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## **Specify the Curve Speed Adaption parameters within the Adaptive Cruise Control system.**

Master's thesis in Automotive Engineering

Josefine Johansson



MASTER'S THESIS 2019:113

# Specify the Curve Speed Adaption parameters within the Adaptive Cruise Control system

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CHALMERS UNIVERSITY OF TECHNOLOGY  
Gothenburg, Sweden 2020

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## Abstract

A growing trend in the automotive industry is the Advanced Driving Assistance System (ADAS). Within this system lies the Curve Speed Adaption (CSA) which is a part of the Adaptive Cruise Control (ACC). By assessing how different drivers perform a cornering, the parameters needed for the development of the CSA control system were evaluated in this report, as well as comparing existing CSA system in competitor vehicles.

Vehicle testing was performed with 14 test drivers using subjective assessment and objective measurements. Three curves were chosen to be analysed further, the first curve was an entrance to a motor way, the second was on a country road and the third on a country road with a stop sign at the end of the curve. To cover all driving situations, more drivers and driving situations need to be tested for the CSA to work properly.

The most important parameters to set the requirements on were the lateral acceleration, longitudinal acceleration and velocity to accomplish a working CSA with access to a map. Other investigated parameters were brake pedal, acceleration pedal and the steering wheel angle which are not needed for the CSA to work properly since the vehicle can regulate them by using the other parameters.

Competitor vehicles were tested to give valuable information on how the systems are working. The competitor vehicles were an Audi E-tron, which performed well in every curve with the CSA activated, and a Tesla Model 3, which had some issues finding the lines in one of the curves with the Autopilot activated.

Keywords: Advanced Driving Assistance System, ADAS, Adaptive Cruise Control, ACC, Curve Speed Adaption, CSA, Subjective assessment, Objective measurement, Vehicle testing.



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## List of Abbreviations

<b>ACC</b>	Adaptive Cruise Control
<b>ADAS</b>	Advanced Driver Assistance System
<b>AV</b>	Autonomous Vehicles
<b>CAN</b>	Controller Area Network
<b>CC</b>	Cruise Control
<b>CSA</b>	Curve Speed Adaption
<b>ECU</b>	Electric Control Unit
<b>GPS</b>	Global Positioning System
<b>HD</b>	High Definition
<b>HMI</b>	Human Machine Interface
<b>IMU</b>	Inertial Measurement Unit
<b>LIDAR</b>	Light Detecting And Ranging
<b>MPP</b>	Most Probable Path
<b>RADAR</b>	Radio Detecting And Ranging
<b>SWA</b>	Steering Wheel Angle

# 1

## Introduction

The Advanced Driving Assistance System (ADAS) is a growing trend in the automotive industry. Not only can it increase the safety, it also reduces fuel consumption and enhance the traffic flow. One of the driving assistance systems is the Adaptive Cruise Control (ACC). ACC has been developed to control the speed of the vehicle relatively to other vehicles and to decrease the driver's mental concentration. Within the ACC system, the Curve Speed Adaption (CSA) facilitates the speed while cornering.

### 1.1 Background

This project is carried out at CEVT, whose current ACC is the basis of this analysis. The ACC is currently limited in functionality, e.g. the speed is not reduced before or in curves, speed bumps, traffic lights etc. It can be experienced by the vehicle users as inconsistent behaviour. By further developing the ACC and include information from maps, route selection and information from the car system, e.g. the ride comfortability can be improved by using lateral acceleration. CEVT is interested in the requirement parameters for the CSA by including objective measurements methods in comparison to subjective assessment.

### 1.2 Aim

The aim is to assess how different drivers drive through corners and to evaluate which measuring parameters are used to create a comfortable cornering on country roads, and on a motor way entrance and exits.

### 1.3 Limitations

The following limitations have been used in the study.

- Investigating the development of the CSA within the ACC system.
- Considering only cornering on country roads, motor way entrance and exits as well as sharp corners on motor way.
- Speed limits are between 0kph and 140km/h, since the maximum legal speed limit for driving is 140kph.
- GPS and digital maps are not available in the Lynk & Co test drive.
- Subjectively evaluate the ride comfort in the front seats and in the rear seat

- Only high  $\mu$  (summer conditions) has been assessed.

### 1.4 Envisioned solution

Include other parameters, e.g. maps, lateral acceleration and other variables from the vehicle, to control the ACC system in the vehicle and develop the control of the speed to give acceptable conditions for the driver and the passengers. To develop the control system with the new parameters it will be required to drive the vehicle in real traffic and subjectively judge the limits for how the speed should be controlled to suit the selected parameters.

### 1.5 Deliverables

The deliverables of this project can be found below.

- Information research to learn about the current Adaptive Cruise Control systems.
- Identify which driving situations should be used when developing the control system.
- Assess how drivers perform a cornering and how it is experienced by the driver and passenger.
- Propose and select parameters that can be used to control the speed of the vehicle when using Adaptive Cruise Control.
- Measure and analyze competitor cars.

# 2

## Theory

There are a lot of sensors and systems in a vehicle to assist the ADAS. The research on the ADAS can be divided into two types, the longitudinal control and the lateral control [1]. The ACC works in the longitudinal control which is to maintain the distance between the vehicle ahead and the host vehicle to avoid collision. The lateral control seeks to maintain the vehicle inside the intended lane. Below is a description of some of the systems in today's vehicles, used sensors and the subjective rating used in the method.

### 2.1 ACC

The ACC, which is a development of the Cruise Control (CC), was one of the earliest ADAS to be introduced to the market [2]. The CC system controlled longitudinal speed that had been selected by the driver. With ACC, the speed can also be controlled relative to other vehicles and therefore relieve the mentally demand of the driver to constantly pay attention to the speed. If the subject vehicle does not detect a vehicle in front, the ACC will adjust the speed to the setting cruise control speed. However, if the system detects a proceeding vehicle with lower speed, the speed in the subject vehicle will adjust to that vehicles speed. It is also possible to adjust the distance between the two vehicles which is set by the driver. The ACC allows the vehicle to autonomously slow down and speed up the vehicle without demanding the driver to intervene [3]. The system can be overridden by the driver at any time for the driver to take control. This system can operate below 30km/h, which was limited by the original CC. The CC was only able to maintain the set speed, while the development has made it possible for the driver to pay less attention as it works in the lateral aspect too. The system usually have the RADAR system together with the camera to detect other vehicles, but it can also be used by a LIDAR system.

The operation view of the ACC usually have four different main functions [3].

- Constant Velocity: When there are no vehicles detected in front of the subject vehicle or a vehicle is too far away, the system will provide a constant velocity.
- Deceleration Control: When the system detects a slower riding vehicle, the velocity will decrease to match the vehicle in front with a set distance between the vehicles.
- Acceleration Control: If the vehicle in front disappears by eg turning, overtake or lane change, the system will accelerate into the set speed.

- **Following Control:** When a vehicle is detected in front, the system will speed up and down to match the vehicle in front with the set distance [4].

### 2.1.1 CSA

The ACC has been developed with many subsystems, for instance matching speed limits and driving through roundabouts. One of the systems which is a major part of the autonomous future is the Curve Speed Adaption [5]. When driving through a sharp curve or exiting a motor way, it can be risky if the speed is not reduced to suit the driving condition. Without ACC and CSA, the driver would decelerate and drive through the curve with comfort and safety, then continue by accelerating up to speed again. The CSA system is developed to do the same, although, with the driver to steer the vehicle to pass the curve. For this to work, the CSA must be able to identify the curve to compute the convenient speed for every curve. The goal for the CSA in ADAS is to make an autonomous cornering by using both the lateral and longitudinal parameters for the control.

## 2.2 Information from maps

Digital maps have been used in cars for a long time, but mainly for navigation purposes [6]. The resolution of these maps was not always accurate and not precise enough to consider for autonomous driving. There were three main challenges for autonomous driving using maps. The first challenge was to localize the exact position of the vehicle, the second was to be able to react to events happening during the drive and the third was to make the drive feel safe for the passengers.

Today, the maps have a much higher resolution and accuracy, called real-time high-definition (HD) map, which covers the three main challenges for autonomous driving. A map today can provide support for the ADAS by predicting the road geometry and possible track attributes in front of the vehicle [7]. This is usually done with the Global Positioning System (GPS), which states the position of the vehicle, together with the internal map.

### 2.2.1 GPS

Since the GPS is based on satellites to determine the position, the reception of the position can be interfered with or interrupted by e.g.:

- Signal shadowing, by ie houses, trees, mountains or tunnels.
- Atmospheric interference
- Multipath reception

By constantly comparing the internal map and the GPS signal, the errors can be compensated. This is called map matching [8].

## 2.2.2 Electronic Horizon

The interaction between the internal map and the GPS, or map matching, has been developed into the Electric Horizon can be calculated which gives the E-horizon data to predict the attributes on the road ahead [9]. This includes data such as curvatures, traffic information, slopes, signs and number of lanes. If the driver has selected a route, it becomes the Most Probable Path (MPP).

## 2.3 Camera

Camera equipped vehicles are essential for gathering data along the road [10]. They are a part of the main key areas for developing the future Autonomous Vehicles (AV). The front facing camera assists the ACC by measuring the distance to an object as well as classifying it [9]. The object detection is even more reliable with the assist of the RADAR, it also makes it possible to extend the range of the ACC.

The video signals from the camera is transmitted to an image processor, then the processor extracts individual images. The processed image is then sent to the Electric Control Unit (ECU) which evaluates the information and sends it to the ECUs to further process the data. For instance, the distance information of the object ahead is needed in both the ACC and the human machine interface (HMI) such as the dashboard.

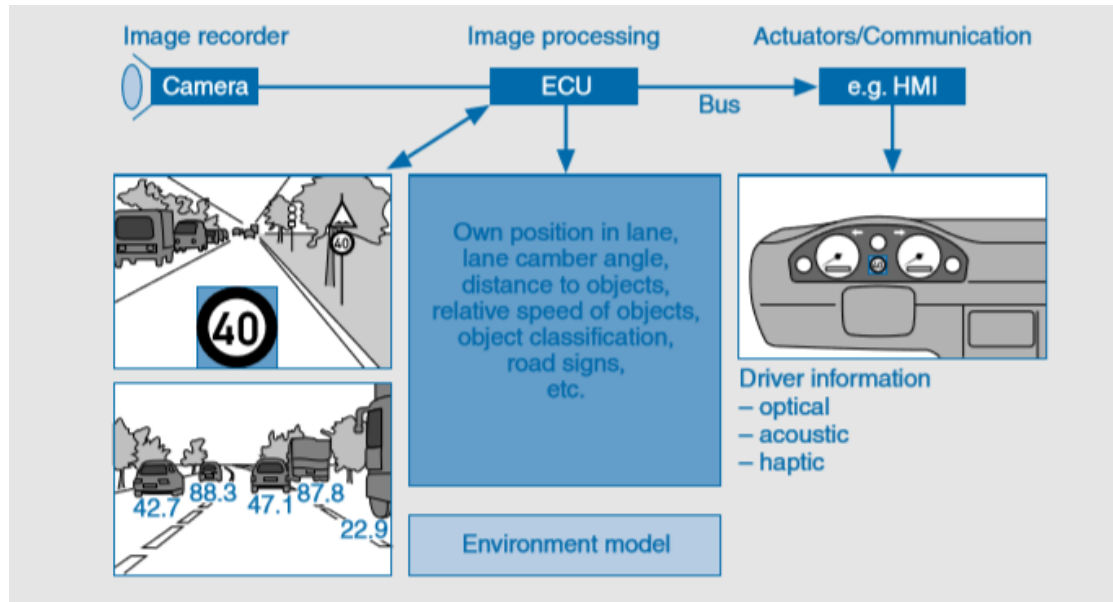


Figure 2.1: Principle of a video sensor showing examples of function [14].

### 2.4 RADAR

The RADAR sensor is usually built into the lower front of the vehicle when assisting the ACC [9]. The placement of the sensor makes it possible to track vehicles ahead, but also to spot other attributes under the vehicles in front. The RADAR sends out an electric wave which bounces off an object and returns to the sensor. The RADAR, together with the camera, detect objects, estimate curvature and parameters. For instance, the distance and speed can be observed by calculating the time it takes for the wave to return. The sensor is usually positioned on the front end of the vehicle. The RADAR used for the ACC usually has a maximum range of 120-250m [10].

### 2.5 Lidar

Another sensor that can be used to measure the geometry around a vehicle is the light detection and ranging (Lidar). Same as the RADAR, the Lidar also observes the distance by calculating the time of the flight [12]. Since the Lidar is dependent on light, it can easily be disturbed by the weather conditions such as heavy rain. This sensor is also very expensive.

