Czech University of Life Sciences Prague

Faculty of Engineering

Master's Thesis

Effects of alcohol fuels on particle emissions from an automotive direct injection gasoline engine

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DIPLOMA THESIS ASSIGNMENT

B.Sc. KALPITA KUMAR PRAHARAJ

Technology and Environmental Engineering

Thesis title

Effects of alcohol fuels on particle emissions from an automotive direct injection gasoline engine

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Objectives of thesis

The focus of the thesis is experimental investigation of particulate matter emissions from a typical contemporary direct injection automobile spark ignition engines during operation on typical gasoline as well as its blends with suitable candidate drop-in fuels such as ethanol, n-butanol and isobutanol.

Methodology

In addition to the gravimetric measurement of particulate matter, advanced methods, including measurement of particle size distributions, should be explored. Repeated measurements are to be done to assess uncertainty and reproducibility of the measurements. The student is expected to actively participate in measurement campaigns, to process and analyze the data, to discuss the results namely in terms of semi-volatile and sub-23-nm particles.

The proposed extent of the thesis

40 – 60 pages

Keywords

particulate matter, ethanol, butanol, operating parameters

Recommended information sources

CLARK, Nigel N., David L. MCKAIN, Tammy KLEIN a Terence S. HIGGINS. Quantification of gasoline-ethanol blend emissions effects. Journal of the Air & Waste Management Association [online]. 2021, 71(1), ISSN 1096-2247. Available from: doi:10.1080/10962247.2020.1754964

Gupta, A., Sharma, S., & Narayan, S. (2016). Combustion Engines. Wiley. ISBN: 1119283760

HU, Zhiyuan, Zhangying LU, Bo SONG a Yifeng QUAN. Impact of test cycle on mass, number and particle size distribution of particulates emitted from gasoline direct injection vehicles. Science of The Total Environment [online]. 2021, ISSN 00489697. Available from: doi:10.1016/j.scitotenv.2020.143128

MERKISZ, Jerzy a Jacek PIELECHA. Nanoparticle Emissions From Combustion Engines. Imprint: Springer, 2015. Springer Tracts on Transportation and Traffic, 8. ISBN 9783319159287

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Prague on 11. 05. 2021

Declaration of authorship

I hereby declare that this master's thesis has been written by me in person. All information derived from other works has been acknowledged in the text and the list of references.

In Prague: 22.06.2021

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Kalpita Kumar Praharaj

Abstrakt:

Tato diplomová práce se zabývá emisemi částic z soudobého automobilového zážehového motoru s přímým vstřikem paliva, provozovaným na běžný benzín a jeho směsi s 15 % etanolu, 25 % n-butanolu a 25 % isobutanolu. Cílem diplomové práce bylo porovnat hmotnostní a početní koncentrace částic naměřené různými pokročilými metodami a posoudit dopad alkoholových paliv na hmotnostní a početní emise částic a na velikostní distribuci částic, včetně vyhodnocení opakovatelnosti měření.

Klíčová slova: Částice, koncentrace částic, gravimetrie, koncentrace sazí, počet částic, distribuce velikosti částic

Abstract

This master thesis is based on particulate matter emission evaluation from a contemporary direct injection automobile spark ignition engine operating on typical gasoline and on its blends with ethanol, n-butanol, iso-butanol. The goal of the thesis is to process and analyse the data of particle mass by gravimetry and of other properties like concentration of soot, total particle count, particle size distributions by multiple advance analytical methods. Sufficient number of measurements from various instruments was analyzed to assess the reproducibility of measurement.

Keyword: Particulate matter, particle concentration, gravimetry, concentration of soot, particle count, particle size distribution

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Table of Contents

1. Introduction

In developed countries there are many public health problems arising and some are getting solved. Quality of drinking water are being improved and along with their supply and sewage system which has a big impact on improving public health. However, with many solutions there are also other environmental health hazards are raising. A far-reaching dependency on vehicles as a means of transport is also a key contributing factor.

Another topical public health effecting factor that has received quite much attention in the recent years due its effect on the public environment is the Particulate Matter (PM) which is produced by cars, trucks, industrial estates, ships, agricultural complexes. Because of its presence it creates a big question marks on the public health safety and what is the best possible way to overcome it. Recent studies have also tried to assess the health effects caused by pollution of the ambient air. "Global Burden of Disease" project of the World Health Organization (WHO) it has been estimated that worldwide, close to 6.4 million years of healthy life are lost due to long-term exposure to ambient particulate matter (Ezzati 2002, WHO world health report 2002). Just in Europe, 428,000 premature deaths were attributed to exposure to particulate matter (EEA, Air quality in Europe, 2018). In the 1990s, WHO updated its Air quality guidelines (AQG) for Europe (WHO Regional Publications, European Series, No 91), to provide elaborated information on the indecorous effects of exposure to different air pollution on human health. Epidemiological and toxicological studies have suggested regarding problem with urban air quality and air pollution, also specifically adverse health effects of particulate matter. Concern for the PM is the particles below 10 nm has the capacity to deposit in the human alveoli through diffusion, the capability to penetrate into the bloodstream and also into brain through olfactory nerve (Elder, et.al, 2006) (Oberdeorster, et.al, 2004)

Now world is moving towards clean and sustainable mobility, and air pollution is one of the huge disadvantages for contemporary internal combustion. Over the years emission norms has been improved quite much and helped reducing the pollution. But number vehicles on the road are increasing every year. But governments are trying to improve the public transport. The overall health effects of long-term exposure to particulates cost at least 4 billion euros a year and could soar to an astronomical 40 billion (Hugo Priemus, 2009).

1.1 Particle Size, Structure and Composition

Particulate matter is defined as any dispersed matter, solid or liquid, in which the individual aggregates are larger than single molecules but smaller than 500 μm (Springer, 1973). The fine particles are composed mainly of combustion particles, secondary aerosols that are formed in environment and condensed vapours of organic and metal compounds (Suresh, 2018). Particles change their size, structure and composition while leaving from the internal combustion engine due to dilution with the air which tends to change in physical and chemical properties. The size of suspended particles in the atmosphere varies over four orders of magnitude, from a few nanometres to tens of micrometres. The aerodynamic property of particles determines how they are travelling in the air and the way to remove it. These particles are in very irregular shape and their behaviour is being expressed in terms of the diameter of an idealised sphere.

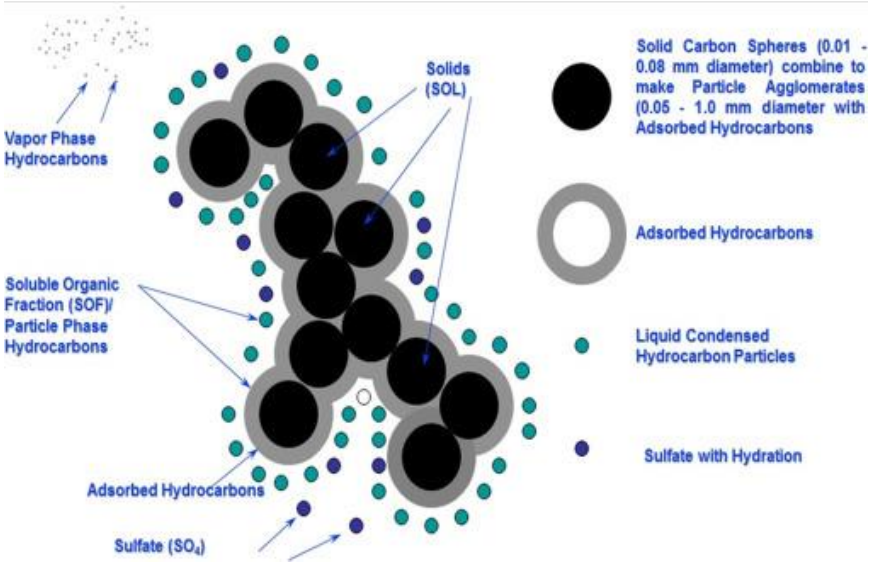


Figure 1. 1 Schematic Representation of Particulate Matter (Mohankumara, P. Senthilkumarb 2017)

Particulate matter can be separated into a soluble and insoluble organic fraction. Composition and size of the of the airborne particles vary. Airborne particulate matters have a complex mixture of organic and inorganic substances. Some particles are very small which can be seen only by microscope and some are large enough to be dust. There are different sizes of particles like PM_{10}, $PM_{2.5}$. PM_{10} particles are inhalable with diameter that are generally 10 μm and smaller and $PM_{2.5}$ are very fine and inhalable particles with diameter generally 2.5 μm and smaller. The smaller particle contains secondarily formed aerosols (gas-to-particle conversion). Mostly the larger

particles contain fugitive dusts from industries, and it contains earth crust materials. Particulate matter is the combination of soot and other liquid, solid phase materials. Soot is mostly formed in the high fuel concentration region with high temperature at absence of oxygen. Liquid phase materials and hydrocarbons are being absorbed on the soot surface according to engine operating condition. Nearly 50% of PM is composed of soot, Soluble fraction present in particulates mainly consists of aldehydes, alkanes, aliphatic hydrocarbons, Polycyclic aromatic hydrocarbons (PAH) and its derivatives (Mohankumara, P. Senthilkumarb 2017).

1.2 Environmental and Health Effects

Long-term exposure to current ambient PM concentration may lead to a marked reduction in life expectancy. The reduction of life expectancy is due to the increased in cardio-pulmonary and lung cancer mortality. This increase is like lower respiratory system and problem in lung function in children and chronic obstructive pulmonary disease and reduced lung function in adults.

On 2003 estimate for Austria, France and Switzerland (combined population of about 75 million) is that some 40 000 deaths per year can be attributed to ambient PM (Health Aspects of Air Pollution, Report on a WHO Working Group EUR/03/5042688, 2003). Size of particle indicates the level of health impact. Particles those are less than 10 μm are so much effective to the human lungs and it can also penetrate to bloodstream. Similarly, high numbers have been estimated for respiratory and cardiovascular hospital admissions which also happens due to the PM. Now the global risk for human health is being increased.

Mortality of the human was assessed, those were living near to the major road and those were staying away for from the road, and the author concluded that the life of span of the people living near major road may go down (United States Environmental Protection Agency, 2016). The main cause is $PM_{2.5}$ particles effect, that tends to reduce of visibility in the urban area. Particles are quite weightless so they can travel long distance within a few minutes. They usually settle down on the water bodies like some water stream or some Lake. They deplete the soil nutrient sand which effects the ecosystem in general also cause the “Acid rain” and “smog” (United States Environmental Protection Agency, 2016).

1.3 Particles in Diesel, MPI, GDI

The existence of fuel rich high temperature region leads to fuel pyrolysis; hence a diesel engine is very likely to produce particulates emission. The process of particulate release in diesel engines is highly dependent on temperature and fuel/air ratio which very local inside the combustion chamber. Diesel cars has been recently become subject to considerable negative publicity thanks to the amount of toxic emission they produce. Some governments are planning to discard the use of diesel vehicles in the urban area. As diesel engine burns with lean mixture so that's why it is being economical to use in the market as well as it is consuming less fuel than the petrol engines, so people like to prefer diesel. Emission from petrol cars is quite much but when it is used with aftertreatment devices the emission is being reduced quite much which is even better than the diesel car except CO and HC. In fact, particulate emissions from petrol cars are so low that they are not routinely measured except gasoline direct injection engine. Before introducing direct injection petrol engines, we thought the same as particulate matter emission in the petrol cars are quite less but later we realised that direct injection petrol engine emits huge number of particulates which is really a big concern for the automotive industry.

1.4 ABATEMENT – DPF, GPF, DOC, TWC

Diesel particulate filters (DPF) has been fitted to the diesel cars almost two decades now, but if not maintained or if it is tempered then there could be some serious consequences for the vehicle. Diesel particulate filter is a filter that captures and stores exhaust soot or particulates in order to reduce the emission from diesel engines. Because they have some finite capacity so the trapped suit must be burned or remove to regenerate the DPF. Regeneration process cleanly burn of the access deposition in the DPF and reducing the harmful exhaust emission which is coming out from the car during higher acceleration.

For gasoline particulate filters (GPF) there are three particulate trapping mechanism which are interception, impaction and diffusion. And trapping mechanism is completely depends on the particle size. The smaller particles are being trapped by the diffusion, the larger particles are trapped by interception and impaction. For the initial filtration efficiency of the new GPF varies for different particle size, Small and big particles are being trapped but the lower filtration efficiency is being observed for the particle size of diameter around 200 nm. Gasoline engines

emits lower soot mass than diesel engines. Therefore, very less frequent regeneration is required, and this allows lower thermal mass well-flow filters then DPF. Also, GPF work with higher temperature compare to the DPF which entails that passive soot regeneration occurs more rapidly.

The diesel oxidation catalyst (DOC) can promote oxidation of exhaust gas components by oxygen, which is present in ample quantities in diesel exhaust. When passed through an oxidation catalyst, carbon monoxide (CO), gas phase hydrocarbons (HC), the organic fraction of diesel particulates (OF), as well as non-regulated emissions like aldehydes or PAHs can be oxidized to harmless products, and those can be controlled by using the DOC. In modern time diesel aftertreatment systems the most important function of the DOC is to oxidize nitric oxide (NO) into nitrogen dioxide (NO_2) a gas needed to support the performance of diesel particulate filters and SCR catalysts used for reduction NO_x (Thuy Chu 2006).

A three-way catalyst oxidizes exhaust gas pollutants hydrocarbons (CmHn) and carbon monoxide (CO) and reduces nitrogen oxides (NOx) into harmless components water (H_2O), nitrogen (N2) and carbon dioxide (CO_2). Depending on conditions of operation of the engine and the exhaust gas composition, conversion rates of close to 100% can be achieved at close to stoichiometric (lambda one) conditions. The necessary reaction conditions can be reached after less than a minute by the introduction of special cold-start measures, especially a fast heat-up of the exhaust gas after engine cranking. This is especially important for city driving, characterized by frequent start-stop events (Umicore Automotive catalyst).

1.5 Legislation, Concerns About PN

In Europe, road transport, is the largest contributor towards NOx (Oxides of Nitrogen) pollution with 39% and second largest in terms of soot (has a significant portion of particulate matter), with 29% next only to commercial, institutional and households' sources (European Environment Agency, 2017). Another regulatory program aimed for controlling PM emissions from the National Ambient Air Quality Standards (NAAQS). NAAQS define the concentration of the pollutant in ambient air that Environmental Protection Agency (EPA) deems to be protective of environment and the human health. Stationary sources of PM are regulated to ensure that their emissions do not exceed these standards of NAAQS (in EPA jargon the phrase is "cause an exceedance"). Over the

last four decades, the PM NAAQS have become more stringent in terms of lower numeric standards, reduced averaging times and regulations imposed on smaller particle sizes.

The Seventh Environment Action Programme, 'Living well, within the limits of our planet' (European Commission, 2013) recognises the long-term goal within the EU to achieve 'levels of air quality which will not give rise to significant negative impacts and risks to human health and the environment'. In addition to this, the Clean Air Programme for Europe which was published by the European Commission in late 2013 (European Commission, 2013), strongly aims to ensure full compliance with existing legislation by 2020 at the latest and also to further improve Europe's air quality so that, by 2030, the number of premature deaths can be reduced by half compared with 2005 (Air quality in Europe 2019).

In 2018, the European Court of Auditors issued a special report following its audit of the EU air quality policy, in which they emphasise the effectiveness of EU actions to protect human health from air pollution was assessed (ECA, 2018). Some recommendations were also made to the European Commission to improve air quality. Also, the report highlighted the importance of good air quality and the importance of achieving not only the EU's air quality standards but also the WHO air quality guidelines. It also stressed the need for better result-oriented air quality plans.

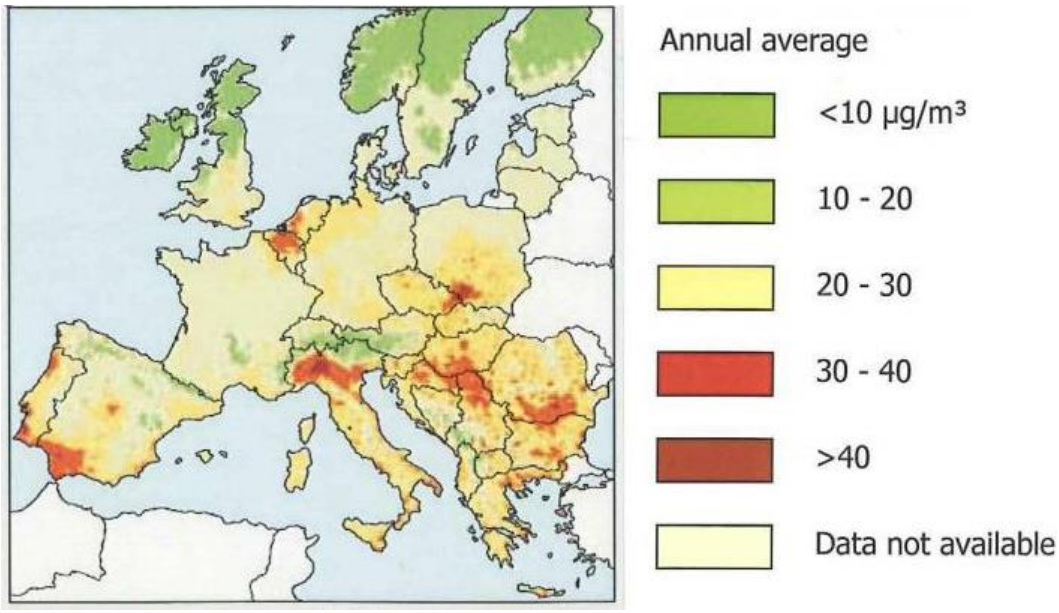
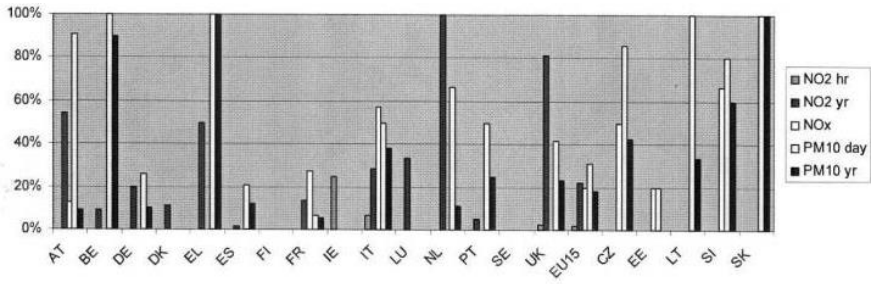


Figure 1. 2 Regional PM10 concentrations in Europe, 2004. (Milieubalans 2007, Milieu- en Natuurplanbureau (MNP); Publ. Nr. 50081004, Netherlands)

Here the above figure provides regional PM_{10} concentrations in Europe as at 2002. We can observe here high concentrations in economic centres and urban regions like the Po Delta in Italy, Paris and the surroundings and above all, the Randstad (the Netherlands), the Flemish Diamond and the Rhein-Ruhr area. Bute here data from Paris and big parts of Germany were unavailable.

