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Department of Automotive, Combustion Engine and Railway Engineering

MASTER THESIS

Comparison of instrumentation for online measurement of particle emissions from direct injection spark ignition engines

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Submitted by: Sairam Polasa

Supervisor: prof. Michal Vojtíšek Ph.D.

MASTER'S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Polasa Sairam** Personal ID number: **473665**

Faculty / Institute: **Faculty of Mechanical Engineering**

Department / Institute: **Department of Automotive, Combustion Engine and Railway Engineering**

Study program: **Master of Automotive Engineering**

Branch of study: **Advanced Powertrains**

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Guidelines:

The goal of the thesis is to evaluate the response of several common commercial instruments to particles produced by direct injection spark ignition (DISI) engines. Online measurements with available instrumentation, such as Engine Exhaust Particle Sizer (EEPS), Electrostatic Low Pressure Impactor (ELPI) or photoacoustic soot analyzer, are to be conducted on multiple DISI engines, or on a suitable DISI engine running on several different fuels. Suitability of the instruments in terms of their measurement range, agreement of the instruments, consistency of differences among engines or among fuels determined by individual instruments, test-to-test repeatability, and related issues are to be assessed.

Bibliography / sources:

Giechaskiel, B., et al.: Review of motor vehicle particulate emissions sampling and measurement: From smoke and filter mass to particle number. Journal of Aerosol Science, 2014, 67: 48-86.
Giechaskiel, B., et al.: European Regulatory Framework and Particulate Matter Emissions of Gasoline Light-Duty Vehicles: A Review. Catalysts 2019, 9, 586.
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Name and workplace of master's thesis supervisor:

doc. Michal Vojtíšek, Ph.D., Department of Automotive, Combustion Engine and Railway Engineering, FME

Name and workplace of second master's thesis supervisor or consultant:

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doc. Michal Vojtíšek, Ph.D. Supervisor's signature	doc. Ing. Oldřich Vítek, Ph.D. Head of department's signature	prof. Ing. Michael Valášek, DrSc. Dean's signature

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In Prague: 14.08.2020

Sairam Polasa

Abstract

This master thesis examines the suitability of online particle monitoring instruments for measurement of particle emissions from Direct Injection Spark Ignition (DISI) engines. A typical passenger car DISI engine was operated on gasoline and its mixtures with 25% iso-butanol and 25% n-butanol on a chassis dynamometer along speed and torque points corresponding to those measured during WLTC driving cycle on a typical midsize passenger car. Multiple cold and warm starts WLTC tests were conducted. Concentrations of particles in raw exhaust were measured by two particle classifiers, Engine Exhaust Particle Sizer (EEPS), Electrostatic Low-Pressure Impactor (ELPI), and by photoacoustic analyzer (Microsoot Sensor, MSS). Mean Total Particle Number Concentration measured by EEPS and ELPI and mean Total Particle Mass Concentration measured by MSS and derived from EEPS and ELPI measurements were compared. A reasonable agreement between the instruments (Particle Number Concentrations measured by EEPS and ELPI, Particle Mass Concentration measured by ELPI and MSS) was observed on gasoline, with somewhat high differences on butanol blends. High temperature version of ELPI, sampling raw exhaust, exhibited the high Signal to Noise ratio (SNR), followed by MSS and EEPS. In general, all instruments have shown a substantial decrease in particle emissions for both isomers of butanol relative to the gasoline, with relatively small differences between the two isomers. In general, all instruments provided useful measurements.

Keywords: Direct Injection Spark Ignition engine, Particulate matter, data analysis, alcohol blended fuels, comparison between instruments, particle size distributions, particle mass distributions.

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1 Introduction

The air is said to be a one of the basic elements of the earth. Ideally air is supposed to be pure, but in the present days the air is getting polluted because of human and natural activities. The human activities contributing to the air pollution mainly consist of heat and power generation (thermal power plants), industries, municipal and agricultural waste, and fuel combustion in motor vehicles [1].

The intermediate products of combustion in internal combustion engines are termed to be pollutants one of the major causes of air pollution comprises Carbon monoxide (CO), Nitrogen oxides (NO_x), Hydrocarbons (HC) or Volatile Organic Compounds (VOC), Particulate matter (PM). The major focus of this thesis will be on Particulate matter because the health effects shown on human health are unimaginable. The particulate matter is divided based on their size as coarse Particulate matter (PM_{10}) 2.5 – 10 µm and fine Particulate matter ($PM_{2.5}$) below 2.5 µm. The prolong exposure of human lungs to the PM is very dangerous rather than the instantaneous exposure [2].

The particulate matter shows the greatest threat to the human life in the form of cardiovascular and respiratory diseases. An individual spends nearly 70 – 90 mins per day in travelling which causes him to be victim of the cardiovascular and pulmonary diseases [3]. From past few years the air quality is decreasing in such way that it is leading to the premature deaths of around 400,000 people in the European nations according to 2012 survey, which is alarming factor for decreasing human life expectancy which is caused by $PM_{2.5}$ [4].

Taking increase of death rates into the consideration every year, the government is updating the regulations of emissions in different categories. However, the regulations couldn't solve the present problem completely, because the number of vehicles is increasing annually. There are approximately 308 million cars registered in the European Union [5].

1.1 Particulate Matter

Particulate Matter (PM) is complex mixture of solid and liquid particles suspended in the air. The physical properties and chemical composition may change according to the source, location and time. Some of the particulate matter sources are forest fires, household appliances, Driving vehicles, Industries, Power plants etc. [6]. About 20% of particulate matter emissions are from mobile sources in European countries such as vehicles, ships, aviation [7].

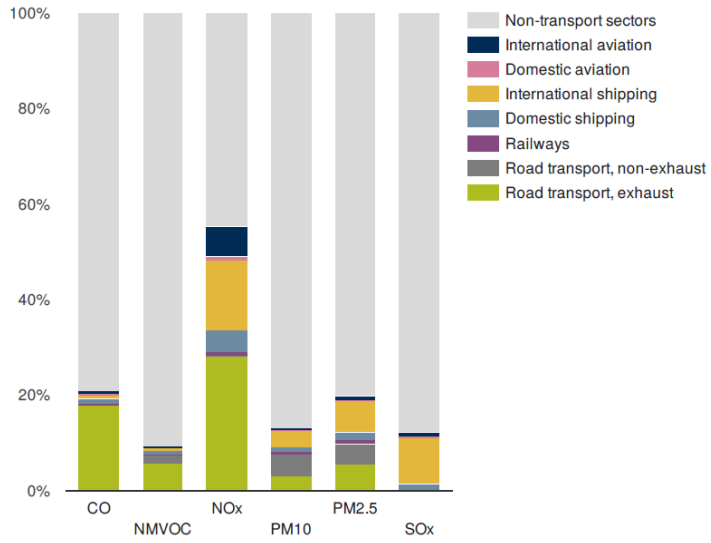

Figure 1.1 pollutants and particulate emissions from transportation sector in EU [7]

1.2 Mechanism of particulate matter Formation

The interaction of flame with the fuel which creates combustion in the cylinder, because of low charge temperatures and reduced time for fuel atomization and associated fuel impingement, in the Nucleation breaking of C-C (carbon to carbon) bond is not performed completely. Hence the hydrogen escapes from the hydrocarbons present in the

fuel which forms soot called as ‘nuclei’ [2], this process is known as Nucleation which is shown in figure 1.2.

The Surface Growth is generation of solid phase materials bulk, surface growth that takes place on the nuclei and on the spheres is responsible for forming the concentric shells, by which surface growth is considered as vital reason for the increase of soot mass and volume shown in figure 1.2 second stage. The formation of soot in surface growth stage mainly depends on the number of nuclei [8].

Agglomeration is the process to combine the particles to increase in the size. The inter particle collision which leads to the agglomeration process, by this inter collisions the decrease in number of particles takes place eventually which leads to increase in their size further it forms chain like structure, which is clearly shown in fourth stage of figure 1.2. The inter collision between particles results in the coagulation in single spheroid. The size of particles is based on the factors such as engine operating conditions, sampling techniques, performance of injectors [9].

Adsorption and Condensation are the final process in the formation of particulate matter which involves in the adsorption and condensation of hydrocarbons. These processes are observed after the cylinder gases are exhausted from the engine, as the exhaust gases are diluted with air. For the measurement of exhaust particulate matter, a dilution tunnel is specified in order to simulate the atmospheric dilution process. Adsorption involves the adherence of molecules of unburned hydrocarbons to the surface of the soot particles by chemical or physical (Van der Waals) forces, Condensation will occur whenever the vapor pressure of the gaseous hydrocarbons exceeds its saturated vapor pressure [8].

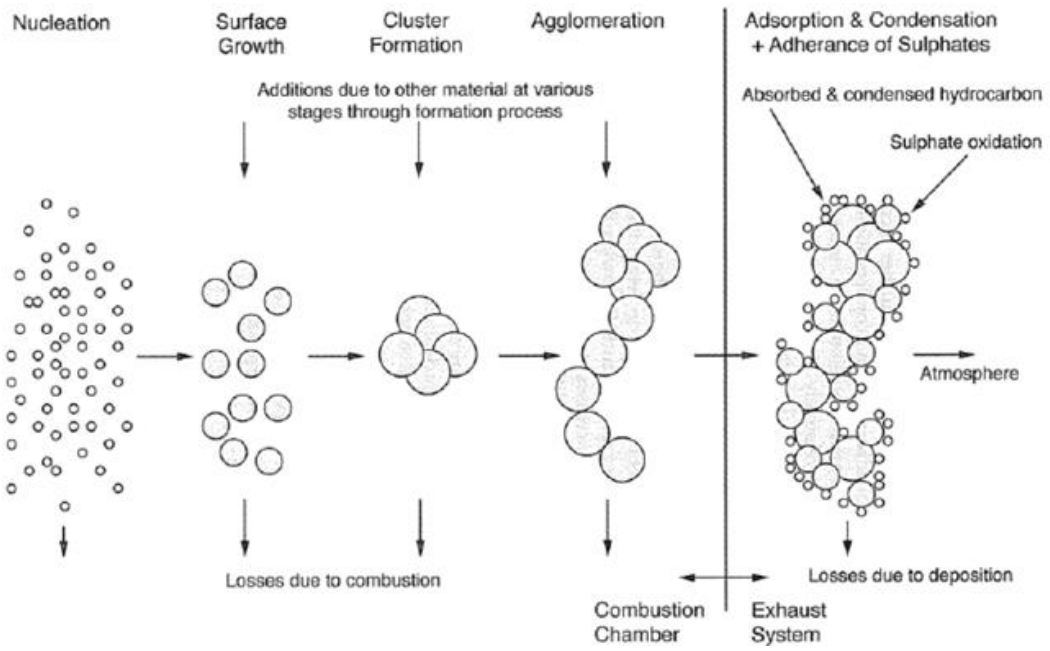

Figure 1.2 Structural and composition formation of Particulate Matter [2]

1.3 Particle Size Distribution

The health effects shown by particulate matter is much worse depending on the size. The particulate matter is classified into four types based upon their sizes:

Coarse particles are the particles with diameter 10 µm and less than 10µm, fine particles are of diameter below 2.5µm, the diameter of ultra-fine particles are below 0.1µm or 100nm [10]. Usually the size of particulate matter in SI engine is below 2.5 µm.

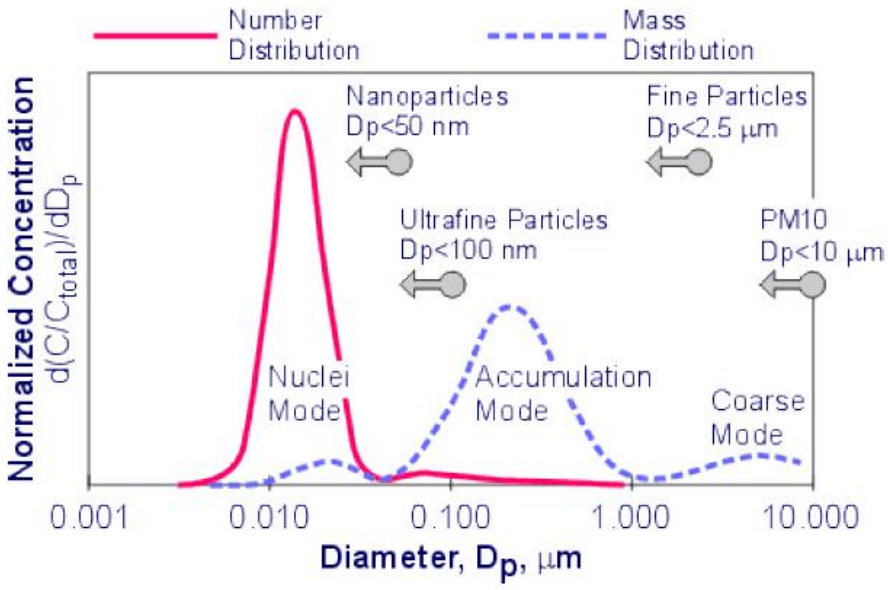

Figure 1.3 Size distribution of Particulate Matter [10]

1.4 Particulate matter formation at different operating conditions of DISI engine

The Particulate matter is formed in engine exhaust with respect to different operating conditions of DISI. The following operating conditions can also be used as trigger points in order to control the particulate matter emissions in other alternate.

1.4.1 Engine load and Air fuel Ratio

The formation of particulate matter (PM) emissions are high in the conditions like high load and low speed and medium load – medium speed because of high nucleation rate, even though the engine is operated in the stochiometric ratio and homogenous combustion [11].

The particulate matter (PM) concentration is quite responsive to the Air to Fuel Ratio (AFR), when the Air to Fuel Ratio (AFR) is decreased i.e. (when the quantity of fuel is more than the quantity which can undergo complete combustion, it is said to be the rich condition) the concentration of particulate matter will increase because there will be less oxygen to the mixture. For slightly lean combustion phase the most of air fuel mixture

is burnt and we can observe ultra-fine particulate matter (PM) in the engine exhaust, but whereas if we are moving to much leaner section there is possibility of sudden increase in particulate matter (PM) because of low combustion temperature and locally rich mixture [12].

1.4.2 Ignition Timing

The initial ignition time points the variations in ignition time and particulate matter (PM) emission. If the suitable timing for ignition is at Maximum Brake Torque (MBT), ideally the zones either sides of Maximum Brake Torque (MBT) will be decrease in particulate matter (PM). Spark advance (early ignition) it must be longer time for combustion, hence there will be decrease in particulate matter (PM) because of oxidation of particles. The spark retarding from Maximum Brake Torque (MBT) timing, we can see increase in Exhaust gas temperature, it can oxidize the particles therefore there will be decreasing trend of particulate matter (PM). But in practicality, there is increase in particulate matter (PM) emission when the spark is advanced [13], because the delayed spark timing will lower the peak combustion temperatures and rise the exhaust temperatures during expansion stroke. It leads to decrease in the hydrocarbons in exhaust, in the mean while the retarding of spark gives enough time to mix the air fuel completely as there will be no locally fuel rich mixture which results in lower particulate matter (PM) emission.

1.4.3 Fuel injection

1.4.3.1 Fuel Injection Timing

The fuel injection timing plays significant role on the particulate emissions from DISI (Direct Injection Spark Ignition) engines. The reason is formation of particulate matter is very sensitive for the combustion of locally rich air-fuel mixture. In early fuel injection could result in impingement of fuel on the surfaces of combustion chamber and leads to

pool fires (combustion of liquid fuel). The retardation of fuel injection causes insufficient time for air-fuel mixing which leads to increase in particulate matter (PM) [14].

1.4.3.2 Fuel Injection Pressure

The importance of fuel injection pressure in the combustion process and particle emission is one of the primary factors to be considered because the high fuel injection pressure results in high fuel injection velocity, hence helps in efficient atomization of fuel droplets which leads to better evaporation. It also increases the fuel spray penetration length and distributes in the combustion chamber, which improves the mixing rate by good utilization of air [12].

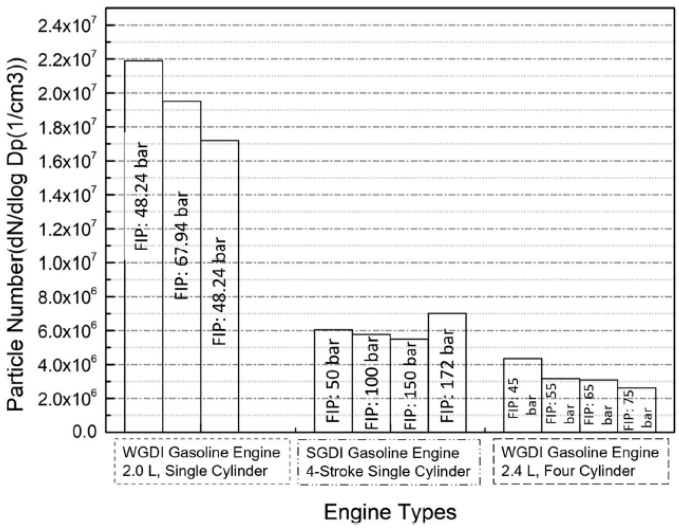

Figure 1.4 The impact of fuel injection pressure on the particulate matter in different Engines at 2000 rpm on DISI engine [14]

1.4.4 Cold start and Ambient start conditions

The recent studies on the particulate matter (PM) emission in different operating conditions of engine states that, the cold start of engine is one of the operating conditions were one can observe high particle emissions from the engine exhaust [14], that is because at cold start the temperature inside the combustion chamber is less. Therefore the heat

transfer between the surface of combustion chamber and air fuel mixer is considerably less this effects the fuel vaporization and air-fuel mixing (heterogenous mixture of air-fuel), in combustion of the non-homogeneous air-fuel mixture (locally fuel rich mixture) leads to formation of particulate matter [14]. In the warm start conditions the particulate matter (PM) emissions will reduce, one can notice that by observing the particle emissions are less compared to cold start conditions in the experiment [15] which conducted based on the Common Artemis Driving Cycle (CADC).

1.5 Gasoline Particulate Filter

As the DISI (Direct Injection Spark Ignition) engines are operated well in the lean air-fuel mixture condition, but because of short mixing time before the ignition of air-fuel mixture will result in formation of particles (Ultra-fine particles). According to AECC (Association for Emission Control by Catalyst) with the help of GPF (Gasoline Particulate Filter) the particle emissions are reduced by 83% (to 17%of its original value) in average raw emissions, compared to the vehicle which is not equipped with the GPF [16].

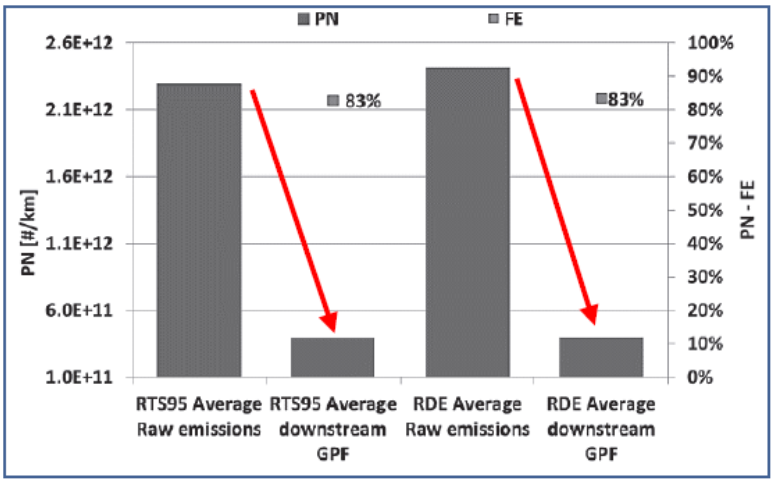

Figure 1.5 Particulate Number emissions in upstream and downstream of GPF [16]

The GPF (Gasoline Particulate Filter) is developed to reduce the number of ultra-fine particles. The GPF is designed in such a way that it will trap the particles by forcing

the exhaust gases to pass through porous walls between inlet and outlet channels of the GPF, causing the particles to be deposited in and on the channel walls. The exhaust gases are forced through the channels in which the larger particles will stick in the channels because of its diameter and the smaller particles will reduce its concentration in the downstream because the particles will diffuse into the pores of the filter. The filtration efficiency of GPF varies on the size of particulate matter, it is observed to be there is less filtration efficiency around 200nm particle in diameter. The clogging of particles is observed in the GPF which results in formation of soot cake. To prevent excessive buildup of soot cake, the process named GPF regeneration comes into play, the soot combustion in the GPF depends on the temperature of exhaust gases and stoichiometric conditions [16].

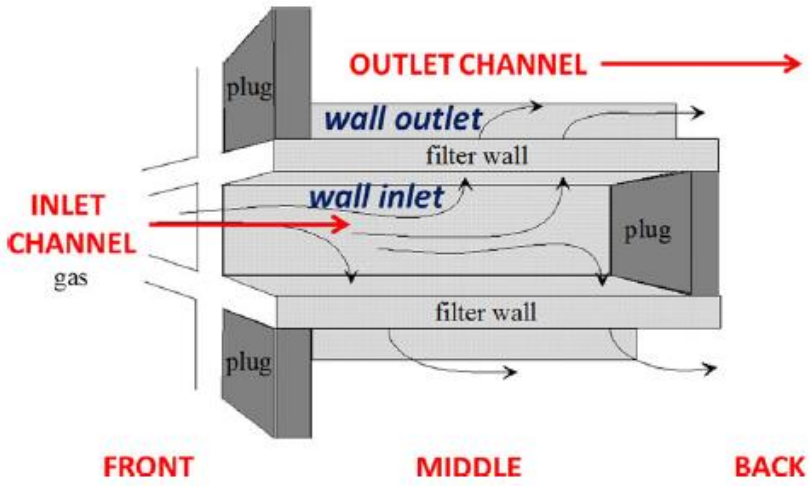

Figure 1.6 Nomenclature of channels in GPF [17]

1.6 Impacts of particulate matter on human health and Environment

The particulate matter with diameter less than or equal to 10µm will easily enter the throat, nose and reach lungs, whereas particulate matter with diameter less than or equal to 2.5µm will get deep into lungs and further into the blood streams [2]. The serial studies on the human health effects caused by particulate matter report the following adverse health effects:

1. Cardiovascular Diseases leads to death.
2. Respiratory Diseases.
3. Chronic productive cough with increased severity of asthma.
4. Cerebrovascular Diseases [18].

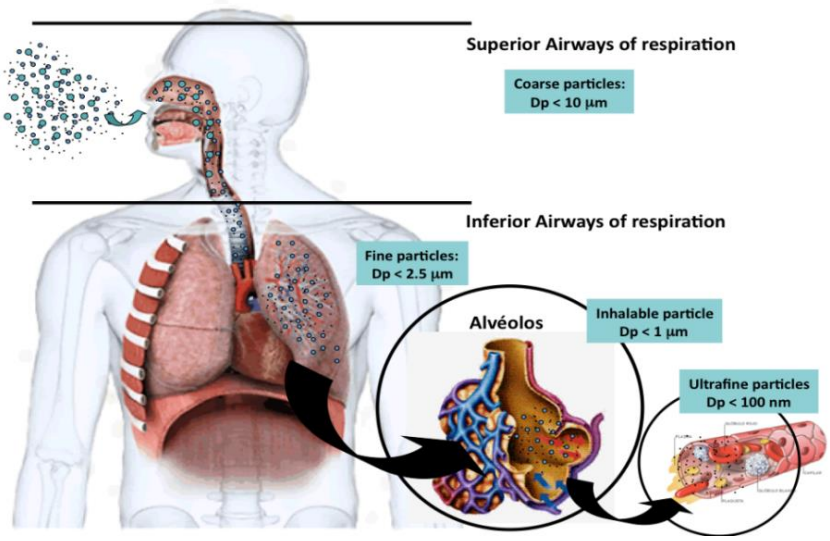

Figure 1.7 Health risks with different size of particulate matter in human beings [2]

The particulate matter is threat not only for human life but also for environment. The extraction of fossil fuels itself is creating the environmental imbalance, and we are releasing the carbon stored in fossil fuels into the atmosphere, contributing to the following climatic changes:

1. Global warming.
2. The particulate matter scatters the solar radiation by this a portion of radiation returned to the space, therefore the decrease in the net energy received by the earth.
3. Particulate matter can alter the lifetime of a cloud so that it may affect rainfall [19].

1.7 Air quality and presence of particulate matter

The Europe air quality in the remaining parts of EU excluding urban is getting cleaner but, in the cities, it is continuing to damage the human health because of excess air pollution. According to the latest report submitted by European Environment Agency (EEA)

in 2019, there were 4000 air quality monitoring stations are installed across Europe in 2017, which had shown the poor air quality in Europe [20].

Table 1.1 Air quality standards in Europe [21]

Pollutant	Averaging period	Standard type and concentration
PM_{10}	Calendar year	EU limit: 40µg/m^3
		WHO AQG: 20 µg/m^3
$PM_{2.5}$	Calendar year	EU limit:25 µg/m^3
		WHO AQG:10 µg/m^3

The European Environment Agency (EEA) received data from 3000 stations with a minimum coverage of 75%. The concentrations above (PM_{10}) annual limit value 40µg/m^3 in 2017 were recorded in 7% i.e. 207 stations located in 13 countries, according to World Health Organization (WHO) Air Quality Guidelines (AQG) the annual mean must be less than 20 µg/m^3 that limit was exceeded got recorded in 51% of the stations [21].

The data regarding $PM_{2.5}$ with 75% valid information obtained from 1396 stations located across the Europe. The limit fixed by World Health Organization (WHO) Air Quality Guidelines (AQG) for $PM_{2.5}$ the annual mean 10 µg/m^3 was exceed at 69% stations in Europe [21].

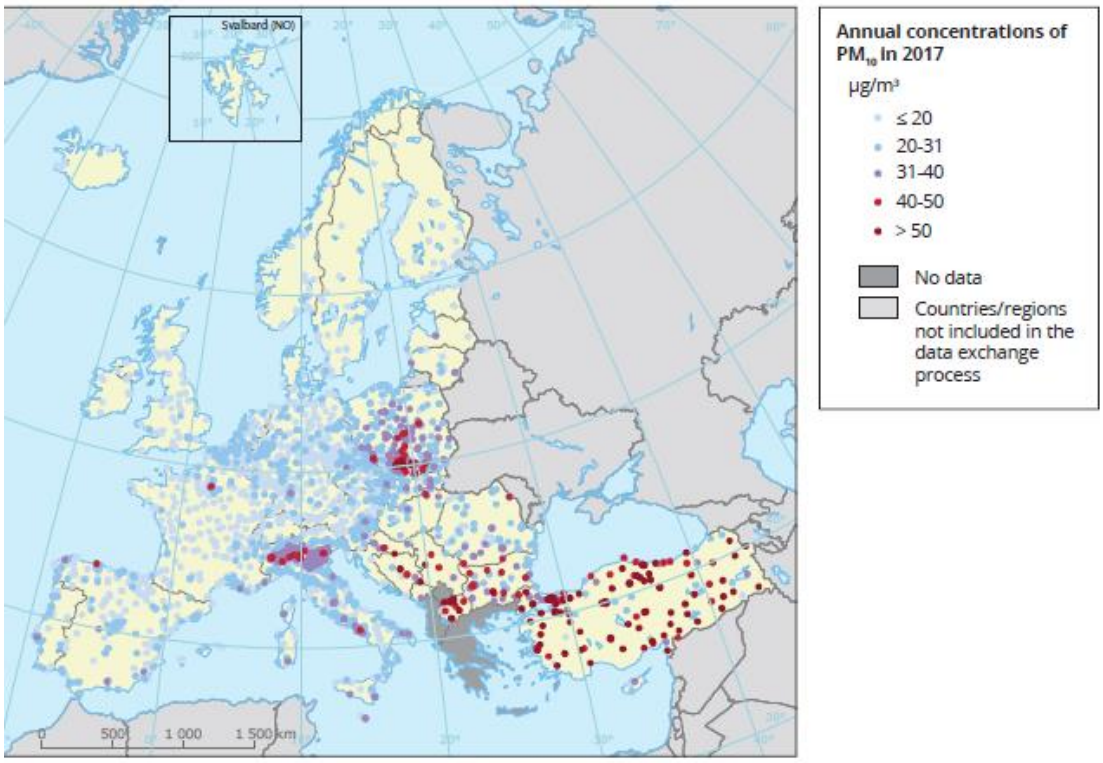

Figure 1.8 Concentration of PM10 annually across Europe [21]

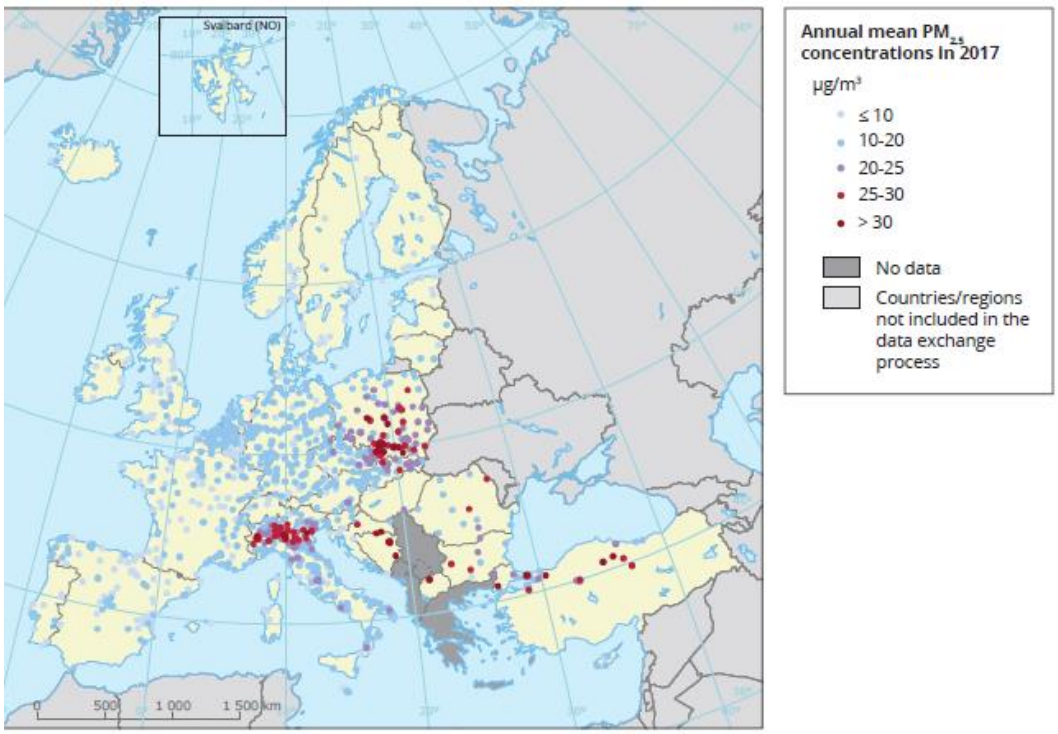

Figure 1.9 Concentration of PM2.5 annually across Europe [21]

From the above figures it is evident that the cities in the Czechia are in the vicinity of the limits framed by the European legislation (2008/50). As per the data collected by EAA in Czechia, the annual concentrations of PM_{10} are found to be 20 – 30 µg/m^3 whereas the annual concentrations of $PM_{2.5}$ are 15 – 25 µg/m^3 [21]

1.8 Emission Standards for Gasoline Engines

The tables 1.2 & 1.3 are summarized EU (European Union) Emission standards. All dates that are listed in the tables refer to new type approvals, all the vehicles that are existing and newly available in the market must follow the norms accordingly.