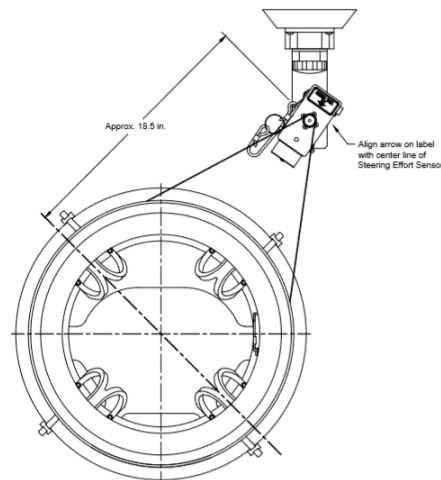
### 2.6 Steering wheel angle and Yaw rate

The angle between the longitudinal axis of the vehicle and the intersection line of the wheel plane and the road surface is called the steering angle. The position of the steering wheel turning together with the wheel angle can be used to calculate the yaw rate and then the lateral acceleration.

The yaw rate sensor reads the rotation velocity of the vehicle, for instance when the vehicle is turning [1]. This sensor can be used to predict the path depending on the rotation velocity.

### 2.7 Steering effort sensor

To measure the steering wheel angle and steering wheel torque of a vehicle without the possibility to use the Controller Area Network (CAN) system of the vehicle, a steering effort sensor can be used [13]. The device is practically an external steering wheel which is mounted on the vehicles steering wheel with four cable ties. When rotating the external steering wheel, a drive chain is mounted around the steering wheel rotates as well. The sensor uses infra red light to detect the position data. The steering effort sensor used in this test was the IR Telemetry Steering Effort Sensor from Sensor Developments Inc.



**Figure 2.2:** The IR Telemetry Steering Effort Sensor from Sensor Developments Inc.

## 2.8 Longitudinal and lateral jerk

Jerking measures the comfort of e.g. acceleration, braking or turning [14]. It is measured by differentiating the acceleration signal with respect to time in the longitudinal or lateral control.

## 2.9 Inertial Measurement Unit

An IMU consists of a rotor which is mounted on a spinning axis in the center of a larger wheel [15]. The device uses the gravity of the earth to determine orientation and position of an object. The rotor remains stationary as the axis turn to indicate the central gravity pull, this makes it possible to know which way is "down". An IMU is used in basically everything that is rotating.



**Figure 2.3:** The IMU RT3000 v3 RT which was used in the testing of the project[16].

## 2.10 Interview

To understand and comprehend peoples opinions, a questionnaire is a good tool [17]. The interview can be done in different ways as there are many methods for it. Usually, it is divided into three methods, unstructured interview, semi structured interview and structured interview. The unstructured interview is to basically have an empty paper and talk to the person being interviewed without an actual plan. The semi structured interview is based on a few planned questions with followup questions on set. The last method is to have a manuscript and only go by it, that is called a structured interview.

# 3

## Method

The methodology to perform the study is described in this section.

### 3.1 Literature study

The literature study has been done in order to understand the different systems that will be used. Resources from the Chalmers library and other research articles were used together with input from engineers at CEVT and Chalmers. The study also included gathering of information from competitive vehicles that use ACC and the future of the CSA.

### 3.2 Vehicle testing

To gather relevant data and to investigate the parameters that effect cornering, a testing session was performed. Testing measurement equipment setup included:

- Inertial Measurement Unit OxTS RT3100
- Logitech HD Pro C920
- Dewesoft DEWE 43

The measured data came from the vehicle CAN system, CAN signals from the IMU and the video from the camera. Professional test drivers and other drivers with different driving style took part of the session to get as many opinions as possible. With two test drivers and the test coordinator in the vehicle each time, both drove the same route and rated the same corners. A total of 18 people took part of the testing. The testing vehicle was a Lynk & Co car equipped with various of testing equipment. Each session included testing of how the driver performed a cornering, without the current ACC activated, depending on the velocity, sight, radius and ground clearance. The testing part was performed on a country road, on a motor way entrance and at Säve proving ground.

A typical test run started with one driver and two passengers. The first driver drove the route, both rated the driving after every curve and explained why they rated the way they did. After the driver change, the second driver drove the same route and both rated the same way as the first drive. In this way were every test driver assessing both driving the vehicle and being a passenger in the front seat. The test coordinator was a passenger in the rear seat and rated all the curves independently.

### 3. Method

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When both finished their route, the testing continued at Säve Proving ground where the test coordinator drove three laps around a route with increasing speed at every lap. The passengers rated the laps and decided which one they preferred. After the test at Säve Proving ground, the test run was completed.

During the test drives, three curves were chosen to be analysed. The data from every curve was analysed for about 40 seconds, while the actual curve was not more than 10 seconds. This was to analyze the data before the cornering and a few seconds after. The red triangles in the figures below describes the beginning of the recordings and the red dots describes the end. Descriptions of the curves can be seen below:

- **Curve 1**, see figure 3.1, was a road towards the entrance of a motor way. Before Curve 1, the road was straight which made the velocity constant and the vehicles had an entering speed before the curve. The curve had a speed limit of  $70\text{km/h}$ .
- **Curve 2**, see figure 3.2, was positioned on a country road with smaller radius which gave the possibility to not get as much lateral acceleration as Curve 1.
- **Curve 3**, see figure 3.3, was situated on a country road as well, but on the end of the curve was a stop sign which made the drivers brake to stop before turning left.

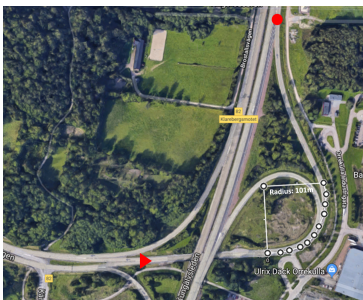


Figure 3.1: Curve 1



Figure 3.2: Curve 2

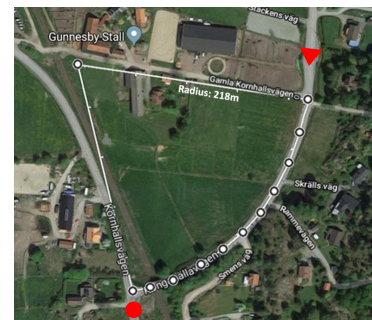


Figure 3.3: Curve 3

The radius of the curves:

- Curve 1 =  $101\text{ m}$
- Curve 2 =  $343\text{ m}$
- Curve 3 =  $218\text{ m}$

#### 3.2.1 Competitor Cars

To compare the test driving data to the functions that are available on the market today, two competitor cars was tested. The first car was a Audi E-tron and the second was a Tesla Model 3. Testing measurement equipment setup included:

- Inertial Measurement Unit OxTS RT3100
- 2x Logitech HD Pro C920
- Dewesoft DEWE 43
- IR Telemetry Steering Effort Sensor

The cameras were pointed towards the road ahead and on the visual board in the vehicles. Since the vehicle CAN system in the competitor cars was not available,

the logging system was limited to the CAN signals from the IMU, analog signals from the steering sensor and videos from the two cameras. See figure 3.4.



**Figure 3.4:** Competitor car measurement set-up, including steering effort sensor, IMU, Dewesoft DEWE 43 and Logitech HD Pro C920

Both cars were driven the same route as the test driving with the CSA function active, except at Säve proving ground due to the lack of lines on the ground. Additionally, both vehicles were driven through more intense corners on another country road to understand the CSA functions and to assess them to the limit.

### 3.2.2 Data logging

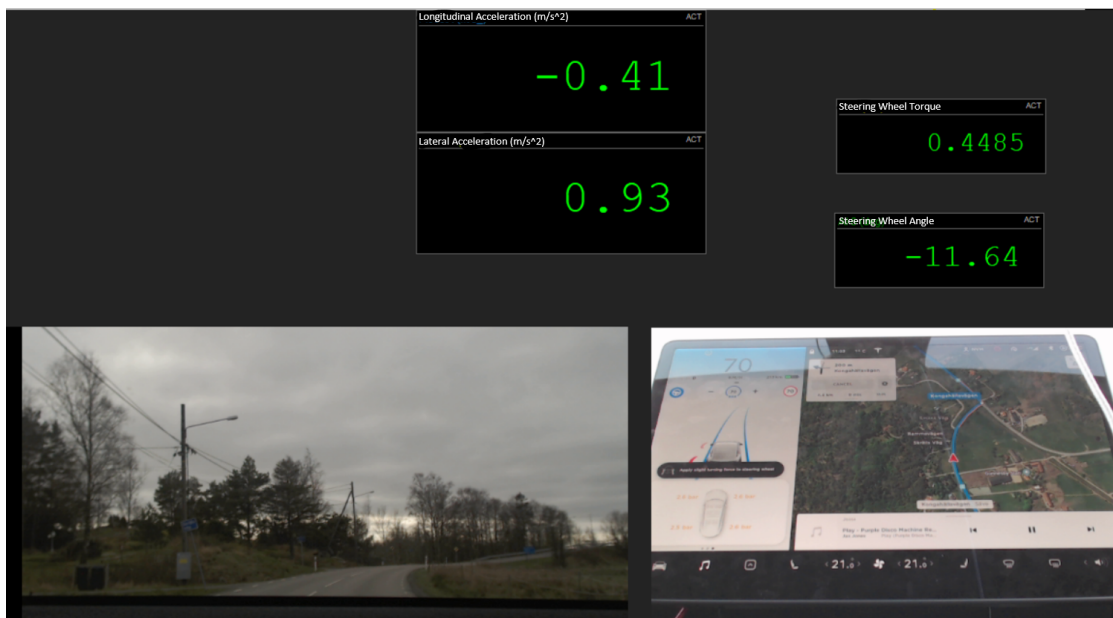
The data from the test drives were logged in the program called Dewesoft X3 which is a data recording and data analysing software. The internal CAN-signals of the vehicle and one camera were connected to the software as the recording started on every test drive. The IMU was calibrated and the coordinate system of the lateral acceleration was positive when turning right and the longitudinal acceleration was positive when accelerating forward. This can be seen in figure 3.5 where the vehicle is accelerating after Curve 1. After the recordings, the chosen parameters were exported as either a Matlab file or Excel file to later be analysed in Matlab. The recording below shows the live path on the camera, measurements in the lateral and longitudinal acceleration and the brake pedal pressed.

### 3. Method



**Figure 3.5:** Dewesoft X3 recording during test drive in Curve 1.

In the competitor cars, the CAN signal from the car was not accessible so other methods were used. Two cameras were attached to record the path and the visual screen. Analog measurements of the steering wheel torque and steering wheel angle were connected to Dewesoft DEWE 43. The pedals were not recorded at all since it was not possible to achieve measurable results without the CAN signals from the vehicle. Otherwise, the lateral and longitudinal acceleration were recorded as in the other test drives, see figure 3.6.



**Figure 3.6:** Dewesoft X3 recording during Benchmark.

Besides driving two times with each competitor cars on the route with the three curves, another road was driven with the competitor cars to get a better under-

standing of the cars. A country road with many curves was chosen and measured. One of the curves, called Curve 4, was chosen to be more analysed, see figure 3.7.

