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Real Driving Emissions, comparison between Ethanol (E85) and Gasoline fuels

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

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SAAB 95 SportsCombi with the A.V.L. MOVE PEMS system installed on the towbar

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Abstract

It is not new that people have been searching for a more environmentally friendly alternative for fossil fuels. In early 2000's, Sweden saw potential in Ethanol and created benefits for people who bought E85 vehicles. Unfortunately, not everything was good about E85 and when people discovered the downsides of this renewable fuel, they started to lose interest, leading to the downfall of E85. Nowadays, the Swedish government tries to revive Ethanol as it is an important step of their 2030 vision to have a vehicle fleet running on renewable fuels only, so they plan on giving money to people to retrofit their old vehicles for E85. This thesis will study the impact of E85 on the emissions, as there are some important differences between gasoline and E85, like well-to-wheel emissions and energy density. The study includes the influence of driving style, route, and cold/warm start for a more complete understanding of factors that contribute to higher emissions. The measurements were done using an AVL M.O.V.E. PEMS device which provides measurements of CO_2, CO, NO_x, and PN. Vehicle parameters data were logged from an i-bus device and then the post-processing was carried in MATLAB. The results show that some parameters, like NO_x and PN are more sensitive to aggressiveness, and the effect is even higher for E85. CO and CO_2 are also increasing for the aggressive driving, but even so, the vehicle complies to EURO IV standards for which it was certified. E85 emits more CO and PN especially during aggressive driving, even though in the case of CO emissions most of them are emitted before the catalyst reaches the operating temperature, making the impact of fuel less notable. There was no important difference between the two routes, so they were studied together.

Key words: Research octane number (RON), Internal combustion engine (ICE), Portable emissions measurement system (PEMS), Renewable fuels, Ethanol, E85, Real Driving Emissions, Emissions, Driving style.

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Contents

Preface

In this study, Real Driving Emissions (RDE) tests were performed with a SAAB 9-5 SprotCombi BioPower. The tests have been performed from March 2021 to April 2021. The work is about comparing the emissions from the same vehicle running with regular 95 RON gasoline and E85. The project is carried out at the Department of Mechanics and Maritime Sciences, Automotive engineering, Chalmers University of Technology, Sweden. The project is financed by Chalmers University of Technology.

The project has been carried with Cosmin Constantin Pascariu and Vinay Vilas Gudihal as researchers, and Professor Jonas Sjöblom and Professor Lucien Koopmans as supervisors. The tests were performed in Västra Gotaland region and the calibrations were done in the laboratory of the Department of Mechanics and Maritime Sciences. The help of Robert Buadu, Alf Magnusson and Anders Mattsson in preparing the vehicle and helping us understand the equipment is highly appreciated.

Göteborg September 2021-09-15

Cosmin Constantin Pascariu & Vinay Vilas Gudihal

Notations

CAN	Control Area Network
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EATS	Exhaust Aftertreatment System
ECU	Electronic Control Module
EFM	Exhaust Flow Meter
EPA	Environmental Protection Agency
GHG	Greenhouse Gas Emissions
GPF	Gasoline Particulate Filter
GPS	Global Positioning System
ICE	Internal Combustion Engine
JRC	Joint Research Center
LDV	Light Duty Vehicle
NEDC	New European Driving Cycle
NDIR	Non-Dispersive Infrared Analyzer
NDUR	Non-Dispersive Ultraviolet Analyzer
NO_X	Nitrogen Oxides
OBD	On-Board Diagnostics
PEMS	Portable Emissions Measurement Systems
PC	Personal Computer
PN	Particulate Number
RDE	Real Driving Emissions
RED	Renewable Energy Directive
RON	Research Octane Number
RPM	Rotations Per Minute
TDC	Top Dead Center
TWC	Three-Way Catalyst
VPR	Volatile Particle Remover
WLTP	Worldwide Harmonized Light-Duty Test Procedure

1. Introduction

The problem of air pollution became noticed in the mid-1900's in the United States of America, when a series of factors led to an increase of vehicles, and as a result, the air pollution from transportation, has been negatively impacted, especially in big cities. To reduce the impact of transportation on climate change and air quality, the EPA was formed, and the Clean Air Act was passed in 1970, to regulate the pollution from transportation sector. Similar measures were taken all around the world, and the results is that most gases coming out of the tailpipe of a new vehicle are around 99% cleaner than the ones from a 60-year-old vehicle [1]. So, does this mean that we won the fight against climate change? Even though the improvement is huge, the emissions are still getting worse, but the technology advancement allows researchers to make cleaner powertrains and EATS.

As part of the measures introduces against climate change, Renewable Energy Directive (RED) was introduced and the goal for 2020 was that Europe should use at least 10% renewable energy out of the total energy used for transportation [2]. In this category, biofuels are also included, as they reduce the engine-out emissions, the emissions generated for the production and distribution of the fuel, and the dependency on fossil fuels. According to Directive 2003/30/EC, bioethanol is one of the renewable fuels included in the Directive 2009/28/EC, and this fuel will be the study objective of this master's thesis [3]. The reason why bioethanol was chosen for this study is that because it is a biofuel that can replace gasoline, and existing vehicles can be converted to work with biofuels [4]. Moreover, the same fuel distribution network can be kept, and in some countries, bioethanol is already sold in various concentrations. In Sweden one can find E85, which normally is a blend of 85% ethanol and 15% gasoline, although this mixture can change depending on the season, as a mixture rich in ethanol reduce the cold start capabilities of the vehicles [5]. For example, one can find on the Circle K's website, which is one of the petrol companies from Sweden, that the gasoline content found in E85 is increased from 15% during the warm months, up to 25% gasoline in the cold months, to improve the cold start capabilities and minimize the emissions from the cold start [6].

To promote the use of biofuels, Sweden intends to give an incentive for people who convert their vehicles to biofuels or biogas. In this way, the government aims to reduce the emissions from existing cars and to reduce the dependency on fossils fuels, with the goal of having a complete fossil free vehicle fleet by 2030 [7-8]. To convert an existing vehicle for E85, one needs to go to a specialized workshop. One company who converts vehicles for E85 is Autoexperten, with a cost of around 10000 SEK depending on the vehicle, and of course only vehicle running on gasoline can be converted for E85.

To take full advantage of ethanol, which has a higher RON than regular gasoline, manufacturers can design engines with higher compression ratio, making them more efficient and more powerful, while reducing the fuel consumption and emissions. Source [9] informs that ethanol has a RON between 120 and 135, which is a much higher value than regular gasoline which has a RON of 95. The disadvantage of this technique is that these vehicles will not be able to run on gasoline found at petrol stations, because auto-ignition from the 95 RON gasoline will destroy the engine. This is an issue because in many countries, E85 is difficult to find, and the vehicle will not be able to run without it. Even in countries like Sweden, where almost every petrol station sells E85 this will be an issue because many people like to go on vacations in other countries, and they will not be able to do this with a vehicle designed to run on maximum efficiency on bioethanol. Some measures can be taken to prevent auto-ignition, for example retarding the ignition, or using high octane fuel only, but these measures have limited capabilities, as the first one reduces the efficiency of the engine, and the latter will increase the costs of ownership for the driver.

As the tests done during this project, will be similar with the tests from source [5], and the vehicle has the same emissions standard, Euro 4, one would expect similar outcomes when comparing regular 95 octane gasoline, with E85, mainly: higher fuel consumption, lower CO_2 emissions and NO_x increase for highway driving.

1.1. Background

The trends of vehicles sold are constantly changing as new technologies evolve and some vehicles are more desirable than others. A major role in how trends evolve is represented by the new regulations and the incentives or taxes for each type of vehicle. This can be observed in Figure 1, where one can note a few interesting behaviors: Firstly, the vehicles with an internal combustion engine account for most car sales even up to date, although electrified vehicles are getting more and more popular.
Secondly, the ethanol vehicle sales peaked in 2008 and then started to decline to the point where in 2020, only 70 vehicles capable to run on E85 were sold in Sweden. This trend is contradicting the view of the Swedish government of having a vehicle fleet running on completely renewable fuels by 2030 [7]. According to [10], in 2006 E85 was the most environmentally friendly fuel, and the Swedish government provided a lot of benefits for E85 vehicles, like green car premium, free parking, exemption from congestion tax, lower vehicle tax, which were very appealing for the people in the search of a new vehicle. After some time, E85 gained a bad reputation of causing engine problems, and at the same time, people started to raise questions about the source of E85 and the fact that those crops can be used to obtain food, and E85 also became expensive. Suddenly, the people who drove a E85 vehicle, became from "being considered the neighborhood's environmental heroes", to people who "contributed to deforestation and took food from starving children". To top out all these, the government cut off all benefits, and suddenly E85 lost its appeal and vehicle sales started to decline. Nowadays, even people who own a E85 vehicle are refueling with regular gasoline, according to [10], and car companies are not even producing new E85 vehicles.
Another interesting observation is that there is a spike in vehicles with an ICE in the beginning of 2018 and a drop in the middle of 2018. This happened because in July 2018, a new increased taxation system for vehicles was introduced, called bonus malus, so people bought a car before the tax was introduced [11]. A similar trend is seen on December 2019, when once again the sales in conventional vehicles spiked and then dropped in 2020, this time because from January 1st,

2020 a change in the bonus malus system was introduced, so that for the vehicles registered before this date, the lowest CO_2 value from NEDC or WLTP was used to calculate the vehicle tax, and after January 1st 2020, the highest CO_2 value would be used, meaning an increased tax [12].

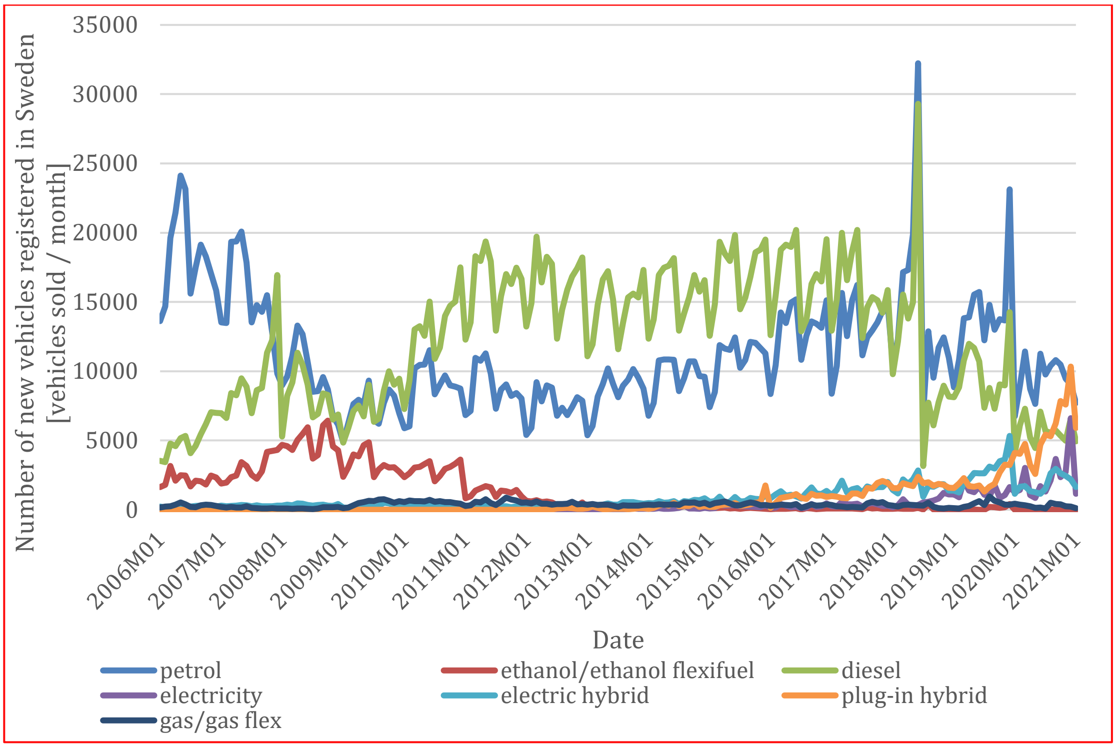

Figure 1. The number of new passenger vehicles registered in Sweden between 2006 and 2021 [13]

One of the advantages of ethanol is that it is made from renewable sources, which is also one of the reasons why it got a bad reputation and people started to look away from it. There are two known ways of making ethanol: the first method and the most common is to make ethanol from starch and sugar-based crops, mainly corn and sugar cane. It is the most common because it is the cheapest way of obtaining it, but because the crops used for ethanol need to be planted on arable land that can be used to make food, it will raise the price of food, which is a negative impact for poor people. The second way of obtaining ethanol is from cellulosic feedstocks, such as grass, wood chips, and crop residues, which is not using crops that can feed people, but instead it uses biomass that would otherwise go to waste [14].

Another advantage of the ethanol is that the well to wheel CO_2 footprint is lower for both methods of obtaining ethanol. The well to wheel footprint considers the life cycle of the ethanol from extraction to use. In the study from reference [15], it was found that for corn based ethanol, the GHG emissions are reduced from 19% to 48% and for the cellulosic ethanol, the well-to-wheel emissions are reduced by 90% to as much as 115% when compared to gasoline, and the reduction depends on the source of ethanol, method of obtaining and transportation method. These results prove that ethanol is better for the environment.
(https://iopscience.iop.org/article/10.1088/1748-9326/7/4/045905/pdf
, https://afdc.energy.gov/vehicles/flexible_fuel_emissions.html)

Even though sales of petrol vehicles are going down, there are many vehicles with a high remaining life and for the Swedish government to meet the 2030 goal of having a completely fossil free fleet, these vehicles need to be converted to E85. According to Autoexperten, the procedure takes around three hours, meaning that the vehicle will not be immobilized for long periods of time, so it will not represent an impediment for the owner. Moreover, the vehicle will still be able to run with regular gasoline, so if the driver does not find E85, the vehicle will run on regular gasoline as before the conversion [16]. The conversion kit contains an ethanol sensor to regulate the fuel flow, a pre-programmed control unit to check the composition of ethanol and weather conditions, and fuel lines designed for E85, although different companies use different conversion kits. For example, other companies like BSR will provide a tool that plugs in the OBD port, and the vehicle can run with E85. To convert a vehicle, Autoexperten requires that it has a port-fuel injection system, as they do not have a way to mount the ethanol sensor for the direct injection engines, while the OBD tool provided by BSR works for all types of vehicles, so the person who wants to convert his vehicle can choose between different types of conversion. [16] [17]

To find the concentration of ethanol in the fuel, one can use an ethanol sensor, or the lambda sensor can be used to calculate the concentration of ethanol. According to [18], ethanol has a lower stoichiometric air-fuel ratio than gasoline when the concentration of ethanol is increased, the engine will run on lean mixture, which will be detected by the lambda sensor, and with this information, a specially designed algorithm will adjust the concentration of ethanol until the mixture is stoichiometric. In the same way, if the concentration of ethanol is decreased, the mixture will be rich, and the algorithm will readjust the concentration of ethanol from the fuel. The limitations of this method are that the lambda sensor needs to be in a closed loop and when the engine runs on a lean mixture, the temperature in the EATS can increase which might cause damage to its components. Similarly, when the engine is run with a rich mixture, the excess fuel might wet the cylinder and dilute the engine oil or end up in the EATS where it can ignite and cause damage. Moreover, the time needed to adjust the concentration of ethanol is a function of how fast the lambda sensor can reach the operating temperature, the type of lambda sensor and the driver behavior, and during this time, the emissions will be significantly increased, as the catalytic converter need stoichiometric air-fuel ratio to work optimally and in the case of the rich mixture, the excess fuel will be released into the atmosphere.

The main emissions created by internal combustion engines are carbon monoxide, particulate matters, hydrocarbons, lubricating oil, and nitrogen oxide. With the recent advancement in technologies like alternatives fuels, hybrid vehicles, electric vehicles, emissions can be lowered down to a greater extent.

Due to incomplete combustion of carbon-based fuels like gasoline, carbon monoxide (CO) is formed. CO being colorless, odorless, and tasteless, it is difficult to find the emission. Its impact on human and animal life is detrimental and may lead to harm the ability of the blood to carry oxygen. Carbon dioxide (CO_2) is a colorless, odorless, and non-poisonous gas formed by combustion of hydrocarbon fuels [19]. With the increase in CO_2 emissions respiration becomes difficult for human beings. Another concern regarding carbon emissions is that they are trapped in atmosphere, leading to global warming. Due to incomplete combustion of hydrocarbons, soot is emitted. Soot is nothing but impure carbon particles, which in dangerous to humans, animals, and environment. The fine particles of soot can enter respiratory system and may lead to lung cancer, asthma, birth defects etc., while the larger particles may get filtered out. When nitrogen and oxygen molecules react at elevated temperatures during combustion, nitrogen oxides (NO_x) are formed, which are released into the atmosphere mainly in the form of nitric oxide. Nitric oxide is readily oxidized to nitrogen dioxide by reaction with ozone. Its effect on humans may lead to premature deaths when the particles are penetrated deep into respiratory system and to environment it is threatening as it can cause ground-level ozone by reacting with volatile organic compounds. Hydrocarbons (HC) are emitted because of incomplete combustion, and these are harmful to human and environmental issues. In the presence of nitrogen oxides, free radicals catalyze the oxidation of hydrocarbons to carbon dioxide and water vapors, ozone is generated as a by-product [20].

