CHALMERS
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Real Driving Emissions (RDE) of a Gasoline PHEV

Master's Thesis in the Master's Program Automotive Engineering

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Abstract

As the gasoline Plug-In Hybrid Electric Vehicle (PHEV) are growing in popularity due to their potential to decrease the levels of exhaust pollutants in the air, the importance of studying the factors affecting the emission levels on these vehicles has increased. This report describes a Real Driving Emissions (RDE) measurement on a Volvo XC90 T8 which is a gasoline PHEV. The goal of the study is to capture the effects of driver behavior, the driving mode and route choice on the emission levels of the RDE cycles. The measurements are conducted using an MSS (Micro Soot Sensor) which means that emissions considered in this study are limited to soot and CO_2. The CO_2 is calculated, in the section of Post Test Calculations, using the sampled engine parameters. The dynamic RDE requirements are checked in Real-Time using the AVL InVehicle application. Using this app, it is possible to reach the maximum level of aggressiveness and softness while driving without exceeding the limits. Additionally, this report includes an analysis of the correlations between the afore mentioned factors and where each of the factors has the most impact in an RDE cycle. The Results show that the more aggressive one drive, the more soot will be emitted and the more inclination a road has, the more of CO_2 will be emitted. When driving in lower speeds and low state of charge, the pure mode which is one of multiple driving modes is more beneficial when it comes to emissions, while the hybrid mode is a better choice when going at higher speeds, e.g. on the motorway. Note that the tests conducted in this report are not included in this vehicle certification procedures. The vehicle is certified for the required emissions according to EU regulation no 692/2008 and 715/2007 which do not require neither a WLTC test nor an RDE test.

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Nomenclature

ALHA	Altitude Ludvig Hybrid Aggressive
ALHC	Altitude Ludvig Hybrid Calm
ALPC	Altitude Ludvig Pure Calm
AMHN	Altitude Mohammed Hybrid Normal
AMPA	Altitude Mohammed Pure Aggressive
AMPN	Altitude Mohammed Pure Normal
EPA	United States Environmental Protection Agency
ECU	Engine Control Unit
ESC	Exhaust Soot Concentration
FC	Fuel Consumption
FLHA	Flat Ludvig Hybrid Aggressive
FLHC	Flat Ludvig Hybrid Calm
FLPA	Flat Ludvig Pure Aggressive
FLPC	Flat Ludvig Pure Calm
FMHN	Flat Mohammed Hybrid Normal
FMPN	Flat Mohammed Pure Normal
HEV	Hybrid Electric Vehicles
MAW	Moving Average Window
MSS	Micro Soot Sensor
NEDC	New European Driving Cycle
NO_X	Nitrogen Oxides
OEM	Original Equipment Manufacturer
PEMS	Portable Emissions Measurement System
PHEV	Plug-in Hybrid Electric Vehicles
PM	Particulate Matter
PN	Particle Number
RDE	Real Driving Emission
RPA	Relative Positive Acceleration
SSC	Sensor Soot Concentration
SOC	State of Charge
VCC	Volvo Cars Corporation
WLTC	Worldwide Harmonized Vehicle Test Cycle
WLTP	Worldwide Harmonized Vehicle Test Procedure

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1. Introduction

Hybrid Electric Vehicles (HEV) and Plug-in Hybrid Electric Vehicles (PHEV) have been increasing in popularity over the past few years. This is partly due to political incentives which are mostly related to the environmental impact of the conventional combustion engine vehicles. There are different types of hybrid electric vehicles with different levels of hybridization which is the degree to which the vehicle can be used as an electric vehicle. However, what they all have in common is the combination of one (or several) electric motor(s) and an internal combustion engine. The electric motor is driven using the electricity provided by an onboard battery. On a Hybrid Electric Vehicle, the battery is recharged either using the internal combustion engine in addition to other smaller sources such as regenerative braking. For a Plug-in Hybrid Electric Vehicle, in addition to being able to recharge the battery using the afore mentioned sources, it can be recharged by a plug to an external power source. By doing this, the user can make sure to have a fully charged battery, i.e.100% State of Charge (SoC), at every start of a trip. Gasoline plug-in hybrid electric vehicles are considered a sustainable replacement for the internal combustion engine. This is due to its potential to decrease the global CO_2 emissions by the means of renewable energy sources for recharging the battery. The total global sales of highway-legal plug-in hybrids reached 2 million units worldwide in December 2016 and reached 0.86% of the total new car market. [1, 2] Continuing at this growth rate means that by 2030, 8 out of 10 vehicles sold will be plug-in hybrid vehicles. This makes the emissions assessment of a gasoline plug-in hybrid electric vehicle more important. The total global sales of highway-legal plug-in hybrids reached 2 million units worldwide in December 2016 and reached 0.86% of the total new car market. [1, 2] Continuing at this growth rate means that by 2030, 8 out of 10 vehicles sold will be plug-in hybrid vehicles. This makes the emissions assessment of a gasoline plug-in hybrid electric vehicle more important.

Traditionally, the vehicle performance with respect to emissions and fuel consumption were evaluated with the means of driving cycles. However, studies have shown that the results from the driving cycles differs widely from the real-world driving, especially with respect to the old cycle called New European Driving Cycle (NEDC) which was designed in the 1980s. The NEDC's test values were based on theoretical driving profiles which due to evolutions in technology and driving conditions became outdated. The newly designed test procedure, Worldwide Harmonized Light-duty Test Procedure (WLTP), was developed using real-driving data gathered around the world. This officially applied to new car models in September 2017. Even though the WLTP gives a better representation of everyday driving profiles, the results still need to be supplemented. Therefore, the European Commission has initiated a new test procedure called Real Driving Emissions (RDE). The RDE will serve as a compliment to the WLTP to ensure that the real driving emissions do not deviate from the laboratory cycle test more than a given conformity factor which accommodates for onboard measurement errors. This conformity factor will be revised each year and will reach 1.5 for NO_X emissions by the year of 2020.[3] The RDE measurements are meant to be conducted using a Portable Emissions Measurement Systems (PEMS) which is attached to the rear of the car and connected to the tailpipe(s).

The aim of this study is to explore the relationship between driving behavior and emissions within the legislation of RDE. To date, there are few studies that have investigated the link between aggressiveness and the emissions. Therefore, this study uses a quantitative method to gather data from a minimum of 12 executed tests, in real-world driving, using three different variables to see how the behavior of the driving correlates to the exhaust emissions. The focus will be directed towards investigating CO2, soot and fuel consumption and how the variables and different parts of the routes affect these outputs.

1.1. Background

From the period of 2006 to 2015 the number of registered commercial vehicles and passenger cars in the world increased by 50% to approximately 1 250 000 000 units.[4] Even Though fully electrified vehicles are counted within this number, vehicles with combustion engines still accounts for the majority of the vehicles in use. With increased numbers of vehicles, the amount of pollutants in the air is increased. The major pollutants associated with vehicle emissions are carbon monoxide, nitrogen oxides, particulate matter and hydro carbons.

Soot is a mass of impure carbon particles resulting from incomplete combustion of hydrocarbons. There are many sources for soot, one of which is the vehicles internal combustion engine.[5] The size of these particles can vary greatly and is the main determinant of how hazardous it can be both for humans, animals and the environment alike. Larger particles are usually filtered in the nose and throat. However, particles with smaller size can penetrate deeply inside the respiratory system of humans and animals and can cause asthma, lung cancer, birth defects and premature death. Regions with high soot concentration can lead to the perishing of some plant species locally. This is due to the soot covering the pores of the plants and interfering with its photosynthesis functions. [6]

Nitrogen Oxides (NOx) is produced when fuel is burned especially at high temperatures and excess of air.[5] As NOx reacts with various compounds to form hazardous substances. In the presence of sunlight, NOx can react with volatile organic compounds and form ground-level ozone which is a large problem in some regions. It can also react with ammonia, moisture and other compounds to form nitric acid and particles that can penetrate deeply inside the human respiratory system which can cause premature deaths.[7]

Carbon Monoxide (CO) is produced due to incomplete combustion of carbon-based fuels such as gasoline. It is impossible to recognize due to it being colorless, odorless and tasteless. However its effect on human and animal life is severe. It impairs the blood's ability to carry oxygen leading to damaged organs and body tissue.[8]

Hydrocarbons (HC) is a term referring to substances with hydrogen and carbon as their main forming element. Hydrocarbons make up for the largest parts of nonrenewable fossil fuels such as petrol and diesel. Therefore, it is the major component burned inside an engines combustion chamber. A small portion of these hydrocarbons is emitted through the exhaust due to incomplete combustion and is a cause for health and environmental issues.

It is important to note that todays vehicle exhaust aftertreatment technologies are quite advanced and the available catalytic converters in the new vehicle models reduces most of the produced pollutants. However, a large amount of pollutants is still emitted. This is because many regions of the world, where the economic situation is low, cars with old technologies are still dominating the markets.[9] People living in low- and middle-income countries account for 91% of the annual 4.2 million premature deaths due to exhaust pollution.[10] The use of older cars is not only specific to low-income regions; old cars are still in use even in Sweden which is a high-income country. Several recommendations are given by the World Mecila Association, one of which is the use of the best available technology (BAT) on all vehicles both on-road and off-road. Doing this would lead to solving most pollution problems associated with vehicle exhaust.[9]

The European Commission has been working on legislation to force OEMs to invest in improving combustion pollution and aftertreatment systems. Due to the diesel gate scandal in 2015, even more attention was directed towards vehicle emissions. After the EPAs discovery of VWs so called “defeat device”, which changed the exhaust emissions while testing the vehicle in an emission test cell, the whole world opened their eyes about the pollution question. By using this sophisticated software, VW was able to pass the criterions of pollutant legislation. However, when the vehicles were tested in on-road real driving conditions, the 2.0-liter turbocharged diesel four-cylinder engines emitted NO_X pollutants of up to 40 times the legal limit in the U.S. This was the event that set the new driving cycle, the WLTC and the RDE, in higher prioritization.[11, 12] However, it is very important to keep in mind that even without the defeat devices, emissions in real world traffic highly deviates from the lab test results. This is partly due to the different driving dynamics and the lack of altitude variations in the test cycles in the test cell.

1.2. Test Procedures

There are a number of test procedures specific for different areas worldwide. However, since this project is focused on the cars used in Europe, only the WLTP and RDE are relevant and are described in this section.

1.2.1. Worldwide Harmonized Light-duty Test Procedure, WLTP

The WLTP provides a strict plan and guidance regarding various conditions of the test such as road load (motion resistance), gear shifting, total car weight (adjusted by the addition of passengers/weight), fuel quality, ambient temperature, and tire selection and pressure.
Vehicles are divided into three different classes based on power/weight ratio [kW/ton].
For each class a different cycle is used.

- Class 1 - low power vehicles with ratio <= 22
- Class 2 - vehicles with 22 < ratio <= 34
- Class 3 - high-power vehicles with ratio > 34

Most common cars have nowadays power-weight ratios of 40-100 kW/Ton, i.e. belong to class 3. Vans and buses can also belong to class 2. The WLTP driving cycle is divided into four parts with different average speeds: low, medium, high and extra high. Each part contains a variety of driving phases, stops, acceleration and braking phases. For a certain car type, each powertrain configuration is tested with WLTP for the car's lightest (most economical) and heaviest (least economical) version. WLTP was developed with the aim of being used as a global test cycle across different world regions, so pollutant and CO2 emissions as well as fuel consumption values would be comparable worldwide. However, while the WLTP has a common global 'core', the European Union and other regions will apply the test in slightly different ways depending on their road traffic laws and needs.[13]

1.2.2. Real Driving Emissions

In contrast to a WLTC test which is performed under specific and controlled conditions as mentioned in section 1.2.1, an RDE test is an emission test that is executed on the road with real traffic, hence the name. When performing an RDE test, certain requirements must be fulfilled with respect to (but not limited to) distance and speed. The designed RDE cycle must consist of urban, rural and motorway driving. These intervals are determined by the maximum speed, and for a cycle to be approved a certain distance in each interval must be driven without major interruptions. To fulfill the requirements for an RDE the percentage driven in each area must lay within these specifications. On the highway part, one also must drive >100km/h for >5 min. These distance and speed specifications are presented in table 1.[3]

Table 1. RDE, Distance and speed specifications

Trip Specifics		Provision set in the legal documents
Total Trip Duration		Between 90 and 120 minutes
Distance	Urban	>16 km
	Rural	>16 km
	Motorway	>16 km
Trip Composition	Urban	29 – 44 % of total driven distance
	Rural	23 – 43 % of total driven distance
	Motorway	23 – 43 % of total driven distance
Average Speeds	Urban	15 – 40 km/h
	Rural	60 – 90 km/h
	Motorway	>90 km/h (>100 km/h for at least 5 minutes)

To have a valid RDE test, the test must be performed within a certain range of aggressiveness i.e. it must neither be too aggressive nor too calm. This is checked with the use of dynamic boundary conditions which require a certain number of accelerations to be fulfilled. The dynamic boundary conditions are presented in figure 1.[14] The graph to the left shows the vehicle speed times positive acceleration which is a measure of the requested power in time steps. For an acceleration to be regarded as positive, it must be equal to, or bigger than 0.1 m/s^2. This is to make sure it is a requested acceleration. The size of this acceleration can be compared with a velocity increase of 20 km/h in 55 seconds. If the velocity multiplied by acceleration value exceeds the line indicated in the left plot in any part (as in the black trip during the urban part), the trip is invalid and is considered too aggressive. The plot to the right illustrated the limit for the relative positive acceleration which is a measure for passivity.

If the RPA value falls below the indicated line (as in the yellow trip during the rural part) then the trip is considered invalid due to being too passive.

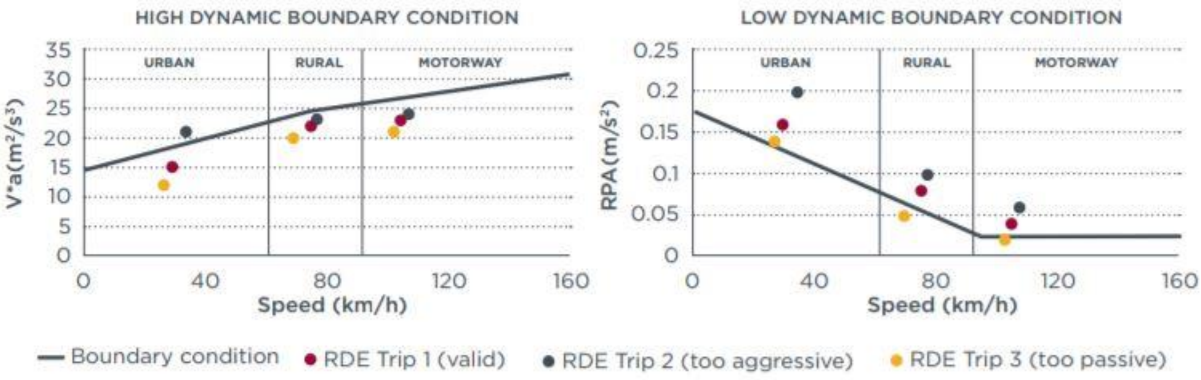


Figure 1. RDE, Dynamic boundary conditions. [14]

Beside these distance and speed specifications, there are also requirements about altitude differences and altitude gain. The test can also be performed in a range of ambient temperatures to cover most of the areas in the EU. During urban driving, the percentage of stops must be within a specific range of the total urban time. All these boundary conditions can be seen in table 2.

Table 2. RDE, Boundary conditions

Parameter		Provision set in the legal text
Altitude	Moderate	0 – 700 m
	Extended	700 – 1300 m
Altitude difference		No more than a 100-m altitude difference between start and finish.
Cumulative altitude gain		1200 m/100km
Ambient temperature	Moderate	0 – 30℃
	Extended	-7 – 0℃ and 30 – 35 ℃
Stop percentage		Between 6% and 30% of urban time
Maximum speed		145 km/h (160 km/h for 3% of motorway driving time)
Dynamic boundary conditions	Maximum metric	95th percentile of v*a (speed X positive acceleration)
	Minimum metric	RPA (relative positive acceleration)
	Curves shapes shown in figure 1	
Use of auxiliary systems	Free to use as in real life	

1.3. Purpose

As gasoline PHEV plug-in electric hybrid vehicles are increasing in popularity due to their potential in decreasing air pollution levels and fuel consumption, the importance of assessing this potential is growing large. Therefore, the tests will be conducted using a PHEV. The aim of this project is to conduct RDE measurement on a state of the art gasoline Plug-in hybrid electric vehicle, the Volvo XC90 T8 model year 2015. The tests will be conducted on different routes which satisfies the RDE legislation. The goal is to provide sufficient data to understand the effects of driving behavior, RDE route and driving mode on the real driving emissions in a gasoline hybrid vehicle. This thesis is a study of how the aggressiveness of driving behavior and route, as well as pure mode and hybrid mode, affects the emissions in an RDE cycle. How these three factors correlate to each other will also be investigated. It is important to note that this specific certified according to EU regulation no 692/2008 and 715/2007 which do not require neither a WLTC test nor an RDE test.

1.4. Delimitations

This thesis work will be limited to the following points:

- Light Duty Vehicle.
- Gasoline Plug-In Hybrid Electric Vehicle.
- Soot Emissions
- Vehicle ECU data.
- Real Driving Emissions (RDE) Legislations.

To be able to carry out this work and get the data needed to analyze the results, there are several tools that will be used in addition to the afore mentioned. This equipment consists of following:

- Volvo XC90 T8 - 2017.
- AVL Micro Soot Sensor (MSS).
- AVL CallApp.
- AVL Smart Mobile Solutions
- ETAS INCA
- MATLAB and similar software.

1.5. Objectives

With this study, some questions about how the driving behavior affects the emissions will be investigated and answered. Through on-road testing and with the necessary measurement equipment together with calculations and analysis of the gathered data, the following questions will be possible to answer.

- What are the effects of driver aggressiveness on RDE?
- What difference does driving in Pure mode yield compared to driving in Hybrid mode with respect to RDE?
- What are the effects of road inclinations in the various routes on RDE?
- What are the correlations between these factors?

2. **Method**

This section describes the methodology used in this investigation. This includes a description of the equipment, test procedure and the design of experiments.

2.1. Test Vehicle

The vehicle used for testing is the Volvo XC90 T8-2017. This is a gasoline Plug-In hybrid electric vehicle or a gasoline PHEV for short. This section includes a description of the vehicle and it’s driving modes.

2.1.1. Vehicle Specification

The relevant vehicle specifications are listed in table 3.

Table 3. Vehicle Specification.

Engine	Number of cylinders	ICE max power [kW]	ICE max torque [Nm]	Electric motor max power [kW]	Electric motor max torque [Nm]
T8 Twin Engine	4	235 @ 5700 rpm	400 @ 2200-5400 rpm	65	240

Note that this vehicle is compliant and certified for the required emissions according to EU regulation no 692/2008 and 715/2007 which do not require neither a WLTC test nor an RDE test. The soot emission limit according to the afore mentioned regulation is 5.0/4.5 mg/km.[15] All the official numbers on fuel consumption and range of electric drive are based on standardized driving cycles in laboratories according to the regulations mentioned above. These cycles are also used for quality check and require therefore high reproducibility. Therefore, these tests are conducted within controlled environments.

2.1.2. Driving Modes

The Volvo XC90 T8 has multiple driving modes that can be chosen by the driver. Various systems in the vehicle are adapted to provide the required performance based on the mode selected. Those systems are listed below.

- Steering
- Engine/transmission/All-Wheel Drive
- Brakes
- Suspension control
- Instrument panel
- Climate system settings

The various driving modes are: Hybrid, Pure, AWD, Power and Off-Road. It is easy to get an understanding of how each mode affects the driving characteristics only by the name of the respective mode. However, the only relevant modes for this thesis are Hybrid and Pure as they are the only ones included in the experiments.

The hybrid mode is the default mode, the engine management unit optimizes the use of the electric motor and the internal combustion engine to provide the optimal level of performance, fuel consumption and comfort. While the Hybrid mode is engaged, the ground clearance is automatically decreased when reaching high speeds thus reducing wind resistance and improving fuel economy. The amount of driving using only the electric motor depends on the state of charge of the HV battery, the torque/power request of the driver and the need to cool/heat the driver compartment. During Hybrid driving, the HV battery is charged when braking, up to a certain braking force applied to the pedal. Reaching the force threshold results in the engagement of the hydraulic brakes.

The Pure mode maximizes the use of the electric motor which means lowering the energy consumption as much as possible resulting in the lowest possible CO_2 emissions. Similarly to the Hybrid mode, the ground clearance is lowered except it is lowered for all speeds to decrease the air resistance. In order to increase the duration of the HV battery, certain climate system functions are reduced. The Pure mode is only available when there is sufficient charge in the battery. The internal combustion engine starts if the vehicle speed reaches approximately 125 km/h, if the driver’s torque/power request is more than the electric motor can provide and if other factors such as cold weather affect the system components.

2.1.3. State of Charge

To acquire comparable data, the battery state of charge must be the same at the start of each test. Ideally, to catch the effects of the driving modes, the state of charge should be at maximum, i.e. fully charged. However, that would result in a significant amount of time spent on charging the HV battery between the experiments. Hence, due to time limitation, the state of charge is chosen to be at minimum at the start of each test. The battery is considered drained at a state of charge between 18-20%. In addition to this, the “Charge” and “Hold” functions will be turned off during the experiments. The former function is used to charge the HV battery using the ICE and the later function is used to save the state of charge of the battery to be used later when desired. To reach the minimum state of charge, the car is put on standby prior to each test until the battery is drained. When the battery is drained, the internal combustion engine will start thus indicating that the SoC is too low to be used.

2.2. Design of Experiment

This thesis work is highly experimental. Therefore, it requires thorough planning to achieve usable results. This is done through a design of experiment (DoE). The DoE is the design of any task with the purpose of explaining the effects of various parameters that are hypothesized to affect the results. It is designed to make as few experiments as possible and maximize the results from the system. Basically, an experiment is designed to study the outcome by introducing changes in the input variables/experimental variables. The change in one or more of these variables is generally predicted to affect the so called "output variable" also referred to as response. Hence, a well-planned DoE dictates that the input variables and responses are well defined beforehand to be able to draw conclusions from the results.