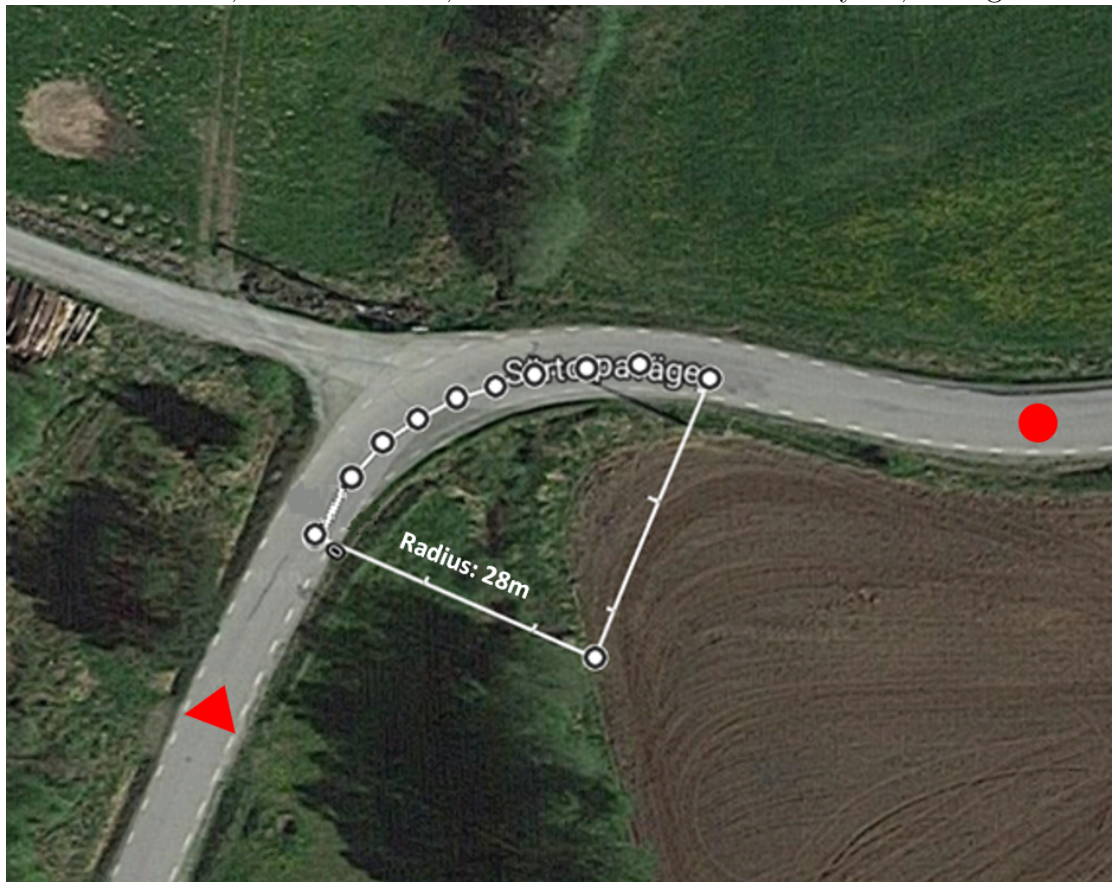


Figure 3.7: Curve 4, radius 28m.

### 3.2.3 Analysis

First, the most important parameters were chosen. These parameters were a part of the collected data and later used to analyse the data in the tool Matlab. These parameters were exported from Dewesoft X3 to Matlab and plotted as function of time. Some of the parameters had to be filtered to eliminate frequencies and smoothing the data, a low pass filter was used in Matlab. This was done on every chosen corner as well as for the the competitor cars. Five curves were rated along the route, three of those curves were chosen to be analyzed due to better measured data. The data were analysed by the parameters together with the subjective data during the test drives. This was later compared to the competitor cars driven on the same route.

## 3.3 Rating

In addition to the objective measurements, a questionnaire with a subjective rating scale was used, see figure 3.8. After every chosen curve, the driver and the passenger gave a subjective assessment according to the scale with two different aspects:

### 3. Method

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comfortability and efficiency. The statistics on the test drivers can be found in Appendix 1. Two criteria were chosen due to the relevance and the limited time of the driver and the passenger to answer before the next curve. Since the ACC is a comfort based function, the first criteria was comfortability. The slower a curve is driven, the more comfortable it is, which is why the other criteria was the efficiency. The comfortability was rated by how safe and satisfying the cornering went while the efficiency was rated by how fast the cornering went and if it was too fast, fast enough or too slow.

Subjective rating										
Vehicle Engineering Rating (VER)	1	2	3	4	5	6	7	8	9	10
Evaluation of Attr. Performance	Very Bad		Bad		OK		Good		Very Good	
Customer Satisfaction	Customer wants repurchase		Average customer complains		Critical customer complains		Satisfied customers		World class	

**Figure 3.8:** Subjective assessment rating scale.

The ratings below 7 is considered as "Critical customer complains" or worse. The decision was then made to not use the ratings below 7 or in some cases to compare the ratings above 7 to the ones below 7. This means that the test drives with ratings above 7 were "approved". There were three ratings on every curve, the driver, passenger and from the test coordinator, who was in the vehicle at every test drive. When driving on a road, it is not unusual that other vehicles effect the driving. If the test car was effected by another vehicle so much that the data became irrelevant, the drive was removed from the analysis.

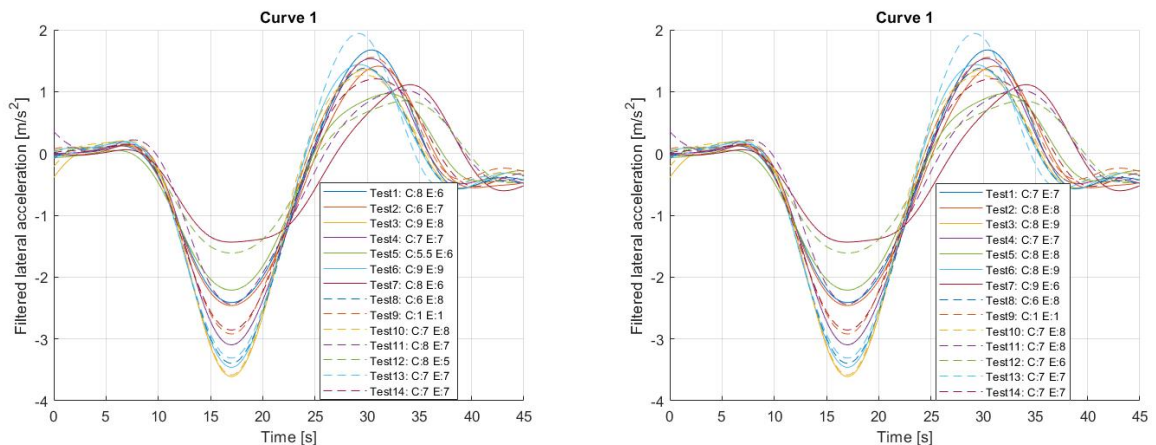
# 4

## Results

The rating, testing results and competitor cars results will be presented in this section. Out of 18 test drives, 4 of them were not analysed due to technical issues during recording.

### 4.1 Rating

The ratings from passengers and the test coordinator were compared and they did not differ much. As seen in figure 4.1, the difference between the ratings were two curves, Test 2 and Test 5, which passed (rating 7 or above) according to the test coordinator. Test 2 were close to passing and only differed by 2 points between the passenger and test coordinator. The other curve differed by 2.5 points according to the passenger but the test coordinator and the driver thought it passed and therefore it is in the analysis. Since everyone will be passengers in the autonomous vehicle, and some of the test drivers were inexperienced on the assessment rating, the ratings from the test coordinator were used. Out of 14 test drives, test 8 and 9 in Curve 1 did not pass the rating and will not be a part of the analysis. This also includes test 10 in Curve 2 and test 5, 6 and 9 in Curve 3.



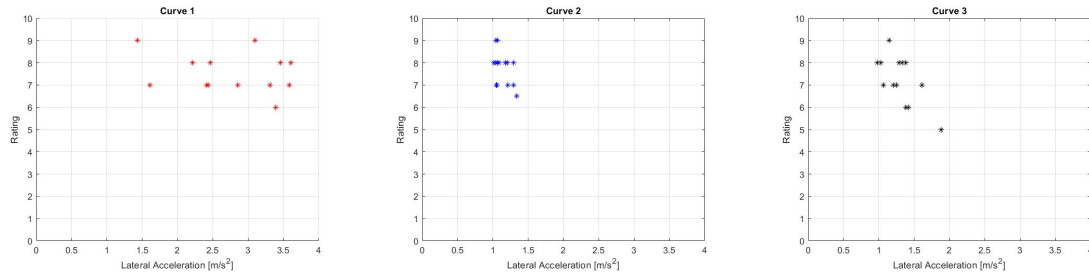
**Figure 4.1:** Curve 1 with ratings from the passengers (left) and test coordinator (right). The full lines are test drive 1-7 and the dotted lines are test drive 8-14. C stands for Comfort and E for Efficiency.

Depending on the lateral acceleration in every curve, the ratings differed, see figure 4.2. A trend can be seen in Curve 2 and 3, but not in Curve 1. Both trends indicates

## 4. Results

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that when the lateral acceleration increase, the rating decrease.



**Figure 4.2:** Rating on lateral acceleration on Curve 1, Curve 2 and Curve 3.

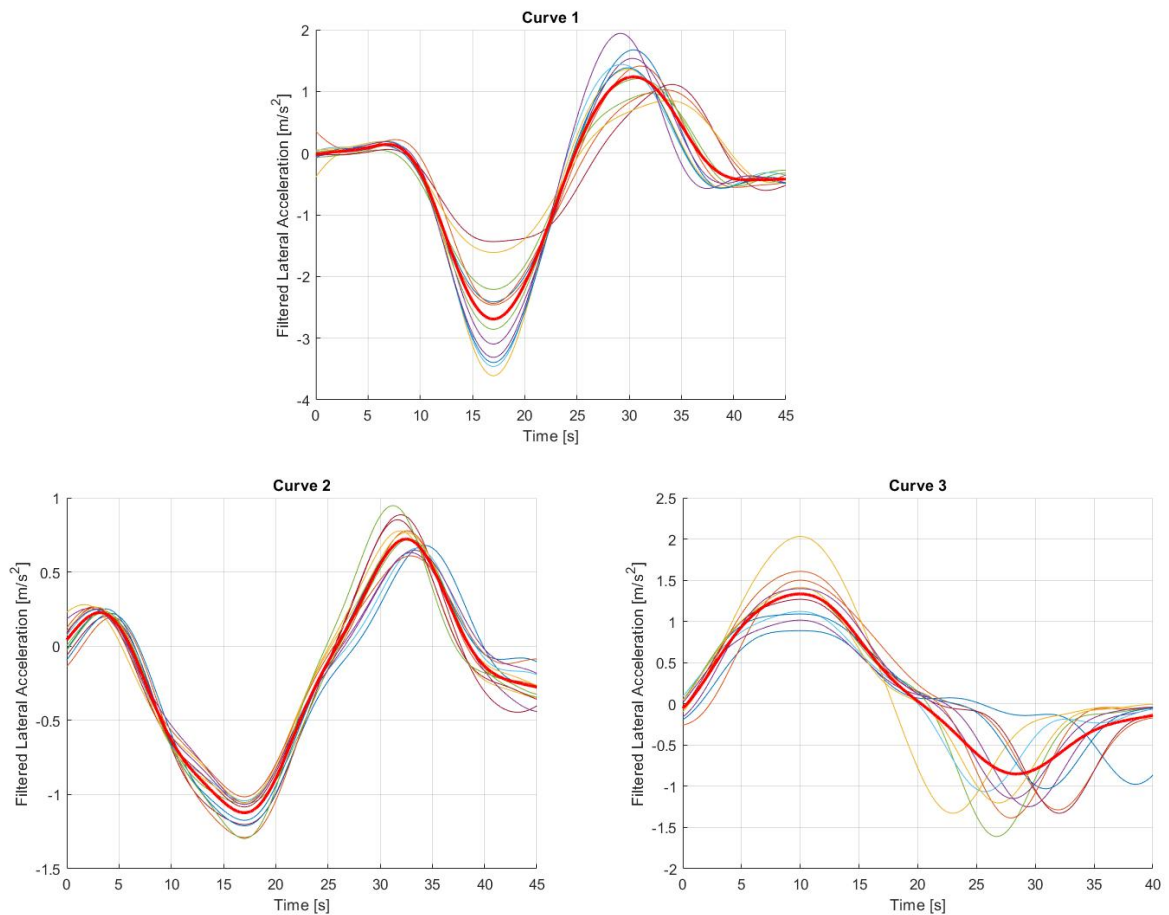
## 4.2 Parameters

Before the test drive, parameters was chosen to analyse the data. Due to the access of information from the cars, different parameters could be chosen. The chosen parameters:

1. **Lateral Acceleration** to identify the lateral acceleration in curves. Measured in  $m/s^2$ .
2. **Longitudinal Acceleration** to identify the longitudinal acceleration driven in curves. Measured in  $m/s^2$ .
3. **Velocity**, the velocity driven in the curves. Measured in  $m/s$ .
4. **Brake Pedal** to identify when the driver uses the brake and how much the pedal is pressed. Measured in % of the maximum pressed pedal.
5. **Acceleration Pedal** to establish when the driver uses the accelerator pedal and how much the pedal is pressed. Measured as on or off, on means that the pedal is pressed.
6. **Steering Wheel Angle** to identify how much the driver turns the steering wheel in the curve. Measured in  $deg$ .

### 4.2.1 Lateral Acceleration

The Lateral Acceleration of the three curves differed quite much among the drivers. To compare all the test drives, the optimal drive would be the mean of all the curves, see figure 4.3. The red line in the figure is the mean value from the different measurements in the specific curve.



**Figure 4.3:** Filtered Lateral Acceleration on Curve 1, Curve 2 and Curve 3. The red line in every figure shows the mean curve.

