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Faculty of Mechanical Engineering

Department of Automotive, Combustion Engine and Railway Engineering

Detection of high particulate matter emitters

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Submitted by: Yuvanesh Suresh

Supervisor: doc. Michal Vojtíšek, Ph.D.

Declaration of authorship

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

In Prague: 20. 08. 2018

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Yuvanesh Suresh

Anotace

Tato diplomová práce se zabývá detekcí vozidel s nadměrným výskytem emisemi částic. Cílem práce je analyzovat reprezentativní podmnožinu dat a využít různé metody měření a analýzy dat, včetně detekce koncentrace částic, rozlišení času, diskriminace mezi hlukem a emisním signálem vozidla, reprodukovatelnost, rozptyl testu na detekovaných vozidlech, vyhodnocení detekčního limitu a nejistoty měření. Práce je rozdělena na tři části - úvod, experimentální postup a jeho charakteristiky, rozdělení velikosti částic a použitá dokumentace. Výsledky tohoto hodnocení jsou zdokumentovány a výpočty provedené pro měření dat jsou automatizovány pomocí Visual Basic for Applications (VBA)

Klíčová slova: Částice, nadměrnými emisemi, analýza dat, emisní faktory, rozdělení velikosti částic.

Abstract

This master's thesis deals with the detection of high particulate matter emitters. The goal of the thesis is to analyze a representative subset of the data, and to investigate different measurement and data analysis approaches, including particle concentration detection method, time resolution, discrimination between noise and vehicle emissions signal, reproducibility and test-to-test variance on vehicles being detected multiple times, and evaluation of detection limit and uncertainty of the measurement. The thesis is divided into three parts - introduction, experimental setup and its characteristics and particle size distributions and documentation. The results of this evaluation are documented, and the calculations done for the measured data are automated using Visual Basic for Applications (VBA).

Keywords: Particulate matter, high emitters, data analysis, emission factors, particle size distributions.

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Content

1 Introduction

High emitters, vehicles with very high exhaust emissions due to malfunction, tampering or excessive wear, disproportionately contribute to the total emissions from motorized transport. Identification of such high emitters, and subsequent repair or removal from the vehicle fleet, was viewed as a relatively fast, cost-effective approach in improving the urban air quality.

The detection of such high emitters can be done by various methods: *in situ* and *in vehicle* (Ropkins, et al., 2006). *In situ* method; the instruments are placed at a fixed point and the emissions are measured for multiple passing vehicles. They include Road tunnel, Inverse dispersion and across road studies. Road tunnel, is one of the most widely applied class of real-world emission measurement methods, employed by many researchers/research groups across the globe (Ropkins, et al., 2006) (Fraser, et al., 1998). Across road measurement technique collects the data from multiple passing vehicle, captures the vehicle (along with the number plate) and process the data. It gives a more direct emission to individual vehicle comparison and more direct interpretation of the measured dataset (Ropkins, et al., 2006) (Bishop, et al., 1997).

In a pilot study conducted in Prague, roadside measurements of exhaust plumes left by individual passing vehicles were analyzed by high time resolution instruments. The goal of the thesis is to analyze a representative subset of the data from the buses recorded in Nádraží Veleslavín (Bus terminal Veleslavín), and to investigate different measurement and data analysis approaches, including particle concentration detection method, time resolution, discrimination between noise and vehicle emissions signal, reproducibility and test-to-test variance on vehicles being detected multiple times, and evaluation of detection limit and uncertainty of the measurement. The results of this evaluation are to be documented, and recommendations made for processing of remaining data and for future measurements.

By the text, particle concentration refers to mass concentration and number concentration. There are several detection methods, which includes: Isokinetic sampling; to capture particles that pass through a defined area for a defined time without disturbing their paths, which is unlikely to maintain in an open environment. Sampling from still air; there are two sources of error when sampling in still air, one due to settling velocity of the particles

and the other due to particle inertia. Gravimetric analysis; the most common way to determine aerosol mass concentration is to pass a known volume of aerosol through a filter and determine the increase in mass of the filter due to collected aerosol particles. This process involves substantial delays and a remote place to perform, so there is a need for portable online instruments, which can measure mass concentration and number instantaneously at the sampling site. This type of detection method, portable online instrument was used in this study (Bischof, 2015) (Hinds, 1982, pp. 187-206).

The thesis is divided into three parts. The first part of the thesis is the introduction part. The introduction part includes the general description of particulate matter, their formation, after-treatment methods, health and environmental impacts. It also includes; the legislations and general introduction about high emitters. The sub-chapter, Legislations and Atmospheric implications emphasizes on the air quality in Europe (European Environment Agency, 2017), European emission standards (DieselNet, 2016) and high emitters. The goal of the thesis is explained in a separate chapter.

The second part of the thesis is the experimental setup and its characteristics. It is divided in two chapters. The chapter, Experimental setup includes the arrangement of the instruments and selection of the sampling site, an overview of the different types of particle concentration detection instruments which were used during the measurement. In the chapter, Experimental setup characteristics the raw data from the instruments are critically analyzed and the steps are shown as each sub-chapter. The investigation of discrimination between noise and vehicle emission signal are emphasized on the sub-chapters: Signal-to-Noise Ratio, Correction of background, Threshold limit of the measured emissions. The various attributes of the instruments such as detection limit, instrument transient response was also highlighted. For comparing the measured vehicles with the EURO stages and limits, specific emissions are calculated with a reasonable assumption of the parameters. The EURO limits are prescribed only for the new vehicles coming to the roads, but in this study, it was used a tool of comparison. This part of the thesis is automated using Visual Basic for Applications (Macros) for a time-saving operation which can be used for future references.