Initially, the input variables are defined as:

X1 = Driving mode
X2 = Aggressiveness
X3 = Route

The responses/effects that will be measured are:

CO_2
Soot
Fuel Consumption
Engine Parameters

Using a factorial design, the influence of all the experimental variables and interaction effects on the responses can be investigated. A total of three variables are investigated with a low level (minus) and a high level (plus). A center level (zero), is also included in order to be able to detect nonlinearity in the response in the middle of the intervals. For the driving mode, the center mode is chosen to be the "Hybrid" mode as it is the most common mode to be used in the real-world traffic. Table 4 illustrates the variables along with their respective levels.

Table 4. DoE variables and their levels.

	(-)	(0)	(+)
Mode	Pure	Hybrid	Hybrid
Aggressiveness	Calm	Normal	Aggressive
Routes	Flat	Intermediate	Hilly

Additionally, the drivers are considered an uncontrolled variable which can lead to unpredictable results. Therefore, it is of interest to see the variation in response between the two drivers with respect to the driver aggressiveness while the other variables are at the center level. Initially, a total of 6 experiments at the center level will be conducted to identify the above-mentioned effects. The following experiments shown in table 5 will be conducted.

Table 5. Experiment for influence of the two drivers

Experiment	Driver	Mode	Aggressiveness	Route
1	Ludvig	Hybrid	Calm	Intermediate – Stenungsund
2	Ludvig	Hybrid	Normal	Intermediate – Stenungsund
3	Ludvig	Hybrid	Aggressive	Intermediate – Stenungsund
4	Mohammed	Hybrid	Calm	Intermediate – Stenungsund
5	Mohammed	Hybrid	Normal	Intermediate – Stenungsund
6	Mohammed	Hybrid	Aggressive	Intermediate – Stenungsund

Regardless of the results of these tests, the driver is not included as a factor in the DoE due to time limitations and the driver for each test is chosen at random. However, it is still of interest to investigate the influence. Once the center level experiments are conducted, the low and high level variable effects can be investigated using a factorial design. There are two factors on two levels and one on three levels resulting in 2*2*3 = 12 experiments. The experiment design matrix is illustrated in table 6.

Table 6. Experiment design matrix

Experiment	Mode	Aggressiveness	Route
7	Pure	Calm	Flat – Kungsbacka
8	Hybrid	Calm	Flat – Kungsbacka
9	Pure	Normal	Flat – Kungsbacka
10	Hybrid	Normal	Flat – Kungsbacka
11	Pure	Aggressive	Flat – Kungsbacka
12	Hybrid	Aggressive	Flat – Kungsbacka
13	Pure	Calm	Hilly – Landvetter
14	Hybrid	Calm	Hilly – Landvetter
15	Pure	Normal	Hilly – Landvetter
16	Hybrid	Normal	Hilly – Landvetter
17	Pure	Aggressive	Hilly – Landvetter
18	Hybrid	Aggressive	Hilly – Landvetter

For an easier referencing the experiments will be named as Route-Driver-Mode-Behavior. This means experiment 7 would be named FLPC given that Ludvig is the driver.

2.3. Routes

When designing the routes that will be driven during the tests, the RDE specifications and boundary conditions has been taken in consideration. The routes are designed to include one with high altitude gain, i.e. a hilly route and one with as little altitude gain as possible, i.e. a flat route. These will then be driven as RDE cycles with as aggressive and as smooth driving as possible without failing the dynamic

boundary conditions. This is to investigate the effect of such driving on fuel consumption and emissions. All the cycles will have a starting point at Chalmers University of Technology, Gothenburg.
A first iteration of the routes is generated using AVLs RDE app, RDE Route Identification, see figure 2, which can be bought through AVL with a MAC-address specific license. Using this app, one can generate an RDE route anywhere in a matter of minutes by selecting and area on the map. The app will take the RDE legislations in consideration when generating the routes. It identifies road speeds based on the speed limits specified for each road in addition to the traffic statics of the past two years. It is also possible to set a specific start point, end point and even a specific portion of a road that one would like to drive through.

Due to the familiarity to the Gothenburg region, there exists a good idea of where the roads are hilly and where it is mostly flat. Therefore, the selected areas for the desired route are based on the knowledge of the region. However, if one is not at all familiar with the region that the cycle is to be tested in, the RDE Route Identification app is very useful. Once the routes are generated, a test run through the cycle is conducted to insure the legal compliance of the route.

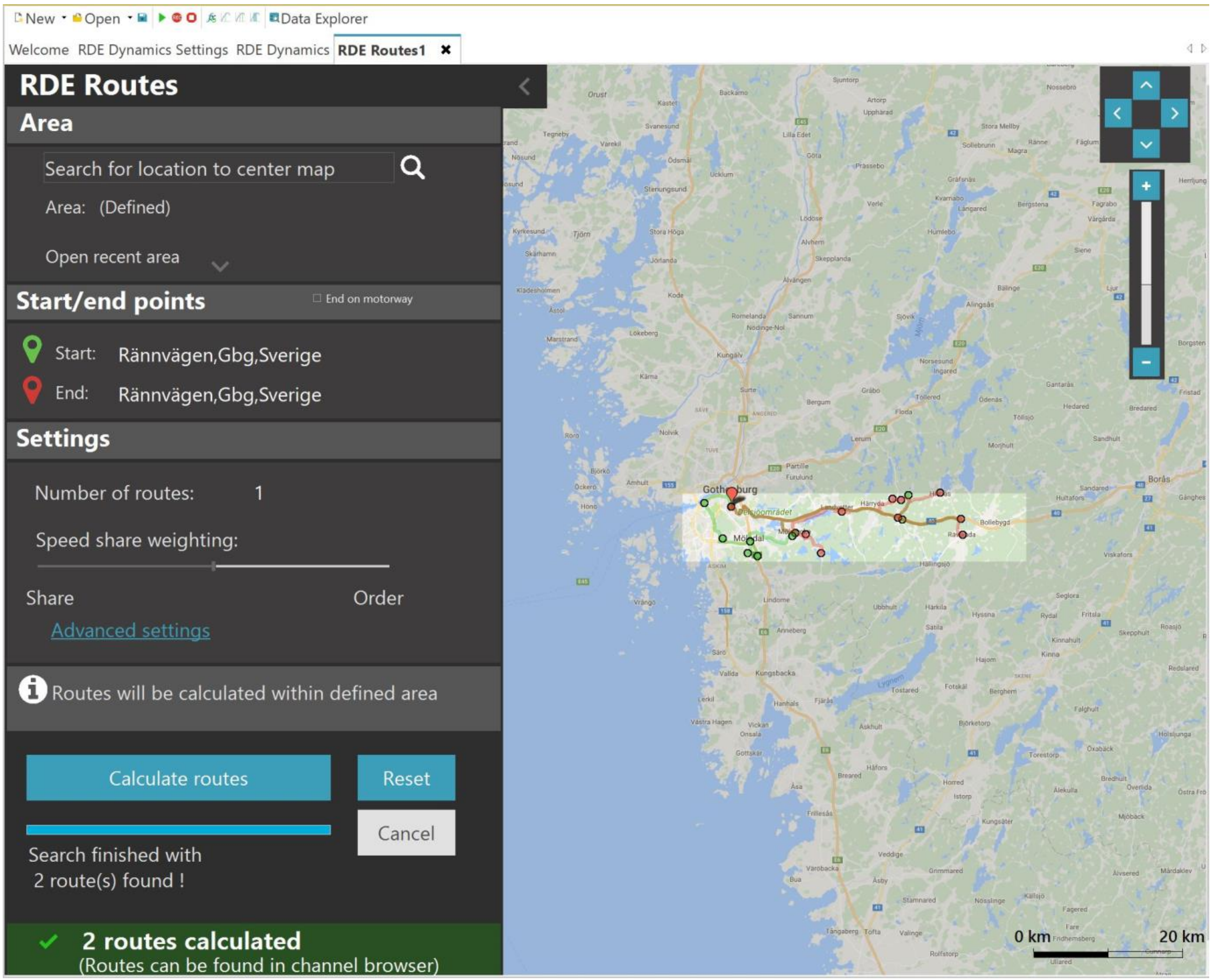


Figure 2. AVLs' RDE Route Identification App. Map with route location and start and end points.

To fulfill all RDE criteria's, some stops and "simulations" of overtaking trucks had to be added. This is mostly to pass the criteria "Vehicle Velocity <1km/h: 6-30% of the Urban part", and to get the required amount of accelerations above 0.1 m/s^2.

The more aggressive route, called "Landvetter", can be seen in figure 3. The "Landvetter" route starts at Chalmers, passes through the city of Gothenburg, mostly Högsbo and Mölndal, and continues out on the rural road towards Kållered, Hällesåker and Härryda to end with the motorway towards Landvetter.

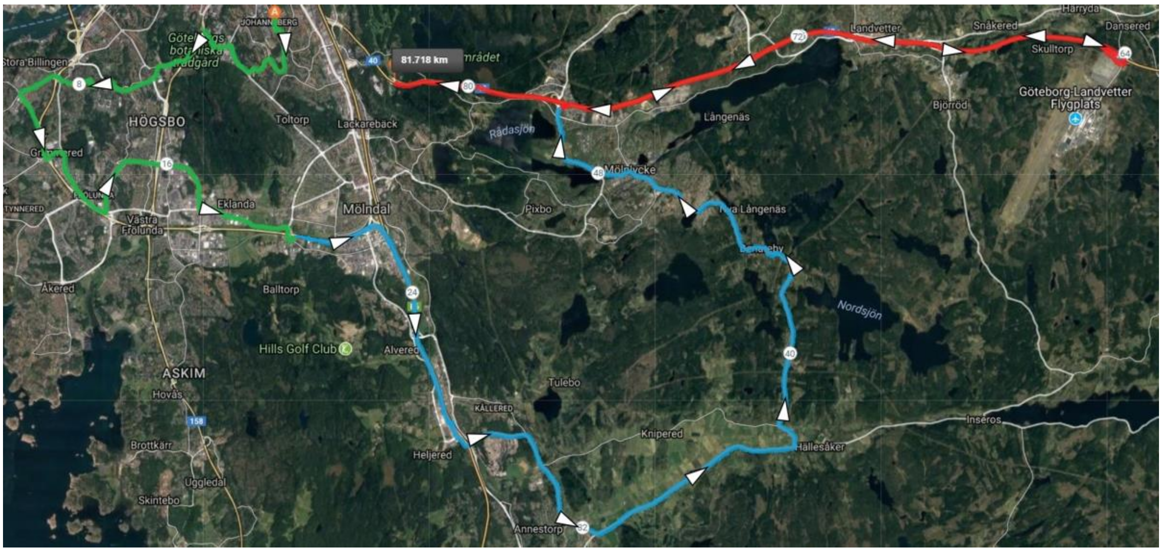


Figure 3. RDE Route – "Landvetter".

The smoother route, called "Kungsbacka", can be seen in figure 4. "Kungsbacka" starts at Chalmers, passes through the city of Gothenburg and onwards through the area of Frölunda, the rural part heads towards Särö and Kungsbacka and ends with the Motorway towards Fjärås and ends in Kållered.

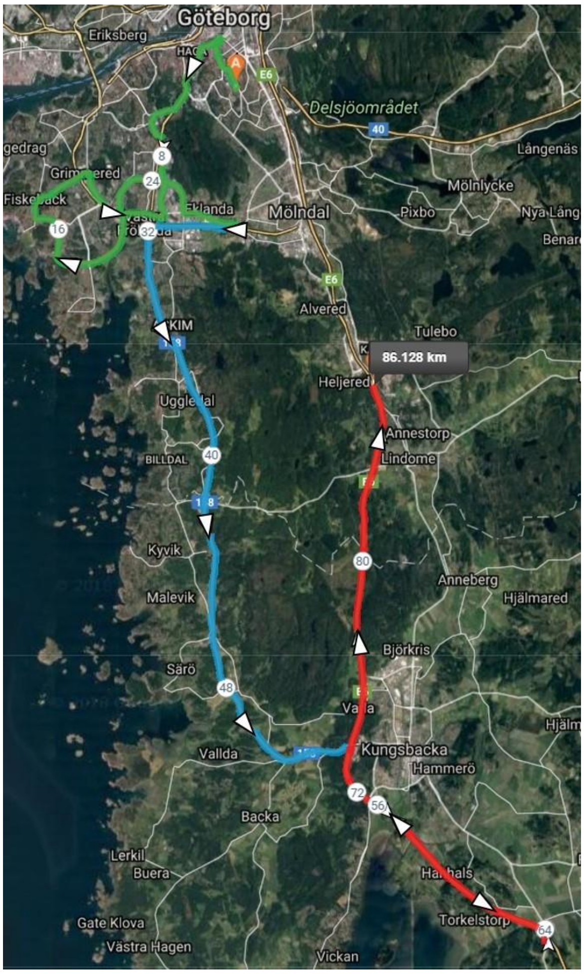


Figure 4. RDE Route - "Kungsbacka".

Figure 5 compares the cumulative positive altitude gain of the two routes named "Kungsbacka" and "Landvetter" respectively. The positive altitude gain is calculated using the road gradient signal sampled through ETAS INCA, it is therefore considered an approximation. Having a GPS signal would result in a much more accurate value. Therefore, it was not possible to check for the maximum altitude gain limit specified by the legal documents.

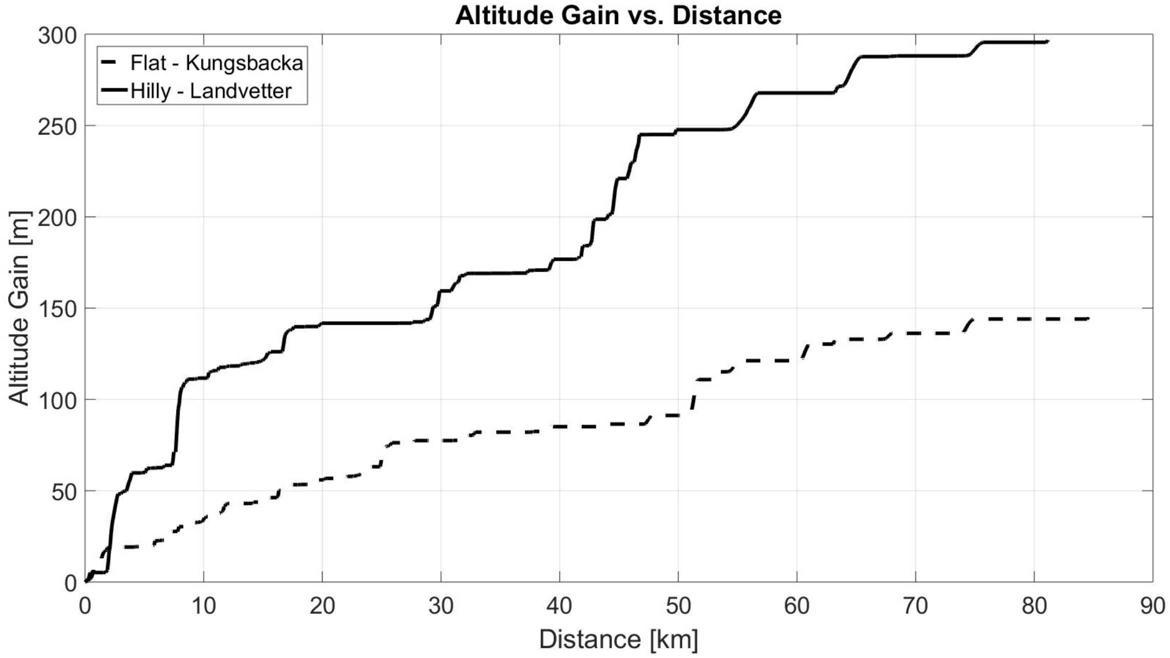


Figure 5. Comparison in Positive Altitude Gain for the Two Routes.

2.4. On Road Testing

The tests were carried out on a Volvo XC90 T8. Since the vehicle has two separate tailpipes, one on each side, a structure was attached to the towing hook of the car. This structure merged the tailpipes using flex pipes to a vertically oriented pipe. The measuring probe is attached to the vertical pipe and straight into the diluter. The gases are diluted and lead through a plastic flex pipe to the MSS device in the trunk of the vehicle. To power up the devices, a 230 V gasoline generator is mounted to the structure. The structure on the car can be seen in figure 6.

Figure 6. Test Vehicle with Mounting Structure.

Note that the MSS device was unavailable the time the picture was taken therefore the diluter is not shown in figure 6.

2.4.1. Micro Soot Sensor

The AVL Micro Soot Sensor used in this thesis bases its measurement on the photoacoustic measurement method. The particles in the exhaust, i.e. the soot, are exposed to modulated light which these dark particles strongly absorb. This leads to a periodical change in temperature of the particles leading to the expansion and contraction of the carrier gas, i.e. the exhaust sample. The expansion and contraction of the gas generates a sound wave which in turn is detected by microphones. Since clean dilution air does not contain particulate matter it generates no signal. However, when it is mixed with exhaust and soot, the signal rises proportionally to the amount of mass concentration of soot in the sample. [16]

To begin with, the dilution factor is decided for each run. The dilution factor is the amount of dilution for each sample i.e. a factor of 3 means that the sample would be mixed with air such that it is 3 times larger. This factor decided by testing with different values for the two extremes, i.e. the hilly-aggressive cycle and the flat-calm cycle. The goal is to have a dilution factor that gives exhaust soot concentration values between 1 and 10 mg/m^3, this is to avoid noise in the readings. With this in mind, the dilution factor for calm and normal driving on the flat route is set to 2. It is set to 3 for aggressive driving on the flat route and for the calm and normal driving on the hilly route. Finally, for the hilly route and aggressive behavior the dilution factor is set to 4.

2.4.2. ETAS INCA

While the MSS is used to sample soot concentration, additional relevant data is gathered using ETAS INCA. INCA is used to collect all the predetermined CAN-signals from the ECU and other electronically controlled systems in the vehicle to analyze the outcome of the tests.

Table 7. INCA and MSS Signals

ETAS INCA		
Signal	**Unit**	**Sampling Frequency**
Acceleration	m/s^2	100 Hz
Velocity	m/s	100 Hz
Road Gradient	rad	100 Hz
Torque Request	Nm	100 Hz
Engine Run Request	-	100 Hz
State of Charge (SoC)	%	100 Hz
Lambda	-	100 Hz
Fuel Consumption	mg/sample	100 Hz
Time	s	100 Hz
AVL Micro Soot Sensor (MSS)		
Signal	**Unit**	**Sampling Frequency**
Exhaust Soot Concentration	mg/m3	5Hz
Dilution ratio	-	5Hz
Time	s	5Hz

Table 7 shows the most relevant signals collected during the test both using the MSS and the INCA software. The MSS signals and INCA signals are sampled with different frequencies. Therefore, to be able to compare the data and make relevant plots, the MSS signals are linearly interpolated to the same size as the INCA signals. This is done using the MATLAB function interp1 for each run. Using these signals additional data was calculated such as power request and distance. The calculations of this can be found in section 2.5.

2.4.3. AVL InVehicle

To make sure that the RDE criterions will be fulfilled during the test, AVL InVehicle App is used. This app is installed on the same computer as the INCA software and uses the pedal position and vehicle speed signals from INCA to, in real-time, determine RDE compliance with respect to the dynamic requirements. The app installed on the INCA laptop also has a useful feature which is the ability to mirror all the data and graphs on to a smartphone using mobile hotspot, this makes it easier for the driver to follow the progress of the RDE cycle. When doing the test, it is of big importance to visually see the level of aggressiveness in the driving behavior since the aim is to analyze the aggressiveness of the driving, and how this correlate to the pollutant emissions. The AVL In Vehicle App "CalApp" that is used, visualizes this behavior with a line and a number that changes accordingly in the span of the lowest and highest limit of an RDE route, which can be seen with the blue curve in figure 7 and 8. This app visualizes all the RDE criterions such that the driver has an easy understandable interface to look at and adjust the driving behavior such that all criterions will be fulfilled with all aspects, such as time, distance, percentage of the three areas (Urban, Rural, Motorway) and number of accelerations greater than 0.1 m/s².

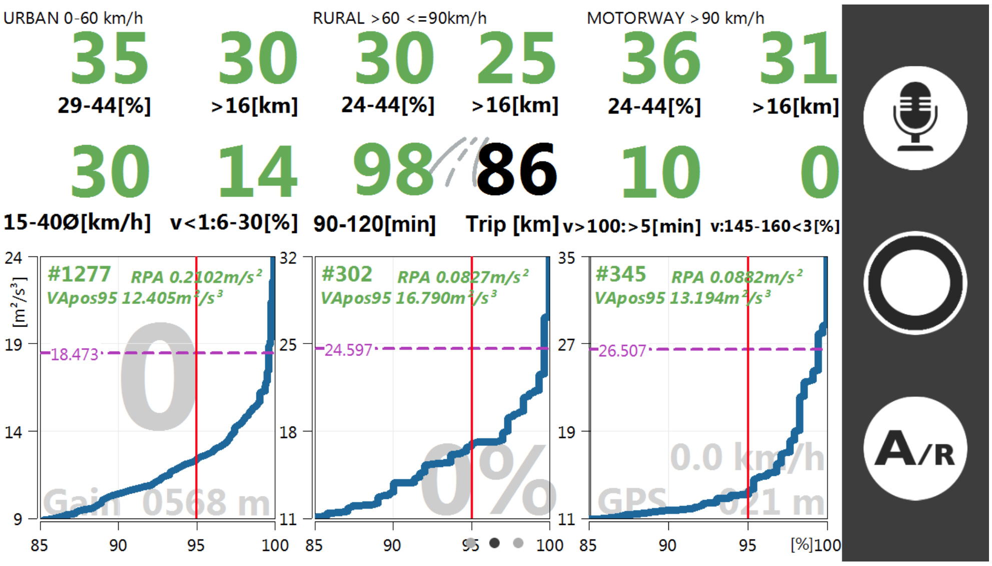


Figure 7. Calm driving behavior, Flat Route.