The above-mentioned emissions can be treated through exhaust after-treatment systems (EATS) as the example shown in [Figure 2]. There is a need to cut down emissions as much as possible for cleaner air and better life for living beings. This can be achieved by using technologies such as three-way catalyst (TWC) as in [Figure 3] and gasoline particulate filter (GPF). TWC filters reduce NOx to N_2, oxidizing HC, CO to H_2O and CO_2. For the TWC to work at the maximum efficiency point, the injection of gasoline needs to be done closer to stoichiometric value ($\lambda = 1$), and its temperature must be above 200 degrees Celsius. The particulate emissions can be reduced with the help of GPF, it traps the nano particles through filter. The same after-treatment technology is also being used in hybrid gasoline vehicles to meet the government regulations.

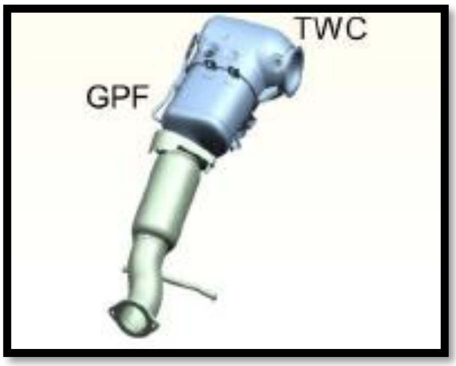

Figure 2. Gasoline EATS

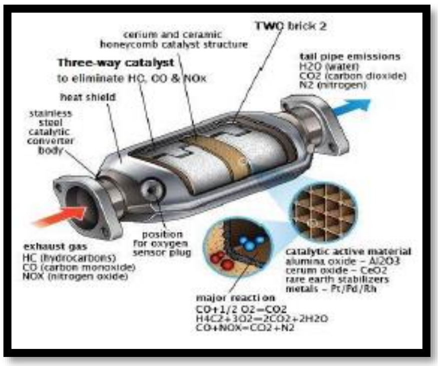

Figure 3. Three Way Catalyst (TWC)

Another technique to reduce emissions is by using alternative fuels in optimized way i.e., mixing ethanol or methanol with gasoline in SI engines. By mixing them with gasoline one can considerably reduce NO_x, CO, HC emissions also due to their lower heating value combustion becomes rapid [21].

1.1.1 Lambda / Oxygen Sensor

When the air/fuel mixture fed to the engine is maintained at stoichiometry a Three-way catalytic (TWC) converter is used in oxidizing carbon monoxide (CO) and hydrocarbons (HC) into carbon dioxide (CO_2) and water, and simultaneously reduce nitrous oxides (NO_x) into nitrogen. The stoichiometry is monitored in a closed loop by means of an oxygen sensor or lambda sensor.

Oxygen/ Lambda sensor measures the oxygen content in the exhaust gas. Zirconia O_2 sensors, Titania O_2 sensors and Wide band O_2 sensors are the different types of oxygen sensors available today. [22]

- Zirconia O2 sensor [Figure 4] is the popular sensor used all over. It comes with two varieties, heated and unheated. The unheated sensor takes up the heat coming from the exhaust gas and then it gets heated up itself. This process takes time to create signal and lights off when the vehicle stops and do not produce any signal then and will lead engine to get back to default setting. The heated sensor has heater circuit and lights on within a short time after the car's start. With this type of sensor, signals will be received quickly and reduces the cold-start smoke. Main advantage of this sensor is it will not light off when the car stops and hence there will be no false signals sent to the ECU. [22]

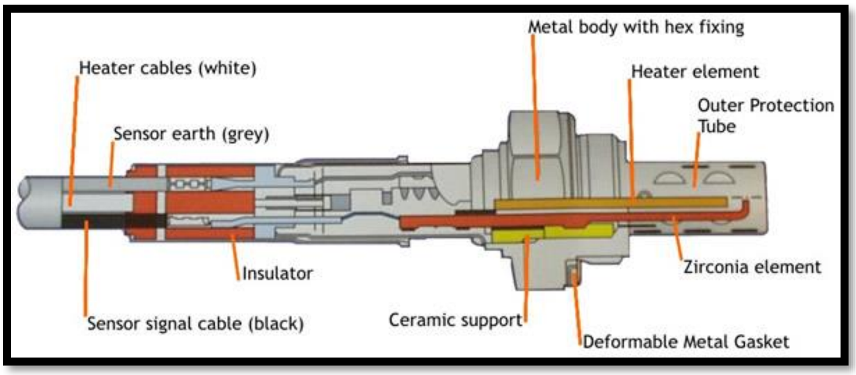

Figure 4. Zirconia lambda sensor [23]

- Titania O2 sensor [Figure 5] is made up of different kind of ceramic when compared to zirconia sensor and is used in partial models. The signal is created through voltage, the sensor lowers its resistance when the fuel is rich, and resistance is increased when engine runs lean. A base voltage produced by ECU is used as a base reference to read the changes in sensor. [22]

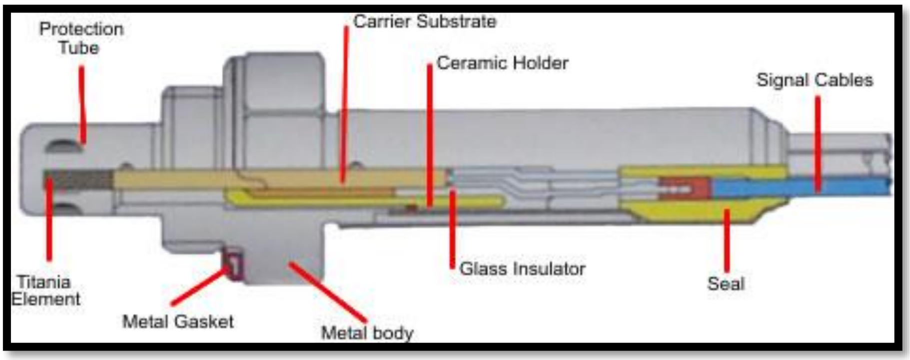

Figure 5. Titania lambda sensor[23]

- In the recent times manufacturers have been using Wide band O2 sensors [Figure 6]. These sensors create high level of voltage resulting in perfect ratio and helps engine to maintain the stability. [22]

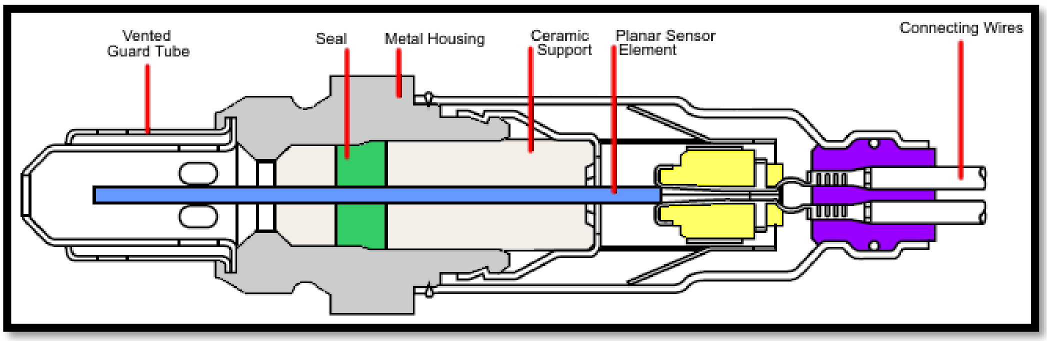

Figure 6. Wideband lambda sensor[23]

1.2. Euro Emission Standards

The first European exhaust emissions standard for passenger cars was introduced in 1970. In 1992 officially Euro 1 was into force asking to be fitted with catalytic converters to reduce CO emissions. [24]

Euro limit/ Emissions	**Euro 3** (January 2000)	**Euro 4** *(January 2005)*	**Euro 5** *(September 2009)*	**Euro 6b** *(September 2014)*
CO (g/km)	*2.3*	*1.0*	*1.0*	*1.0*
HC (g/km)	*0.20*	*0.10*	*0.10*	*0.10*
NO_x (g/km)	*0.15*	*0.08*	*0.06*	*0.06*
PM (g/km)	*No limit*	*No limit*	*0.005*	*0.005*
Driving cycle	*Revised ECE + EUDC*	*Revised ECE + EUDC*	*Revised ECE + EUDC*	*Revised ECE + EUDC*

[Note: From Euro 6d (September 2017) , WLTC + RDE cycle was used]

Table 1. European exhaust emission standards [25]

1.3. Test Procedures

To determine the emission level of a vehicle, different test procedures were developed to make a fair assessment for all vehicles. NEDC, WLTP and RDE are the test procedures conducted by the automobile industry and they are described in the below subsections.

1.3.1 New European Driving cycle (NEDC)

The NEDC procedure was used to assess fuel economy and emissions of light duty vehicles [26] prior September 1st, 2019. It was first introduced in 1970's, when it only had an urban part, and later received two updates, one which included an extra-urban part and one when CO_2 emissions started to be measured. The test procedure is conducted in two sections, urban driving, and extra urban driving conditions. For this test, the total distance covered will be approximately 11 km at an average speed of 33.6 km/h for a duration of 1180 seconds [24].

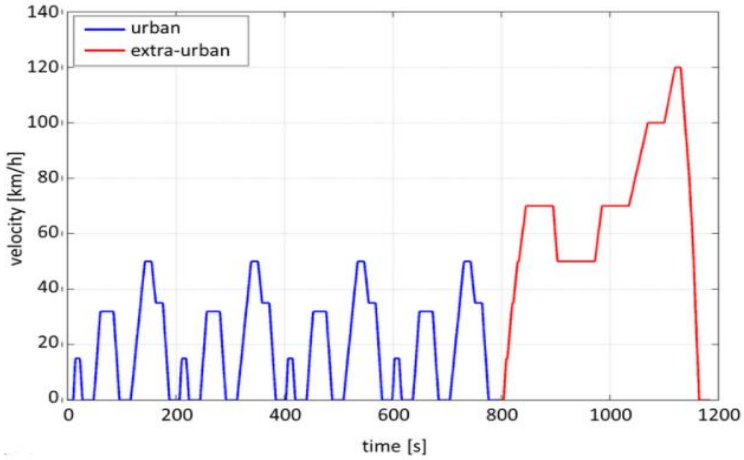

Figure 7. New European driving cycle [27]

From [Figure 7] it can be understood that urban driving section is longer while the extra-urban section is shorter. For extra urban driving, the accelerations are smooth for both sections and the gear shifting points are fixed for all vehicles, which is unrealistic. This driving cycle has been criticized for its unreal projection of real driving conditions, hence there was a need for development of a new driving cycle, which is more representative to real driving conditions from today's world, and is suitable to measure emissions, while being more dynamic and adaptive for different vehicles.

1.3.2 Worldwide Harmonized Light-duty Test Procedure (WLTP)

WLTP test procedure replaces New European Driving cycle (NEDC) and has been implemented from Euro 6d legislation. This test is conducted to decide the emission levels and types of emissions emitted, fuel consumption of conventional vehicles, hybrid vehicles and to find the range of fully electric vehicles.

The test procedure for WLTP includes gear shifting, weight ratio of vehicle, motion resistance, fuel quality, ambient temperature, tire type and pressure of it. There are three types of categories based on power to weight ratio (W/kg) as presented in Table 2:

Category	**Power type**	**Power to weight ratio (W/kg)**
Class 1	Low	≤ 22
Class 2	Medium	22 < ratio ≤ 34
Class 3	High	> 34

Table 2. WLTP classification of different categories [28]

As the power to weight ratio is very low even for the high-power type, only the Class 3 driving cycle will be presented. Usually, vans and busses belong to Class 2.

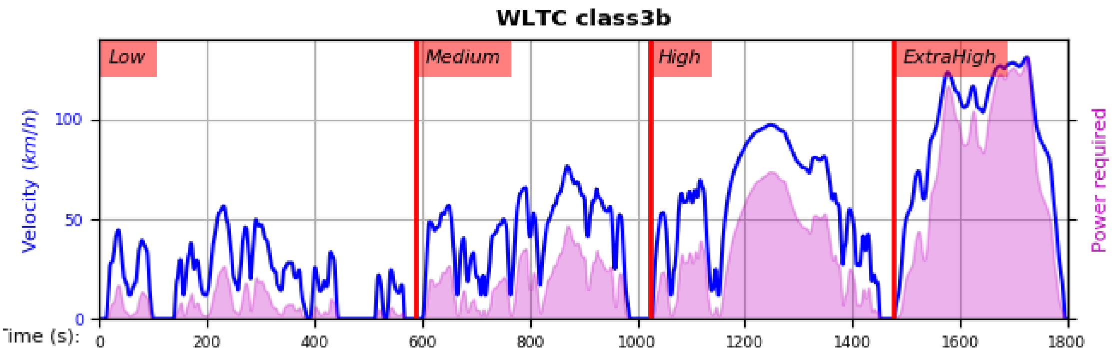

Figure 8. WLTC class 3b speed profile [29]

WLTP driving cycle is divided into four different average speeds: extra high, high, medium, and low, which test for different varieties of acceleration, braking, and maximum speed [30]. One can see that compared to the NEDC driving cycle, this one is more dynamic, having a larger range of accelerations, and the accelerations, especially compared to the urban section of NEDC, are not just from maximum speed to standing still, but WLTC also has parts simulating a speed bump for example, where one only reduces the speed up to 20-30 km/h and then accelerates again. A result of this is that the total stop time was lowered from 25% in NEDC to 13% for WLTP, which is closer to what one can expect in real driving conditions.

1.3.3 Real Driving emissions (RDE)

As most people were aware that the test procedures for emissions and fuel consumption are very optimistic, it was inevitable that at some point, researchers will test vehicles in the real world. The emissions resulted from real world testing were substantially exceeding the declared limits from laboratory testing. By using a PEMS, the Joint Research Center (JRC) found out that NO_x emissions from light-duty vehicles of Euro 3 to 5 show no significant reductions, even though the regulations were much stricter. As this issue became more apparent, in January 2011 the European Commission created a group of people with the responsibility

to develop a complementary test procedure for light-duty vehicles, named Real Driving Emissions – Light-Duty Vehicles (RDE-LDV) [31].
RDE was first introduced in the European region to complement WLTP. This test measures pollutants emitted by a car when driven on the roads in real traffic conditions [32]. The table below displays trip requirements for a valid RDE trip:

Driving portion	***Urban***	***Rural***	***Motorway***
	Speed ≤ 60 km/h	60 < Speed ≤ 90 km/h	90 km/h < Speed
Minimum distance	16 km	16 km	16 km
Distance share	29 – 44%	23 – 43 %	23 – 43%
Total trip duration	90 – 120 min		
Average speed including stops	15 < Avg < 40 km/h	–	–
Total stop time (v < 1 km/h)	6 – 30% of urban time	–	–
Individual stop time	≤ 300 s	–	–
v > 100 km/h	–	–	≥ 5 min
v > 145 km/h	–	–	< 3% motorway time
Cumulative positive acceleration gain	< 1200 m / 100 km		
Start/end test elevation difference	≤ 100 m		
Altitude	Moderate	0 – 700 m	
	Extended	700 – 1300 m	
Ambient temperature	Moderate	0 – 30°C	
	Extended	-7 ≤ T < 0°C 30 < T ≤ 35°C	
Payload	< 90% of maximum vehicle weight		
Use of auxiliary systems	Free to use as in real life (parameter not recorded)		

Table 3. Trip requirements for a valid RDE trip [33]

In addition to the requirements from Table 3, a light-duty RDE trip must start with a cold engine start, and it also has dynamic requirements for each trip section. They are implemented, so that even though the tests are conducted in real driving conditions, they will be repetitive and at the same time, the aggressiveness should represent normal driving behavior. The cold start requirements are stated below, and the dynamic requirements are presented in Table 4.

The conditions which should be met for a valid cold start are [33]:

- A cold start is defined as the first 5 minutes from starting the engine, or until the coolant temperature reaches 70°C
- Maximum speed ≤ 60 km/h
- The average speed including stop time: 15 ≤ Speed ≤ 40 km/h
- Total stop time < 90 s
- Idling after engine start < 15 s
- Vehicle conditioning: drive the vehicle for at least 30 min and then let it soak for 6 to 56 hours
- If the last 3 hours of conditioning were done in temperatures between -7 and 0°C, or between 30 and 35°C, a corrective factor of 1/1.6 must be applied to pollutant emissions during cold start, but not to CO_2.