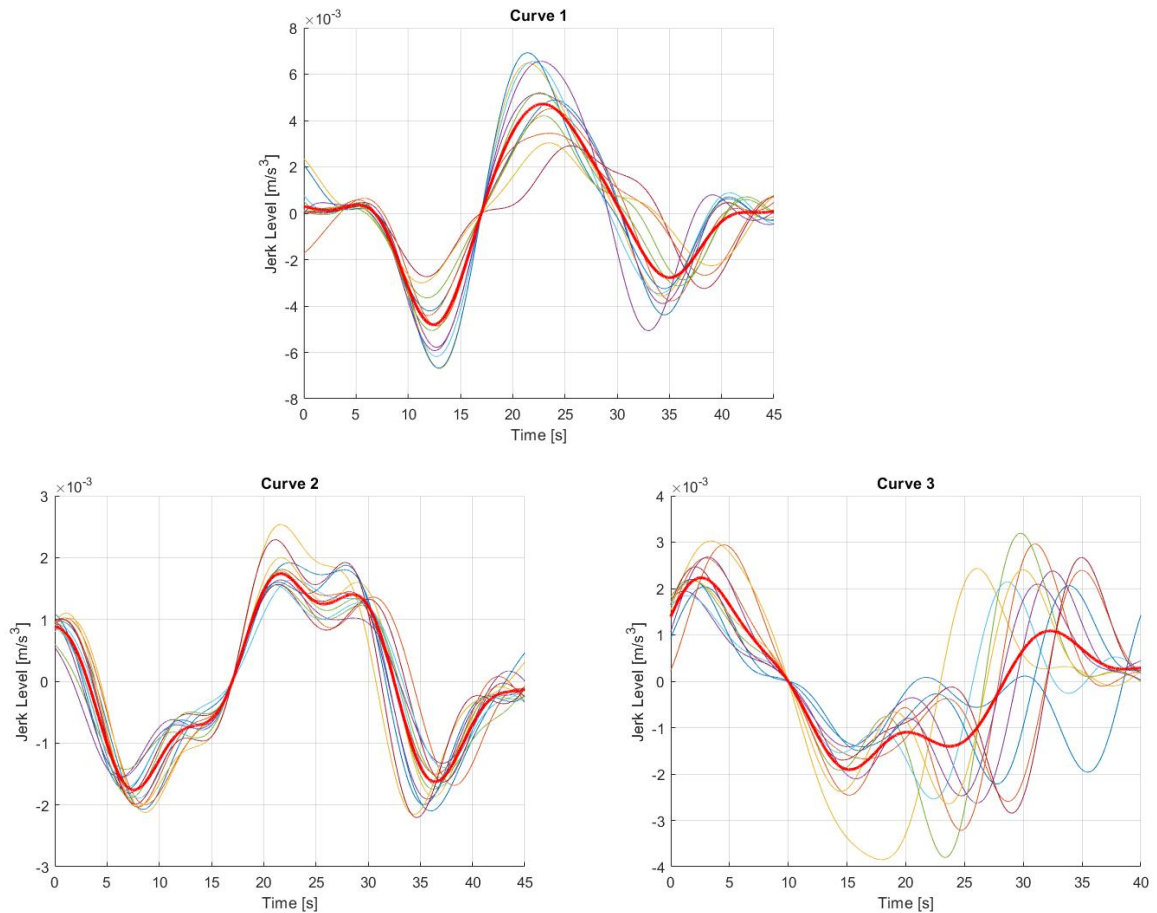
The maximum mean lateral acceleration in the curves are:

- Curve 1 =  $2.7 \text{ m/s}^2$
- Curve 2 =  $1.1 \text{ m/s}^2$
- Curve 3 =  $1.3 \text{ m/s}^2$

## 4. Results

### 4.2.1.1 Lateral Jerk Levels

A way to measure comfort is to use the lateral jerk levels in the curves which is the differentiate of the lateral acceleration. As seen in figure 4.4, the lateral jerk levels are higher in Curve 1 than the other curves. Because of the very low jerk levels this will not be further analyzed.



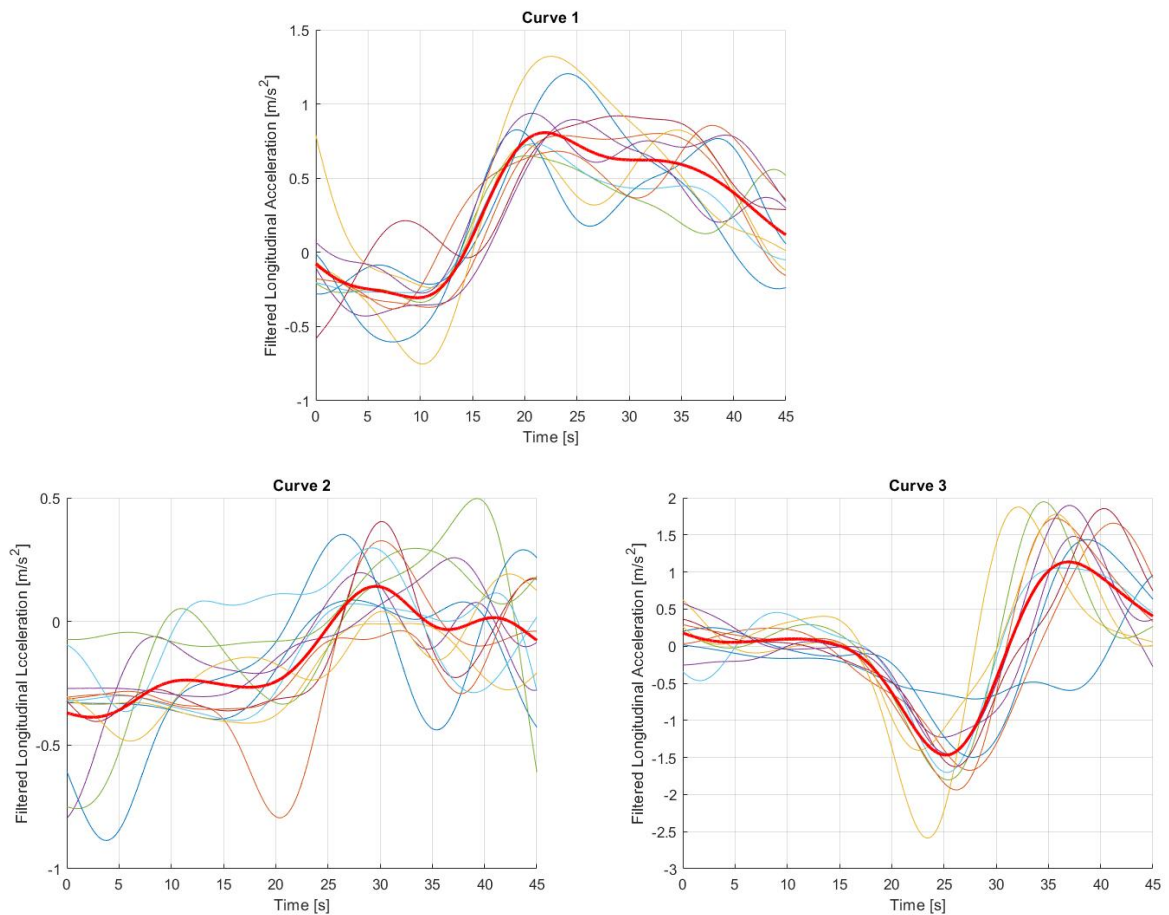
**Figure 4.4:** Filtered lateral jerk level on Curve 1, Curve 2 and Curve 3. The red line in every figure indicates the mean curve.

The maximum mean lateral jerk levels in the curves are:

- Curve 1 =  $0.0048 \text{ m/s}^3$
- Curve 2 =  $0.0018 \text{ m/s}^3$
- Curve 3 =  $0.0022 \text{ m/s}^3$

### 4.2.2 Longitudinal Acceleration

The longitudinal acceleration differed more among the drivers compared to the lateral acceleration. In Curve 1, the longitudinal acceleration was higher than the other curves. Test 11 in Curve 1 was removed due to a vehicle in front which caused the driver to brake. In Curve 3, the braking to a stop can be seen due to the high positive longitudinal acceleration.



**Figure 4.5:** Filtered Longitudinal Acceleration on Curve 1, Curve 2 and Curve 3. The red line in every figure indicates the mean curve.

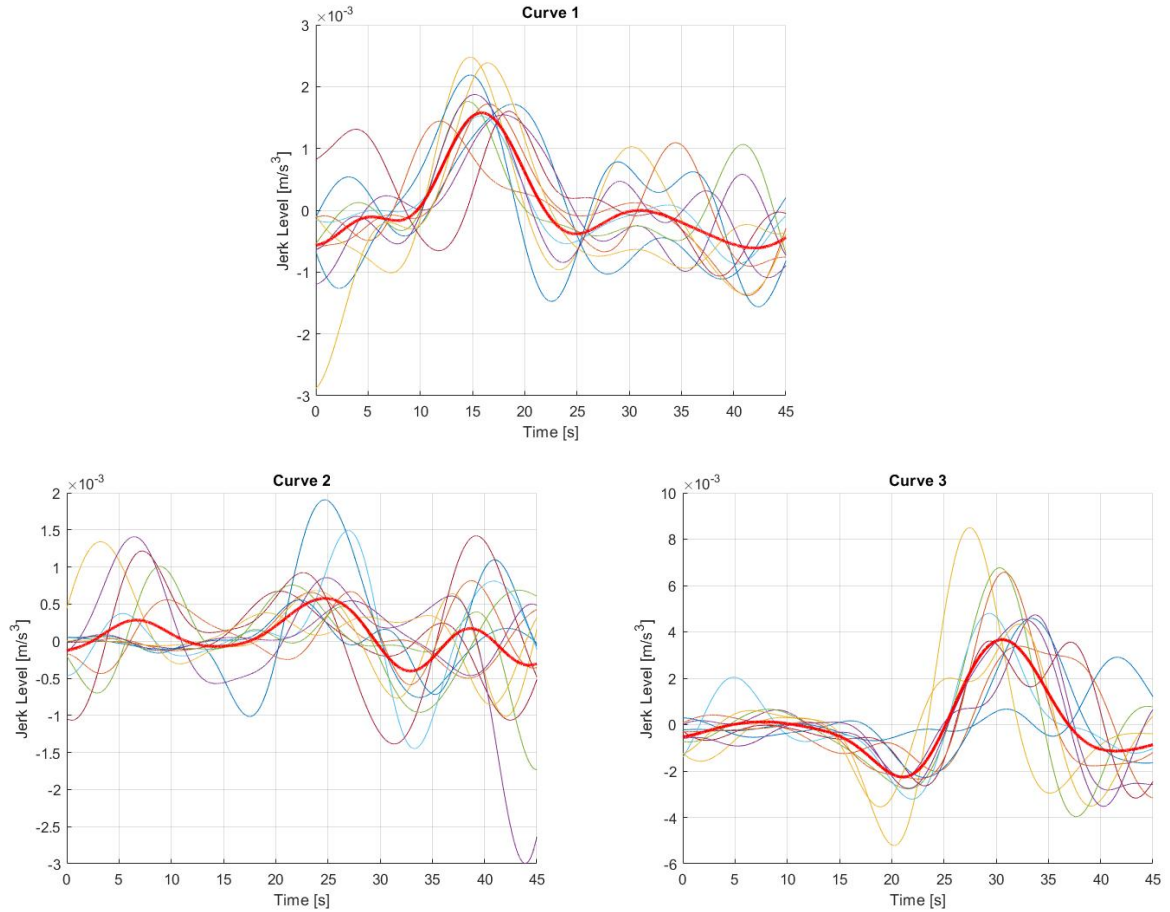
The maximum mean longitudinal acceleration in the curves are:

- Curve 1 =  $0.28 \text{ m/s}^2$
- Curve 2 =  $0.40 \text{ m/s}^2$
- Curve 3 =  $1.46 \text{ m/s}^2$

## 4. Results

### 4.2.2.1 Longitudinal Jerk Levels

A way to measure longitudinal comfort is to use the longitudinal jerk levels in the curves which is the differentiate of the longitudinal acceleration. The highest value of the longitudinal jerk levels is found in Curve 3 where all the vehicles had to brake to a stop. Because of the very low jerk levels this will not be further analyzed.