According to the European standards, effective from 1 January 2005 the maximum annual average for PM_{10} should not exceed 40 micrograms per cubic metre. The 24-hour average should not exceed 50 micrograms per cubic metre more than 35 times in a year. Many countries of the European union (including local sites) are unable to meet these standards (especially the 24-hour standards).



AT	=	Austria	NL	=	The Netherlands
BE	=	Belgium	PT	=	Portugal
DE	=	Germany	SE	=	Slovenia
DK	=	Denmark	UK	=	United Kingdom
EL	-	Greece	EU 15	=	15 EU member states
ES	=	Spain	CZ	=	Czechia
FI	=	Finland	EE	=	Estonia
FR	-	France	LT	=	Lithuania
IE	=	Ierland	SI	=	Sweden
IT	=	Italy	SK	=	Slovakia
LU	=	Luxemburg			

Figure 1. 3 Percentage of zones exceeding the limit value (plus margin of tolerance if existing) for NO2/NOx and PM10 in 2003 (8)

The EU's air quality directives (2008/50/EC Directive on Ambient Air Quality and Cleaner Air for Europe and 2004/107/EC Directive on heavy metals and polycyclic aromatic hydrocarbons in ambient air) set pollutant concentrations thresholds that should not be exceeded in the given period. In case of exceedances, authorities must develop and implement air quality management plans. These plans should help to bring the concentrations of air pollutants to levels below the limit and target values.

Table 1 Air quality standards for the protection of health for PM, given in the EU Ambient Air Quality Directives (EEA, Air quality in Europe, 2018)

Pollutant	**Averaging Period**	**Legal nature and concentration**	**Comments**
PM_{10}	1-day Calendar year	Limit value:50 μg/m^3 Limit value: 40 μg/m^3	Not to be exceeded more than 35 days per year
$PM_{2.5}$	Calendar year	Limit value: 25 μg/m^3	

1.6 Replacement of Fossil Fuels

Proponents of alternative energy argue that fossil fuels are unsustainable, environmentally destructive, inefficient and the contributor to global climate change in very big scale. They also believe that renewable energies are a viable and immediately needed alternative for fossil fuel and can be a big game changer that could boost the economy and reduce reliance on foreign energy sources.

"It will take at least three decades to completely leave behind fossil fuels. But we can do it... stated by Richard Heiberg (100% Renewable Energy: What We Can Do in 10 Years, Article by Yes! Magazine). Nearly everyone thinks that the easiest way to kick-start the transition would be to replace coal with solar and wind power for electricity generation. There are many different types of carbon-based source containing huge amount of energy such as coal, oil, natural gas. As of now they are most common source to create energy. Especially in Turkey almost all source of energy comes from the fossil fuels. Also, industries are also looking towards the electric vehicle technology. But as of now the battery technology is not enough efficient also it is quite expensive. But for battery production also we are producing huge amount of CO_2 and electricity source is from coal powerplants which is quite similar problem in long term application. Also, we have started using different bio-fuels which shows that some fuel has better performance compare to fossil fuel.

The world has different kind of alternative energy sources such as wind, hydroelectric, solar, geothermal, and biofuels are possible energy type which can take big part to replace fossil fuels. These energy types have also several advantages and disadvantages. Wind and solar power cause

no pollution and are renewable and wind and solar power are free except installation and construction of the structure but both energy source is inconsistent. Wind intensity or sunny weather can change which is unpredictable. Moreover, other energy sources are also not completely renewable and dependable because these projects need huge amount of investment and maintenance. Even ethanol from corn is also expensive which is creating energy.

1.7 Alcohol Fuels in SI Engine

Alcohols such as ethanol have been blended with gasoline in the for several decades. Most common is E10, a 90% gasoline/ 10% ethanol blend and available nationwide (In USA). United States Environmental Protection Agency has approved E15, a 85% gasoline/ 15% ethanol blend for use in 2001 and newer vehicles. You will also find Ethanol Flex-Fuels in the USA marketplace which range from E51-E85, this fuel is sold for use in flexible fuel vehicles (FFVs) only (Ethanol Blend Fuel). There is an ongoing study to commercialise the production of ethanol from sources other than vegetables, such as cellulosic materials like wood or paper wastes (Van den Hout D. 2006).

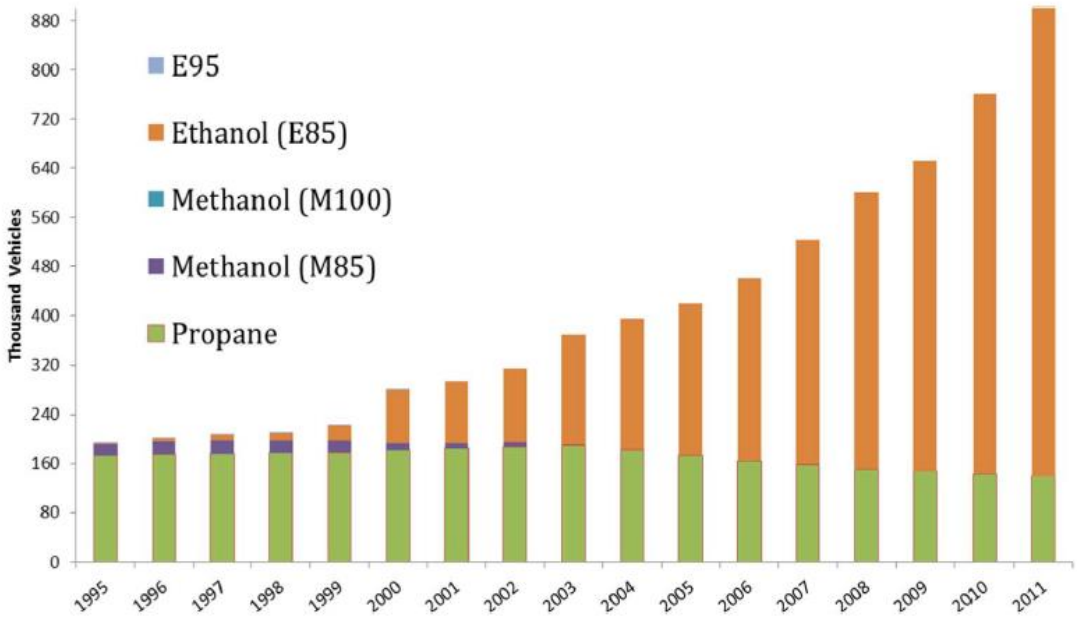


Figure 1. 4 Number of vehicles that use alcohols as fuel in the U.S. during 1995–2011 (U.S. department of energy, U.S: Alternative Fuels Data Center 2016)

Ethanol has an established track record as a neat fuel in Brazil, where almost five million cars currently run on 190-proof ethanol (95% ethanol, 5% water) (Pitstick ME. 1992). Ethanol can be utilised as a primary car fuel in either the neat (pure) or near-neat form (Pistick M, 2006). Although 100% of butanol can be utilised in SI engine and butanol probably has the higher realistic possibility to be blended with gasoline. Many studies recommend that butanol can be blended into either gasoline or diesel to as much as 45% without engine modifications (Y. Liu 2008).

1.8 Effects of Cold Start and Operating Conditions

Cars emit the highest number of pollutants when an engine is cold. On a cold day, a diesel car usually takes longer to warm up and starts to operate at maximum efficiency and a gasoline car may only take less time. Consequently, diesel cars usually produce less unburned fuel during a cold start, due to which there are lower emissions of carbon monoxide and hydrocarbons. Diesel cars could make a huge impact on air quality in the urban areas where most cold starts occur, especially when it is considered that a gasoline car with catalyst would take several minutes to reach its required operating temperature. Overall, diesel cars emit a smaller number of hydrocarbons, carbon monoxide and lead pollution compared to petrol cars, but produces more noxious gases and significantly more particulates but also direct injection petrol engines emit a significant amount of particulate matter.

During cold start, significant heat generated from combustion is used to transfer heat to the engine block, coolant and lubricant. During the first minute, compared to the second minute, emissions of particle number (PN), carbon monoxide (CO), particulate matter (PM), and nitrogen oxides (NOx) were approximately 10, 4, 2 and 1.5 times higher, respectively (Thuy Chu 2006). The engine control unit (ECU) has a vital role in reducing engine emissions by changing the engine injection strategy required to the engine coolant temperature.

2. Goal of the thesis

The focus of the thesis is an experimental investigation of particulate matter emissions from a contemporary direct injection automobile spark ignition engine operating on typical gasoline and on its blends with ethanol, n-butanol and iso-butanol.

The goal is to obtain results from various repetitive measurements of particle mass by gravimetry and of other properties (concentration of soot, total particle count, particle size distributions) by multiple advanced analytical methods and analyse the data. Measurement from various instruments to analyse to assess the reproducibility of the measurements.

3. Experimental Test Condition

This Chapter discuss with the experimental conditions used in the project with engine test condition, different fuels used and with different instruments.

3.1 Engine test Condition

The aim of the whole project to study the exhaust emission from the engine used with different condition. Here we have used 1.4 litre R4 16 valve TSI/TFSI gasoline direct injection engine from Volkswagen which was announced at 2005 Frankfurt Motor show. In order to give a reasonably accurate representation of the typical exposure of engine exhaust, the following conditions are considered:

i. A transient engine cycle which represents the typical city driving - world Harmonized Light Vehicle Test (WLTC)
ii. Dynamic operation load with various load condition and also cold start effects should be represented - speed regulating dynamometer control and torque regulating dynamometer control and also cooling of engine with a blower
iii. Advance aftertreatment technology used in production engines must be used – catalytic converter

The world Harmonized Light Vehicle Test (WLTC) is chosen as it satisfies our requirement conditions, and it is one of the modern types of approval tests.

The WLTC are chassis dynamometer tests used to determine emission characteristics and fuel consumption from light-duty vehicles. The tests have been developed and by the UN ECE GRPE (Working Party on Pollution and Energy) group (Dieselnet, 2019). The WLTC cycles are part of the Worldwide harmonized Light vehicles Test Procedures (WLTP) and these WLTC cycles are different with different kind of vehicles on their power to weight ratio. It is now replacing the New European Driving Cycle (NEDC) as the standard type of approval procedure over 2017-2019 (Dieselnet, 2019).

The WLTC Has different kind of versions according to the countries with their requirements. Class 3 for vehicles in Europe and Japan, class 2 for vehicles in India and low power vehicles in Europe and Japan, class 1 for vehicles in India (Dieselnet, 2019). Class one test is depending on vehicles with lowest power to weight ratio and class 3 test are for vehicles with highest power to weight ratio. WLTC cycles are consist of 30 minutes of test in which they have different phases of speed from low speed to the extra high-speed including medium speed and high speed.

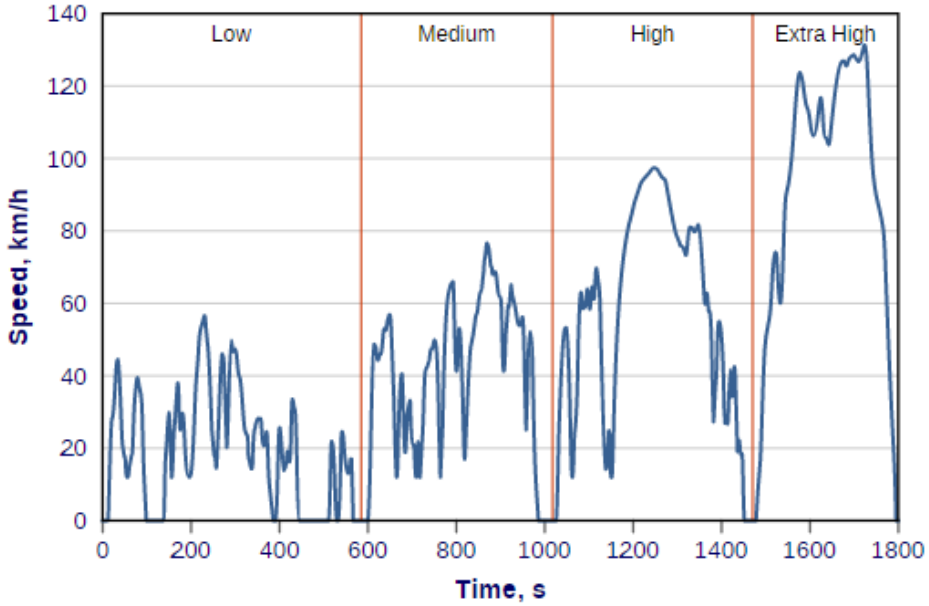


Figure 3. 1 WLTC cycle for Class 3b vehicles (Dieselnet, 2019)

As per the other requirements Initially we planned to run one cold start during the morning followed by three warm test cycle but due to requirement of some other projects later we opted for doing one morning cold start followed by one warm cycle. And then we were cooling the engine for two hours by a blower to obtain the same cold start condition. Along with that which changed various kind of fuel and, we changed the working load of the engine to obtain various results.

3.2 Exhaust Sampling

Before the emission can be measured from the engine it has to be sampled from the exhaust sampling system. If works like a very important Interface between the exhaust and the measurement system. Its role to precondition the exhaust from the engine as per the requirement of the instruments which are being used to measure and those requirements could be temperature,

concentration or the presence of moisture while considering the minimal changes to the measured exhaust gas. Most of the measurement devices are designed to be work nearly to the ambient temperature for which the exhaust must be cooled before reaching the instrument to adequate level.

3.2.1 Diluted Sampling

There are volatile materials like water, sulphur compounds in the exhaust, so cooling may supersaturate these species so it can lead to be condensation or nucleation. So, to avoid that the exhaust gas must be diluted where we can avoid these supersaturations and the volatile material must be removed from the exhaust. We used dilution to reduce the temperature as well as concentration as per the requirement of instruments. In particulate matter sampling nucleation and condensation may change the particles. So, the sampling conditions must be very precise to avoid nucleation or condensation. This is done by keeping the temperature in the dilution tunnel within some limit and coagulation creates another issue in the particulate sampling. There is collision between the particles due to thermal motion unlike gas molecules, particles are usually close to unify after collision, which makes the particle size distribution to continuously changing towards larger particles. To have better results the time which the particles remain in the sampling system must be very small to keep this affect negligible. Immediate strong dilution is a very good way to reduce the effect of coagulation.

3.2.2 Raw Gas Sampling

Raw gas sampling is also very common type of technique because the relative simplicity of the sampling system. Due to high concentration of moisture, high temperature and particulates it is always not an easy task to have reliable results. so mostly it is used in field testing. Instruments like opacity meters for smoke metres can handle such high concentration of undiluted exhaust gas and can operate at elevated temperatures to avoid condensation. For some stationary power generation plants or marine diesel engines undiluted sampling is used to collect the filter sample to determine the particulate mass.

3.3 Different fuel Used

To check All emission characteristics of the engine we tried using different kind of fuels which give us different results and it was done under different engine load condition. We used standard petrol (E95), Iso-Butanol 25%, n-Butanol 25%, Ethanol 20 (E20).

4. Experimental Setup

We can see in the fig. 4.1 that the engine exhaust is going to four devices which are MD-19 rotating disc diluter, Smart simpler, Micro soot sensor (MSS) and Nanomet. Diluted Exhaust from rotating disc diluter are going to Engine Exhaust Particle Sizer (EEPS) and from smart simpler to Condensed Particle Counter (CPC).