Driving portion	***Urban***	***Rural***	***Motorway***
Minimum number of acceleration points	150	150	150
95th percentile of $v \cdot a_{pos}$	$v \cdot a_{pos\ [95]} < 18.7$	$v \cdot a_{pos\ [95]} < 24.3$	$v \cdot a_{pos\ [95]} < 26.6$
Relative positive acceleration (RPA)	RPA > 0.13	RPA > 0.06	RPA > 0.03

Table 4. Dynamic boundary conditions for a valid RDE trip

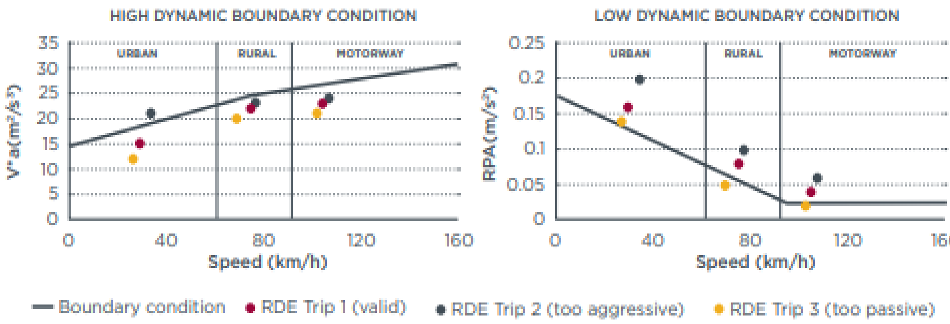

Figure 9. Dynamic boundary conditions with three illustrative trips [34]

For the RDE trip to get validated, rural, urban and highway section must satisfy high dynamic and low dynamic boundary conditions [Figure 9]. The driving sections for High dynamic boundary condition should be under the line representing speed multiplied by positive acceleration. While for Low dynamic boundary condition, all the sections should fall above the line representing relative positive acceleration. The trip is considered as invalid for being aggressive, when speed multiplied by positive acceleration is higher than the indicated line. Similarly, when the trip is smooth it is rejected that is, if relative positive acceleration less than the indicated line. [34]

1.4 Scope:

- Investigate local emissions (CO_2, CO, NOx, and PN) behaviour based on,
    - Type of fuel - Gasoline and Ethanol (E85),
    - RDE route – Hilly and flat,
    - Driving style – Calm and Aggressive drive,
    - Cold start - morning and warm start - afternoon.

- Understand the fuel consumption based on these parameters.

1.4.1 Limitations:

- Variance in Ethanol blend at fuel station
- Lack of technology to purge fuel while refuelling
- Single test driver - less variance in driving style
- Two test drives need to be discarded (ECU was not working)
- Lack of time – hampering repeatability and reproducibility
- Certain inaccuracies at times from measuring devices

2. Methodology

In this section, the instruments used in the measurement, connections, and data transfer will be explained. The instruments used in the test are GPS, ambient sensors, AVL PEMS device, exhaust flow meter (EFM), I-bus tool to obtain vehicle speed, engine speed, engine temperature. The data obtained from I-bus tool and PEMS are monitored in AVL M.O.V.E system control. The data stored is post-processed in AVL's concerto and calculations were made in MATLAB software.

2.1. Vehicle used for testing

For our Thesis, Saab 95 Sport-Combi biopower model was used. It runs on both E85 and gasoline from the factory and the specifications are presented in Table 5.

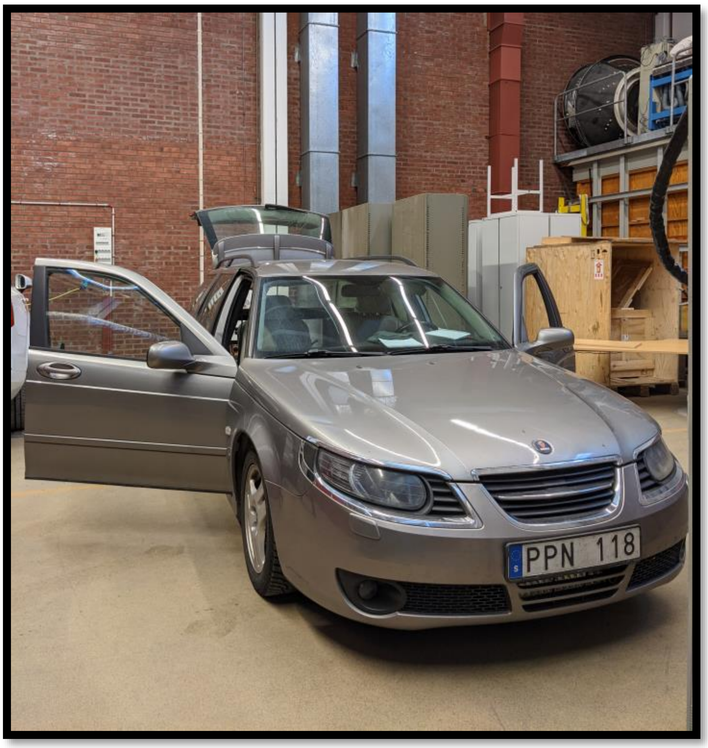

Figure 10 Test vehicle Saab 95

Parameter	Specifications E85	Specifications Gasoline
Engine	Internal Combustion Engine	
Number of cylinders	4	
Displacement	1985 cm^3	
Max power	132 kW	110 kW
Max torque	280 Nm	240 Nm
Fuel	E85	Gasoline
Model year	2006	
Emission standard	Euro 4	Euro 4

Table 5. Saab 9-5 sport combi specifications [35]

2.2. Portable Emissions Measurement System (PEMS)

PEMS is an equipment used to measure emissions emitting from the combustion engines, which is placed on a towbar of a test vehicle. The data obtained from PEMS is used to check the impact of emissions emitting from the combustion engines upon the atmosphere [36]. For this Thesis AVL PEMS device is used for emissions measurements. The device consists of 'AVL Gas PEMS iS' which analyzes characteristic of exhaust gases and 'AVL PN PEMS iS' which measures particle concentration of exhaust gases. GPS sensor, ambient sensors, charger, batteries, Exhaust flow meter (EFM) and calibration unit are the auxiliary components which are connected to respective ports of GAS PEMS and PN PEMS for measuring.

Figure 11. Test setup

The GPS and ambient sensors are placed in the middle of the roof of the vehicle connected to PEMS unit. The batteries provide electric supply for the PEMS device and to other auxiliary units (as mentioned earlier) while testing on the road and when stationary, the supply is done directly from the grid. To monitor and record the data, AVL M.O.V.E system control software is used via ethernet connection between the PEMS computer and external PC. All the auxiliary units are fixed and placed firmly at respective places to protect them from getting damaged also the PEMS unit is covered in a proper way to keep it protected from dust contamination and other conditions. The test runs were made on completely sunny days, though the weather conditions were bit on colder side 3°-9° C.

2.2.1. PEMS Working Principle

The very first test performed is calibration test which is called pre-test in which GAS, PN, condensate leak check is performed with the help of eCAL box and after completing the test drive, post-test is performed. The exhaust temperature, pressure and flowrate are measured at EFM, and the gases are fed to it via EFM probes. The VPR (volatile particle remover) is attached to the sample gas inlet, which dilutes the exhaust gas and disregards volatile particles before sending the gas to the PN PEMS. Through the VPR system, the gas for the GAS PEMS is sent untreated. The drain hose should be ensured it is facing towards the ground for smooth and easy flow of gases and it should be made sure that no condensate will be formed inside the measuring unit.

2.2.2. GAS PEMS working principle

Initially a raw exhaust gas of 2 l/min is fed via heated sampling line to the GAS PEMS. The particles from the raw exhaust gas are removed by the filter present in the heated sampling line. The filtered gas is pre-cooled by ambient conditions and transported to two-stage chiller.

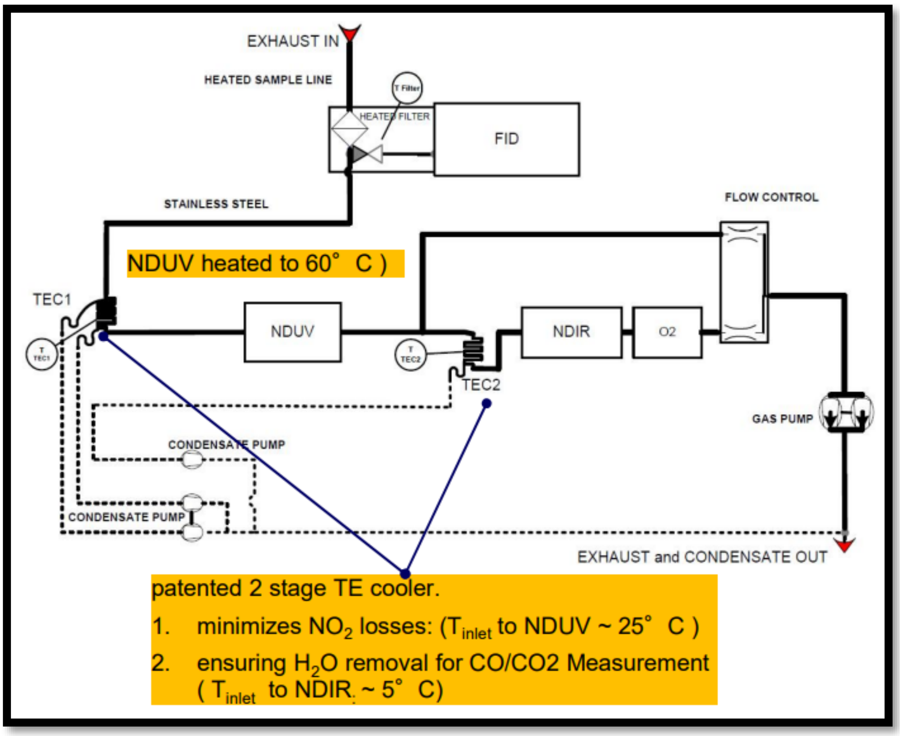

Figure 12. AVL GAS PEMS Working principle [37]

Non-dispersive Ultraviolet Analyzer (NDUV) measures the NO and NO_2 from the gas flow after the first chiller stage and downstream of this, the gas flow is split into two separate flows. One gas flow is bypassed, and the second flow enters second stage chiller where Non-dispersive Infrared Analyzer (NDIR) measures CO, CO_2 and O_2 sensor measures oxygen level in the gas flow. The flow is restricted by critical orifices present in the orifice block. Two individual pump circuits are used to draw the condensate and sample gas into two stage chiller. The gas flows and condensate flows are remerged after the orifice block and passes out of the device through drain outlet [38].

2.2.2.1. Non-dispersive Ultraviolet Analyzer (NDUV) working principle

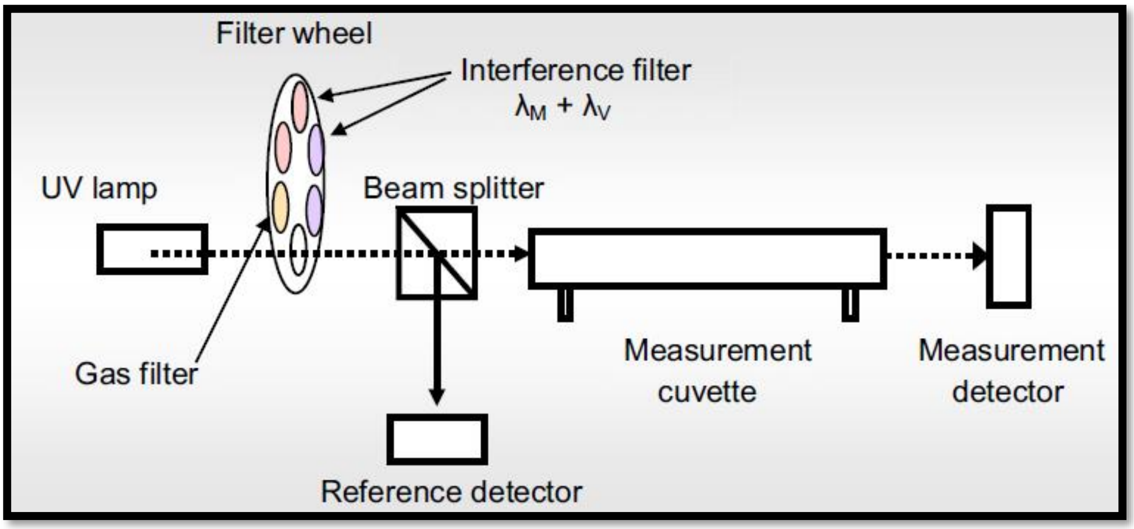

Figure 13 . AVL GAS NDUV Working principle [39]

NDUV analyzer consists of UV radiation source, filter wheel, beam splitter, reference detector, measurement cuvette and detector. NDUV is used to measure NO and NO_2 from the sample gas flow. The UV lamp emits the radiation which will be then toned by the filter wheel and the beam splitter splits the radiation into measuring beam and reference beam. With the help of these beams four signals are recorded for two interference filter positions. For the NO measurement, four-beam method produces high measuring stability. This measuring method is therefore a resonant method and is referred to as resonance absorption spectroscopy [39].

2.2.2.2. Non-dispersive Infrared Analyzer (NDIR) working principle

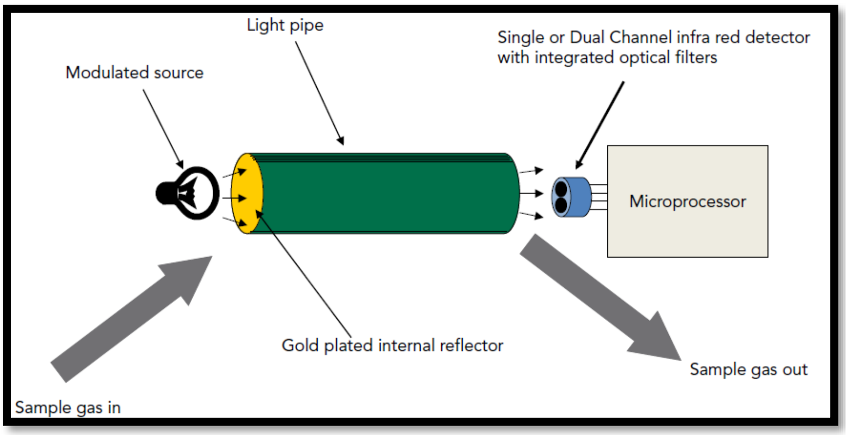

Figure 14 AVL GAS NDIR Working principle [40]

NDIR analyzer measures the concentration of CO_2 and CO present in the exhaust gas stream. Infrared lamp, tube/pipe , and a detector are the components of NDIR.

The sample gas is allowed to pass through the tube, infrared radiation projecting towards tube absorbs molecules in specific wavelength as per Beer-Lambert law. The detector determines the gas concentration through reduction of wavelengths.

2.2.3. PN Sensor

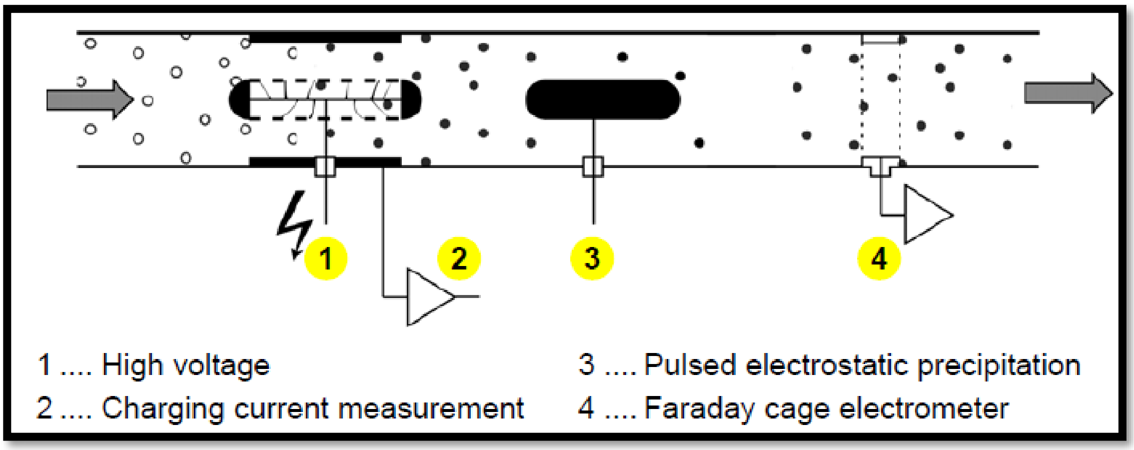

Figure 15 AVL PN PEMS Working principle [41]

The sample aerosol is made to pass through unipolar diffusion charger and further into pulsed electrostatic precipitator, this setup produces a charge modulation in aerosol which is detected in Faraday cage. Corona wire is used to charge the diluted exhaust gas which has entered through aerosol inlet and hence charged ions are released. These ions in turn charge the particles present in the aerosol. Whenever a charged particle cloud pass though Faraday cage, a signal is sensed. Due to electrostatic induction, compensation currents are formed through which signal originates. These compensation currents are directly proportional to charge of the particles, thus the detected peak corresponds to number of particles [41].

2.2.4. AVL M.O.V.E System Control software

To record the data, to monitor, AVL's M.O.V.E system control software is used. The software is designed in such a manner that it integrates all the data from auxiliary units like GPS, ambient temperature, pressure, EFM, CAN bus signals from ETAS INCA and stores in database and performs calculations.