Table 1.2 EU emission standards for passenger cars (SI Engine) [22]

Stage	Date	CO	HC	NO_X	PM	PN
		(g/km)				(#/km)
Euro 1	1992.07	2.72(3.16)				
Euro 2	1996.01	2.2				
Euro 3	2000.01	2.30	0.2	0.15		
Euro 4	2005.01	1.0	0.1	0.08		
Euro 5	2009.09	1.0	0.1	0.06	0.005	
Euro 6	2014.09	1.0	0.1	0.06	0.005	6.0×10^{11}

Table 1.3 EU emission standards for light commercial vehicles (SI Engine) [22]

Category	Stage	Date	CO	HC	NO_X	PM	PN
			(g/km)				(#/km)
N_1 (class I) <=1305kg	Euro 1	1994.10	2.72				
	Euro 2	1997.01	2.2				
	Euro 3	2000.01	2.3	0.20	0.15		
	Euro 4	2005.01	1.0	0.1	0.08		
	Euro 5	2009.09	1.0	0.1	0.06	0.005	
	Euro 6	2014.09	1.0	0.1	0.06	0.005	6.0×10^{11}
N_1 (class II) 1305-1760kg	Euro 1	1994.10	5.17				
	Euro 2	1998.01	4.0				
	Euro 3	2001.01	4.17	0.25	0.18		
	Euro 4	2006.01	1.81	0.13	0.10		
	Euro 5	2010.09	1.81	0.13	0.075	0.005	
	Euro 6	2015.09	1.81	0.13	0.075	0.005	6.0×10^{11}
N_1 (class III) >1760kg	Euro 1	1994.10	6.90				
	Euro 2	1998.01	5.0				
	Euro 3	2001.01	5.22	0.29	0.21		
	Euro 4	2006.01	2.27	0.16	0.11		
	Euro 5	2010.09	2.27	0.16	0.082	0.005	
	Euro 6	2015.09	2.27	0.16	0.082	0.005	6.0×10^{11}
N_2	Euro 5	2010.09	2.27	0.16	0.082	0.005	
	Euro 6	2015.09	2.27	0.16	0.082	0.005	6.0×10^{11}

N_1=Vehicles designed and constructed for the carriage of goods and having mass not exceeding 3.5 tons.

N_2= Vehicles designed and constructed for the carriage of goods and having mass exceeding 3.5 tons but not exceeding 12 tons.

1.9 Alcohol blended fuels in Internal Combustion Engine (ICE)

From the beginning of usage of fuels in internal combustion engines (ICE) the consumption of crude oil has been increased, that resulting in depletion of fossil fuels. In order to eradicate this problem, one of the solutions is invention of alcohol blended fuels. Ethanol-gasoline is the alcohol blended fuel which is available in the EU market in different proportions such as E5, E10, E85 in Ethanol-gasoline blend. Here E5 represents 5% vol of ethanol and 95% vol of gasoline, which is the most used fuel across the Europe [23]. The

usage of alcohol blended fuels will help increase in cylinder gas pressure results in high wheel power and the exhaust temperatures is low compared to gasoline fuel [24].

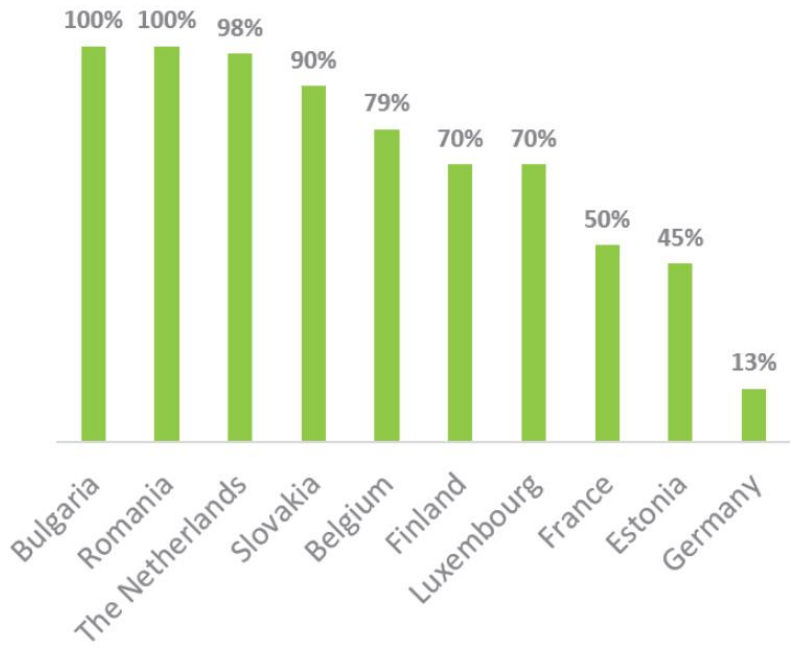

Figure 1.10 Share of E10 in gasoline market in different European countries [25]

2 Goal of the Thesis

The primary goal of this thesis is to evaluate the response of the commercial instruments to the particles produced by DISI (Direct Injection Spark Ignited) Engine.

I. Analyze the data which is obtained from three instruments namely EEPS (Engine Exhaust Particle Sizer), ELPI (Electrical Low-Pressure Impactor), Photoacoustic Soot Analyzer or MSS (Micro-Soot Sensor).

II. To evaluate the response of instruments tested on DISI Engine running on different alcohol blended fuels for particulates Emission.

III. Agreement of the instruments.

   a) Total Particle Number.

   b) Particle Size Distribution.

   c) MSS vs Estimated mass through ELPI vs Estimated mass through EEPS.

IV. Consistency of differences among fuels determined by individual instruments, test to test repeatability and related issues.

3 Experimental Test conditions

This chapter explains about the conditions in which the engine had tested with three different fuels (Gasoline, 25% iso-butanol, 25% n-butanol), subjected to detect particulate matter emissions with the help of three different instruments. The experiment conducted in the months of August 2019 and September 2019 which shown detail in the following figure.

Fuels	EEPS				ELPI				MSS			
	Morning		Afternoon		Morning		Afternoon		Morning		Afternoon	
	Cold start	Warm start	Cold start	Warm start	Cold start	Warm start	Cold start	Warm start	Cold start	Warm start	Cold start	Warm start
			20-Aug	20-Aug			20-Aug	20-Aug				20-Aug
	21-Aug	21-Aug	21-Aug	21-Aug					21-Aug	21-Aug	21-Aug	21-Aug
iso-butanol	22-Aug	22-Aug	22-Aug	22-Aug	22-Aug	22-Aug	22-Aug	22-Aug			22-Aug	
	23-Aug	23-Aug	23-Aug	23-Aug	23-Aug	23-Aug	23-Aug	23-Aug			23-Aug	23-Aug
	6-Sep	6-Sep							6-Sep	6-Sep		
	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug
	27-Aug	27-Aug	27-Aug	27-Aug								
Gasoline	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug
	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug
	30-Aug	30-Aug	30-Aug	30-Aug	30-Aug	30-Aug			30-Aug	30-Aug	30-Aug	30-Aug
			2-Sep	2-Sep			2-Sep	2-Sep			2-Sep	2-Sep
n-buatnol	3-Sep	3-Sep	3-Sep	3-Sep	3-Sep	3-Sep	3-Sep	3-Sep			3-Sep	3-Sep
	4-Sep	4-Sep	4-Sep	4-Sep	4-Sep	4-Sep	4-Sep	4-Sep				

Figure 3.1 The list of experiments conducted on different instruments and different fuels with respect to above months in the year 2019

3.1 Engine Test conditions

This experiment is performed on the 1.4-liter R4 16 valve TSI/TFSI spark ignited gasoline direct injection engine (EURO 5) by Volkswagen. The engine is subjected to following conditions to detect the particulate matter emission.

I. The engine speed and accelerator pedal position were programmed to match the same model engine used in Skoda Octavia during WLTC cycle driven on chassis dynamometer for the evaluation of particulate emissions in different driving conditions.

II. The engine must operate in cold start and warm start conditions.

3.1.1 WLTC (Worldwide Harmonized Light Vehicle Test Cycles)

The WLTC (Worldwide Harmonized Light vehicle Test Cycles) is developed by UNECE GRPE (working party on pollution and energy) [26] is used to determine the emissions and consumption of fuel in light-duty vehicles. The WLTC is part of the WLTP (Worldwide harmonized Light vehicles Test Procedures). The WLTP is a replacement of NEDC (New European Driving Cycle) which is based on procedure for type approval testing of Light Duty Vehicles. The WLTC cycles are classified with respect to different vehicle categories depending on Power to Mass Ratio (PMR) which defined as ratio of rated power (W) to curb mass (kg) [27]. In this study the engine speed and accelerator position were programmed to follow WLTC, cycle which is conducted on chassis dynamometer for the European middle class passenger car consisting of same model engine [28].

Table 3.1 Categorization of WLTC Test Cycles [27]

Category	**PMR (W/kg)**	**v_ max (km/h)**	**Duration (sec)**	**Speed Phase Sequence**
Class 3b	PMR > 34	v_ max => 120	1800	Low + Medium + High + Extra – High
Class 3a		v_ max < 120	1800	Low + Medium + High + Extra – High
Class 2	34 => PMR > 22		1800	Low + Medium + High + Extra - High
Class 1	PMR <= 22		1611	Low + Medium + Low

Table 3.2 WLTC class 3b for Light Duty Vehicles [27]

Phase	Duration	Distance	v_ max
	sec	m	Km/h
Class 3b (v_ max => 120 km/h)			
Low	589	3095	56.5
Medium	433	4756	76.6
High	455	7162	97.4
Extra - High	323	8254	131.3
Total	**1800**	**23266**	

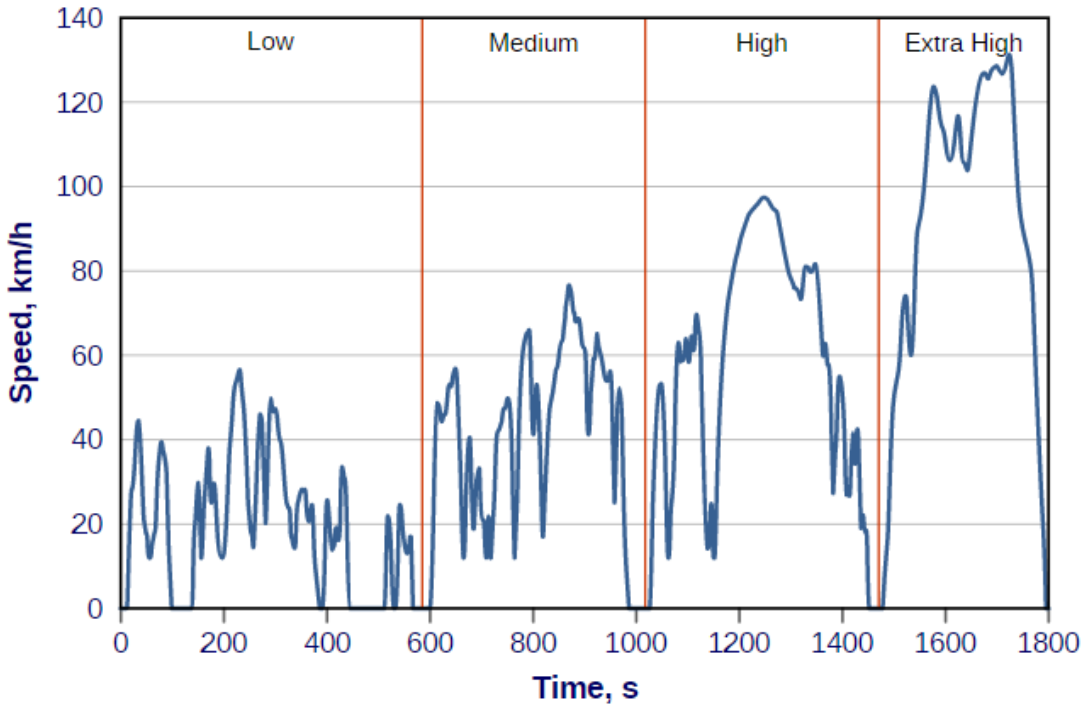

Figure 3.2 WLTC cycle for class 3b Light Duty Vehicles [27]

The experiment conducted in this Thesis is divided into two sessions morning and afternoon respectively. Each session consisting of two WLTC cycles which are the cold start followed by warm start conditions with five minutes break in between each cycle. The afternoon sessions also consist of two WLTC cycles same as above with five minutes pause between each cycle. The cold start performed in the both sessions are done by cooling of engine which would take around two hours.

3.2 Fuels used in the Test

The test had conducted by using three different fuels in which two fuels (iso-butanol 25%, n-butanol 25%) are alcohol blended in a proportion of 25% to vol and the other fuel is petrol. Butanol is a four-carbon alcohol with the properties relatively close to gasoline, which is produced from biomass [29].

Table 3.3 Properties of Gasoline, n-butanol, iso-butanol [29]

Properties	**Gasoline**	**n-butanol**	**Iso-butanol**
Research octane number (RON)	95	94 - 96	113
Density (kg/m^3)	753	810	806
Lower heating value (MJ/kg)	42.9	33.3	33.3
Chemical formula	Complex mixture	C_4H_9OH	C_4H_9OH
Boiling point (^{0}C)	199	118	108
Stoichiometric air/fuel ratio	14.7	11.2	11.2

3.3 Sampling of the Engine Exhaust

The exhaust is sampled from the engine before the instruments measures the exhaust and its compounds. The exhaust sample is pre-conditioned in order to meet the initial conditions of the measuring instruments such as temperature, concentration, reducing the presence of moisture and volatile compounds (because to minimize the errors in measurement of exhaust particles by avoiding any physical or chemical change of the exhaust sample) [30].

3.3.1 Diluted Sampling

The cooling of exhaust in some cases may results in supersaturation of volatile materials (water, sulfur compounds, VOCs (Volatile Organic Compounds)), which leads to nucleation and condensation. To eradicate this condition the following two processes can be included in measuring process [30].

I. To dilute the sample which avoids the supersaturation of sample.
II. Removal of volatile materials from reduced temperature levels.

3.3.1.1 Particle diluted sampling

The nucleation and condensation are the two important factors to be avoided or limited in the particulate matter sampling, this process is performed by keeping temperature constant in the dilution tunnel in specified limits. The other issue in particle sampling is coagulation, when particles are subjected to the collision due to thermal motion, the particles are combined to become single particle, which results in continuous change towards the larger particles in the size distribution of the particulate matter. The dilution sampling is the way to end the coagulation [30].

3.3.2 Raw Gas Sampling (or) Undiluted Gas Sampling

The Raw Gas (or) Undiluted Gas Sampling is relatively simple sampling system. But the problem with this sampling procedure is the existence of high concentration of moisture, particles and high temperature which makes this sampling procedure a complicated one to obtain the reliable results. Raw Gas sampling mainly used for field testing applications stationary power generators and marine engines. The instruments such as opacity meters are used this kind of sampling technique to operate at high temperatures to overcome the condensation [30].

4 Particle measurement instrumentation

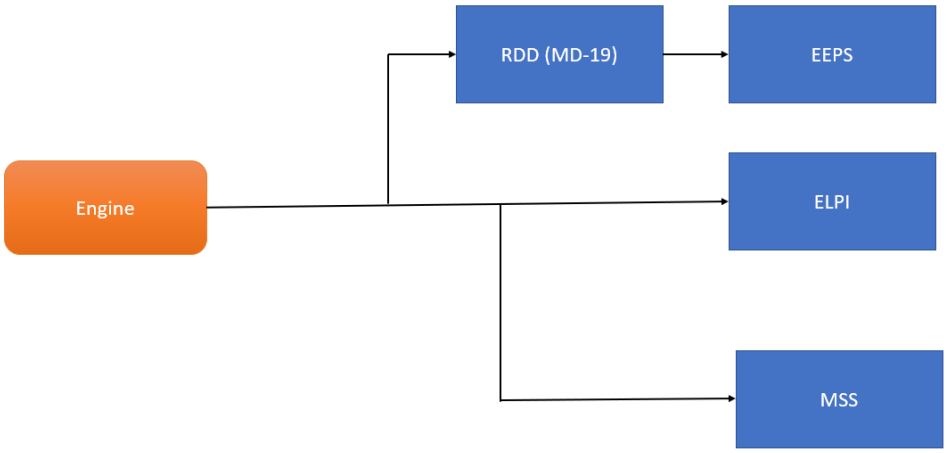

Figure 4.1 Schematic representation of Experimental Setup

Figure 4.1 represents the exhaust flow from engine to different instruments, ELPI (Electrical Low-Pressure Impactor) and MSS (Micro soot Sensor) is receiving the raw exhaust because the dilution is performed internally for ELPI & MSS instruments. But whereas the RDD (Rotating Disk Dilutor) is in between the engine and EEPS (Engine Exhaust Particle Sizer) in order to dilute the exhaust gases in 450:1. In this thesis every graphical result obtained from EEPS is multiplied with Dilution Ratio (DR) (450:1).

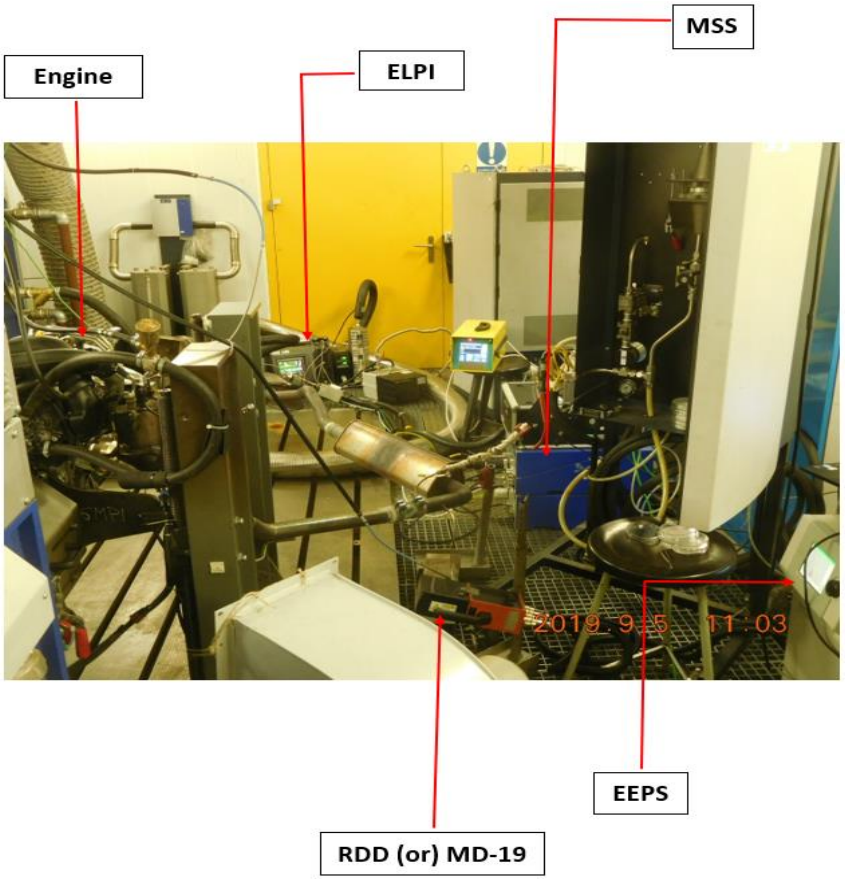

Figure 4.2 Experimental Setup with instruments in detail, conducted in VTP Roztoky Engine Laboratory

4.1 Instruments used in Experiment

The measurement of particulate emission in online procedure of this experiment the following instruments are used:

Rotating Disk Diluter MD-19, EEPS (Engine Exhaust Particle Sizer), ELPI (Electrostatic Low-Pressure Impactor), (MSS) Micro-soot sensor.

4.1.1 Rotating Disk Diluter (or) MD-19 (RDD)

The Rotating Disk Diluter (RDD) used in this experiment is from Matter Engineering AG, Switzerland, this diluter is a partial-flow dilution system means this instrument dilutes only fraction of flow from the raw exhaust flow. RDD is also called as MD-19, it is mostly used in the experiments of Particle measurement. The gas is first diluted and then cooled to overcome condensation of volatiles. The dilution can be performed from 1:15 until 1:3000 by varying the rotation frequency and selecting the discs with different number of cavities. A Dilution ratio (DR) of 1:15 indicates Dilution Factor (DF) 15 [31].

4.1.1.1 Working principle of Rotating Disk Diluter (RDD)

The working principle of Rotating Disk Diluter (RDD) is mainly based on the rotating disc with cavities, that used to transfer small volumes of the particles into the stream of fresh air. The volume of cavities, rotation frequency of the disc and the flow of air in diluted gas channel determines the Dilution Factor (DF) [31].

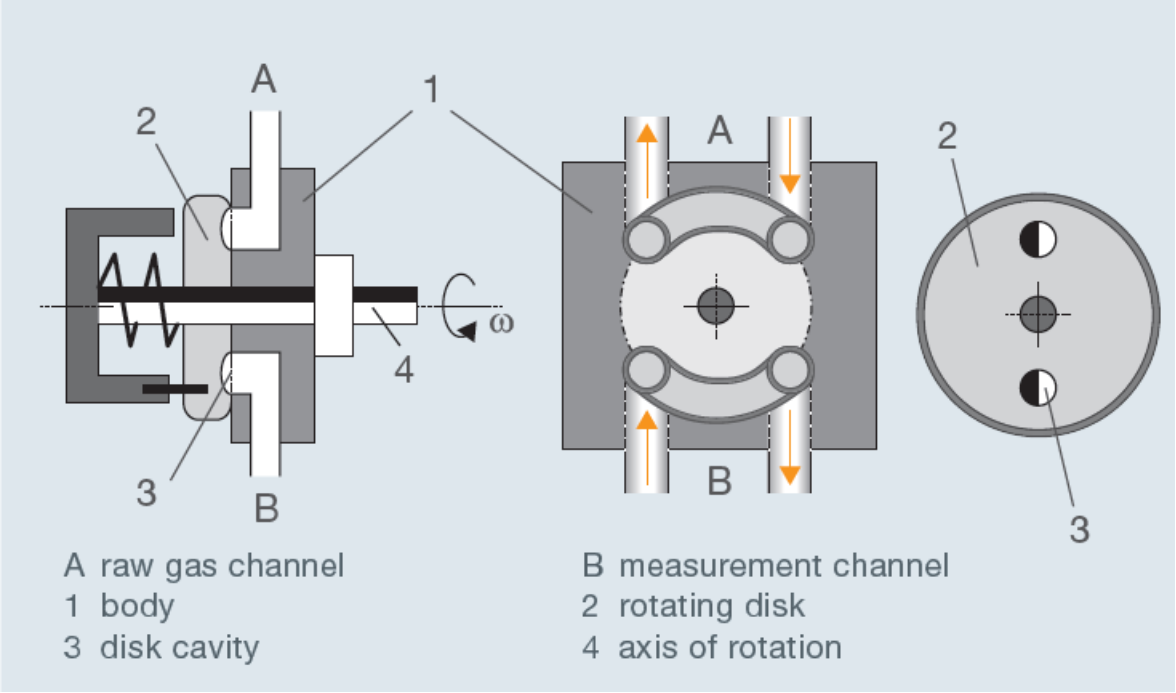

Figure 4.3 Working Principle of Rotating Disk Diluter (RDD) with components in detail [32]

The figure 4.2 is working principle of the RDD, there are two separate gas channels. The channel A has raw gas and in the channel B there is diluted gas, the rotating disk with cavities is placed in front of the two gas cannels; therefore, transportation of small volumes of particles from the raw gas channel to the measurement channel [33].

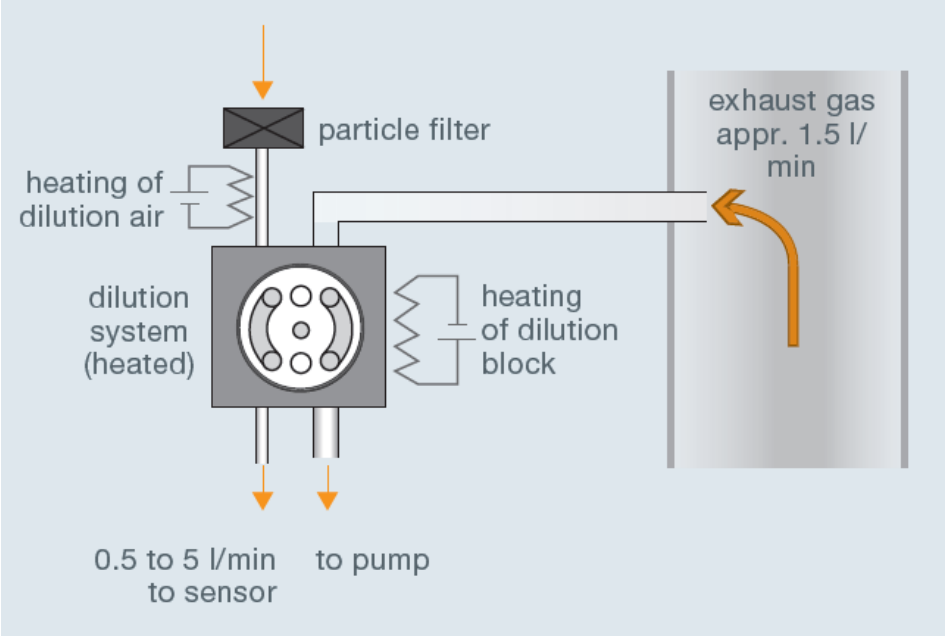

Figure 4.4 The explanation of raw exhaust from source of exhaust and dilution air flows

The figure 4.3 shows the dilution unit, which is made of stainless steel, the diluted air is heated by heating resistors in order to regulate the temperatures. The maximum possible temperature is 150^0C.

4.1.2 Engine Exhaust Particle Sizer (EEPS)

The Engine Exhaust Particle Sizer (EEPS) is a fast response instrument with higher resolution that can measure very low particle number concentrations in diluted exhaust. EEPS is very suitable for dynamic and transient test because the time resolution it can offer 10 Hz. The size distribution and number concentration of engine exhaust emission in the range from 5.6 – 560 nanometers [34].

4.1.2.1 Working principle of Engine Exhaust Particle Sizer (EEPS)

The sample flow of aerosol is drawn into the EEPS which is charged by corona charger positively to the predicted level. The positive charged aerosol enters in region between the inner rod and outer column consisting of 22 electrometers. The inner rod is separated into the three sections, each section is independently charged with high positive voltage. The aerosol is transported down the column, the positively charged individual aerosol particles are repelled from center column and impact the electrometers. The particle impacts depend on diameter and state of charge [34].

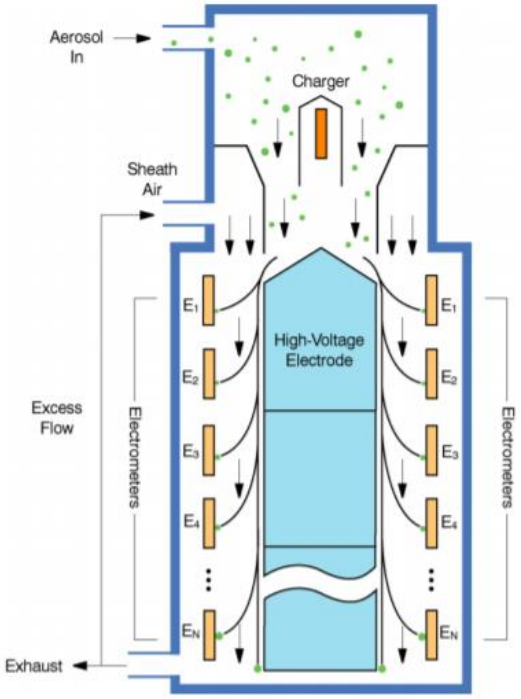

Figure 4.5Engine Exhaust Particle Sizer (EEPS) Schematic Diagram [34]

4.1.3 Electrical Low-Pressure Impactor (ELPI)

Electrical Low-Pressure Impactor (ELPI) is widely used in the measurement of real-time particle size distribution and concentration, the range of particles is from 6 nm – 10 µm. The ELPI is designed to work in harsh environmental and sample conditions such as the instrument can withstand the sample aerosol directly with 180^0C, the ELPI measures the size distribution and concentration in real time at 10 Hz sampling rate, particles are size classified into 14 size fractions in a impactors [35].

4.1.3.1 Working Principle of Electrical Low-Pressure Impactor (ELPI)

The aerosol particles pass through a unipolar corona charger, here the particles are positively charged then the particles are classified based on their aerodynamic size in 14 different cascade impactors. The main principle behind this classification is inertia of the particles, the particles with more inertia (it means the larger size particles) will be collected in the upper impactor and smaller particles in lower stages. Each impactor connected with electrometer, when the charged particle collected in the impactors the charge carried by the particles are detected by the electrometers, the current measured by electrometers is related to the number of particles [35].

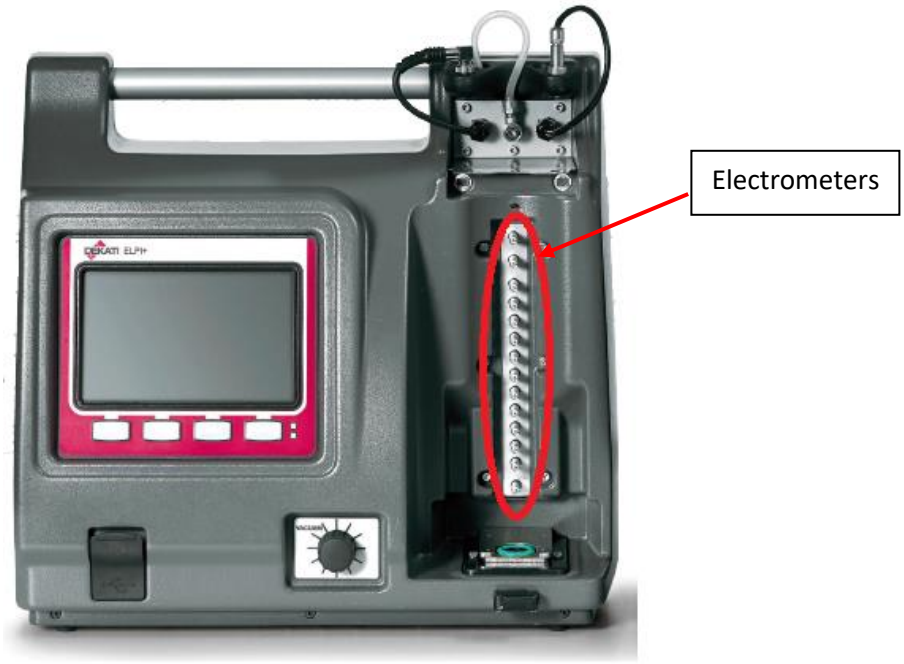

Figure 4.6 Electrical Low-Pressure Impactor (ELPI) with Electrometers encircled [35]

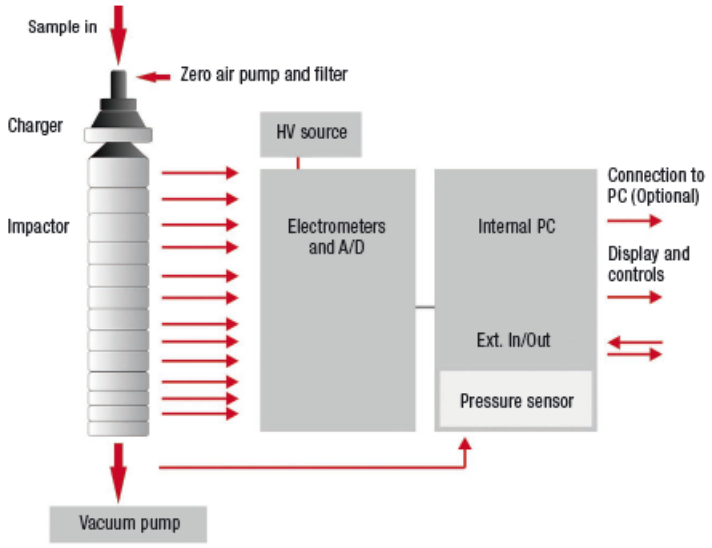

Figure 4.7 The impactors in the ELPI and sample flow through, charge detected by electrometers (block diagram) [35]

4.1.4 Photoacoustic Soot Analyzer (or) Micro-Soot Sensor (MSS)

Micro-Soot Sensor (MSS) measures the soot concentration based on Photoacoustic measurement principle, the operating temperature of the instrument is 5^0C - 40^0C. The concentration of particles directly is expressed in (mg/m^3) units, the minimum detection limit of MSS is 1 µg/m^3. MSS is having very high sensitivity which is in the range of 1-1000 mg/m^3, even in low detection limits with help of the electronics used in this instrument can reduce signal noise very effectively [36].

