excluded by this study due to time constraints. Moreover, the necessity of choosing vehicles that can be used by the participants considering a limited training time was another limiting factor. This can be overcome if time limits were less stringent or choosing already trained participants for the data collection.
Finally, a study on the rider posture while riding can be performed. Knowing the rider movements, especially in some vehicles in which the body position is very relevant for the vehicle's dynamic, can be very helpful to better understand the vehicles and analyze their safety level.

5

Conclusion

The developed procedure to acquire data has shown to properly work during the two pilot tests that were performed. It has shown to be a solid procedure to properly collect and analyze data sets from participants.
The training procedure was really appreciated, especially by the less experienced participants. It helped them to familiarize themselves with the vehicles and to feel more comfortable in doing the tests.
The data analysis procedure showed to properly analyze the data. It correctly created the data sets, filtered and analyzed the signals and computed the performance indicators required to analyze the vehicles.
All the choices that were made demonstrated to be efficient and to correctly solve the required tasks. The conditions used to segment the maneuvers correctly segmented the signals, the parameters used to cluster the Lidar data demonstrated to correctly solve the task and the used filters demonstrated to properly filter the signals.
In conclusion, the procedure is ready to be used for future data collections.

For what concerns the instrumented vehicles, all of them worked properly during the tests and no major problems were encountered during the data collection.
The segway has shown to be the most complicated vehicle and so the most time demanding during the training procedure. It has demonstrated to be very maneuverable at low speed but at the same time very difficult to handle when speed increased. This can be a consequence of its speed limiter, which was highly contested by the participants and described as "destabilizing" and "unsafe". Moreover, longer reaction times and lower braking capabilities than the bikes are an indicator of a low level of safety. Its overall evaluation from the participants is the lowest between the four vehicles.
The e-scooter was generally appreciated by the participants and perceived almost as safe as the bikes. It has shown lower braking capabilities than the other vehicles, which affects its safety level. On the other hand, a high maneuverability level was obtained in acceleration considering its sprint capabilities and in turning conditions considering the lower steering angle needed to perform the slalom. To conclude, a high level of comfort was perceived by the participants for this vehicle.
The conventional bike and the e-bike were graded almost the same by the participants. Very stable and comfortable for what concerns the longitudinal kinematics, and less appreciated when the lateral motion is considered. The bike was perceived a bit heavy and hard to move from standing still (probably because of the absence of the electric motor). The e-bike demonstrated to be not very maneuverable in low-speed maneuvers in which the on-off mechanism of the electric motor disturbed

the participants. High braking capabilities and low reaction times give it high a maneuverability and safety levels.

In Figure 5.1, it is possible to observe the position of the four vehicles in the safety matrix[15]. Their positioning on the safety matrix comes from the fusion of the questionnaire and the experimental results previously described. In order to do so, the questionnaire results have been used as a starting point and then the relative positioning has been adjusted by analyzing the experimental results.