Where the blue curve crosses the purple line shows the level of aggressiveness and the value of "VApos95" is the value of where the blue curve crosses this line. The value on the purple line is the maximum value of VApos95 that is allowed before the test becomes "too aggressive". The blue line has to cross the purple line between the right side of the graph and the red line. The closer to the red line, the more aggressive is the driving behavior and the closer to the right side, the more conservative is the driving behavior. Since this app was still in development during the time of this thesis, an agreement were able to be made with AVL to give them feedback on the performance of the app in exchange for a free license. It is however intended to be sold in packages upon full release. The "CalApp" interface can be seen in figure 7 and 8.

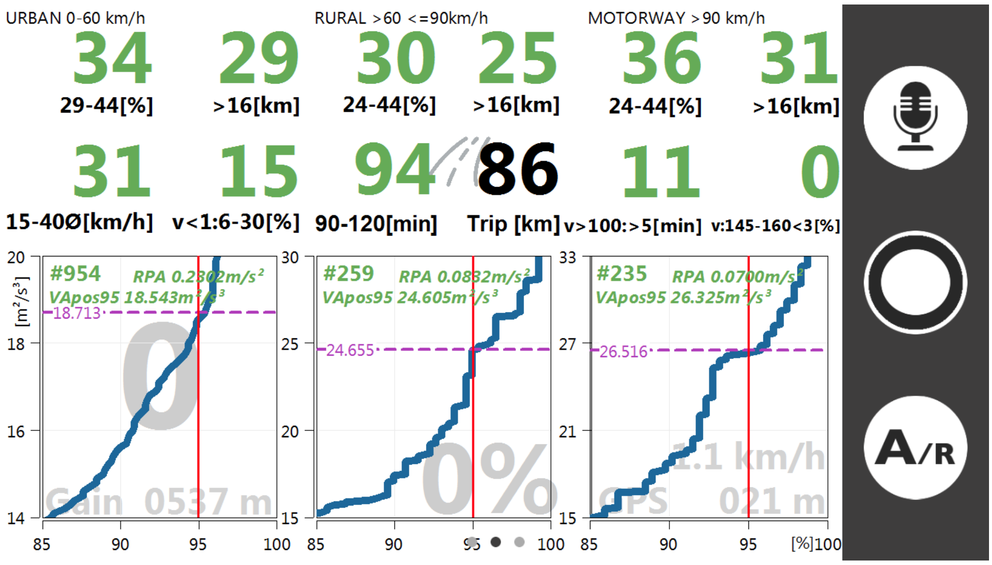


Figure 8. Aggressive driving behavior, Flat Route.

Figure 7 illustrates the calm driving behavior while figure 8 illustrates the more aggressive driving behavior. The RDE criterions of the route is fulfilled when everything has turned green. On the right side of figure 7 and 8, one can see a big white dot. This button is pressed by the driver when the measurements shall start, and the button turns red to indicate that the measurements are ongoing. When the route is done, the driver presses the same button and the measurements stops and the data gets saved to a predefined location. The driver can also record a voice message if something happens during the route. This voice message is then saved at the location of the route of where it was recorded to easily follow up on where in the route something happened.

The three percentage values (above 29-44[%], 24-44[%], 24-44[%]) in the upper part of figure 7 and 8 represents the driven distance of each part (urban, rural, motorway) of the total travelled distance. The values above ">16[km]" indicates the driven distance for each part of the route. In the urban part, one has to drive with a velocity of <1km/h for 6-30% of the total urban distance travelled, and must have an average speed between 15-40 km/h. According to the RDE legislation, the route has to be within 90-120 minutes, and the big black number shows how long the total distance travelled is. When performing the motorway part of the route, one must drive at a speed above 100 km/h for more than a total time of 5 minutes and is not allowed to drive in the speed range between 145-160 km/h for more than 3% of the total distance of the motorway part, which on the Swedish roads is not even possible due to speed limits. The number zero that can be seen in the left window of figure 7 and 8 indicates the real time velocity. This number changes between the three windows accordingly to which part of the route one is performing at the moment. The percentage number that is visible in the middle window shows how much, in percentage, the acceleration pedal is pressed. The x-axis in the graphs shows the percentile, which the red line indicates the 95th percentile that is used when calculating the VApos95.

In addition to conducting RDE cycles, a WLTC run is performed. This is to compare the on-road testing with one that is performed in a test cell. This test was conducted at Volvo Cars Corporation by professionals.

Before the initiation of the RDE test procedures, Original Equipment Manufacturers (OEM)s performed NEDC test to prove that their vehicles were compliant with the emissions legislation. The NEDC is now replaced with the WLTC that is designed in such a way that will represent the real world driving behavior in a more accurate manner. [17] The differences between the NEDC, WLTC and one of the test routes is shown below in figures 9, 10 and 11, where the two lines in figure 11 represents the speed limits 60 km/h and 90 km/h, i.e. the switch from urban to rural and from rural to highway.

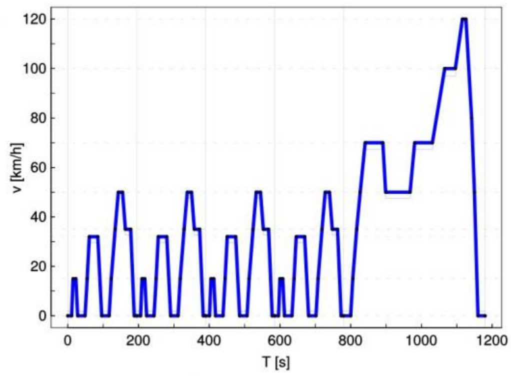


Figure 9. NEDC.

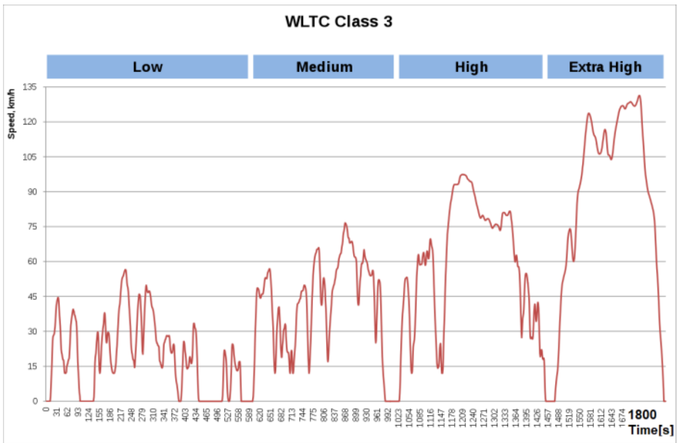


Figure 10. WLTC Class 3. [18]

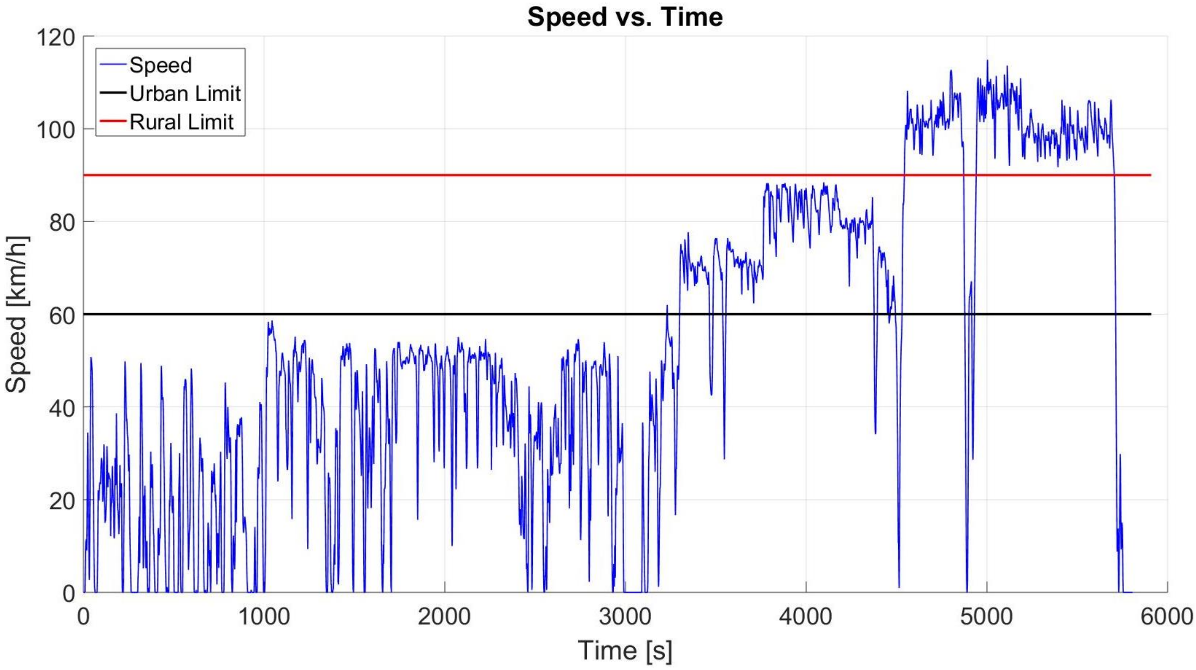


Figure 11. Speed Profile of Test Route "Kungsbacka".

2.5. Post Test Calculations

Since we were not able to measure all the pollutants to be studied, additional calculations were required. These calculations are done to verify the trip dynamics, calculate the CO_2 emissions and convert the soot exhaust concentration to mass

2.5.1. CO_2

These calculations are based on the sampled values of lambda and injected fuel, see table 6 in section 2.4.2. The amount of CO_2 produced is therefore estimated using the fuel oxidation for petrol. The petrol used consists of 10% ethanol and has a hydrogen to carbon ratio of 1.93 that includes the carbon and hydrogen that are within both the hydrocarbons and the ethanol in this fuel. The H/C ratio and the fact that the amount of ethanol in the fuel is 10% (based on weight) yields in the following balanced fuel oxidation reaction.

$$1.97\ \mathrm{O_2} + 0.97\mathrm{CH_{1.87}} + 0.033\mathrm{C_2H_6O} \rightarrow 1.03\ \mathrm{CO_2} + 1.93\ \mathrm{H_2O} + \mathrm{energy}$$

This shows that for every 1.97 moles of O_2, 1.03 moles of CO_2 are produced. The amount of O_2 required is calculated using the sampled lambda and fuel injection values.

$$m_{O_2} = 0.21 * m_{air}\ [mg]$$

Where

$$m_{air} = m_{fuel} * AFR$$

and

$$AFR = \lambda * AFR_{stoich}$$

The stoichiometric air to fuel ration (AFR_{stoich}) is assumed to be 14.7 which is a typical value for petroleum.

Using the molar weights of CO_2 and O_2 together with the oxidation reaction presented above, the CO_2 emissions are calculated using the following relation:

$$m_{CO_2} = \frac{1.03 * 44}{1.97 * 32} * m_{O_2} [mg]$$

Keep in mind that these calculations are highly approximate since the boost pressure is not considered and that the lambda is varying throughout the test. The air in to the combustion chamber gets a higher density when boost pressure is taken in to account. Depending on the boost pressure and the lambda value these calculations might either be slightly higher or slightly lower. Additionally, these calculations assume perfect reduction of NO_X and CO in the catalytic converter to CO_2.

2.5.2. Soot

Since the MSS device measure soot concentration i.e. mg/m^3 the exhaust volume must be calculated in order to derive the total soot emission. The exhaust mass is calculated using the law of conservation of mass.

$$m_{exh} = m_{air} + m_{fuel} [mg]$$

Note that the MSS measures only the gaseous portion of the exhaust and while the exhaust system temperature is still low, a portion of the exhaust is condensate. However, the temperature of the exhaust system rises quickly which means that this effect is only relevant for the first few minutes after the first time the engine starts and can therefore be neglected. Having the exhaust mass, the exhaust volume is calculated using the exhaust density. The exhaust density is assumed to be equal to the ambient air density. This assumption is made due to the lack of data for the exhaust temperature and pressure. Hence, the exhaust volume is:

$$V_{exh} = \frac{m_{exh}}{\rho_{air}} [m^3]$$

2.5.3. Verification of trip dynamics

After a conducted cycle, the excess and absence of dynamics during urban, rural and motorway driving must be determined. Since the trip dynamics are already checked during the test, as seen in figure 7 and 8, these calculations are done for analytic purposes. As mentioned before, the RDE legislation states that the driver aggressiveness must be within a certain limit. The driver behavior must neither be too aggressive nor too calm. Based on the Official Journal of European Union, the driver aggressiveness is measured as the 95th percentile of the velocity multiplied by the positive acceleration[3]. The positive acceleration is defined as:

$$a_{pos} = a > 0.1\ \left[\frac{m}{s^3}\right]$$

The velocity which correspond to each positive acceleration defined above is then extracted and $v*a_{pos}$ is calculated. The 95th percentile is then calculated by assigning percentile values for each value of $v*a_{pos}$. The lowest value gets the percentile $1/M_k$, the second lowest value gets the percentile $2/M_k$ etc. until the highest value M_k/M_k where M_k is the number of samples with positive acceleration as per definition above and k is the index for urban, rural and motorway[3].

$$va_{pos95} = \frac{\left(v * a_{pos}\right)_{i,k}}{M_k} = 95\%$$

3. Results

This section presents the results of the RDE tests that were conducted during the project. The data is presented in the following tables. Since the MSS was not available during the time the Stenungsund tests were conducted, data for soot emission for these tests are missing. Therefore, it is decided not to include these tests in the emission analysis but only in the analysis of driver influence. To clarify, the test names are derived as Route - Driver name - Driving mode - Behavior. For example, the test called ALHA is basically Altitude(Hilly)-Ludvig-Hybrid-Aggressive.
Note that the WLTC test is conducted with NEDC loads which vary significantly from the actual WLTC load. This is why the deviation from the conducted WLTC test results and the RDE test results is large.

Table 8. Soot emission [mg/km]

Route	Experiment	Full cycle	Urban	Rural	Motorway
Flat route "Kungsbacka"	**FLPC**	0.49	0.47	0.46	0.51
	FLHC	0.46	0.48	0.47	0.44
	FMPN	0.74	0.89	0.7	0.65
	FMHN	0.77	0.72	1.01	0.61
	FLPA	1.00	0.78	0.69	1.43
	FLHA	0.93	1.20	0.72	0.85
Hilly/Altitude route "Landvetter"	**ALPC**	0.56	0.43	0.52	0.69
	ALHC	0.53	0.52	0.59	0.50
	AMPN	0.74	0.51	1.19	0.44
	AMHN	0.83	0.88	1.10	0.55
	AMPA	0.63	0.82	0.56	0.59
	ALHA	1.06	1.40	0.89	1.01

Note that even though there is a significant difference in soot emissions between the various aggressiveness levels (as can be seen in table 8), the soot values are still below the legal limits of 4.5 mg/km.

Table 9. CO_2 emissions [g/km}

Route	Experiment	Full cycle	Urban	Rural	Motorway
Flat route "Kungsbacka"	**FLPC**	221.10	219.30	218.87	224.44
	FLHC	230.10	240.06	231.72	220.16
	FMPN	240.73	250.98	235.08	236.59
	FMHN	229.72	231.58	238.34	221.25
	FLPA	235.62	259.76	217.55	228.92
	FLHA	232.50	246.35	231.08	221.56
Hilly/Altitude route "Landvetter"	**ALPC**	225.70	251.70	233.41	201.59
	ALHC	214.85	239.31	213.66	200.29
	AMPN	230.70	238.89	229.57	226.54
	AMHN	235.53	269.30	234.34	215.02
	AMPA	217.25	227.93	200.83	226.22
	ALHA	236.10	269.18	225.94	224.69
	WLTC	167.61	-	-	-

Table 10. Fuel Consumption [l/100km]

Route	Experiment	Full cycle	Urban	Rural	Motorway
Flat route "Kungsbacka"	**FLPC**	13.3	13.1	13.2	13.7
	FLHC	13.9	14.4	14.0	12.2
	FMPN	14.5	15.0	14.1	12.3
	FMHN	13.9	13.8	14.4	13.1
	FLPA	14.2	15,5	13.1	13.7
	FLHA	14.1	14.9	14.0	13.7
Hilly/Altitude route "Landvetter"	**ALPC**	13.6	15.0	14.1	13.5
	ALHC	13.0	14.3	12.9	13.4
	AMPN	13.9	14.3	13.9	14.0
	AMHN	14.2	16.1	14.2	13.6
	AMPA	13.1	13.7	12.1	13.4
	ALHA	14.3	16.1	13.7	14.4
	WLTC	7.48	-	-	-

4. Analysis

This section includes an analysis to identify the effects of the various factors on the results of the conducted RDE cycles.

4.1. Driver Influence

To find the influence of the driver on the results of the RDE cycles, the pre-designed VCC RDE route "Stenungsund" is used. This route is used by Volvo Cars Corp. for certificates and is known to be valid with respect to the RDE requirements. By having the two drivers conduct the cycle once for each level of aggressiveness and keeping all other factors constant i.e. hybrid driving mode and same route, the influence can be determined. Regardless of the magnitude of driver influence, the driver is not chosen to be a factor as mentioned previously. This is mainly to decrease the number of required tests by 50%. Using the aggressiveness measure defined in section 2.4.3 the difference between the two drivers can be determined. The va_{pos95} for the six tests conducted are presented in table 11. The "Difference L/M" shows the difference in percentage between the two drivers and "Difference A/C" shows the difference between the aggressive and calm driving behaviors.

Table 11. Driver influence

	SLHA	SMHA	SLHN	SMHN	SLHC	SMHC
$Va_{pos95}\left[\frac{m^2}{s^3}\right]$	23.74	21.08	18.54	18.84	16.91	13.37
$Difference\ \frac{L}{M}$ [%]	+12.6		-1.59		+26.5	
	(SLHA+SMHA)/(SLHC+SMHC)					
$Difference\ \frac{A}{C}$ [%]	+48					

As can be seen in Table 11, the influence of driving behavior is larger than the influence of the driver which means that the driving behavior has a greater importance. Thus, justifying having the driving behavior as a factor instead of the driver. The variation in va_{pos95} is not only affected by the driver per se. There are multiple additional factors that influences the aggressiveness such as weather condition, traffic situation, driver focus and attention. It is not feasible for a single driver to replicate the same driving behavior in two different tests let alone replicating the driving behavior for one driver by another. However, for a deeper and more accurate result to be obtained, one should account for the driver as well. The inclusion of exact replicas of cycles i.e. same driver and same factors would give a better representation of the driver influence since the influence of random factors could be decreased and the mean values could be used.

4.2. RDE cycles vs WLTC test with NEDC load

As has been mentioned, a WLTC is conducted to compare the on-road tests with data from a laboratory test cell. The CO_2 mass per km and fuel consumption in liter per 100km for the WLTC test and RDE tests are presented in table 9 and 10. Figure 14 illustrates the CO_2 emissions vs the fuel consumption for the various tests.

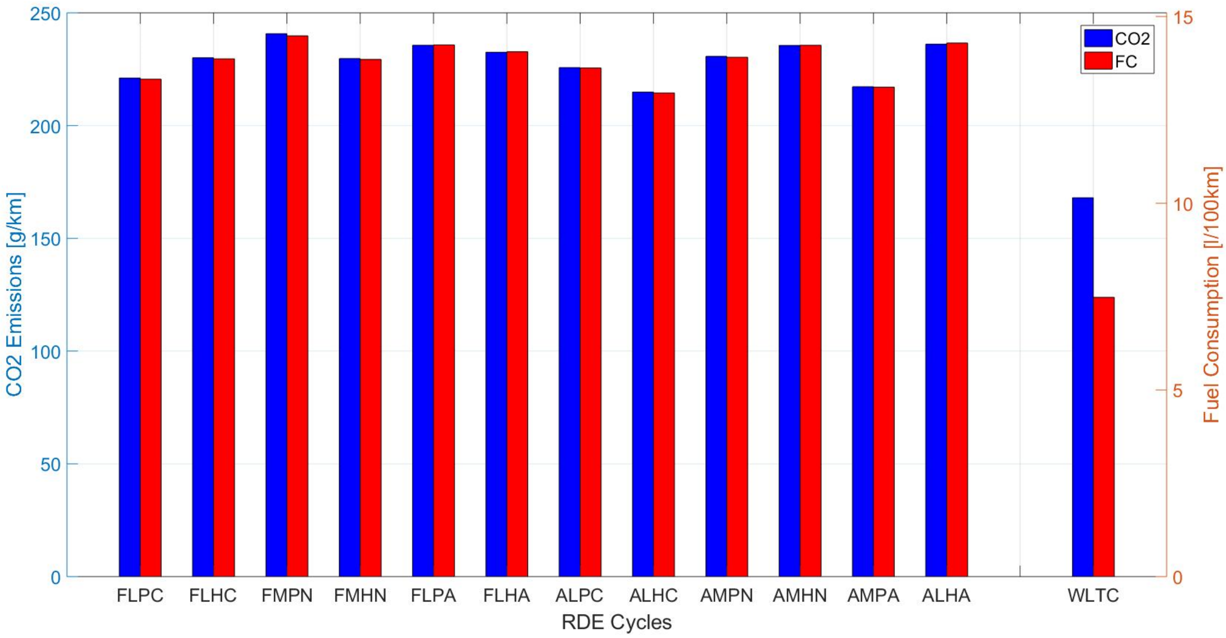


Figure 12. CO_2 emissions (blue bar) and fuel consumption (red bar) for all the RDE cycles in addition to the WLTC test.