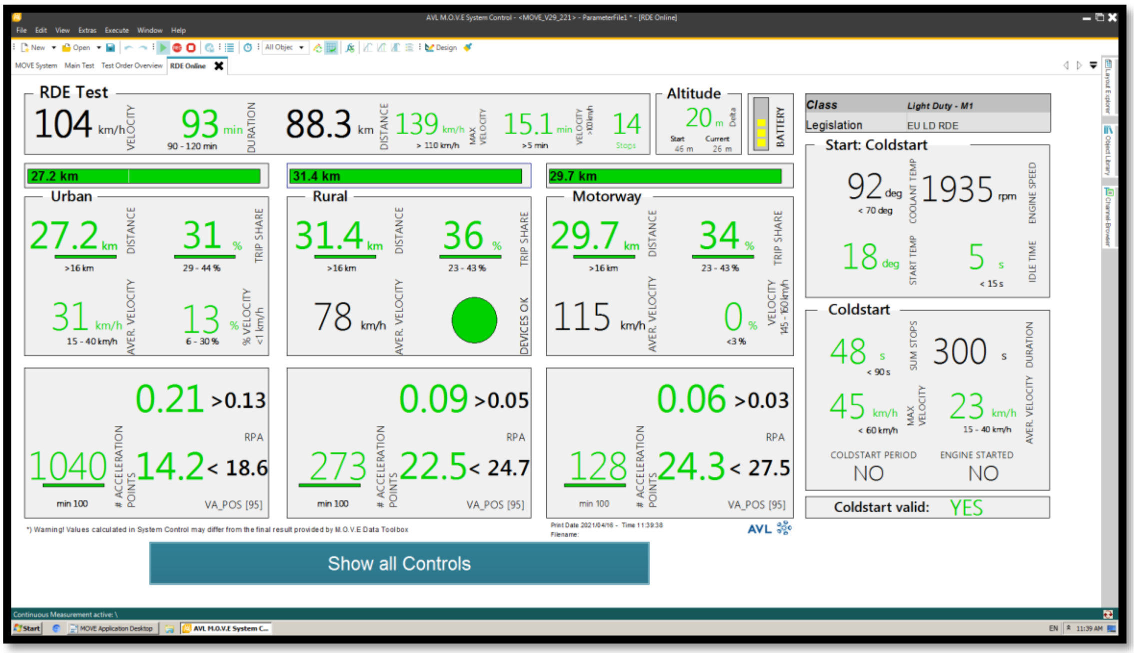

Figure 16. AVL M.O.V.E system control

When the main test is activated in the software, data logging starts and a live RDE monitoring window pops up (Figure 16) where one can see the various criteria like total duration of the trip, max velocity of the test vehicle, urban, rural, motorway driving conditions that need to be fulfilled to make the test valid for analysis. When the respective criteria are met, the complete dashboard turn out to be green colored indicating the test is legal and ok for analysis. After completing the RDE test requirements to save the obtained data, stop and save function is pressed. The data logging of the emissions, driving situations, ambient conditions are recorded in real-time by PEMS unit. The CAN bus data such as vehicle speed, engine speed, engine temperature is taken from ECU through ETAS tool. During calculations, the CAN bus data from ECU is compared with GPS signals to detect any inconsistencies and is then post-processed.

2.3. RDE Routes

For the RDE testing, the test routes Landvetter and Kungsbacka was inspired from the 2018 Master thesis carried out by Ludvig Andersson and Mohammed Saeed [42]. The routes are created considering RDE legislations, speed limits, traffic conditions with the help of AVL software 'Route Identification' application. All the tests conducted had their starting point from Chalmers University. The route is designed in such a way that the three parameters Urban, Rural, Motorway has proper share of kilometers, total duration, total trip length to match RDE light duty test requirements.

- Landvetter is termed as a hilly route, the test begins from the Chalmers University moving onto urban part Högsbo, Mölndal further into rural area Kållered, Härryda and lastly motorway area.

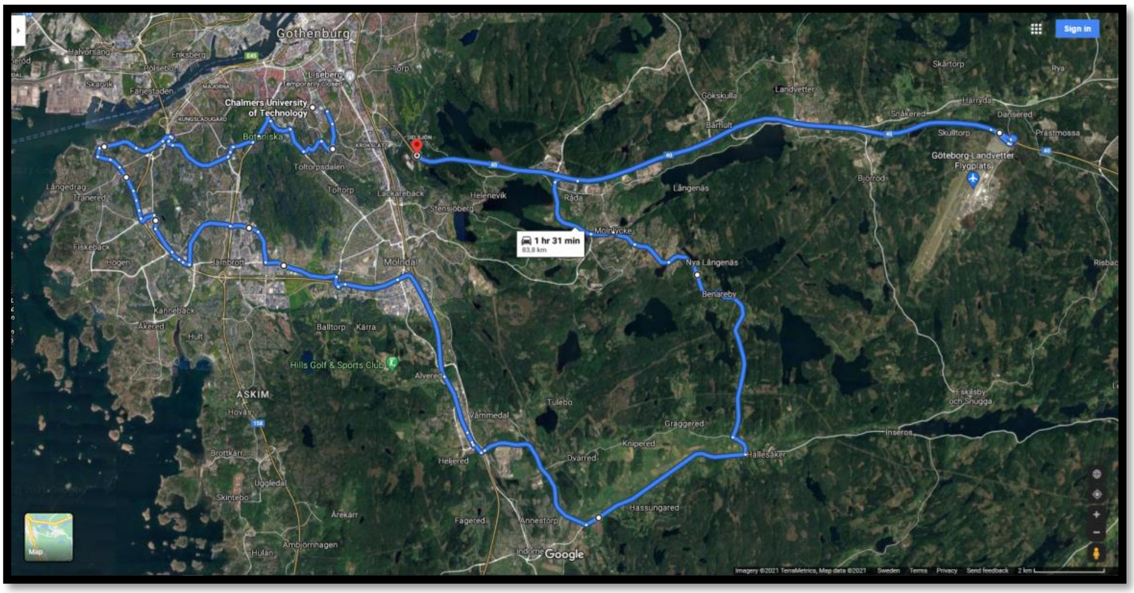

Figure 17. Landvetter route

- Kungsbacka is termed as flat route, starts from Chalmers University heading towards urban area Frölunda, passing onto rural part towards Särö and Kungsbacka leading to motorway and ends at Kållered.

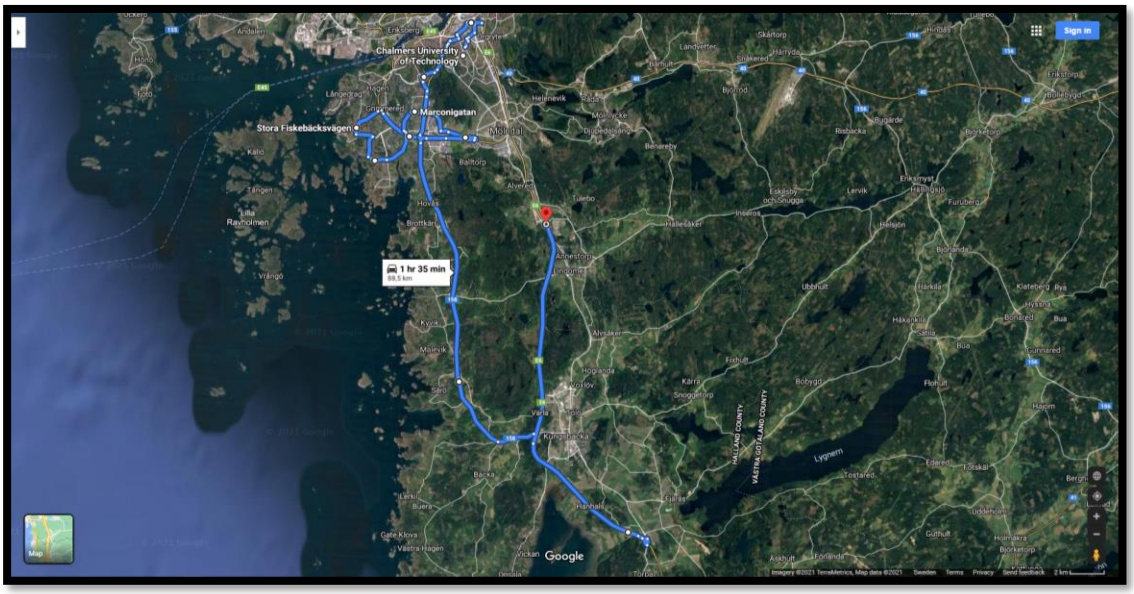

Figure 18. Kungsbacka route

2.4. On-road RDE testing

The test runs are made on Kungsbacka and Landvetter routes. The test was conducted with two different fuels, Ethanol (E85) and Gasoline, with different driving styles that is aggressive driving and calm driving, to compare the nature of emissions during the drive. In total 16 test drives were performed, among them two tests had to be discarded due to inconclusive results. During testing, the temperatures were usually cold averaging around 7 degrees. Calibration tests was performed at indoors, pre-test conducted before the start of the test drive and post-test after completing the test drive.

2.5. EFM issues

While analyzing the data, it was noticed that the Exhaust Flow Meter (EFM) was not measuring properly all the time, as sometimes it was measuring negative values of the exhaust volume flow rate, leading to negative values of emissions, which is not possible. This issue is presented in Figure 19.

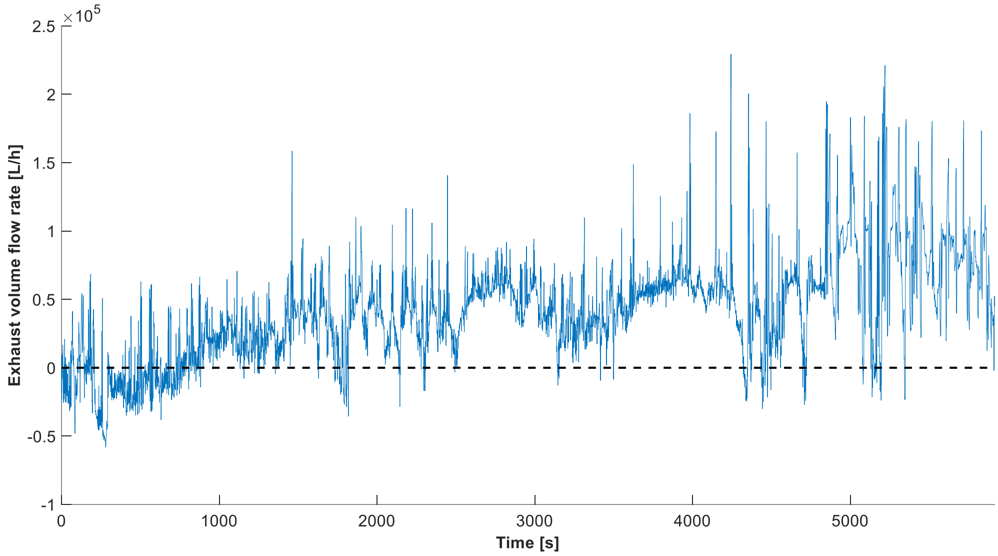

Figure 19. A representation of the exhaust volume flow rate measured with the EFM for Kungsbacka afternoon E85 aggressive

As these measurements are not reliable and lead to invalid results, a solution to replace this data was searched. The best way that we found for approximating the exhaust volume flow rate was from the intake mass air flow rate, by using equation (1):

$$\dot{V}_{exh} = \frac{\dot{m}_{air} \cdot 3600}{\rho_{air}} \quad (1)$$

,where:

$\dot{V}_{exh}$ $[{}^{L}/_{h}]$ is the exhaust volume flow rate

$\dot{m}_{air}$ $[{}^{g}/_{s}]$ is mass air flow rate from intake

ρ_{air} $\left[{}^{kg}/_{m^3}\right]$ is the air density

As the air density varies with temperature and the intake air temperature was logged through ECU, the air density at every point was found by interpolating between known values of the density at given temperatures.

To get a better overview of the results, a dataset where EFM was measuring without big errors was searched, and the results are presented in Figure 20.

A source of error for this calculation was given by the fact that the fuel was not considered, but as the air fuel ratio is around 14, depending on the fuel, the error will be around 7%. The fact that the issue was discovered late during the thesis, made it more difficult to make a better approximation of the exhaust volume flow rate.

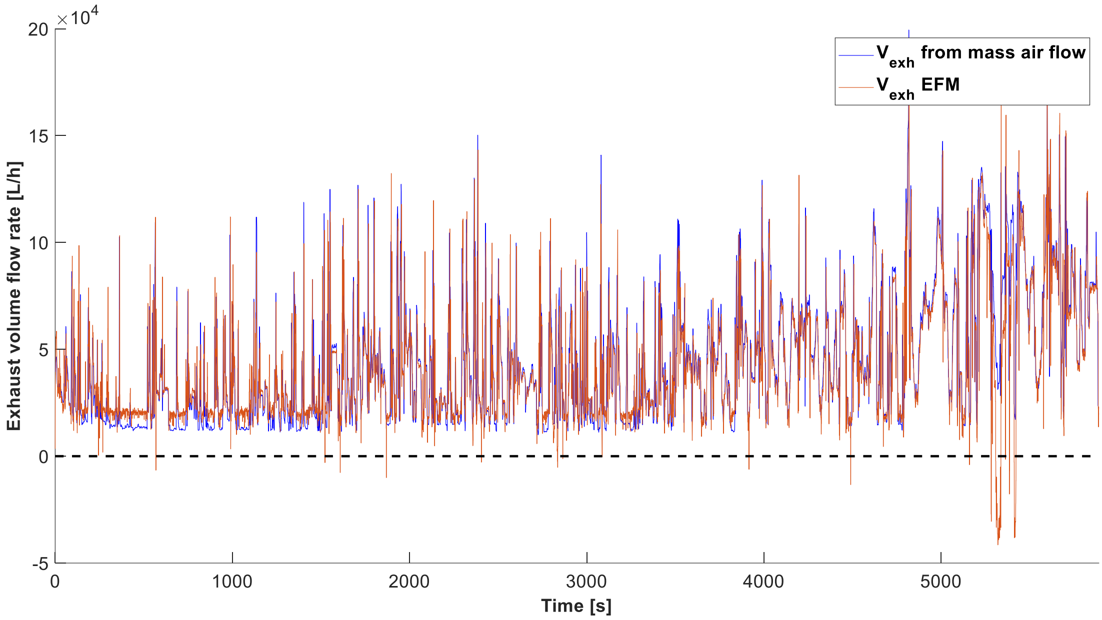

Figure 20. Comparison between exhaust volume flow rate calculated and measured for Kungsbacka E85 morning calm

From Figure 20, it can be observed that this method of approximating the exhaust volume flow rate is precise for most of the time, which makes it valid for using it in calculating the emissions. Moreover, the mass air flow rate is taken from the ECU, and as it is an important parameter for the engine, it will be more precise than the EFM.

Another observation from Figure 19 is that for low speeds and the engine running at idle speed, there is a big difference between the two variables, so a shift on y-axis will be applied in this case. Regarding the x-axis, there is a time delay of around 2 seconds between them, as it takes time for the intake air to reach the exhaust, so a 2 second shift on x-axis will be applied for the calculated exhaust volume flow rate.

An issue with the data taken from the ECU is that sometimes the logging is interrupted. For these time instances, the EFM data will be taken. For the dataset presented in Figure 20, the measurements were interrupted for 0.5% of the total time (around 30 seconds).

Finally, the moving average function will be applied to the data, to reduce the peaks.

After applying the shifts, Figure 21 is obtained:

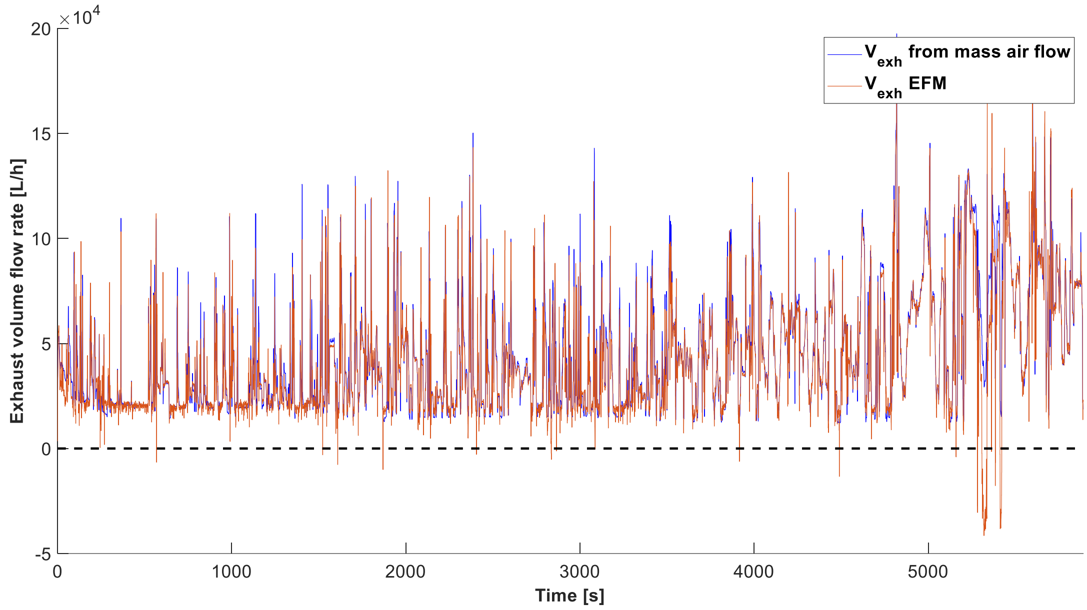

Figure 21. The exhaust volume flow rate for Kungsbacka E85 morning calm after the idle speed offset was applied to the calculated exhaust volume flow rate

Next, the sum of CO_2 emissions for the whole trip will be presented in Figure 22.