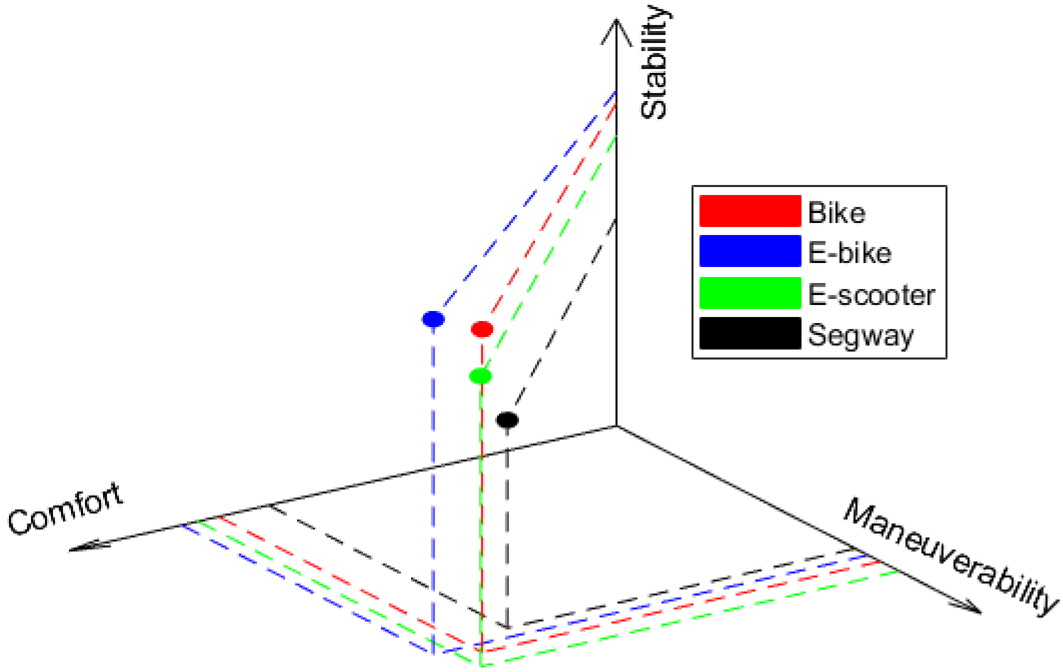


Figure 5.1: Safety matrix

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A

Appendix 1 - Vehicles technical specifications

	Bike/E-bike	E-scooter	Segway
Model	Monark - "Karin,3-VXL"	Ninebot KickScooter ES2	Segway Ninebot S
Max range (km)	40	25	22
Net weight (kg)	26	12.5	12.8
Vehicle size	51	Not specified	Not specified
Dimensions (cm)	Not specified	102x43x113	54.8x26x59.5
Battery (Wh)	417.6	187	263
Tyre size (in)	28	Front:8, Rear:7.5	10.5
Brake type	Front:disc, Rear:coaster brake	Front:electric and regenerative, Rear:step fender	Electric
Shock absorption	No	Front and rear	No
Max driver weight (kg)	Not specified	100	85
Max climb angle (%)	Not specified	10	15
Driver position	Seated	Standing	Standing
Steering mechanism	Handlebar	Handlebar	Knee-control bar

Table A.1: Vehicles technical specifications

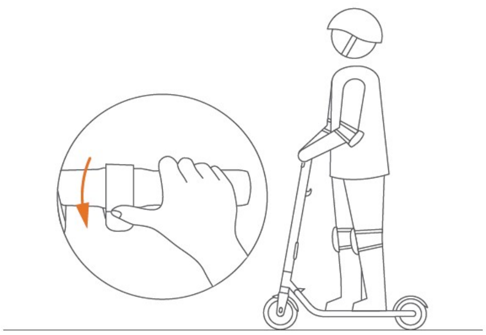
B

Appendix 2 - Training procedures

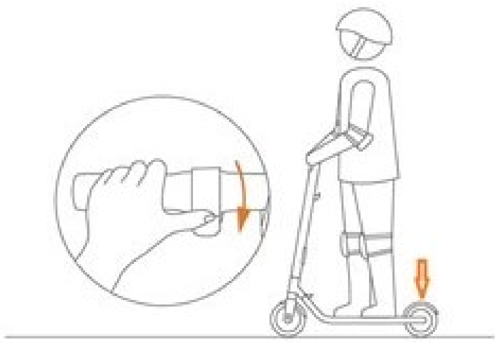
B.1 Scooter

- Task 1: Drive straight

Step on the vehicle with one foot and use the other to push you forward. Reached the minimum speed of 3 km/h use the right lever to accelerate the vehicle. To brake use either the left lever or the foot brake or both.



(a) Accelerate



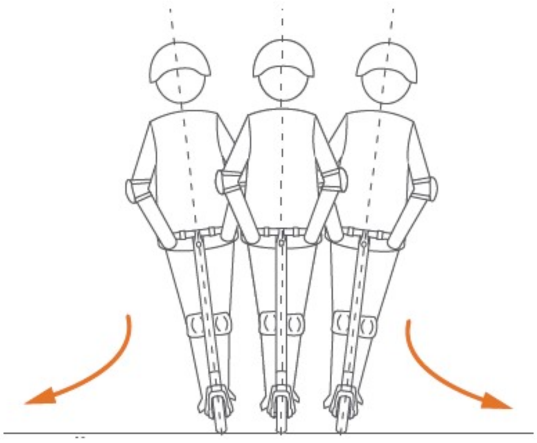
(b) Brake

- Task 2: Familiarize with the different brakes

You will be asked to brake with different brakes. Try to familiarize with both, try to brake only with one, with both and in a harsh and gentle way. During the task procedure you will be asked to use the procedure that you prefer.