The final part of the thesis is the particle size distributions and documentation. This part includes three chapters: Particle size distributions, Emission factors of buses and Test-to-test variances and Uncertainty in the experiment. In the chapter, Particle size distributions; the evaluated high emitters were statistically approached, and the Count Mean Diameter and

the Mass Mean Diameter were found to justify the presence of Diesel Particulate Filter (DPF). All the major findings and the specific emissions from individual vehicles were documented in the chapter, Emission factors of buses. The chapter, Test-to-test variances and Uncertainty in the experiment includes the variations in the result for the vehicles which were recorded multiple times and the differences between the instruments

1.1 Particulate matter

Particulate matter is a mixture of solid, solid or liquid and liquid particles suspended in the air. Particulate matter includes both organic and inorganic particles such as dust, pollen, soot, smoke and liquid droplets. The main sources of these particulate matter include: Automobiles, Household appliances (Chimneys, burning of wood, etc.), Smoking, and many others (United States Environmental Protection Agency, 2016) (World Health Organization. Regional Office for Europe, 2003).

Automobiles particularly contribute more than a quarter of the soot particle pollution (European Environment Agency, 2017) and they are formed due to the incomplete combustion of fuel, engine lubricating oils and wear metals.

1.1.1 Particles size and structure

The particles change their structure, size and composition (which directs to the change in physical and chemical properties when diluted with air) as they are leaving the Internal Combustion Engines (Vítek, 2017).

These particles are classified based on their sizes: coarse particles and fine particles. The smaller or the finer particles are mainly the combustion particles, secondary aerosols (which are formed in the environment), re-condensed organic and metal vapors. The major categories of these fine particles are: PM_{10} and $PM_{2.5}$. PM_{10} are particles with diameter 10 μm and smaller, they are inhalable. $PM_{2.5}$ are fine inhalable particles with the diameter 2.5 μm and smaller. These finer particles are more dangerous in aspects of health. These finer particles are again sub classified based on their diameter, as nanoparticles and ultrafine particles and shown in the figure 1.1 (United States Environmental Protection Agency, 2016)

(World Health Organization. Regional Office for Europe, 2003) (World Health Organization, 2018).

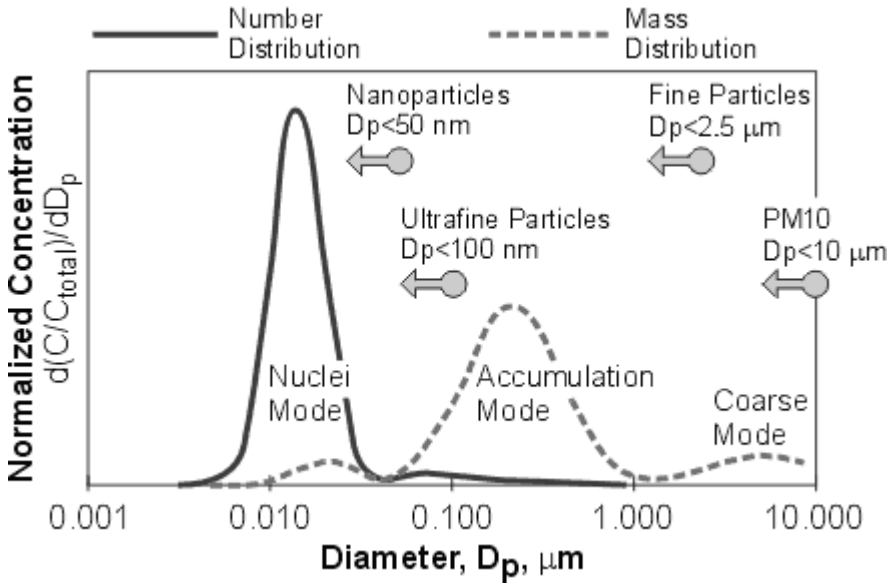

Figure 1.1 Size distribution of Particulate Matter (Majewski, 2016)

1.1.2 Formation of diesel soot particles

For a properly adjusted SI engine, soot in the exhaust is not a significant problem (Heywood, 1988, p. 626). Hence, the formation of diesel soot particles is more emphasized. The soot formation in diesel engine takes place at a temperature of 1000 to 2500 K and pressure of 50 to 100 atm and sufficient air overall to burn the fuel completely. The time available for the soot formation from the fraction of fuels are usually in the order of milliseconds. The soot formation is summarized as the following stages as shown in the figure 1.2 (Heywood, 1988, pp. 635-648):

The first stage is the particle formation or nucleation, where the first condensed phase materials arise from the fuel molecules by oxidation and/or pyrolysis products. They include unsaturated hydrocarbons and polycyclic aromatic hydrocarbons. The condensation reaction paves the appearance of first recognizable soot particles (d < 2 nm), called as “nuclei” (Heywood, 1988, pp. 635-648).

The next stage is the particle growth; includes surface growth, coagulation and aggregation. Solid phase materials generated in the surface growth, involves attachment of gas phase species to the surface of the particles and their incorporation into particulate phase.

Next, the condensation of species with the higher content of hydrogen followed by dehydrogenation or a combination of both these processes are required. These surface growths tend to increase the amount of soot and the number remains the same. Whereas, in coagulation the particles collide and fuse thereby the numbers becoming less, and amount remains the same. After surface growth ceases, continuous aggregation of particles into chains and clusters are formed (Heywood, 1988, pp. 635-648).