4.1.4.1 Working Principe of Micro-Soot Sensor (MSS)

The emissions Containing particles is subjected to modulated light beam. When the light beam is turned on the temperature of the particles is raised with the help of light beam which releases heat from them this results in pressure fluctuations (i.e. because of expansion and contraction of the exhaust with particles) are detected by a sensitive microphone [37].

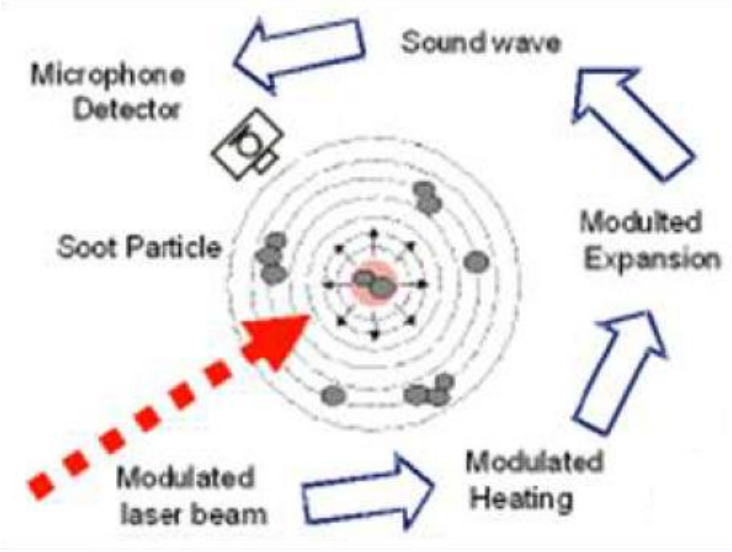

Figure 4.8 Working Principle of Micro-Soot Sensor (Photoacoustic Soot Analyzer) [37]

5 Analysis Procedure

The next procedure after performing the experiment is analyzing the data which is obtained from the experimental procedures in the different measuring instruments, in this procedure analyzation of particulate matter can be observed. While analyzing the data one must overcome the errors in the signal which is produced by the different factors caused in and on the instrument.

5.1 Selection of WLTC cycles

In this study the experimental procedure has done for one day with two sessions i.e. morning and afternoon session, each session includes two cycles (cold start & warm start) which are based on WLTC. In the experiment the instruments are turned on first and later the engine is started, the time period between starting of engine and instruments the signal is generated by instruments then that is added up to signal generated after starting of engine in this process it will be difficult to identify the starting point of particles concentration from the engine exhaust.

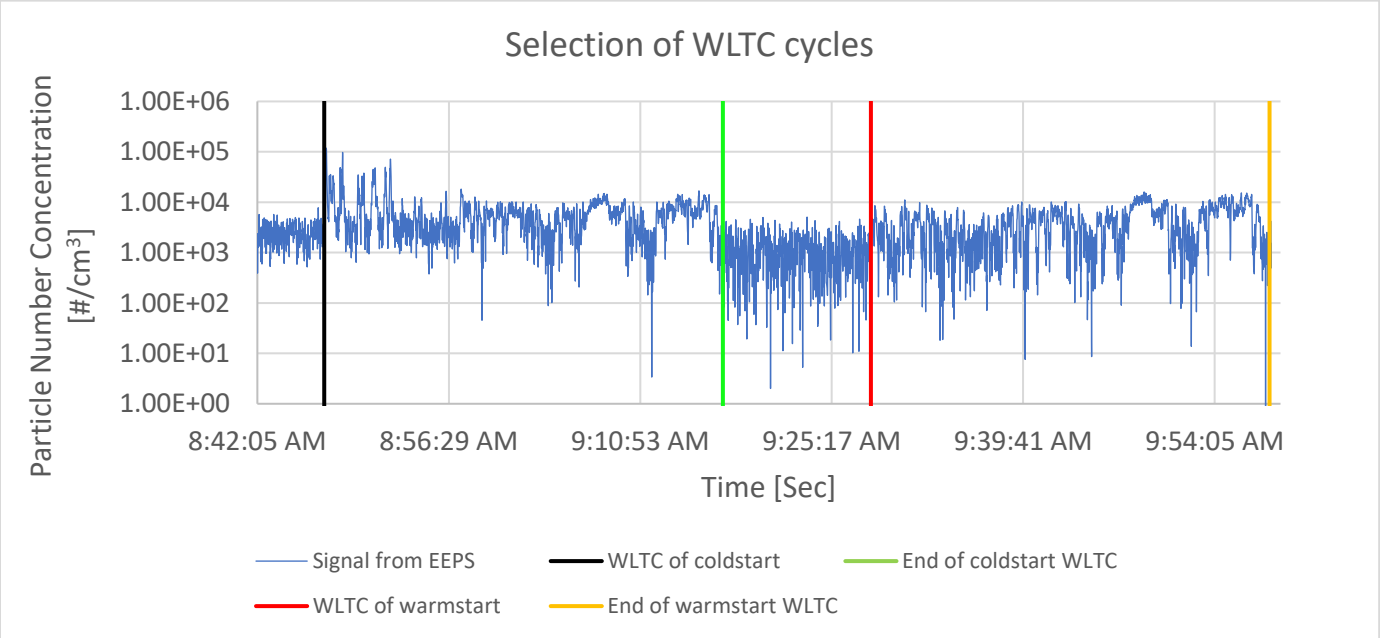

Figure 5.1 Selection of WLTC cycles for experiment conducted on EEPS in the morning session

The figure 3.2 describes the Particle number concentration in the exhaust which is measured with EEPS on Gasoline fuel. In figure 3.2 there are two WLTC cycles which are following the same trends but the only difference between those two cycles are the concentrations, the concentrations in the first WLTC cycle is higher in magnitude compared second WLTC because the first WLTC is conducted in the cold start conditions. The cycles are selected based on the trend and concentration of signal generated by instrument. In detail the experiment had started at 08:42:05 AM, but the engine started at 08:47:07 AM the signal obtained between this time period is background noise recorded by instrument. The first WLTC cycle (cold start) is got recorded between 08:42:05 AM and 09:17:06 AM, the second WLTC cycle (warm start) is recorded from 09:28:14 AM until 09:58:13 AM. The period between two WLTC cycles is break for 11 minutes and 08 seconds.

5.2 Signal to Noise Ratio

The useful information obtained from the instrument by quantifying the physical quantities is termed as signal. The physical quantities represent the particles from engine exhaust and noises are the unwanted signal. The noises are classified into two types based on sources of noise, namely external noise and internal noise [38]. The external noise is caused by the human, environment such as the vibrations, the signal interruption caused by nature. Whereas the internal noise is caused by the faults in the internal components of instrument. The Signal to Noise Ratio (SNR) is formulated as ratio of the mean of signal to the standard deviation of the noise formed in background.

$$Signal\ to\ Noise\ Ratio\ (SNR) = \frac{\mu}{\sigma}$$

μ = Mean of Signal

σ = Standard Deviation of noises in background

The Signal to Noise Ratio expressed in decibels (dB) written mathematically as follows

$$(SNR)_{dB} = 10 * log_{10}(SNR)$$

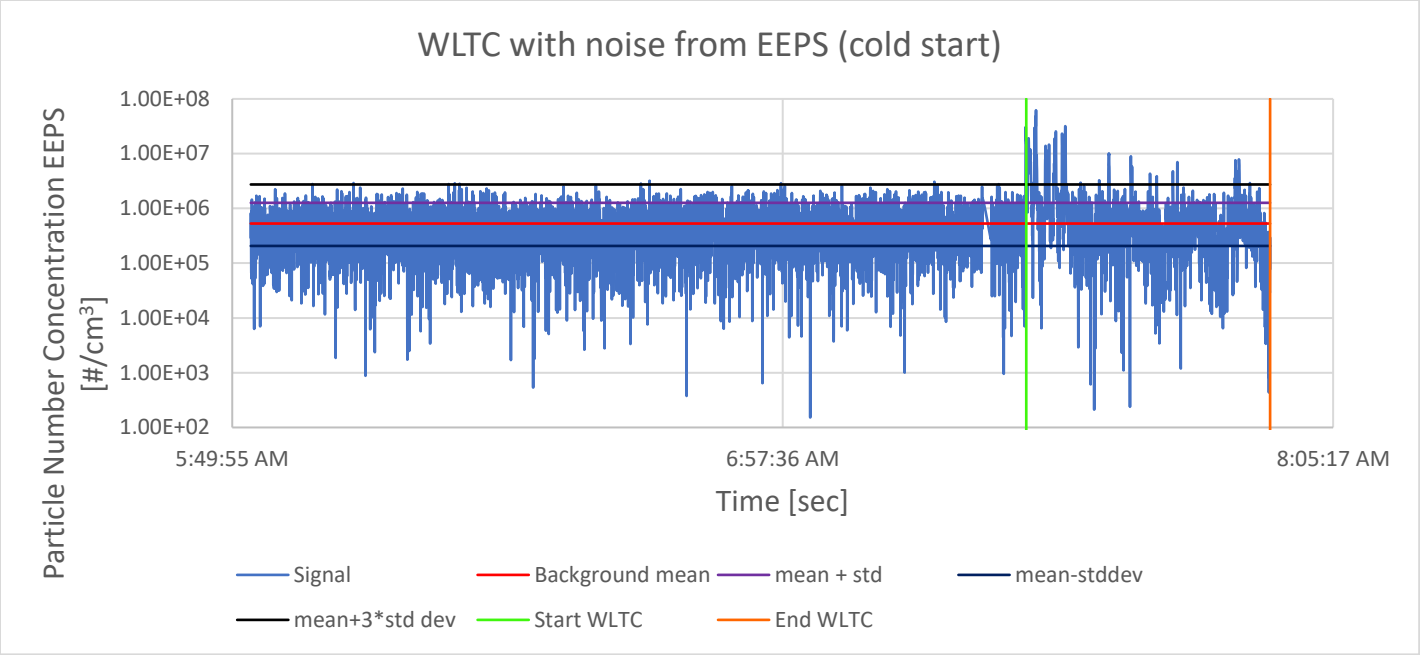

Figure 5.2 The signal generated by EEPS including WLTC cycle with Avg of Background Noise (for n-butanol in cold start condition) logscale on Y-axis.

The figure 5.2 explains about noise level from signal generated by EEPS for iso-butanol fuel. The background noise is obtained from the signal, before starting of engine because in that time period the instrument will not show any signal ideally. But in practical there will be signal obtained from instrument, that may be because noise of instrument, some spikes are generated by left over particles in exhaust system. One should take into the consideration that either in the cold start condition or in the warm start condition, the signal obtained before the WLTC cycles should consider as background data of instrument. Because in the pause between two WLTC cycles there will be spikes in signal with higher magnitudes (the left-over particles will be more compared to the signal before the cold start). In figure 5.2 the peaks above the average of background noise are said to be useful signals and the remaining are noise by instrument. In order to warm the instrument power supply is turned on whole night before the experiment day. But for this study, the signal generated by instrument 2 hours prior to the experiment is taken into the consideration which is shown in the figure 5.2.

The instruments used in this study was EEPS, ELPI which are working with a frequency of 1 Hz, whereas MSS is operating with a frequency of 5 Hz. In order to equalize

the MSS reading to the remaining two instruments, the Averaging of the five values had done to obtain single value (1 Hz).

5.3 Synchronization of time between the instruments

The data which is obtained from each instrument is aligned according to the time, in order to show uniformity in functioning of the instruments. Even though the engine starts in the exact time but there will be some delays and advances in the output signal between the respective instruments due to following reasons

I. The varying lengths of conducting pipes which are used to connect the probes to the instruments which varies time to reach the particles into instrument.
II. Human errors.
III. The individual time response of the different instruments.

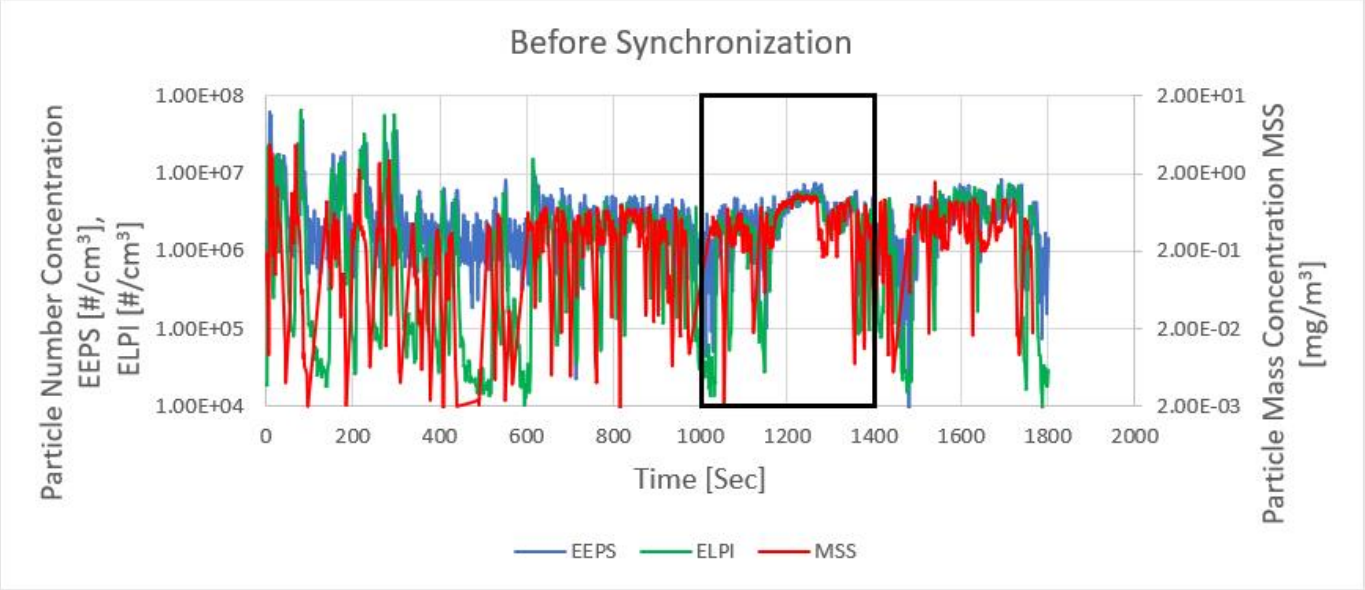

Figure 5.3 Before Time synchronization with differences (thinner lines) between the peaks which are highlighted in the box (logscale on Y-axis)

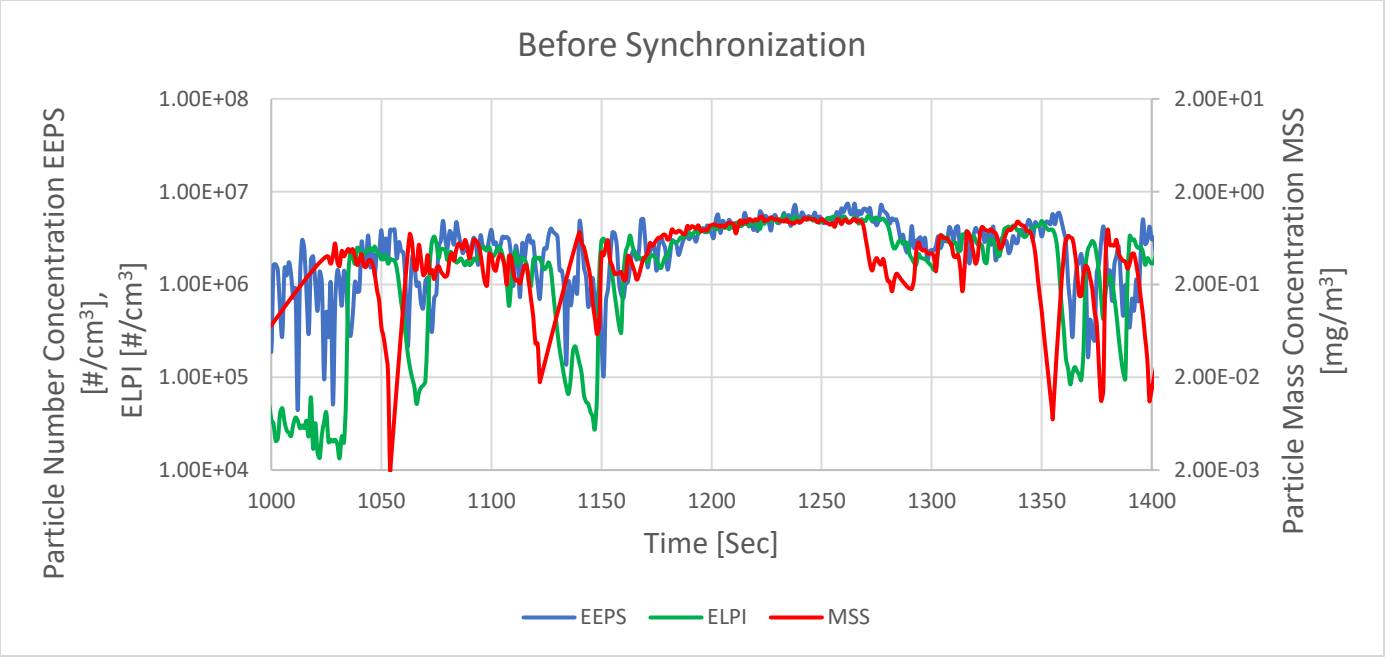

Figure 5.4 The Enlarged view of the highlighted box in before Time synchronization graph (logscale on Y-axis)

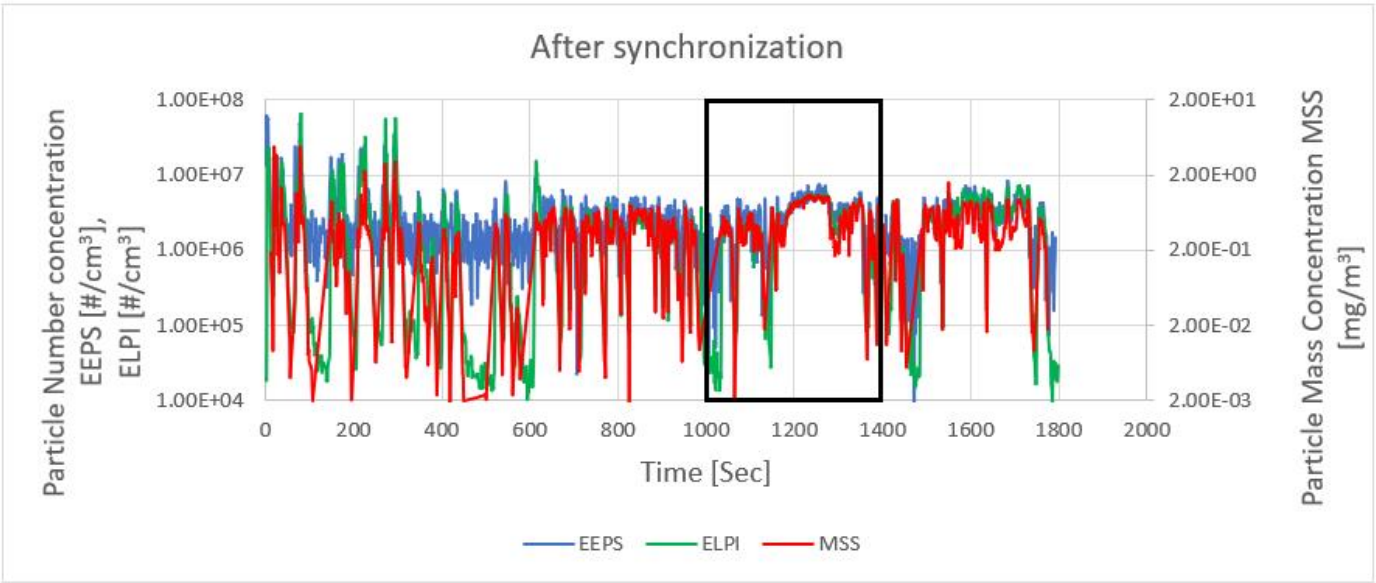

Figure 5.5 After Time Synchronization differences no differences between the peaks which are highlighted in the box (logscale on Y-axis)

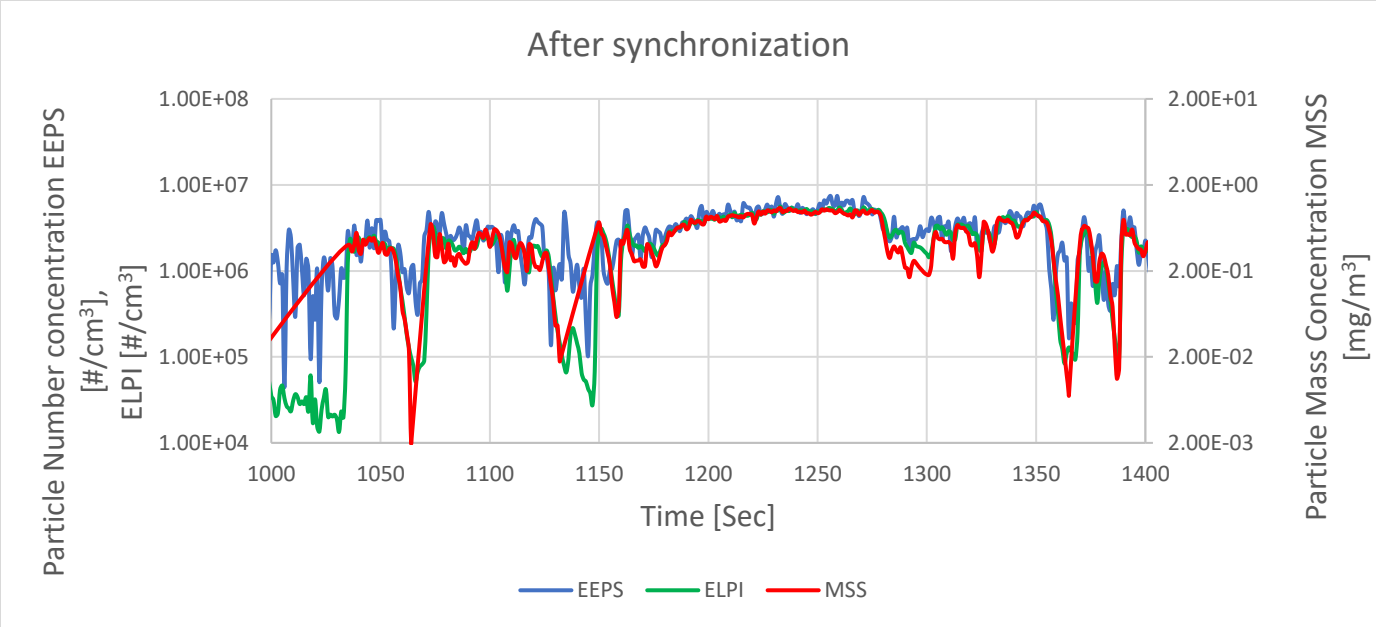

Figure 5.6 The Enlarged view of the highlighted box in After Time synchronization graph (logscale on Y-axis)

In figure 5.3 the differences between the signals can by noticed which is highlighted with in the black box, in figure 5.4 (enlarged view) the signal from MSS is advanced with respect to signal from ELPI. The signal obtained from EEPS is delayed with respect to signal from ELPI, in such case the peaks of respective instruments must be matched by dragging them back and forth in order to synchronize them which is shown in the figure 5.6.

5.4 Size Distribution and Mass Distribution

The 'particle diameter' defines the 'size' of the particles in uniformly distributed aerosol. But in most of aerosols the particles are polydisperse, the particle sizes are range over with difference in their magnitudes. The physical properties of aerosols depend on particle size; therefore, the size distributions are represented with the help statistical means and represented in graphical form [39].

In the EEPS (Engine Exhaust Particle Sizer) Particles are charged positively with corona charger and enters high voltage column region travels downwards by getting attracted towards electrometers this phenomenon based on the electro mobility this is background of segregation in EEPS deposited into 32 channels [34].

In the ELPI (Electrical Low-Pressure Impactor) there are 14 impactors which are different in their sizes depending on particle diameter and the segregation is performed based on the inertia of the particles [35].

In the graphical representation of size distribution the width of bars in histogram indicates the size interval of EEPS and the height denotes the concentration number of particles in each interval of EEPS [39].

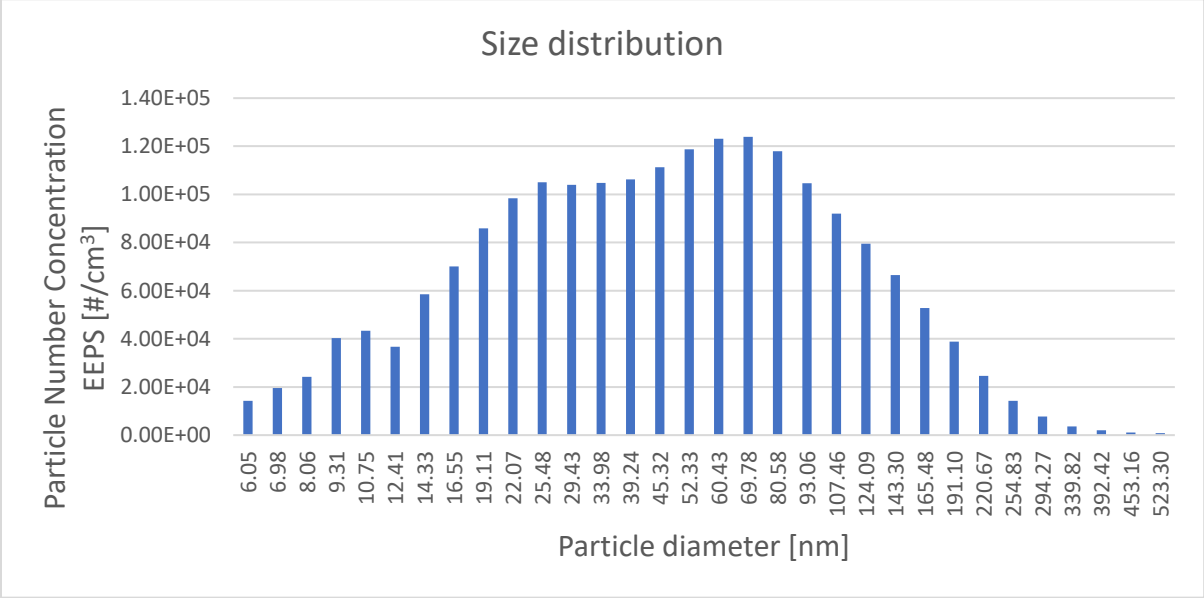

Figure 5.7 Particle Size distribution of Gasoline in warm start condition

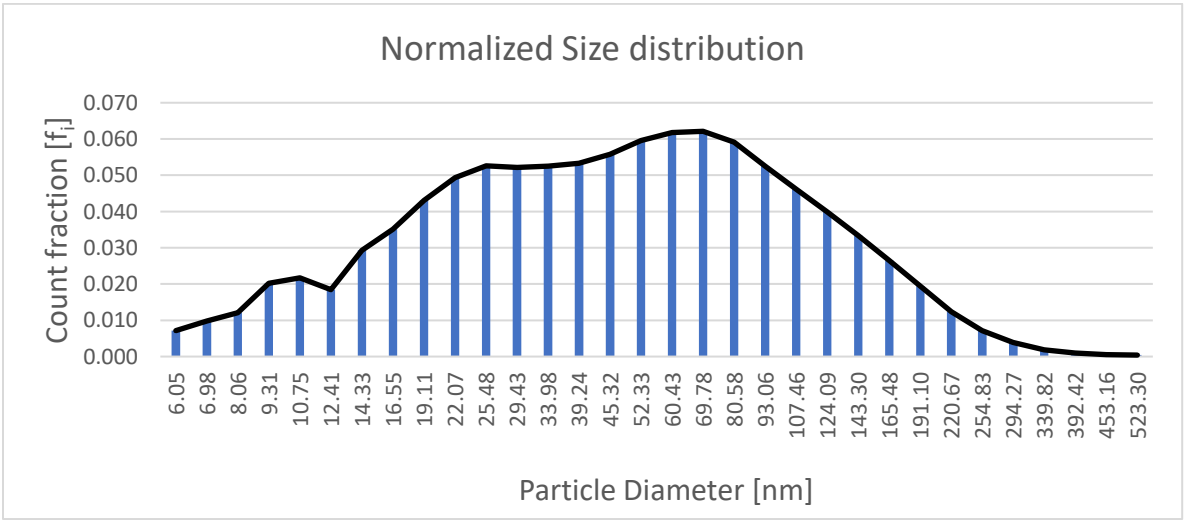

Figure 5.8 Normalized size distribution curve of Gasoline in warm start condition from EEPS

The figure 5.8 refers to the normalization of size distribution, we perform normalization because to compare shapes of the size distribution. The relative proportion of each size particles without evaluating the absolute number i.e. (An individual can say in relative proportions, there is more smaller particles than the larger particles but not the absolute number).

Total number of particles in sample N

$$N = \sum_i n_i \text{ [40]}$$

Where n_i = number of particles in each channel.

Fraction of particles per unit size interval f_i [39]

$$f_i = n_i / N$$

$$\sum f_i = 1$$

The mass distribution is function of particle size. Mass distribution represents the fraction of total mass particles contribute by the particles in any size range, whereas number distribution indicates total number of particles in any size range. The graphical representation of mass distribution explains, among different particle sizes how the mass is distributed [39] which is shown in figure 5.7. The particle mass concentration is calculated as follows with the help of Particle Number Concentration.