Figure 12 shows a significant different between the values of the RDE tests and the WLTC test. The CO_2 and fuel consumption values from WLTC are 60% and 54% respectively of the average fuel consumption from the RDE tests. This is due to the test being performed with the loads from the NEDC test cycle, which the test vehicle is certified with. If the WLTC loads would have been applied, the emissions and energy used would be similar to the RDE tests. However, the values from the WLTC cycle would still be lower than those of the RDE tests since it is performed in a test cell where the road inclination is at constant zero and the velocity profile is much smoother than in real world traffic in addition to the lack of general dynamics such as turns. While performing the RDE tests the AC system and radio is turned on which they are not during the WLTC test. All the afore mentioned factors result in less torque which leads to less emissions and fuel consumption. Note that the fuel consumption and CO_2 emission values for between the RDE tests follows the same trend whereas it is different for the WLTC test values. This is because the CO_2 emission values for the RDE tests are derived using the fuel consumption in contrast to the WLTC results where the values are measured.

4.3. Effects of Driving Behavior

The aggressiveness of the driving behavior can be measured with the measure $v{*}apos_{95}$, which a kind of indication of the requested effect and the smoothness of the driving behavior. $v{*}apos_{95}$ is the value of what to follow to achieve the three different levels of driving behavior. This variable was followed by looking at its graph in real time for each part of the route as described in section 2.4.3. The $v{*}apos_{95}$ value for the RDE tests are presented in table 12.

Table 12. Aggressiveness variables, $v{*}apos_{95}$.

Test	$v{*}apos_{95}$ [m^2/s^3]			
	Urban	Rural	Motorway	Total
FLPC	13.75	20.08	23.11	18.27
FMPN	15.93	19.78	18.98	18.01
FLPA	20.01	25.49	34.74	24.51
FLHC	13.36	16.92	19.45	16.03
FMHN	16.01	17.36	18.82	17.26
FLHA	21.80	19.99	24.29	22.05
ALPC	13.29	20.75	20.70	18.57
AMPN	14.96	19.20	18.15	17.37
AMPA	19.75	23.46	17.42	20.53
ALHC	13.16	19.40	19.37	17.13
AMHN	18.12	22.74	18.66	20.15
ALHA	21.40	25.71	31.31	24.62

From $v{*}apos_{95}$, in table 12, one can see that the highest values are for the aggressive RDE cycles. In the urban part, the increase in $v{*}apos_{95}$ is clear with the increase of aggressiveness. However, it is not as clear a difference between the calm and normal driving behavior and the normal and aggressive behavior in the urban and motorway parts. During these two parts, less sample points are gathered in comparison to the urban part. Due to this, even a single sample with slightly aggressive acceleration, for example when entering the rural part or the motorway, has a large impact on the overall dynamics of the part and can make the change between calm and normal driving (or normal and aggressive driving) behavior according to this $v{*}apos_{95}$ value.

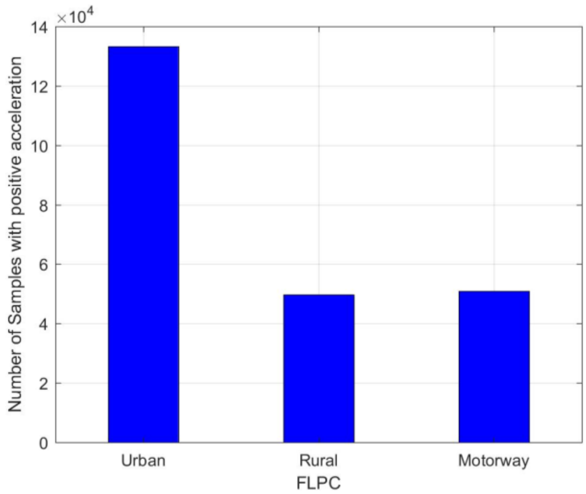


Figure 13. Number of samples Used for the Calculation of $v{*}apos_{95}$ in the Three Parts of FLPC.

Figure 13 illustrates the number of positive acceleration samples in the various parts of FLPC. These samples are used to calculated $v{*}apos_{95}$. The figure shows that the number of samples is almost triple that of the rural and motorway parts. This trend is similar for all RDE tests.

To analyze how the emissions are affected by the driving behavior, number of engine starts, $v{*}apos_{95}$ and 95th percentile of the requested power is plotted. Through this section, 4.3 Effects of Driving

Behavior, the colors will indicate the level of aggressiveness. Blue represents the calm behavior while pink and red represents Normal and Aggressive respectively. The bars grouped to the right are the altitude (hilly) routes and the rightmost bars in the two groups represents hybrid mode.

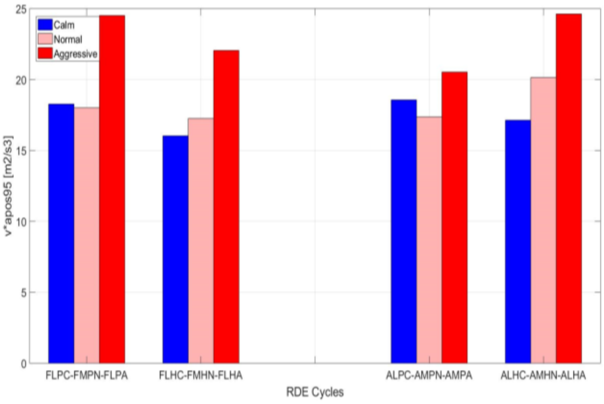


*Figure 14. v*apos$_{95}$.*

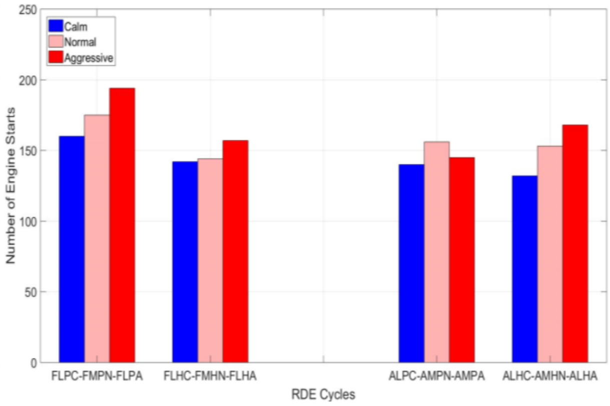


Figure 15. Number of engine starts.

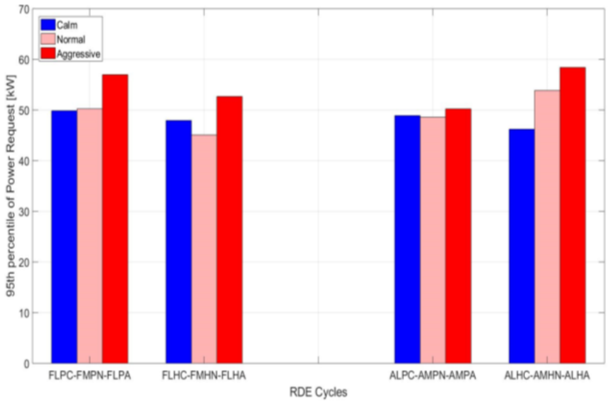
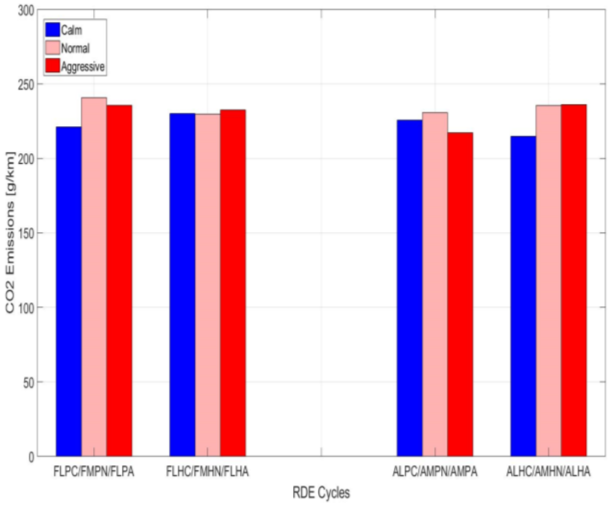


Figure 16. 95th percentile requested power, behavior comparison

Figure 14 shows that the requested power is highest for all the tests that are performed with the aggressive behavior. The calm and normal tests are harder to distinguish since there is a minimum level of aggressiveness which cannot be crossed, thus these two levels of behavior can be somewhat alike. Here, the 95th percentile of the power request is used to see this correlation with the 95th percentile of v*apos, see figure 16. Observing the aggressive tests, a clear correlation can be detected. When the power request passes the limit of what the electric powertrain can deliver, the propulsion switches from electric to combustion. The number of engine starts are therefore presented, in figure 15, to see how often this occurs during a test. The most alike tests to each other, with respect to these three behaviors, are the hilly ones with pure mode. One can in hilly and hybrid mode tests see a typical trend from increased aggressiveness in the driving behavior as well as for the flat route performed in pure mode. The more amount of times the engine starts, the more combustion will occur. This is reflected on the amount of soot emitted since it was observed during the tests that a peek occurs every time the engine starts.



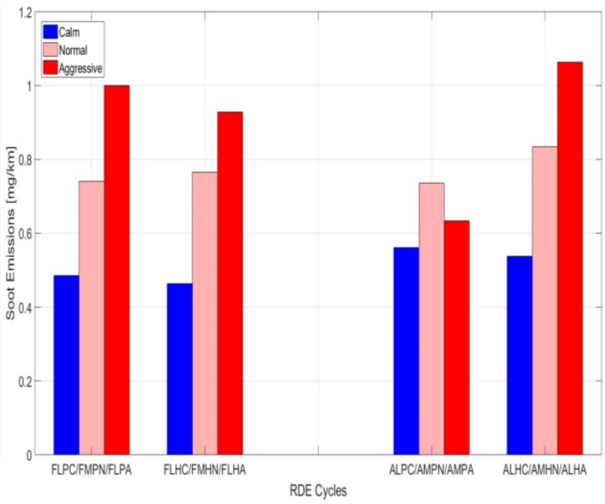


Figure 17.CO_2 emissions [g/km], behavior comparison. *Figure 18.Soot emissions [mg/km], behavior comparison*

By comparing figure 15 with figure 18, a clear relation between the number of engine starts and the soot emission can be identified. With an increased aggressiveness in the driving behavior, there is an increase of emitted soot. Unluckily, there is some kind of error in the test AMPA (Hilly/Altitude Pure Aggressive) that causes less engine starts than the trend prediction of increased engine starts with increased aggressiveness. Figure 17 shows the emitted CO_2, in which can be seen a more even level of amount emitted. There is no tendency of any kind of trend. The CO_2 is, as mentioned in section 2.5.1 CO_2, calculated from the injected fuel, hence this has a correlation to the fuel consumption which in general are quite uniform. The CO_2 is also less sensitive to changes in throttle as compared to the soot emission, which can be seen in figure 19 and 20 that illustrates the change in emissions over distance travelled.

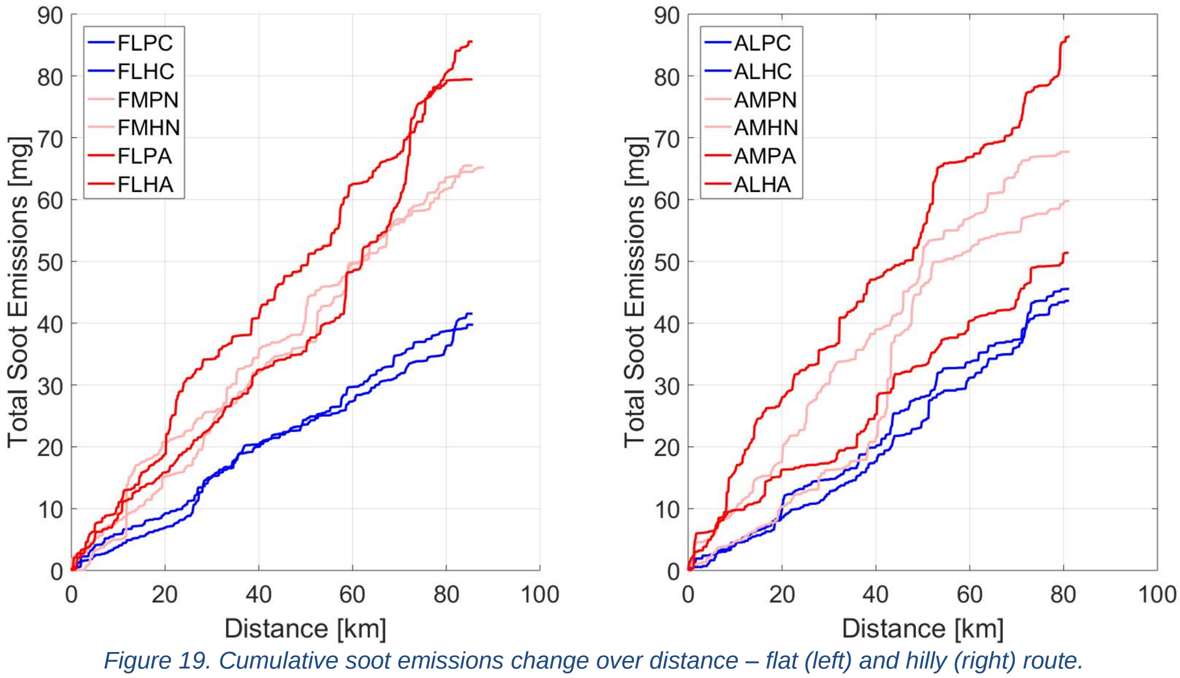


Figure 19. Cumulative soot emissions change over distance – flat (left) and hilly (right) route.

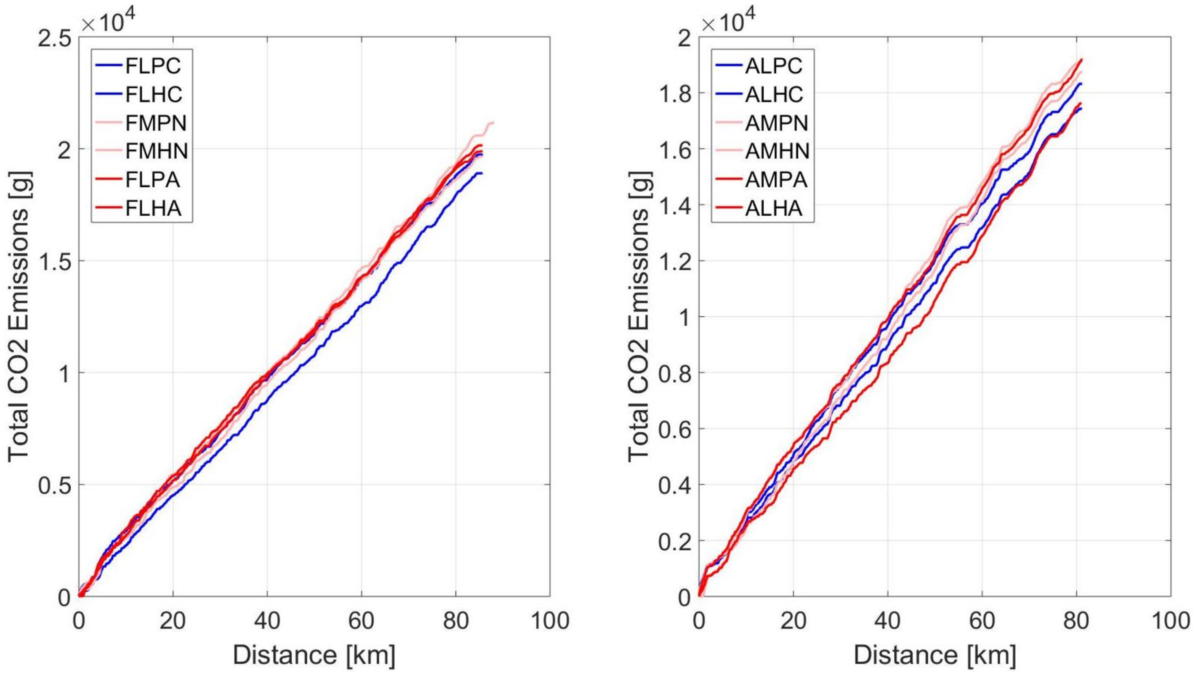


Figure 20. Cumulative CO_2 emissions change over time, flat (left) and hilly (right) route.

4.4. Effects of Driving Mode

4.4.1. Full RDE Cycle

Since the state of charge is at minimum at the start of each experiment, the effects of the driving modes become more unpredictable. Table 13 shows the start and end state of charge for each experiment as well as the fraction of the total distance driven using the electric motor only in addition to the number of decelerations. Note that throughout section 4.4 the red color illustrates the hybrid mode and the blue color illustrates the pure mode in all the plots.

Table 13. Comparison of Various Parameters for the Two Modes for the Full Cycles

RDE Cycle	Start SoC [%]	End SoC [%]	SoC Difference	Fraction distance	Number of decelerations [sample points]
FLPC	20.0	22.5	2.5	0.36	259672
FLHC	18.6	23.1	4.5	0.30	238094
FMPN	20.5	24.0	3.5	0.35	263382
FMHN	18.1	23.3	5.2	0.29	233010
FLPA	19.0	22.6	3.6	0.33	244130
FLHA	19.9	22.8	2.9	0.27	269205
ALPC	17.0	23.7	6.7	0.37	258408
ALHC	18.0	23.3	5.3	0.32	256850
AMPN	19.8	23.9	4.1	0.30	289411
AMHN	18.1	23.1	5.2	0.25	263361
AMPA	19.7	23.4	3.7	0.37	256015
ALHA	18.3	23.0	4.7	0.28	288376

As can be seen in table 13, the number of decelerations is reflected on the fraction distance driven using the electric motor. The use of the electric motor is highly dependent on the amount of braking in each experiment which is the only source of electricity into the HV battery, since the charge feature is turned off. As mentioned in section 2.1.2, using the pure mode means that the electric motor is used as much as possible which can be seen in the difference between the start SoC and end SoC. This difference is less for the experiments conducted using the pure mode compared to the ones using the hybrid mode. However, this does not necessarily mean less emissions which will be shown later in this chapter.

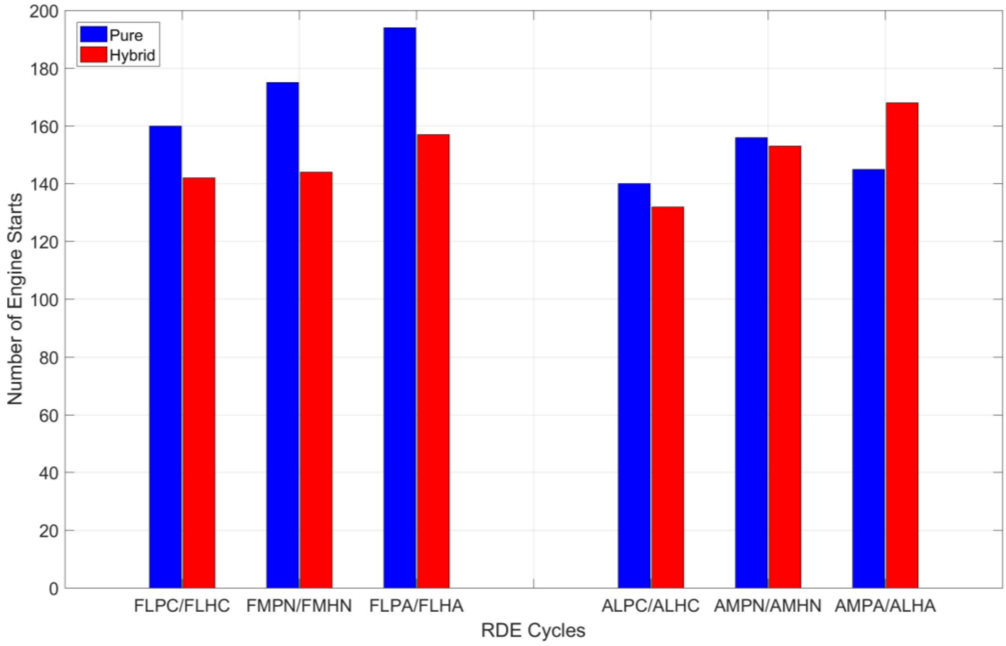


Figure 21. Number of Engine Starts for All RDE Cycles (Full Cycles)

Since the battery SoC is generally low, the switch between the use of the ICE and the electric motor is more frequent during pure driving compared to hybrid driving as the electric motor is used as soon as there is enough charge in the battery until its fully. The pure mode has a higher threshold of power request before switching to the ICE whereas the hybrid mode utilizes the use of the electric motor such that it is used at lower loads making the charge last longer. This behavior is shown in figure 21 where the number of switches to the ICE is generally higher for the pure mode especially for the flat route (left bars). This behavior is not as clear for the experiments conducted on the hilly route (right bars). This is due to the fact that the engine start is not only a function of the state of charge but also of the torque request which is also related to the road inclination, see section 2.1.2. The general increase of the number of engine starts from calm to aggressive is expected since the power request is higher as mentioned in section 4.3.

The cumulative engine run is presented in figure 22 and 23 to see the total use of the internal combustion engine during the test cycle.