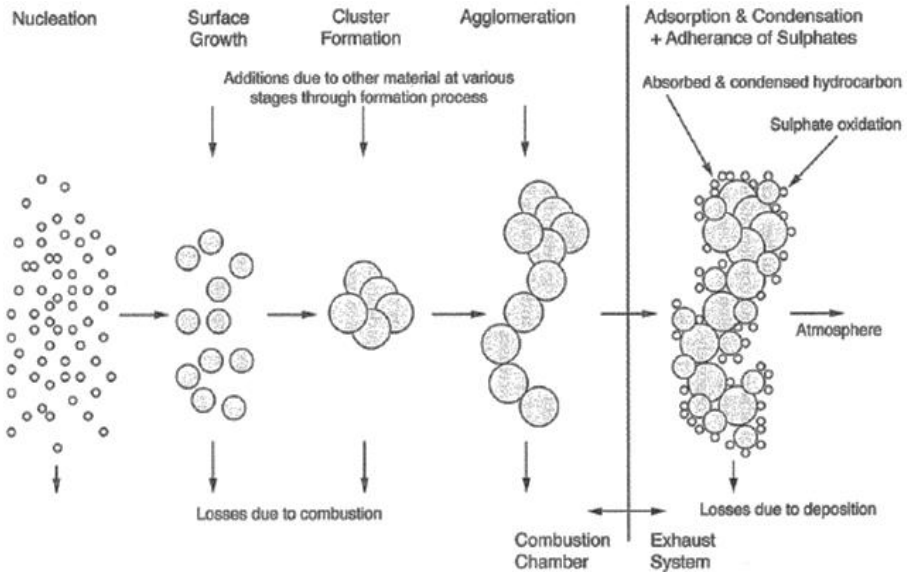

Figure 1.2 Stages of soot particle formation (Vítek, 2017)

The final step of soot formation is adsorption and condensation. This usually happens after the particles exit from the engine. For measurement purposes, exhaust gases are usually sent into dilution tunnel. Adsorption and condensation occurs in the dilution tunnel. Adsorption involves the adherence of the unburned hydrocarbons onto the surfaces of the soot particles by chemical or physical forces. Condensation occurs when the vapor pressure of the gaseous hydrocarbons exceeds its saturated vapor pressure. Increasing the dilution ratio decreases the gaseous hydrocarbons and vapor pressure (Heywood, 1988, pp. 635-648).

1.1.3 Methods to reduce Particulate matter emissions

Particulate matter can be reduced in two possible ways: by avoiding the production of particulates or by after treatment devices – mainly, Diesel Particulate Filter (DPF).

Advances in engine technology including combustion geometry, multi point fuel injection systems, common rail, etc., reduces the particulate matter by 90 % (Vojtíšek, 2017).

But, however most of the diesel engines are employed with Diesel Particulate Filter (DPF) which has a soot trapping efficiency of 95 – 99.9 % (Majewski, 2001).

1.1.4 Diesel Particulate Filter

An exhaust aftertreatment which substantially traps particulate emissions is Diesel Particulate Filter. A Diesel Particulate Filter (DPF) is a filter that physically captures and stores the exhaust soot which is periodically "burned off" to regenerate DPF. It must be remembered that traps may have limited effectiveness, or be totally ineffective, in controlling the non-solid fractions of PM, such as the SOF or sulfate particulates (Majewski, 2001). Hence, the overall efficiency of DPF was only accounted to 70 - 95 %.

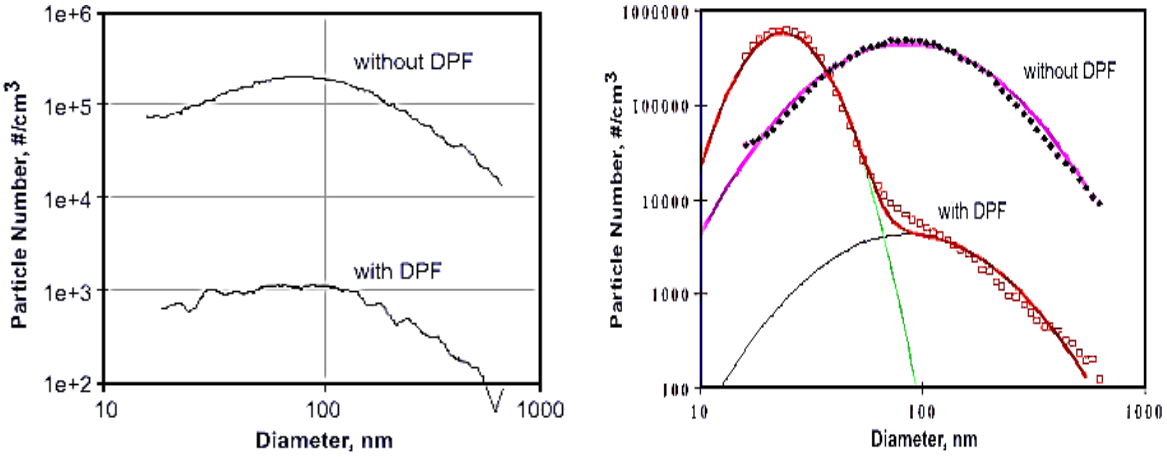

Figure 1.3 Particle size distribution for a vehicle with DPF and without DPF (Majewski, 2001)

Particulate filters also tend to increase the formation of nanoparticles through nucleation. In effect, DPFs reduce the numbers of mostly solid agglomeration mode particles, replacing them by mostly liquid nuclei mode nanoparticles as shown in the figure 1.3 (Majewski, 2001). Another important factor, affecting this variation were exhaust gas temperature, presence of nanoparticulate precursors, particulate sampling parameters, etc. (Majewski, 2001).

The filter must be periodically cleaned from the trapped soot particles by regeneration processes. Regeneration can be done in two ways: active regeneration and passive regeneration (Majewski, 2001).

Active regeneration is done by raising the temperature of the soot trapped in the filter by an outside energy source: diesel fuel. Injection of diesel fuel into the exhaust gas (post –

injection) which increases the temperature of exhaust gas and completely burns the deposited soot.