Density of Particle ρ,

$$\rho = {M_p}/{V * N_c}$$

Where M_p = Particle Mass Concentration (g/cm^3)

V = Volume of Particle (cm^3)

N_C = Particle Number Concentration ($\#/cm^3$)

Volume of Particle is written as;

$$V = \frac{1}{6} * \pi * d^3$$

d = diameter of Particle (width of channel) (cm)

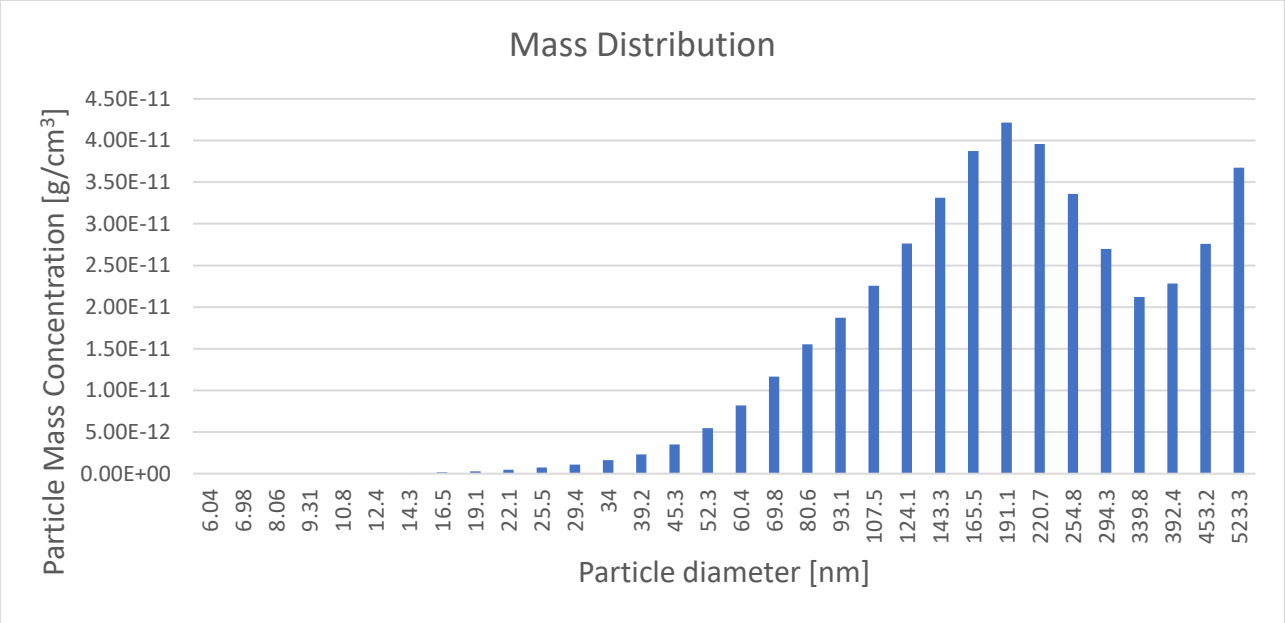

Figure 5.9 Particle mass distribution of 25% iso-butanol in cold start from EEPS

The fraction of total mass of particles per unit size interval g_i is [39]

$$g_i = {m_i}/{M}$$

$$\sum_i g_i = 1$$

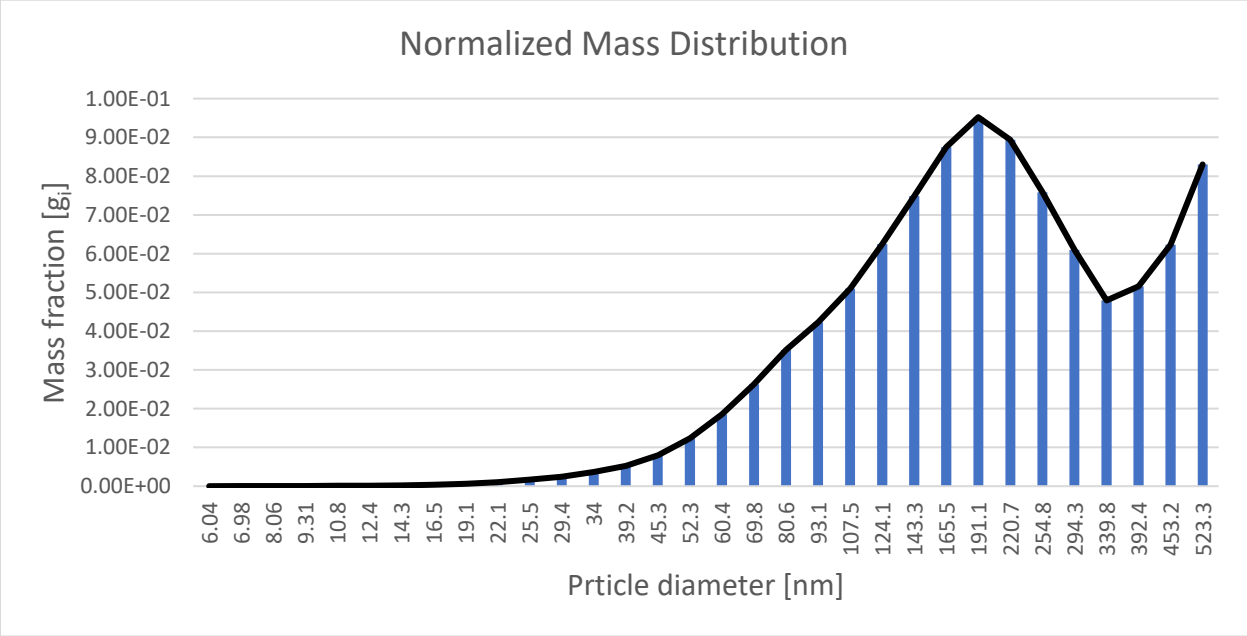

Figure 5.10 Normalized mass distribution of 25% iso-butanol in cold start from EEPS

5.4.1 Lognormal Distribution

The lognormal distribution is used empirically to fit the wide range and skewed shape particle distributions. In most of the cases the particles are skewed in the size distributions shown in figure 5.11, therefore it is used rarely, even though normal distribution is symmetrical shown in figure 5.12 but the problem with normal distribution is, in any function of aerosol particle which is applied with normal distribution the quantity of the function varies wide range such as aerosol particle size is that the normal distribution requires certain fraction of particles to have negative size which is physically impossible. When this problem combined with frequently applied skewed shape of distribution results in use of the logarithmic transformation to obtain lognormal distribution. The logarithmic scale has no negative values therefore the theoretical possibilities of negative values are solved.

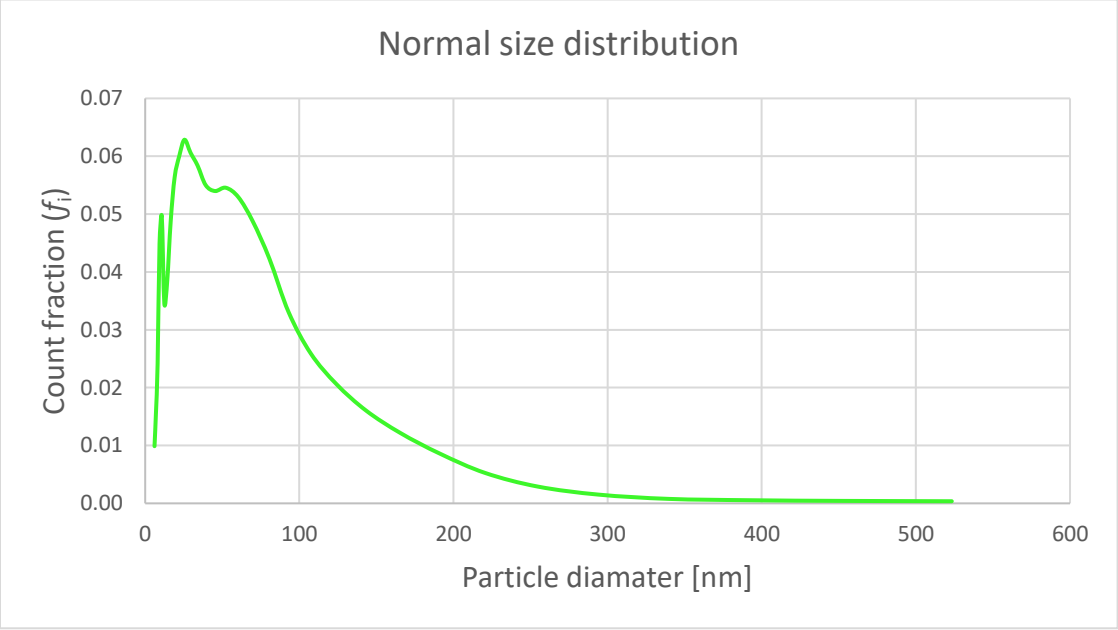

Figure 5.11 Skew shaped graph obtained from EEPS for 25% iso-butanol (size distribution)

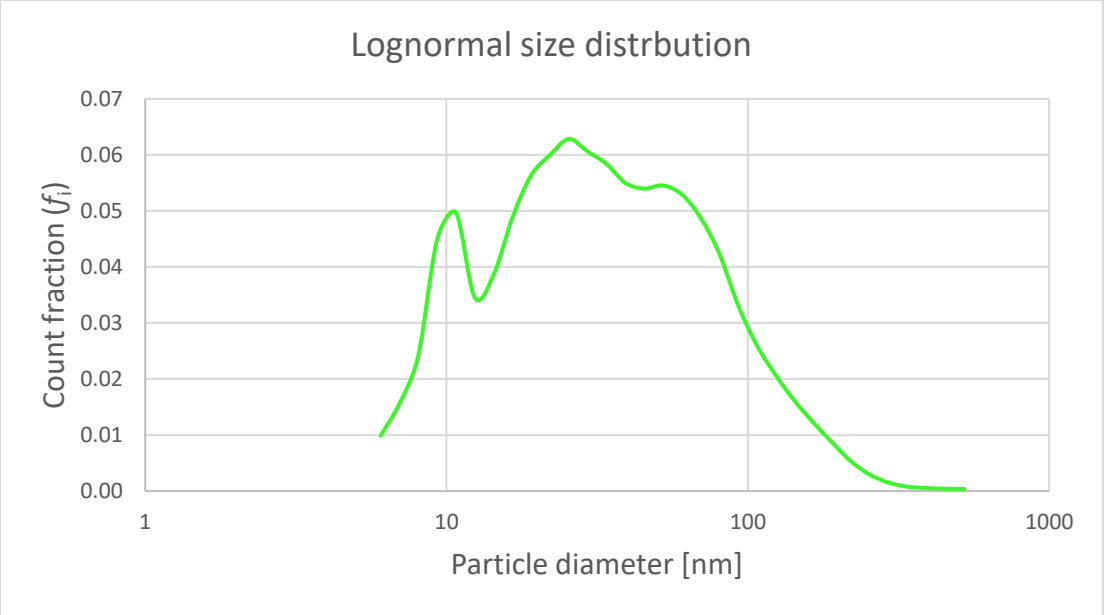

Figure 5.12 Lognormal size distribution graph obtained from EEPS for 25% iso-butanol (logscale used in x-axis)

5.4.2 Particle Size and Mass distributions in EEPS & ELPI

In this study the particle size and mass distributions of each particle in the EEPS & ELPI are done based on bin sizes of an instrument. In detail the size bins are defined by particle diameter (D_p), because the size range vary based on the instrument design and settings whereas the range of instrument is fixed. According to the instrument D_p resolution (the number and range of particle diameter size bins) the concentration is normalized so as to compare the instruments. Therefore, the lognormal number concentration ($dN/d\log D_p$) and lognormal mass concentration ($dM/d\log D_p$) is taken as ordinate in the graphical representation, here the log function is decadic logarithm [41].

Lognormal Number Concentration (#/cm^3) $= \frac{dN}{d \log D_p}$

$= \frac{dN}{\log D_{p,u} - \log D_{p,l}}$ [42]

Where, dN = Number concentration for each particle bin.

$D_{p,u}$ = upper bin diameter

$D_{p,l}$ = Lower bin diameter

Lognormal Mass Concentration (g/cm^3) $= \frac{dM}{d \log D_p}$

$$= \frac{dM}{\log D_{p,u} - \log D_{p,l}}$$

Where, dM = Mass concentration for each particle bin

$D_{p,u}$ = upper bin diameter

$D_{p,l}$ = Lower bin diameter

The figures 5.11 and 5.12 are the results obtained by using the Lognormal Number Concentration with respect to two different fuels and two different instruments. In the same way figures 5.13 and 5.14 are the results obtained with the help of Lognormal Mass Concentration.

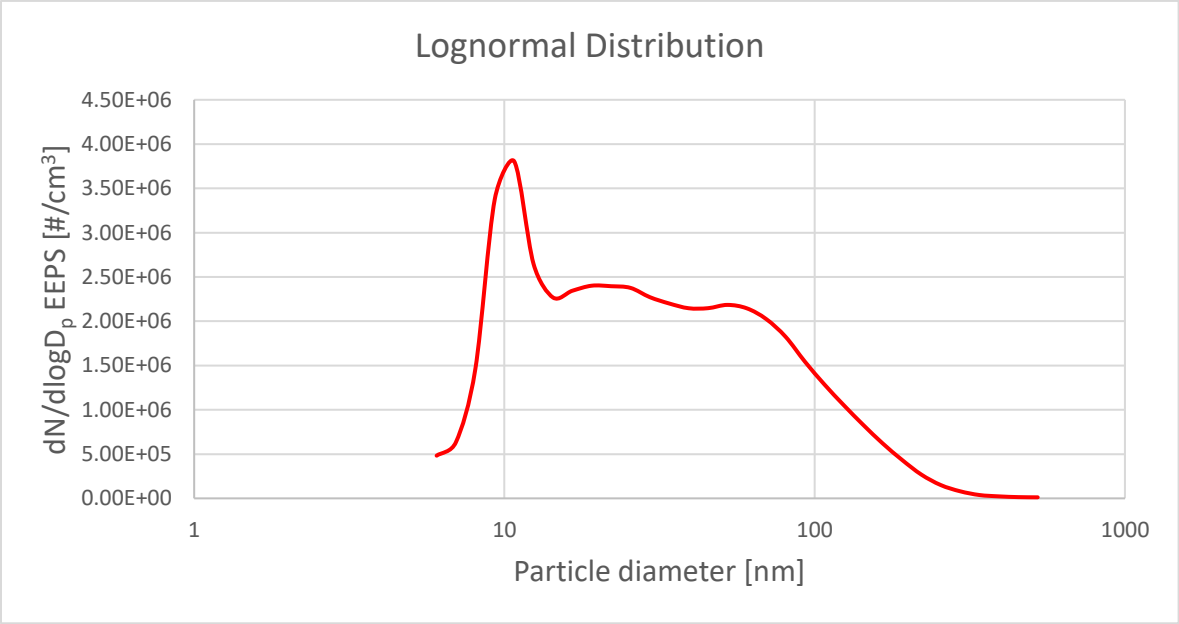

Figure 5.13 Lognormal Size Distribution from EEPS for Gasoline cold start condition (logscale used in X-axis)

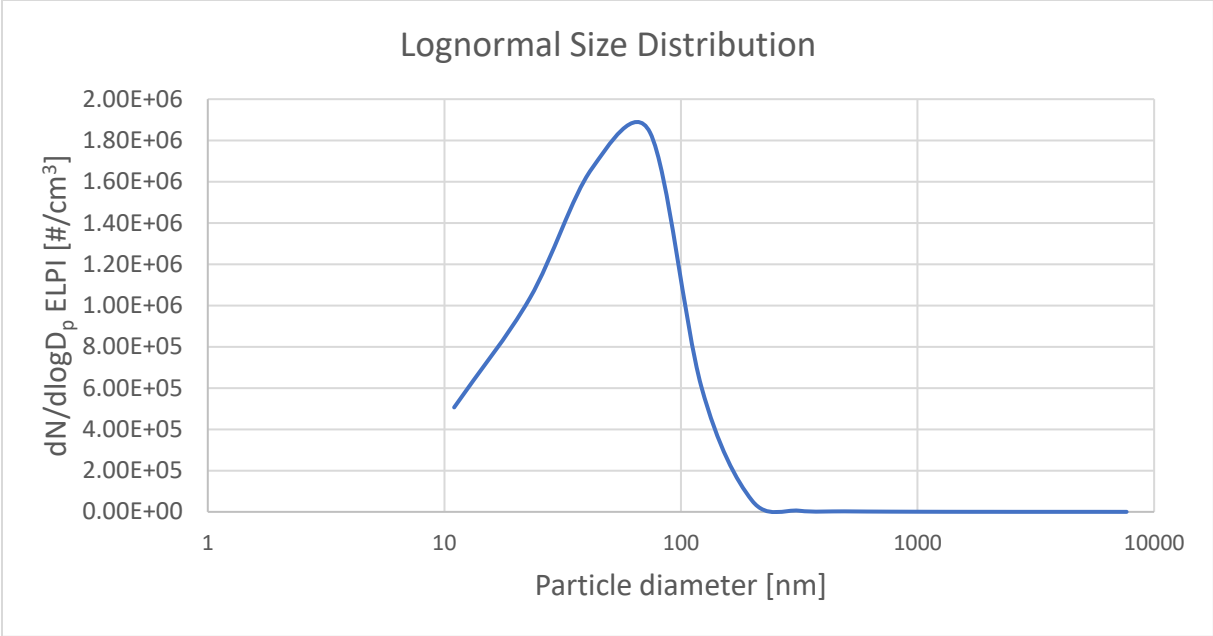

Figure 5.14 Lognormal Size Distribution from ELPI for 25% n-butanol in cold start condition (logscale used in x-axis)

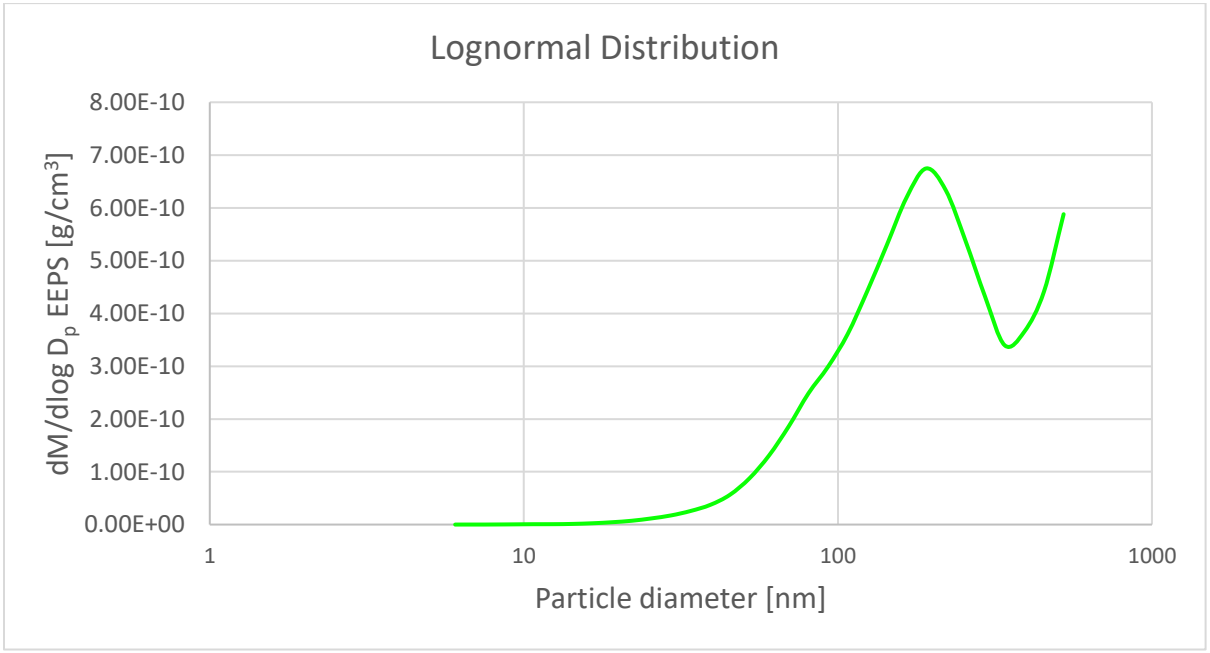

Figure 5.15 Lognormal Mass Distribution from EEPS for 25% iso-butanol cold start condition (logscale used in X-axis)

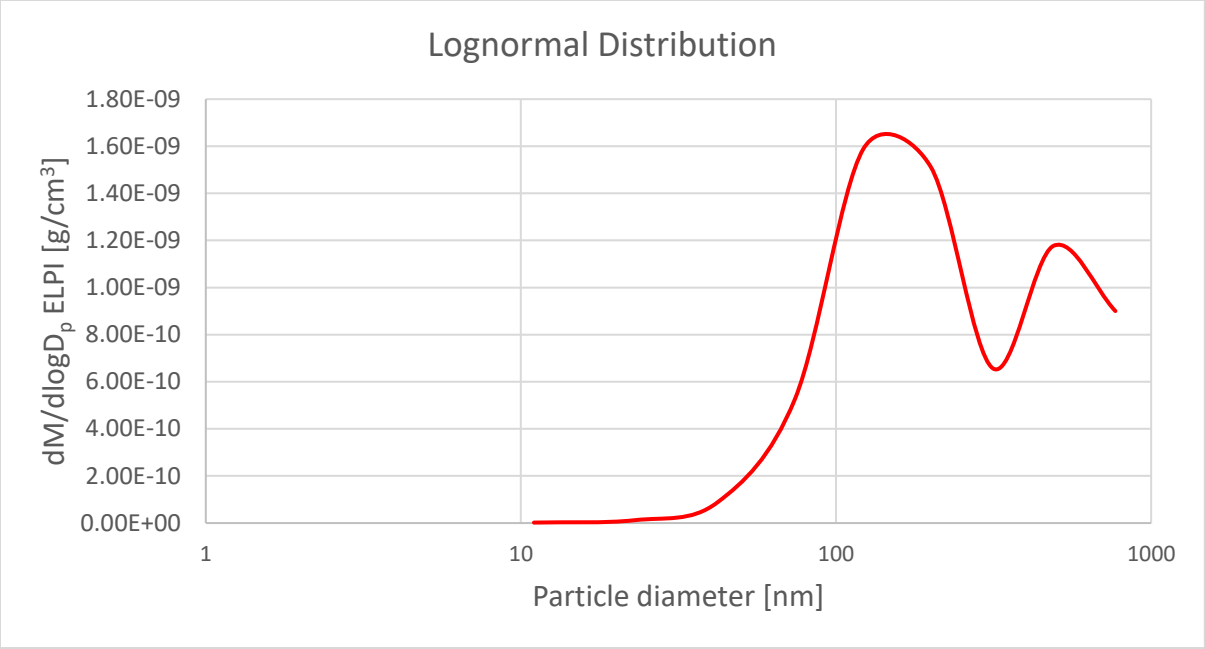

Figure 5.16 Lognormal Mass Distribution from ELPI for Gasoline cold start condition (logscale used in X-axis)

5.5 Repeatability of Tests

Repeatability is defined as the closeness or precision among the independent results obtained from the tests with identical methods and same sources (fuels) under same conditions (either cold start or warm start) [43]. To apply repeatability technique the following conditions must be same they are [44]:

I. Location.
II. Measuring instruments.
III. Observer.
IV. Time period (Repeating of experiment on same day (or) consecutive days).
V. Engine.

In this study the experiment is conducted on same engine (1.4-liter R4 16 valve TSI/TFS DISI engine) for the three different fuels (Gasoline, 25% iso-butanol, 25% n-butanol) with same operating cycles (WLTC Cycle) with two different conditions (cold start and warm start). The same experiment is conducted on morning session and afternoon

session in consecutive days which is explained detail in figure5.15. In this study the repeatability technique is applied to three different cases they are namely:

I. Repeatability of Total Particle Number Concentration.
II. Repeatability of Total Particle Mass Concentration.
III. Repeatability of Particle Number Concentration in different channels.
IV. Repeatability of Total Particulate Number Concentration of segments in WLTC (Low, Medium, High, Very High).

Fuels	EEPS				ELPI				MSS			
	Morning		Afternoon		Morning		Afternoon		Morning		Afternoon	
	Cold start	Warm start	Cold start	Warm start	Cold start	Warm start	Cold start	Warm start	Cold start	Warm start	Cold start	Warm start
			20-Aug	20-Aug			20-Aug	20-Aug				20-Aug
	21-Aug	21-Aug	21-Aug	21-Aug					21-Aug	21-Aug	21-Aug	21-Aug
iso-butanol	22-Aug	22-Aug	22-Aug	22-Aug	22-Aug	22-Aug	22-Aug	22-Aug			22-Aug	
	23-Aug	23-Aug	23-Aug	23-Aug	23-Aug	23-Aug	23-Aug	23-Aug			23-Aug	23-Aug
	6-Sep	6-Sep							6-Sep	6-Sep		
	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug	26-Aug
	27-Aug	27-Aug	27-Aug	27-Aug								
Gasoline	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug	28-Aug
	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug	29-Aug
	30-Aug	30-Aug	30-Aug	30-Aug	30-Aug	30-Aug			30-Aug	30-Aug	30-Aug	30-Aug
			2-Sep	2-Sep			2-Sep	2-Sep			2-Sep	2-Sep
n-buatnol	3-Sep	3-Sep	3-Sep	3-Sep	3-Sep	3-Sep	3-Sep	3-Sep			3-Sep	3-Sep
	4-Sep	4-Sep	4-Sep	4-Sep	4-Sep	4-Sep	4-Sep	4-Sep				

Figure 5.17 The following Repeatability calculations performed based on the experiments mentioned in this figure

5.5.1 Repeatability of Total Particle Number Concentration:

The calculation procedure of repeatability among three instruments starts with, taking the average of total particle number concentration of the two cold starts that had conducted in the morning and afternoon sessions, same procedure is followed for two warm starts conducted in the morning and afternoon sessions, which is shown in equations 1 & 2. Then the mean is applied for whole WLTC cycles of both cold start and warm start so, that average of Total Particle Number Concentration is obtained each day for cold start and warm start separately. Further once again the mean is taken for all the days when the experiment conducted, and standard deviation is taken for all cycle

averages when the experiment is conducted because to represent the difference between average of Total particle concentrations of all days.

$$TPNC_{cs} = \frac{\sum_{i=Morning}^{Afternoon} TPNC_i}{2}$$

Equation 5-1 Average of Total Particle Number Concentration between morning and afternoon cold starts

Where $TPNC_{cs}$ = Total Particle Number Concentration in cold start.

TPNC = Total Particle Number Concentration (individually in morning & afternoon sessions).

$$TPNC_{ws} = \frac{\sum_{i=Morning}^{Afternoon} TPNC_i}{2}$$

Equation 5-2 Average of Total Particle Number Concentration between morning and afternoon warm starts

Where $TPNC_{ws}$ = Total Particle Number Concentration in warm start.

TPNC = Total Particle Number Concentration (individually in morning & afternoon sessions).

$$TPNC_{mean\ (cs)} = \frac{\sum_{i=1}^{1800} TPNC_{(cs)\ i}}{1800}$$

Equation 5-3 The mean of whole WLTC cycle (1800 seconds) for cold start condition

Where $TPNC_{mean\ (cs)}$ = Mean value of Total Particle Number Concentration in cold start.

$TPNC_{cs}$ = Total Particle Number Concentration in cold start (WLTC cycle).

$$TPNC\ _{mean\ (ws)} = \frac{\sum_{i=1}^{1800} TPNC_{(ws)\ i}}{1800}$$

Equation 5-4 The mean of whole WLTC cycle (1800 seconds) for warm start condition

Where $TPNC_{mean\ (ws)}$ = Mean value of Total Particle Number Concentration in warm start.

$TPNC_{ws}$ = Total Particle Number Concentration in cold start (WLTC cycle).

$$overall\ TPNC_{AVG\ (cs)} = \frac{\sum_{i=Starting\ day\ of\ test}^{Ending\ day\ of\ test} TPNC_{mean\ (cs)\ i}}{N}$$

Equation 5-5 The Average of Total Particle Number Concentration of all the days when experiment is conducted for cold start

Where overall $TPNC_{AVG\ (cs)}$ = Average of Total Particle Number Concentration of all the days when experiment is conducted in cold start condition.

$TPNC_{mean\ (cs)}$ = Mean value of Total Particle Number Concentration in cold start.

N = Total number of days when the test conducted with respect to fuel.

$$overall\ TPNC_{AVG\ (ws)} = \frac{\sum_{i=Starting\ day\ of\ test}^{Ending\ day\ of\ test} TPNC_{mean\ (ws)\ i}}{N}$$

Equation 5-6 The Average of Total Particle Number Concentration of all the days when experiment is conducted for warm start

Where Total $TPNC_{AVG\ (ws)}$ = Average of Total Particle Number Concentration of all the days when experiment is conducted in warm start condition.

$TPNC_{mean\ (cs)}$ = Mean value of Total Particle Number Concentration in warm start.

N = Total number of days when the test conducted with respect to fuel.

$$STD\ dev_{cs} = \sqrt{\frac{\sum_{i=Starting\ day\ of\ test}^{Ending\ day\ of\ test} \left(TPNC_{mean\ (cs)\ i} - overall\ TPNC_{AVG\ (cs)}\right)^2}{N}}$$

Equation 5-7 Standard deviation of all the days when the experiment is conducted for cold start condition

Where $TPNC_{mean\ (cs)}$ = Mean value of Total Particle Number Concentration in cold start.

overall $TPNC_{AVG\ (cs)}$ = Average of Total Particle Number Concentration of all the days when experiment is conducted in cold start condition.

N = Total number of days when the test conducted with respect to fuel.

$$STD\ dev_{ws} = \sqrt{\frac{\sum_{i=Starting\ day\ of\ test}^{Ending\ day\ of\ test} \left(TPNC_{mean\ (ws)\ i} - overall\ TPNC_{AVG\ (ws)}\right)^2}{N}}$$

Equation 5-8 Standard deviation of all the days when the experiment is conducted for warm start condition

Where,

$TPNC_{mean\ (ws)}$ = Mean value of Total Particle Number Concentration in warm start.

overall $TPNC_{AVG\ (ws)}$ = Average of Total Particle Number Concentration of all the days when experiment is conducted in warm start condition.

N = Total number of days when the test conducted with respect to fuel.

The above mentioned equations are applicable for the three instruments (EEPS, ELPI, MSS), therefore these equations are used to analyze the data recorded by the instruments for the two different conditions and arranged with respect to three different fuels and represented graphically, the results are discussed in chapter 6. The same procedure is followed in the case of repeatability of Total Particle Mass Concentration calculations and repeatability of Total particle Number Concentration of segments in WLTC.