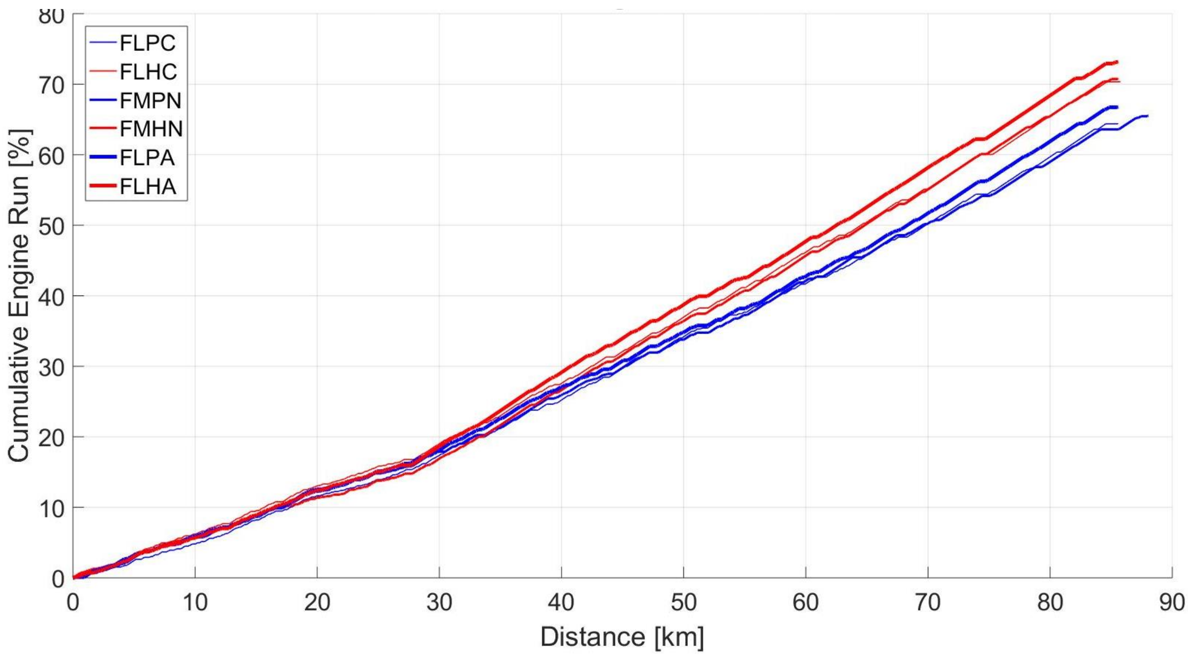


Figure 22. Cumulative Engine Run vs. Distance for Flat Route cycles. Blue is Pure, Red is Hybrid

It is visible in figure 21 that the electric powertrain has a greater contribution overall when pure mode is used compared with hybrid mode. The inclination of the curves becomes steeper at the distance of where the route enters the rural part, at ~27 km. This is an indication that the combustion engine will be used more frequently when the velocities are higher.

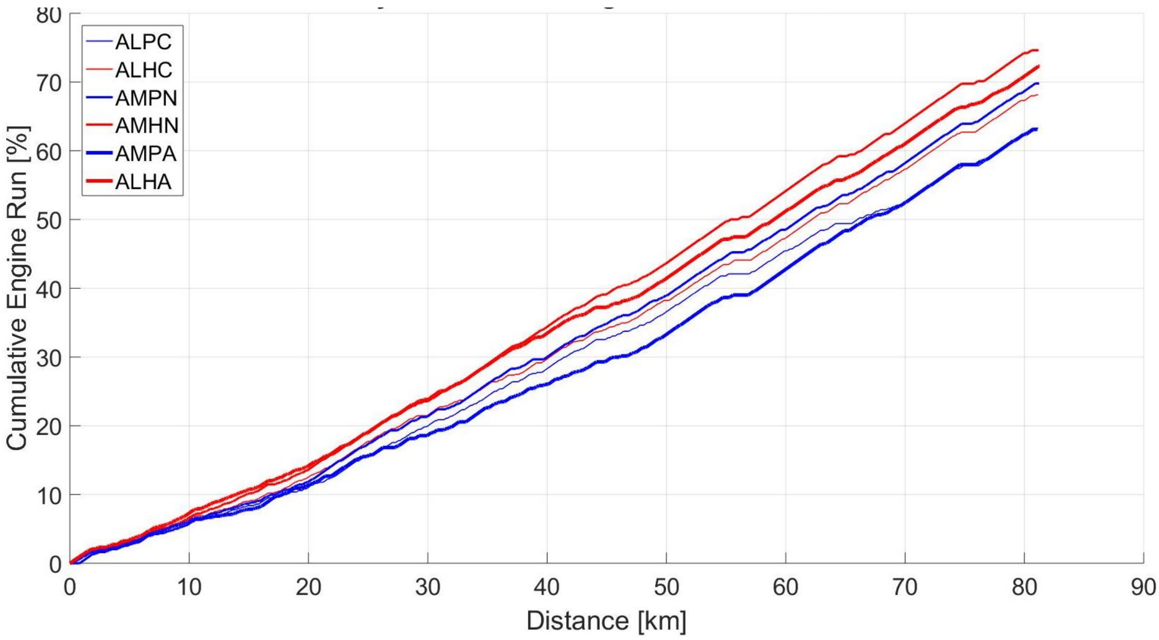


Figure 23. Cumulative Engine Run vs. Distance for Hilly Route cycles. Blue is Pure, Red is Hybrid

The graphs show that the total usage of combustion engine is higher for hybrid mode than for pure mode. However, at which speeds the electric motor is used plays a large role in the total emissions for an RDE cycle. Using the electric motor in the motorway part is more beneficial than in the urban part as the emission magnitudes are higher which is not clear in the graphs in figure 21 and 22.

To investigate what effect driving mode has on emissions, the CO_2 and soot emissions per kilometer driven are plotted in figure 24 and 25 respectively. What these histograms highlight are the emission levels between the hybrid and pure mode for each identical cycle i.e. identical factors except for the driving mode. Consequently, each pair of bars is the same cycle except with different driving modes.

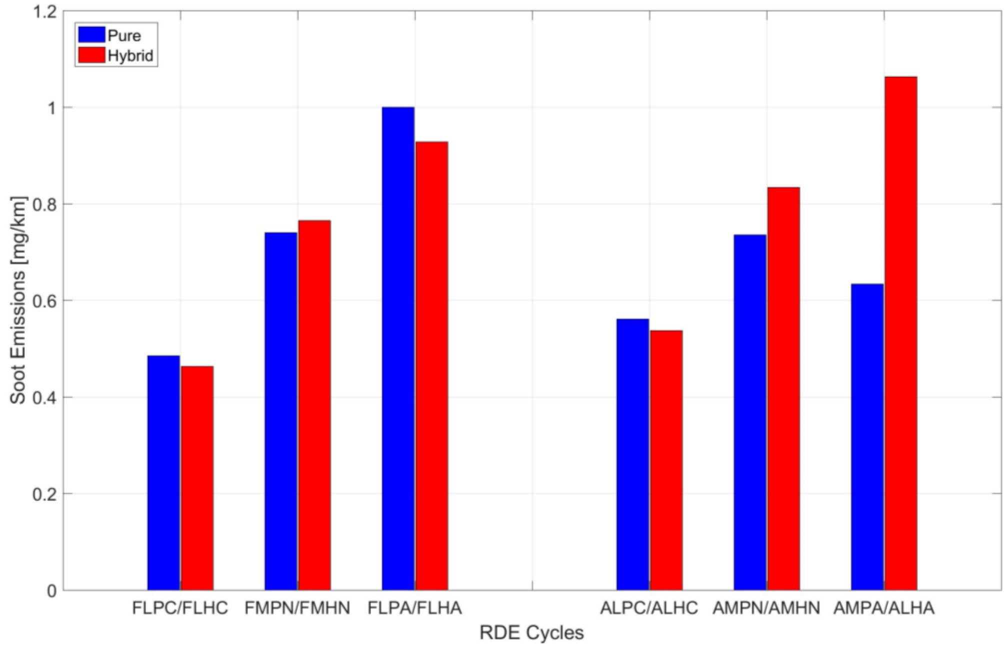


Figure 24. Comparison of Soot Emission Between all RDE Cycles (Full Cycles). Right Group is Hilly Route cycles and left group is Flat Route cycles.

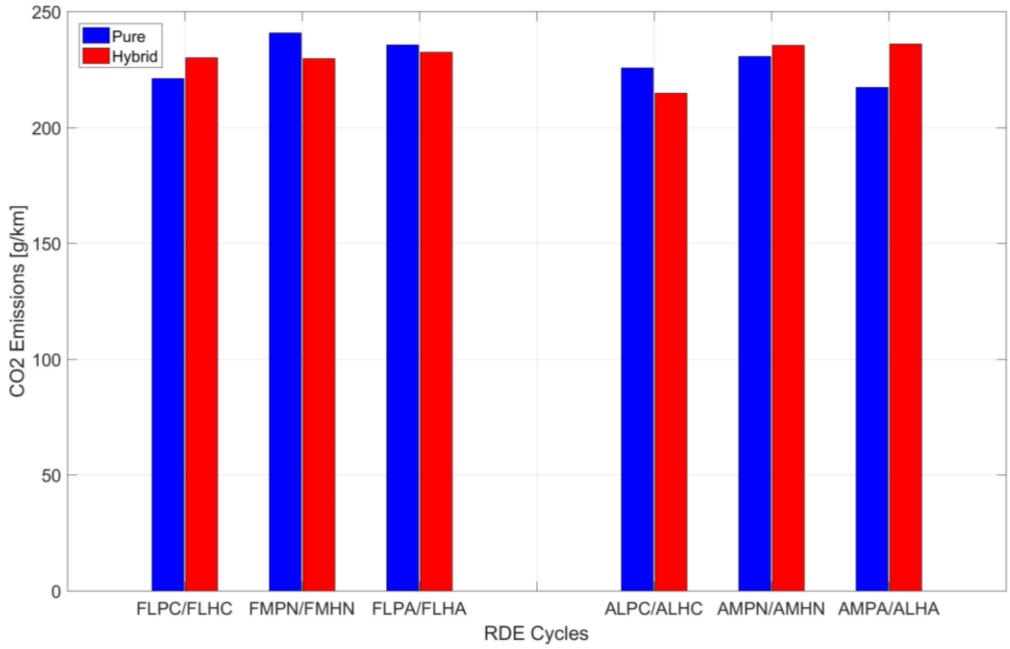


Figure 25. Comparison of CO_2 Emission Between all RDE Cycles (Full Cycles). Right Group is Hilly Route cycles and left group is Flat route cycles.

The amount of emissions is very similar for the two modes except for some outliers. What can be seen in figure 24 and 25 is that the emission values follow no obvious trend (except the increase in soot emission due to the driving behavior, see section 4.3). Therefore, observing a single part at a time, i.e. urban, rural and motorway, would give a better understanding of the mode influence.

4.4.2. Urban, Rural and Motorway

Since the effect of the driving mode was unclear when observing the full RDE cycles, the cycles are divided into the three portions specified by the RDE legislation i.e. urban, rural and motorway. Table 14 presents the fraction distance driven using the electric motor for the urban, rural and motorway portions of the RDE cycles.

Table 14. Fraction Distance Driven Using the Electric Motor for Urban, Rural and Motorway

RDE Cycle	Fraction Distance		
	URBAN	RURAL	MOTORWAY
FLPC	0.52	0.28	0.27
FLHC	0.48	0.23	0.19
FMPN	0.49	0.31	0.25
FMHN	0.54	0.19	0.16
FLPA	0.49	0.31	0.21
FLHA	0.50	0.15	0.16
ALPC	0.55	0.31	0.30
ALHC	0.49	0.30	0.22
AMPN	0.52	0.27	0.20
AMHN	0.45	0.19	0.19
AMPA	0.54	0.41	0.22
ALHA	0.42	0.26	0.20

It is clear from table 14 that the urban part has a higher fraction as compared to the other parts. This is due to the lower velocities and power request as compared to the other two parts. Therefore, what little charge gained while driving can be used to a larger extent.

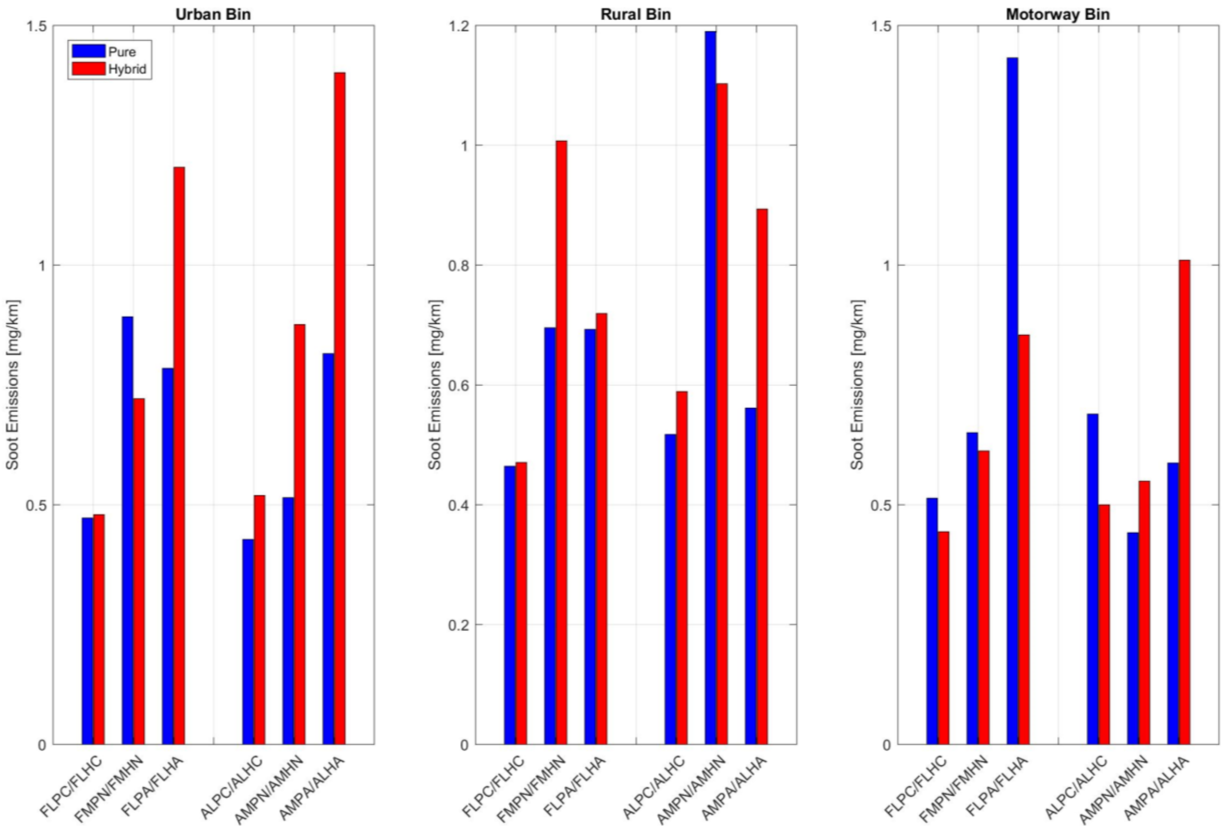


Figure 26.Comparison of Soot Emission Between all the Three Parts Within each RDE Cycles

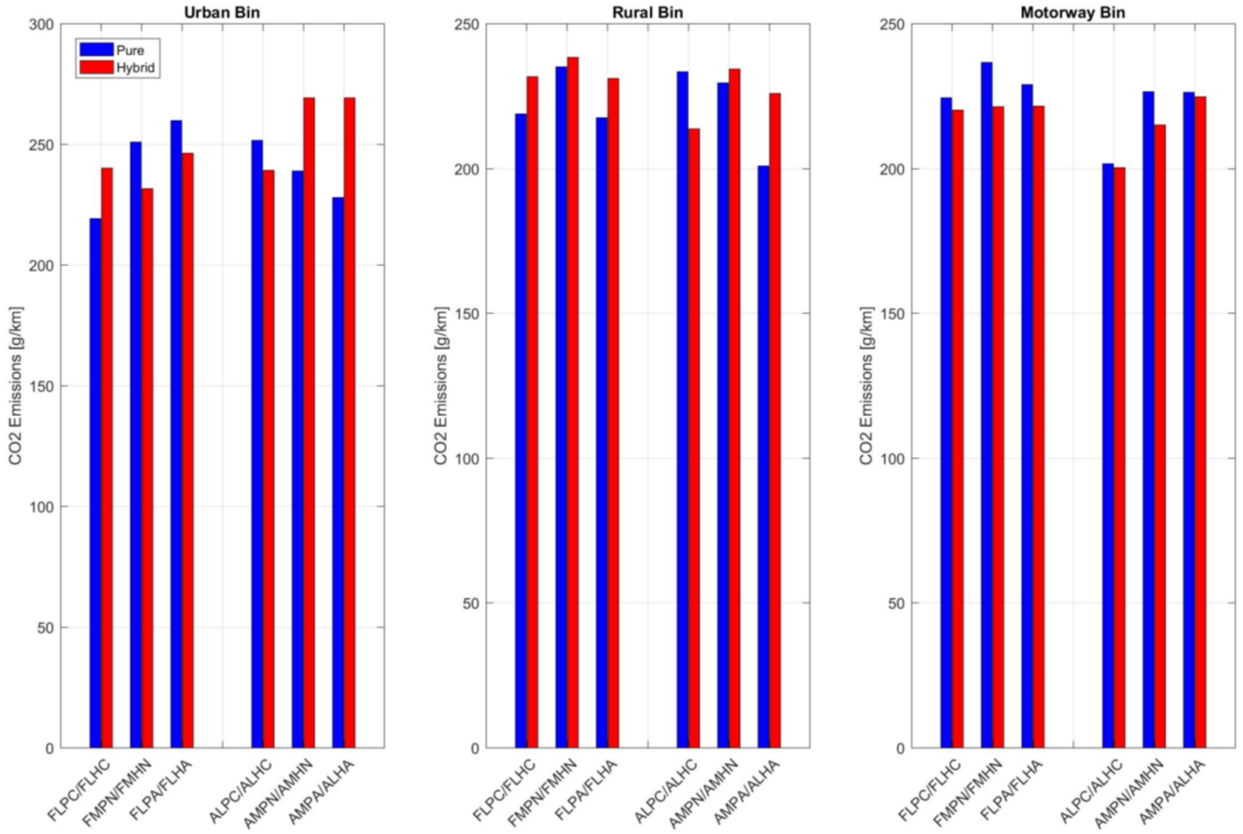


Figure 27.Comparison of CO_2 Emission Between all the Three Parts within each RDE Cycles

The emission values between the pure and hybrid mode for the three parts of each RDE cycle are related to the fraction distance as can be seen in figure 26 and 27 if compared to the values in table 14. Based on the definition of the pure mode, the electric motor is used for longer periods as compared to the hybrid mode. This is possible in the urban part and rural parts due to the relatively low velocities and power request and therefore yields a larger fraction distance which is also reflected on the emission levels. However, in the motorway part, the velocities are high which requires more power. As a consequence, the SoC is drained quickly while using the pure mode. On the other hand, the hybrid mode optimizes the use of the SoC such that it is used as efficiently as possible.

4.5. Effects of Route

With the difference in positive altitude gain, the two routes can be compared. To make it easier for the reader, a copy of figure 5 is presented below.

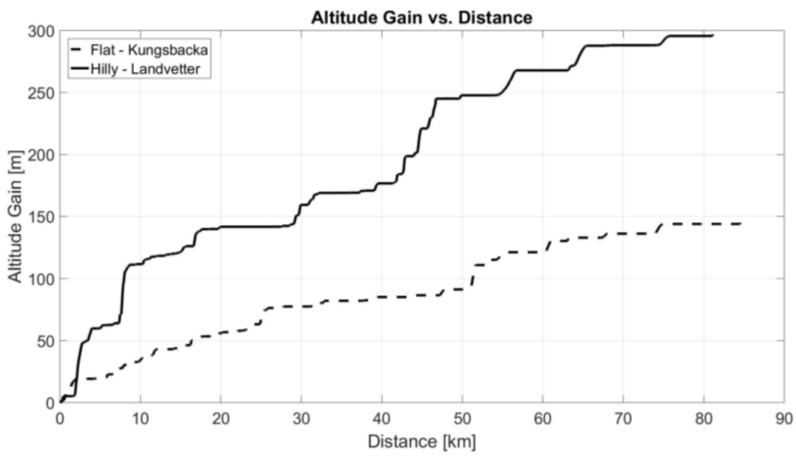


Figure 28. Comparison in positive altitude gain for the two routes.

Figure 28 illustrates the difference between the two routes with respect to the amount of uphill driving. In order to capture the effect of the road inclination by itself, the other factors must be kept constant in the comparison. Therefore, to negate the effects of driving behavior the acceleration must be constant in this analysis. Hence, only the points with positive road inclination and an acceleration of 0.5-0.6m/s^2 will be considered in this section. The reason for using this acceleration interval is that the average positive acceleration for all the RDE tests lies within this interval thus resulting in the most number samples to be used for this comparison. Using a fixed acceleration value is not possible since some RDE cycles does not have a single sample with that specific acceleration. Therefore, using a small interval as described above is as close to having a constant acceleration as possible. To get an understanding of the magnitude of this acceleration, it corresponds a vehicle speed increase of 20 km/h in approximately 10 seconds.

To negate the effect of driving mode, the comparison will be made between each pair of cycles with the same driving mode for example FLPC/ALPC etc. A plot comparing these two cycles would therefore be called Pure Calm etc. To make the analysis easier to follow, only a single pair will be analyzed to determine the effects of the routs, the chosen pair is the Pure-Calm cycles. However, similar plots of the remaining cycles can be found in the Appendix.

The hypothesis is that the average power request should increase with increased road inclination at constant acceleration. This should in turn reflect on the average magnitude of emissions at different inclination where the values are low at low inclination levels and higher at higher inclinations. Even with a catalytic converter with high efficiency, this effect should be visible. This is because higher inclination requires higher power to overcome which means more fuel burnt leading to a larger amount of unfiltered emissions. To verify this hypothesis, the average power request at different road inclination is illustrated in figure 28. Note that the colors blue and red in this section represents flat and hilly respectively.