Passive regeneration, the soot oxidation temperature is lowered to a level allowing for auto-regeneration during regular vehicle operation. It is achieved by introducing an oxidation catalyst to the system. The catalyst promotes oxidation through two mechanisms (Majewski, 2001).

i. Oxygen mechanism - catalytic oxidation of carbon by oxygen, or
ii. Nitrogen dioxide mechanism - catalytic oxidation of NO to NO_2, followed by the oxidation of carbon by nitrogen dioxide.

Usually the catalyst is placed on the upstream of the filter.

1.1.5 Health and Environmental impacts of Particulate matter

The size of the particle is a direct indication to the level of health impact. The particles which are smaller than 10 μm have the greatest problem of entering in to the lungs and even penetrating in to the bloodstream. Hence, exposure to these particles affects both the lungs and heart directly. There are numerous scientific studies that links the particulate matter and the health problems, such as (United States Environmental Protection Agency, 2016):

i. Premature death in people with heart or lung disease.
ii. Restrictive lung expansion
iii. Increased respiratory symptoms, such as irritation of airways, coughing or difficulty breathing, Asthma

Environmental effects include the visibility impairment and environmental damage. The main cause of this effect is $PM_{2.5}$, which reduces the visibility in urban areas. Particles, generally are weightless can travel a longer distance within a few minutes. They usually settle on the water bodies such as lakes, streams and contaminate them. They deplete the soil nutrients and affects the eco system in general. They also cause the “Acid rain” and “Smog” (United States Environmental Protection Agency, 2016).

1.2 Legislations and Atmospheric implications

In Europe, road transport, is the largest contributor towards NO_x (Oxides of Nitrogen) pollution with 39% and second largest in terms of BC (Black carbon, has a significant portion of particulate matter), with 29% next only to commercial, institutional and households sources (European Environment Agency, 2017). The unchecked exhaust emissions from the vehicles contributes more than a quarter of the global pollutants, which were harmful not only to the atmosphere and air quality but also to the human beings. According to the European Environment Agency's report, statistics from the year 2015 says, $PM_{2.5}$ (Particulate matter, diameter of 2.5µm or less) single handedly was responsible for 399 000 premature deaths originating from long-time exposure and NO_2 (Nitrogen dioxide) and Ozone (O_3) was responsible for 75 000 and 13 600 premature deaths respectively in the European Union annually, whereas road accidents contribute only to 26 000 deaths for the year 2015 in European Union (European Environment Agency, 2017) (European Commission, 2017).

1.2.1 Air Quality Standards of Particulate matter (PM_{10} and $PM_{2.5}$)

Air Quality standard is the limit value set by many governmental agencies and health organizations throughout the world for different harmful pollutants based on protection of health. EU Ambient Air Quality standards for both PM_{10} and $PM_{2.5}$ was given in the table 1.1

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

Table 1.1 Air quality standards for the protection of health for both PM_{10} and $PM_{2.5}$ (European Environment Agency, 2017)

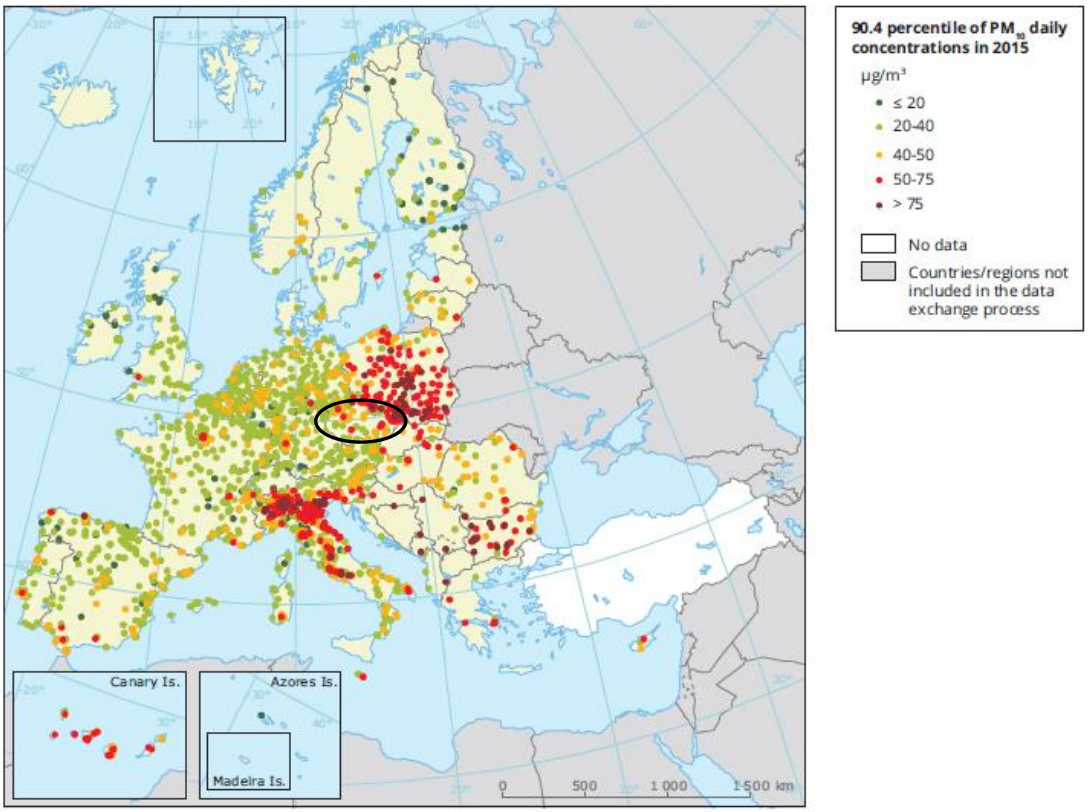

Figure 1.4 Observed daily mean concentration of PM_{10} in 2015 (European Environment Agency, 2017)

Figure 1.4 corresponds to the daily mean concentration of PM_{10} for the year 2015 in Europe Union. The measurements were taken in 2 380 stations throughout EU-28. The observation allows 35 exceedances of the limit: 50 µg/m^3 over 1 year. The stations with concentrations above this daily limit value was indicated by red and dark red dots. Out of 28 Member states, 19% of the stations in 20 members states exceeds the PM_{10} EU daily limit value. And 95% of these stations were either urban or sub-urban (European Environment Agency, 2017).