5.5.2 Repeatability of Total Particle Number Concentration between channels

The Procedure of repeatability of Total Particle Number Concentration between channels begins by taking average of both WLTC cycles with identical conditions (either cold start or warm start) performed in the morning and afternoon respectively. The calculations continue by applying mean of entire WLTC cycles separately (cold start & warm start) according to the channels with respective instruments (EEPS & ELPI). Arrange the obtained means according to the days when the experiment is conducted, further once again the average Particle number concentrations is performed with respect to the days when experiment is conducted, and standard deviation is taken for Particle number concentrations.

$$PNC_{cs} = \frac{\sum_{i=Morning}^{Afternoon} PNC_i}{2}$$

Equation 5-9 Average of Particle Number Concentration between morning and afternoon cold starts (with respect to channel size)

Where PNC_i = Particle Number Concentration (morning and afternoon separately) with respect to channel size.

$$PNC_{ws} = \frac{\sum_{i=Morning}^{Afternoon} PNC_i}{2}$$

Equation 5-10 Average of Particle Number Concentration between morning and afternoon warm starts (with respect to channel size)

Where PNC_i = Particle Number Concentration (morning and afternoon separately) with respect to channel size.

$$PNC_{mean\ (cs)} = \frac{\sum_{i=1}^{1800} PNC_{cs\ (i)}}{1800}$$

Equation 5-11 The mean of whole WLTC cycle (1800 seconds) for cold start condition (with respect to channel size)

Where PNC_{cs} = Particle Number Concentration in cold start (WLTC cycle) with respect to channel size.

$$PNC_{mean\ (ws)} = \frac{\sum_{i=1}^{1800} PNC_{ws\ (i)}}{1800}$$

Equation 5-12 The mean of whole WLTC cycle (1800 seconds) for warm start condition (with respect to channel size)

Where PNC_{ws} = Particle Number Concentration in warm start (WLTC cycle) with respect to channel size.

$$TPNC_{AVG\ (cs)} = \frac{\sum_{i=Starting\ day\ of\ test}^{Ending\ day\ of\ test} PNC_{mean\ (cs)}}{N}$$

Equation 5-13 The Average of Particle Number Concentration of all the days when experiment is conducted for cold start (with respect to channel size)

Where $PNC_{mean\ (cs)}$ = Mean value of Particle Number Concentration in cold start.

N = Total number of days when the test conducted with respect to fuel.

$$TPNC_{AVG\ (ws)} = \frac{\sum_{i=Starting\ day\ of\ test}^{Ending\ day\ of\ test} PNC_{mean\ (ws)}}{N}$$

Equation 5-14 The Average of Particle Number Concentration of all the days when experiment is conducted for warm start (with respect to channel size)

Where $PNC_{mean\ (ws)}$ = Mean value of Particle Number Concentration in warm start.

N = Total number of days when the test conducted with respect to fuel.

$$STD\ dev_{cs} = \sqrt{\frac{\sum_{i=Starting\ day\ of\ test}^{Ending\ day\ of\ test} \left(PNC_{mean\ (cs)} - TPNC_{AVG\ (cs)}\right)^2}{N}}$$

Equation 5-15 Standard deviation of all the days when the experiment is conducted for cold start condition (with respect to channel size)

Where $PNC_{mean\ (cs)}$ = Mean value of Particle Number Concentration in cold start.

$TPNC_{AVG\ (cs)}$ = Average of Particle Number Concentration of all the days when the experiment is conducted for cold start.

N = Total number of days when the test conducted with respect to fuel.

$$STD\ dev_{ws} = \sqrt{\frac{\sum_{i=Satring\ day\ of\ test}^{Ending\ day\ of\ test} \left(PNC_{mean\ (ws)} - TPNC_{AVG\ (ws)}\right)^2}{N}}$$

Equation 5-16 Standard deviation of all the days when the experiment is conducted for warm start condition (with respect to channel size)

Where $PNC_{mean\ (cs)}$ = Mean value of Particle Number Concentration in warm start.

$TPNC_{AVG\ (cs)}$ = Average of Particle Number Concentration of all the days when the experiment is conducted for warm start.

N = Total number of days when the test conducted with respect to fuel.

The results obtained from above equations are represented graphically which will be discussed in chapter 6. The above equations are performed individually with respect to each channel sizes of instruments.

6 Results and Discussions

6.1 Comparison of instruments

The comparing of instruments is performed because if there are some changes are implemented in engine calibration (or) changing engine design (or) changing fuels, this kind of changes leads to relative differences. These differences can be measure by different instruments.

In this study 3 different fuels were used to run the engine and the relative differences were measured by 3 different instruments (EEPS, ELPI, MSS). The measurements performed by all instruments are analyzed to check consistency between them.

6.1.1 Comparison between the instruments for Repeatability of Total Particle Number Concentration

The repeatability between the instruments is performed to evaluate the consistency between the instruments and experiments conducted at different sessions, in consecutive days. In the cold start (figure 6.1) it is evident that the Avg Total Particle Number Concentration ($TPNC_{Avg(cs)}$) of ELPI is greater than Avg Total Particle Number Concentration ($TPNC_{Avg(cs)}$) of EEPS in all the fuels because the range of ELPI is comparatively higher than the EEPS. But, whereas in the warm start (figure 6.2) EEPS is dominating the ELPI in 25% iso-butanol, 25% n-butanol and in gasoline the $TPNC_{Avg\ (ws)}$ are almost same this is due to production of less particles compare to cold start conditions.

There are differences in the repeatability of instruments with good consistency in experiments conducted by using 25% iso-butanol and 25% n-butanol compared to gasoline because there is no good consistency between experiments conducted with help of EEPS rather than ELPI the reason for this problem will be explained in the chapter 6.1.4.

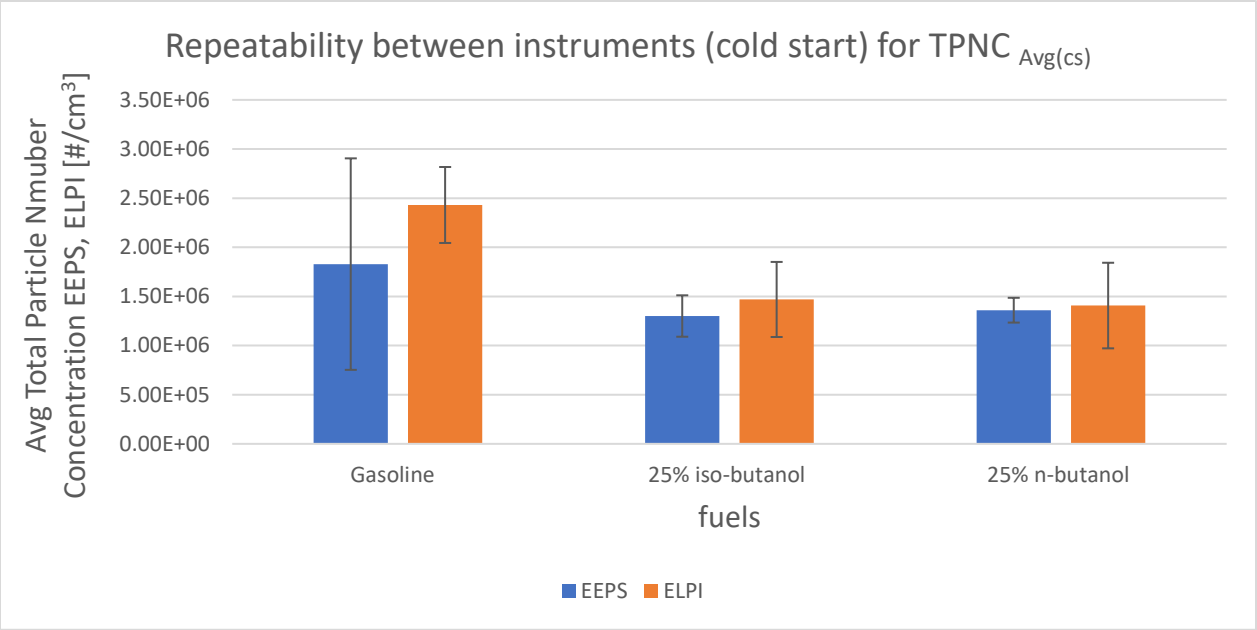

Figure 6.1 Repeatability of Total Particle Number Concentration between the instruments in cold start conditions

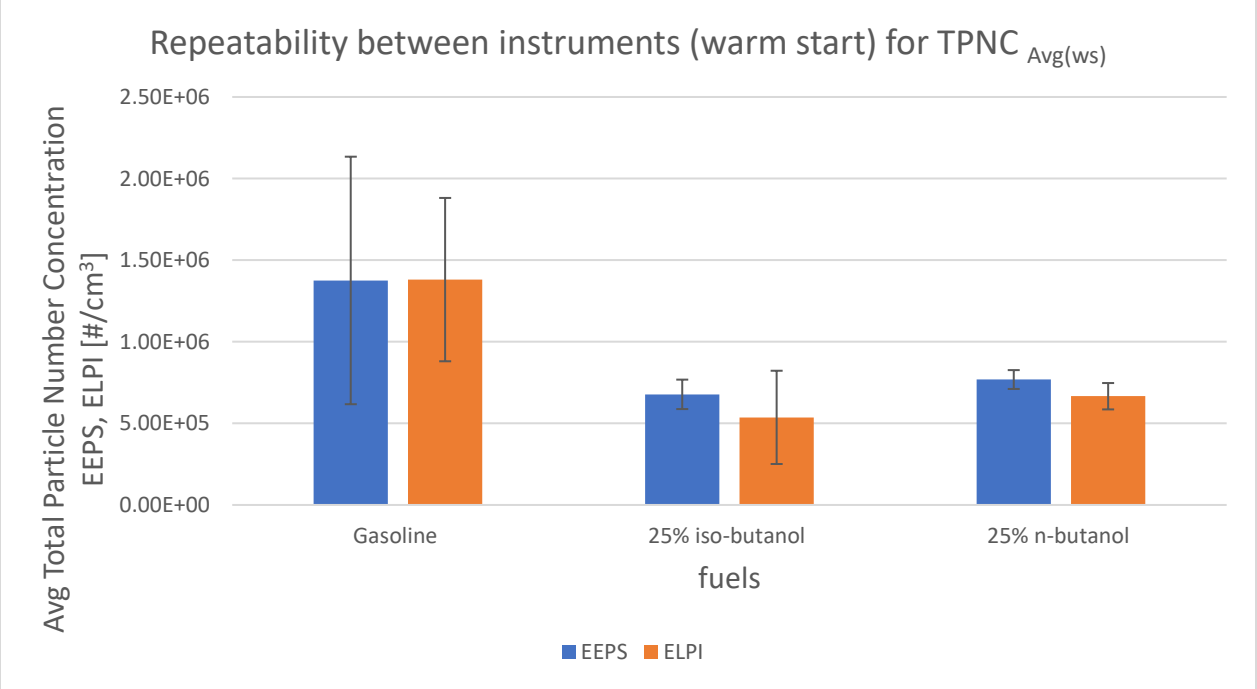

Figure 6.2 Repeatability of Total Particle Number Concentration between the instruments in warm start conditions

6.1.2 Comparison between the instruments for Repeatability of Total Particle Mass Concentration

In figure 6.5 the repeatability of Avg Total Particle Mass Concentration ($TPMC_{Avg(cs)}$) in cold start is represented graphically. It is observed that the average Total Particle Mass Concentration ($TPMC_{Avg(cs)}$) recorded by EEPS is dominating the average Total Particle Mass Concentration ($TPMC_{Avg(cs)}$) recorded by ELPI and MSS in 25% iso-butanol & 25% n-butanol fuels, but whereas in Gasoline there is slight increase in EEPS measurement compared to ELPI & MSS. In warm start conditions the average Total Particle Mass Concentration ($TPMC_{Avg(ws)}$) recorded by EEPS is high compared to ELPI & MSS.

Generally, the average Total Particle Mass Concentration ($TPMC_{Avg}$) of ELPI will not be the same as EEPS and MSS readings shown in figure 6.5 & figure 6.6, i.e. because of the range of ELPI originally which lies between 6-10000nm. Therefore, the particles sized which are in the range of 800 – 10000nm are above the range of EEPS and MSS, these particles with larger diameter contribute extra mass compared to other instruments, this makes ELPI to record more Avg total Particle Mass Concentration ($TPMC_{Avg}$) than EEPS and MSS shown in figure 6.3 & 6.4.

In order to eradicate the above-mentioned problem, the range of ELPI is reduced to 6 – 743 nm (which will be explained clearly in the chapter 6.1.6.1), then it is comparable with EEPS and MSS. The repeatability between each instrument is satisfying in all fuels with 3 instruments but there is no good consistency between the experiments which are conducted by the EEPS instrument with gasoline fuel in both cold start and warm start conditions. In figure 6.5 & 6.6 even though after deleting the PMC from channels above 743 nm, Avg Total Particle Mass Concentration ($TPMC_{Avg}$) recorded by MSS is less compared to EEPS and ELPI, there are 2 reasons behind this inconsistency they are:

I. MSS works under principle of absorbing laser light, if the particle is very small then the particle doesn't absorb enough light, therefore the Avg Total Particle Mass Concentration ($TPMC_{Avg}$) is low.

II. MSS detects soot (black carbon) but not volatile materials, therefore MSS is not sensitive to the semi volatile (or) organic fractions of particulate matter.

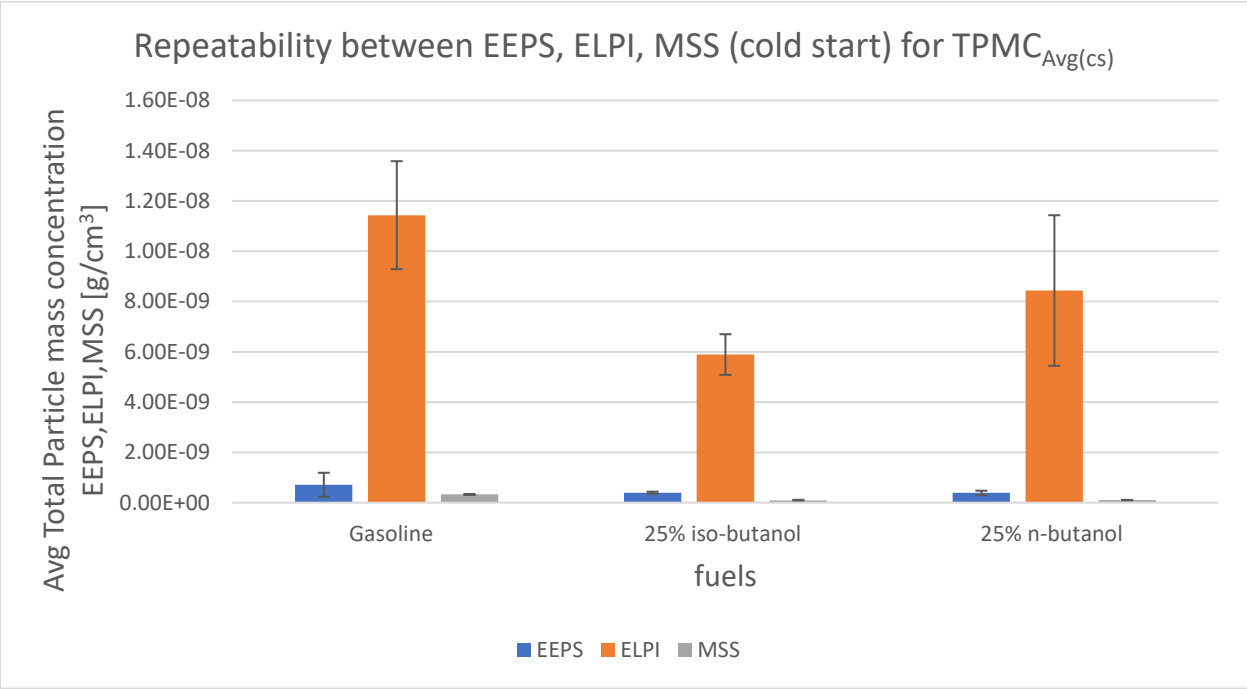

Figure 6.3 Repeatability of Avg Total Particle Mass Concentration between instruments in cold start conditions (ELPI range of 6-10000nm)

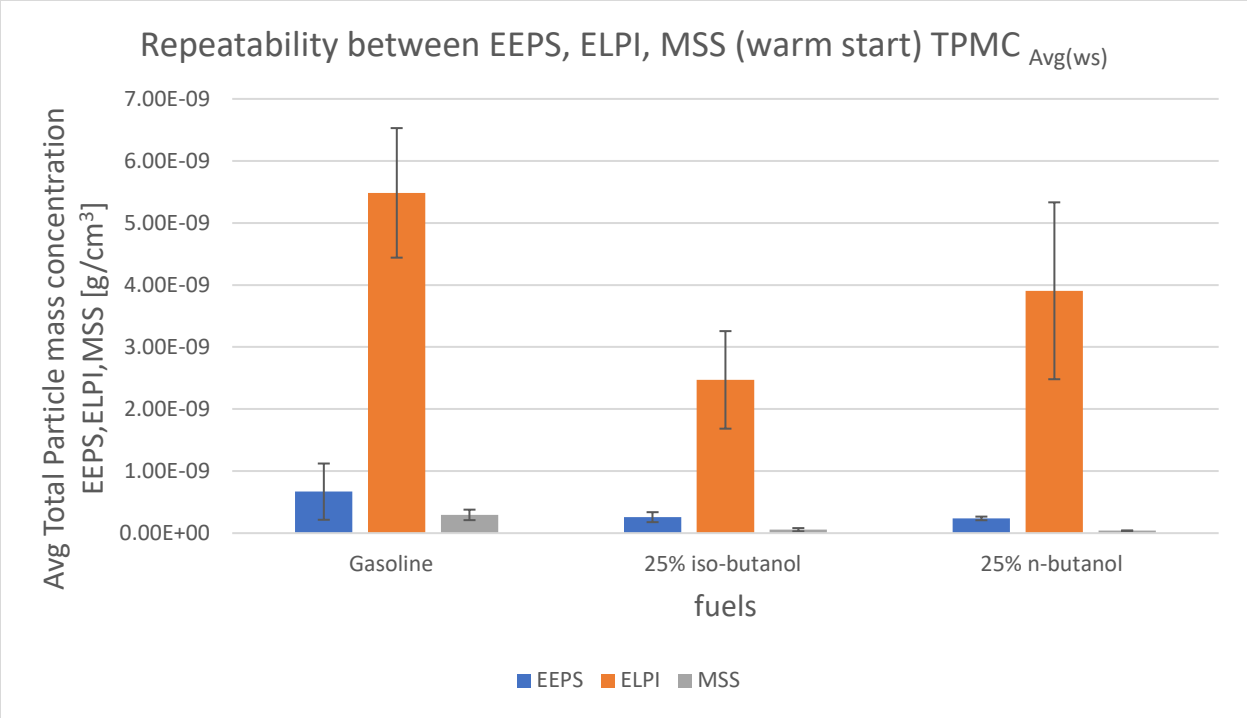

Figure 6.4 Repeatability of Avg Total Particle Mass Concentration between instruments in warm start conditions (ELPI range of 6-10000nm)

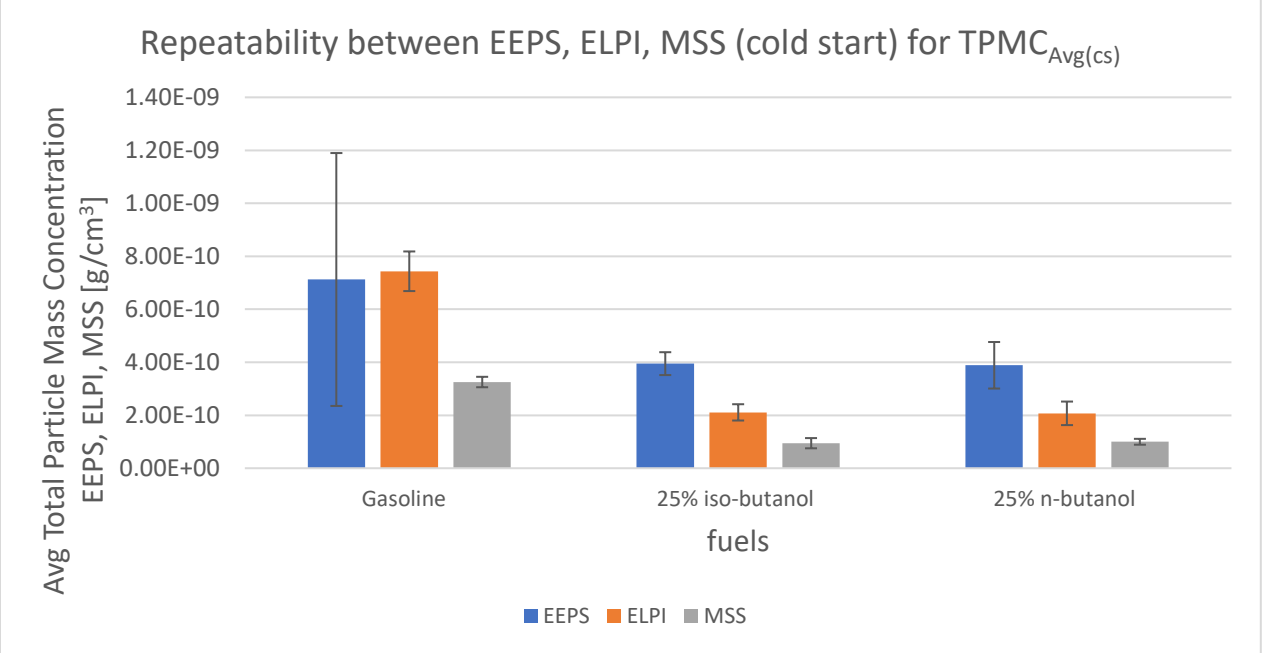

Figure 6.5 Repeatability of Avg Total Particle Mass Concentration between instruments in cold start conditions (ELPI range of 6-743nm)

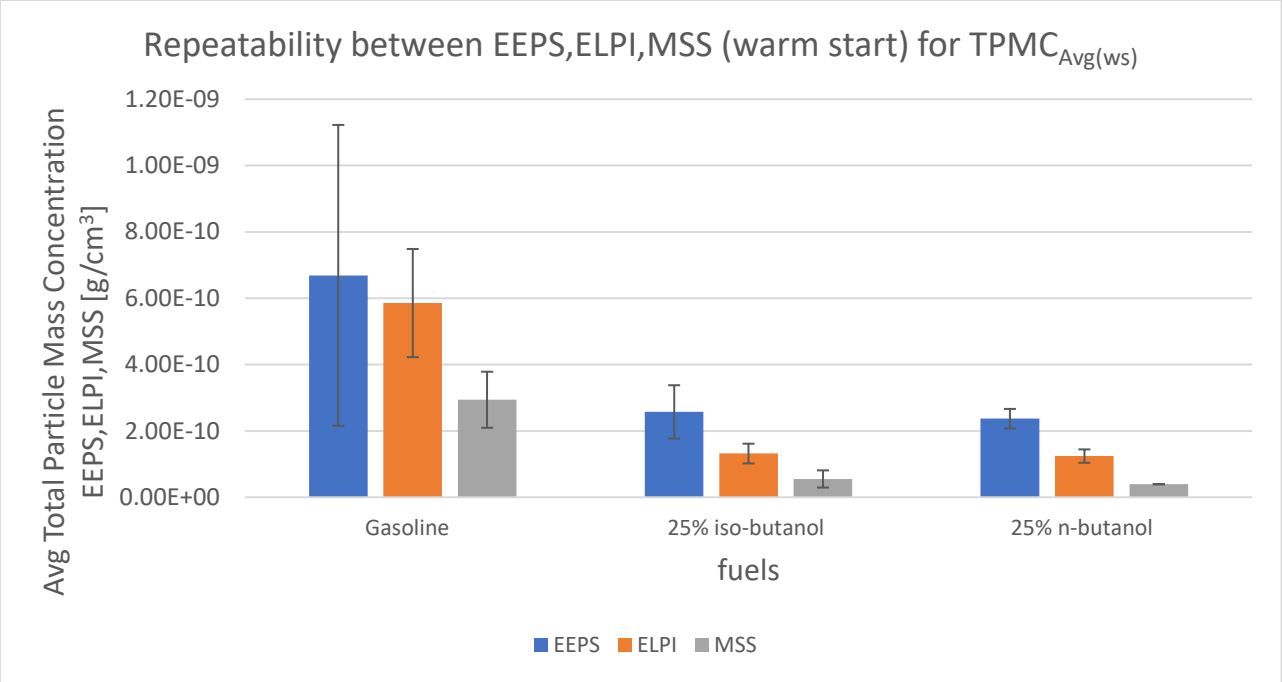

Figure 6.6 Repeatability of Avg Total Particle Mass Concentration between instruments in warm start conditions (ELPI range of 6-743nm)

6.1.3 Comparison between the instruments for the Repeatability of segments in WLTC

The purpose of repeatability between instruments for WLTC segments is to ensure, whether that the inconsistency between the instruments is caused in the segments which are involved in WLTC cycle i.e. (if the variance is high for an instrument using specific fuel, one has to check the reason behind high variance is because of the wrong installation of instrument, may be leakages in the sampling line, or because of the hard accelerations and running the engine in very high speed which are different phases involved in the segments of WLTC).

Ideally in the cold start condition more particles are produced from an engine due to rich air-fuel mixture. The Low speed segments is comprising of high acceleration modes compared to the remaining segments, where one can observe in figures 6.7, 6.8, 6.9 the Avg Total Particle Number Concentration ($TPNC_{Avg\ (cs)}$) in Low speed segments are higher than remaining segments. Whereas in the warm start conditions it is not the case because

already the engine is in good enough temperatures which doesn't require rich air-fuel mixtures.

In figures 6.7, 6.8, 6.9 there are high variances in the test conducted using Gasoline fuel only for the EEPS instrument compared to ELPI. But whereas with the remaining 2 fuels (25% iso-butanol & 25% n-butanol) are having good consistencies between the experiments.

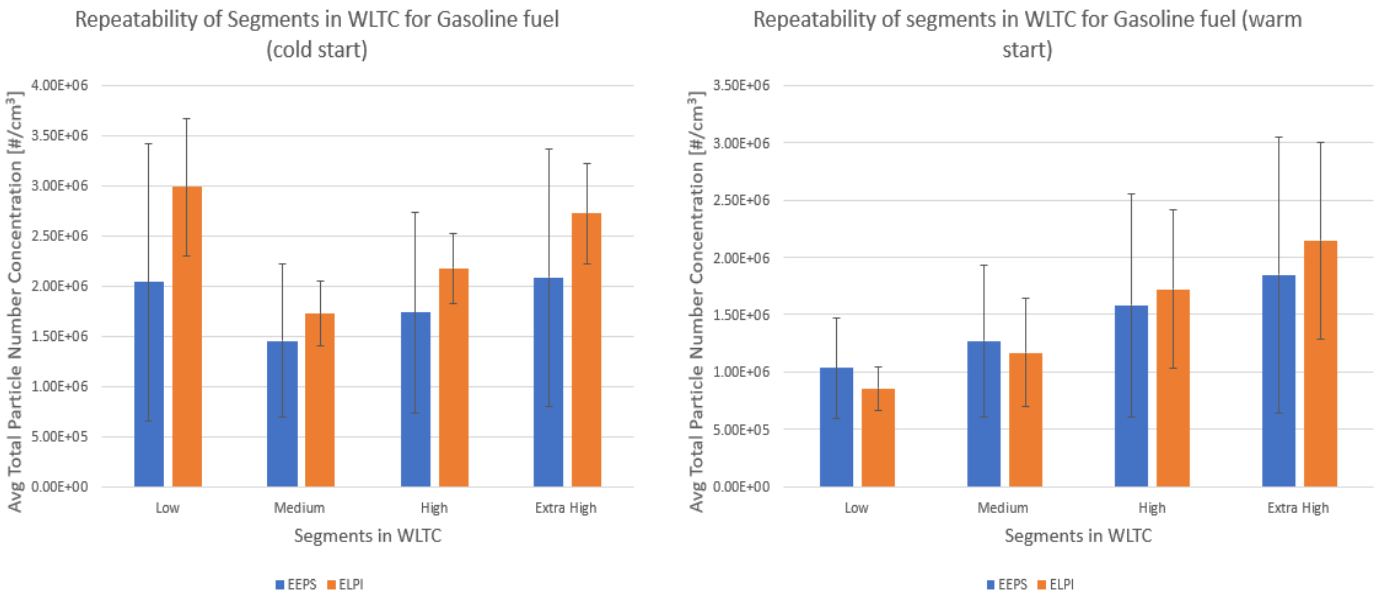

Figure 6.7 Repeatability of segments in WLTC for Gasoline (cold start and warm start conditions)

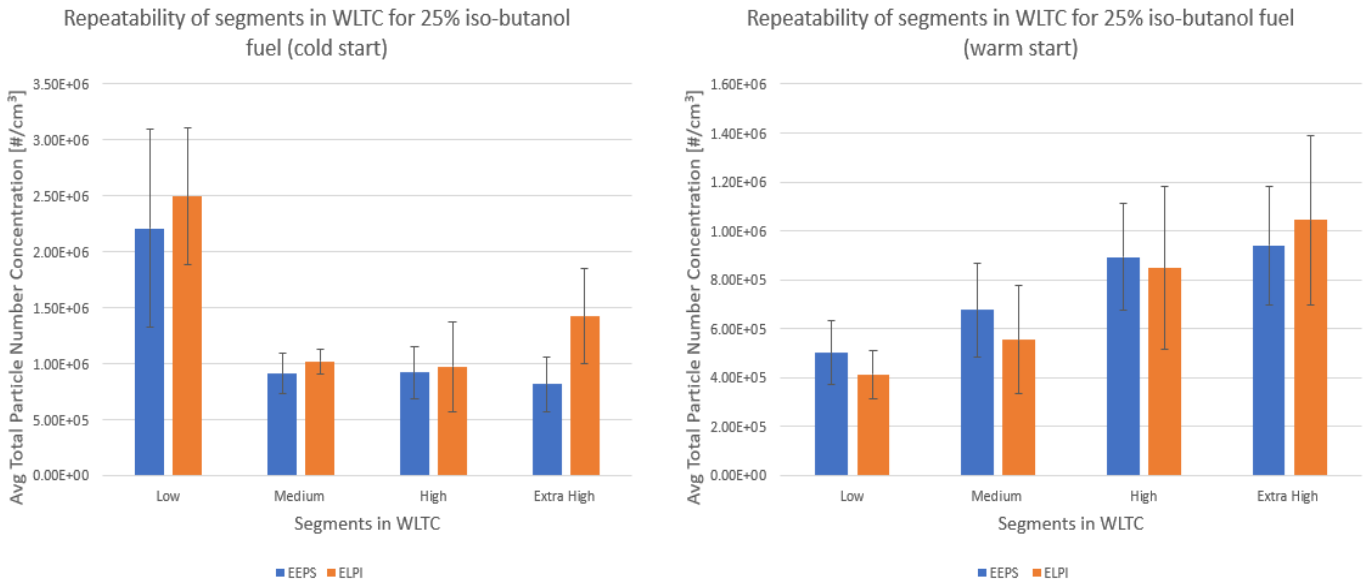

Figure 6.8 Repeatability of segments in WLTC for 25% iso-butanol (cold start and warm start conditions)

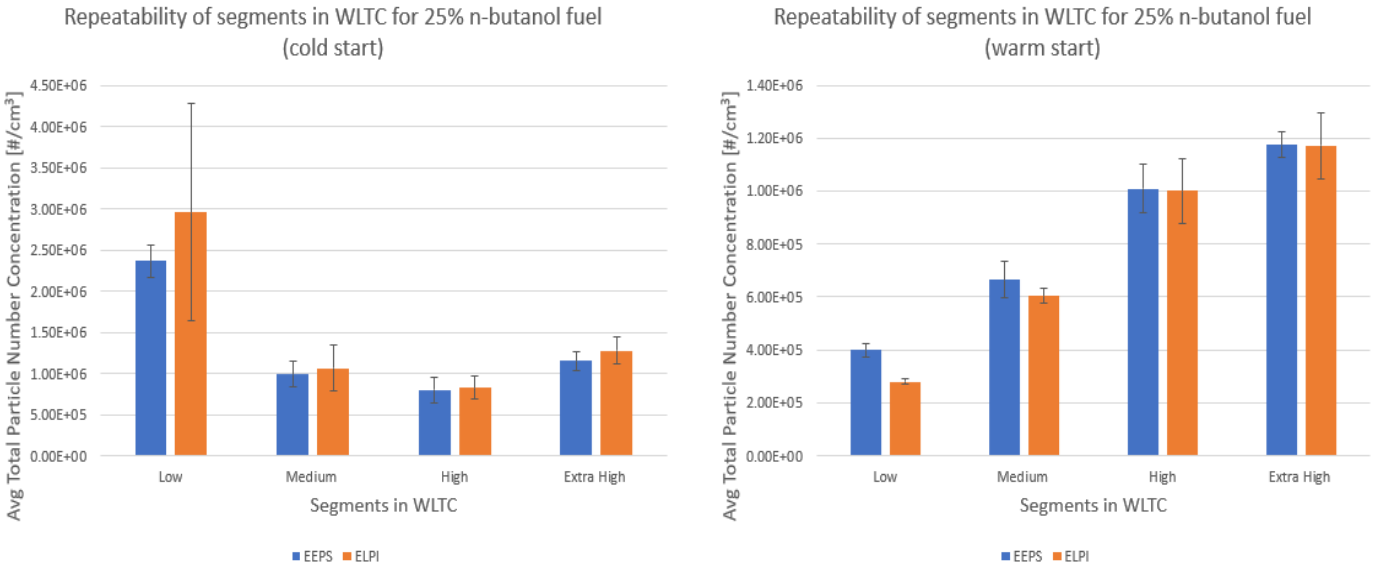

Figure 6.9 Repeatability of segments in WLTC for 25% n-butanol (cold start and warm start conditions)

6.1.4 Comparison between instruments for Repeatability of PNC in different channels

The repeatability of Particle Number Concentration (PNC) in different channels contributes the production of different size particles with respect to channels of EEPS & ELPI, the variance in the different channels explains the consistency of each day when the experiment had conducted. It is very evident that there no good consistency between the experiments with respect to the channel sizes for EEPS instrument and Gasoline fuel which is shown in figure 6.10 & 6.11.