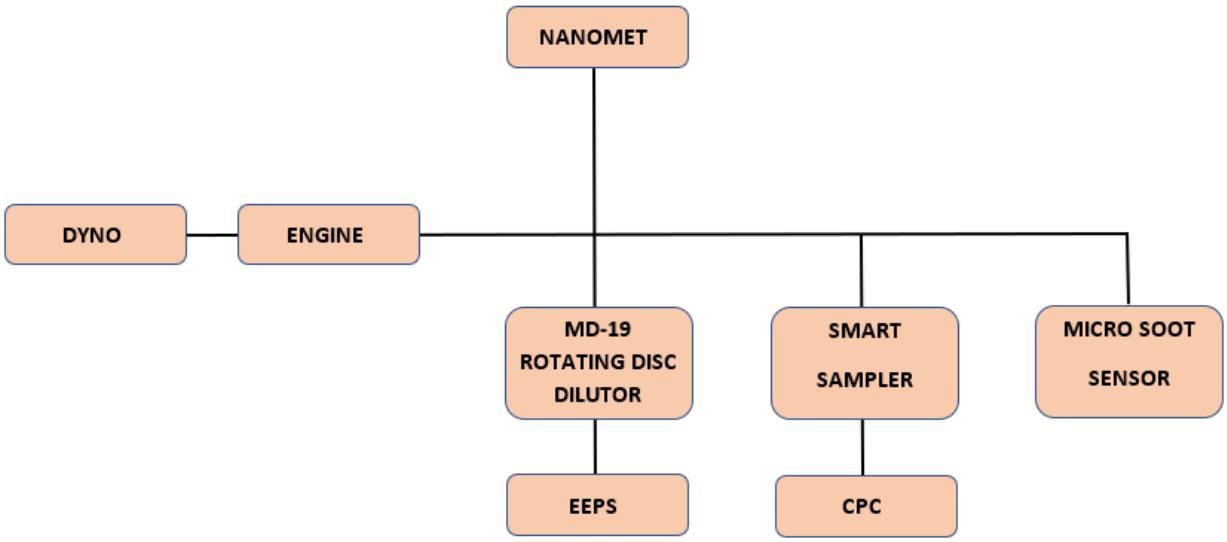


Figure 4. 1 Schematic figure of Test

4.1 Instruments used in the experiment

I. Dilution systems – A proportional gravimetric AVL dilution system called SmartSampler, and a rotating disc diluter from Matter Engineering MD-19
II. Engine Exhaust Particle Sizer (EEPS) from TSI
III. Condensation Particle Counter (CPC) from TSI
IV. Micro soot Sensor (MSS) Plus from AVL
V. Nanomet3 from Matter Aerosol AG

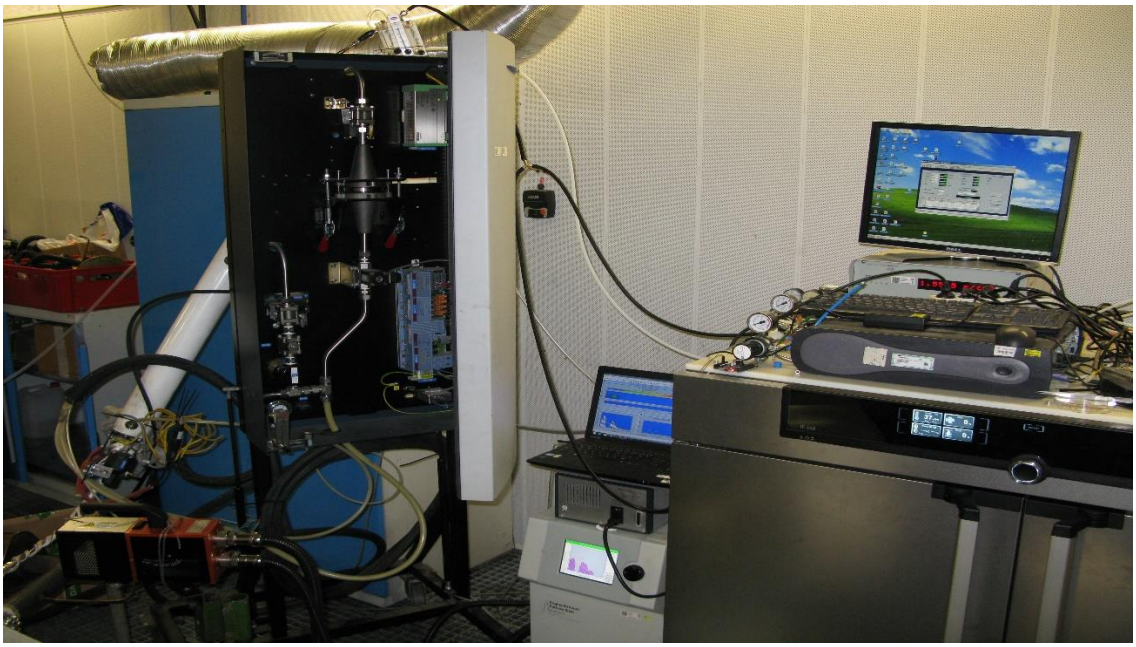


Figure 4. 2 Experimental Setup

4.1.1 Dilution Systems

Dilution System is the most important in this experimental setup because it is diluting the exhaust gas to the required condition of the instruments for measuring exhaust gas. Here we have chosen two dilution systems to check the differences of particles and compare the particle from two different instruments.

a) AVL Smart Sampler

The AVL Smart Sampler is a partial flow dilution system intended for gravimetric sampling of exhaust particulates from internal combustion engines under both steady state and transient conditions (AVL Product Information). This type of dilution system maintains a constant flow of

the diluted sample through the gravimetric filter and regulates the inflow of the exhaust indirectly by varying the flow of filtered air (Vojtisek, et.al, 2019).

Figure 4. 3 AVL SmartSampler

For the experiment purpose we created a bypass path before the engine exhaust flows to the filter, at the upstream junction, in order to extract the sample flow (Rameswaran 2019, Master Thesis).

b) Matter Engineering MD-19

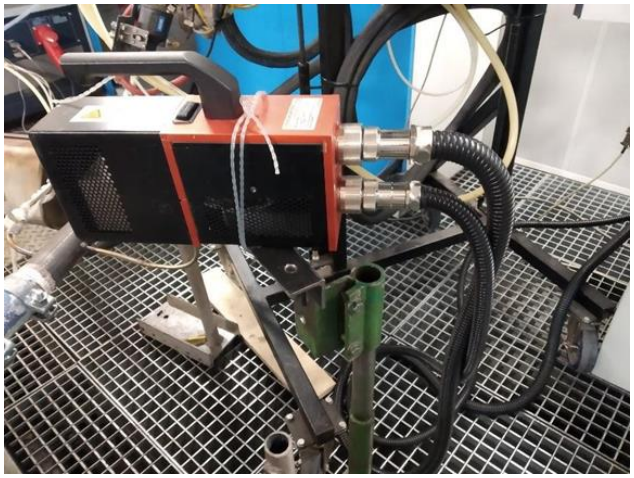


Figure 4. 4 MD-19 Rotating disc diluter

It is a rotating disc diluter from Matter Engineering. This type of dilution system consists of a rotating disc which transfers a metered quantity of sample from the sample inlet into the stream of dilution air (Homolya, et.al, 1972). The dilution ratio of the exhaust gas is being varied by the speed of rotation of the disc. Faster the disc rotates, the dilution ratio goes down. s. It is connected to the control unit by one electrical and one pneumatic connection. In the control unit, power supply, all controls and signal LED's, and control electronics are located, dilution air is filtered and provided to the diluter head, and a membrane pump sucks the raw aerosol through the diluter block. The rotational speed of the diluter disk depends on the dilution air flow which also is determined in the control unit. This was an alternative to the Smartsampler and it was connected to the EEPS.

4.1.2 Engine Exhaust Particle Size

The Engine Exhaust Particle Sizer (EEPS) Spectrometer 3090, manufactured by TSI Incorporated, is used in this experiment to measure particle size distribution. It is a fast response, high-resolution instrument that measures particulate matter of very small sizes, from 5.6 to 560 nanometres (TSI Incorporated, 2005). The EEPS spectrometer helps to visualize emissions of particles during transient engine test cycles with a 10-Hz time resolution.

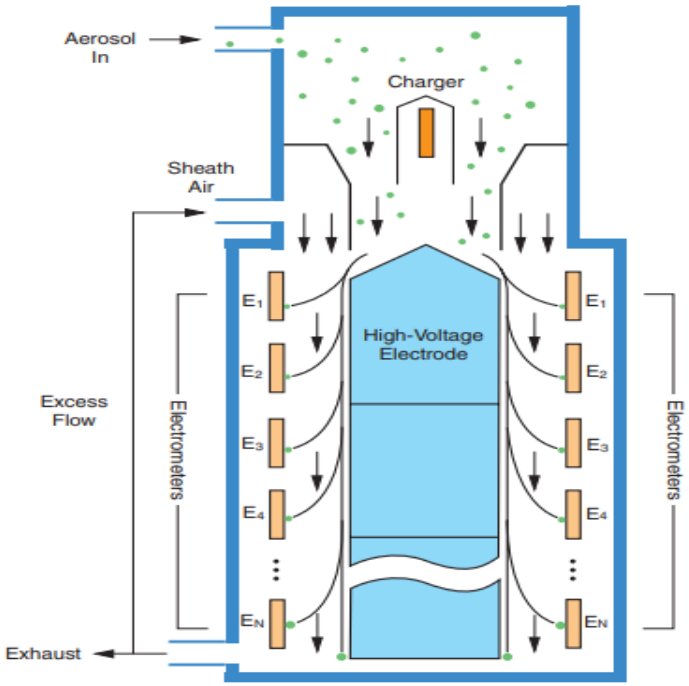


Figure 4. 5 EEPS Flow Schematic (Model 3090 Engine Exhaust Particle Sizer Spectrometer Pdf)

The EEPS works on the principle of size-based particle size segregation, as shown in figure 4.5. The instrument first draws the exhaust sample into the inlet and the maintained flow rate into the instrument is 9.0 lpm. Also, we had to supply certain quantity of exhaust to the exposure chamber (Project of Rajesh Rameswaran). Thus, an additional system HEPA filter and a control valve used to supply a controlled quantity of additional filtered air before the inlet to the EEPS, so that the exhaust gases can be supplied at a constant 2.0 lpm to the EEPS, in order to replace the bypass flow that was created to improve the metering of CO_2 into the system (Rejesh 2019).

The particles are then positively charged to a predictable level with the help of a corona charger. They are then transported through a high voltage electrode column with the help of HEPA filtered sheath air, where the total flow rate is 40lpm (Rajesh 2019). A positive voltage is applied to the column, creating an electric field that repels the positively charged particles outwards depending on their level of charge (TSI Incorporated, 2005).

The particles with higher charge strike the electrometers at the top, and the particles with subsequently lower charge strike the electrometers that are present lower down the column (Rajesh 2019). The electrometers have high sensitivity, which makes it possible to measure multiple particle sizes continuously (TSI Incorporated, 2005). A built-in Digital Signal Processor (DSP) is used to synchronise time delay between the electrometers, particle charge variability, image charge and to present a size distribution with respect to time as output (TSI Incorporated, 2005).

4.1.3 Condensation particle counter

A condensation particle counter from TSI Incorporated, CPC Model 3022, is used here to measure particle number concentrations. This instrument can detect particles with a diameter as low as 7nm. It has two modes of detection, single-count and photometric modes, which enables accurate measurements for concentrations as high as 10^7 particles/cm^3 (TSI Incorporated, 2019).

Exhaust flow rate to the inlet of CPC is 0.3 lpm, as we used the same flow for the exposure box for which flow should be 0.2 lpm (rajesh Rameswaran Project). This is a continuous, laminar flow, thermally diffusive instrument which uses butanol to enlarge particles through condensation, after which they are detected by optical methods (Bischof, 2006). Particles smaller than 50 nm are generally undetectable by optical methods, which is why a working fluid, in this case, n-butanol

is used to enlarge the particles to a size of 10-12 μm through condensation (Centre for Atmospheric Science, 2019, CPC).

The process of controlled super-saturation to typically about 100-200% is maintained to induce nucleation on the particles that takes a part for subsequently enlarging them. The method used to achieve this is called diffusional thermal cooling, where the exhaust passes through a heated porous block or wick that is in contact with butanol and becomes saturated (Centre for Atmospheric Science, 2019, CPC).

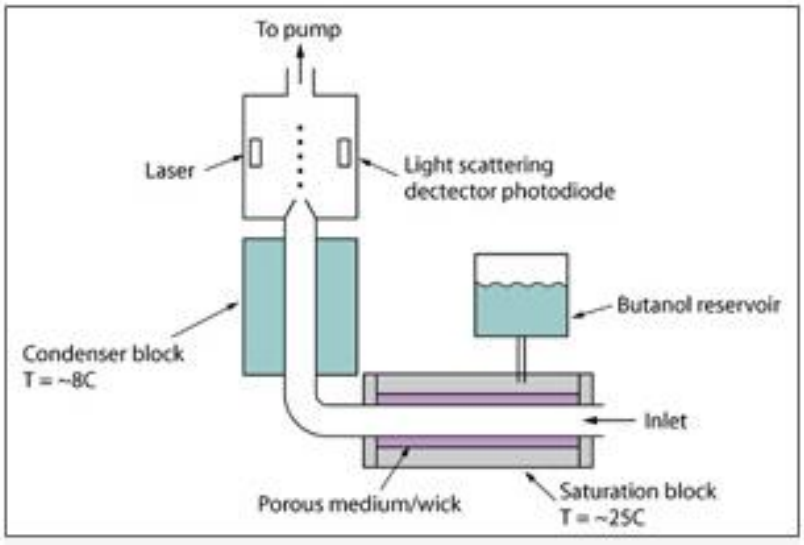


Figure 4. 6 Schematic of a Condensation Particle Counter (Centre for Atmospheric Science, 2019)

The particles are later enlarged and, detected and countered by the Laser scattering which is like the standard optical particle counters. Here we have used this instrument to compare with the EEPS to check the differences between two measurement with different dilution systems and compare the result.

4.1.4 AVL Micro Soot Sensor

The AVL Micro Soot Sensor is a system for the continuous measurement of soot concentrations in the exhaust gas from internal combustion engines. It can measure the concentration of soot directly and without cross-sensitivity to other exhaust components. It operates based on the photoacoustic measurement principle. Due to the measurement cell design and enhanced

electronics of the MSS, a particularly low detection limit of 1 $\mu g/m^3$ in combination with a reduced signal noise is achieved (MSSPlus Manual by AVL).

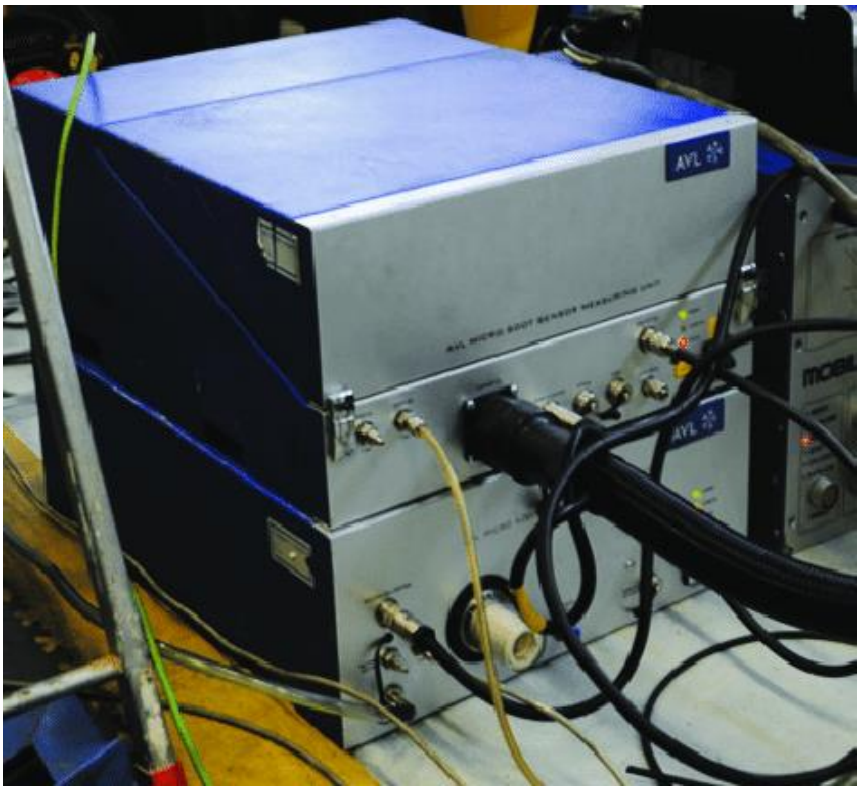


Figure 4. 7 Micro soot sensor Plus (From Test Bench)

It is being refined for low emission measurements, but also for the measurement of raw exhaust gas with the integration of an automated thermophoretic loss compensation (TLC). The TLC function compensates the particle losses resulting from thermophoretic deposition at the sample point and enables an automatic calculation, display and logging of the loss corrected soot signal (MSSPlus Manual by AVL).

It works for transient measurement of soot concentration in the form of mg/m^3 and it is only sensitive to soot while without any exhaust component interference. It is basically working on photoacoustic measurement method. The black gas (Mentioned in Instrument manual) which has absorbed very strong amount of soot particles is being exposed to modulated light. Due to periodical warming and cooling of the particles, the resulting expansion and contraction of the carrier gas can be regarded as a sound wave and detected by means of microphones (MSSPlus Manual by AVL).

In this project we have measured the soot concentration from the exhaust of an engine running at different condition and it is being compared in daily basis to verify the repeatability and differences.

4.1.5 NanoMet

NanoMet3 solid particle counter is especially suited for sampling, diluting, conditioning and counting exhaust particles from diesel and spark-ignition direct injection engines, light oil burners, or wood or coal combustion, as well as performing stack emission studies (Matter Aerosol NanoMet3 Manual). It has a separate exhaust probe and control unit which dilutes the sample at from the source (smart sampler, CVS, tailpipe) to preserve it for accurate measurement. It has a Diffusion Size Classifier (DiSC), a new instrument to measure number concentration and average diameter of nanometer sized particles in the size range 10…300 nm (21).

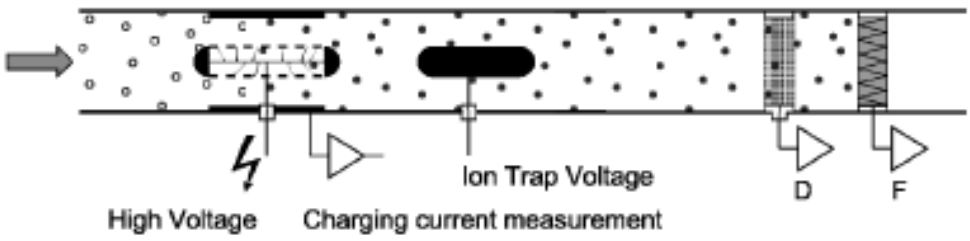


Figure 4. 8 Setup of particle sensor DiSC (21)

The DiSC sensor charges the aerosol in a unipolar diffusion charger and excess ions are removed in an iron trap after charging. The charged aerosol passes through a diffusion stage where particles are deposited by diffusion and detected as an electrical current and then the remaining particles end up in a second stage, the filter stage, and also the current is measured and later on the ratio of the two currents is a measure of the average particle size and is determined during the instrument calibration (Matter Aerosol NanoMet3 Manual). The particle number is computed by total current and flow rate because charge per particle is the function of particle diameter.

Particles in the nanomet range has the tendency to coagulate, due to which smaller primary particles stick to each other and build larger secondary particles, during high particle concentrations. This leads to smaller particle numbers and a change the particle size distributions towards larger diameters. In the diluter head of the NanoMet3 the particle concentration is reduced

as close to their emission source as possible before being transported to the measuring sensor, and the agglomeration effects are reduced significantly (Matter Aerosol NanoMet3 Manual).

4.2 Calculation Procedure

The most important part of the thesis is to analyse the data, which was obtained from all four instruments EEPS, CPC, NanoMet, MSS. And the basic intention to use various instruments to compare all obtained data and check repeatability as well as difference in various condition.