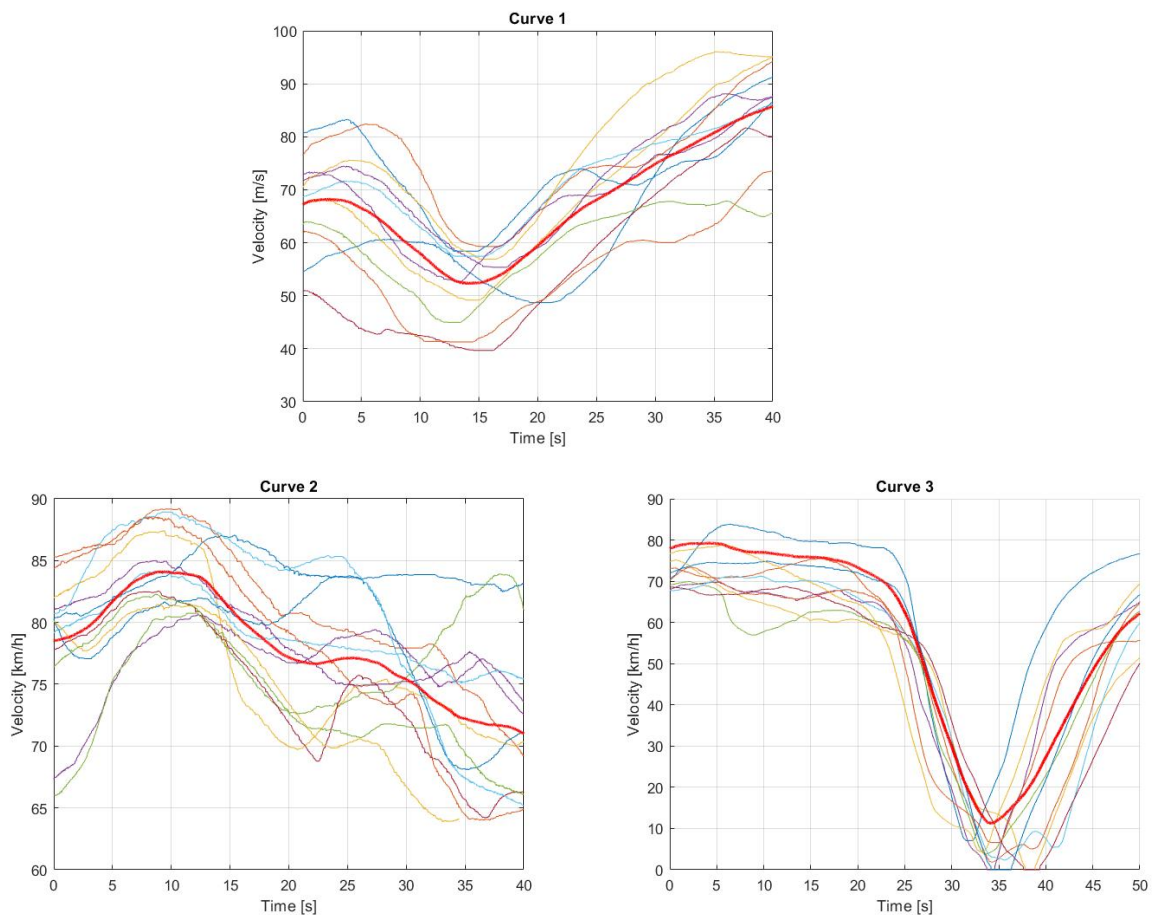
**Figure 4.6:** Filtered longitudinal jerk levels on Curve 1, Curve 2 and Curve 3. The red line in every figure indicates the mean curve.

The maximum mean longitudinal jerk levels in the curves are:

- Curve 1 =  $0.0016 \text{ m/s}^3$
- Curve 2 =  $0.0006 \text{ m/s}^3$
- Curve 3 =  $0.0023 \text{ m/s}^3$

### 4.2.3 Velocity

Test 11 was also removed along with test 8 and 9 in Curve 1 due to a braking from the vehicle in front. The velocity in every curve, see figure 4.7, differs among the drivers. Though every driver had a constant velocity through the curves, the amplitude differed. The results of the amplitude depends on the driver, some are more comfortable when driving and might know the road before while others do not drive as often and might never have seen the road. This can clearly be seen in Curve 2 where one driver reached almost  $95\text{km/h}$  and another driver was just above  $80\text{km/h}$  as the highest velocity. In Curve 3, the velocity dropped to zero before the stop sign where the driver should stop before turning in the T-junction.



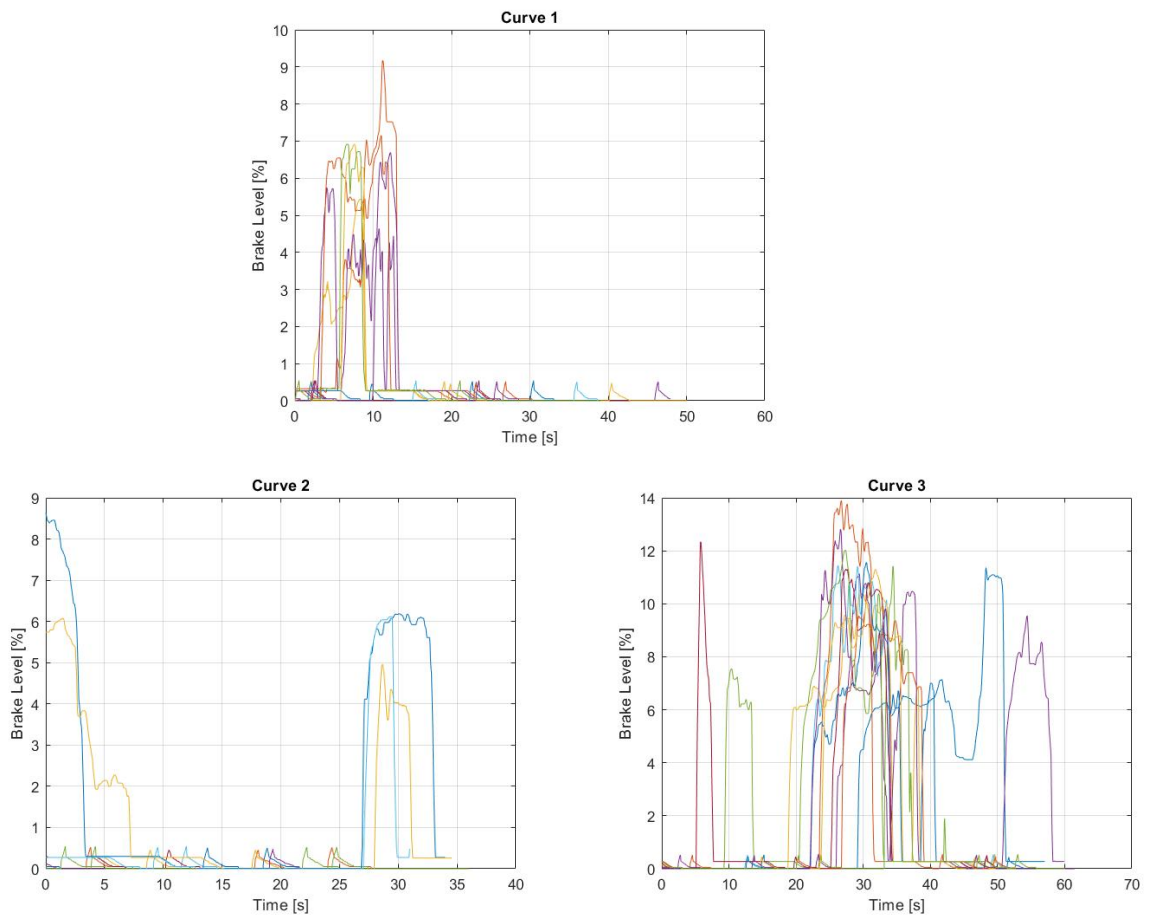
**Figure 4.7:** Velocity in Curve 1, Curve 2 and Curve 3. The red line in every figure indicates the mean curve.

The highest mean velocity in each curve are:

- Curve 1 =  $52.3\text{ km/h}$
- Curve 2 =  $81.2\text{ km/h}$
- Curve 3 =  $77.0\text{ km/h}$

### 4.2.4 Brake Pedal

The brake pedal is measured in %, which is the percentage of the maximum braking of the pedal. The braking does not reach above 9% of the maximum pedal length in Curve 1. The same scenario occurs in Curve 2 with a few brakes before the curve and some after due to a vehicle in front. In Curve 3, there is a sign after the curve which implies every vehicle to make a full stop, hence the braking is harder through the curve and reaches a maximum pedal press of 14%. Some drivers braked long before the stop sign as well, the reason for it was because of a vehicle in front or they were unsure of how the road was formed, the stop sign can not be seen until almost at the end of the curve.



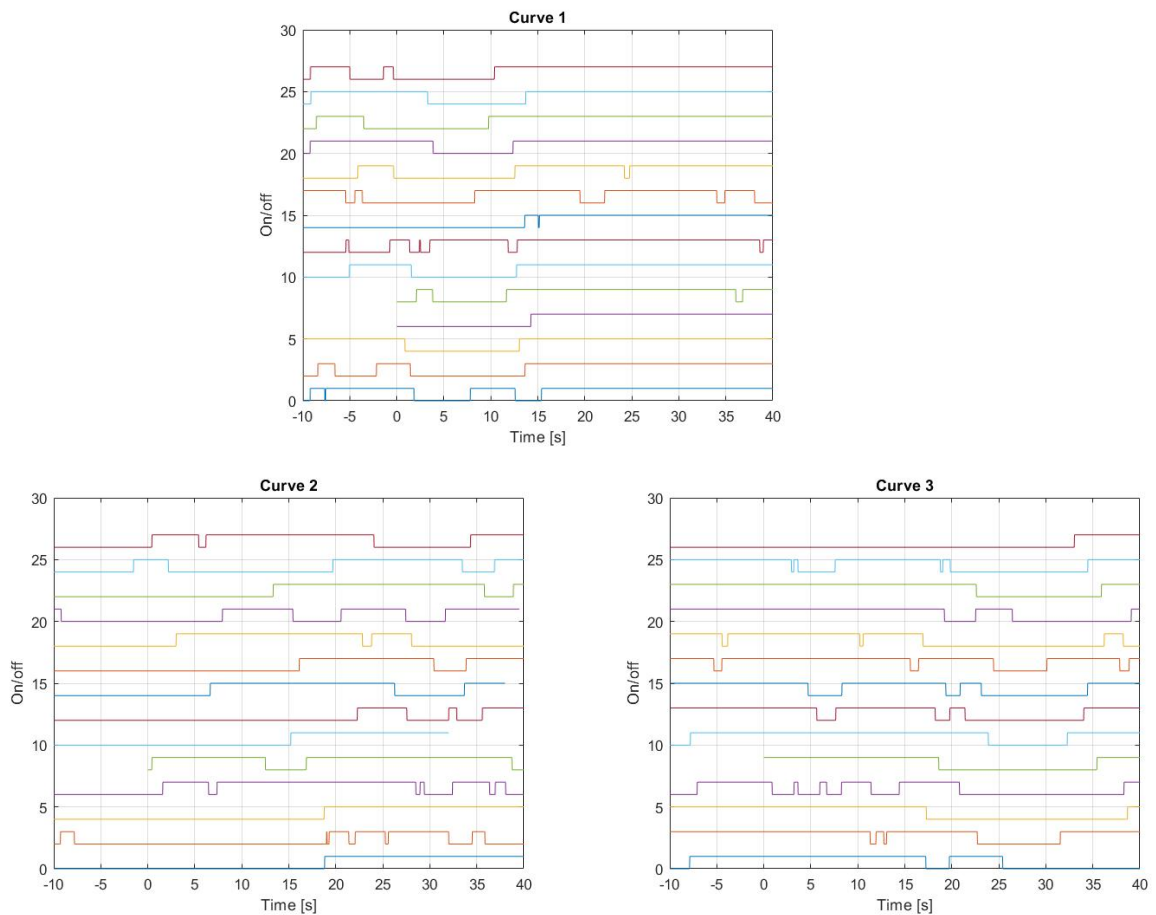
**Figure 4.8:** Brake pedal movement in Curve 1, Curve 2 and Curve 3.