The black circle in the figure was an approximate border of Czech Republic. It was also evident that the red spots were seen in the principle cities (e.g.: Prague, Ostrava, Brno, etc.) Pressing particularly on Czech Republic, the Annual concentration for both PM_{10} (20 to 30 µg/m^3) and $PM_{2.5}$ (10 to 20 µg/m^3) were lower than the annual prescribed limit but exceeding on the daily prescribed limit (European Environment Agency, 2017).

1.2.2 European emission standards for Heavy-duty Truck and Bus engines

European emission standards define the acceptable limit for exhaust emissions of the new vehicles sold in European Union (EU) and European Economic Area (EEA) member states. All dates listed in the tables 1.2 and 1.3 refer to new type approvals - the dates for all vehicles are in most cases one year later (DieselNet, 2016).

Stage	Date	Test	CO	HC	NO_x	PM	PN	Smoke
			g/kWh				1/kWh	1/m
EURO I	1992, ≤ 85 kW	ECE R-49	4.5	1.1	8.0	0.612		
	1992, > 85 kW		4.5	1.1	8.0	0.36		
EURO II	1996.10		4.0	1.1	7.0	0.25		
	1998.10		4.0	1.1	7.0	0.15		
EURO III	1999.10 EEV only	ESC & ELR	1.5	0.25	2.0	0.02		0.15
	2000.10		2.1	0.66	5.0	0.10		0.8
EURO IV	2005.10		1.5	0.46	3.5	0.02		0.5
EURO V	2008.10		1.5	0.46	2.0	0.02		0.5
EURO VI	2013.01	WHSC	1.5	0.13	0.40	0.01	8.0×10^{11}	

Table 1.2 EU Emission Standards for Heavy Duty Diesel Engines – Steady state Testing (DieselNet, 2016)

Stage	Date	Test	CO	NMHC	CH_4[a]	NO_x	PM[b]	PN[e]
			g/kWh					1/kWh
EURO III	1999.10 EEV only	ETC	3.0	0.40	0.65	2.0	0.02	
	2000.10		5.45	0.78	1.6	5.0	0.16[c]	
EURO IV	2005.10		4.0	0.55	1.1	3.5	0.03	
EURO V	2008.10		4.0	0.55	1.1	2.0	0.03	
EURO VI	2013.01	WHTC	4.0	0.16[d]	0.5	0.46	0.01	6.0×10^{11}

Table 1.3 EU Emission Standards for Heavy Duty Diesel and Gas Engines – Transient state Testing (DieselNet, 2016)

Additional provisions of the Euro VI regulation (DieselNet, 2016) include:

i. An ammonia (NH_3) concentration limit of 10 ppm applies to diesel (WHSC + WHTC) and gas (WHTC) engines.
ii. A maximum limit for the NO_2 component of NO_x emissions may be defined at a later stage.

In the table 1.3,

a. for gas engines only (Euro III-V: NG only; Euro VI: NG + LPG)
b. not applicable for gas fueled engines at the Euro III-IV stages
c. PM = 0.21 g/kWh for engines < 0.75 dm3 swept volume per cylinder and a rated power speed > 3000 min-1
d. THC for diesel engines
e. for diesel engines; PN limit for positive ignition engines TBD (DieselNet, 2016)

1.3 High emitters

The strictest emission norms are applicable to the new vehicles in the market but the older vehicles which were already on the road, has a major share in the overall pollution. The government also monitors the emissions regulation every two years by the standard test cycle procedures. However, the standard test results also vary from the real-world emissions (Ropkins, et al., 2006). After all the necessary steps taken by the government, the number of high emitters on the road is not reduced. There are also many illegal activities done like emulating the Diesel Particulate Filters, switching off Exhaust Gas Recirculation, etc. These unlawful activities should be stopped.

"More than a thousand diesel cars have been caught without an essential pollution filter that traps deadly particles, according to government figures. But experts warn the rogue practice of removing the filters, which contributes to air pollution-related deaths, could be far more widespread" (The Guardian, 2016).

There are many emulating services available worldwide in the internet for removing the filters, switching off the Exhaust Gas Recirculation, Selective Catalytic Reduction, etc. Although emulation should be dealt from practices, there are also some vehicles with malfunctioning Diesel Particulate Filters on the roads. The two extremities of emulating DPF

and non-functioning DPF were studied, and experiments were carried out and the useful information about the high emitters were reported.

2 Goal of the thesis

The goal of the thesis is to analyze a representative subset of the data from the buses recorded in Nádraží Veleslavín (Bus terminal Veleslavín), and to investigate

i. Different measurement and data analysis approaches, including particle concentration detection method, time resolution, discrimination between noise and vehicle emissions signal and evaluation of detection limit of the instruments used in this setup.
ii. Reproducibility and test-to-test variance on vehicles being detected multiple times, and uncertainty of the measurement.
iii. The results of this evaluation are to be documented and recommendations made for processing of remaining data and for future measurements.