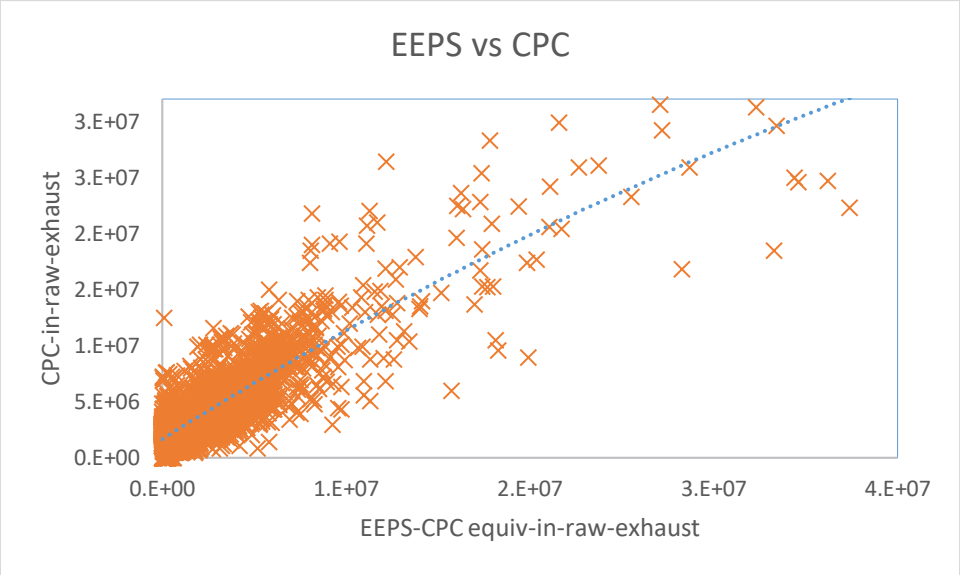


Figure 4. 9 EEPS vs CPC Comparison (Example of variation in measured data)

The first step is the calculation process to find the CPC equivalent particle concentration for the concentration collected from the EEPS. The CPC has a measurement efficiency that is dependent on particle size. Sintered silver particles have been recommended as a suitable calibration aerosol for soot particles (Nowak, et.al, 2014). The detection efficiency of silver particles with respect to particle size is shown in figure 4.10.

Detection efficiency increases with particle diameter which is taken into consideration while doing comparisons between particle concentrations measured by EEPS and the CPC. Since the EEPS measures particles based on their size, it is easy to derive the particle number concentration that would theoretically be detected by the CPC from EEPS size distribution by multiplying the measured particle concentration in each size bin by the corresponding CPC detection efficiency (Rajesh 2019).

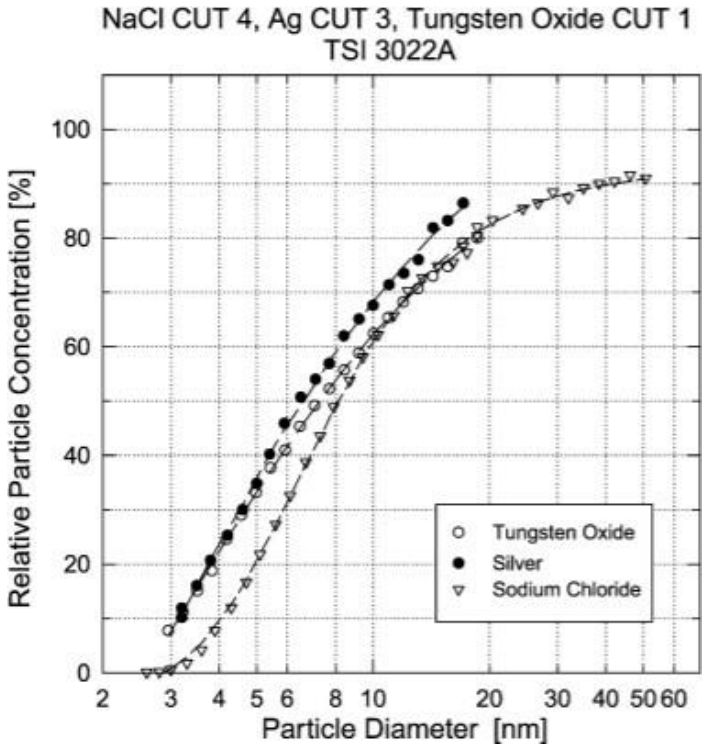


Figure 4. 10 Comparison of the response characteristics of the TSI 3022A CPC with respect to NaCl, Ag and Tungsten oxide test aerosols (Ankilov, 2002)

Since we have used two different dilution systems, now we must calculate the equivalent raw exhaust particle concentration from each set of values for direct comparison. Depending on the configuration used in our test there are different calculations to determine the raw exhaust concentration for each device as follows:

I. When CPC samples from SmartSampler – 10:1 from the SmartSampler and CPC has no additional dilution
II. When EEPS samples from MD-19 – 95:1 from the MD-19 and additional dilution in the EEPS of 9/2:1 = 425:1

The basic method of comparing two devices is to identify the distinct beginning and end of each WLTC cycle. And while comparing different results obtained in different runs conducted during different days, the beginning and end of each cycle is being compared.

Most of the results we have shown in the logarithmic scale to avoid skewness towards the large values. Some values at the beginning of test we will see a quite large which is the cold start period compared to other time. There are also some values that have discrepancies due to some artifacts in the dilution system or defects in measuring instruments. So, it is better to use the logarithmic scale to visualize the whole cycle more clearly.

In some cases, for further analysis a set of data mean particle size distributions are also plotted. This can be done only when the results which we obtained from the EEPS as it records size dependent particle concentration. To do this, first, one distinct cycle is chosen and the average concentration over the entire cycle for each particle is found. Here we have plotted dependency between particle size and average particle concentration.

As NanoMet has its own dilution system so we don't need any external dilution system for this, and the particle number is measured directly and stored in the memory. Also, the MSS works for transient measurement of soot concentration in the form of mg/m3 and it is only sensitive to soot while without any exhaust component interference also for this we do not need any calculation. It stores soot concentration directly in the memory.

5. Results

There were multiple phases of experimentation over the first half of 2019 and during the month of August and September. Here we will discuss the result obtained from different instruments and different fuels used in the entire test phase. First half of the phase one we used EEPS and CPC and the second half NanoMet and MSS were included in the experiment and for second phase of test except CPC we used all other instruments. The combined results of all the tests are discussed in this chapter after discussing the challenges encountered during their execution.

Experiment Phase	**Type of fuels used**
Phase I (Jan – May)	Petrol & E20
Phase II (Aug- Sept)	Petrol, iso-butanol 25% and n-butanol 25%

Table 2 Experimental phases

5.1 Limitations and Challenges Encountered During the Experiment

I. Issues with dilution system: The Smartsampler was having some dirtiness for which we saw the difference in both measuring instruments quite much. But later on, we cleaned the instrument, and the measured value was improved.

II. Miscellaneous issues: There were some issues caused due to the flow of compressed air to the smartsampler, some malfunction of the instruments and also data collection which was monitored and solved on a day-to-day basis.

Most of the major problems and challenges we faced during the initial stages of testing, and all the systems were perfected during the course of experimentation. Due to which we had the better understanding and working of various components and instruments by which we make sure the data which collected is reliable. Data of average concentration of particles measured from various instruments are added in the appendix and all statements below in result comes from those analyzed data.

5.2 Results from EEPS

5.2.1 Particle concentration comparison between petrol and E20

In the First half of test phase, we used typical gasoline and E20 and obtained the particle concentration. We have done 28 number of tests in a time period of 5 months (between January to May) and after analysis of each day data which was quite similar with other days and there was not any significant difference. One of the examples of different concentration of particles with respect to different fuels is shown in fig. 5.1.

Here in figure 5.1, we can see significant difference of particle concentration between petrol and E20. It is not only during the beginning of test the difference is quite significant in entire test procedure. Here during the cold start, we can see the difference is of particle concentration is quite high and E20 has more than 12% less concentration of particles compared to gasoline. And we can see the difference is 18% lower concentration of particles during the beginning of test and it consistently lower compare to gasoline for the entire period of the cycle.

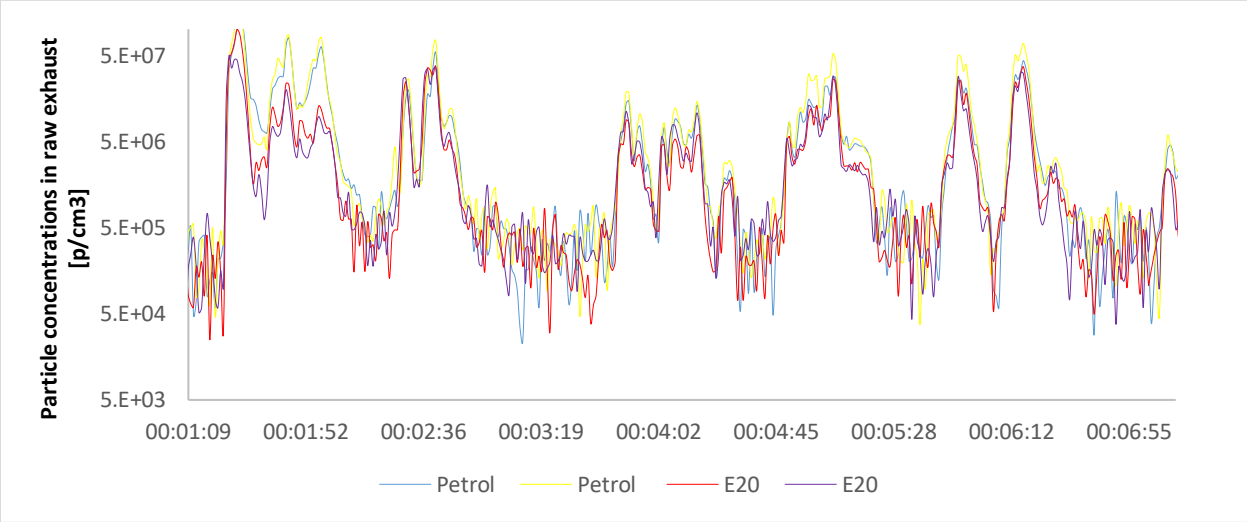


Figure 5. 1 Comparison of concentration of particles EEPS in raw exhaust from petrol and E20

This result is being obtained after comparing various days of data and almost all the data were quite similar. Table of all EEPS average is added in the appendix.

5.2.2 Comparison of particle concentration with different fuel

In the above figure indicates the particle concentration in all different fuels used in the test phase. During the first phase of the test, we had different engine load due to which we can see particle concentration is significantly higher compare to second phase of test with petrol and it is consistent with the entire test result. We can see here the least amount of particle concentration is from Iso-butanol 25%. At the first phase of the WLTC Cycle we can absorb that n-butanol 25% has very least amount of particle concentration compared to petrol and it is significantly lower than The E20 and Iso-butanol 25% as well.

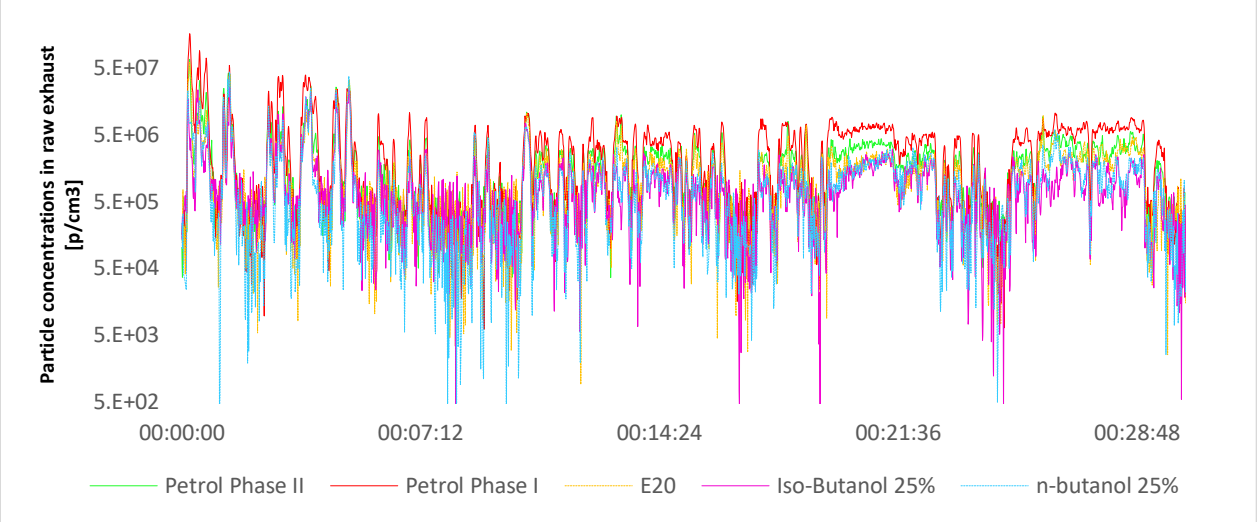


Figure 5. 2 Particle concentration from EEPS among all fuels used

The fig.5.2 is an example of yearlong test data comparison and we observed that this is similar with various days of test. Also, there were some non-similarities in two to three days of data which can be attributed to defects in the sampling system or sometimes also due to the defect in the measurement.

5.2.3 Comparison of Cold start and Cooled start effect gasoline

As we performed four WLTC cycle to measures the particle concentration in different engine condition. Out of which two were done in morning and two in the afternoon. So, for the first half the engine was cooled naturally by overnight unused and after two WLTC cycle the engine was

rested for 2 hours and accelerated cooling by help of an air blower to obtain the cold start condition. All data of different days are shown in table at appendix.

Figure 5.3 indicates the difference of cold start and cooled start of WLTC cycle, and we can see the morning cold start has more particulate emission compared to the afternoon cooled start. The ratio of difference in concentration of particle is 1.5(±0.5). And we can see some part of cycle the cold start also has less particulate emission compared to the cooled start and most of the results are similar with the yearlong test data.

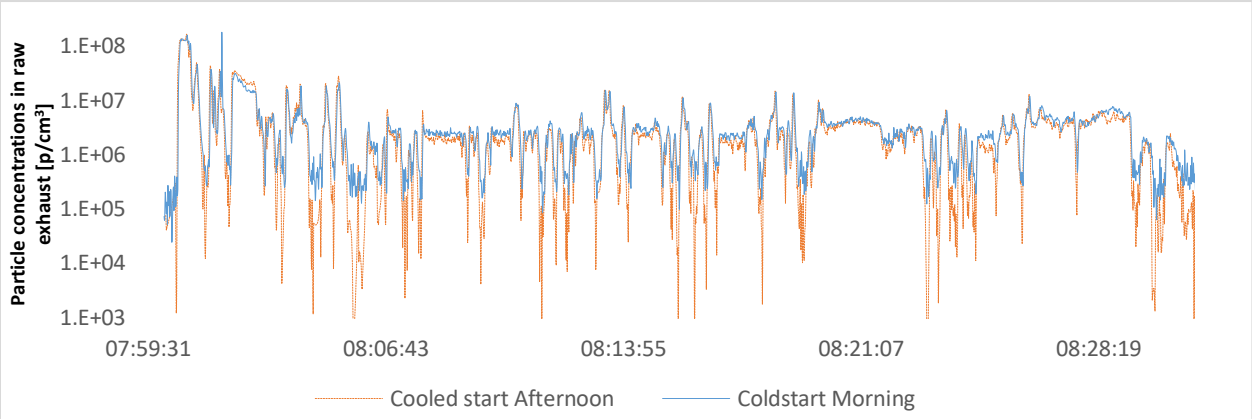


Figure 5. 3 Particle concentration from EEPS at Cold start vs Cooled start condition

But more or less the particulate emission with cold start and cool start not so different and also, we will show comparison of cold start with warm start.

5.2.4 Comparison of cold start and warm start effect

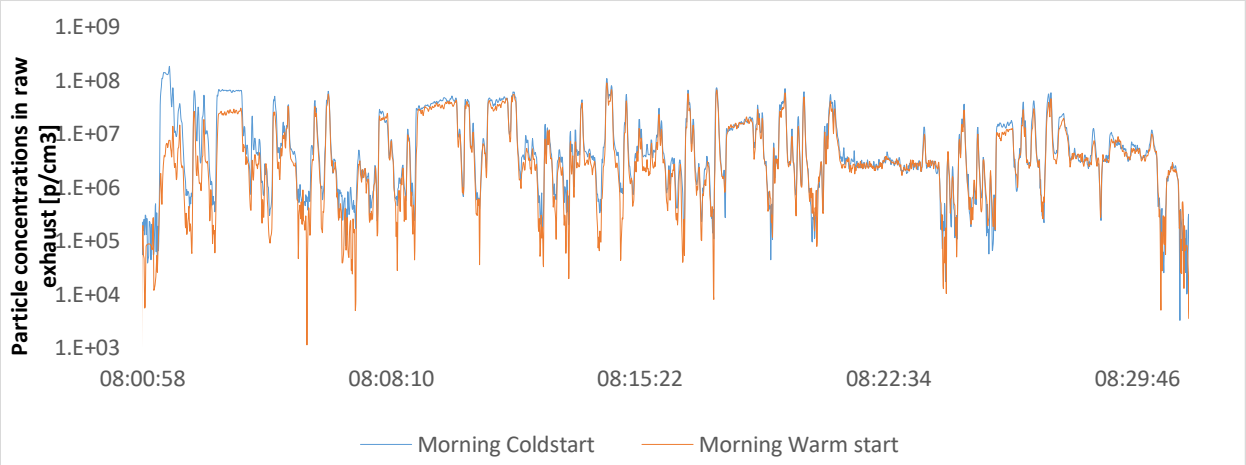


Figure 5. 4 Effect of cold start from EEPS by comparing Cold start and warm start

In this part of discussion is to observe the cold start effect on particle concentration from engine exhaust when we compare cold start cycle with warm start cycle. After overnight natural cooling the engine runs for a 30 minutes WLTC cycle and after that we run again another cycle when the engine is hot. The total emissions during a cold start where generally several times higher than during a subsequent hot start test.

In the fig. 5.4 we can see the effect of cold start is highest at the beginning of the cycle, With the particle concentration are nearly 2 order of magnitude higher compared to the warm start, and it is gradually decreasing with respect to time. We can see the effect is relatively minor about 10 to 12 minutes and there are no observable differences after 18 minutes of the cycle.