The graph shown in figure 6.10 & 6.11 of EEPS is formed in combination of experiments conducted in 5 days (26, 27, 28, 29, 30 August respectively). The graphs which are having good agreement between the experiments are considered to be consistent (26,27 August) remaining graphs are outliers (28,29,30 August) which are shown in the figures 6.16 & 6.17. This is also for the inconsistency raised in the Total Particle Number Concentration (TPNC) for EEPS in both cold start and warm start conditions mentioned in chapter 6.1.1.

There 3 different factors which are affecting the consistency between the experiments in EEPS instrument they are

I. An artefact in measurement.
II. Not warming up the instruments up to suitable temperatures.
III. The measurements of exhaust gases in EEPS are performed at low temperatures, this condition is very suitable for detection of volatile particles.

The variance in channels with respect to channels in remaining all figures are satisfying, but the figure 6.12 is best variance recorded compared to remaining results which are obtained.

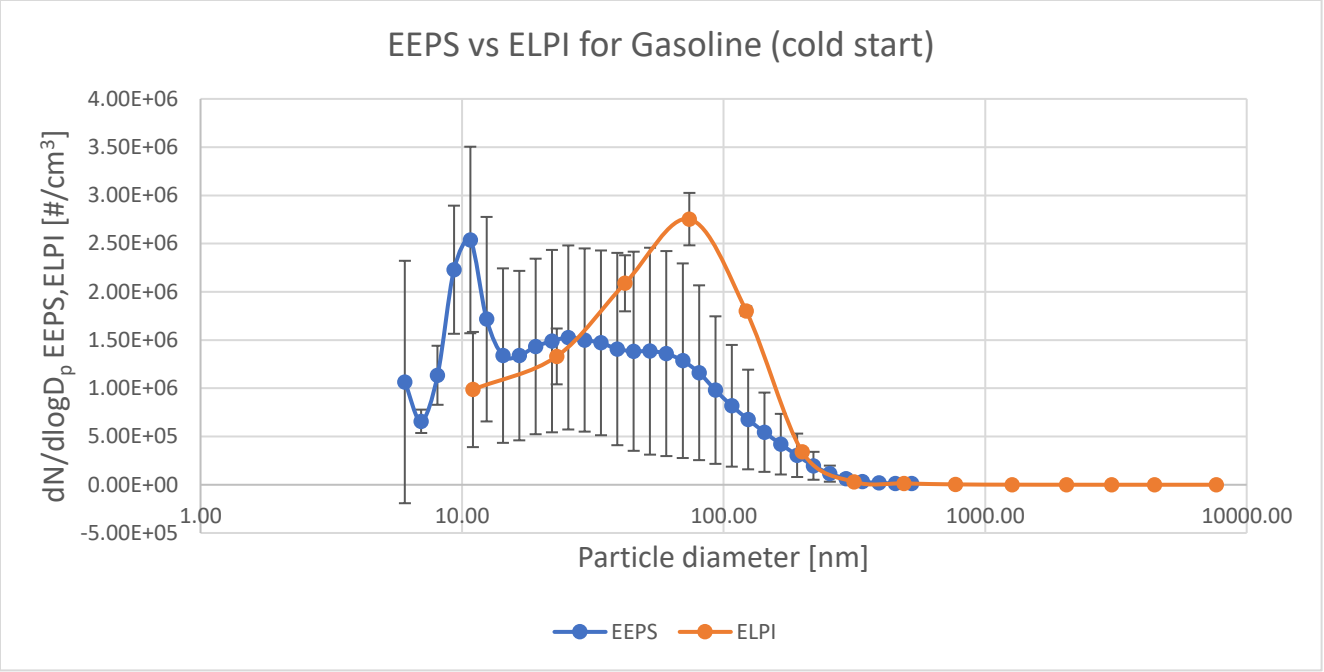

Figure 6.10 Repeatability of PNC in the channels between instruments for Gasoline fuel (cold start)

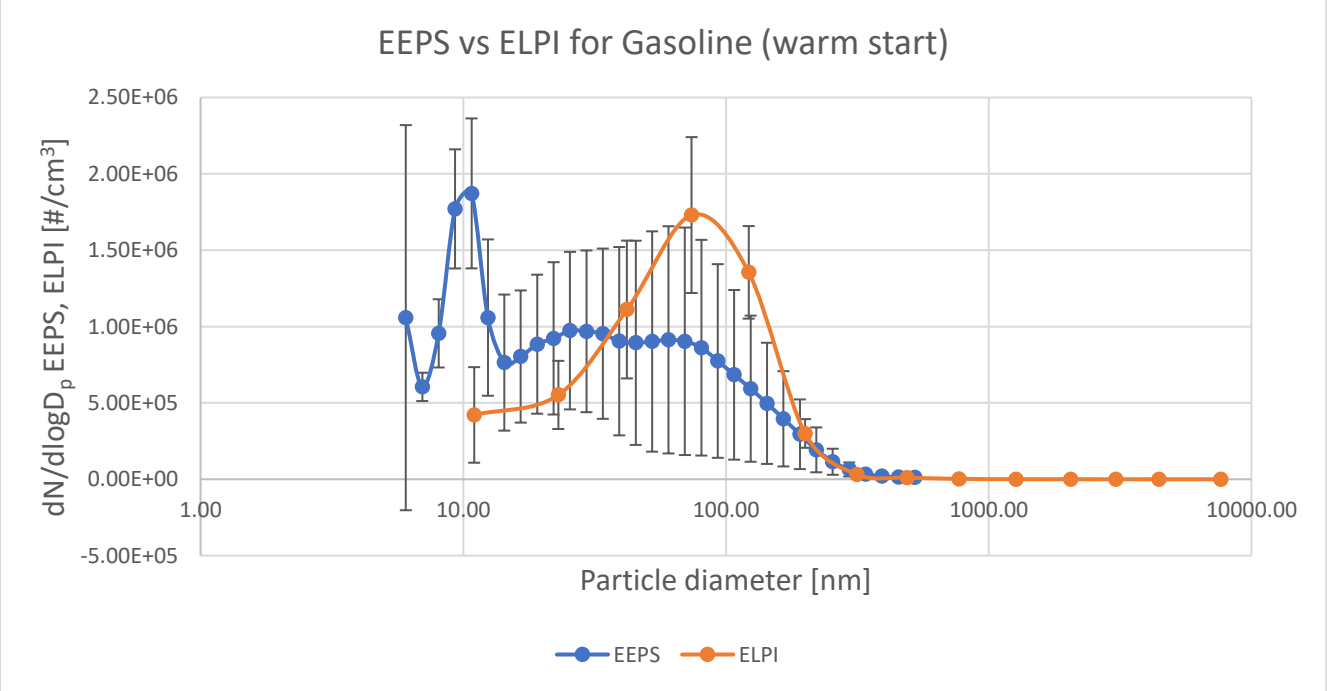

Figure 6.11 Repeatability of PNC in the channels between instruments for Gasoline fuel (warm start)

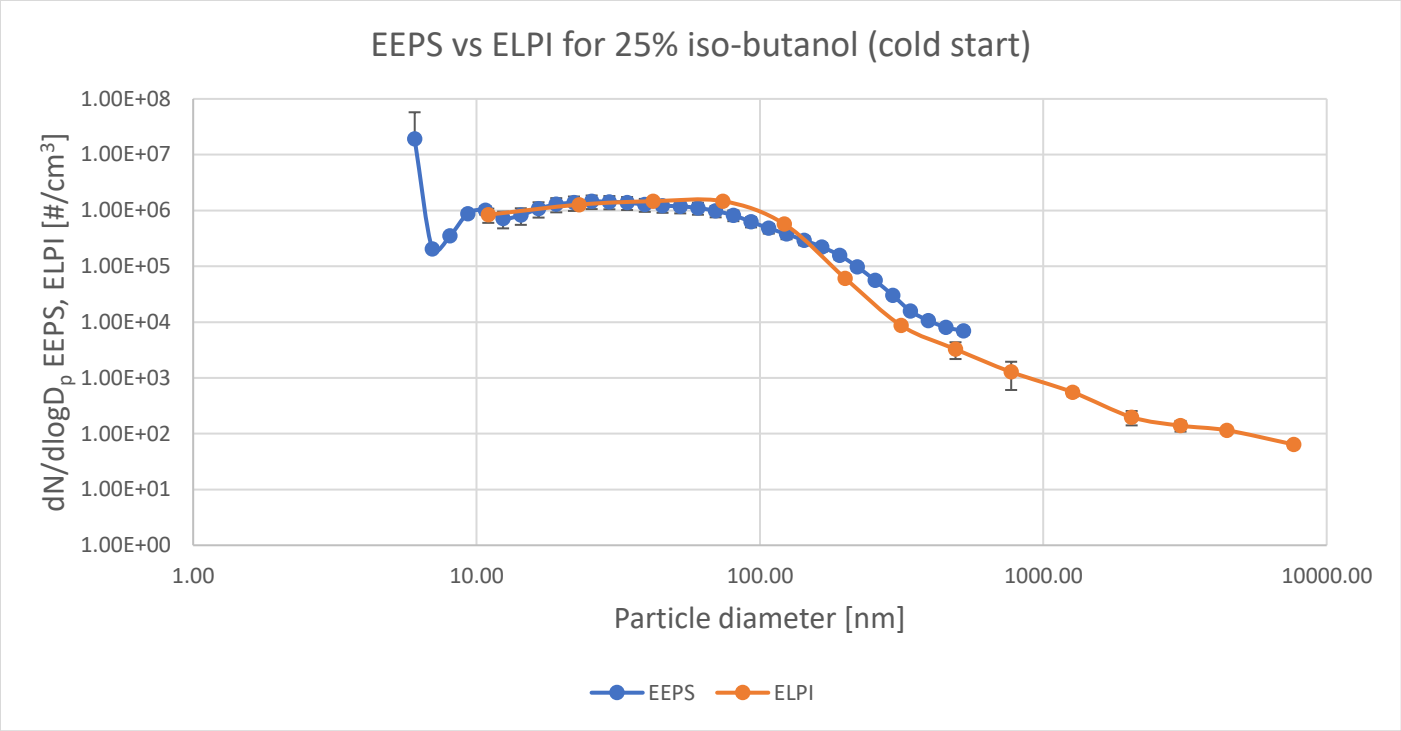

Figure 6.12 Repeatability of PNC in the channels between instruments for 25% iso-butanol fuel (cold start)

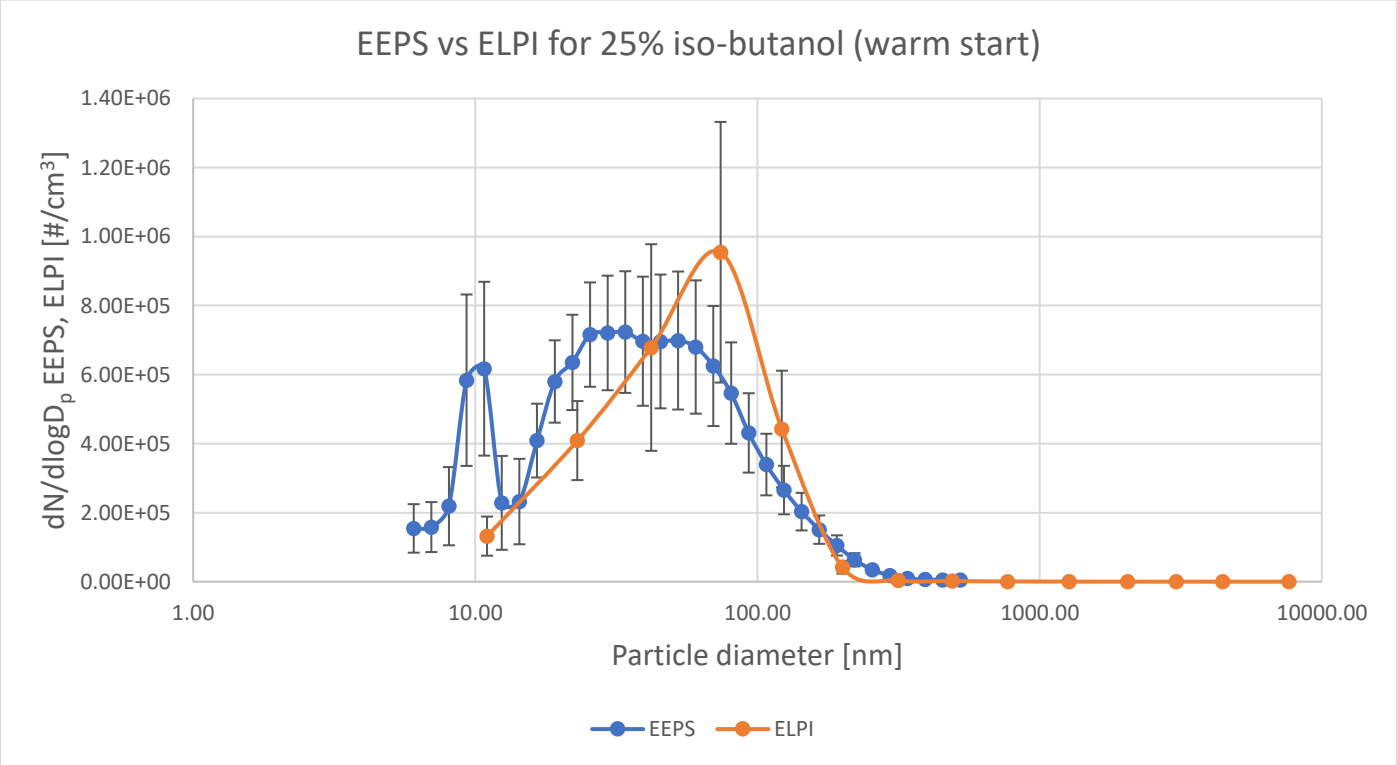

Figure 6.13 Repeatability of PNC in the channels between instruments for 25% iso-butanol fuel (warm start)

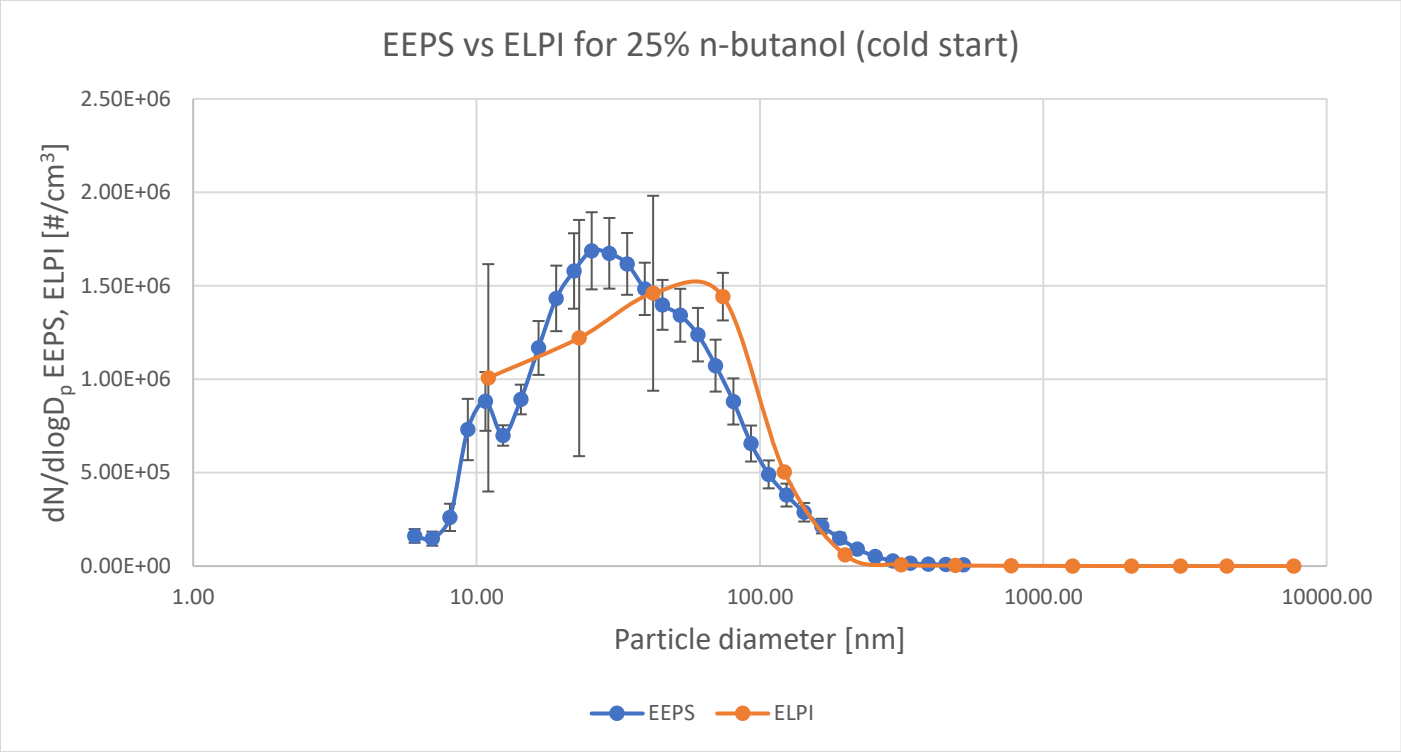

Figure 6.14 Repeatability of PNC in the channels between instruments for 25% n-butanol fuel (cold start)

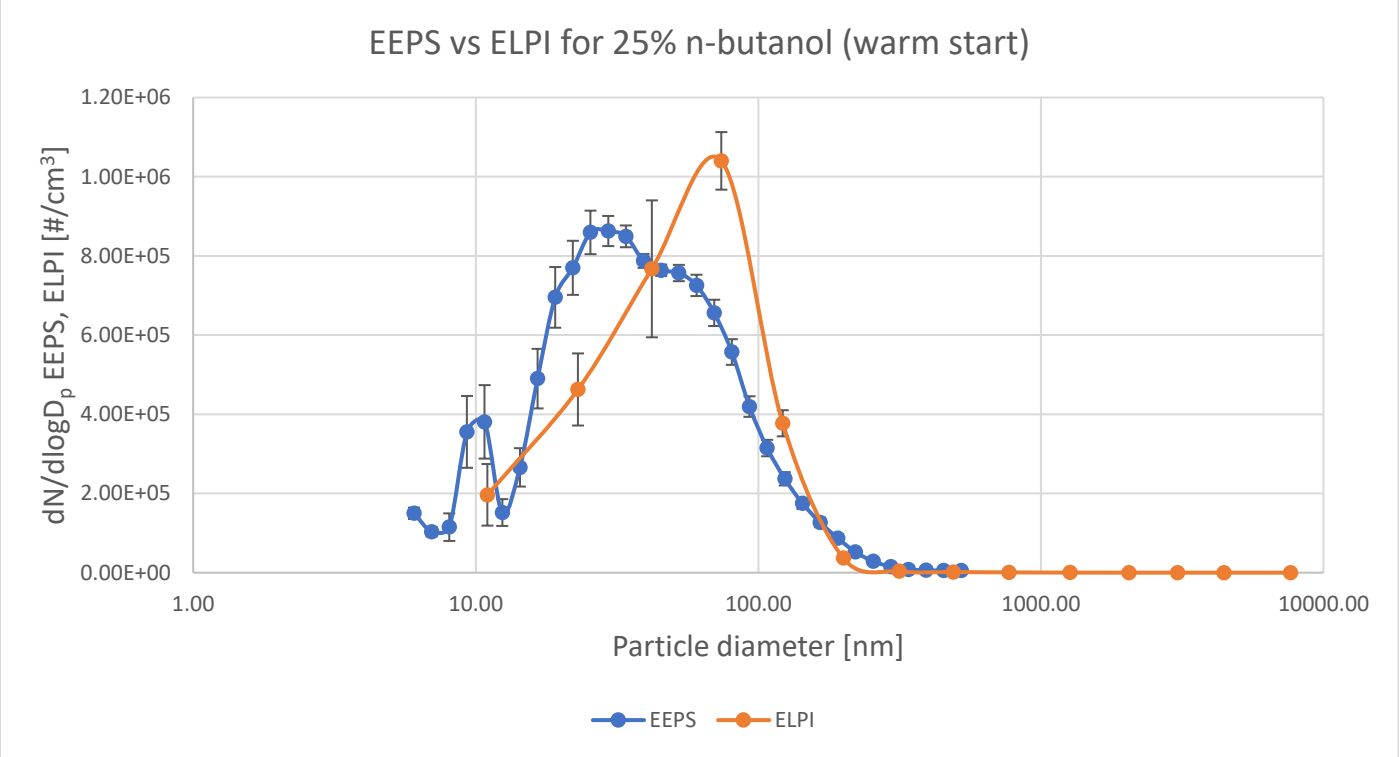

Figure 6.15 Repeatability of PNC in the channels between instruments for 25% n-butanol fuel (warm start)

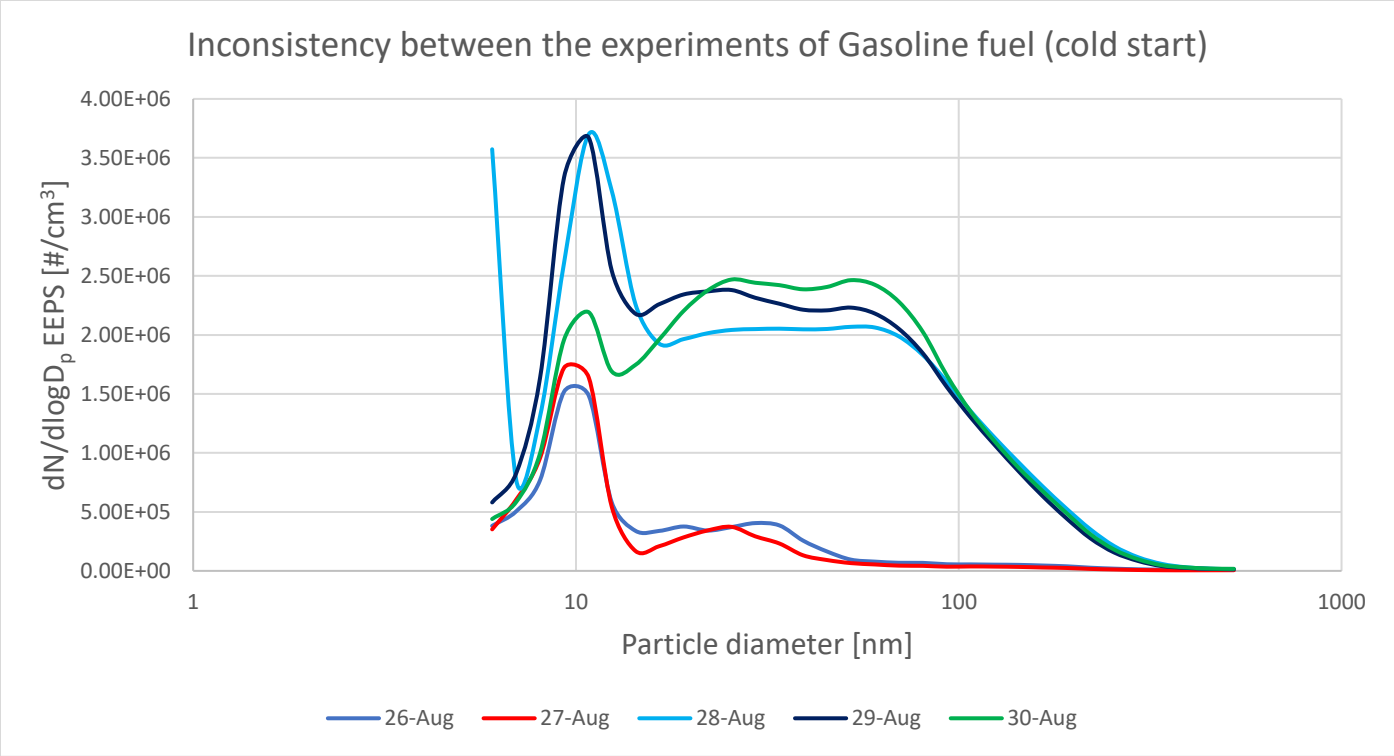

Figure 6.16 The inconsistency between experiments from EEPS for Gasoline fuel (cold start)

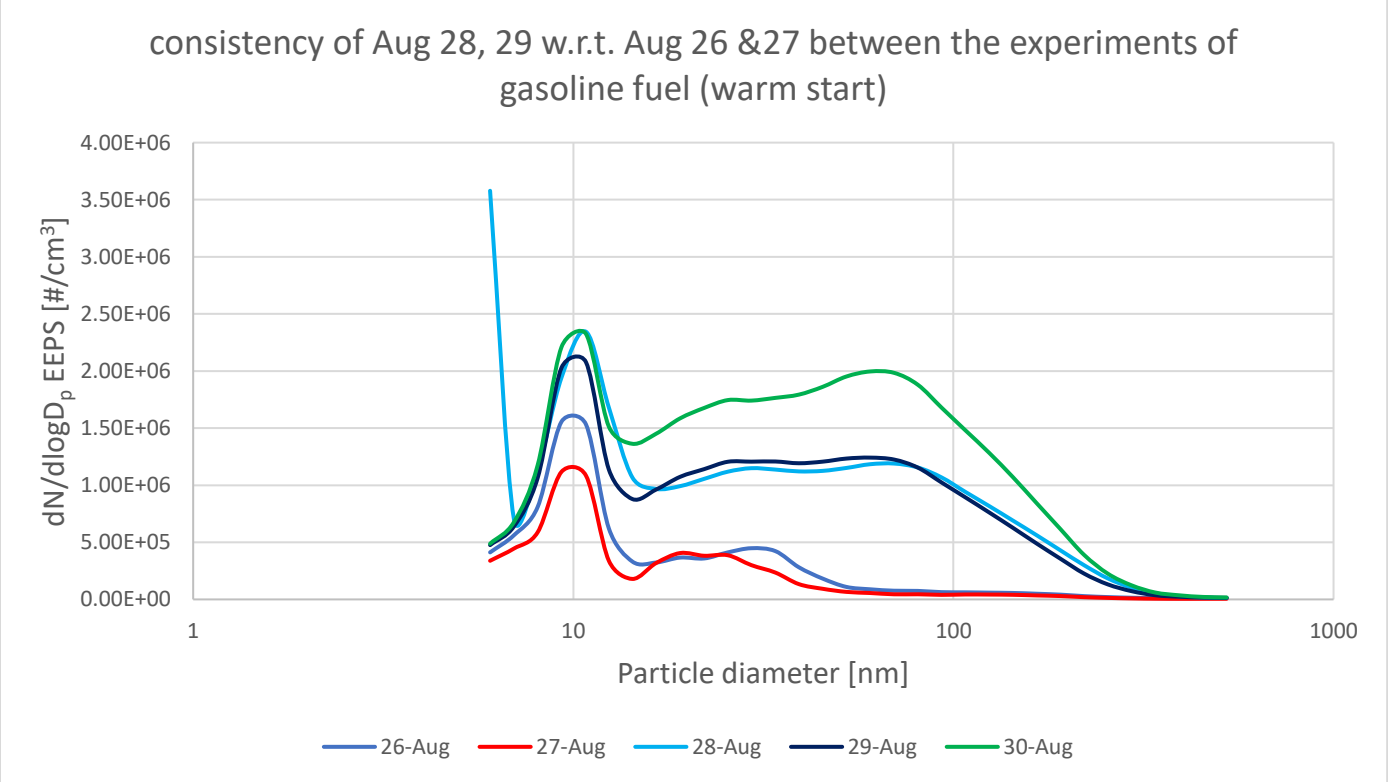

Figure 6.17 The inconsistency between experiments from EEPS for Gasoline fuel (warm start)

6.1.5 Comparison of Size Distribution between the instruments

The first observation made in all the figures in this section is the difference in range of the instruments (EEPS [5.6-560nm] & ELPI [6-10000nm]). The accumulation of particles with different sizes in channels with respect to their sizes are low in warm start compared to cold start in both EEPS and ELPI. There are few disagreements of Particle Number Concentration (PNC) in channels observed between the instruments. In figure 6.18, 6.19 (Gasoline fuel) there is a raise of PNC in the Nuclei mode (D_p< 50 nm) in both cold start and warm start conditions with EEPS , whereas with ELPI in figure 6.18 (cold start) the high PNC from the particles with smaller diameter (from 11 nm) but in figure 6.19 (warm start) the PNC less in Nuclei mode compared to Accumulation mode.