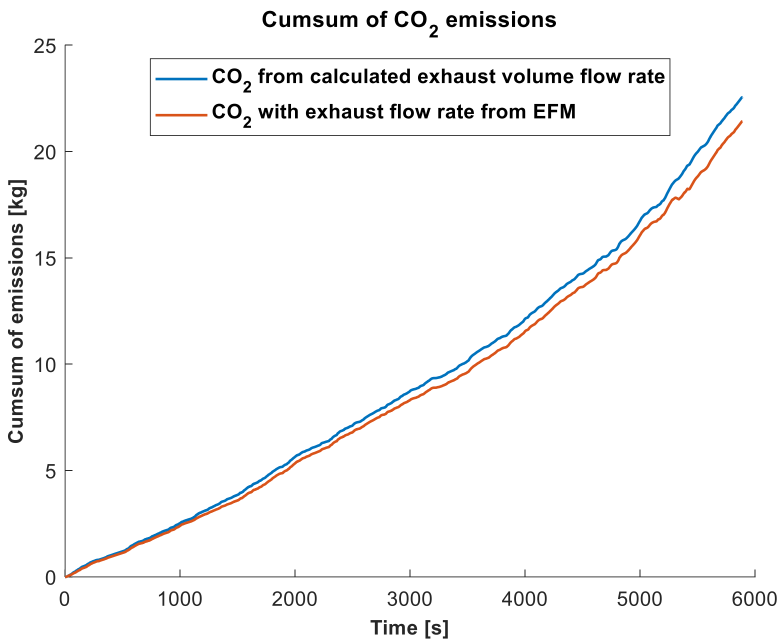

Figure 22. Total CO2 emissions resulted from the two-exhaust volume flow rate calculations

From Figure 22, the emissions resulted from the approximated exhaust volume flow rate are higher, which was expected, as the EFM was giving negative values at times, and sometimes it was reading lower values than the actual ones. The difference between the total CO_2 emissions resulted from the calculation is 1 kg CO_2 for this case, but for other data sets, the difference is even higher.
To validate this approximation of $\dot{V}_{exh}$, more examples will be presented in the figures below:

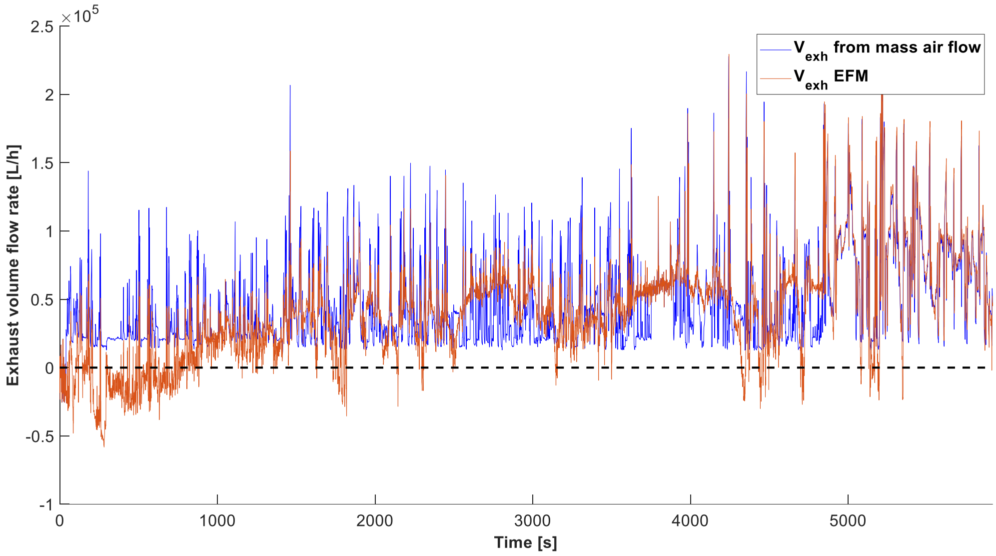

Figure 23. The exhaust volume flow rate from Kungsbacka, afternoon, E85, aggressive

What is interesting about Figure 23 is that the EFM was being faulty not only when it was registering negative values, but it was also registering too high values from 2500 to 3000 seconds and from 3500 to 4300 seconds, meaning that if one would only replace the negative values, the results will still be wrong. To verify that the ECU gave correct values, the vehicle speed vs time from PEMS raw data and ECU are displayed in Figure 24, and as one can see, the ECU values for vehicle speed match the ones from the ibus, meaning that the source of error is not represented by the ECU readings.

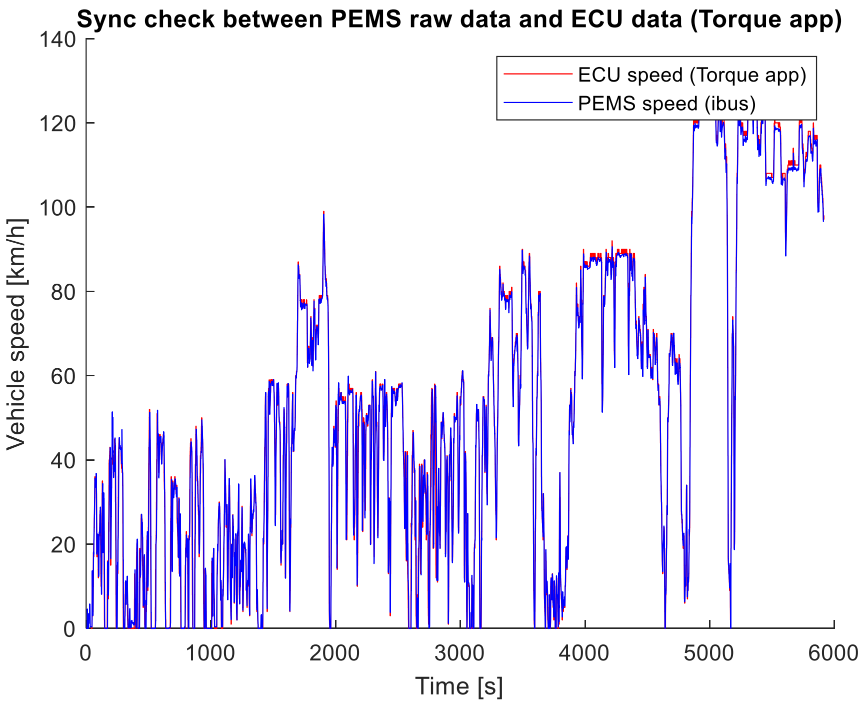

Figure 24. Sync check between PEMS raw data and ECU data

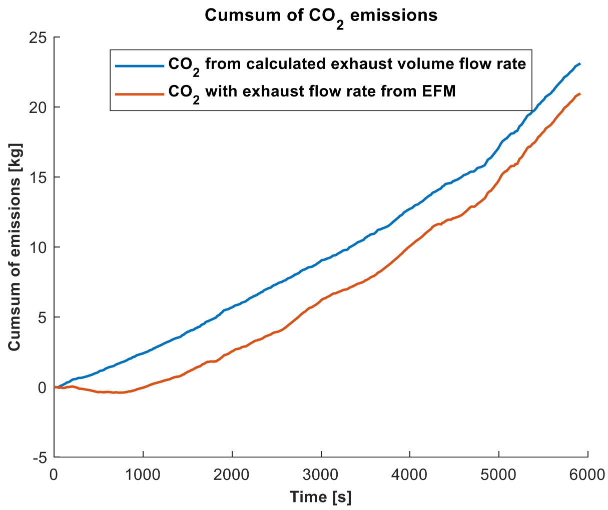

Figure 25. The total CO2 emissions from Kungsbacka, afternoon, E85, aggressive

In the case presented in Figure 22 and Figure 25, the difference between the total CO_2 emissions resulted from the two exhaust volume flow rates is about 2 kg, which is almost 25%.

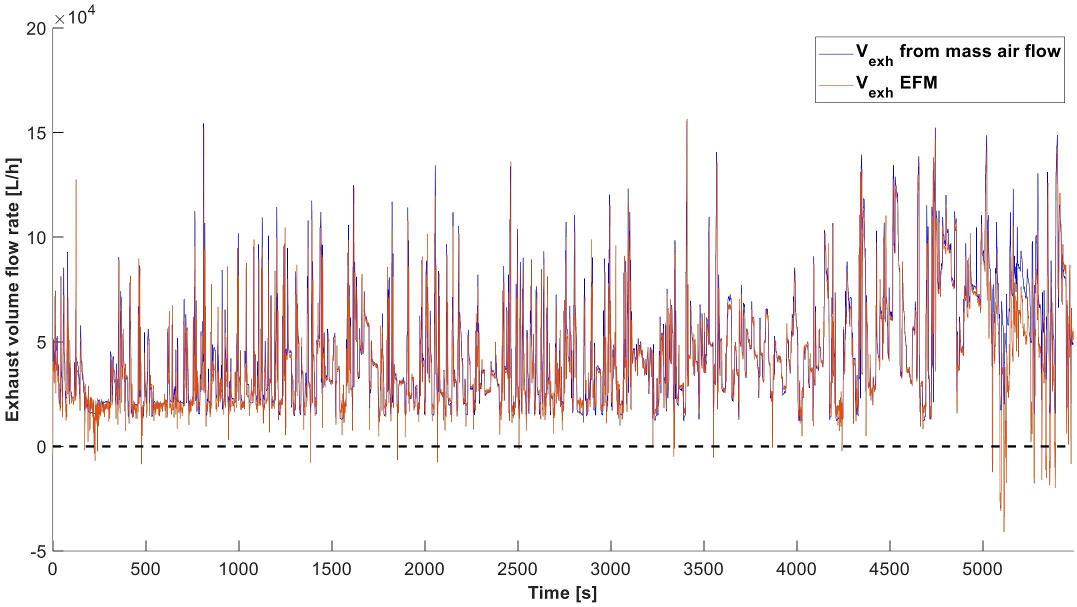

Figure 26. The exhaust volume flow rate for Kungsbacka, morning, gasoline, calm

Figure 26 displays a nice match between the two measurements and at the same time, the EFM registering negative values, mainly in the motorway part.

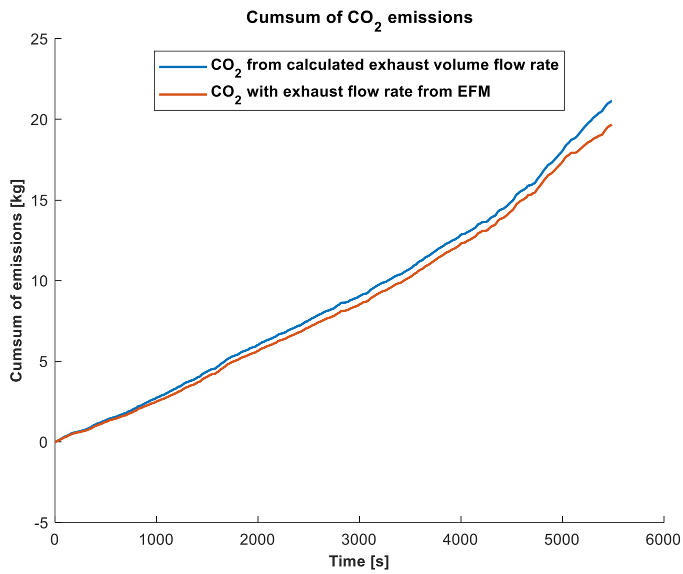

Figure 27. Total CO_2 emissions for Kungsbacka, morning, gasoline, calm

As for this case the EFM was working relatively good in the first 4000 seconds, there is not a considerably high difference between the CO_2 emissions calculated with the different $\dot{V}_{exh}$ values.

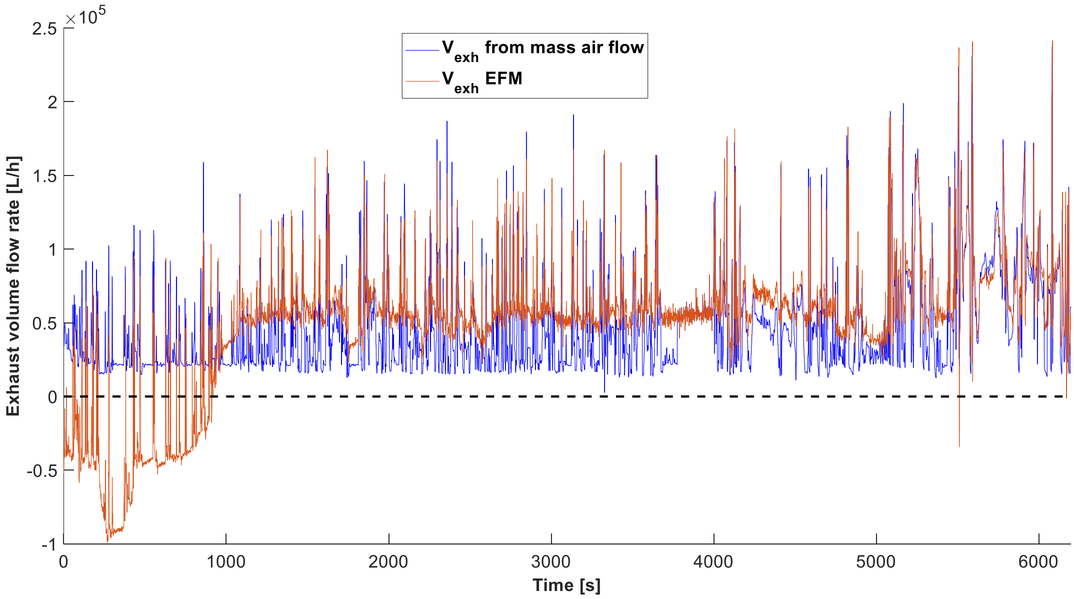

Figure 28. The exhaust volume flow rate for Kungsbacka, afternoon, gasoline, aggressive

The difference between the two exhaust volume flow rates in the case presented in Figure 28 is very high and it is also present for most of the time. For this data set, as well as the one from Figure 20 and Figure 19, it looks like the EFM had a positive offset, which might be the result of a wrong calibration, making the emissions resulted from the calculations with EFM data invalid, leading to wrong conclusions.

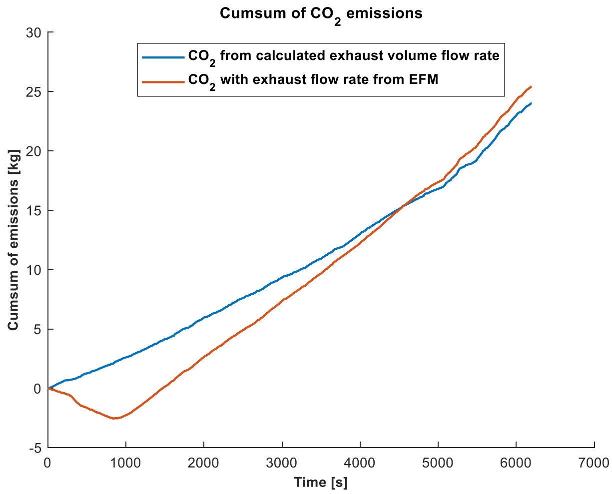

Figure 29. The total CO_2 emissions for Kungsbacka, afternoon, gasoline, aggressive

As for the last case, the $\dot{V}_{exh}$ from EFM was mostly negative in the first 1000 seconds, the CO_2 emissions are also negative, and because EFM measurements had a positive offset on y-axis, in the end, the total CO_2 emissions are higher for the EFM.

2.6. Data processing

Data gathered from the RDE trips was post processed in Concerto and the raw data was imported in MATLAB for the calculations. As the calculations were done in MATLAB, raw data had to be converted from ppm into units used in the EURO legislation to check the compliance. For RDE tests, firstly, one has to make a moving average of 1 second of the raw data. To calculate the emissions in [g/km] we need to have the pollutants in [g/s]. This is calculated with equation 1, using the pollutant [ppm], a coefficient specific for each gas and the exhaust mass flow rate. The exhaust mass air flow rate is calculated from the exhaust volume flow rate and the exhaust gas density, which has predefined values for each fuel. Finally, the pollutant in [g/km] is calculated using equation 3.

$$\text{POLLUTANT [g/s]} = \text{pollutant [ppm]} \cdot u_{gas}\ [-] \cdot \dot{m}_{exh}\ [\text{g/s}] \qquad (1)$$

,where:

u_{gas} [-] is the molecular weight of the gas / molecular weight of the exhaust gas

$\dot{m}_{air}$ $[{}^{g}/_{s}]$ is exhaust mass flow rate

$$\dot{m}_{exh}\ [\text{g/s}] = \frac{\dot{V}_{exh}\ [\text{l/h}]}{3600} \cdot \rho_{exh}\ [\text{kg}/m^3] \qquad (2)$$

,where:

ρ_{exh} $[\text{kg}/m^3]$ is the exhaust gas density

$$\text{POLLUTANT [g/km]} = \text{pollutant [g/s]} \cdot \frac{3600}{vehicle\ speed\ [km/h]} \qquad (3)$$

3. Results

The section starts with explaining the difference between calm and aggressive driving styles, continuing with presenting the fuel consumption figures obtained from the tests and then the exhaust-out emissions of the vehicle for both E85 and gasoline.