5.2.5 Comparison of a full day WLTC test to see the cold start effect

In the figure 5.5 here we can see the effect of cold start comparing with the other test cycle of the day. Here we can see the cold start and cooled start test has white higher concentration of particles compared to warm start effect in the morning as well as afternoon.

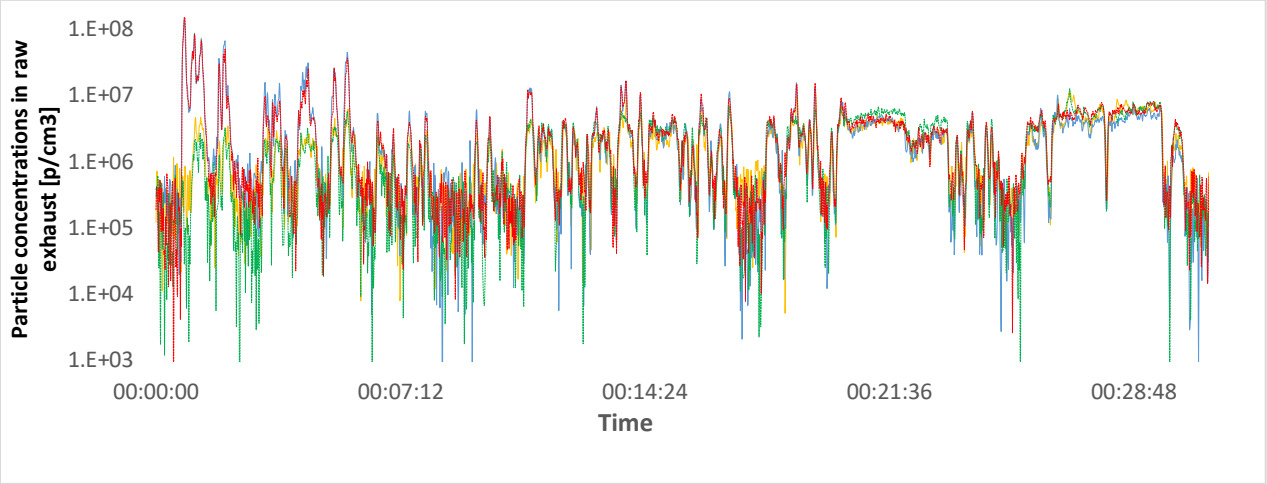


Figure 5. 5 Cold start particle concentration comparisons from all-day test

We can observe here from the figure 5.5 the side effect of the Morning Cold start and afternoon cooled start Is highest at the beginning of the cycle and both warm start in the morning and afternoon significantly lower. Here we can see the effect of cold start is up to 11 to 12 minutes while gradually decreasing over time. And after 17 minutes of the WLTC cycle we can see the

cold start effect is almost gone. And the afternoon cold start particle concentration is slightly lower than the morning cold start.

5.2.6 Mean Particle Size Distribution

a) The mean particle size distributions over the entire day are shown in fig. 5.6 which includes 4 times WLTC as cold start, warm start, cooled start and warm start for the day. Here we can see the morning cold start and afternoon cooled start are quite similar and warm cycles are similar as well. This data is provided here is an example of comparing different days test cycle data over a year time period and most of the days results were similar and few days of data was not appropriate due to measurement error

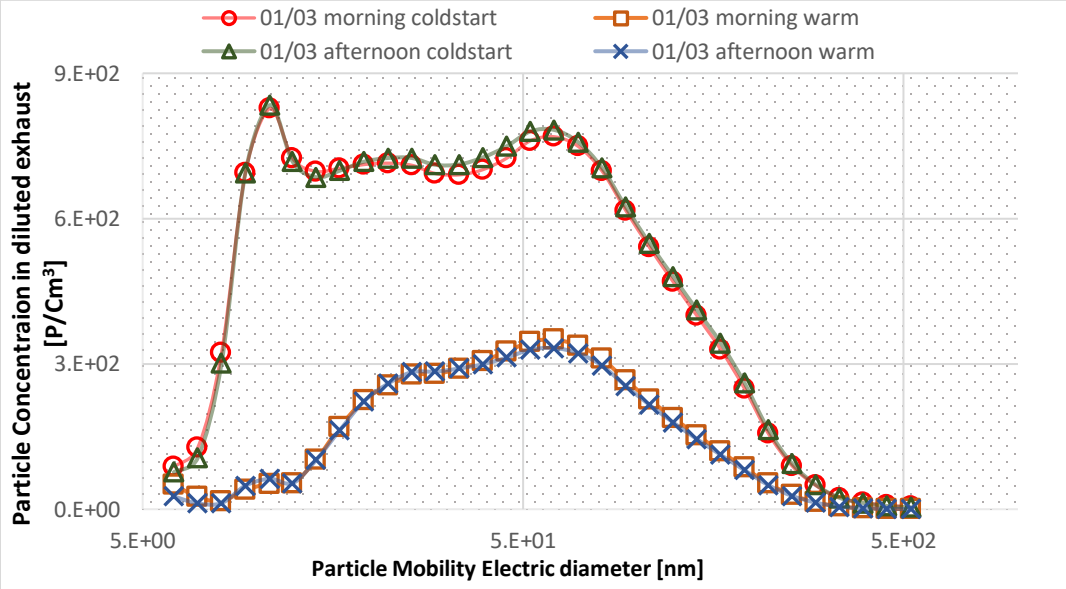


Figure 5. 6 Mean particle size distributions of full cycle

b) Figure 5.7 shows the Particle concentration in raw exhaust of cold start WLTC cycle. Here we have shown WLTC cycle in different speed. The effect of cold start is mostly visible here due to high concentration of particulate in the raw exhaust. And at other speed of the WLTC cycle like medium speed, high speed and very high speed has lower concentration but at very high speed we can see the concentration of particulate matters are high compared to others. Analysis of the full data set including other preliminary runs the demonstrated artifacts suggest that prior engine operating conditions may affect

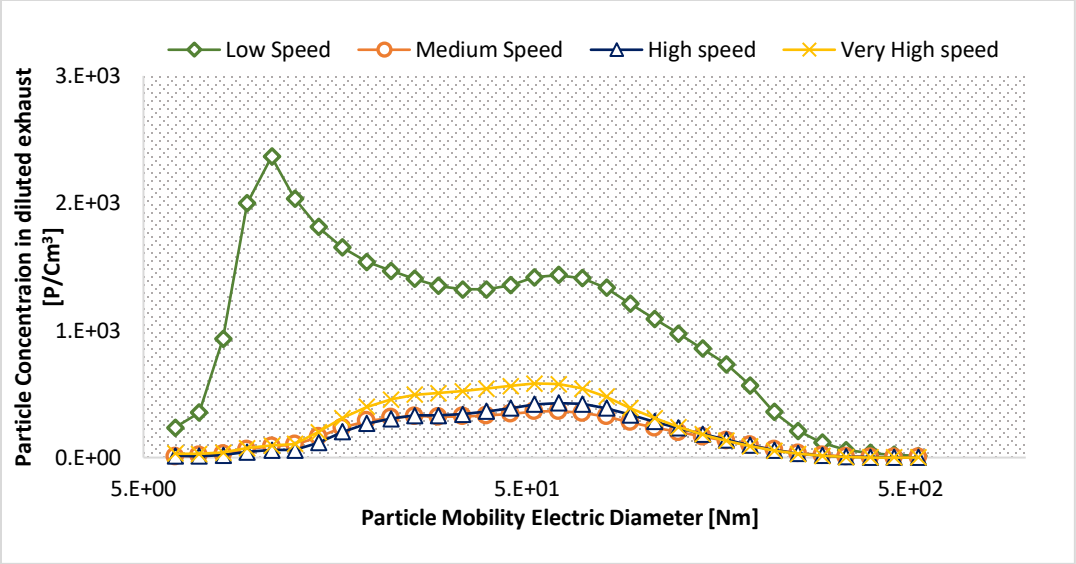


Figure 5. 7 Mean particle size distributions of cold start WLTC cycle

engine emissions over a day or more of testing and which is quite high compared to the warm start condition. Unlike with diesel exhaust, where particle size distribution has one or two visible peaks, the size distributions observed here are relatively flat.

c) Figure 5.8 is the mean particle size distribution of a warm start WLTC cycle. Here we can see the concentration of particle in the raw exhaust with different speed of the WLTC cycle. At high speed of the engine, we can see the particle concentration in the raw exhaust is higher compared to the other speed of the cycle.

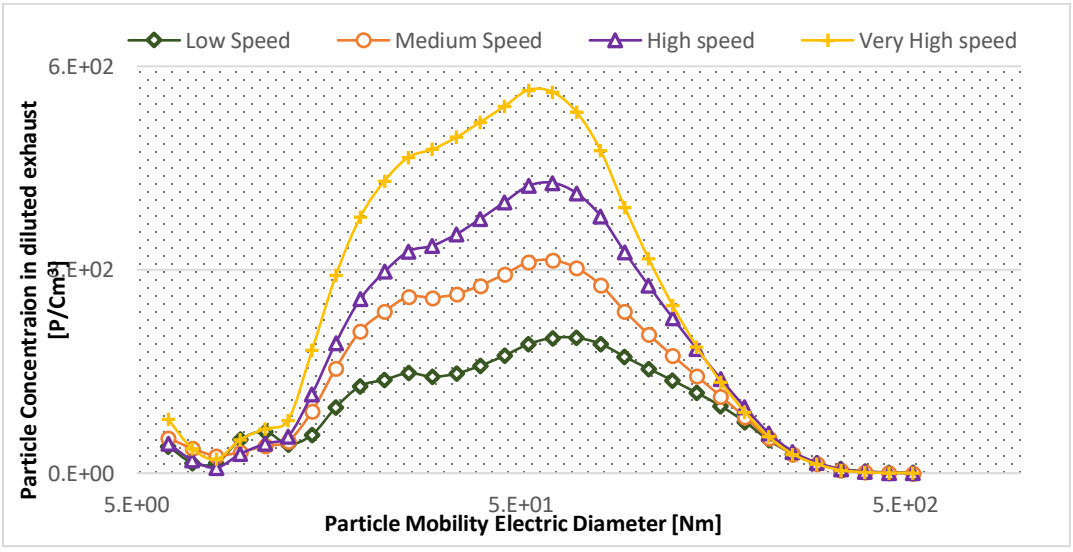


Figure 5. 8 Mean particle size distributions of warm start WLTC cycle

There was no difference found between the substituent cycles later done on the day which is the cooled start and afternoon warm start, those were almost like the morning particle concentration. Also, sometimes there are some measurements obtained claims the concentration of particles are lower can be attributed to nucleation from the smart sampler.

d) In the below figure 5.9 shows the mean particle size distribution in different fuels used in a cold start WLTC cycle. We have compared the cold start condition of a WLTC cycle to see higher concentration of particles among all fuels compared to other WLTC cycle. After various test data analyzed and compared, we saw that petrol Phase I has the highest number of particle concentration in the exhaust compared to other fuels. As we know the engine load during phase I test Was higher compared to the Phase II test condition.

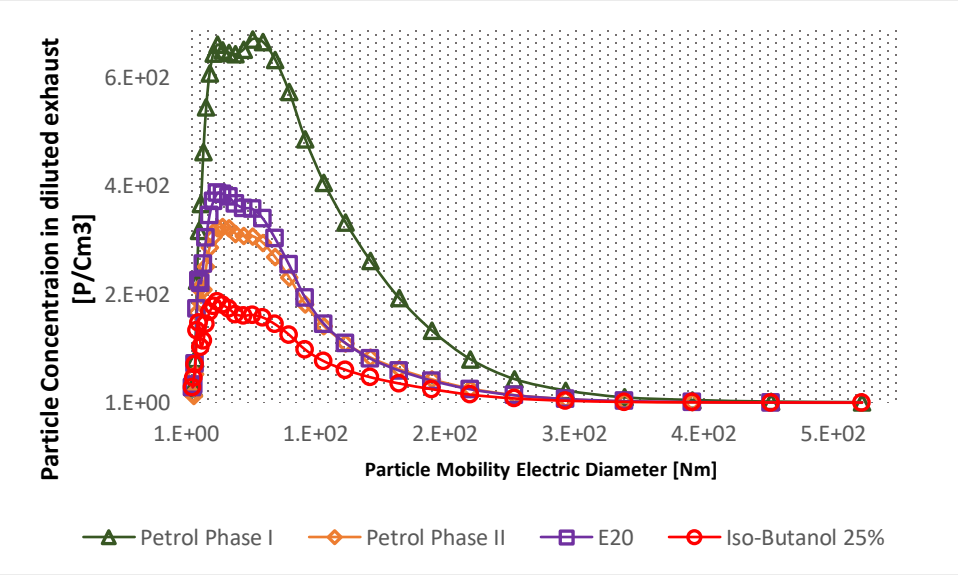


Figure 5. 9 Mean particle size distributions of various fuel in cold start WLTC cycle

The least amount of particle concentration in raw exhaust is from iso-butanol 25%. The concentration is about three times lower from the phase I petrol concentration. Also, we can see E20 has higher concentration then iso-butanol 25%. Because the E20 was during the Phase I we can also assume that it will be less than the petrol Phase II concentration.

5.3 Results from Gravimetry

Figure 5.10 shows the particle mass by gravimetry for all different fuels used in the entire test period. We can clearly see that the particle mass from gasoline exhaust in Phase I test is highest compared to other fuels. Also, we have the blank filters, those were used while cooling the engine to observe the presence of particulates in the smart sampler. Iso-butanol 25% has the least concentration of particle deposited on the filter. Particle mass from gravimetry for E20 was 16±2% lower compare to gasoline and for isomers of butanol it was 40±4% lower.

We have some filters those weights are not compatible with other days of data and it can be due to the nucleation in the smart sampler which was later cleaned and repaired to obtain better result. As we can see the alcoholic fuels have lesser particle concentration compared to petrol and the E20 has significantly less concentration than the gasoline.

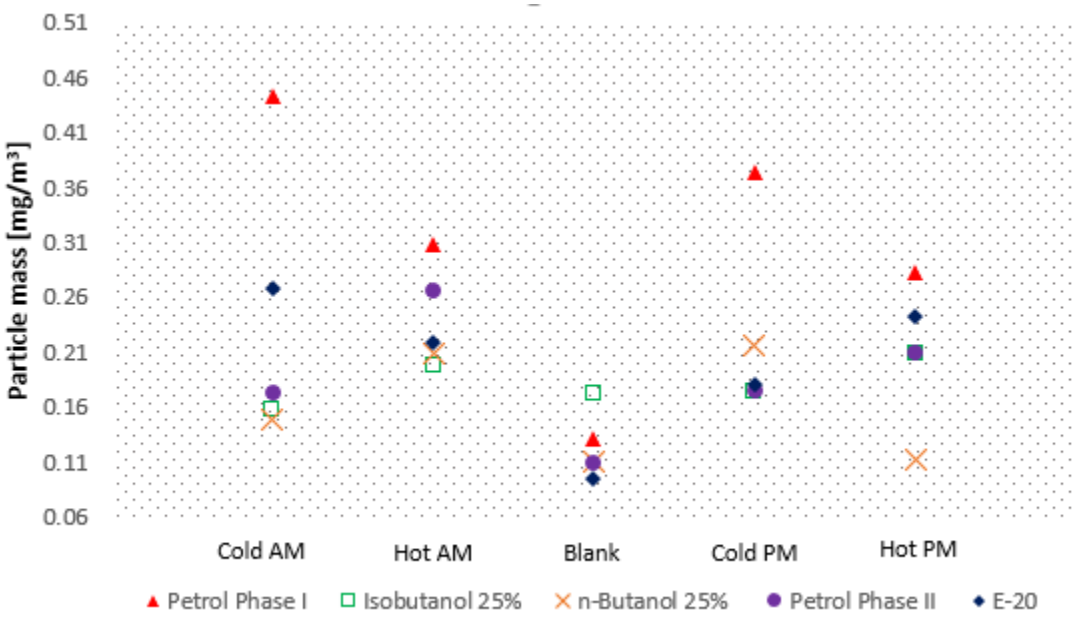


Figure 5. 10 Comparison of filter weights among different fuels

In the figure 5.11 we have compared the gravimetry data with average mass concentration calculated from the EEPS and in this we wanted to see if both the data from various tests were compatible and not.

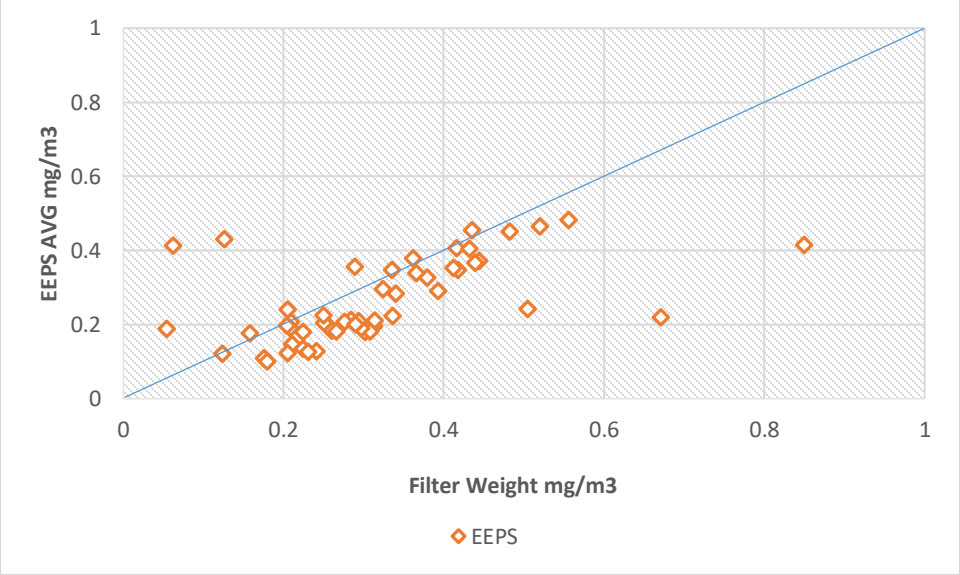


Figure 5. 11 Comparison of gravimetry with EEPS

And we can clearly see the average of particle concentration in EEPS from the raw exhaust is quite comparable with the measured filter weight from smart sampler. Also, we can see there are some irrelevant results, those can be taken as defects in the sampling system or measurement of the filters or physical property changes of the particles. Because the filters were stored for a day to condition the filters so that their temperature and humidity is comparable during the weighing before and after the test.