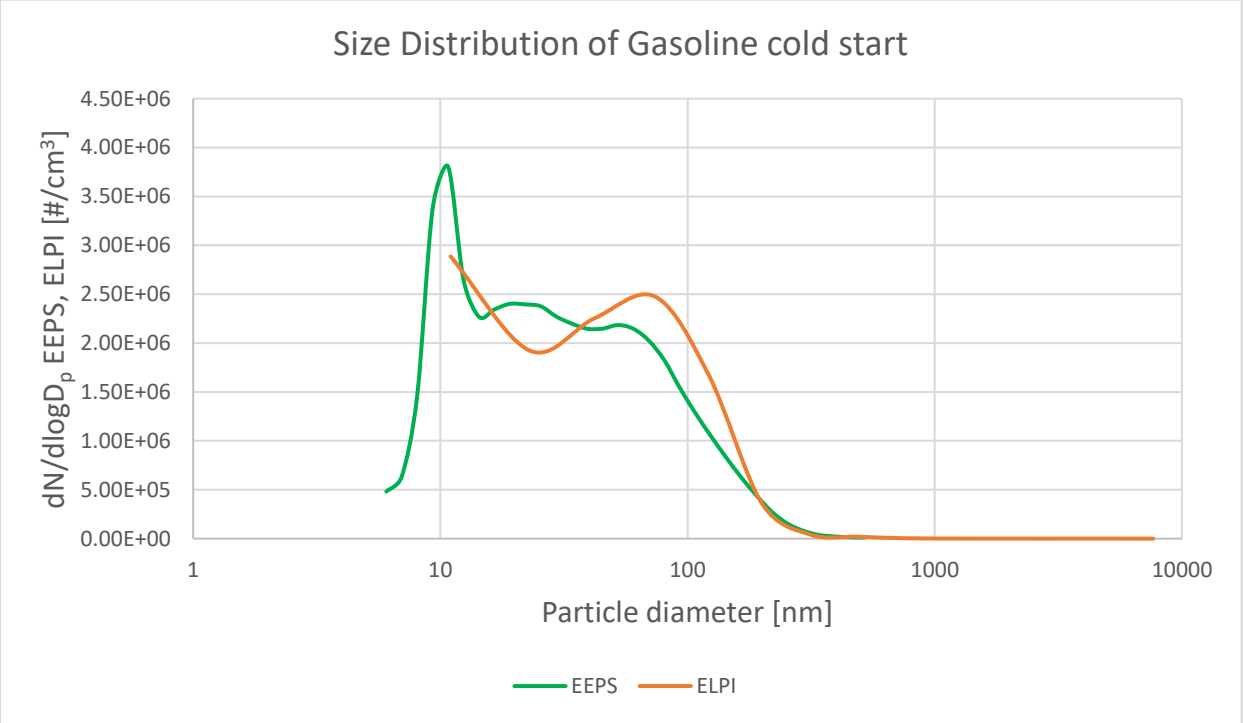

Figure 6.18 Comparison of size distributions between EEPS & ELPI for Gasoline fuel in cold start condition

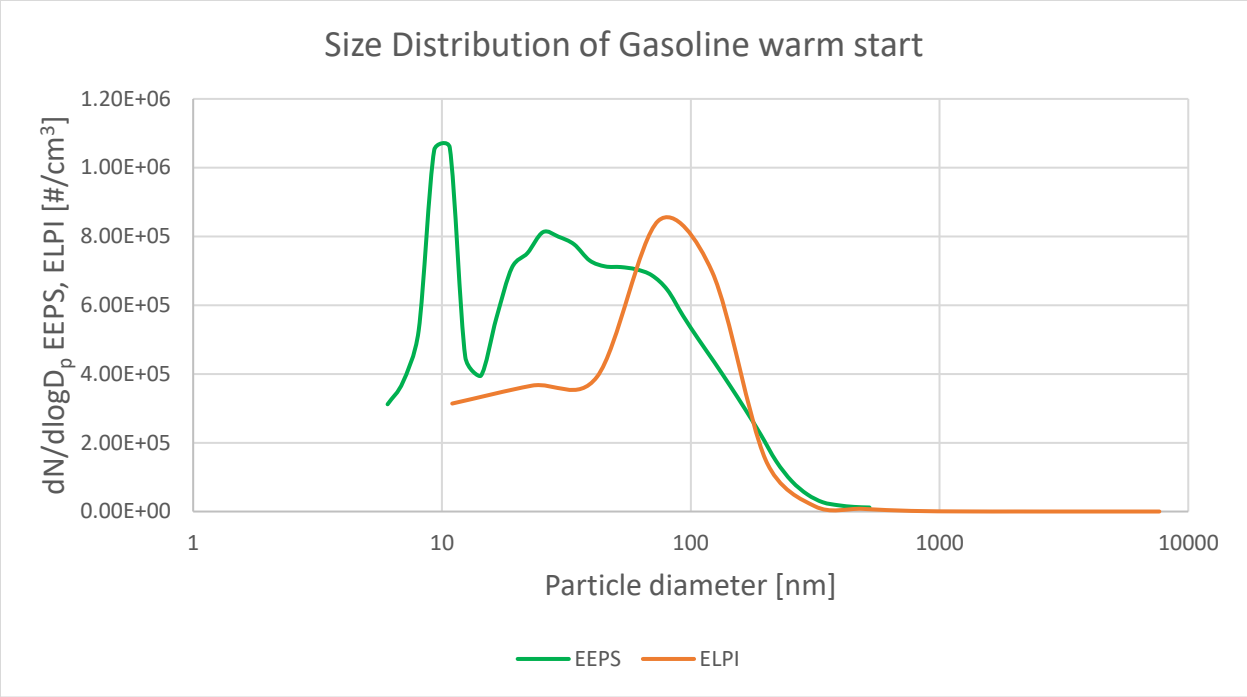

Figure 6.19 Comparison of size distributions between EEPS & ELPI for Gasoline fuel in warm start condition

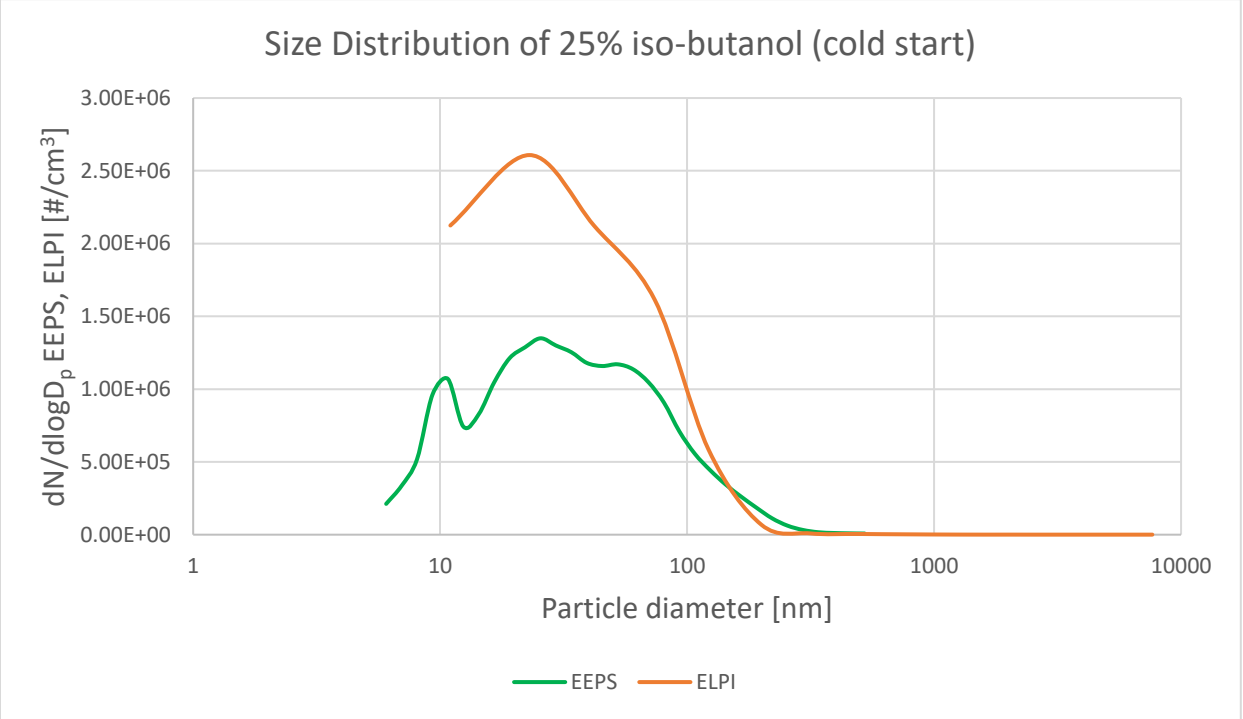

Figure 6.20 Comparison of size distributions between EEPS & ELPI for 25% iso-butanol fuel in cold start condition

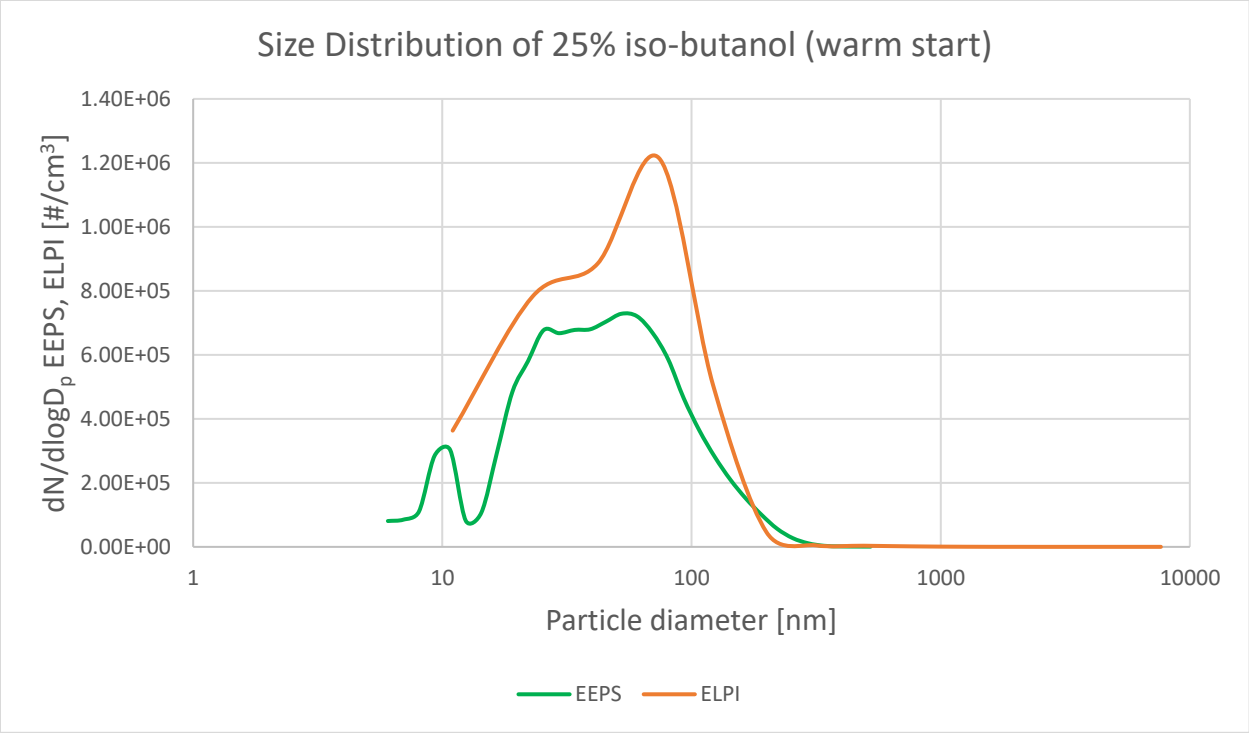

Figure 6.21 Comparison of size distributions between EEPS & ELPI for 25% iso-butanol fuel in warm start condition

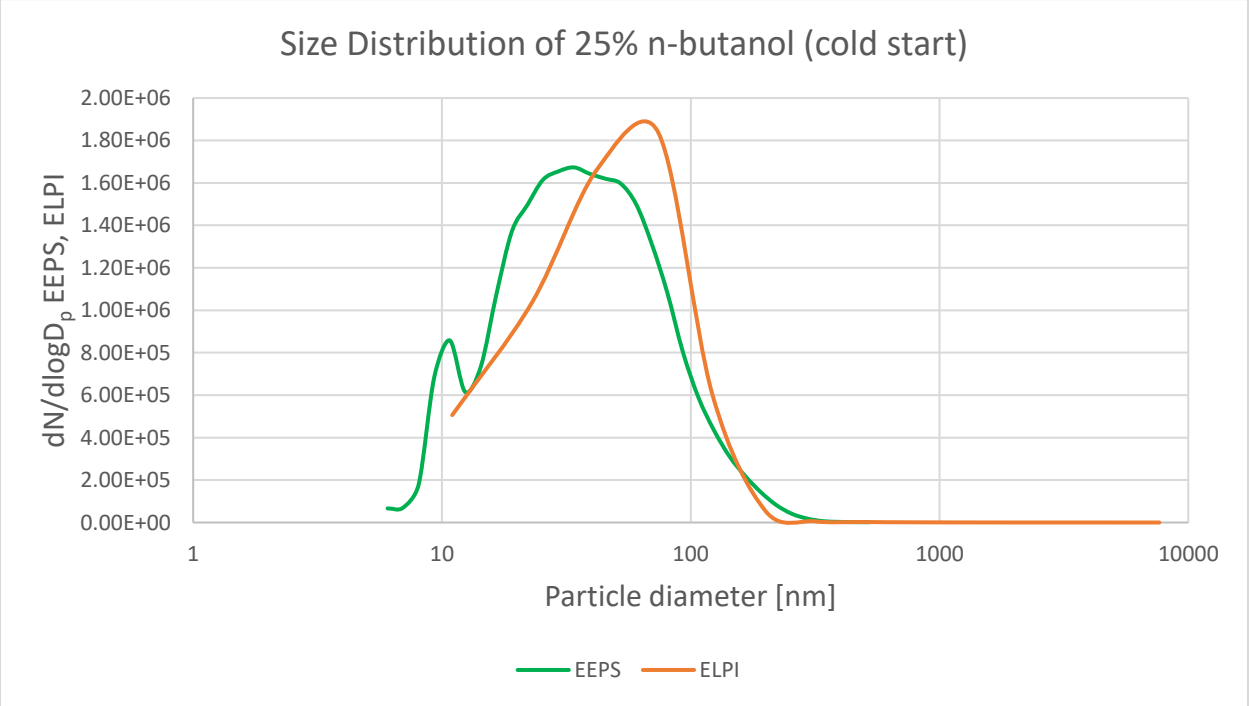

Figure 6.22 Comparison of size distributions between EEPS & ELPI for 25% n-butanol fuel in cold start condition

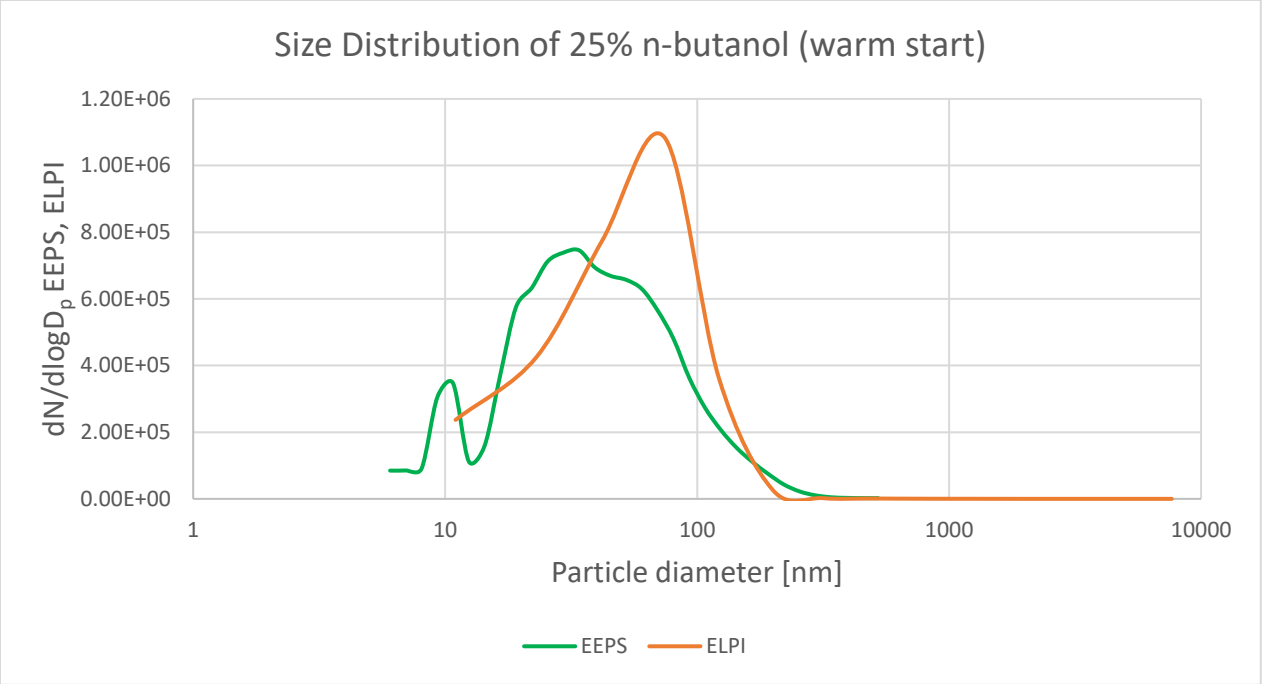

Figure 6.23 Comparison of size distributions between EEPS & ELPI for 25% n-butanol fuel in warm start condition

6.1.6 Comparison of Mass Distributions between the instruments

The primary observation regarding the mass distribution graphs in this section is that all the graphs are following same trend, therefore it is said to be the instruments are in good agreement with each other. There is presence of both modes Accumulation mode and coarse mode in all figure in this section but there are differences in their magnitudes depending on the fuels used, in the figure 6.2 & 6.29 (25% n-butanol fuel) one can observe the Particle Mass Concentration (PMC) low in Accumulation mode and coarse mode compared to other fuels in cold start & warm start conditions. From figures 6.24 & 6.25 the Gasoline fuel producing more ultra-fine particles (D_p<100 nm) which contribute more Particle Mass Concentration compared to other fuels.

The graphs obtained from ELPI are comparable with EEPS after eliminating the Particle Mass which is accumulated in the channels above 743 nm which is explained in the chapter 6.1.6.1.

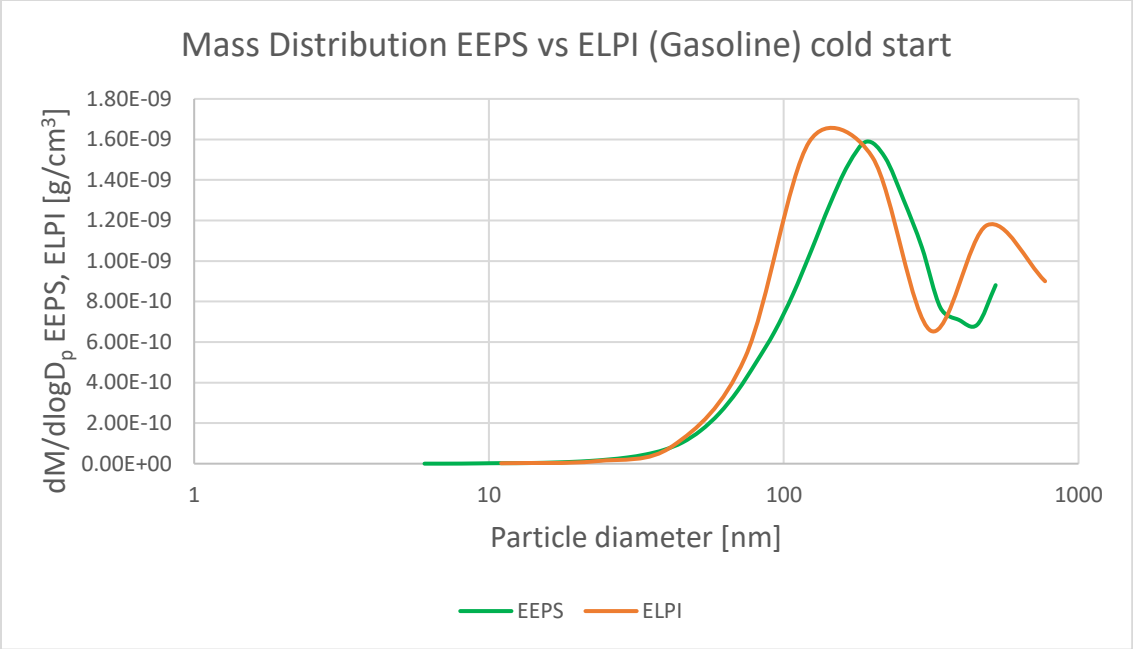

Figure 6.24 Comparison of Mass Distributions between EEPS & ELPI for Gasoline fuel (cold start)

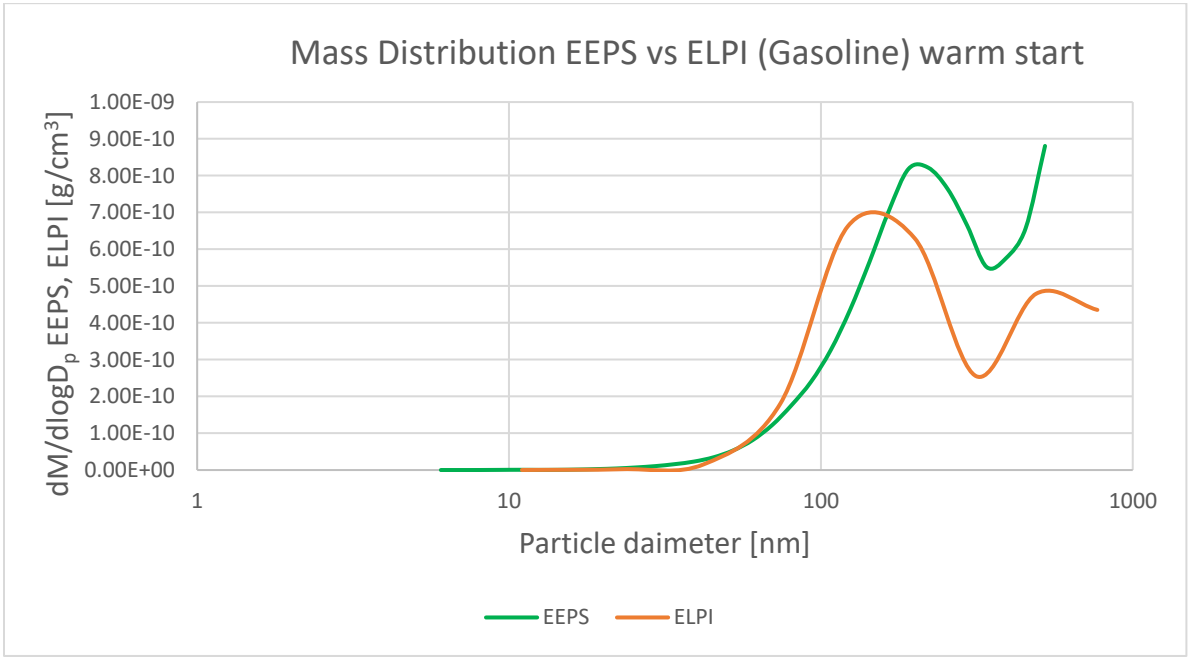

Figure 6.25 Comparison of Mass Distributions between EEPS & ELPI for Gasoline fuel (warm start)

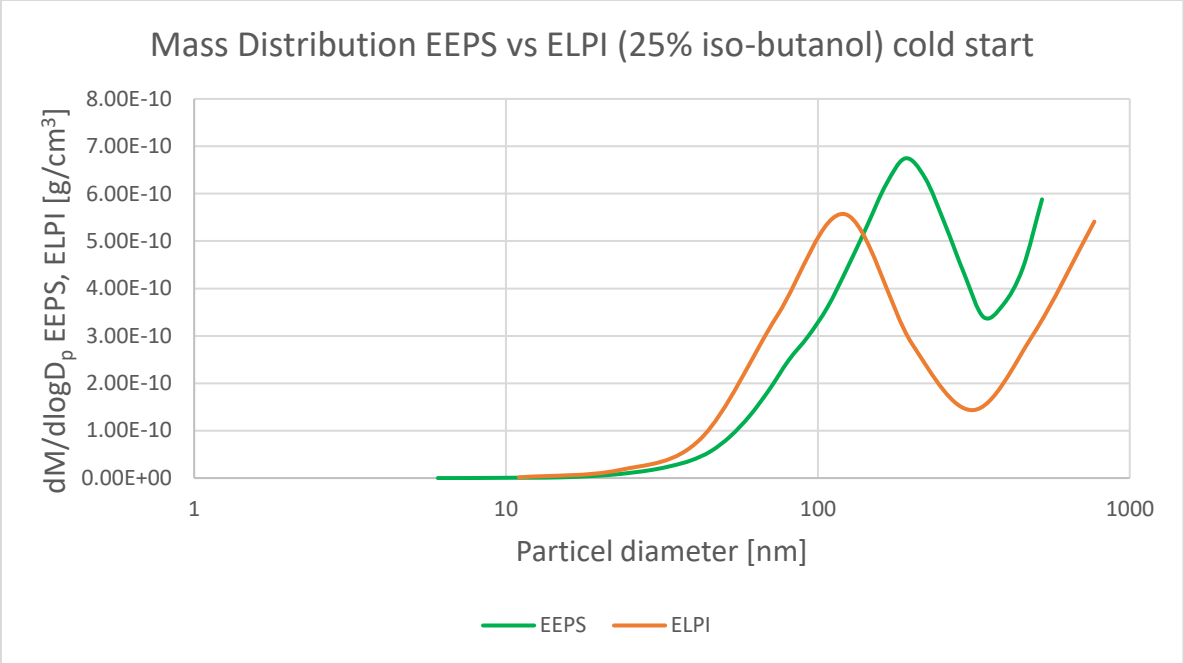

Figure 6.26 Comparison of Mass Distributions between EEPS & ELPI for 25% iso-butanol fuel (cold start)

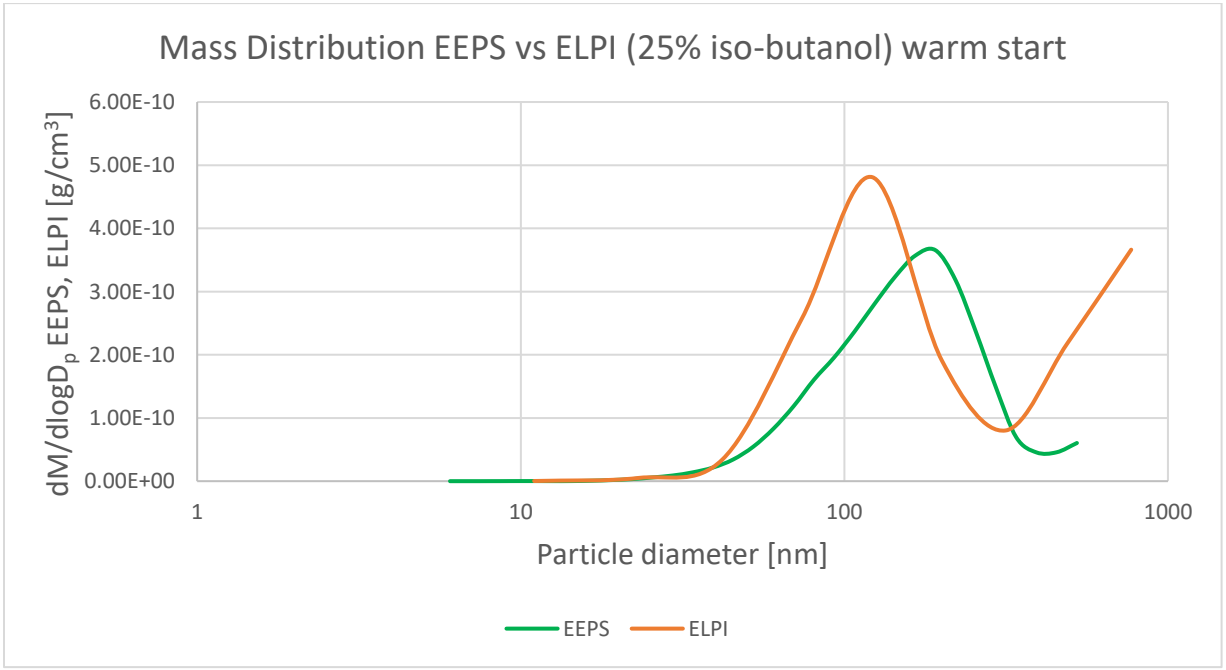

Figure 6.27 Comparison of Mass Distributions between EEPS & ELPI for 25% iso-butanol fuel (warm start)

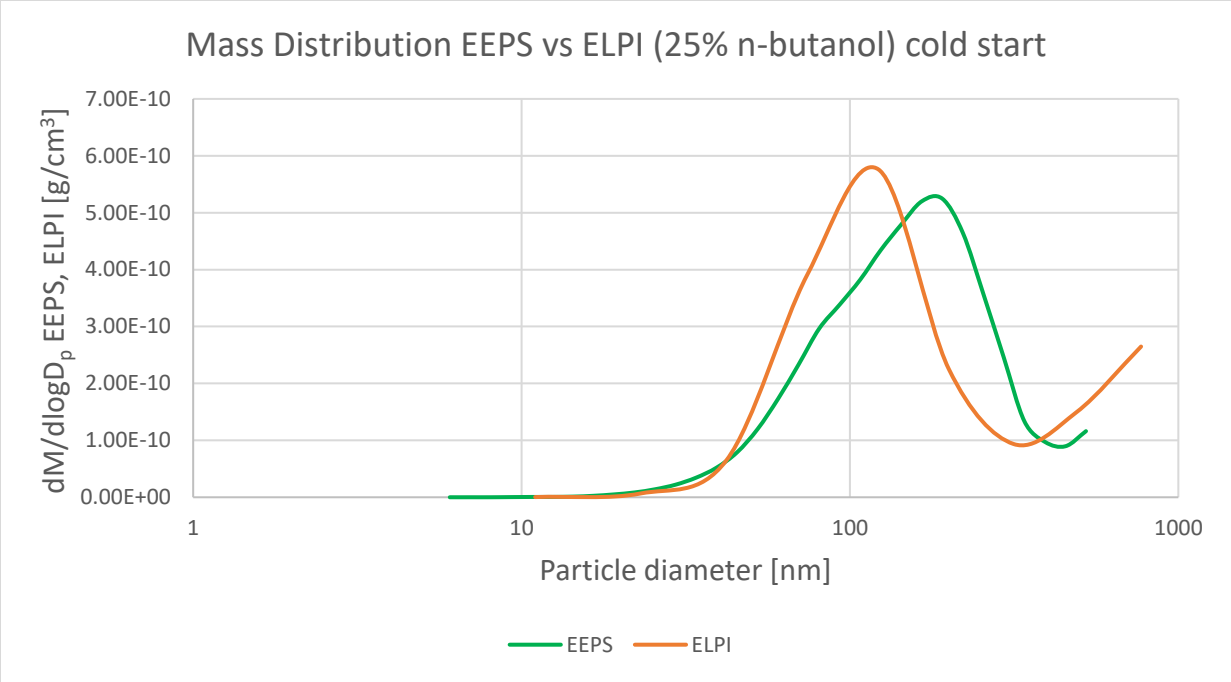

Figure 6.28 Comparison of Mass Distributions between EEPS & ELPI for 25% n-butanol fuel (cold start)

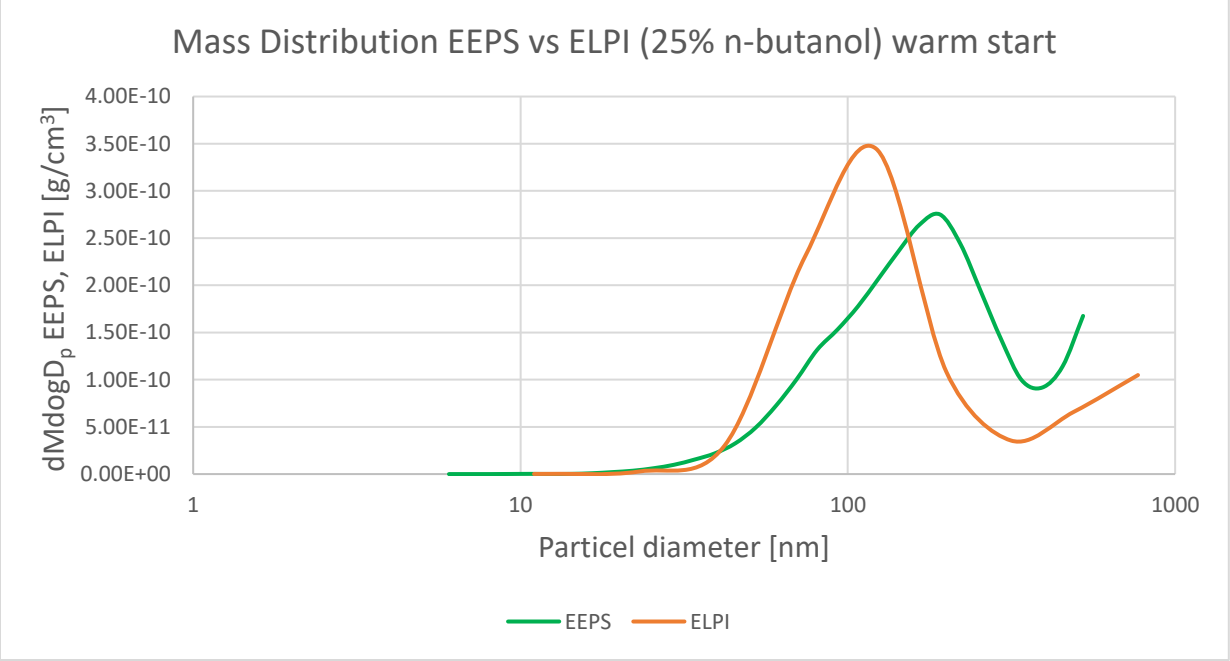

Figure 6.29 Comparison of Mass Distributions between EEPS & ELPI for 25% n-butanol fuel (warm start)

6.1.6.1 Elimination of the Particle Mass which is accumulated in the channels above 743 nm

Ideally when the comparison will be done between instruments with complete particle mass is accumulated in entire channels of EEPS and ELPI with difference in the range of the both instruments, the Particle Mass Concentration (PMC) in ELPI exceeds the Particle Mass Concentration (PMC) in EEPS which is shown the figure 6.30 therefore, it finally leads to increasing in the levels of Avg Total Particle Mass Concentration ($TPMC_{Avg}$).