3 Experimental setup

3.1 Field measurement setup

The vehicle of interest in this study were the buses. This experiment for the buses were conducted on the following dates: 17.10.2017, 27.10.2017. The sampling site selected was a Bus terminus which satisfies the following condition for a useful and promising measurements:

i. The buses should accelerate, at the sampling area or the measurement area. Considering the fact that the vehicles will be on a high load conditions producing the measurable emissions.
ii. There should always be a considerable amount of gap between the successive vehicles, for an easier distinguishment of the vehicle emission signals.
iii. There shouldn't be any traffic congestion or the vehicle shouldn't stay at the same place for period of time
iv. Also considering the aerodynamic behaviour of the vehicle which disperses the particle when they are travelling, the vehicle speed should be optimum.

On considering all the facts, the suitable place for the measurement was narrowed to Veleslavín Bus Terminal, Prague. The instruments along with their time resolution, working principle and arrangement were shown in the figures below.

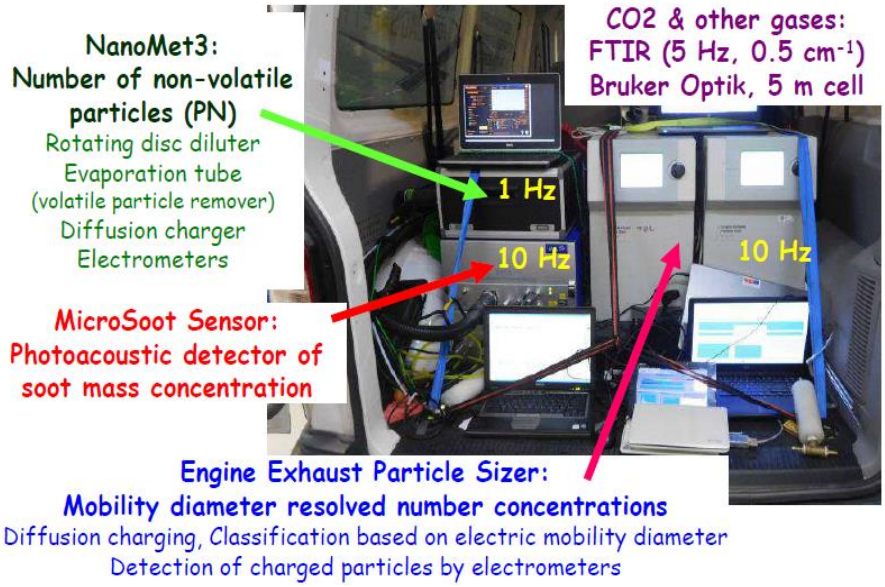

Figure 3.1 Arrangement of instruments inside the van used for transportation of them (Vojtíšek, 2017)

Figure 3.2 The van carrying the instruments was placed on the side of the road with an extending sample line

The vehicle carrying the instruments was placed on the side of the road where the sample line to collect the exhaust plumes is extended onto the road. The collected sample was distributed among the instruments where they connected to their respective computers for storing and reviweing the results. The entire event was powered by a generator and/or the supply from the transporting vehicle.

In this study the vehicle number were noted manually keeping the time of any one of the computer connected to a instrument as a reference time. Considering the fact that the time between successive buses are quantifiable.

The technical data of the measured vehicle were provided by the Ministry of Transport, Czech Republic. The technical data includes Bus registration details: model, version, vehicle class, type, weight, fuel, engine size, power, making year, first registration, vehicle identification number. The first registration were used to obtain the euro regulations for the measured vehicles of interest.

3.2 Instruments used in the measurement

Some of the higher end portable online instruments for particle concentration detection used in this experiment were AVL Micro Soot Sensor ^{plus} (MSS ^{plus}) – photoacoustic principle of operation, TSI Engine Exhaust Particle Size (EEPS) spectrometer – Electric mobility, Testo NanoMet3 – Unipolar diffusion chargers.

3.2.1 Micro soot sensor ^{plus} (MSS ^{plus})

Manufacturer: AVL LIST GmbH. It measures the concentration of the soot particles directly without cross-sensitivity of the other exhaust gases. It is based on the principle of Photo-acoustic measurement. The detection limit provided by the manufacturer was 1 $\mu g/m^3$. However, the manufacturer detection limit and the noise range are subjected to closed environmental conditions. The experiments were carried out in an open atmosphere and these values are subjected to change which will be explained in detail in the later chapters. It has a measuring unit and a conditioning unit. They are also suitable for raw exhaust gases, with the help of an integrated automated thermophoretic loss compensation (TLC) (AVL LIST GmbH, 2018).

3.2.1.1 Photoacoustic measurement principle

In this method, the sample gas with "black", i.e. strongly absorbing soot particulates, is exposed to modulated light. The soot particles absorb the light and periodically warms, and

cools and the resulting expansion and contraction of the carrier gas can be regarded as a sound wave and detected by means of piezoelectric detectors (AVL LIST GmbH, 2018).