5.4 Results from Micro Soot Sensor

Figure 5.12 shows the soot concentration from the engine of a cold start WLTC cycle between two different fuels in first phase of test which was petrol and E20. We can clearly see from the below figure that petrol has higher soot concentration compared to E20.

I have compared all results of yearlong experiment to check the repeatability and most of the test had similar trend and we can see the difference in soot concentration in these two fuels progress with the entire course of the cycle.

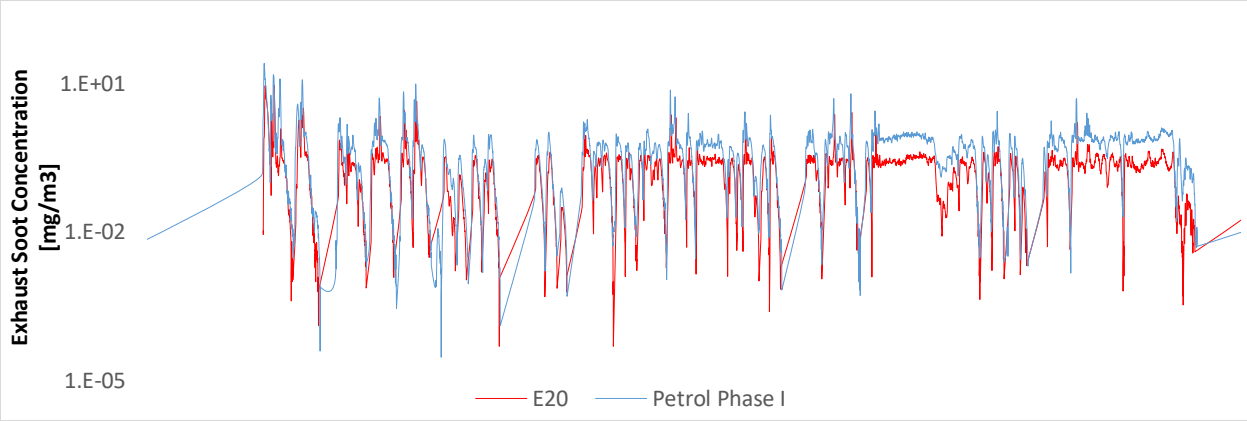


Figure 5. 12 Exhaust Soot Concentration comparison between Petrol Phase I and E20

Figure 5.13 compares soot concentration from engine exhaust from gasoline and isomers of butanol. Butanol isomer has soot concentration 32% (±4%) lower relative to gasoline. The difference is consistent in the entire test cycle.

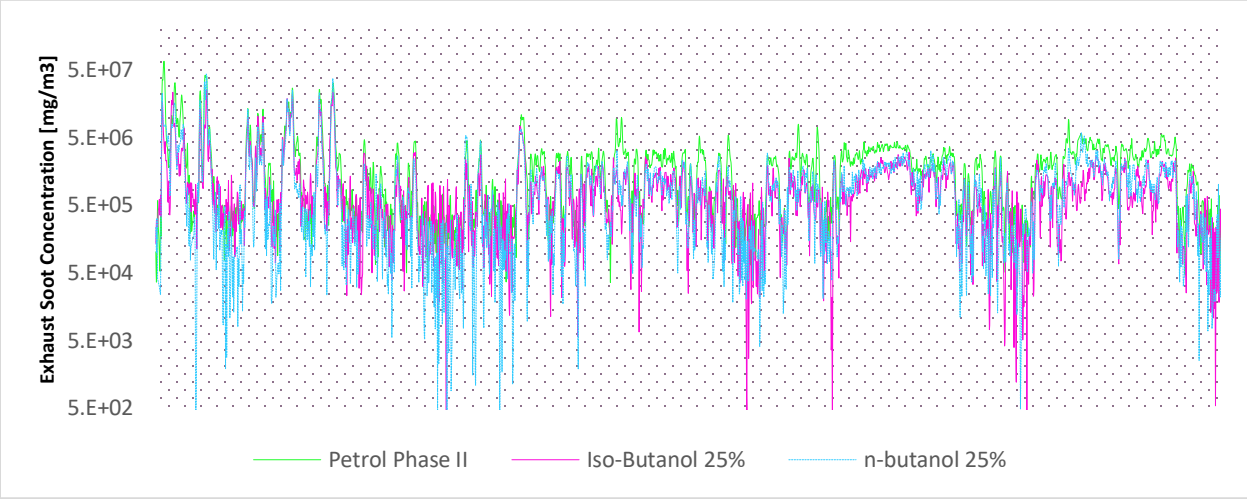


Figure 5. 13 Exhaust Soot Concentration comparison between gasoline and isomers of butanol

Also, we have compared the cold start data with the warm start to evaluate the cold start effect on exhaust soot concentration. Figure 5.14 is an example of cold start effect of the engine and here we can clearly see the effects of cold start from the beginning of the cycle.

I have compared a cold start WLTC cycle with a warm start WLTC cycle in which we can see the cold start WLTC cycle has higher soot concentration compared to the Warm WLTC cycle and the effect of cold start is observed up to 14 minutes of duration and which gradually decreases with

respect to time and after 17 minutes of the cycle there is no differences in concentration of soot particles in the engine exhaust.

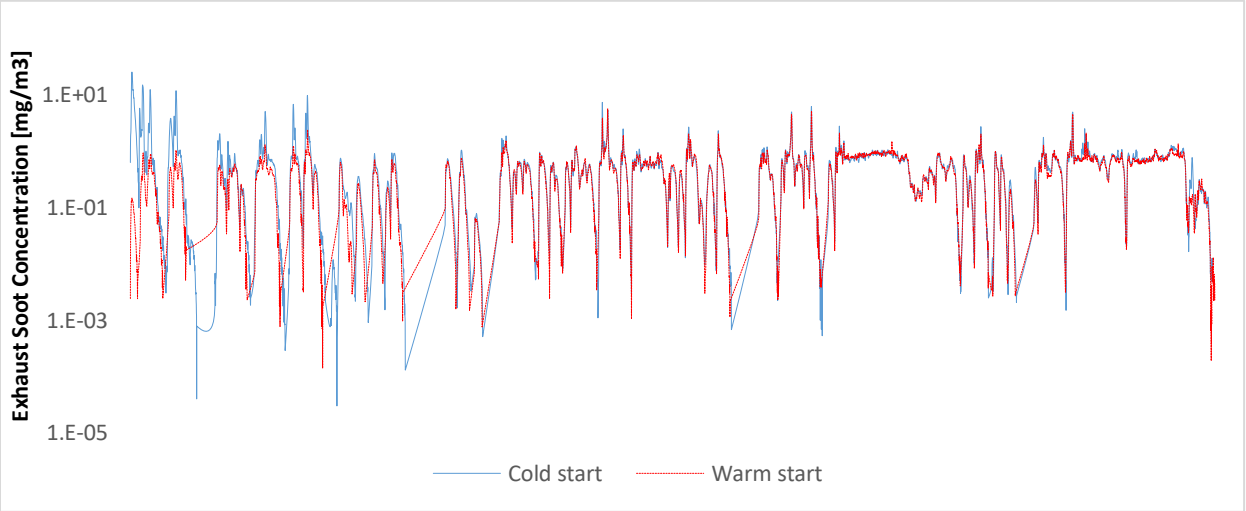


Figure 5. 14 Effect of coldstart in engine exhaust soot concentraton

During the afternoon test which is forced cooling test cycle we can see kind of similar result which is higher than the warm test cycle. Also we found some test with higher concentration of soot in the warm cycle compare to cold cycle.

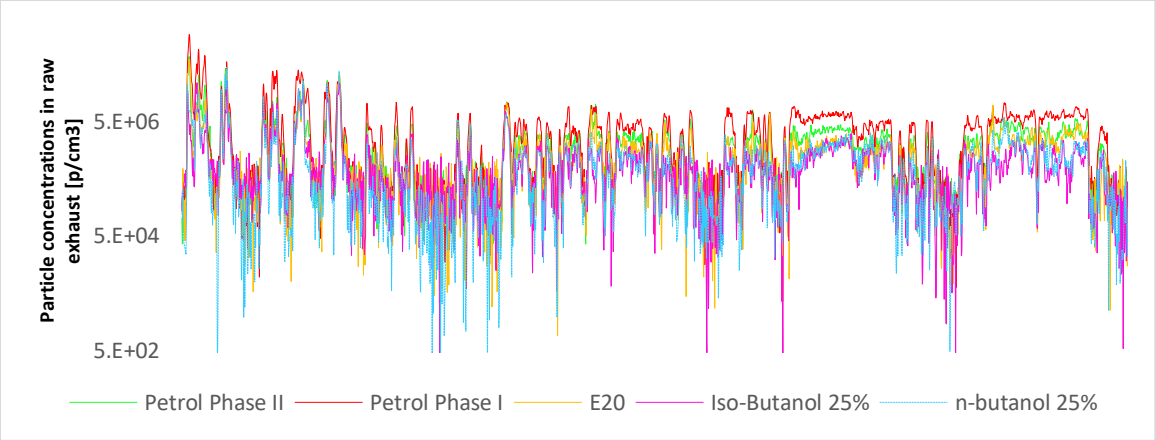


Figure 5. 15 Exhaust soot particle concentration in different fuel

In the above figure 5.15 We have compared all fuels used in the entire experiment which are petrol, E20, iso-butanol, n-butanol. Soot particle concentration in the Phase I petrol test is highest among other fuels used. And the least soot particle concentration in the exhaust is from n-butanol 25%. Also, we can see soot particle concentration from Phase II petrol test is less than the Phase I petrol

which is due to the difference of load on the engine on different test phase. E20 has quite less concentration of soot particle which is quite similar to the iso-butanol 25%.

5.5 Measured particle concentration from NanoMet

We used NanoMet to measure particle concentration from engine exhaust to compare with other instruments like EEPS and CPC. But for the NanoMet we were only able to measure with three kind of fuels as petrol Phase I, E20 and iso-butanol 25%. Due to some measurement error in the instrument the data was not recorded for which the Phase II petrol and n-butanol emission characteristics are not compared here.

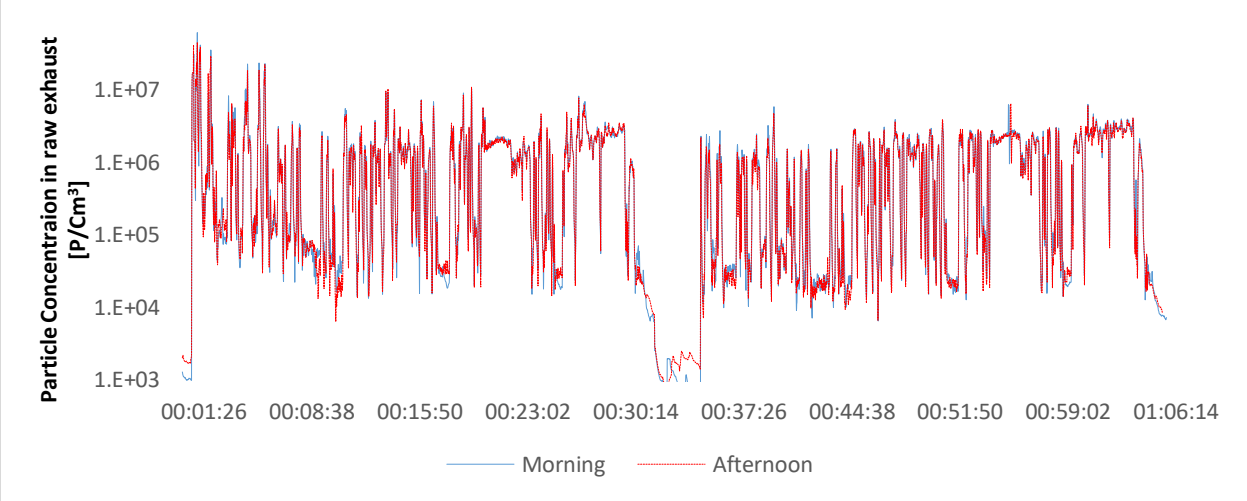


Figure 5. 16 Particle concentration comparison between morning and afternoon test

In figure 5.16 we have compared the morning particle concentration with the afternoon particle concentration and here we can see we have very little difference of particle concentration between two different timing. Here also there is no difference between the cold start and the cooled start particle concentration, but morning cold start has a little bit of higher concentration.

The effect of cold start in the exhaust particle concentration can be seen on figure 5.16. we can see significant differences between the cold start and the warm start WLTC cycle. Particle concentration in the cold start WLTC cycle has 2 magnitude higher concentration compared to the warm start cycle. We can see the effect of cold start is gradually decreasing over time period. The effect of cold start can be clearly seen up to 13 minutes of the beginning of cycle. After 17 minutes we can see there is no effect of cold start and it is approximately zero.

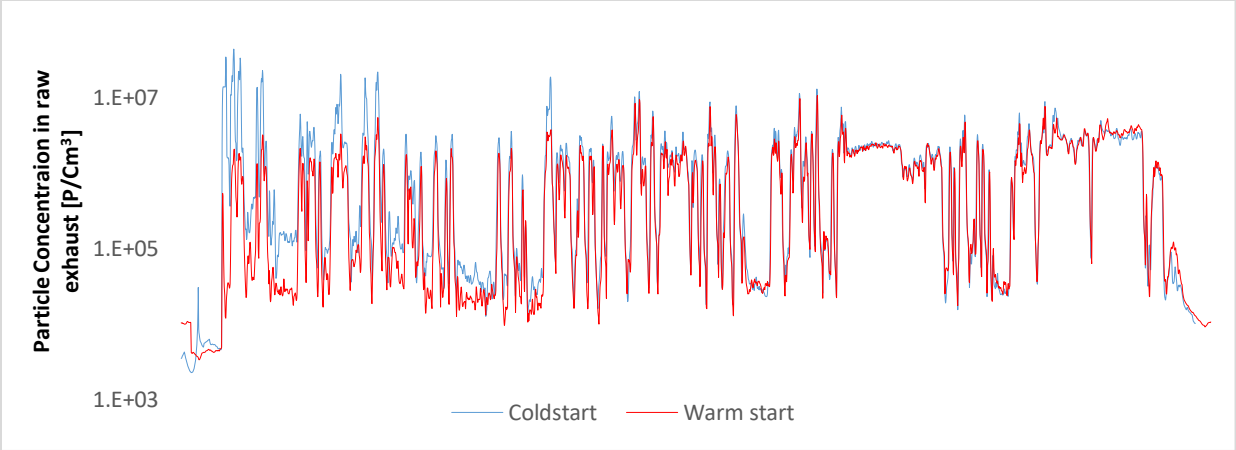


Figure 5. 17 Particle concentration comparison with the effect of cold start

We have compared Phase I petrol and E20 to check the difference of particle concentration in the exhaust with same engine load. The concentration of particles in the petrol is significantly higher than E20 and it is continuing for the entire cycle. And the difference of particle concentration is about 12%.

In most of the collected data with different days has approximately same kind of structure and from this we believe and subjected an example of analyzed result of the particles here. At this condition the engine load was higher compared to the Phase I test. So, we can expect the gasoline in Phase II with lower engine load will have lower concentration of particle.

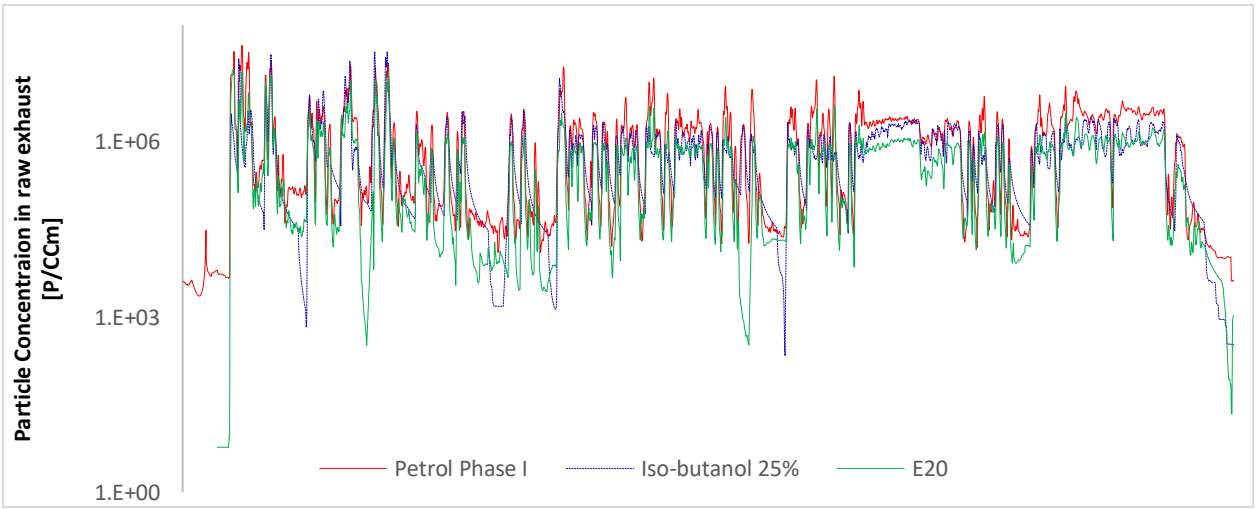


Figure 5. 18 Particle concentration comparison in engine exhaust from all fuel used in entire experiment

For the entire test we have only three different fuels and the difference of particle concentration has been shown in the figure 5.18. We can clearly see particle concentration in the petrol is the highest among all 3 different fuels. And iso-butanol 25% has more concentration of particle then

the E20 which has the least amount of particle. After various measurement in different days, we have shown the analyzed compatible result which was similar with different days. And here in NanoMet we did not use any dilution system because it has its own dilution system.

5.6 Measured Particle Concentration From CPC

CPC is the most dependable measuring instrument which we used to compare for particle concentration from EEPS. We know the CPC was collecting the diluted exhaust from the smart sampler and the EEPS was collecting from the rotating disc dilutor.