- Task 3: Learn how to turn

While you're going straight try to slowly lean on both sides and familiarize with the lateral motions of the vehicle.



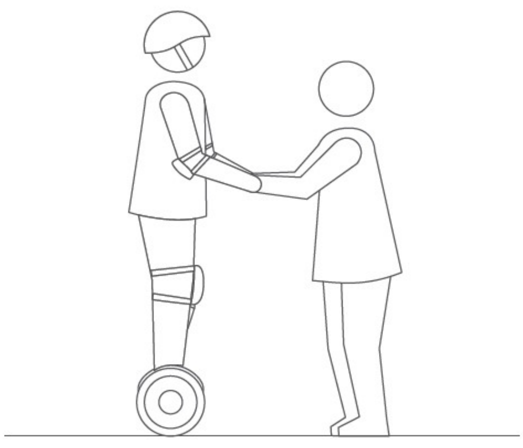
- Task 4: familiarize with the whole vehicle

Now that you have learnt the different movements of the vehicle try to familiarize a bit more with it. Try to accelerate, brake, go straight, make a circle, keep a constant speed for several meters, brake before a marked line in a gentle and in a harsh way, etc.
When you feel ready tell us and we can start the procedure.
REMEMBER: you can always tell that you don't feel comfortable with a vehicle and you will not perform the test with that vehicle.

B.2 Segway

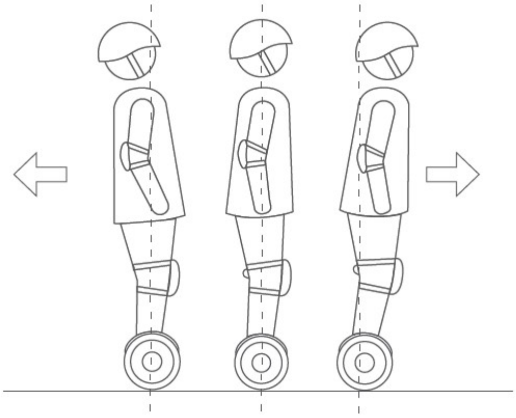
- Task 1: Balance

Step in the vehicle with the help of someone and try to keep the balance for 10 seconds. Stand on both feet with your weight evenly distributed and relax, press you knees against the turning stick. Look straight ahead and avoid violently rocking backwards and forwards.



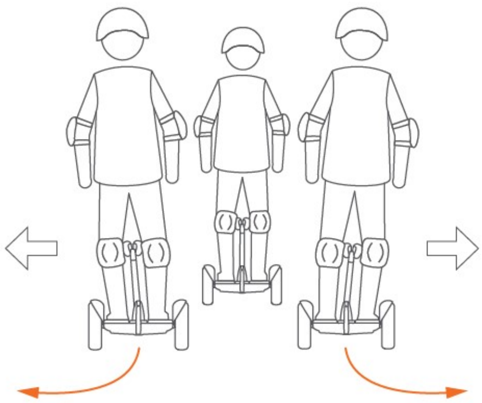
- Task 2: Forward and backwards movements

Slowly move your body's center of gravity forwards and backwards to control your movement. Try to go straight for a couple of meters and repeat this procedure a couple of times until you take some familiarity with the vehicle.



- Task 3: make a circle with the vehicle

Slowly lean against the knee control pads left and right to make a turn. Try to rotate left and right until you feel familiar with the turning mechanism.



- Task 4: familiarize with the whole vehicle

Now that you've learnt the different movements of the vehicle try to familiarize by combining task 2 and task 3. Try to accelerate, brake, go straight, make a circle. When you feel ready tell us and we can start the procedure.
REMEMBER: you can always tell that you don't feel comfortable with a vehicle and you will not perform the test with that vehicle.

C

Appendix 3 - Riding task questionnaire

Background information

Age		Height [cm]		Weight [kg]		Gender	Female ☐ Male ☐

	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 a Segway?	☐	☐	☐	☐	☐
How often do you use an E-Scooter?	☐	☐	☐	☐	☐

Do you think that the training time was enough in order to perform all the tasks safely?	Yes: ☐	No: ☐
Comments:		

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 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							

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:

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