3.1. Assessing the aggressiveness

The variable for aggressiveness assessment is the 95th percentile of VAPOS, defined as the average of the positive acceleration. To ensure repeatability, the VAPOS values were monitored constantly throughout the tests and the driving style was adjusted to get the VAPOS as close as possible to the values from the previous trips made with the same aggressiveness level. For the calm driving style, the accelerations were smooth, and the gears were shifted at lower engine speeds compared to the aggressive drives. For the latter, we tried to get as close as possible to the maximum VAPOS limit, so a few overtakes were simulated for the rural and motorway parts. For the urban part the difference between the driving styles was less obvious because of traffic limitations, still the harder accelerations meant that indeed there is a difference between calm and aggressive driving styles. Moreover, it was observed that other drivers were usually accelerating in an aggressive manner.

To compare the difference between the trips and driving styles, the optimal solution was to create a VAPOS histogram for each trip and to set apart the calm and aggressive driving styles. The results are presented in Figure 30 and Figure 31.

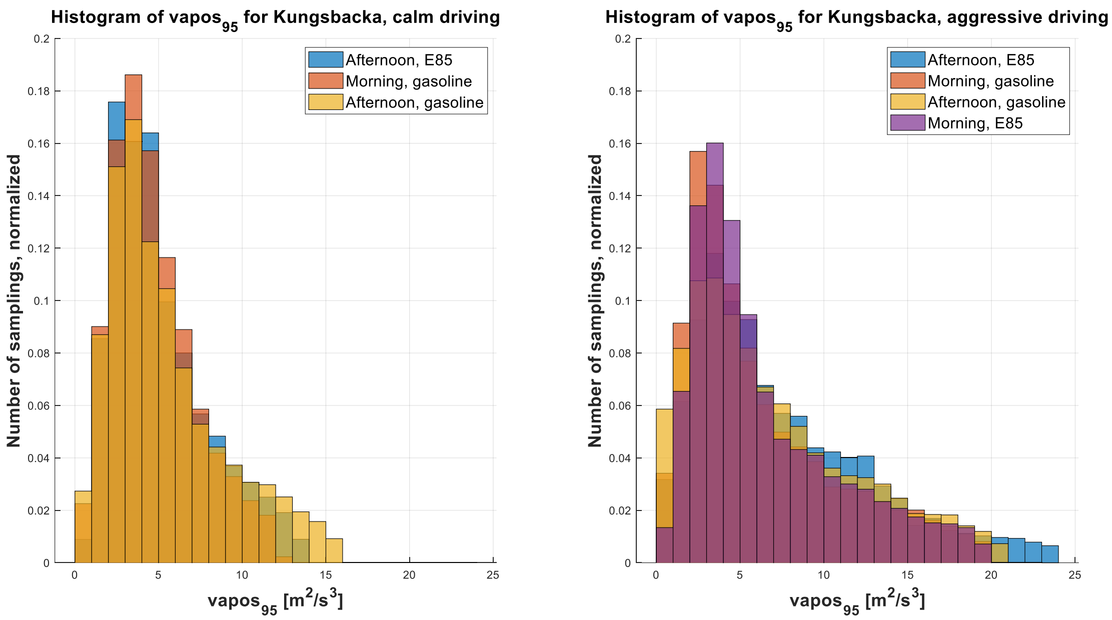

Figure 30. VAPOS histograms for Kungsbacka route

From Figure 30 it can be observed that maximum VAPOS was higher for the aggressive drives, meaning that the driving was more aggressive. While simulating the overtaking's, gears were shifted at around 4000 rpm, to achieve higher acceleration values.

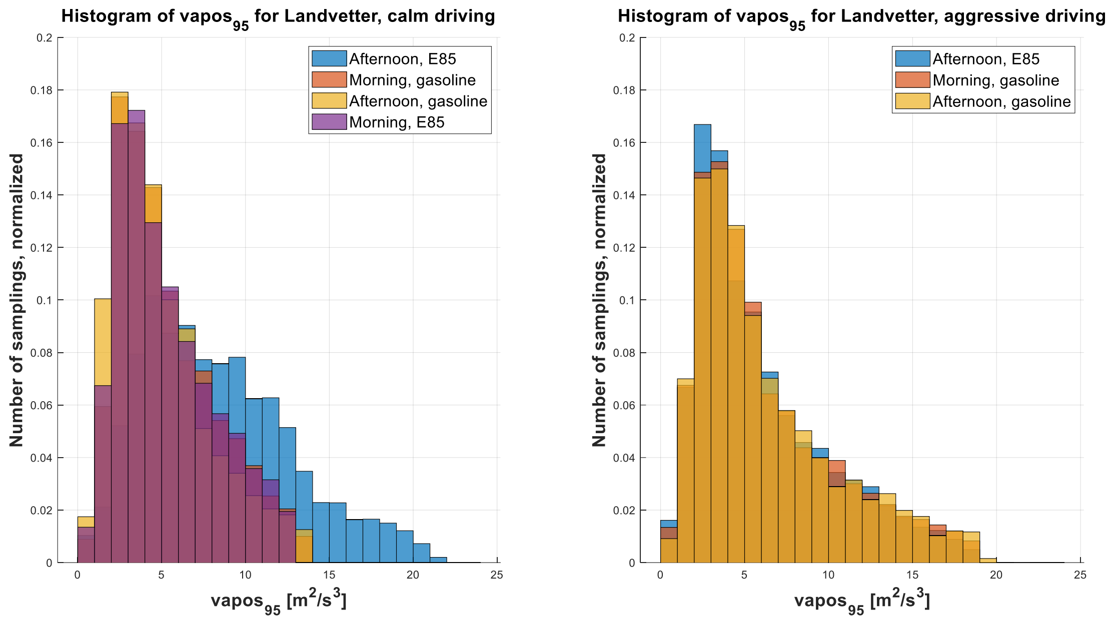

Figure 31. VAPOS histograms for Landvetter route

Figure 31 shows a similar trend as Figure 30, with the addition that case Landvetter, Afternoon, E85, calm (the blue histogram from the left) is an aggressive drive.

3.2. Fuel consumption

The fuel consumption was recorded during each trip using the trip computer. This is not the best solution but because the vehicle knows exactly the composition of the fuel, and that the EFM would increase the error when calculating the fuel consumption, the trip computer seems like the best estimation. In Table 6 there will be presented the fuel consumption given by the trip computer.

Route	Driving style	Gasoline		E85	
Kungsbacka	*Calm*	9.5	9.6	12.0	11.9
	Aggressive	10.1	10.6	12.0	12.4
Landvetter	*Calm*	9.6	9.6	11.9	11.9
	Aggressive	10.1	10.4	11.8	12.0

Table 6. The average fuel consumption for each trip [L/100 km]

As one can see from Table 6, the route does not impact the fuel consumption, but the driving style seems to be the factor that matters. To better understand the data, Table 7 shows the average fuel consumption, considering only the driving style and the fuel.

	Gasoline		E85	
	Fuel consumption [L/100km]	**Standard deviation**	**Fuel consumption [L/100km]**	**Standard deviation**
Calm	9.6	0.05	11.9	0.05
Aggressive	10.3	0.24	12.0	0.25

Table 7. The average fuel consumption with the standard deviation for each fuel and driving style

From Table 7 the standard deviation is much higher for the aggressive drives for both fuels, and it also has very similar values, meaning that the driving style is indeed the decisive factor for fuel consumption. It can also be noted that there is 24% increase in fuel consumption between gasoline and E85 for calm drive, and 16% increase for aggressive drive, meaning that the engine seems to be more efficient on E85 when driving more aggressive.
A better way of representing the energy consumption is by looking at the energy consumption, as it considers the energy density for each fuel. The energy consumption is calculated with equation 4:

$$E.c.[kWh/100km] = f.c.[l/100km] \cdot u_{fuel}\,[kWh/l] \quad (4)$$

,where:

E.c. $[kWh/100km]$ is the average energy consumption

f.c. [l/100km] is the average fuel consumption

u_{fuel} [kWh/l] is the energy density for each fuel

u_{E85} = 6.3591 [kWh/l]

$u_{gasoline}$ = 8.976 [kWh/l]

From equation 4 one can see that E85 has 29% less energy density than regular gasoline (E5), and the fact that the fuel consumption was 16% more in the case of E85 for the aggressive driving suggests that the engine runs more efficiently on E85.

	Gasoline		E85	
	Energy consumption [kWh/100km]	**Standard deviation**	**Energy consumption [kWh/100km]**	**Standard deviation**
Calm	85.5	0.8	75.8	0.3
Aggressive	92.4	2.2	76.6	1.6

Table 8. The average energy consumption with the standard deviation for each fuel and driving style

From Table 8 it can be seen that the energy consumption for E85 is much less than for gasoline, Still, the fact that the actual blend used is not accurately known, the energy density of E75 would be higher than the one of E85, meaning that the engine runs more efficiently on E85. Still, the fact that the actual blend used is not accurately known, the energy density of E75 would be higher than the one of E85, meaning that the energy consumption for E85 will be higher. There are also other factors like the molar expansion ratio which affect the efficiency of the engine, but this is outside of the scope of this thesis.

3.3. CO_2 emissions

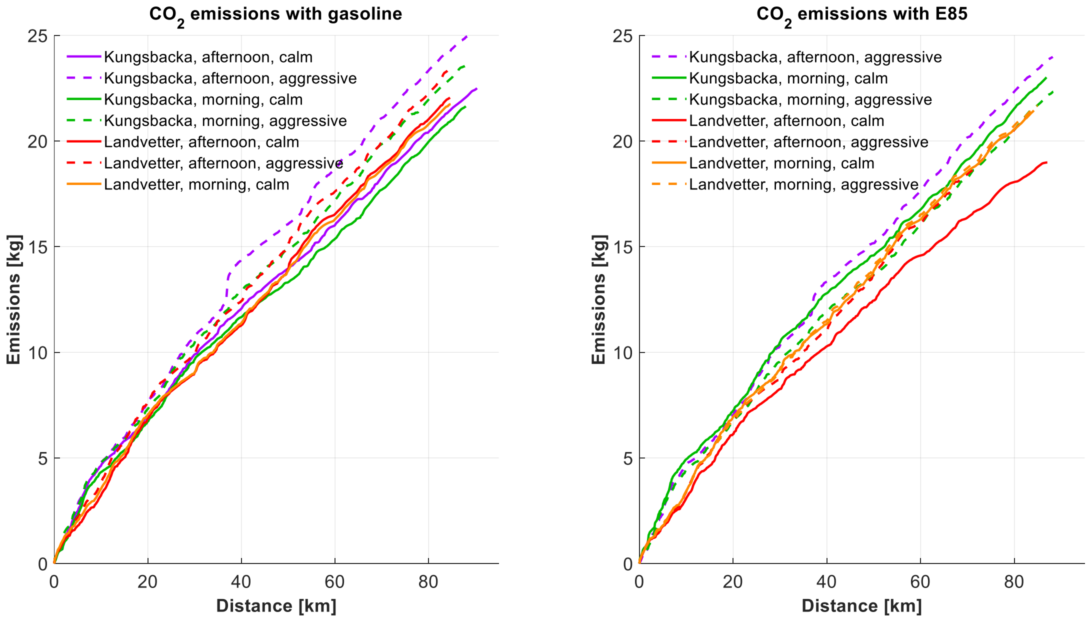

Figure 32. Cumulative CO_2 emissions

On the left side of Figure 32, there are gasoline trips and on the right side the E85 trips are presented. To see the difference between calm and aggressive driving styles, the calm ones were marked with full line and the aggressive ones were marked with dashed line.

What is interesting to see is that there is no noticeable difference in CO_2 emissions between gasoline and E85, or between the two different routes.

Another observation is that the driving style seems to have a bigger influence with gasoline than with E85.

To better understand what influences the CO_2 emissions, more detailed plots will be presented below.

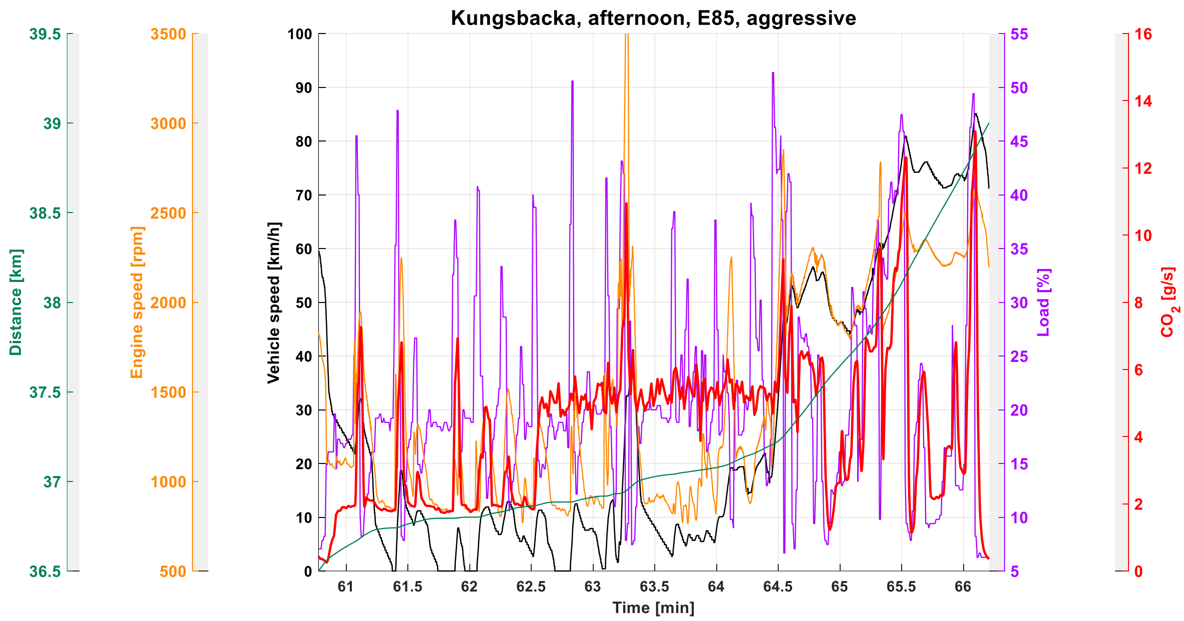

Figure 33. Detailed plot for CO_2 emissions for E85

From Figure 33 one can see that the emissions increase because there was a lot of stop and go driving as there were constructions on the highway, and a queue was formed in the afternoon. The CO_2 emissions are higher right after the vehicle starts to move and during accelerations, especially in low gears. Other factors include the load applied to the engine, and the engine speed.

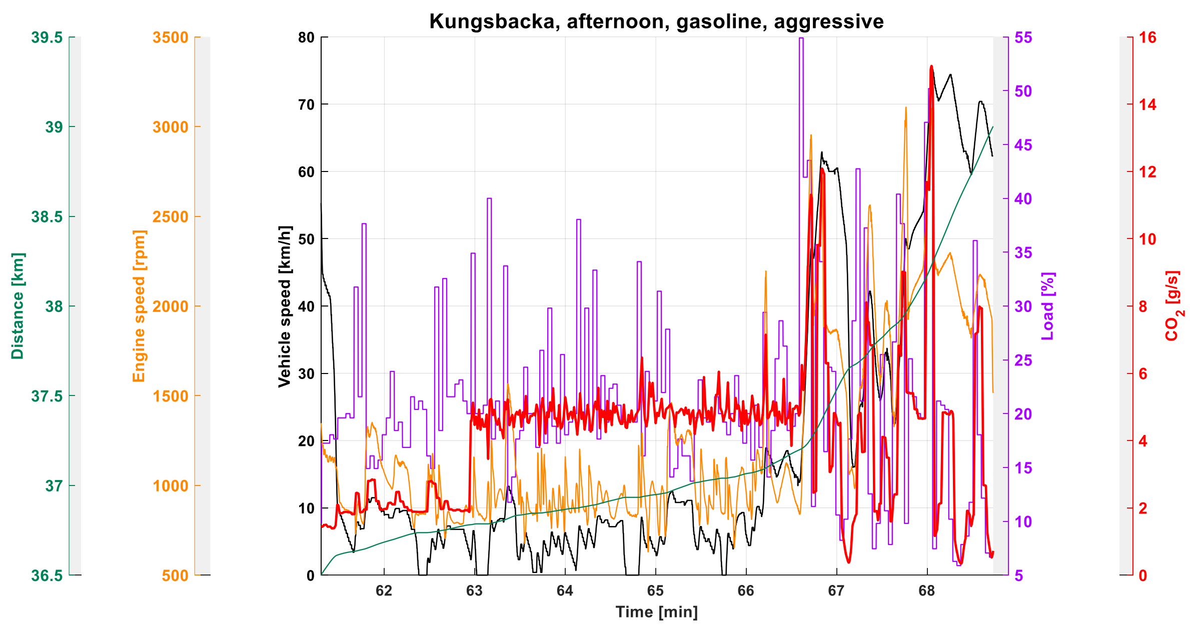

Figure 34. Detailed plot for CO2 emissions for gasoline

The same observations can be done for Figure 34, as CO_2 increases during accelerations and low speed traffic.