The highest pressed brake pedal levels in the curves are:

- Curve 1 = 9.2 %
- Curve 2 = 0.3 %
- Curve 3 = 7.6 %

## 4.2.5 Acceleration Pedal

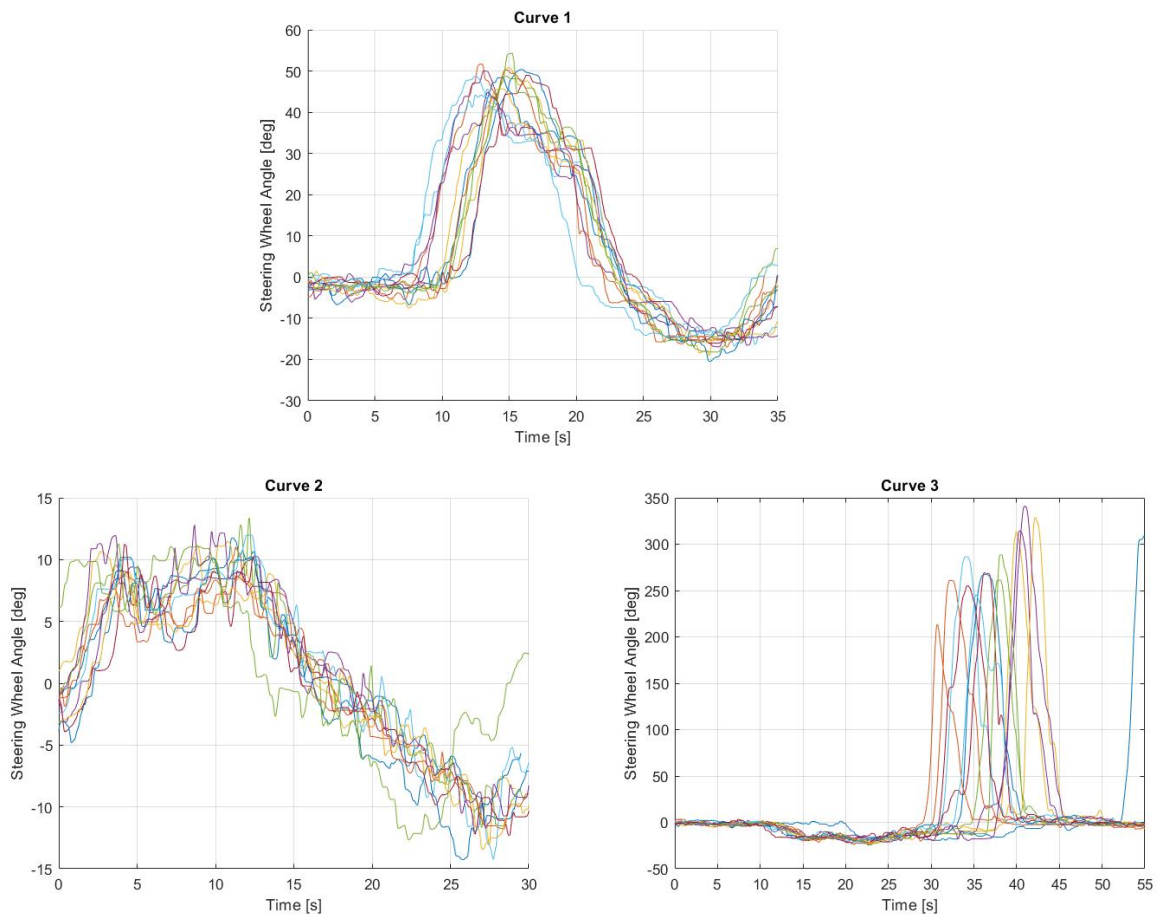
The acceleration pedal is measured as on or off, when the pedal is pressed it is on. As seen in figure 4.9, when the pedal is pressed it varies a lot. The recording was measured from minus 10 seconds, compared to the other parameter plots, to evaluate the pressing of the pedal before the curve. Two test drives were not measured 10 seconds before Curve 1, because the recording was not started until just before the curve. In Curve 1, every driver pressed the pedal after the curve to reach the velocity needed for the motor way entry since the velocity decreased during the curve.



**Figure 4.9:** Acceleration pedal movement in Curve 1, Curve 2 and Curve 3, for all test drives.

### 4.2.6 Steering Wheel Angle

The steering wheel angle in the Curve 1 and 2 are similar. The angle in Curve 3 is not as visible as the other curves due to the left turn after the stop sign. In Curve 1, it is more obvious when the drivers started the turning, some waited a bit while other started turning earlier, this also depended on the velocity. Same can be said on Curve 3, though the timing of turning the steering wheel depended on how long the vehicle had to wait by the stop sign. Considering all drivers had to follow the road and turn in every curve, all tests of the steering wheel were plotted. The difference in time when the steering is started is also dependent on the speed the vehicle had.



**Figure 4.10:** Steering Wheel Angle in Curve 1, Curve 2 and Curve 3.

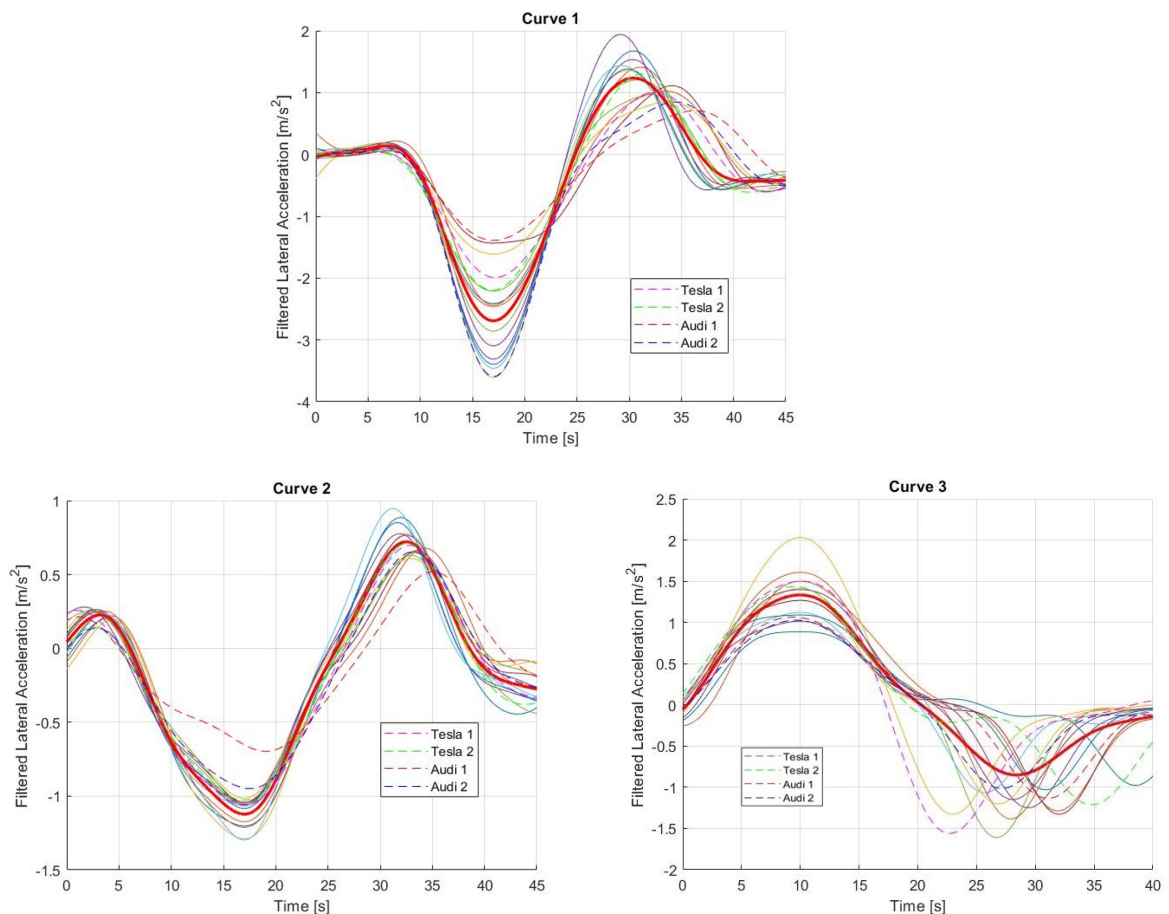
### 4.3 Competitor Cars

The chosen parameters of the competitor cars:

1. **Lateral Acceleration** to identify the lateral acceleration in curves. Measured in  $m/s^2$ .
2. **Longitudinal Acceleration** to identify the longitudinal acceleration driven in curves. Measured in  $m/s^2$ .
3. **Steering Wheel Angle** to identify how much the driver turns the steering wheel in the curve. Measured in  $deg$ .
4. **Steering Wheel Torque** to establish the torque needed from the driver when driving in autonomous mode. Measured in  $Nm$ .

#### 4.3.1 Lateral Acceleration

The lateral acceleration on the competitor cars varies among each other in every curve, same as the test drives. In Curve 2, one of the competitor cars has a low negative lateral acceleration compared to the other measurements.

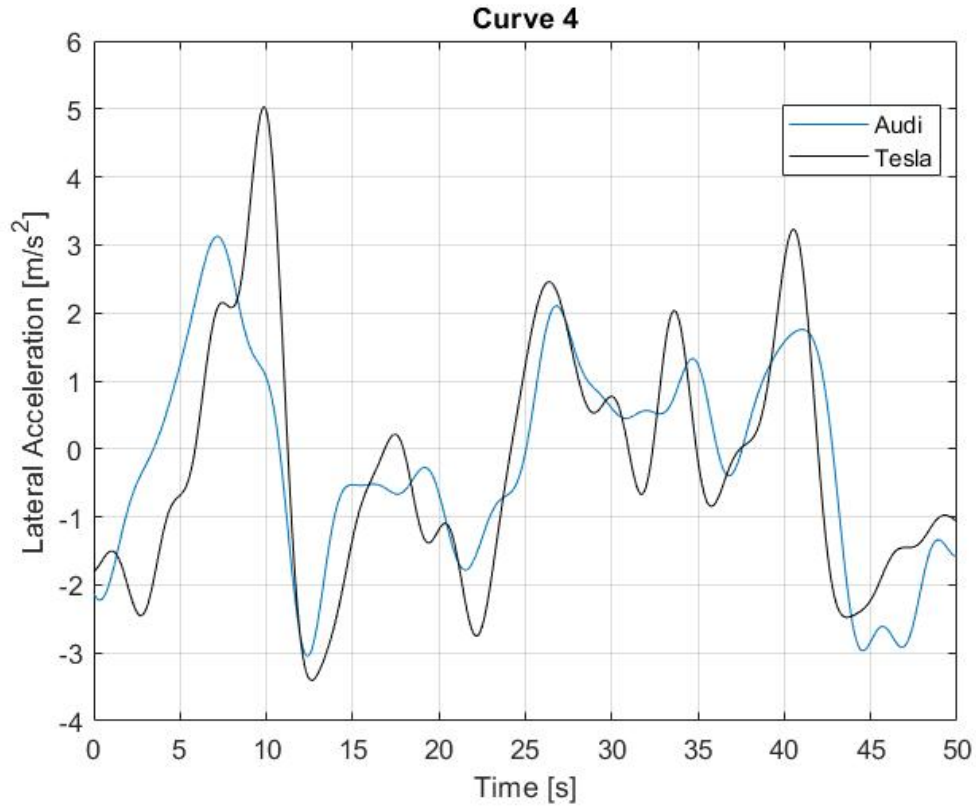


**Figure 4.11:** Filtered Lateral acceleration on the competitor cars, marked with dashed lines, compared to the test drives in Curve 1, Curve 2 and Curve 3. The description of "Tesla 1" means the first out of two driven routes.

## 4. Results

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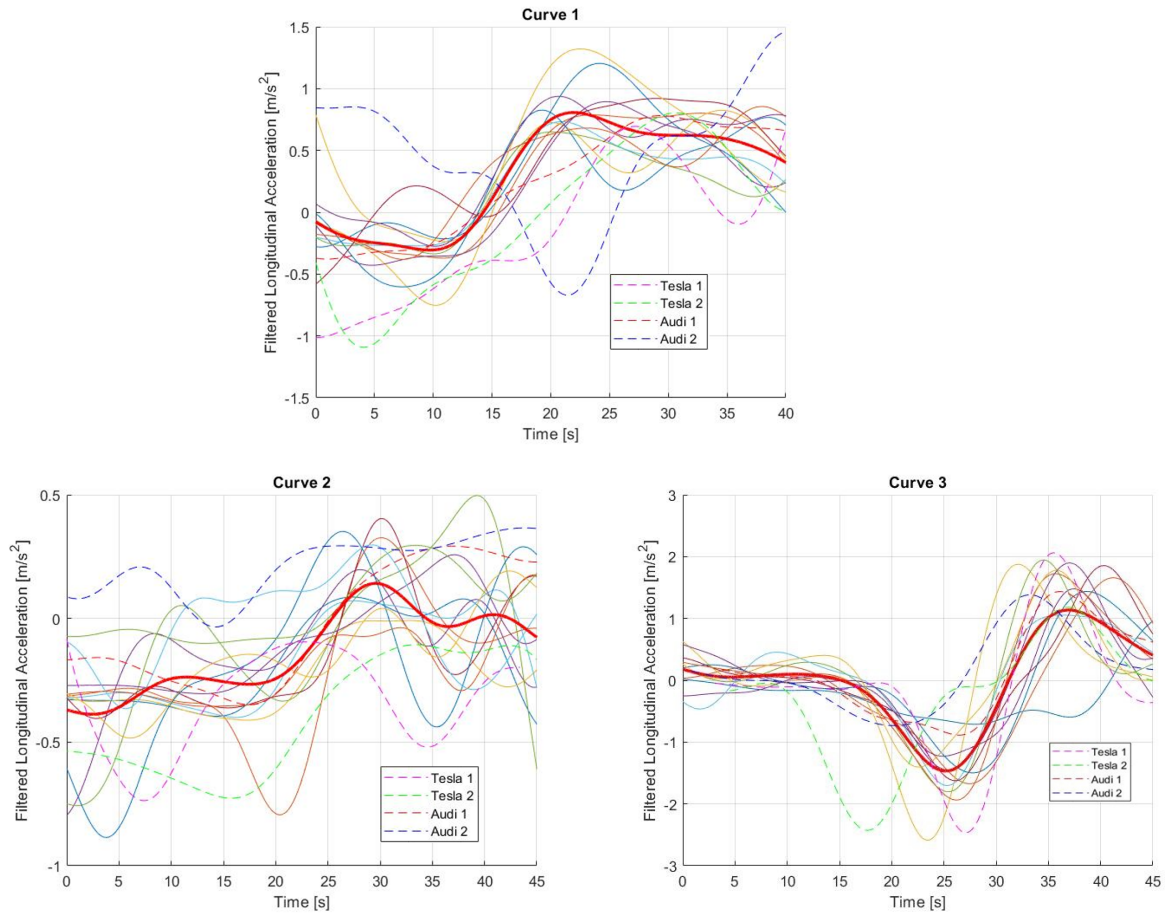
In Curve 4, both vehicles were also driven with the CSA active. The Audi E-tron braked before the curve which made it easy to turn in the curve and the lateral acceleration decreased, see the blue line in figure 4.12. It continued to brake before every curve and accelerate after the curve. While the Tesla had trouble finding the lines on the road and did not see the curves and the driver had to take control. This made the lateral acceleration increase as high as  $5m/s^2$ .