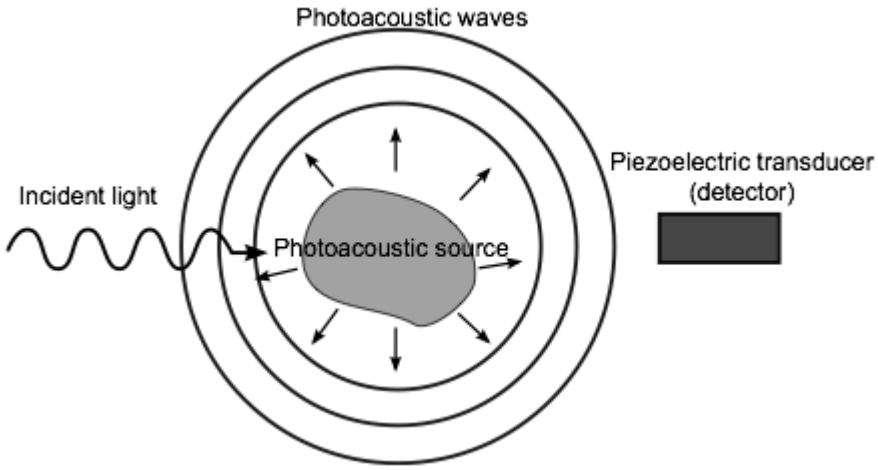

Figure 3.3 *Photoacoustic measurement principle (bagustris@wordpress, 2012)*

3.2.2 Engine Exhaust Particle Sizer (EEPS) Spectrometer

Manufacturer: TSI Incorporated. The Engine Exhaust Particle Sizer (EEPS) spectrometer is a fast-response, high-resolution instrument that measures even the lower concentration of the exhaust particles in the diluted exhaust. It has a time resolution of 10 Hz, making it well suited for dynamic and transient test conditions. It measures the size distribution and number concentration of engine exhaust particle emissions in the range from 5.6 to 560 nanometers (TSI Incorporated, 2005).

3.2.2.1 Operating principle of Engine Exhaust Particle Sizer (EEPS) Spectrometer

The instrument draws the exhaust sample into the inlet continuously. The exhaust particles are positively charged to a predictable level with the help of a corona charger. These charged particles are then introduced to the high voltage electrode column and they are transported down with the help of a HEPA filtered sheath air. A positive voltage is applied to the electrode which creates an electric field around them repelling the positively charged particles outwards according to the electrical mobility (TSI Incorporated, 2005).

These charged particles strike their respective electrometer, the particle with the higher charge strikes the electrometer at the top and the lower one in the bottom. The electrometers

used are of high sensitivity and allows continuous measurement of multiple particle sizes (TSI Incorporated, 2005).

It has a built-in Digital Signal Processor (DSP) which synchronizes the time delay between the electrometers, variability in the particle charge, image charge and presents a size distribution that corresponds to a specific time (TSI Incorporated, 2005).

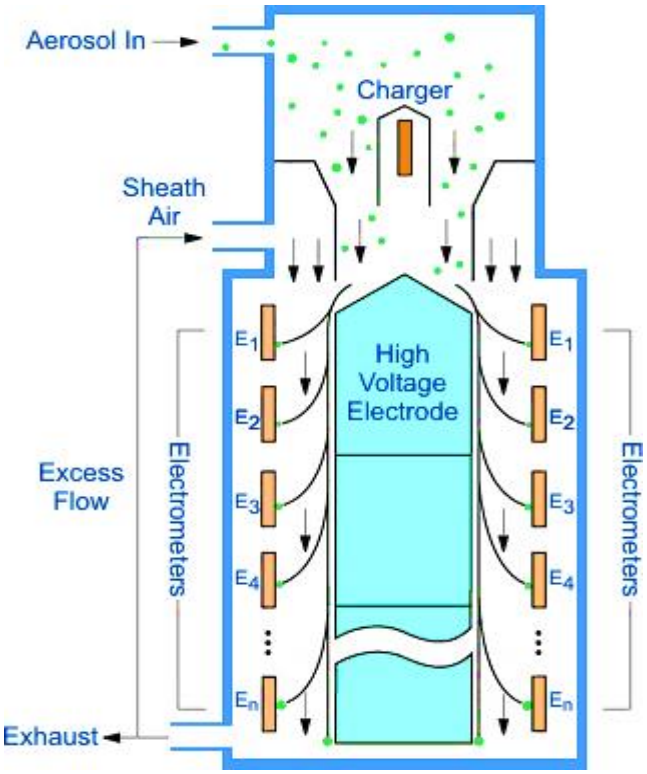

Figure 3.4 Engine Exhaust Particle Sizer Spectrometer flow schematic (TSI Incorporated, 2005)

3.2.3 NanoMet3

Manufacturer: Testo SE & Co. NanoMet3 is a Portable Emissions Measurement System – (PEMS) to measure number concentration and average diameter of solid nanoparticles. It measures the particle in the range between 10 – 700 nm under real driving conditions. They are compact, robust, reliable and has rugged design making it suitable for external conditions. They are suitable for non-laboratory conditions and OBD instrumentations too (Testo SE & Co. KGaA, 2017).

3.2.3.1 Operating principle of NanoMet3

It works on the principle of "Unipolar Charge Diffusion". To measure the solid particle fraction, NanoMet3 features a separate sample at the source to thermally remove the volatile fractions, by Thermo-Dilution principle, which is Particle Measurement Protocol (PMP) compliant. The portable system is completed with Testo proprietary Diffusion Size Classifier technology, which measures the number concentration and the average diameter of the nanometer sized particles. It electrically charges the particle and measures the particles count. The cost of acquisition and the cost per test are significantly lower (Testo SE & Co. KGaA, 2017).

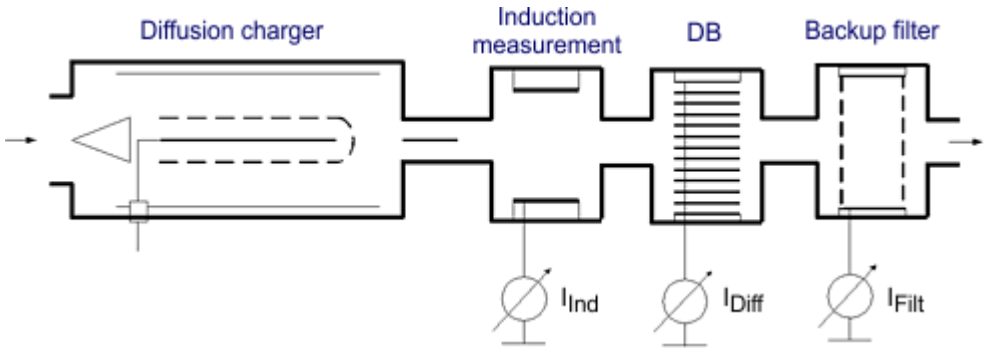

Figure 3.5 Unipolar charge diffusion (Burtscher, et al., 2017)

Although the study doesn't include any gaseous pollutants, but the measurement of Carbon monoxide and Carbon dioxide are used for the fuel specific emission factors calculation. The measurement of Carbon dioxide is a direct indication that the vehicle was measured. These gases are measured by Fourier Transform Infra-red spectrometer (FTIR spectrometer).