In figure 5.19 we are comparing the cold start WLTC cycle with the cooled start WLTC cycle from the data collected by CPC. Here we can clearly see that the cold start particle concentration is little bit higher compared to the afternoon cooled start. In some part of the cycle, we can see the data is significantly higher but mostly the data which we collected after analyzing we saw are similar with other days. We are seeing the difference which is between 2 to 3% between the morning cold start and afternoon cooled start.

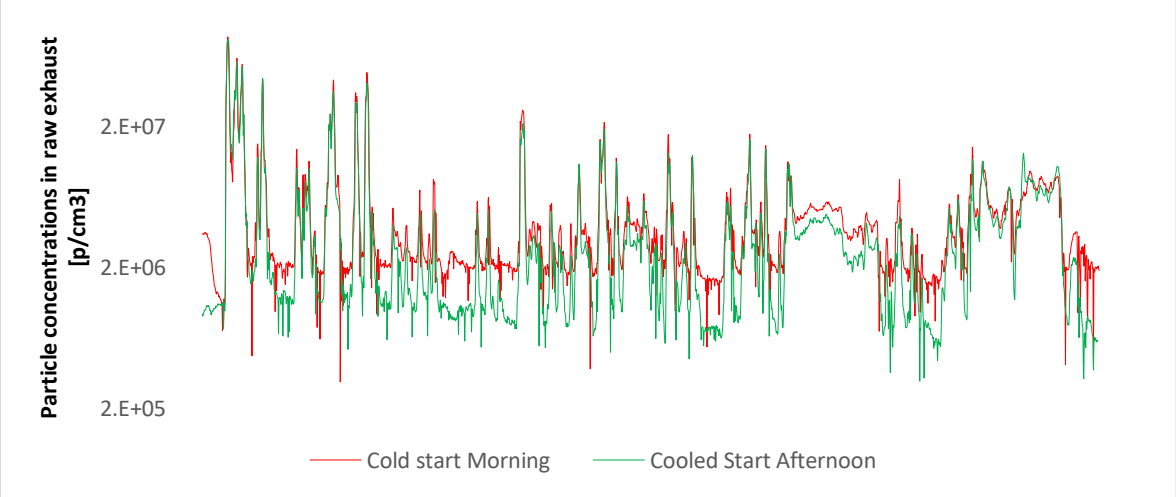


Figure 5. 19 Particle concentration comparison in engine exhaust between morning cold start and afternoon cooled start

Here the figure 5.20 shows the cold start effect on the particle concentration where we have compared WLTC cycle of the morning cold start and a warm start WLTC cycle. Here we can clearly see the dynamic effect of cold start on the particle concentration. We can see a huge difference of particle concentration which is gradually decreasing with respect to time, but the

difference is probably two magnitude higher and we can see the cold start effect up to approximately 12 minutes of the cycle with higher difference and later on the difference in concentration is reducing but still there is a little bit of effect throughout the cycle. But as we know EEPS has a different scenario compared to this result so we can say it could be due to the nucleation in the smart sampler.

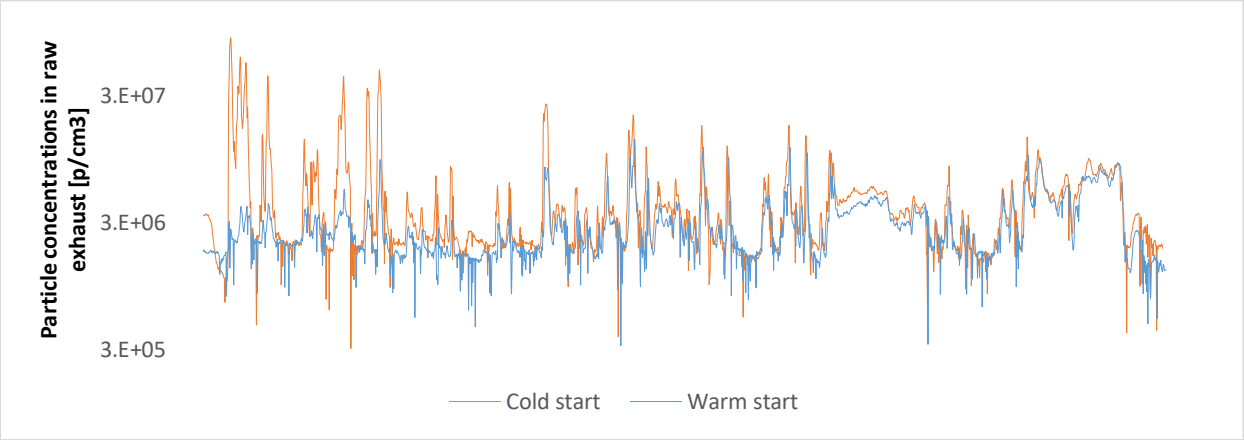


Figure 5. 20 Particle concentration comparison with the effect of cold start

During the second phase of test CPC had some problem with the measurement due to which we could not measure for other fuels.

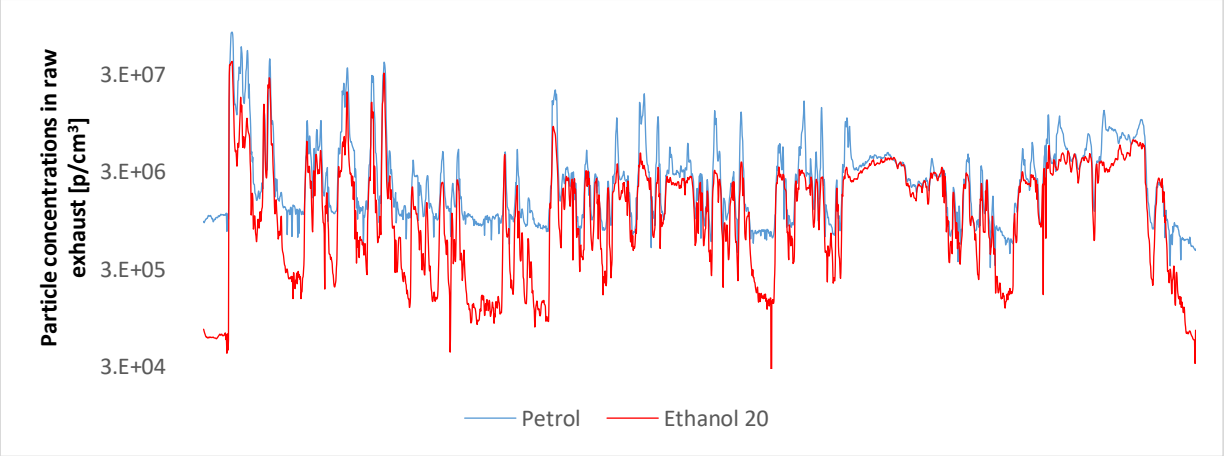


Figure 5. 21 Particle concentration comparison between petrol and E20

Figure 5.21 we are comparing the particle concentration between petrol and E20. Here we can clearly see petrol has higher particle concentration in the exhaust compare to E20 and it is continuing with the entire cycle. This figure is an example of various data collected and analyzed and there are similar for each day.

5.7 Comparison Between Measuring instruments

The smart sampler was operating at a dilution ratio of 10:1, and this dilution ratio was used for the toxicological studies for Czech Science Foundation project MUCILTOX, within which there were multiple smaller projects, such as design of the exposure chamber, or PM measurement. Operation at a dilution ratio of 5:1 has lead to water condensation and operating at higher dilution ratio increase the uncertainty in the dilution ratio, Increasingly small flow of raw exhaust inflow is regulated indirectly as a difference between two large regulated flows of the dilution air and the total sample (Vojtisek 2019).

The rotating disc diluter has a wide dilution ratio range from 15:1 to 3000:1. A nominal DR of 75:1 (note: the rotating disc diluter uses a term „particle concentration reduction factor“(PCRF) which slightly differs from the volumetric dilution ratio), corresponding to the actual particle concentration reduction factor of 95:1 after adjustments for individual calibration and for temperature of the diluter head was used here (Vojtisek 2019).

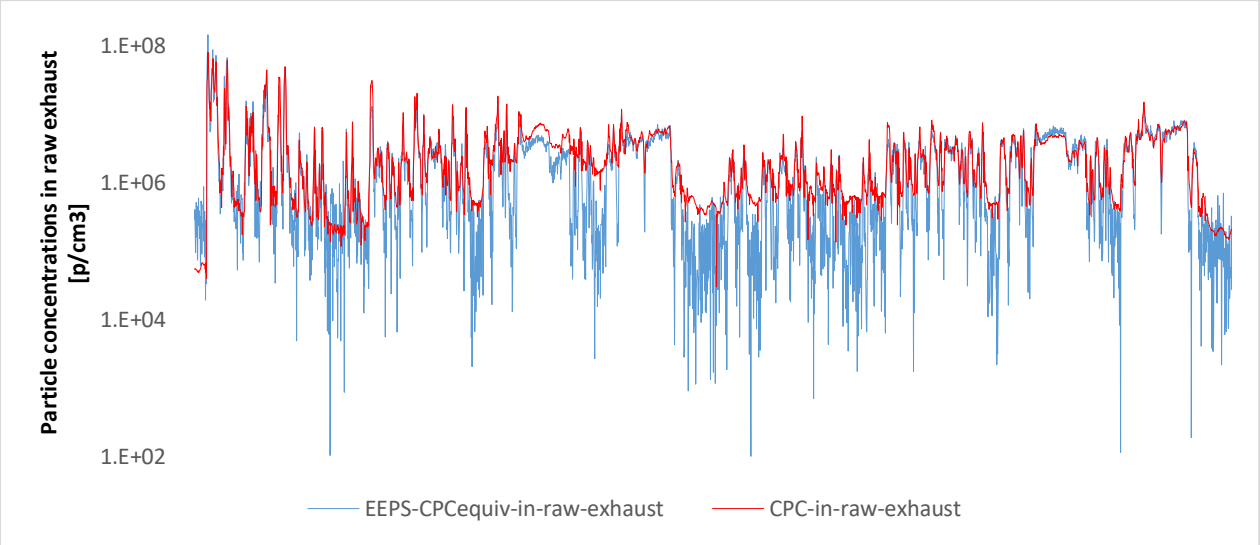


Figure 5. 22 Particle concentration measured by EEPS and CPC comparision

The figure 5.22 is the comparison between particle concentration measured by EEPS and CPC. Here we can see the difference of data and a strong peak is apparent in the smart sampler samples which is absent in the rotating disc diluter samples which can be attributed to nucleation taking place due to low dilution ratio.

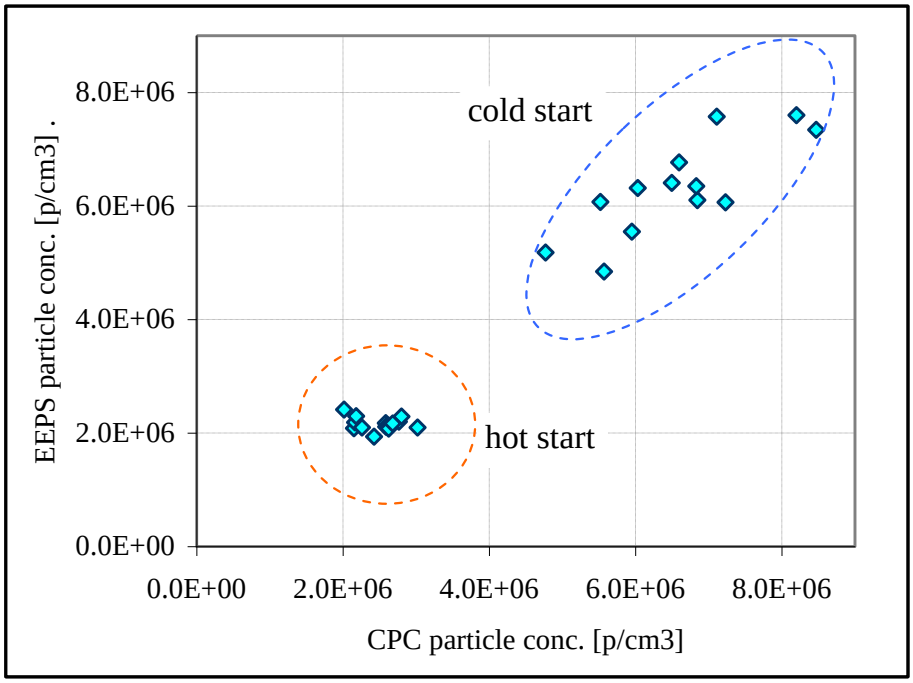


Figure 5. 23 Particle number comparison measured by EEPS and CPC comparison (Assessing Exhaust Toxicity with Biological Detector: Configuration of Portable Air-Liquid Interface Human Lung Cell Model Exposure System, Sampling Train and Test Condition, SAE 2019-24-0050)

Below figure 5.24 Is the comparison of particle concentration between EEPS, CPC and NanoMet. As we know NanoMet has its own dilution system, and EEPS and CPC are also working with different dilution systems.

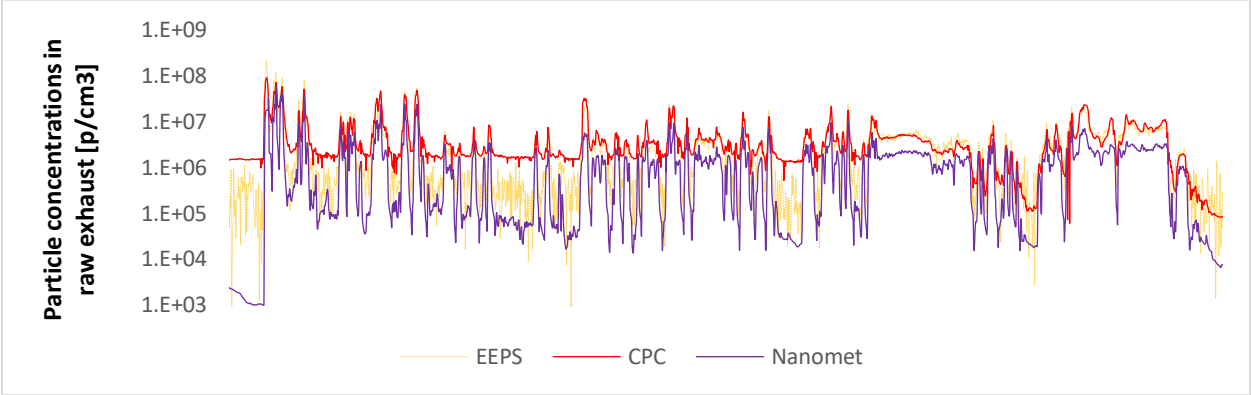


Figure 5. 24 Particle concentration comparison between different instruments

Nanomet is having a separate exhaust probe and control unit that effectively dilutes the sample at the source in order to preserve it for accurate measurement. Nanomet is completed with a Diffusion Size Classifier (disc), a new instrument which measure number concentration along with average

diameter of nanometer sized particles in the size range 10…300 nm. Nanomet is measuring non-volatile particles larger than 23 nm thus reported concentrations are lower than those form other instruments.

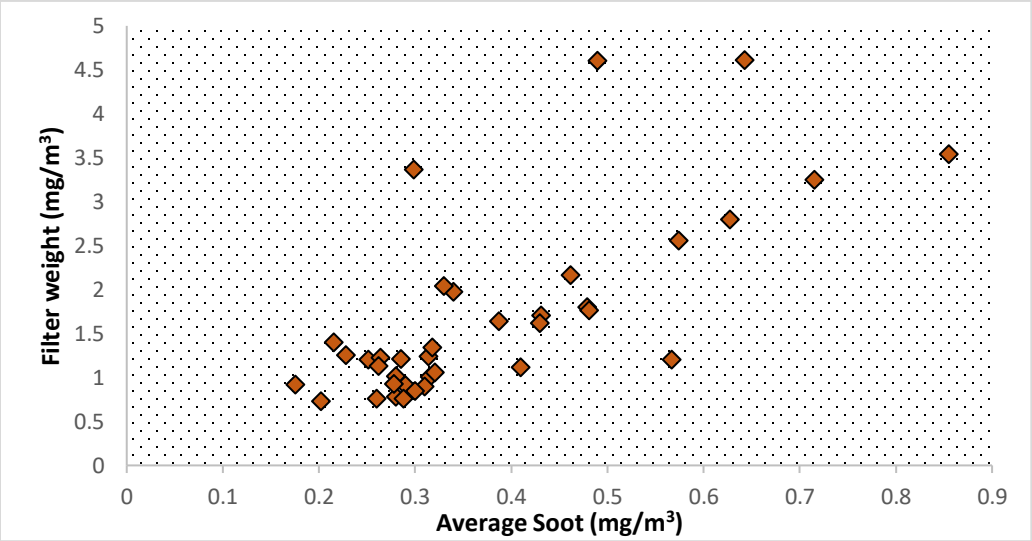


Figure 5. 25 Comparison of gravimetry with Soot (MSS)

In the figure 5.25 shows the comparison of particle mass between gravimetry with average mass concentration calculated from the MSS and in this we wanted to see if the result were comparable.

And we can clearly see the average of particle concentration in MSS from the raw exhaust is not quite comparable with the measured filter weight from smart sampler. There are some irrelevant results, those can be taken as defects in the sampling system or measurement of the filters or physical property changes of the particles or measurement defect of instrument. Because the filters were stored for a day to condition the filters so that their temperature and humidity is comparable during the weighing before and after the test. Also, here we can observe significant discrepancy in the data of MSS.

6. Discussion and Future scope

The chapter deals with general discussion about the project, laying down explanation for some phenomenon that were observed.

The goal of the thesis was to compare the particle emissions. We used various dilution systems provided mostly similar results, and there is also some variation which could be attributed to the nucleation artefact in the SmartSampler. The smart sampler was harder to mount and set up compared to MD-19. It also needs an external compressed air supply which was causing problem due to some issues in the air supply.

The MD-19 was very easy to use, and it was not requiring any additional source to operate. Despite the issue we had to use smartsampler because we needed lower dilution ratio(Sample handling and proportional dilution, Rameswaran 2019). We used all four particulate measuring instruments out of which we needed smartsampler and MD-19 to supply diluted exhaust gas to EEPS and CPC. Other two instrument Nanomet and Microsoot sensor where very easy to set up and record the data because they were having their own dilution system.

The smart sampler also has a gravimetric sampling system which allows for further analysis of particle weight with other instruments. Also, to control the smart sampler we had to keep an eye on the flowmeter every time and it was really a concern part of our experiment. At the mean time other instruments, were not having such problem but there were certain issues like cleaning the EEPS and controlling the NanoMet and sometimes we had to clean the NanoMet.