**Figure 4.12:** Filtered Lateral Acceleration of the Tesla Model 3 and Audi E-tron on Curve 4, the measured curve is between 0-13 seconds.

### 4.3.2 Longitudinal Acceleration

Same as in the lateral acceleration, the competitor cars varies among the test drives. One of the competitor cars has a lower longitudinal acceleration in Curve 2, the reason is a vehicle in front which made the car brake.

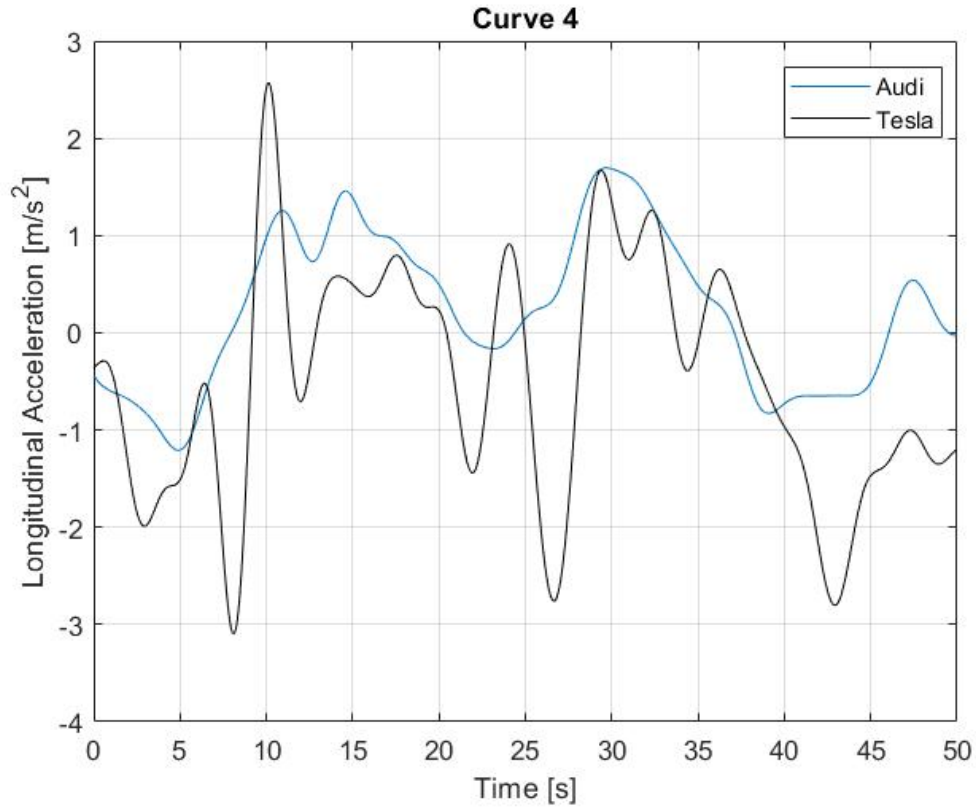


**Figure 4.13:** Filtered Longitudinal acceleration on the competitor cars compared to the test drives in Curve 1, Curve 2 and Curve 3. The red line in every figure indicates the mean curve.

## 4. Results

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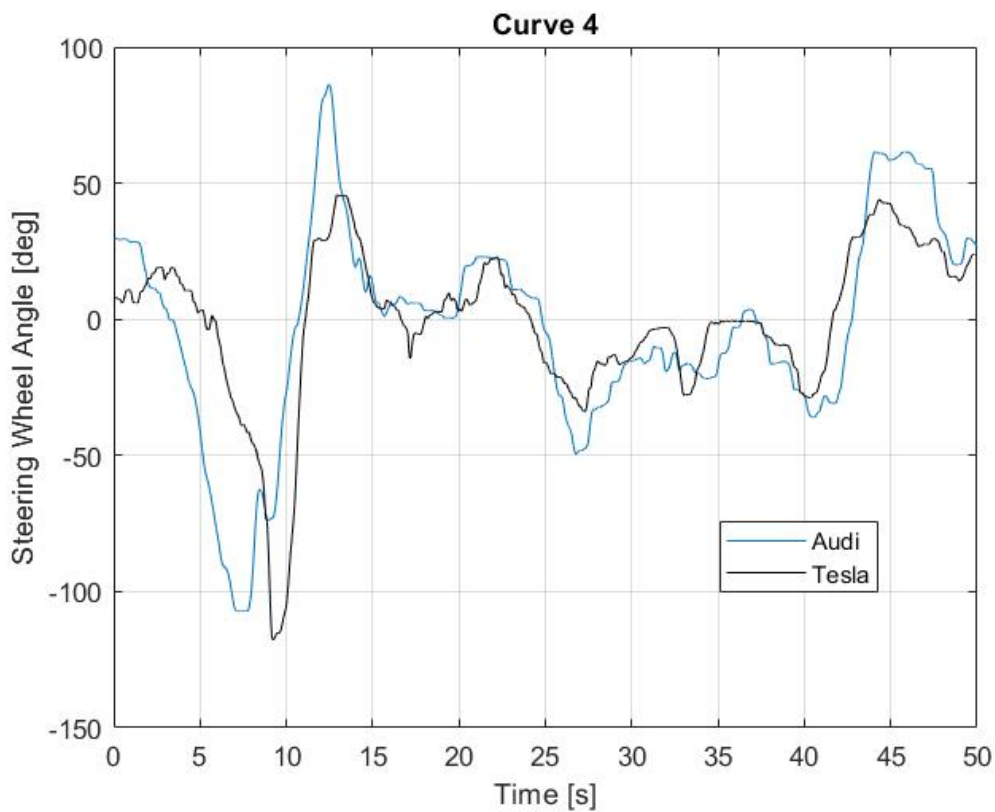
In Curve 4, see section 3.2.2, both vehicles were driven with the CSA active. As seen in figure 4.14, the Audi E-tron makes a smooth drive with the CSA active. It brakes before the curve and accelerates after which makes the longitudinal acceleration to not vary much in the measurement. While the Tesla Model 3 map did not find the lines and the driver had to take control of the vehicle and brake late. As a consequence, the level of the longitudinal acceleration increased.



**Figure 4.14:** Filtered Longitudinal Acceleration of the Tesla Model 3 and Audi E-tron on Curve 4.

### 4.3.3 Steering Wheel Angle

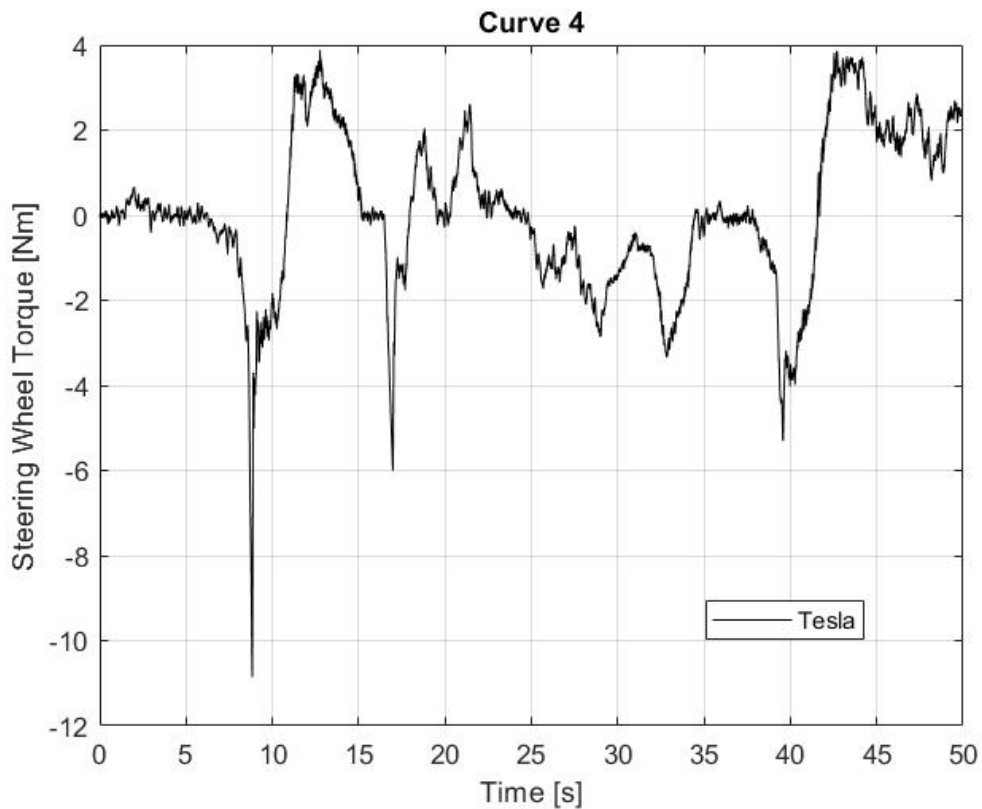
The steering wheel angle of the Audi E-tron and the Tesla Model 3 correlates quite well except for in the actual curve. The driver had to take over the steering wheel in the Tesla during the curve due to the lack of lines on the road. The Tesla Model 3 was on autonomous mode and since the vehicle did not turn until the driver took control of the steering wheel, it delayed the steering and increased the curve radius which increased the steering wheel angle. The Audi E-tron turned more in order to keep the car in the lane as the driver steered the vehicle.



**Figure 4.15:** Filtered Steering wheel angle from Tesla Model 3 and Audi E-tron on Curve 4.

### 4.3.4 Steering Wheel Torque

Some technical issues lead to the steering wheel torque in the Audi was not recorded in Curve 4. Therefore, the steering wheel torque in the Tesla was the only recording to be analysed. The torque was not recorded when the vehicle steers by itself, only when the driver is adding torque by steering. As mentioned, in Curve 4, the Tesla did not find the road lanes in this curve. The driver had to take control over the car and steer it in the right direction. By doing that, the torque needed to control the car was almost  $12Nm$ . After the curve, the driver controlled the vehicle until the end of the recording.



**Figure 4.16:** Steering wheel torque from Tesla Model 3 on Curve 4

# 5

## Conclusion

The conclusion is divided into four parts, driving situations, method, parameters and competitor cars.

1. There is a need to test different types of driving situations, for instance roundabouts and crossings, to ensure that all driving situations are covered.
2. The method, including objective measurements and subjective assessment, that was developed to use in the test drives gives the parameters that are required for the development of the control system for CSA.
3. After assessing the results it is recommended to use the lateral acceleration, longitudinal acceleration and the velocity parameters as major input when developing the control system. A map needs to be implemented in the vehicle as well.
4. Assessment of competitor cars gave valuable information on how the systems are working.

# 6

## Discussion and future work

The discussion of the test drive, rating, parameters and recommendations to future work is written in this chapter.