3.4. CO emissions

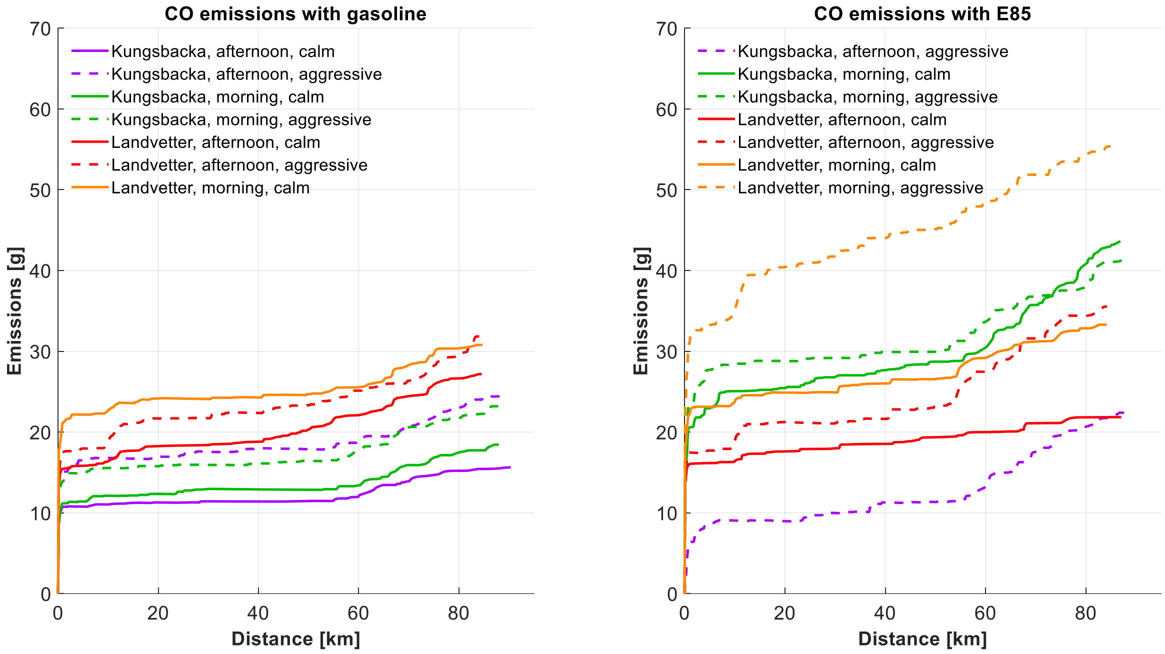

Figure 35. Cumulative CO emissions

Unlike the CO_2 emissions, where the slope of the cumulative plot was relatively constant, most of the CO emissions are emitted in the first minutes after the engine was started, until the catalyst warms up. This makes it difficult to compare the trips with each other, as the emissions during the driving are not having a big importance on the overall trip. There was an issue with the data from Kungsbacka, afternoon, E85, aggressive, as we forgot to start the app before the engine was started, so ECU data from the first 30 seconds is missing. Considering that the shortest route had 83 km, the legal EURO 4 limit of CO would be at 66g CO, meaning that the vehicle is below the limit, even with the aggressive driving.
To be able to compare the influence of driving behaviour, fuel, and routes, the first 3 minutes will be cut from the plot, so the warm-up phase will be eliminated. This will be presented in Figure 36.

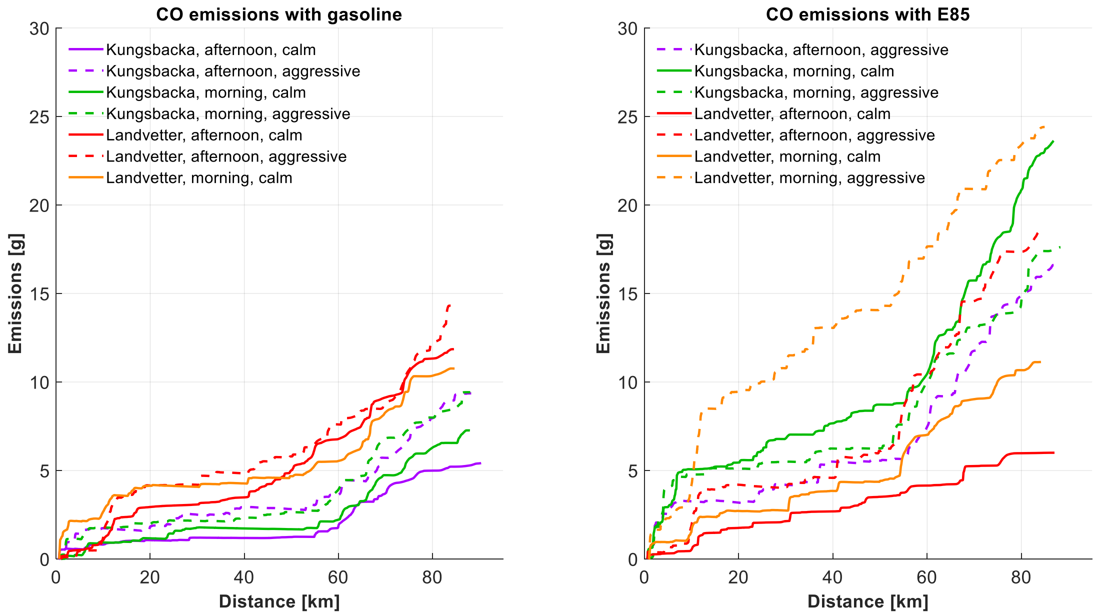

Figure 36. Cumulative CO emissions after the catalyst warm-up phase

The figure above shows that E85 emits more CO, especially during aggressive driving and the difference between calm and aggressive is higher for E85. Moreover, Landvetter route has higher emissions than Kungsbacka route for both driving styles, so the road gradient influences the CO emissions.

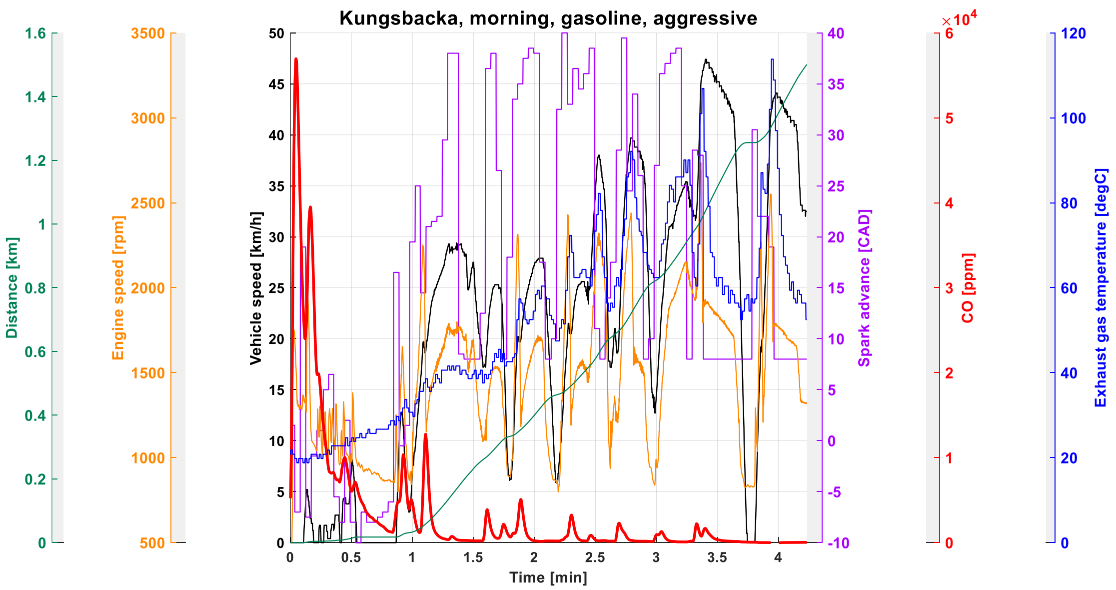

Figure 37. Detailed plot for CO emissions during catalyst warm-up phase for gasoline

As Figure 35 showed, most of the CO is emitted in the catalyst warm-up phase. This is because the catalyst has a very low conversion efficiency until it reaches the operating temperature of around 150 degrees Celsius, and as it has a large surface, it takes approximately one minute for it to heat up. During this time, the spark advance is negative, meaning that the spark is given after the Top Dead Center (TDC), so that the temperature in the cylinder will be higher when the exhaust valves are opened, heating up the catalyst faster. A similar behavior can be seen in Figure 38 for the case of E85, as the fuel does not influence considerably the warm-up strategy.

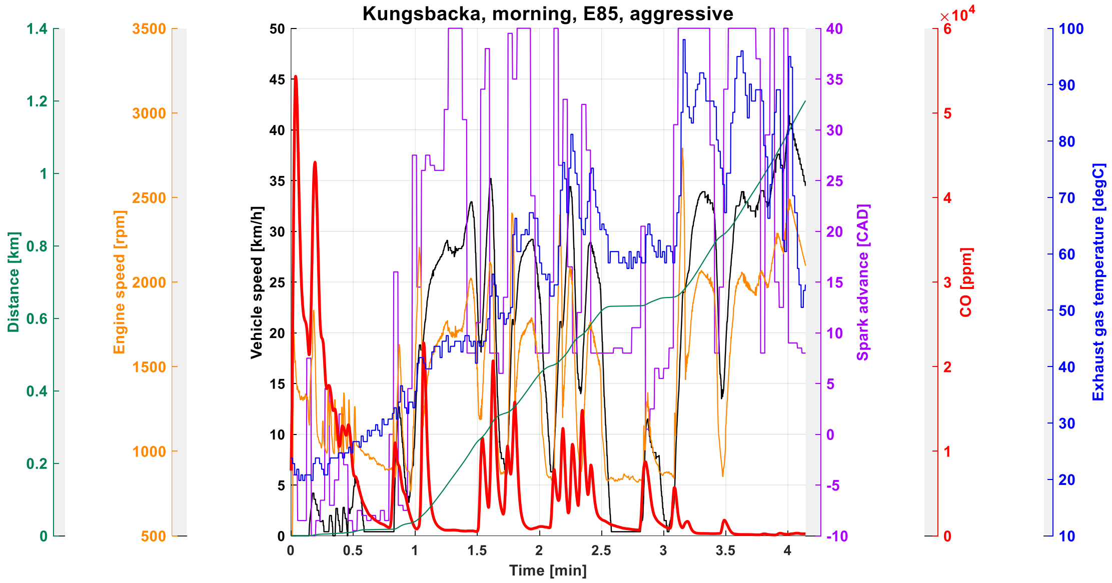

Figure 38. Detailed plot for CO emissions during catalyst warm-up phase for E85

Unlike the gasoline case, it seems that for E85 the CO emissions are high for a longer time, and they seem more affected by the engine speed and accelerations. The warm-up strategy is the same, as the spark is given after the TDC for about one minute, and the exhaust gas temperature is the same, there are higher CO emissions for E85 in the first 3 minutes.

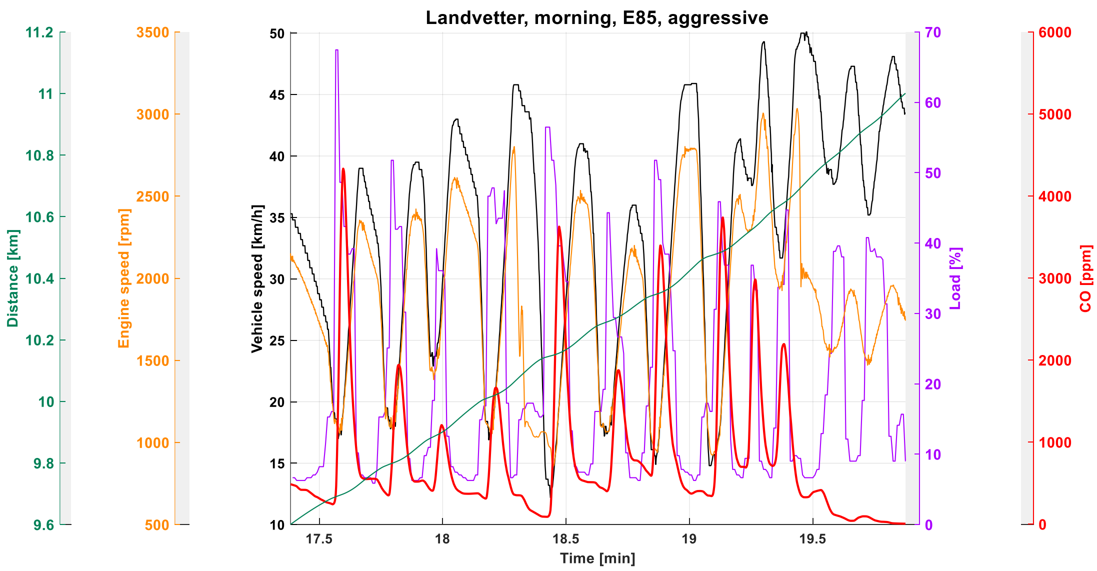

Figure 39. Detailed plot for CO emissions after catalyst warm-up phase for E85

In this scenario, CO has increased because of multiple accelerations from low vehicle velocity and low engine speed, meaning that CO increases at very low engine speeds and it is also proportional with load.

3.5. NO_x emissions:

NO_x is formed at high temperatures when nitrogen and oxygen molecules react during combustion. The NO_x emissions trend can be seen in Figure 40 for Kungsbacka and Landvetter routes with different driving styles for morning and afternoon drive.

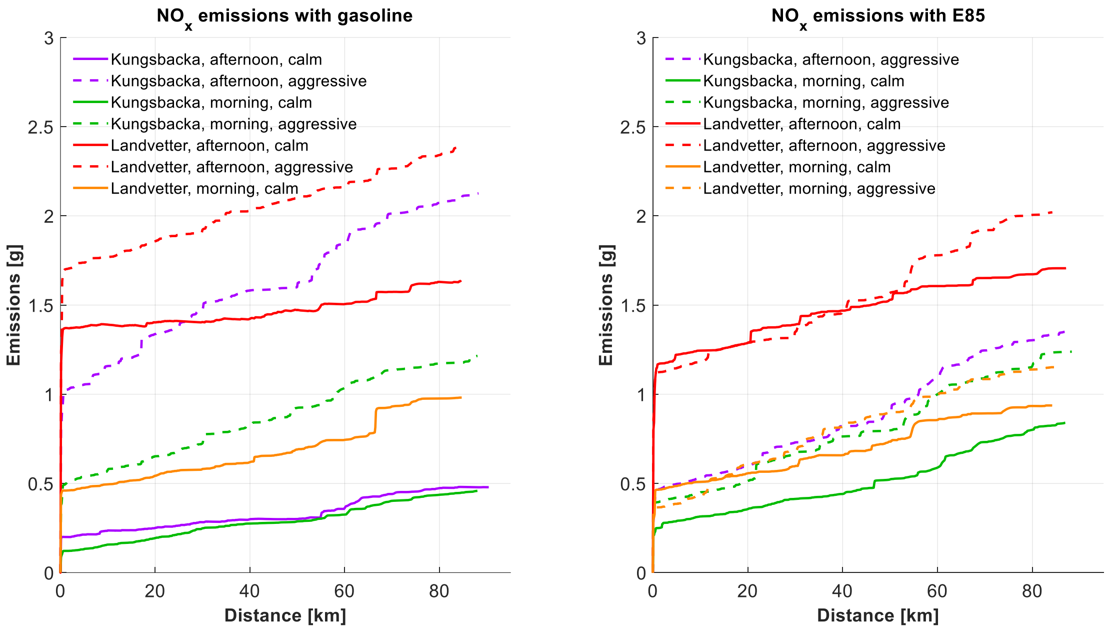

Figure 40 Cumulative NO_x *emissions*

As in the case of CO emissions, it can be seen there are high spikes at the start of the engine as the catalyst is not warm enough to convert the emissions. Gasoline engines produce lesser NO_x emissions when compared to diesel engines because CI engines has higher compression ratio which produces more heat and pressure. Lambda sensor plays a significant role in TWC operating efficiency as it measures the oxygen content in exhaust emissions and sends feedback to ECU, based on the feedback the engine will be made run on lean or rich. From Figure 40 it can be seen aggressive drive style emits more NOx in both the cases. Though it seems like afternoon calm drive has emitted comparatively higher for both the fuels, but once the catalyst got warm enough for operating conditions and started working efficiently it emitted less, this trend can be seen in Figure 42. Overall, the emissions for both the fuels are well under Euro 4 limit of 0.08g/km. Considering that the shortest route used had 84 km, the total limit for NO_x would be 6.7g, and as it can be seen from Figure 40, the vehicle emitted less than half of the allowed limit for both fuels, even in the case of the aggressive driving.

In this section a detailed study on NOx emissions at the start of the engine is analyzed. To understand the behavior of NOx emissions it is plotted along with engine speed, vehicle speed, spark advance, exhaust gas temperature; can be seen in Figure 41.