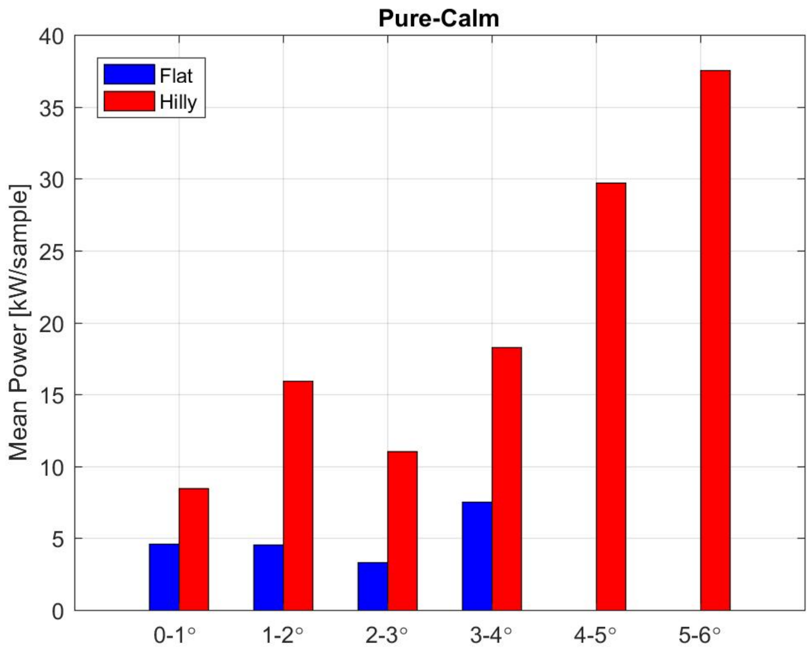


Figure 29. Average Power Request at different inclinations with constant acceleration

Figure 29 shows a clear dependcy between power and road inclination as the average power increases with road inclination. The inclinations here are presented in degrees (°), while on the roads, i.e. on road signs, it is more common to describe it as gradient in %. To get some understanding of these inclination angles; an inclination of 2.3° represent a gradient of 4%, which is a level of steepness that is clear to see and feel. Note that the power illustrated in figure 29 is only that which is delivered from the ICE. At a first glance, it seems that the power request is generally lower for the flat route even at the same road inclinations. However, this plot shows the MEAN power request meaning that a power request of zero (using electric motor) decreases the mean value. To verify this effect, the fraction samples of zero power at the 1-2 degrees interval is calculted. The results show that approximately 80% of the samples are at zero power at the flat route as compared to 20 % at the hilly route. This means that the electric motor is in use thus the mean ICE power per sample is decreased.

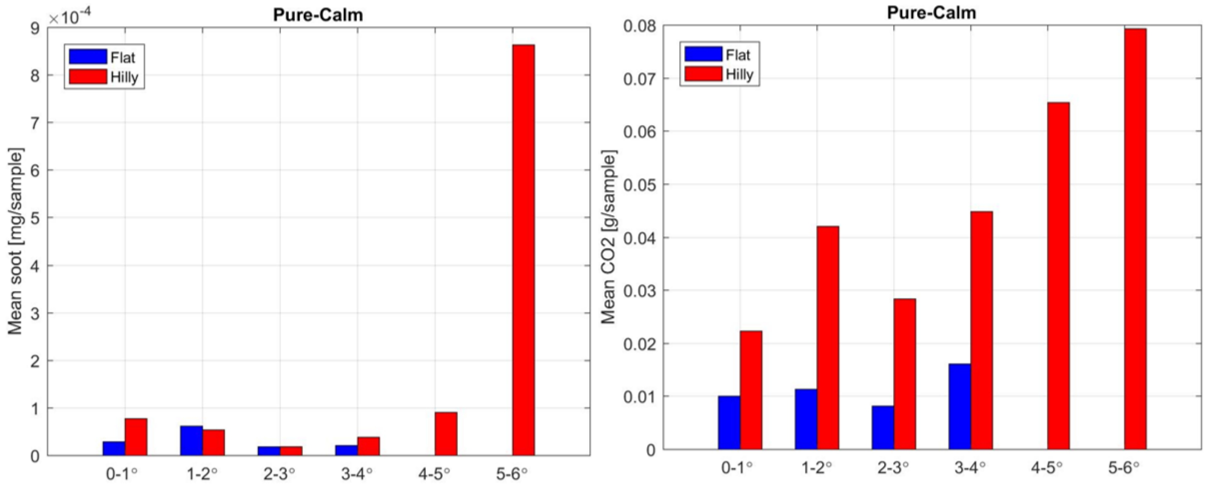


Figure 30. Average Emissions for Different Road Inclinations. Soot (left) & CO_2 (right).

Figure 30 illustrates the average emissions for the pure-calm pair of cycles. The first observation that can be made is that the hilly route reaches steeper angles as there are no sample points for the flat route in the interval 4-6°. The average values of emissions are closely reflected to the power request which is as was expected in the hypothesis. It is obvious that for steeper hills, the power request is increased to maintain a constant speed therefore increasing the CO_2 emission levels. However, no direct correlation between soot emissions road inclination could be found using the test results. As can be seen figure 29, there is a significant increase in soot emissions from the inclination interval 4-5° to 5-6°. This is since the mean value is dependent on both the magnitude of emissions per sample but also the number of samples at a specific angle.

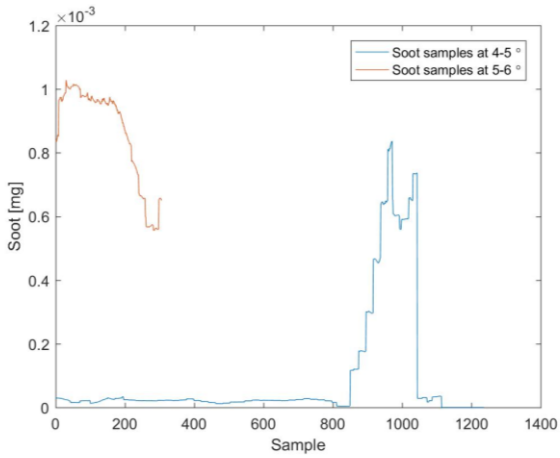


Figure 31. Soot Emissions at Two Different Angles for ALPC.

Figure 31 shows that the angle interval 5-6 results in high levels of soot at a relatively small number of samples. Whereas the soot values are at zero for the most part of the 4-5 interval which decrease the mean value as can be seen in figure 30. This shows that at the lower values, the electric motor is used more often as compared to the steeper inclinations since it can deliver the required power for a longer period even with a low state of charge.

4.6. Correlation Between the Factors

To find a correlation between the factors, a software called MODDE Pro is used. Using this software, the factors and the responses are defined together with their respective values. In general, there are multiple types of factors, but in this study there are only quantitative factors that could be defined. However, there are two types of quantitative factors, one being "Quantitative Multilevel" and the other being "Quantitative". The former is basically defining the factors only as levels. The driver behavior factor would then be 1, 0 and -1. 1 being the aggressive driving, 0 is normal driving and -1 is calm driving and similarly defining the other factors. Using this type of factors did not yield any reasonable correlation. Therefore, quantitative factors are used. This means that the factors are defined as quantities with specific values. Hence, the factors are quantified as follows.

- Route: Total altitude gain [m]
- Mode: Fraction distance driven using the electric propulsion system, i.e. the combustion engine is off.
- Driver behavior: $vapos_{95}$, see section 2.4.3.

The responses are defined as soot mg/km and CO_2 g/km. It is easier to capture the effects of the factors on the responses by analyzing the two extreme parts, i.e. the urban and motorway parts

4.6.1. Urban Part

The effects of the factors on the CO_2 and soot emissions in the urban part are presented in figure 32 and 33. In these plots, the magnitude of the effect is represented by the size of the coefficient i.e. the green area and the effect characteristic is represented by the orientation of the coefficient. If the coefficient is below the zero limit, then the effect is negative and vice versa.

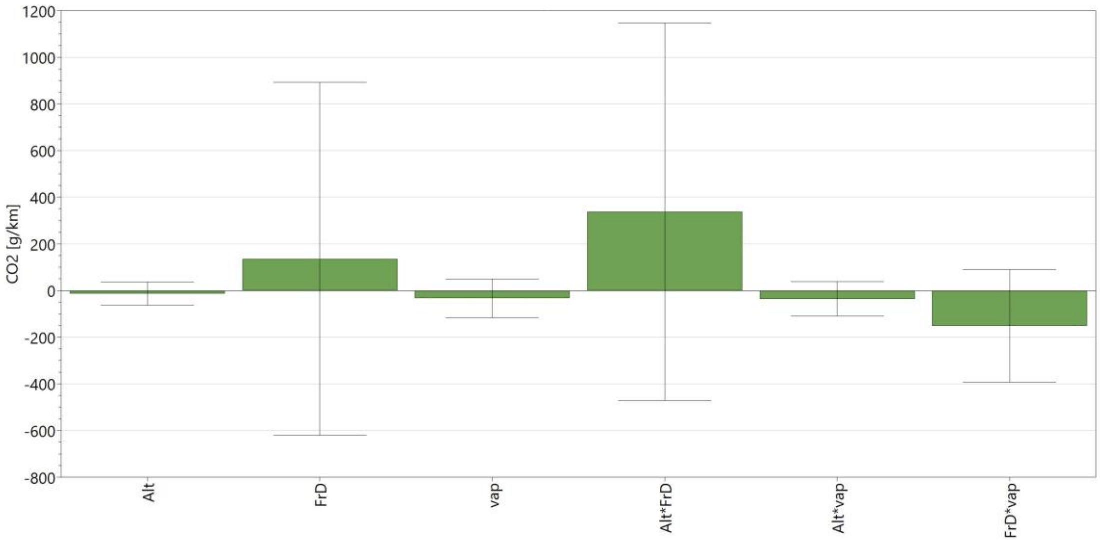


Figure 32. Factor effects and correlations on CO_2 (Urban).

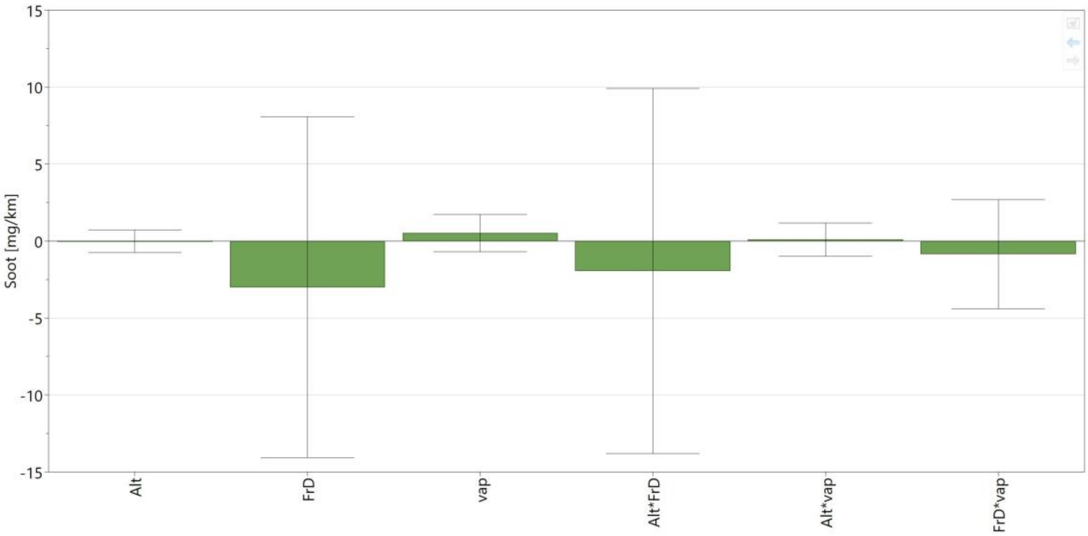


Figure 33. Factor effects and correlation on Soot (Urban).

Figure 32 illustrates the effect coefficient of the individual factors as well as the effect coefficient of the interaction between the various factors. “FrD” is the fraction distance driven with electric propulsion while “Alt” is the total altitude gain and “vap” is the $vapos_{95}$ value. These are used to quantify driving mode, route and driving behavior respectively as mentioned above.

As can be seen, the fraction distance has the largest effect on the soot emissions in the urban part as compared to the other two factors. This is since almost 50% of the urban part is usually driven with the internal combustion engine off as can be seen in table 14. Since a large part of the urban section is driven using electricity, the effects of driver behavior are negated as can be seen in the plot (FrD*vap). However, the effect of the driving mode is decreased with increased altitudes as this leads to increased power demand. This is represented by the Alt*FrD interaction coefficient. The reason for why the behavior of CO_2 looks like this in the urban parts can unfortunately not be explained since it tells that the more electric drive is utilized, the more of CO_2 will be emitted. It also tells that the more aggressive the behavior is, the less of CO_2 emissions will occur. To explain this behavior, more investigations has to be made.

4.6.2. Motorway Part

The effects of the factors on the CO_2 and soot emissions for the motorway part are presented in figure 34 and 35.

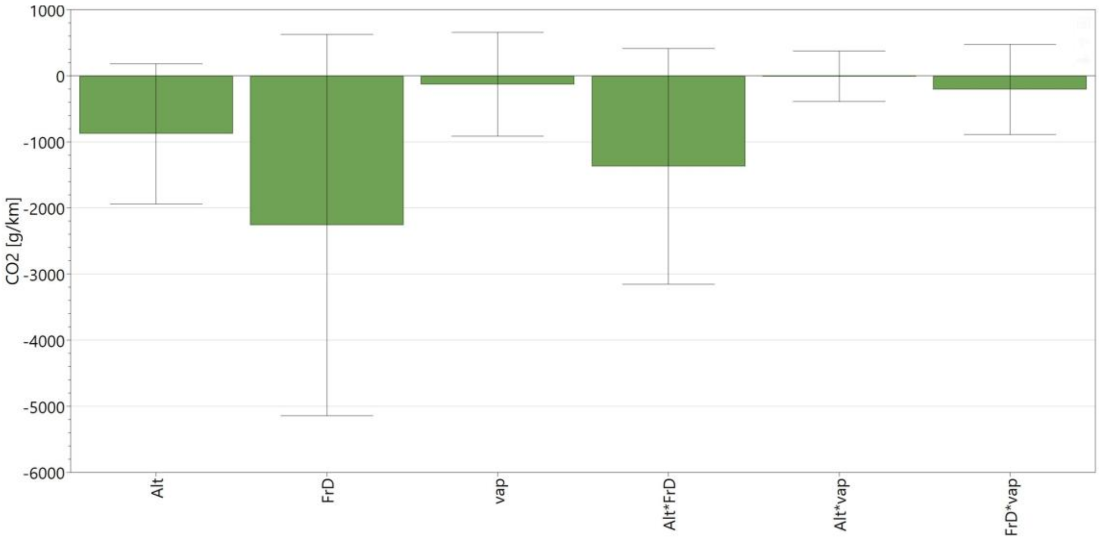


Figure 34. Factor effects and correlations on CO_2 (Motorway).

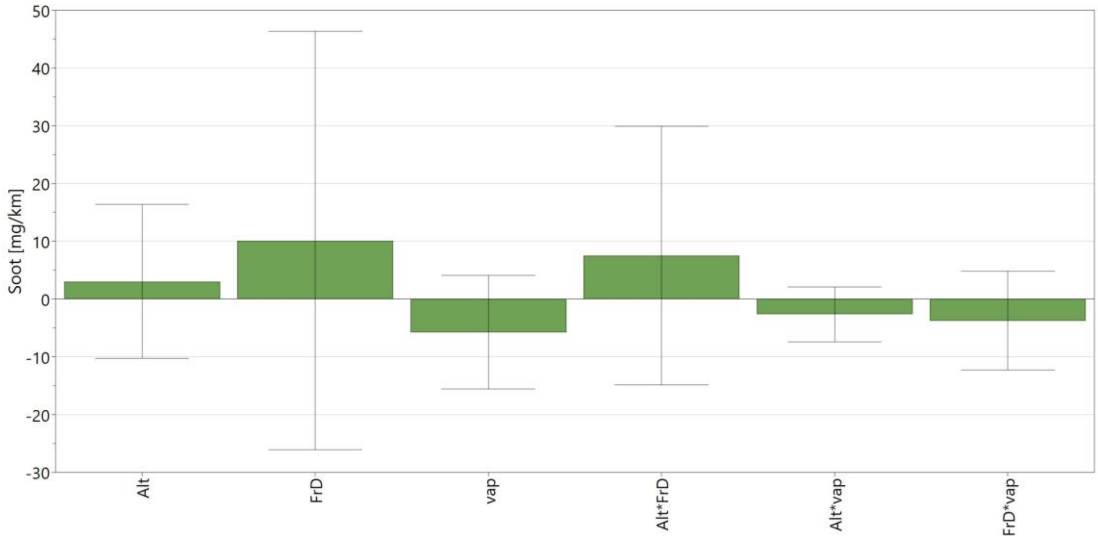


Figure 35. Factor effects and correlation on Soot (Motorway).

In figure 34 one can see how the factors effects the CO_2 emissions in the motorway part. From the Alt (Altitude gain), it can be concluded that the more uphill there are, also the more downhills it will be. When going in a downhill the combustion will be shut off and the electric drive will start. This results in a larger fraction distance driven with electric propulsion hence the large coefficient FrD. This in turn affect the CO_2 negatively which by this graph means that the CO_2 emissions will decrease with more utilization of electric drive.

Figure 35 shows how the same factors affect the soot emissions. Since the soot and the CO_2 is not affected in the same way from the different factors, this graph looks different. One can read the graph as the more electric drive used, the more soot will be emitted. Due to the tests starting with an empty battery, there will be little amount of charge to be used for longer periods during the test. This means that the electric drive is used for short intervals. The more electric drive used, the larger amount of engine starts will occur. Since it is already established that engine starts correlates strongly with soot emissions the larger FrD the more engine starts and the more soot emitted. Observing the factor “vap”, (v*apos), which is a measure of driving behavior, from the same plot, one can see that the more aggressive the behavior is, the less soot is emitted. The reason for this is that when driving aggressively with a low SoC, the power request is high. It will therefore exceed the power threshold that the electric drive can provide rendering the electric drive unused. If the electric drive is not used, then the number of engine starts is decreased which in turn decreases the soot spikes and the total soot emissions.

5. Conclusion & Discussion

From the analysis of the gathered data throughout this project, several conclusions can be drawn on the vehicles emission levels when running on low SoC.

The driving behavior is shown to have a significant impact on the soot emissions while the CO_2 is not as sensitive to driver aggressiveness. Since the SoC is generally low, the higher the aggressiveness the more probable it is that the power limit for the electric propulsion is reached thus triggering an engine start. Since it was observed that a spike in soot emissions is generated with each engine start we can conclude that with increased aggressiveness the soot emissions are increased. On the other hand, when it comes to the CO_2 emissions, the driver behavior is not as significant since CO_2 is not as sensitive to engine starts. The fuel consumption is generally similar between the cycle with different aggressiveness levels which leads to similar CO_2 emissions. This is due to the majority of the cycles driven at the speed limits specified by the roads and the RDE requirements. The driver aggressiveness plays the largest role at acceleration occurring for longer periods such as an acceleration from the rural part to the motorway part which due to the length of the cycles have little impact on the total fuel consumption.

The Pure mode is defined such that it maximized the use of the electric propulsion. Since the SoC is low, the pure mode will switch between the two propulsion systems at a higher frequency than for the hybrid mode. This implies that the pure mode would result in more soot emissions due to the accompanied spikes in soot emissions. However, since the pure mode uses the electric propulsion more often than the hybrid mode, a larger fraction of the cycle is driven using the electric propulsion on the pure mode as compared to the hybrid mode which results in less emissions in general. This implies that the effects of the pure mode neglect each other resulting to similar soot emission values between the two modes when considering the full cycles driven at low SoC. As a conclusion, at low SoC, the pure mode is more beneficial at low speed i.e. the urban/rural parts where the power request is generally low and within the electric propulsion limits resulting in more distance driven with the electric propulsion. At higher speeds, pure emits more soot as the hybrid mode is able to use the electric drive in a more optimized way and can therefore use it during the motorway part while cruising.

The aggressiveness level of the route shows what can be expected. The hilly route has higher amount of emissions than what the flat route has. The difference in positive altitude gain between these two routes are about 150m, which can be described such as the hilly route has 100% more positive altitude gain throughout the whole route. When going uphill, a greater power is needed to obtain the vehicle speed. The requested power increases as the road inclination increases thus for the hilly route, there are more samples for the different inclinations as the flat route is intended to be as flat as possible with just a few uphill's.

The CO_2 emissions is very well mirrored from the power requested and the conclusion can be drawn that CO_2 and power has a clear relation. With increased power request, the fuel consumption is increased which results in higher CO_2 emissions.

When it comes to soot emissions in general, it has a high correlation to engine starts. The number of engine starts is highly dependent on the driver aggressiveness, driving mode and route. At low speeds, increased driver aggressiveness and altitude gain decreases the fraction distance driven with electric propulsion as what little battery charge existing is depleted at a higher rate and results in more emissions as the combustion engine is used for a larger portion. At higher speeds, the low SoC is ineffective and has little use as it is depleted quickly. The switch to the electric propulsion has a more negative impact than positive. This is because the use of the electric propulsion means a switch back to the ICE which results in an emission spike. Having a higher road inclination and/or driver aggressiveness implies that the power request exceeds the limit of what the electric propulsion can provide. This in turn decreases the number of engine starts as the electric propulsion is not used to begin with. Since this limit is lower for the hybrid mode than for the pure mode, the hybrid mode is mode effective at low SoC and high speeds with respects to soot emissions.

It is important to note that starting the tests with a fully charged battery would results in very different results where most of the urban and rural parts would be driven using the electric propulsion and resulting in almost no emissions at these parts. Additionally, conducting the tests with a fully charged battery would yield in a better comparison between the effects of the two driving modes as their definitions become vaguer when the battery is depleted.

It is also worth mentioning that the way these tests are conducted are not necessarily realistic as the driving behavior was not natural and included a number of “simulated overtakes” and stops to achieve the required number sample points and fulfill the RDE requirements. It is therefore not totally true to conclude that the RDE emissions are as “real” as they are meant to be.

As a final remark, the tests conducted in this thesis are not nearly enough to draw major conclusion. No replicas on any test where conducted and therefore not much could be said on the variance of the results. This is reflected on the confidence intervals in figures 32-35 which shows how large the spread is. To be able to draw better conclusions multiple replicas of the experiments should be conducted and more variables should be included to capture as much data as possible. This could not be done in this thesis due to time limitations.