Another objective of this experiment was to compare particle emission from various fuels. Some fuels where used for long period of time and some were for few days. After collecting many days of experimental data and analyzed we tried to compare which gave us desired result. Properties like soot concentration, particle size distribution, total particle where compared and also cold start effects were compared. In the period of experiment, we really found very good data and sometimes also we had some inappropriate measurement results.

The effect of cold start was observed up to 11(±2) minutes of the cycle and 16 (±2) minutes later of the cycle there was no observable difference. The difference of particle concentration of cold start was around 2(±1) magnitude higher compare to hot start cycle. When we compared

morning cold start with afternoon cooled start there was not significant difference in particle concentration, and it was observed in all instrument data.

Another factor was different kind of fuel and we saw a big impact of change in fuel in particle concentration. In the first phase of test after comparing petrol with E20 we observed it really has such a big impact like 19-23% of lower particle concentration. But in the phase II after using two isomers of butanol we observed the difference of particle concentration is about 35 to 40 % lower and it is really a good sign to move forward for biofuel but also for that we have certain limitation like production and price as well.

Also, we saw the particle size distribution for various fuels and isomers of butanol had least amount of particle concentration with highest in gasoline and E20 had significantly lower than gasoline. Exhaust soot concentration was also least in isomers of butanol.

Objective of the project was to evaluate particulate matter emission from a gasoline engine using different fuel. It has been accomplished and very successful results are obtained. For moving forward there are many factors must be addressed which can help to make the experimental work more convenient and efficient instruments to have least error in result.

Most of the time there was some problem in each instrument which was the biggest concern for which we could not run CPC for phase II measurement, very often EEPS charger need to be cleaned or the instrument will not provide accurate data. There could be some better reliable instrument which will not need maintenance for long period which can help to get the test done faster.

The NanoMet was not able to record data for few days of second phase test though it was in running condition. To avoid such kind of problem everyday test data should be checked and verified before next day test which will help to obtain more accurate and reliable data.

There is very large uncertainty and complexity in performing these measurements that makes it unideal for type approval legislations, but it could provide very valuable information about the effect of new and emerging engine technology, modifications made on vehicles, new fuels and other changes on human health (Vojtisek, et.al, 2019).

Now we should start to find more easy and convenient way to replace fossil fuel which will have a huge impact on environment health also it can help to improve future scope of internal combustion engine.

7. Conclusion

These experiments were conducted for a time span of one year on a contemporary gasoline direct injection engine using high time resolution instruments – Micro Soot Sensor (MSS), Engine Exhaust Particle Sizer (EEPS), Condensation particle counter (CPC), NanoMet3 for particle concentrations and particle mass by gravimetry from Smart Sampler using various fuels. The goal of the thesis was to process and analyze the entire test period data. We conducted four WLTC cycles per day, two of which were cold start and two were warm runs.

The exhaust flow from engine passes through the aftertreatment devices, after that it was sampled to two dilution systems. Gravimetric proportional dilution system – the SmartSampler (AVL) and a rotating disc diluter–MD-19 (TSI Incorporated) were tested to dilute and sample the exhaust to the CPC and EEPS respectively. The SmartSampler operated at a low dilution ratio of 10:1 and the MD-19 dilution ratio was 95:1. The SmartSampler also had the advantage of gravimetric particle sampling for further analysis. Due to lower dilution ratio and other complex factors led to an issue of nucleation in the SmartSampler latter. The dilution tunnel was eventually cleaned to remove some artefacts that could be created inside the tunnel. The MSS and NanoMet was having their own dilution system for which the chances of any dilution error were minimized.

After investigating various days of repeatable data related to different fuel further information are stated here. The particle mass from gravimetry was reduced to 14% (±4%) for E20 and 45% (±5%) for isomers of butanol relative to gasoline was found. But there were many measurement errors for the filters in several tests who had nucleation in the smart sampler took place and mistake in filter measuring process were neglected from this comparison.

Particle concentration in engine exhaust was also lower for E20 and isomers of butanol (n-butanol 25% and iso-butanol 25%) compare to gasoline 21% (±2%) and 38% (±4%) respectively. Also, the cold start has a huge impact on particle concentration because it can be actively seen up to first 12(±2) minute for all instruments in a cycle and has minor effect up to 15(±2) min.

After comparing EEPS and CPC together for particle concentration we found that there is nucleation in the smart sampler. After cleaning the smartsampler it helped to reduce artifacts

in the sampling system. Because of very small size of particles categorizing them and investigating is a complicated process, and these were the best possible conclusion that could be investigated from the existing data.

The complete experimental system which was designed and used in this project could be very useful in future investigations on different fuel use in internal combustion engines and their effects to the environmental health.

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Appendix

A. Technical data of Engine Exhaust Particle Sizer

Specifications	Range
Particle size range	5.6 to 560 nm
Particle size resolution	16 channels per decade (32 total)
Charger mode of operation	Unipolar diffusion charger
Time resolution	10 size distributions/sec
Flow rates Sample flow	10 l/min
Sheath air	40 l/min
Inlet sample temperature	10 to 52°C
Operating temperature	0 to 40°C
Storage temperature	-20 to 50°C
Atmospheric pressure correction range	70 to 103 kPa (700 to 1034 mbar)
Humidity	0 to 90% RH (noncondensing)
User interface	Rotary knob and display; EEPS software
Computer requirements	Pentium® 4 processor, 2 GHz speed or better, at least 512 MB RAM
Operating system required	Windows® XP or better
Weight	32 kg
Sample inlet	3/8-in. Outer diameter (without inlet cyclone)
Cyclone inlet	3/8-in. Outer diameter
Exhaust/Outlet	3/8-in. Outer diameter
Power requirements	100 to 240 VAC, 50/60 Hz, 250W

Technical data of Engine Exhaust Particle Sizer (TSI Incorporated, 2005)

B. Technical Data of Condensation Particle Counter

Specifications	Range
Particle size range	Minimum detectable particle: 50% of 7-nm particles Maximum detectable particle: >3 µm
Particle concentration range	0 to 9.99 × 106 particles/cm3; counts single particles in concentrations from 0 to 104 particles/cm3, photometric calibration from 104 to 107 particles/cm3; provides running-average over 1, 2, 20, and 200 seconds depending on concentration range; display updated every second
Concentration accuracy	±10% up to 5 × 105 particles/cm3, ± 20% from 5 × 105 to 107 particles/cm3; coincidence less than 2% at 104 particles/cm3; live-time particle counting from 103 to 104 particles/cm3 provides automatic correction for coincidence
False background counts	<0.01 particle/cm3
Response time	<13 sec for 95% response to concentration step change when sampling in high-flow mode; <20 sec for low-flow mode
Aerosol medium	Recommended for use with air; safe for use with

	Inert gases such as nitrogen, argon, and helium (Performance specifications are for air.)
Signal-to-noise ratio	25:1 nominal
Light source	Stable, 5-mW, 780-nm laser diode
Flow	Aerosol flow rate: 300 ± 15 cm3/min High-flow inlet: 1500 ± 150 cm3/minnLow-flow inlet: 300 ± 15 cm3/min
Condensing liquid	Working fluid: Reagent-grade n-butyl alcohol (not included) Filling system: Electronic liquid- level sensor initiates automatic filling as needed, requires connection to fill bottle (provided with instrument
Operating temperatures	Saturator: 35 ± 0.3 °C Condenser: 10 ± 0.3 °C Optics: 36 ± 2.0 °C
Communications	Protocol: Command set based on ASCII characters Interface: RS-232, 9-pin, "D" subminiature connector, pinouts compatible with standard IBM-style serial cables and interfaces

	output (linearized concentration, log concentration, aerosol flow, pump control, photodetector voltage) (For use in TSI SMPS systems, a Host mode allows output to 11 volts.) Pulse: BNC connection, 13V square pulse, typically 3.3 µsec wide
Software	Supplied with CPCount™ Software
Calibration	Recommended annually; calibrated with 50-nm monodisperse NaCl using primary differential mobility analyzer method
Power requirements	100/120/230/240 VAC, 50/60 Hz, 200 W maximum
Dimensions (LWH)	24 cm × 38 cm × 20 cm (9.5 in. × 15 in. × 8 in.), not including fill bottle and bracket
Weight	: 12.5 kg
Environmental operating conditions	Ambient temperature range: 10 to 35 °C Ambient humidity range: 0 to 90% RH, noncondensing

Technical data of Condensation Particle Counter (TSI Incorporated, 2019)

C. Specifications of AVL Micro Soot Sensor Plus

MEASURING UNIT	
Measuring range Measured value concentration of soot (mg/m3, µg/m3)	0.001 – 50 mg/m3
Turndown ratio (min:max concentration)	01:50.0
Display resolution	0.01 mg/m3
Detection limit	1 µg/ m3
Data rate: digital / analog	up to 10Hz / 100 Hz
Rise time	(t10-t90) < 1 sec
Operation temperature	5°C to 40°C
Sample flow	~ 4 l/min
Interfaces	TCP/IP, RS232 with AK protocol, digital I/O and analog I/O
Power supply	90...240 V AC, 50/60 Hz, 400 VA
Laser class	Class 1 laser product
Unit dimensions	W x H x D
measuring unit	~ 19" x 5HU x 530mm
Unit weight measuring unit	~ 20 kg

CONDITIONING UNIT	
Dilution ratio (DR) The actual DR will be displayed with the accuracy noted below	Adjustable from 2 - 20
Accuracy (DR display)	Max. +/- 2 + (DR*0.5)%
Pressurized air input	1 +/- 0.2 bar gauge pressure required
Flow	Min. 4 l/min
Exhaust gas temperature	Up to 1,000 °C
Exhaust gas back pressure	Up to 2,000 mbar (mean pressure)
Pressure pulsation	+/- 1,000 mbar, but max. 50% of exhaust gas back pressure (mean pressure)
Blow by amount of the pressure reduction unit depending on pressure	~ 40 l/min at 1,000 mbar exhaust gas pressure and 25°C
Power supply	90…240 V AC, 50/60 Hz, 500 VA
Dimensions conditioning unit	W x H x D ~ 19" x 4HE x 530 mm
Weight conditioning unit	~15 kg

Technical data of MSS plus - AVL Micro Soot Sensor (www.avl.com/-/mssplus-avl-micro-soot-sensor)

D. Specifications of Nanomet3 from Matter Aerosol AG

Aerosol	Primarily diluted exhaust gases or air which contains nanoparticles
Concentration range	Sensor: 1e3...1e6 pt/ccm; diluted: 1e4...3e8pt/ccm
Particle size	10...700 nm = 0.01...0.70 µm
Average particle size range (mode diameter)	10...300 nm = 0.01...0.30 µm
Sensor accuracy	±30% in size and number concentration
Inlet gas flow	4.0 ln/min, actively fed to the diluter by internal pump and returning from there
Raw gas pressure	Raw aerosol pressure should never exceed 300 mbar (relative). Pressures at the dilution air inlet and diluted measuring gas outlet within the limits of ±20 mbar (relative)
Dilution factor	Standard: 10, 100, 300. Optional one custom df
Measuring gas	1.0 ln/min measuring gas
Power supply	12 24 vdc, max. 60a. 90 240 vac 50/60 hz
Power consumption	Nominal 650w; 300 w under standard ambient conditions; power supply fuse 10a slow blow / 250 v
Evaporation tube temperatures	Ambient...300°c / 572°f; accuracy 3°c/5,4°f
Assembly	19" case with handles
Weight	Approx. 18 kg; with complete connections: ca. 23 kg
Operating conditions	Tamb: 5 ... 35°c; 0...80% relative humidity, max. 80%@30°c, linearly degrading to 50%@35°c, non condensing
Sensor calibration	Standard calibration with nacl particles

Technical data of Nanomet3 from Matter Aerosol AG (Instrument Manual)

E. EEPS data for Phase I test

	Morning		Afternoon	
Date	Cold Start (p/cm3)	Warm Start (p/cm3)	Cooled Start (p/cm3)	Warm Start (p/cm3)
Phase I - Gasoline				
25.02.2019	5723155.34	2093233.134	3316008.371	2191320.011
26.02.2019	12410976.46	7997767.971	6300601.013	2305719.53
27.02.2019	4883798.389	2626788.66	3397049.344	2000059.703
28.02.2019	5034579.645	2023717.328	4704907.152	1876581.454
01.03.2019	6122719.108	2104054.686	6208176.064	2041494.6
04.03.2019	7028452.64	2041039.976	5307546.693	1983916.079
05.03.2019	5833849	2115389	4506897	2021115
07.03.2019	7260802.87	2308883.437	5823429.986	2011833.894
08.03.2019	6537574.767	2225792.512	5882500.967	2110146.301
Phase II – Gasoline(E95), Iso-Butanol 25%, n-Butanol 25%, Ethanol 20 (E20)				
18.04.2019	2556418.889	1447001.666	Not available	Not available
24.03.2019	3266264.451	2070384.89	Not available	Not available
25.03.2019	3469282.578	2042267.354	3565546.43	1899424.151
26.04.2019	3399218.353	1799085.097	3531203.405	1963465.951
27.04.2019	3711508.319	1971027.791	Not available	Not available
28.04.2019	3781857.575	1835614.137	3484965.552	1813859.58
29.04.2019	4516800.308	1812642.376	3662826.611	2420089.678
30.04.2019	4658052.791	1905015.18	4312763.938	2136347.529
02.05.2019	4060640.662	2074933.568	4139154.811	2106320.902
04.05.2019	4148315.492	2205933.675	4043774.527	2233632.859
05.05.2019	4541939.193	2910887.314	4818149.093	2840334.393
10.05.2019	2092041.659	1290311.669	2012148.683	1094089.073
12.05.2019	1970775.907	1480420.101	1769564.744	1209547.753
13.05.2019	2656681.138	1278869.515	1867016.341	1556838.79
16.05.2019	1880146.672	1350748.178	2256347.945	1001207.05
18.05.2019	2409103.183	1226248.363	1799142.291	1266302.962
27.05.2019	3545583.252	1286849.251	1782343.338	1483030.836
28.05.2019	1761784.913	868049.2953	1516726.376	Not available
03.09.2019	1374792.973	700451.1903	Not available	Not available

Measured data from EEPS

F. CPC Measurement data

	Morning		Afternoon	
Date	Cold Start (p/cm3)	Warm Start (p/cm3)	Cooled Start (p/cm3)	Warm Start (p/cm3)
Phase I - Gasoline(E95)				
25.02.2019	421090	198872	3491995	2419802
26.02.2019	17282975	13067579	6080440	2270029
27.02.2019	4434286	2259742	9945589	7065913
28.02.2019	4772086	2148415	5568547	2425132
01.03.2019	6497469	2590381	6628508	2441128
04.03.2019	8470557	2622616	5947877	2625101
05.03.2019	7330170	2762734	5914741	2665317
07.03.2019	7110114	2015743	5522090	2258571
08.03.2019	6565490	2185333	7205986	2685996
Phase II – Gasoline(E95), Iso-Butanol 25%, n-Butanol 25%, Ethanol 20 (E20)				
18.04.2019	2954213	1923076	Not available	Not available
24.04.2019	7408173	2544068	Not available	Not available
25.04.2019	4239247	2319983	3790171	1947585
26.04.2019	5010933	3017593	4083705	2279478
27.04.2019	4883745	3704970	Not available	Not available
28.04.2019	3326569	1542127	870290	1200114
29.04.2019	8686329	2978762	4019794	2204640
30.04.2019	5929932	2243992	4187445	1887584
02.05.2019	4544276	2092950	4232722	2122549
04.05.2019	4895332	2341105	4421860	2231901
05.05.2019	4897144	2662954	4524056	2638318
10.05.2019	3413412	1370584	2246260	1255934
12.05.2019	7385096	2564979	2125694	1718233
13.05.2019	3174649	2109127	1969166	1906914
16.05.2019	2063812	1472359	2225084	1100186
18.05.2019	19802539	3941408	3199868	3490313
27.05.2019	5513224	1709545	2111553	1391027
28.05.2019	5837089	1729002	1841269	Not available

Measured data from CPC

G. Micro Soot Sensor Measurement Data Phase II - Gasoline(E95), Iso-Butanol 25%, n-Butanol 25%, Ethanol 20 (E20)

	Morning		Afternoon	
Date	Cold Start (mg/m3)	Warm Start (mg/m3)	Cooled Start (mg/m3)	Warm Start (mg/m3)
30.04.2019	Not available	Not available	0.31606794	0.43858507
03.05.2019	Not available	Not available	0.43532981	0.32602361
04.05.2019	0.50783894	0.38602272	0.55626810	0.40479795
05.05.2019	0.57780921	Not available	0.61622109	0.54219075
06.05.2019	0.55582751	0.50414389	0.55626810	0.40479795
09.05.2019	0.33411758	Not available	0.22626414	0.24651602
10.05.2019	0.18290341	0.21318855	0.27097617	0.18341418
11.05.2019	0.23242794	0.12635388	0.19573389	0.11646437
13.05.2019	0.24738376	0.12279777	0.14135845	0.22081549
16.05.2019	0.15790603	0.20400477	0.25199059	0.10925106
17.05.2019	0.16304008	0.05482203	0.24813909	0.08013459
18.05.2019	0.19582871	0.17632617	0.20607211	0.19813428
19.05.2019	0.14072122	0.18265892	0.10251100	0.17643722
20.05.2019	0.11997023	Not available	0.10038399	0.12177817
27.05.2019	0.26596254	0.19016935	0.12078655	0.16864328
28.05.2019	0.11398529	0.07369825	0.12917671	Not available
21.08.2019	0.13543784	0.07454871	0.06881447	0.04100816
22.08.2019	Not available	Not available	0.04624975	0.01324185
23.08.2019	Not available	Not available	0.08390426	0.01925887
26.08.2019	Not available	Not available	0.23570734	0.13865869
28.08.2019	0.30861372	0.37302966	0.34909901	0.18558794
29.08.2019	0.33347974	0.16411010	0.34702951	0.37374629
30.08.2019	0.29935291	0.41825374	0.30074095	0.43378824
02.09.2019	Not available	Not available	0.06251774	0.03967115

Soot concentration in Engine exhaust