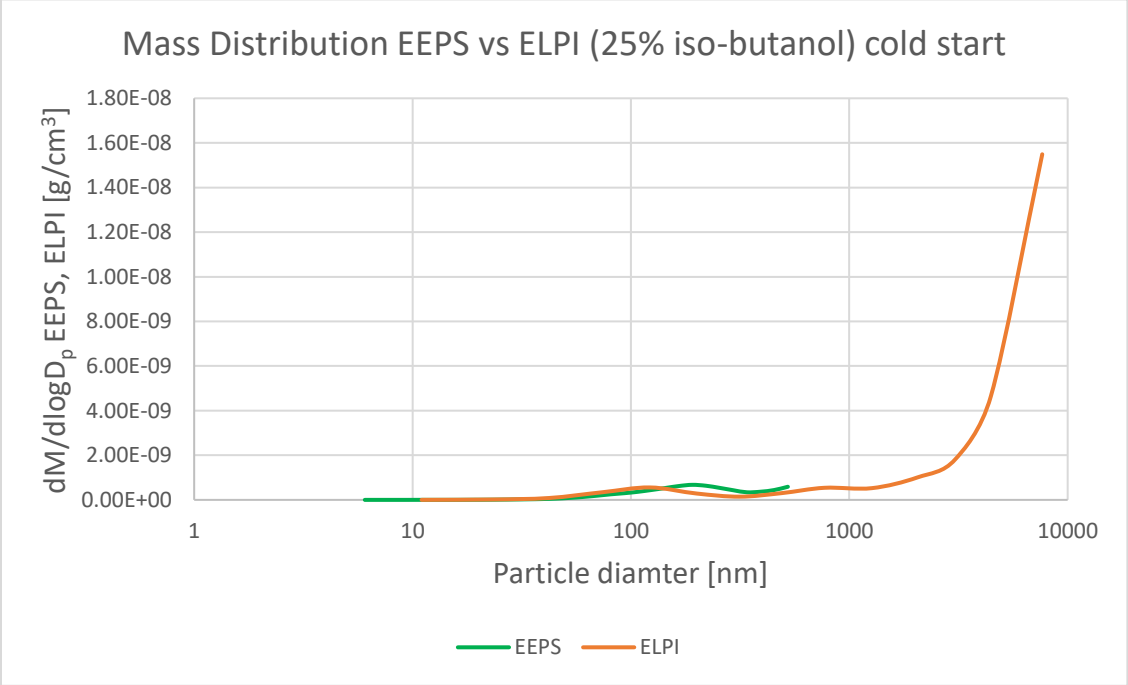

Figure 6.30 Comparison of Mass Distributions between EEPS & ELPI for 25% iso-butanol fuel (cold start) including all channels in ELPI

6.2 Effect of 25% iso-butanol and 25 % n-butanol relative to Gasoline

On conducting the experiments with 3 different fuels on 3 instruments one can say that the reduction of particle emission in percentages comparing the 25% iso-butanol & 25% n-butanol with the commonly used fuel in passenger vehicles (Gasoline) and also comparison between instrument to make sure that all the instruments are following same trend in particle emission.

From tables 6.1 to 6.2 it is observed that the all instruments shown the decrement of Avg Total Particle Number Concentration (TPNC) and Avg Total Particle Mass Concentration (TPMC) of 25% iso-butanol & 25% -butanol compared to gasoline by this decrement the instruments are consistent. The instruments show relatively small differences between 25% iso-butanol & 25% n-butanol. For both 25% iso-butanol & 25% n-butanol compared with gasoline, the evaluation done by the EEPS is different form the evaluation of ELPI in Avg TPNC. Whereas in Avg TPMC different evaluation is seen in 3 instruments.

Table 6.1 Percentage change of Avg TPNC of 25% iso-butanol and 25% n-butanol relative to gasoline fuel in cold start

Cold start					
Instrument	**Gasoline**	**25% iso-butanol**	**25% n-butanol**	**25 % iso-butanol change relative to Gasoline (%)**	**25 % n-butanol change w.r.t Gasoline (%)**
EEPS (#/cm^3)	1.83E+06	1.30E+06	1.36E+06	- 28.89	- 25.64
ELPI(#/cm^3)	2.43E+06	1.47E+06	1.41E+06	- 39.56	- 42.10

Table 6.2 Percentage change of Avg TPNC of 25% iso-butanol and 25% n-butanol relative to gasoline fuel in warm start

Warm start					
Instrument	**Gasoline**	**25% iso-butanol**	**25% n-butanol**	**25 % iso-butanol change relative to Gasoline (%)**	**25 % n-butanol change relative to Gasoline (%)**
EEPS (#/cm^3)	1.38E+06	6.78E+05	7.69E+05	- 50.73	- 44.14
ELPI(#/cm^3)	1.38E+06	5.37E+05	6.66E+05	- 61.14	- 51.75

Table 6.3 Percentage change of Avg TPMC of 25% iso-butanol and 25% n-butanol relative to gasoline fuel in cold start

Cold start					
Instrument	**Gasoline**	**25% iso-butanol**	**25% n-butanol**	**25 % iso-butanol change relative to Gasoline (%)**	**25 % n-butanol change relative to Gasoline (%)**
EEPS (g/cm^3)	7.12E-10	3.95E-10	3.89E-10	- 44.58	- 45.45
ELPI(g/cm^3)	7.44E-10	2.11E-10	2.07E-10	- 71.64	- 72.13
MSS (g/cm^3)	3.25E-10	9.45E-11	9.99E-11	- 70.96	- 69.31

Table 6.4 Percentage change of Avg TPMC of 25% iso-butanol and 25% n-butanol relative to gasoline fuel in warm start

Warm start					
Instrument	**Gasoline**	**25% iso-butanol**	**25% n-butanol**	**25 % iso-butanol change relative to Gasoline (%)**	**25 % n-butanol change relative to Gasoline (%)**
EEPS (g/cm^3)	6.69E-10	2.57E-10	2.37E-10	- 61.51	- 64.57
ELPI(g/cm^3)	5.85E-10	1.32E-10	1.24E-10	- 77.49	- 78.79
MSS (g/cm^3)	2.94E-10	5.52E-11	3.93E-11	- 81.21	- 86.63

6.3 Effects of cold start and warm start with respect to Instruments & Fuels

Cold start and Warm start are the two conditions will be having a crucial part behind the production of Particles. Generally, the more particles are produced in cold start compared to warm start because of rich air fuel mixture. But in this section the percentage of change in Particles in warm start relative to cold start is calculated and tabulated according to fuels.

From tables 6.5 to 6.9 shows the contribution of warm start relative to the cold start by the instruments. In Avg Total Particle Number Concentration (TPNC), there is significant difference in evaluation done by ELPI compared to Evaluation of EEPS. But whereas in Avg Total particle Mass Concentration (TPMC) is not much difference in evaluation done by the 3 instruments for 25% iso-butanol & 25% n-butanol.

Table 6.5 Percentage change in Avg TPNC of warm start w.r.to cold start in different fuels

Operating conditions	**Gasoline**	**25% iso-butanol**	**25% n-butanol**
EEPS cold (#/cm^3)	1.83E+06	1.30E+06	1.36E+06
EEPS warm (#/cm^3)	1.38E+06	6.78E+05	7.69E+05
% warm start relative to cold start	**- 24.78**	**- 47.88**	**- 43.49**

Table 6.6 Percentage change in Avg TPNC of warm start w.r.to cold start in different fuels

Operating conditions	**Gasoline**	**25% iso-butanol**	**25% n-butanol**
ELPI cold(#/cm^3)	2.43E+06	1.47E+06	1.41E+06
ELPI warm(#/cm^3)	1.38E+06	5.37E+05	6.66E+05
% warm start relative to cold start	**- 43.18**	**- 63.47**	**- 52.65**

Table 6.7 Percentage change in Avg TPMC of warm start w.r.to cold start in different fuels

Operating conditions	**Gasoline**	**25% iso-butanol**	**25% n-butanol**
EEPS cold(g/cm^3)	7.12E-10	3.95E-10	3.89E-10
EEPS warm(g/cm^3)	6.69E-10	2.57E-10	2.37E-10
% warm start relative to cold start	**- 6.11**	**- 34.80**	**- 39.01**

Table 6.8 Percentage change in Avg TPMC of warm start w.r.to cold start in different fuels

Operating conditions	**Gasoline**	**25% iso-butanol**	**25% n-butanol**
ELPI cold(g/cm^3)	7.44E-10	2.11E-10	2.07E-10
ELPI warm(g/cm^3)	5.85E-10	1.32E-10	1.24E-10
% warm start relative to cold start	**- 21.27**	**- 37.51**	**- 40.08**

Table 6.9 Percentage change in Avg TPMC of warm start w.r.to cold start in different fuels

Operating conditions	**Gasoline**	**25% iso-butanol**	**25% n-butanol**
MSS cold(g/cm^3)	3.25E-10	9.45E-11	9.99E-11
MSS warm(g/cm^3)	2.94E-10	5.52E-11	3.93E-11
% warm start relative to cold start	**- 9.66**	**- 41.56**	**- 60.64**

6.4 Signal to Noise Ratio

In figure 6.32 the signal obtained from EEPS including background one can observe that there is very less difference between the signal of noise and signal of WLTC. In EEPS the particles are carried from inside the cylinder and outside the cylinder, which are attracted by electrostatic force, therefore the EEPS is having high sensitivity compared to ELPI and MSS. In ELPI signal there is clear difference between the WLTC signal, and the noise generated by instrument. From table 6.10 it is observed that signal to noise ratio of ELPI is high compared to EEPS and MSS.

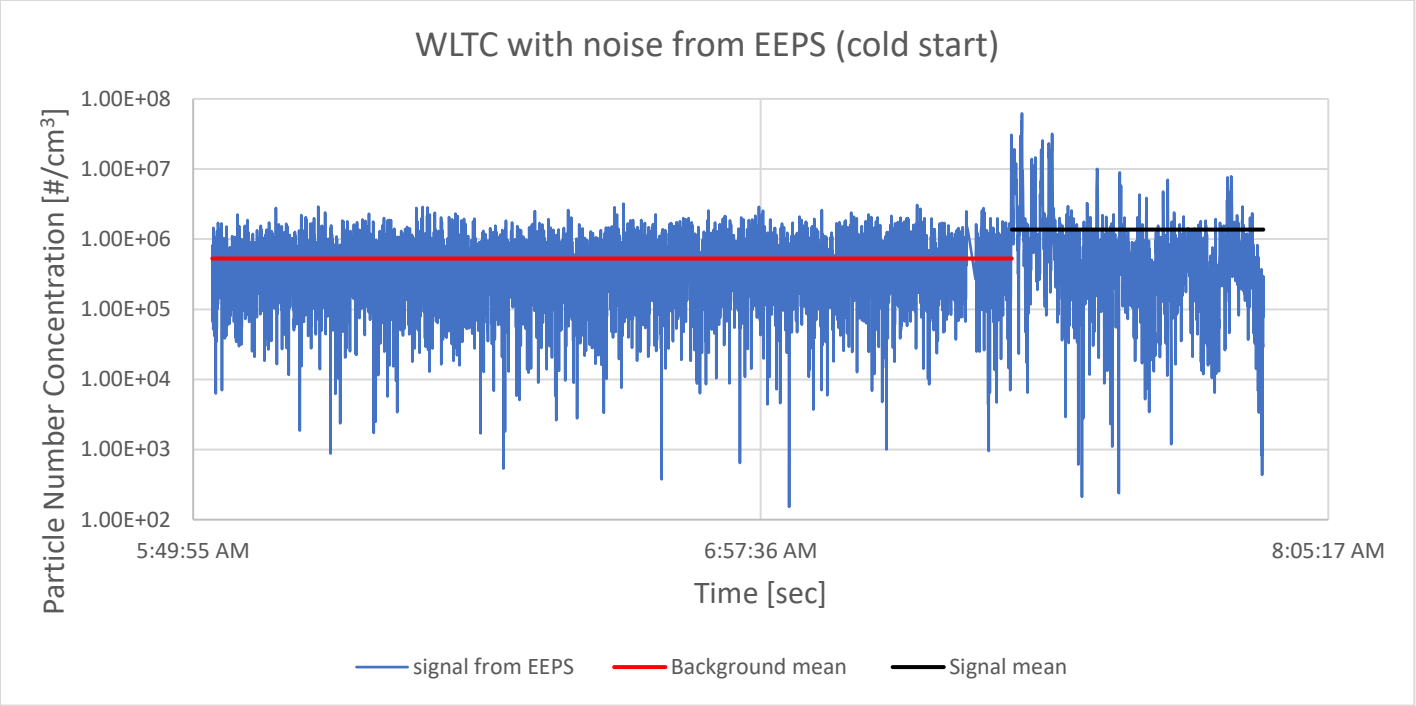

Figure 6.31 Signal generated by EEPS with WLTC preceded by noise for n-butanol fuel cold start

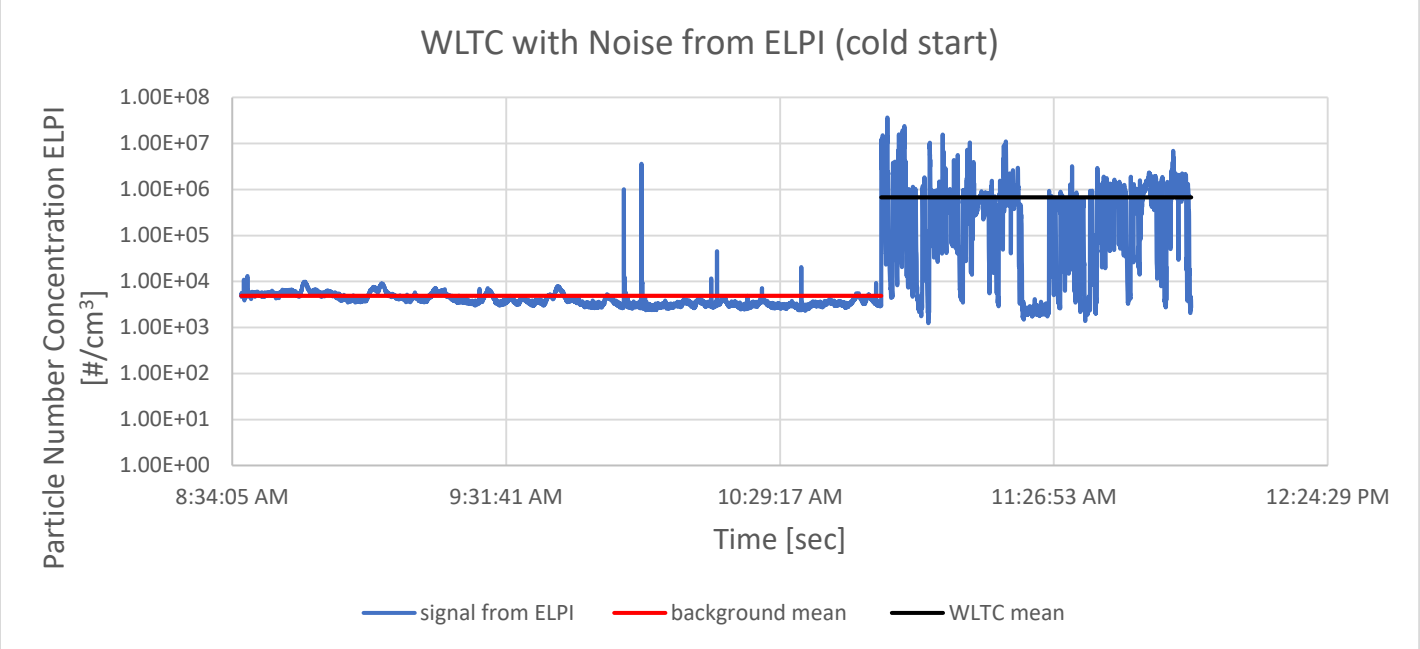

Figure 6.32 Signal generated by ELPI with WLTC preceded by noise for n-butanol fuel cold start

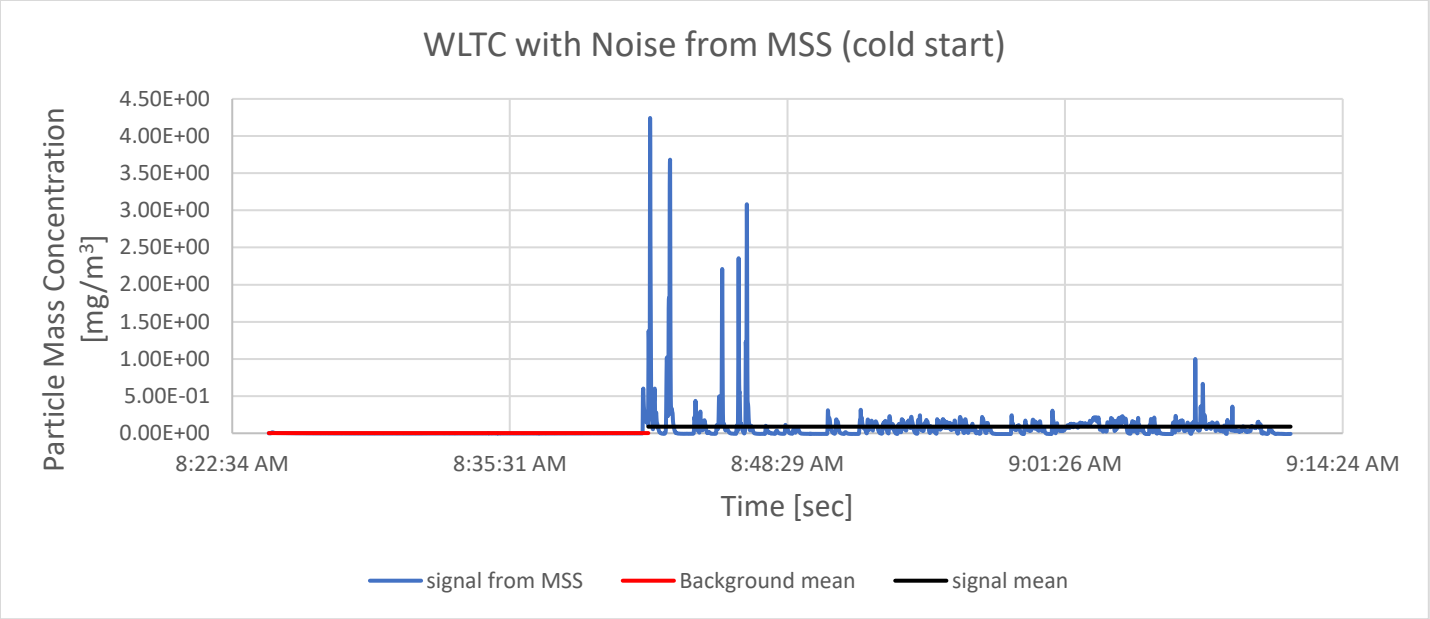

Figure 6.33 Signal generated by MSS with WLTC preceded by noise for n-butanol fuel cold start

Table 6.10 Avg Signal to Noise Ratios of EEPS, ELPI, MSS

Instrument	**Background Std dev**	**WLTC Mean**	**Avg Signal to Noise Ratio (SNR)**	**Avg Signal to Noise Ratio (SNR) In (dB)**
EEPS (#/cm³)	7.36E+05	1.37E+06	1.86	2.70
ELPI (#/cm³)	4.88E+03	6.75E+05	15.56	11.92
MSS (mg/m³)	4.17E-02	8.88E-02	2.13	3.28

7 Conclusion

The aim of this study is to analyze particle concentration data measured by three online instruments while sampling particle emissions from a typical automobile DISI engine operated along a transient test cycle on three different fuels: gasoline and its mixture with 25% of iso-butanol and with 25% of n-butanol. The particle concentrations were measured by two particle sizers, EEPS (sample diluted by a rotating disc diluter) and ELPI (high temperature version running at 160^0C sampling undiluted exhaust). Soot concentrations were measured by a photoacoustic sensor (MSS). The engine was operated along speed and torque points corresponding to WLTC vehicle driving cycle. These measurements were conducted at the VTP Roztoky laboratory in the months of August and September of 2019.

The tests conducted in a day comprises of 4 WLTC cycles, in which 2 WLTC cycles are ran in the morning session and remaining 2 WLTC cycles in the afternoon session. In each session there is cold start WLTC cycle and warm start WLTC cycle, from these tests the Particle Number Concentrations are obtained. The Particle Mass Concentrations for EEPS and ELPI were estimated, whereas for MSS Particle Mass Concentrations are measured.

Initially the WLTC cycles (cold start & warm start) were separated from the experiments ran in the morning and afternoon sessions respectively. The data analysis is started by observing the consistency between the experiments and evaluating the agreement between the instruments. The repeatability analysis is done in different approaches such as Repeatability of total particle number concentration and individual size channel and also within individual segments of the WLTC. By comparing EEPS & ELPI one can conclude that there is a good agreement between the instruments and the consistency of experiments are good for 25% iso-butanol and 25% n-butanol compared to Gasoline. In the case of comparison between three instruments for repeatability of total particle mass concentration, the instruments are in good agreement. The mass concentration measured by the photoacoustic sensor are lower compared to those calculated from size distributions measured by EEPS & ELPI; this is because the

photoacoustic method is only sensitive to soot particles and not to the organic fraction (semi volatile compounds), and possibly also because MSS is not very sensitive to very small particles.

The size distributions and mass distributions for EEPS and ELPI were in relatively good agreement throughout the tests. In comparison of 25% iso-butanol & 25% n-butanol relative to gasoline fuel, the decrement in percentage of change in Avg TPNC and Avg TPMC of 25% iso-butanol & 25% n-butanol compared to Gasoline in all instruments explains that the instruments are relatively consistent both in terms of absolute values and the relative differences among the fuels. From the percentage change in particle production in warm start relative to the cold start it is observed that there is difference between concentrations measured by ELPI and those measured by EEPS. Finally, in the calculations of Signal to Noise Ratio (SNR) for all the instruments, it is found that ELPI is having high Signal to Noise Ratio (SNR) compared to EEPS and MSS which are detailed in Table 6.10.

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Abbreviations

AECC	Association for Emission Control by Catalyst
AFR	Air to Fuel Ratio
AQG	Air Quality Guidelines
CADC	Common Artemis Driving Cycle
C-C	Carbon to Carbon
CO	Carbon monoxide
CS	Cold Start
dB	decibels
DF	Dilution Factor
DISI	Direct Injection Spark Ignition
DR	Dilution Ratio
EEA	European Environment Agency
EEPS	Engine Exhaust Particle Sizer
ELPI	Electrical Low-Pressure Impactor
GPF	Gasoline Particulate Filter
HC	Hydrocarbons
ICE	Internal Combustion Engines
MBT	Maximum Brake Torque
MSS	Micro-Soot Sensor
NEDC	New European Driving Cycle
NO_x	Nitrogen oxides
PM	Particulate matter
PMC	Particle Mass Concentration
PMR	Power to Mass Ratio
PNC	Particle Number Concentration
RDD	Rotating Disk Dilutor
RON	Research octane number
SNR	Signal to Noise Ratio
STD dev	Standard deviation
TFS	Turbocharged Fuel Stratified Injection
TPMC	Total Particle Mass Concentration
TPNC	Total Particle Number Concentration
TSI	Turbocharged Stratified Injection
VOC	Volatile Organic Compounds
WHO	World Health Organization
WLTC	Worldwide Harmonized Light Vehicle Test Cycles)
WLTP	Worldwide harmonized Light vehicles Test Procedures
WS	Warm Start

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Appendix

Technical specifications of EEPS

Technical details of EEPS [34]

Particle Size Range	5.6 to 560 nm
Particle Size Resolution	16 channels per decade (32 total)
Electrometer Channels	22
Charger Mode of Operation	Unipolar diffusion charger
Inlet Cyclone 50% Cut point	1 µm
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
Dimensions (HWD)	70.4 × 34.3 × 43.9 cm
Weight	32 kg
Power Requirements	100 to 240 VAC, 50/60 Hz, 250W

Technical specifications of ELPI

Technical details of ELPI [35]

Particle size range	0.006 - 10 µm
Number of size classes	14
	100/500 with High Resolution ELPI+
Sample flow rate	10 lpm
ELPI+ dimensions	H407 x W454 x D242 mm
Collection plate diameter	25 mm
Unit weight	15 kg without impactor
	22 kg with impactor in its place
Pump requirements	20 m3/h @ 40 mbars
Sample temperature	10-50 ºC
	10-180 °C with the High Temperature ELPI+
	Up to 600 °C when combined with Dekati Sample Conditioning Instruments
Sample humidity	0-90 % RH Non-condensing
Sampling rate	10 Hz
Power	100-250 V, 50-60 Hz, 200 W
Computer requirements	MS-Windows 7, MS-Windows 8, MS-Windows 10
Connection to PC	RS-232 or Ethernet
6 analogue inputs	0-5 V
3 analogue outputs	0-10 V

Technical specifications of MSS

Technical details of MSS [36]

Measuring unit	
Measuring range: Measured value concentration of soot (mg/m3, µg/m3)	0.001 – 50 mg/m3
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
Power supply	90...240 V AC, 50/60 Hz, 400 VA
Laser class	Class 1 laser product
Unit weight measuring unit	~ 20 kg
Conditioning unit (Consists of conditioning unit, pressure reduction unit and dilution cell)	
Dilution ratio (DR) The actual DR will be displayed with the accuracy noted below	Adjustable from 2 - 20
Pressurized air input	1 +/- 0.2 bar gauge pressure required
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)

Technical specifications of RDD (or) MD-19

Technical details of RRD (or) MD-19 [32]

aerosol	exhaust gases or air which contains nanoparticles
raw gas flow	approx. 1.5 l/min
measuring gas flow	full dilution range: 0.6 to 1.5 lN/min @ high dilution factors up to 5 lN/min
raw gas pressure	-20 to +300 mbar relative to ambient for low dilution (high rotational speed) -20 to +400 mbar relative for short time and high dilution
power supply	90 to 240 VAC, 50/60 Hz, max. 300 VA
local operation	pump switch, temperature dial, dilution potentiometer, LED indicators
remote operation	· via Ethernet in combination with testo CU-2 · controlled with analog DC signals 0 to 10 VDC
assembly	· together with testo ASET 15-1 integrated in 19" case · stand alone in a 3U / 42HP laboratory case
operating conditions	Tamb: +10 to +40 °C 0 to 80 %RH, max. 80% @ +30°C, linearly degrading to 50% @ +40°C, non-condensing
calibration	· standard calibration with 90 nm NaCl particles in air, diluter temp: +80 °C · UN-ECE R83 calibration possible if integrated in testo ASET 15-1 system

Bins sizes of EEPS

Engine Exhaust Particle Sizer bin notations and diameters [41]

Bin Number	Bin max Dp (nm)	Bin min Dp (nm)	Bin midpoint Dp (nm)
B1	6.48	5.61	6.05
B2	7.48	6.48	6.98
B3	8.64	7.48	8.06
B4	9.98	8.64	9.31
B5	11.52	9.98	10.75
B6	13.3	11.52	12.41
B7	15.36	13.3	14.33
B8	17.74	15.36	16.55
B9	20.48	17.74	19.11
B10	23.65	20.48	22.07
B11	27.31	23.65	25.48
B12	31.54	27.31	29.43
B13	36.42	31.54	33.98
B14	42.06	36.42	39.24
B15	48.57	42.06	45.32
B16	56.09	48.57	52.33
B17	64.77	56.09	60.43
B18	74.79	64.77	69.78
B19	86.37	74.79	80.58
B20	99.74	86.37	93.06
B21	115.18	99.74	107.46
B22	133	115.18	124.09
B23	153.59	133	143.30
B24	177.37	153.59	165.48
B25	204.82	177.37	191.10
B26	236.52	204.82	220.67
B27	273.13	236.52	254.83
B28	315.41	273.13	294.27
B29	364.23	315.41	339.82
B30	420.61	364.23	392.42
B31	485.71	420.61	453.16
B32	560.89	485.71	523.30

Bin sizes of ELPI

Electrical Low-Pressure Impactor bin cutoffs and stages [35]

Stages	Upper Bin cutoff (µm)	Lower Bin cutoff (µm)	Midpoint (µm)
1	0.016	0.006	0.0080
2	0.03	0.016	0.0156
3	0.054	0.03	0.0286
4	0.094	0.054	0.0499
5	0.15	0.094	0.0916
6	0.25	0.15	0.1656
7	0.38	0.25	0.2806
8	0.6	0.38	0.4544
9	0.94	0.6	0.7439
10	1.6	0.94	1.2531
11	2.5	1.6	2.0534
12	3.6	2.5	3.1027
13	5.3	3.6	4.5987
14	10	5.3	7.5922