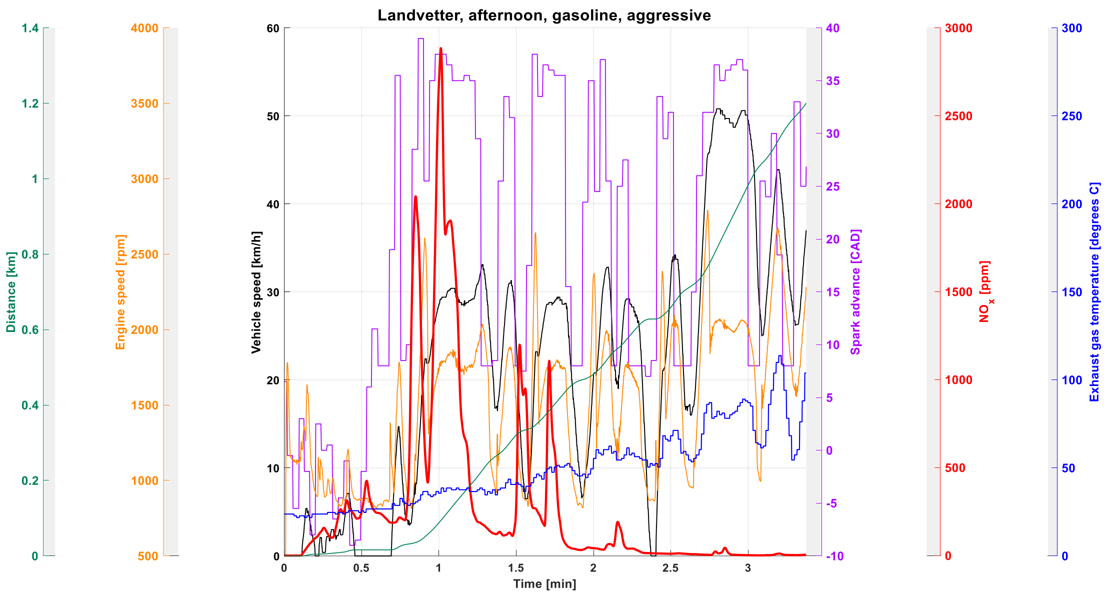

Figure 41 Detailed plot for NO_x *emissions during catalyst warm-up phase for gasoline*

From the above graph, it can be seen there is a huge spike at the start of the engine, and lower temperature of exhaust gases. The initial temperature of exhaust gases is around 30 degrees, catalyst will not be warm enough to work efficiently. Catalyst works effectively around 200 degrees and hence to increase the temperature of the exhaust gases there is a series of spark advances performed to increase the temperature of the catalyst and when it reaches optimum working temperatures the catalyst works effectively and then we can see the NO_x line almost flattens by the end of 1km. Figure 42 shows the NO_x emissions behavior when the catalyst works efficiently i.e. after the warm-up phase.

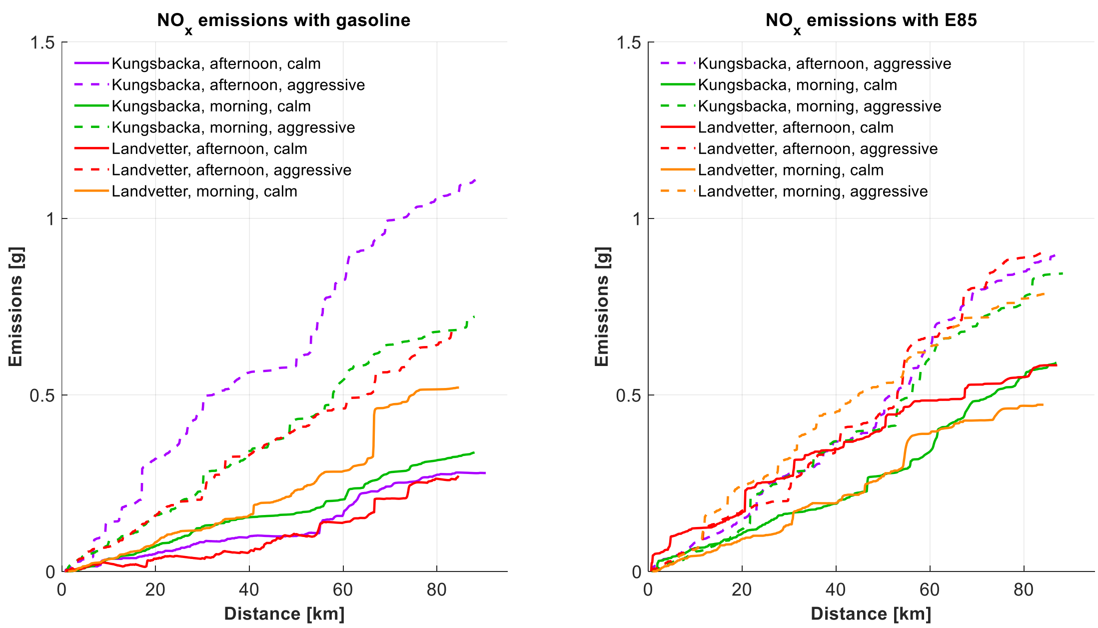

Figure 42 Cumulative NO_x *emissions after the catalyst warm-up phase*

3.6. PN emissions:

Figure 43 represents cumulative PN emissions and further the behavior of PN will be studied. For gasoline engines with indirect injection, PN emissions are formed when the local mixture is rich.

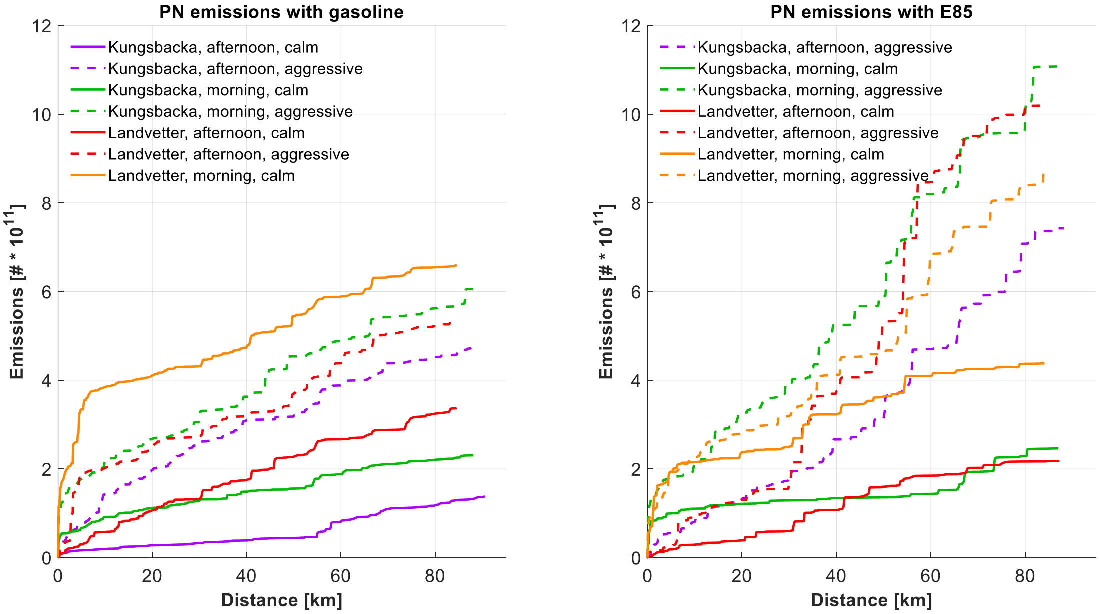

Figure 43 Cumulative PN emissions

Due to partial combustion PN emissions are observed. The E85 fuel behavior is drastic, though it emits lesser emissions at the start of the engine when compared to gasoline, but with the progress in distance (motorway part roughly starts around 50 kms) the emissions peak for aggressive drive case.

Interesting observations for gasoline is, Landvetter morning drive being calm one emitted the most during cold start. The trend as it was seen for NO_x emissions, the calm drives emitted lesser and for aggressive cases emissions emitted are high. Some of the reasons for peaks might be due to advancement in ignition timing, higher loads, supply of rich air-fuel mixture, inlet air conditions, fuel injection pressure. The mentioned reasons might lead to unburned hydrocarbons during combustion which will later be the reason for increase in particle emissions. Also to mention our test vehicle being 2006 model does not have Gasoline particulate filter (GPF), in case if it were present the particulate emissions would have been much lower.

There is a need to understand the PN emissions behavior at higher engine speed and vehicle speed.

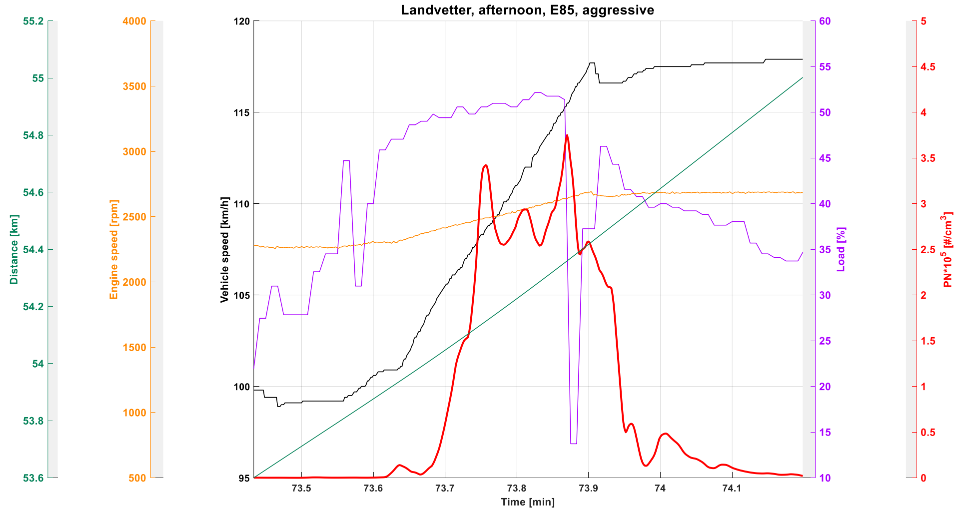

Figure 44 Detailed plot for PN emissions at higher engine and vehicle speed for E85

From Figure 44 and Figure 45 we can understand PN emissions are dependent on engine speed and engine load. At higher speeds with increase in throttle, there will be power requirement resulting in higher load, rich fuel will be supplied in this situation, high chances of partial combustion and leading to higher PN emissions. The PN peak drops when load demand is lower, engine and vehicle speed get stable.

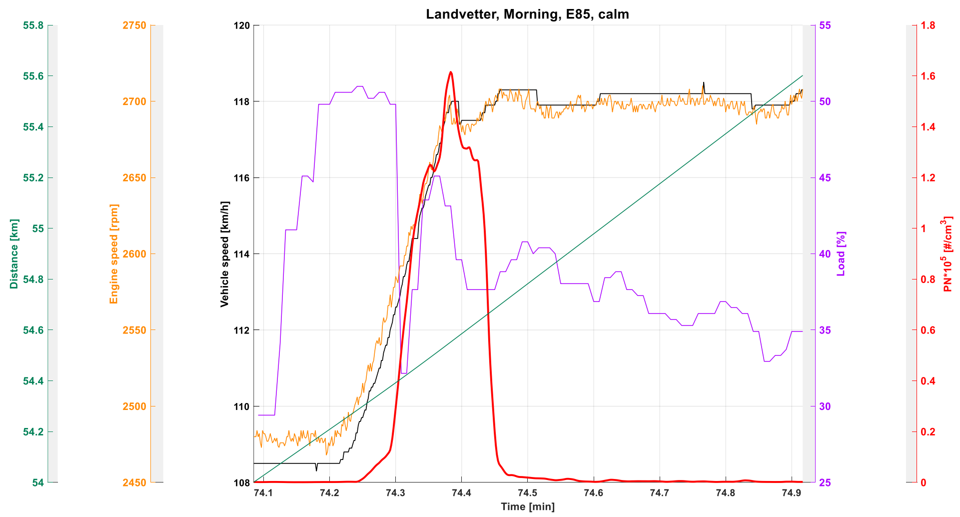

Figure 45 PN depending on engine speed relation

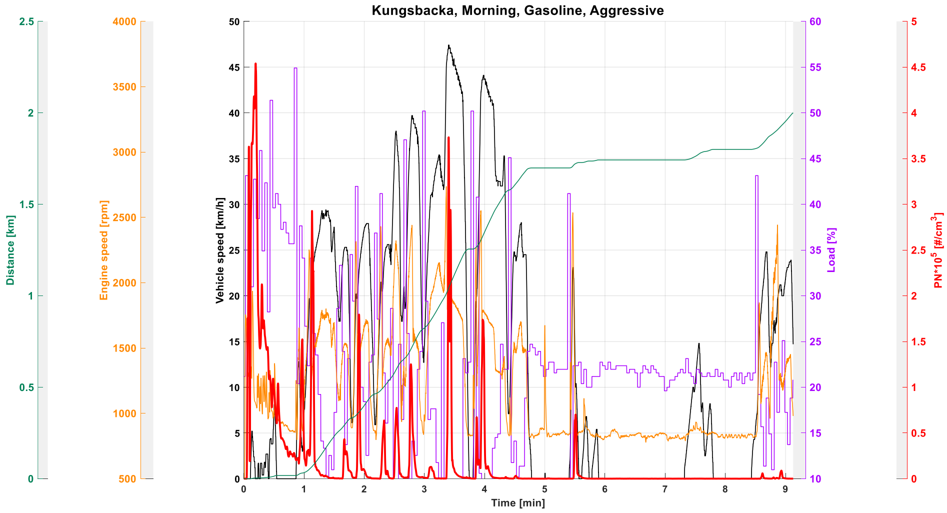

Figure 46 Detailed plot for PN emissions during catalyst warm-up phase for gasoline

Figure 46 demonstrates PN emissions behavior during cold start. For the first start of the engine there will be a rich fuel injection supply, engine being cold the fuel vaporization does not happen as expected and there are high chances of incomplete or poor combustion leading to high PN emissions.

3.7. The impact of the composition of E85

One can argue that this was the biggest limitation of the thesis, as for the calculation of the emissions, one needs the composition of the fuel. Normally, E85 consists of 85% Ethanol and 15% gasoline, but the actual blend depends on the season, and the petrol stations do not provide the exact blend used. In cold months, due to cold start issues, E85 is actually made of 75% Ethanol and 15% gasoline, but at the petrol stations it is still called E85. As the tests were made during the months of March and April and the outside temperatures were around 10 degrees Celsius, one could wonder how this change in the blend would affect the results.
Let us start with the fuel consumption. As the figures presented were given by the trip computer, which knows exactly the composition of the fuel, the fuel consumption figures are only influenced by the precision of the trip computer.
Regarding the CO_2 emissions, there was no noticeable difference between the two fuels, so it should be expected that by increasing the quantity of Ethanol, there will be no noticeable difference in the results.
For CO emissions it was observed that by increasing the concentration of Ethanol, the powertrain emits more CO, so if in our case the blend was actually E75, the CO should have had higher values for E85.
In the case of NO_x emissions, one can see that the fuel does not make a noticeable difference, as most of it is emitted while the catalyst is warming up, like in the case of CO.

PN is where fuel makes a difference, as it can be seen in Figure 43, and it would be expected that a further increase in the Ethanol content, particles will increase as well, but what matters the most for PN emissions is the driving style. Even in the case of PN, when the fuel matters for emissions, the difference between regular gasoline (E5 in this case) and E75 is much higher than the difference between E75 and E85, so it is expected that the results would have been very similar.

4. Conclusions

In this Thesis study, a flex-fuel vehicle was used to understand the Real Driving Emissions (CO_2, CO, NO_x, PN) behavior based on E85 and gasoline fuels, hilly and flat RDE routes, driving styles, cold and warm start. From the results obtained the conclusions are:

- CO_2 emissions increase during low-speed traffic.

- CO and NO_x emit the most at the start of the engine as the catalyst will not have reached optimum working temperature to work efficiently, and after a two-hour conditioning period of the vehicle, the emissions are as high as the morning cold start.

- Driver behavior considerably influences emissions for both the fuels.

- CO emissions increase right after starting from a standstill. For example, during traffic light stop and go, speed bumps, and during transients.

- PN emissions are mainly dependent on engine speed and load.

- For E85 fuel, PN emissions emitted are higher when compared to gasoline fuel, and it is also more sensitive to aggressiveness.

- During aggressive drive, NO_x and PN emissions emitted are significantly higher than calm drive.

Some of the results graphs show contradicting theories hence, to understand the proper emissions behaviour there should be a greater number of tests to be performed which accounts to repeatability. It is also important to log more variables during the tests, like lambda, catalyst temperature, fuel composition, power request, fuel flow, and a study considering the gradient of the road would be interesting. There were inconsistencies at times during logging of the data, so it is advised to check for errors after completing every test drive, also some of the data could not be logged due to some reasons hence these things need to be considered for the future research purpose. Overall, our test vehicle having a mileage of more than 200,00 kilometres performed great, with the same emissions levels as specified by the manufacturer, even with the aggressive driving.

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