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Appendix

Results

The total amount of soot and CO_2 emissions as well as total fuel consumption are here presented to show how big amount that is emitted throughout a test. This is to complement the amount per km that is presented in section 3. Results.

Table 15. Total Soot Emission [mg]

Test fc	Full cycle	Urban	Rural	Motorway
ALHA	86.41	28.03	26.81	31.57
ALHC	43.63	10.39	17.67	15.56
ALPC	45.54	8.55	15.52	21.46
AMHN	67.73	17.51	33.08	17.13
AMPA	51.4	16.30	16.84	18.26
AMPN	59.78	10.29	35.69	13.81
FLHA	79.46	33.71	18.34	27.40
FLHC	39.75	13.43	12.00	14.32
FLPA	85.62	21.98	17.67	45.97
FLPC	41.54	13.22	11.84	16.48
FMHN	65.53	20.20	25.68	19.65
FMPN	65.19	24.99	17.72	22.48
SLHA	-	-	-	-
SLHC	-	-	-	-
SLHN	-	-	-	-
SMHA	-	-	-	-
SMHC	-	-	-	-
SMLN	-	-	-	-

Table 16. Total CO_2 Emissions [kg]

Test fc	Full cycle	Urban	Rural	Motorway
ALHA	19.19	5.38	6.78	7.02
ALHC	17.43	4.79	6.41	6.24
ALPC	18.32	5.03	7.00	6.28
AMHN	19.12	5.39	7.03	6.71
AMPA	17.62	4.56	6.02	7.03
AMPN	18.74	4.78	6.89	7.08
FLHA	19.90	6.90	5.89	7.11
FLHC	19.73	6.72	5.91	7.10
FLPA	20.17	7.27	5.55	7.35
FLPC	18.92	6.14	5.58	7.20
FMHN	19.66	6.48	6.08	7.10
FMPN	21.20	7.03	5.99	8.18
SLHA	19.98	5.71	6.09	8.10
SLHC	22.14	6.25	6.80	9.09
SLHN	20.74	6.11	6.19	8.45
SMHA	20.00	6.32	5.80	7.88
SMHC	19.50	5.83	5.74	7.93
SMLN	18.93	6.03	5.00	7.91

Table 17. Total Fuel Consumption [l]

Test fc	Full cycle	Urban	Rural	Motorway
ALHA	11.6	3.2	4.1	4.4
ALHC	10.5	2.9	3.9	4.3
ALPC	11.1	3.0	4.2	5.0
AMHN	11.6	3.2	4.3	4.3
AMPA	10.6	2.7	3.6	4.5
AMPN	11.3	2.9	4.2	4.3
FLHA	12.3	4.1	3.6	3.8
FLHC	11.9	4.0	3.6	3.8
FLPA	12.2	4.4	3.3	4.3
FLPC	11.4	3.7	3.4	4.1
FMHN	11.9	3.9	3.7	4.3
FMPN	12.8	4.2	3.6	4.3
SLHA	12.0	3.4	3.7	4.9
SLHC	13.3	3.7	4.1	5.5
SLHN	12.5	3.6	3.7	5.1
SMHA	12.1	3.8	3.5	4.7
SMHC	11.7	3.5	3.4	4.8
SMLN	11.4	3.6	3.0	4.8

Effects of Driving Behavior – Full Route

The total CO_2 and soot emissions on the full route are here presented with respect to the effect of driving behavior.

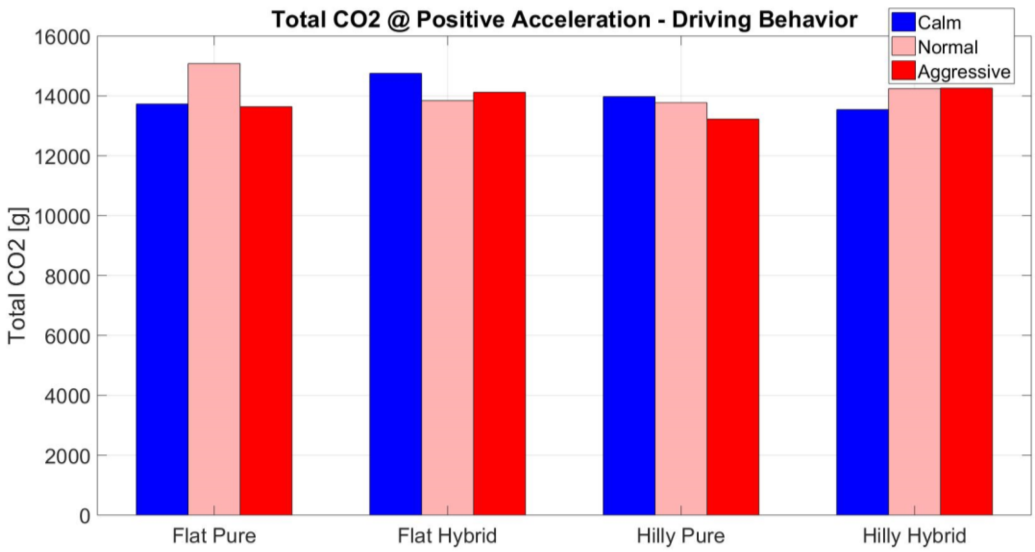

Figure 36. Total CO_2 Emissions at Positive Acceleration - Driving Behavior

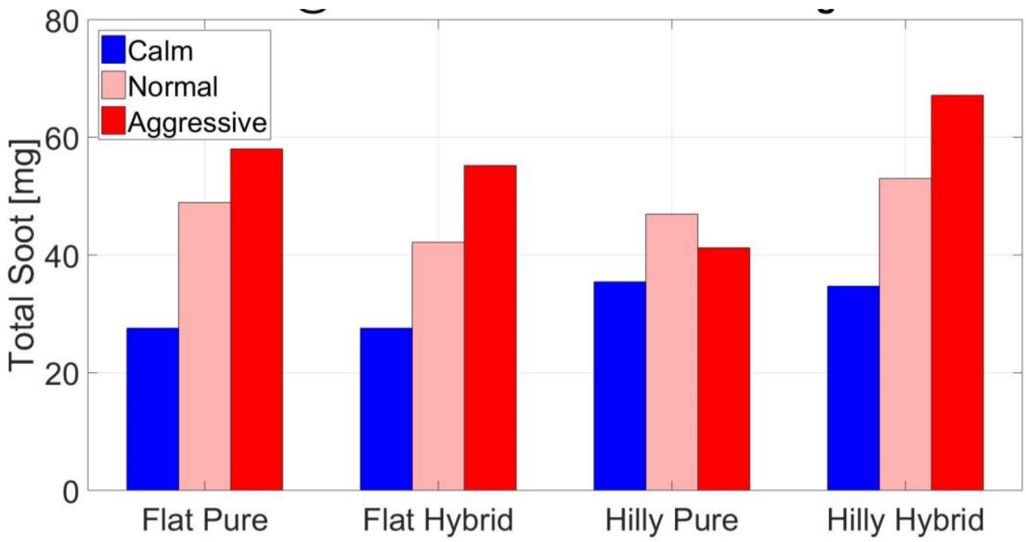

Figure 37. Total Soot Emissions at Positive Acceleration - Driving Behavior

Effects of Driving Behavior – Total CO_2 – Urban, Rural, Motorway

The total CO_2 is here presented for the flat and hilly route with the two modes pure and hybrid. These are complements to section 4.3 Driving behavior.

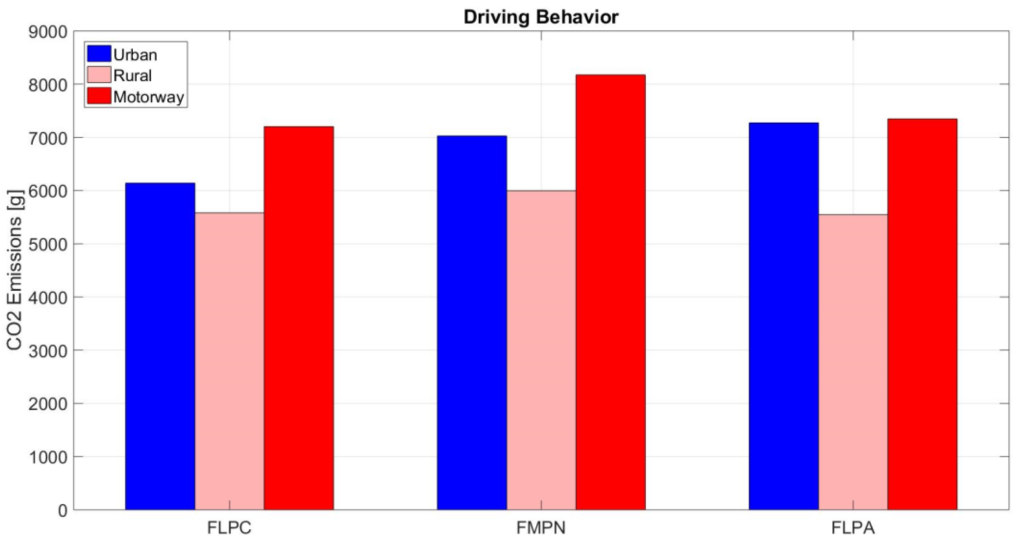

Figure 38. Total CO_2 Emissions on Flat Pure Route – Driving Behavior

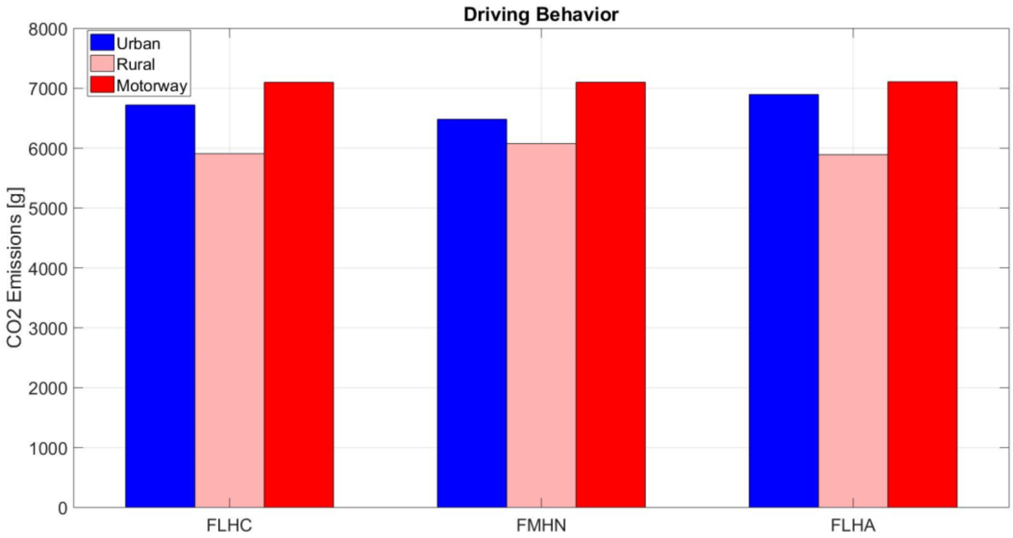

Figure 39. Total CO_2 Emissions on Flat Hybrid Route - Driving Behavior

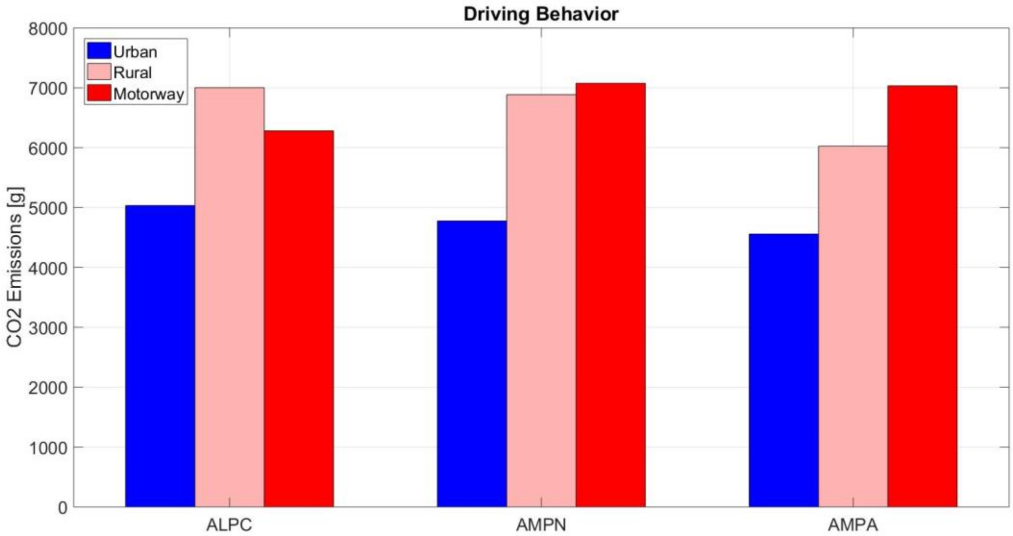

Figure 40. Total CO_2 Emissions on Hilly Pure Route - Driving Behavior

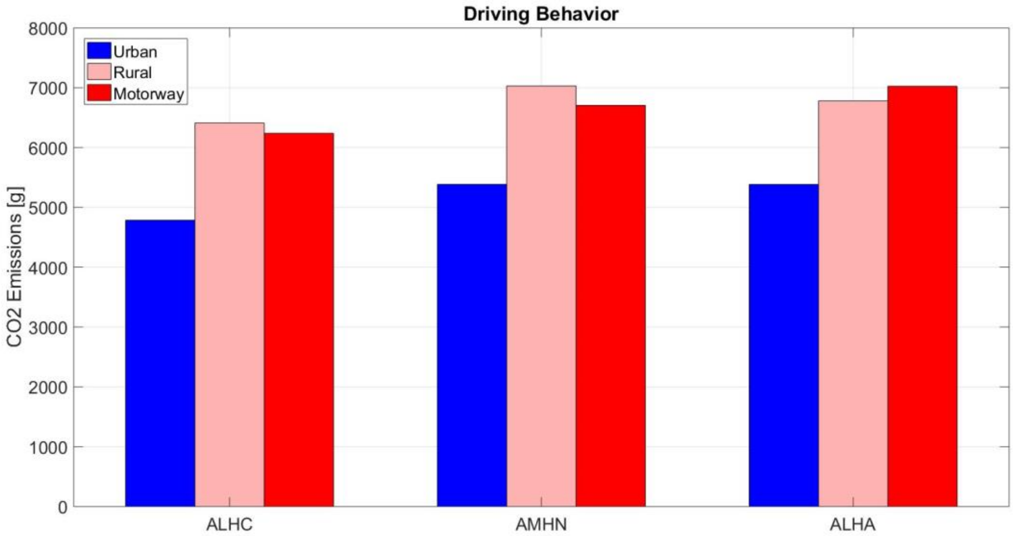

Figure 41. Total CO_2 Emissions on Hilly Hybrid Route - Driving Behavior

Effects of Driving Behavior – Total Soot – Urban, Rural, Motorway

The total soot is here presented for the flat and hilly route with the two modes pure and hybrid. These are complements to section 4.3 Driving behavior.

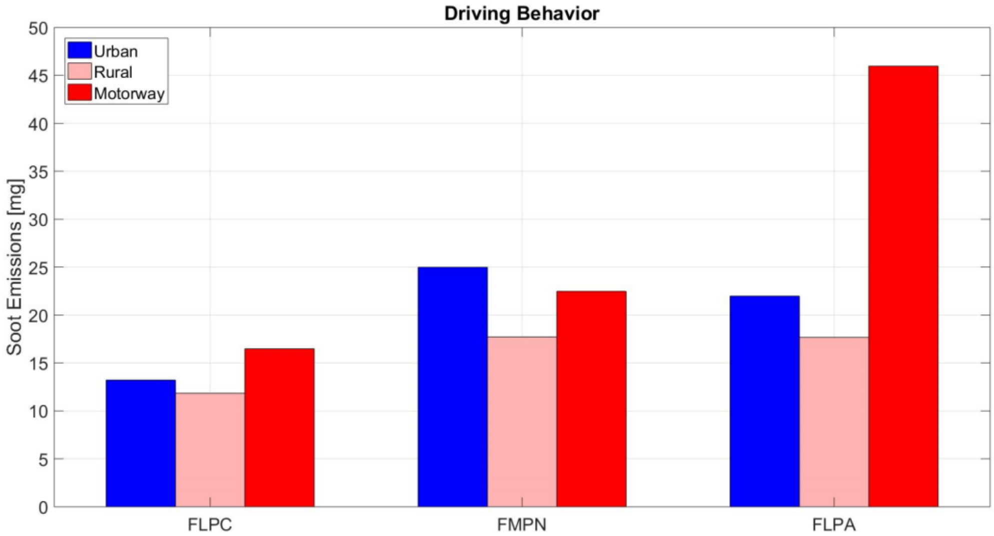

Figure 42. Total Soot Emissions on Flat Pure Route - Driving Behavior

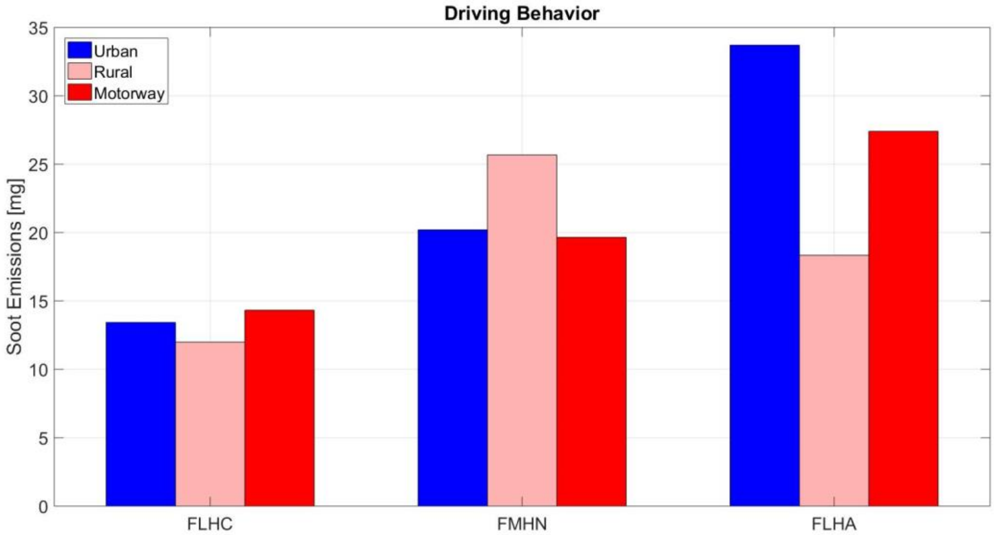

Figure 43. Total Soot Emissions on Flat Hybrid Route - Driving Behavior

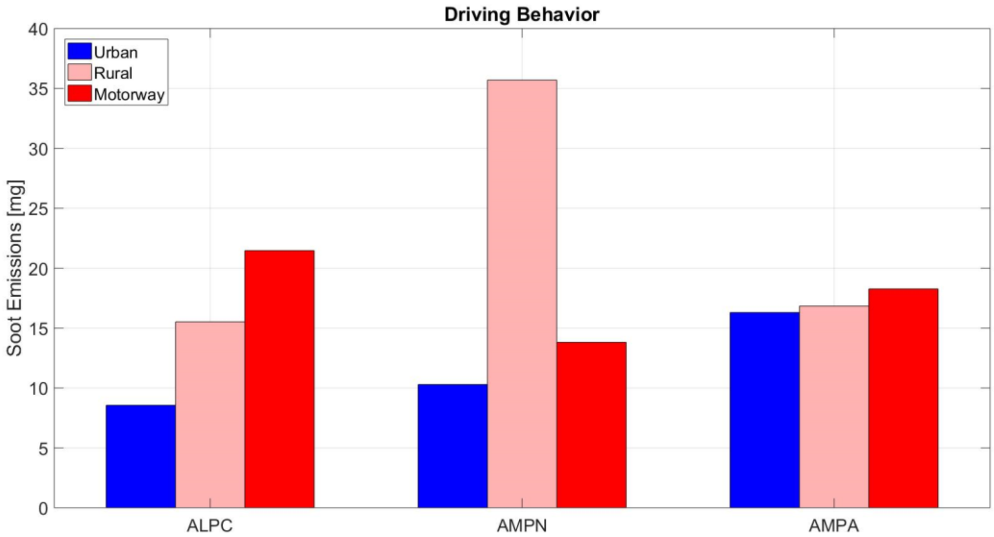

Figure 44. Total Soot Emissions on Hilly Pure Route - Driving Behavior

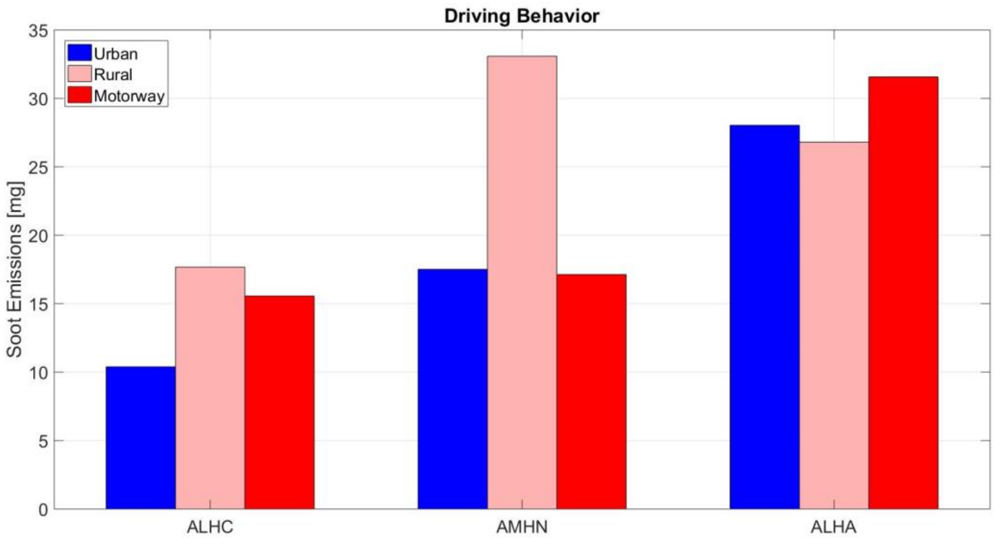

Figure 45. Total Soot Emissions on Hilly Hybrid Route - Driving Behavior

Effects of Route – Mean CO_2

The average CO_2 emissions that are remaining from section 4.5. Effect of Route, are here presented to be able to investigate the results from these tests.