### 6.1 Test drive

A total of 14 drives were analysed while 18 test drives were made. Due to some technical issues, 4 of the test drives were not possible to be evaluated. When testing with technical equipment, it is usual to have some problems along the way. Therefore, the best testings are the ones with the most amount of data. For future work, it is recommended to have more test drivers and test drives for more data. The method was limited to the country road and the motor way entrances and exits, other roads and driving situations should be measured and analysed to get better input for the development of the CSA control system.

### 6.2 Ratings

Some of the test drivers had not used the subjective rating scale while others are using it daily. Therefore, the outcome of the rating may differ. The test coordinator was in the the vehicle during every test and also rated the cornering. Some of the ratings by the inexperienced test drivers were a bit off and differed depending on the person. The rating made by the test coordinator was most consistent and were therefore used. For future work, the suggestion is to mostly use people with experience with the assessment rating scale.

The test drivers rated the curves in two parts, comfortability and efficiency. When a vehicle is driving through a curve, the most important parameter is for the ride to be comfortable and then the ride can be tuned to be efficient. Therefore, the priority rating was the comfortability.

### 6.3 Parameters

The lateral acceleration and longitudinal acceleration are the parameters that describes how the vehicle is driven through the corner. The velocity was evaluated to understand the speed of every driver and see how it related to the lateral and longitudinal acceleration in every curve. The brake and acceleration pedal were used to

estimate when the drivers let go of the accelerator pedal and started braking before the curve, if they used the braking pedal at all and when they pressed the acceleration pedal after the curve. This correlates to the driving style and the difference between drivers. The steering wheel angle was also important to consider, it relates to the lateral acceleration and it was also possible to understand how much every driver turned the steering wheel in each corner.

In the future, to make the ride comfortable and efficient for every driver, it is recommended to tune the performance from the drivers. By logging the acceleration levels while the driver is controlling the vehicle to comprehend which levels the driver is comfortable with. The vehicle can then use those levels to control the CSA. Another way is to use three settings where the driver can choose between different driving modes i.e. Eco, normal and sport. A map in the vehicle is needed for this to work. Another recommendation is to use regenerative braking, if the vehicle is a hybrid or battery car, together with the CSA to make the braking more efficient and to save fuel.

Another recommendation for the future is to connect the parameters to the specific driver. It would be interesting to compare for instance the longitudinal acceleration to the velocity from the same driver.

### **6.3.1 Lateral Acceleration**

Even though some drivers in Curve 1 had higher lateral acceleration than the other curves, they passed the subjective rating. The reason for that is because the velocity was so low that it did not feel dangerous in any way. The lateral acceleration partly depends on the radius of the curve and the velocity of the vehicle. The radius in curve 1 was almost  $1/3^{rd}$  of Curve 2 and  $1/2$  of Curve 3. Therefore, the test drivers had to slow down in Curve 1 to be able to make the cornering.

### **6.3.2 Longitudinal Acceleration**

The longitudinal acceleration in all the test drivings did not become too uncomfortable either since almost all the subjective ratings were approved. If a test drive peaked, it was a vehicle in front which made the driver brake or a slightly aggressive acceleration was made after a curve. The highest longitudinal acceleration came from Curve 3 where the drivers had to make a fully stop.

#### **6.3.2.1 Jerk Levels**

All the test drivers made it through the curves without it being too uncomfortable. According to the subjective ratings, the test drives that were not analysed, were not far from being approved. Since the lateral and longitudinal accelerations were not very high, the jerk levels were quite low as well. To get higher jerk levels, other curves or driving situations needs to be measured. Because of the very low jerk levels this will not be further analyzed.

### 6.3.3 Velocity

Although Curve 1 has a speed limit of  $70\text{km/h}$ , it was almost impossible to keep that velocity through the curve because of the sharp curve. In Curve 2, the speed differed more among the drivers. The visibility of Curve 2 was better than the others and therefore it became easy to accelerate in the curve. The road was also leaning a bit downhill which made the vehicle to not slow down as much by itself. In Curve 3, most of the drivers had a high speed before the curve and slowed down rapidly because of the curve and then the stop sign.

The speed limit is needed for the map to have a speed limitation when cornering as well as the current velocity of the vehicle to later be regulated. Junction and other information about the curve, such as if the curve is too sharp and can not be driven in the allowed speed limit is also important for the map. The velocity parameter is therefore important for developing the control system of the CSA.

### 6.3.4 Brake Pedal, Acceleration Pedal and Steering Wheel Angle

The brake pedal, acceleration pedal and the steering wheel angle made it possible to understand the driving behaviour of the test drivers. But for the ACC to work, the vehicle will regulate the pedals and the steering wheel (if the steering assist is not available) and these parameters will not be relevant.

## 6.4 Competitor Cars

The testing of the competitor cars were done to understand more about existing systems. It is important that the control system finds the lines on the road for the CSA to work properly. A recommendation is to add lines on roads which have none.

The autonomous mode of the Tesla included the steering wheel assist which means that the driver did not have to do anything except for paying attention to the road. The CSA on the Audi made the driver in charge of the steering wheel at all times.

### 6.4.1 Lateral Acceleration

The lateral acceleration is a good parameter to use when controlling the vehicle. By understanding and comparing the lateral acceleration in the competitor cars, it can facilitate the development of the CSA.

The maximum lateral acceleration of the competitor cars were similar to the test drivers, which was approved. In Curve 4, the lateral acceleration of the Audi was higher than on the route with  $3\text{m/s}^2$ , while the Tesla was even higher with  $5\text{m/s}^2$ . The road had no lines which made it hard for the RADAR and cameras to find the actual road. Hence the Tesla did not find the curve and the driver had to take

control of the vehicle. Curve 4 has a radius of  $28m$  and is a steep curve, compared to the radius of  $101m$  in Curve 1.

### 6.4.2 Longitudinal Acceleration

The longitudinal acceleration is also a parameter which is used to control a vehicle. When knowing the limits of the parameter, the vehicle regulates the speed and keep the vehicle safe while moving. In the CSA, the parameters can be used to regulate the brake and acceleration pedal.

The maximum longitudinal acceleration did not exceed the test drives on the route, both cars found the lines of the road and the driving passed as the other test drives. Even though, in Curve 4, the Tesla did not detect the road, the velocity of the car was quite low which made it possible for the driver to press the brake a bit and turn in the middle of the curve. If both cars are to be compared, there is a big difference in amplitude of the longitudinal acceleration. The lower the amplitude, the more comfortable the driving is.

### 6.4.3 Steering Wheel Angle

The steering wheel angle in Curve 4 was analyzed, it was specially interesting in the Tesla due to the autonomous driving where the vehicle turned by itself. The steering wheel of the Audi had to be turned a bit more than the Tesla, that is likely to be because of different steering ratios.

### 6.4.4 Steering Wheel Torque

The steering wheel torque was also interesting because if the driver had to take over the steering wheel, a certain amount of torque was needed from the driver. Although, the steering wheel torque did not take measures when the vehicle controlled the steering wheel. The needed steering wheel torque was almost  $11Nm$  which is a lot considering the time of the turning.

## 6.5 Säve proving ground

One part of the test drive was to use the Säve proving ground. The test coordinator drove three laps around a track with increasing speed at every lap. The test drivers would compare the laps and decide which one they would prefer if a car would have driven the laps. The laps were not driven exactly the same, the lateral and longitudinal acceleration differed too much between the test drives. Therefore, this was not a part of the analysis. For future work, a driving robot could be used to get the same experience every time.

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# 7

## Appendix 1

Below are the statistics of the drivers. It describes sex, time of driverslicense, how many hours the person drives each day on an average, if the driver owns a car and if the driver consider themselves as a professional driver.

<b>Driver:</b>	<b>Sex:</b>	<b>Time of license (år):</b>	<b>Driving (h/day):</b>	<b>Own a car:</b>	<b>Professional Driver:</b>
<b>1</b>	<b>Male</b>	<b>27</b>	<b>1</b>	<b>Yes</b>	<b>No</b>
<b>2</b>	<b>Male</b>	<b>19</b>	<b>3</b>	<b>Yes</b>	<b>Yes</b>
<b>3</b>	<b>Male</b>	<b>29</b>	<b>3</b>	<b>Yes</b>	<b>No</b>
<b>4</b>	<b>Male</b>	<b>14</b>	<b>0.25</b>	<b>Yes</b>	<b>No</b>
<b>5</b>	<b>Female</b>	<b>14</b>	<b>0</b>	<b>No</b>	<b>No</b>
<b>6</b>	<b>Male</b>	<b>33</b>	<b>0.66</b>	<b>Yes</b>	<b>Yes</b>
<b>7</b>	<b>Male</b>	<b>46</b>	<b>0.14</b>	<b>Yes</b>	<b>No</b>
<b>8</b>	<b>Female</b>	<b>7</b>	<b>0</b>	<b>No</b>	<b>No</b>
<b>9</b>	<b>Male</b>	<b>7</b>	<b>2</b>	<b>No</b>	<b>Yes</b>
<b>10</b>	<b>Female</b>	<b>24</b>	<b>0.21</b>	<b>Yes</b>	<b>No</b>
<b>11</b>	<b>Male</b>	<b>13</b>	<b>1</b>	<b>Yes</b>	<b>Yes</b>
<b>12</b>	<b>Male</b>	<b>12</b>	<b>1</b>	<b>Yes</b>	<b>Yes</b>
<b>13</b>	<b>Male</b>	<b>27</b>	<b>1</b>	<b>Yes</b>	<b>No</b>
<b>14</b>	<b>Male</b>	<b>9</b>	<b>1</b>	<b>Yes</b>	<b>Yes</b>

The driver, passenger and test coordinator rated every curve and the statistics of the ratings can be seen below.

			Test 1						Test 3						Test 5						Test 7					
			Driver 1		Driver 2 (passenger)		Test Coordinator		Driver 3		Driver 4 (passenger)		Test Coordinator		Driver 5		Driver 6 (passenger)		Test Coordinator		Driver 7		Driver 8 (passenger)		Test Coordinator	
Road	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency
Curve 1	8	8	8	6	7	7	9	9	9	10	9	9	9	9	5.5	6	5.5	6	8	8	8	8	8	8	9	6
Curve 2	9	9	8	8	8	8	8	9	8	10	9	8	9	7	7	8	8	8	7	7	7	7	7	7	7	8
Curve 3	9	8	9	7	8	8	10	10	9	9	9	8	8	6	7	6	6.5	5	6	6	7	7	7	7	8	8
			Test 2						Test 4						Test 6						Test 8					
			Driver 2		Driver 1 (passenger)		Test Coordinator		Driver 4		Driver 3 (passenger)		Test Coordinator		Driver 6		Driver 5 (passenger)		Test Coordinator		Driver 8		Driver 7 (passenger)		Test Coordinator	
Road	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency
Curve 1	9	9	6	7	8	8	7	7	7	7	7	7	7	7	9.5	9	9	9	8	9	6	7	6	8	8	8
Curve 2	10	6	7	9	7	8	9	10	9	10	9	9	9	9	9	9	9	9	9	9	8	7	7	7	8	8
Curve 3	9	5	6	7	8	7	7	7	7	7	7	7	6	7	7	8	8	6	8	6	7	7	7	7	8	8
			Test 9						Test 11						Test 13						Test 14					
			Driver 9		Driver 10 (passenger)		Test Coordinator		Driver 11		Driver 4 (passenger)		Test Coordinator		Driver 13		Driver 14 (passenger)		Test Coordinator		Driver 13		Driver 14 (passenger)		Test Coordinator	
Road	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency
Curve 1	1	1	1	1	1	1	8	8	8	8	3	7	6	7	7	7	7	7	7	7	7	7	7	7	7	7
Curve 2	8	9	8	9	8	9	9	8	9	8	9	8	9	7	7	8	8	8	8	8	8	8	8	8	8	8
Curve 3	5	5	5	6	5	6	8	8	8	8	7	8	6	7	7	7	7	7	7	7	7	7	7	7	7	7
			Test 10						Test 12						Test 14											
			Driver 10		Driver 9 (passenger)		Test Coordinator		Driver 12		Driver 4 (passenger)		Test Coordinator		Driver 14		Driver 13 (passenger)		Test Coordinator		Driver 13		Driver 14 (passenger)		Test Coordinator	
Road	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency	Comfort	Efficiency
Curve 1	7	8	7	8	7	8	7	3	8	5	7	6	7.5	7	7	7	7	7	7	7	7	7	7	7	7	7
Curve 2	6	8	6.5	8	6	8	8.5	7.5	8.5	8	7	8	8	8	8	8	7	7	7	7	7	7	7	7	7	
Curve 3	8	9	8	10	8	9	9	8	6	8.5	6	8	8	8	7	9	9	9	9	9	9	9	9	9	9	9