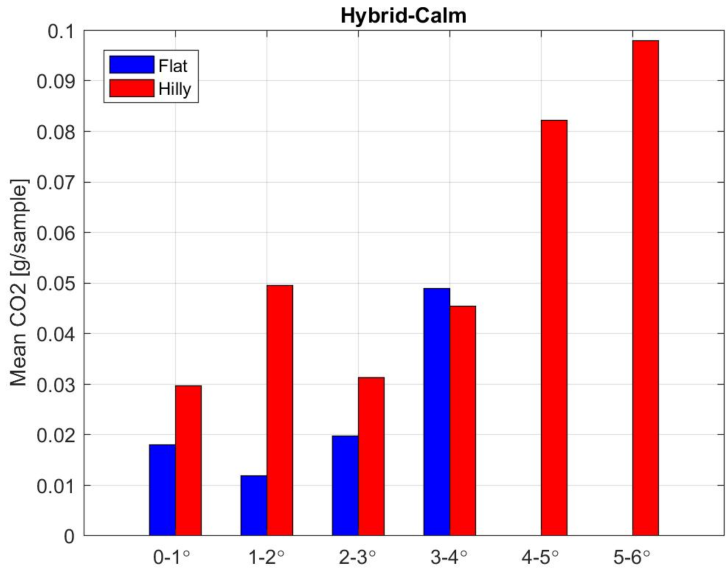

Figure 46. Average CO_2 Emissions at Different Road Inclinations – Hybrid Calm Route

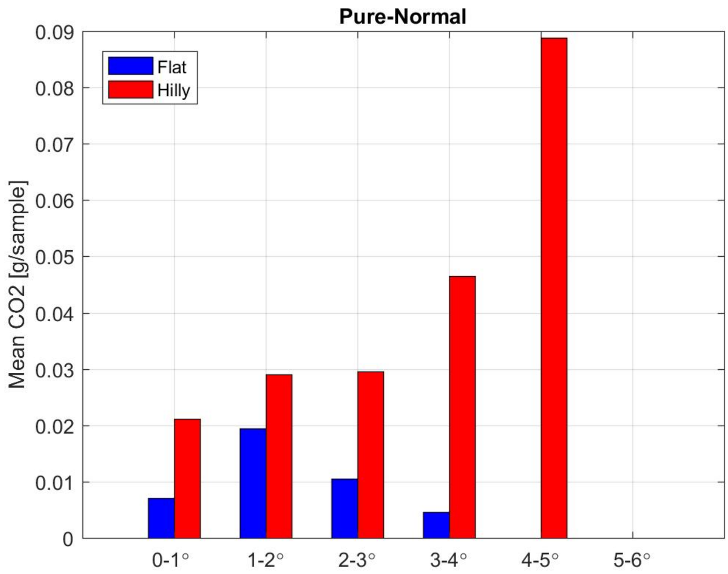

Figure 47. Average CO_2 Emissions at Different Road Inclinations - Pure Normal Route

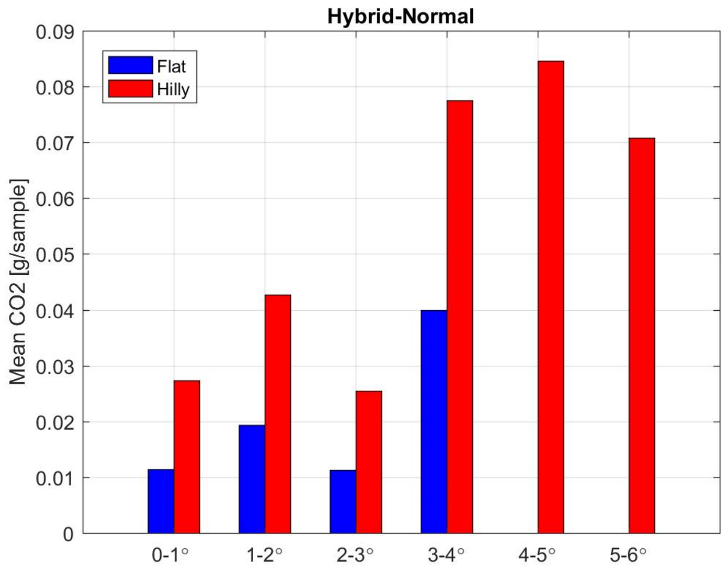

Figure 48. Average CO_2 Emissions at Different Road Inclinations - Hybrid Normal Route

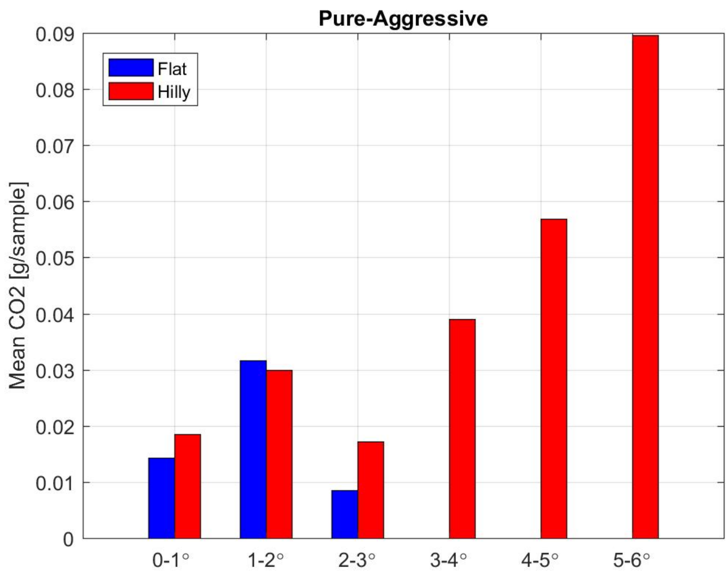

Figure 49. Average CO2 Emissions at Different Road Inclinations - Pure Aggressive Route

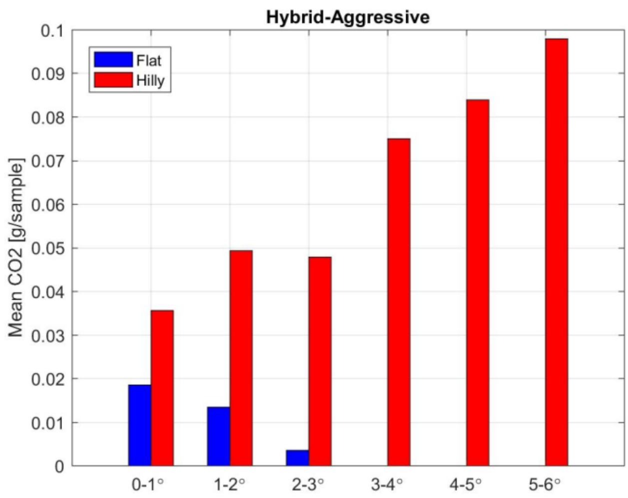

Figure 50. Average CO2 Emissions at Different Road Inclinations - Hybrid Aggressive Route

Effects of Route – Mean Power

The average power request that are remaining from section 4.5. Effect of Route, are here presented to be able to investigate the results from these tests.

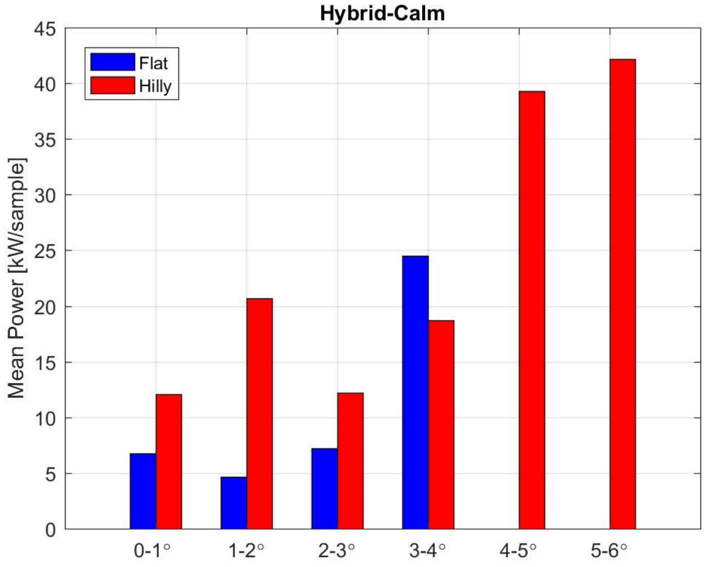

Figure 51. Average Power Request at different road inclinations with constant acceleration - Hybrid Calm Route

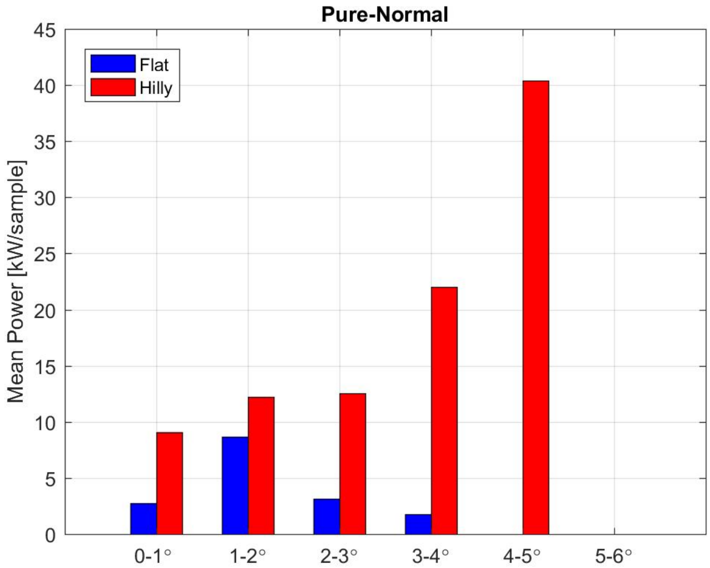

Figure 52. Average Power Request at different road inclinations with constant acceleration - Pure Normal Route

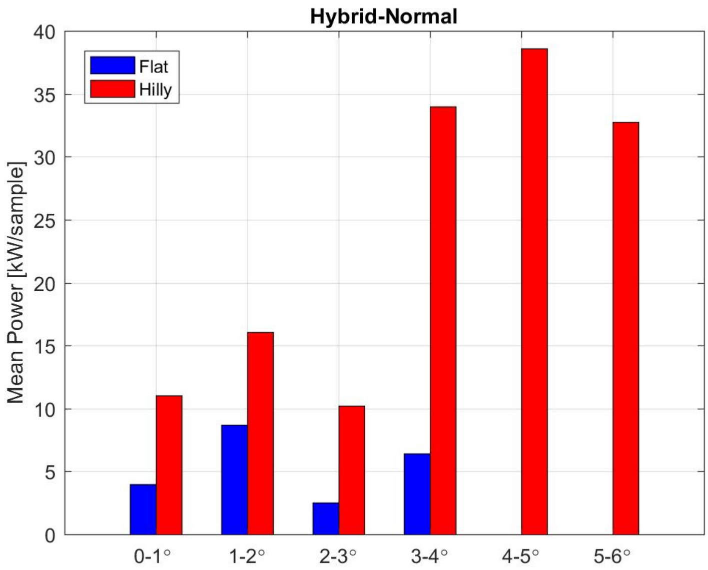

Figure 53. Average Power Request at different road inclinations with constant acceleration - Hybrid Normal Route

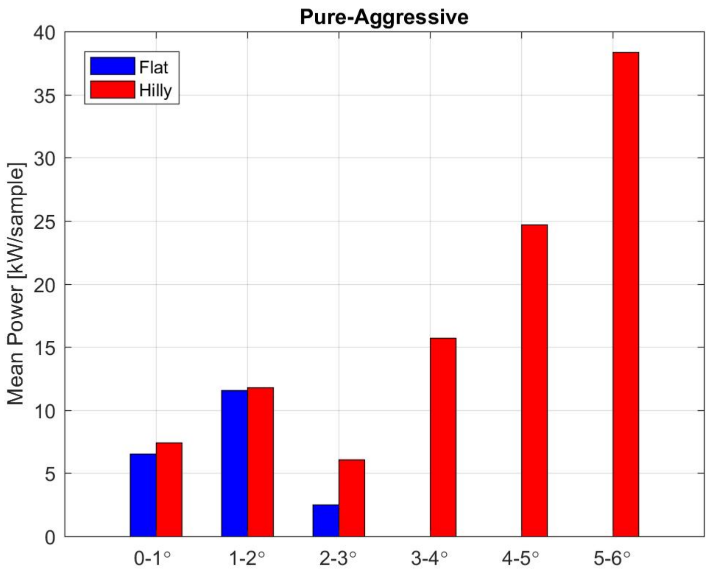

Figure 54. Average Power Request at different road inclinations with constant acceleration - Pure Aggressive Route

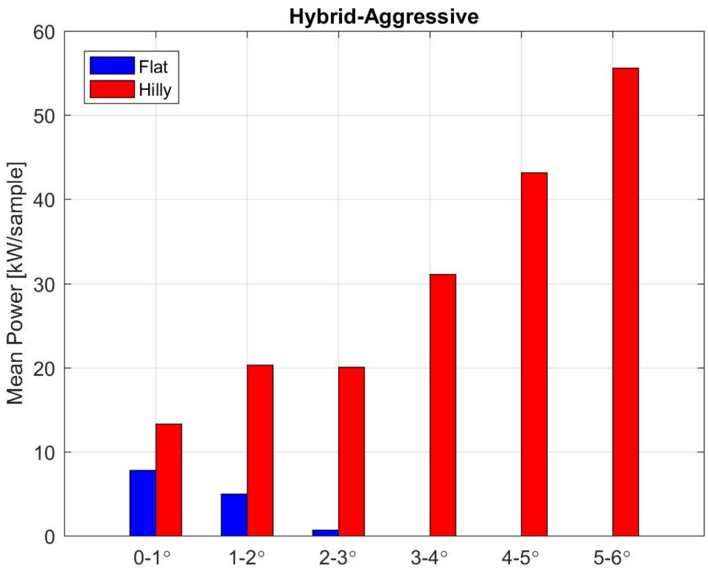

Figure 55. Average Power Request at different road inclinations with constant acceleration - Hybrid Aggressive Route

Effects of Route – Mean Soot

The average soot emissions that are remaining from section 4.5. Effect of Route, are here presented to be able to investigate the results from these tests.

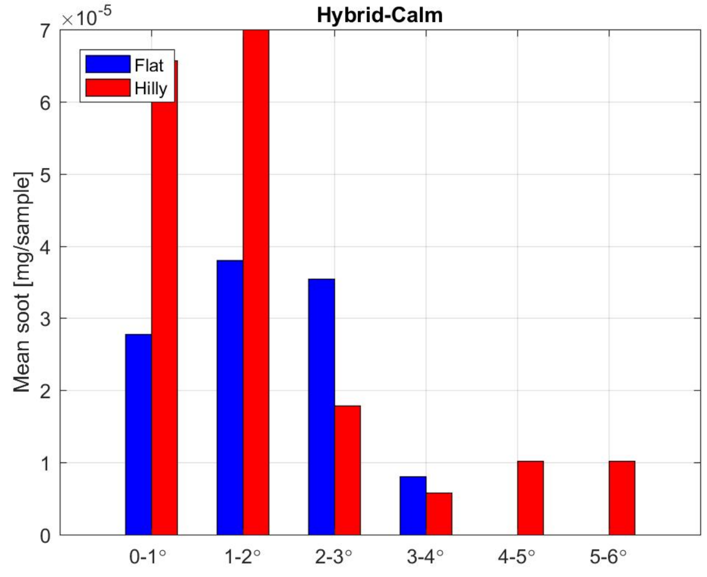

Figure 56. Average Soot Emissions for Different Road Inclinations - Hybrid Calm Route

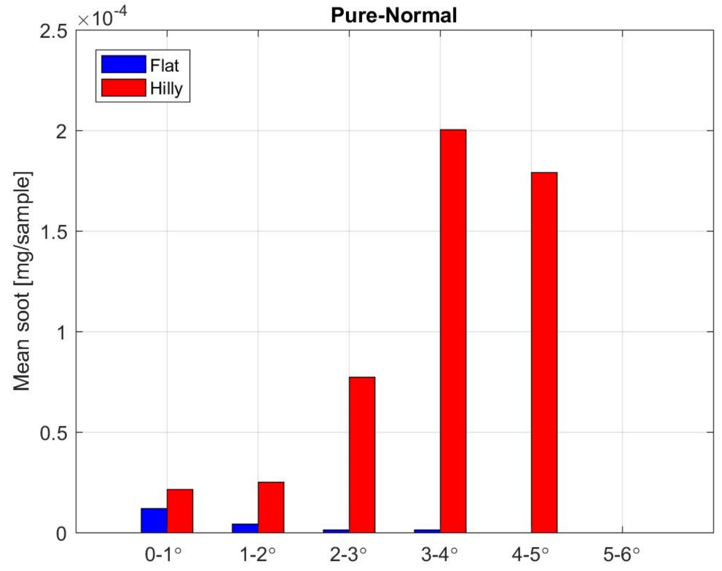

Figure 57. Average Soot Emissions for Different Road Inclinations - Pure Normal Route

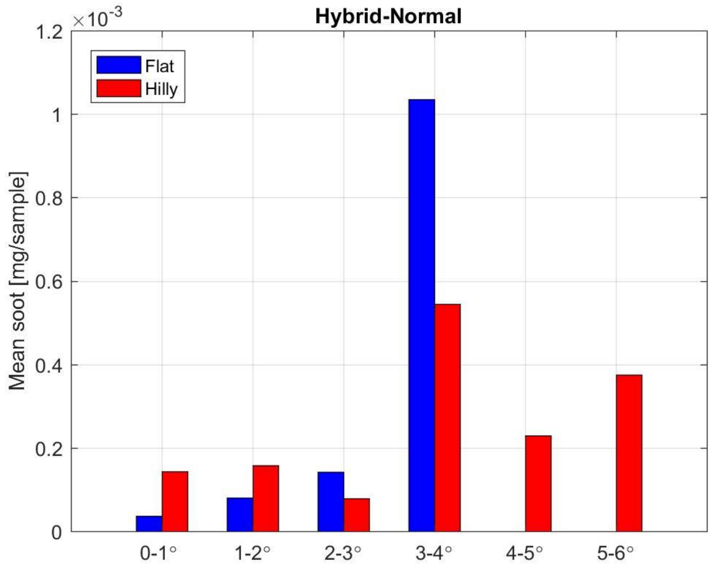

Figure 58. Average Soot Emissions for Different Road Inclinations - Hybrid Normal Route

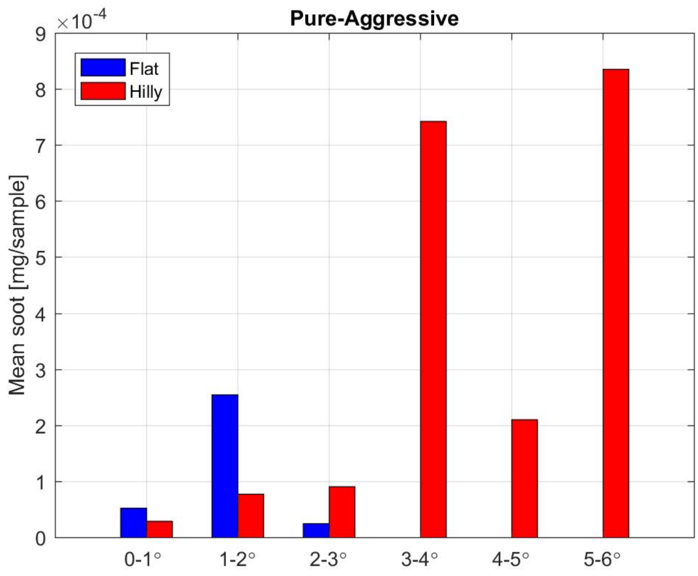

Figure 59. Average Soot Emissions for Different Road Inclinations - Pure Aggressive Route

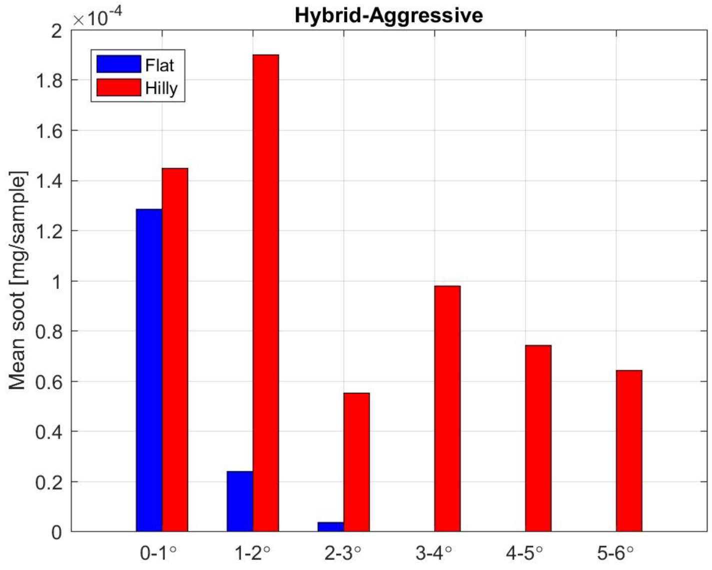

Figure 60. Average Soot Emissions for Different Road Inclinations - Hybrid Aggressive Route