Fourier Transform Infra-red spectroscopy works on the basic concept of each gas absorbs light at different wavelength (Indian Institute of Technology Kanpur, 2012). This uses the mathematical process of Fourier transforms to covert the raw data into useful spectrum. The instrument is usually attached with a pump to pickup the gases which have a very low parts per million level. The useful gases from this spectroscopy are Carbon dioxide and Carbon monoxide.

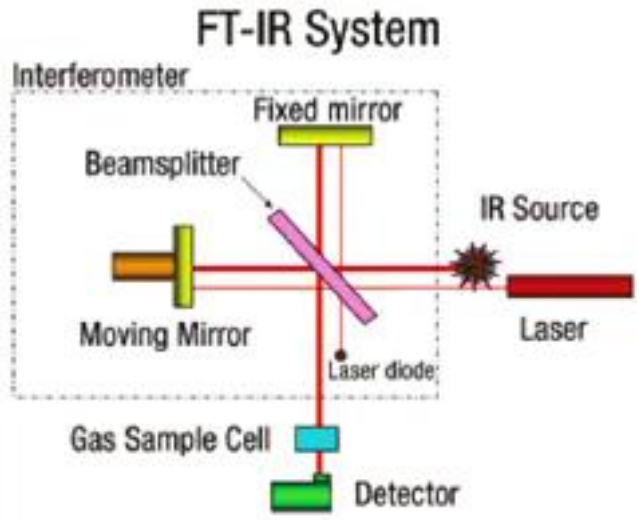

Figure 3.6 Working principle of FTIR (Indian Institute of Technology Kanpur, 2012)

4 Experimental setup characteristics

The raw data from the measurements were analyzed to get a useful information. The exhaust gases of interest from the instrument, Fourier Transform Infra-Red spectrometer (FTIR) was Carbon dioxide (CO_2) and Carbon monoxide (CO) concentrations (in ppm). The Micro Soot Sensor (MSS) measures the mass of the soot particles per m^3 of air and Engine Exhaust Particle Sizer (EEPS) for the particle number data per cm^3 of air and particle mass concentrations per m^3 of air are derived based on mass mobility approach (Park, et al., 2003). NanoMet3 gives both particle number per cm^3 of air and mass per m^3 of air. Herein after the instruments will be specified in their abbreviated form and their corresponding measured entity.

4.1 Signal-to-Noise Ratio (SNR)

Signals are the useful information or physical quantities that varies with time. In this study, it is referred to the vehicle emissions. Whereas, noises are the unwanted electrical or magnetic phenomena that corrupts the useful signal. Noises are broadly classified into internal noises and external noises (Vávra, 2017).

Internal noises are generated by components associated with the signal itself.

External noises are the natural or man-made electrical or magnetic phenomena influence the signal as it is being transmitted. They also include the environmental factors.

One way to discriminate or study about the signal strength is the calculation of Signal to Noise Ratio (SNR). It is a measure used in science and engineering that compares the level of a desired signal to the level of background noise.

It is defined as the ratio of the mean of the signal to the standard deviation of the noises (Schroeder, 2000, p. 433) (Bushberg, 2006, p. 280). This can be used only to a non-negative data. The entire study deals with the measurement of emissions with the background. So, this relation can be used.

Signal to Noise Ratio (SNR), $= \mu / \sigma$

where, μ = Signal mean

σ = Standard deviation of the noises

Signal mean is calculated by excluding the noises and the standard deviation of the noises were calculated by excluding the signals.

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

They are often expressed in decibels (dB). In general, the signals can be sufficiently detected when they are greater than 10 dB. The Signal to Noise Ratio $(SNR)_{dB}$ for the different instruments were calculated for both original data as well the resolved data, to investigate the level of the noise reduction. The instruments used in this measurement were higher-end. But, also because the experiment was carried out outdoor, the chances of higher external noises were high. So, the result will be a considerable one.

The ratio was calculated for a specific subset of data sample where, there were reasonable peaks picked by the instrument (which were the measured vehicles and not infiltrated by the outgoing vehicles).

Instrument	**SNR_{dB} (Original data)**	**SNR_{dB} for (Resolved data)**
FTIR-CO_2	20.4 dB	21 dB
MSS-PM	25.2 dB	27 dB
EEPS-PN	24.8 dB	27 dB
NanoMet3-PN	27.9 dB	-

Table 4.1 SNR_{dB} comparison between the instruments for their original data and resolved data

In this table 4.1, Original data refers to the 5 Hz for FTIR, MSS and EEPS and 1 Hz for NanoMet3. Whereas, resolved data refers to the 1 Hz data for all the instruments. The resolution of the measurement of data was done as there were an adequate time difference between the successive vehicles, which will be easier to distinguish themselves from the rest of the vehicles. The method used to resolve the data was: Maximum Approach, which was explained in the sub-chapter 4.5. There is no resolution of measurement of data for NanoMet3, as it itself measures data in 1 Hz.

In all instruments except NanoMet3, the signal strength which is a direct implication of $(SNR)_{dB}$ increases only by a decibel. But, this $(SNR)_{dB}$ is sufficient to discriminate the signals and noises easily.

The comparison of the Original data and the resolved data for MSS was shown in the figures below.

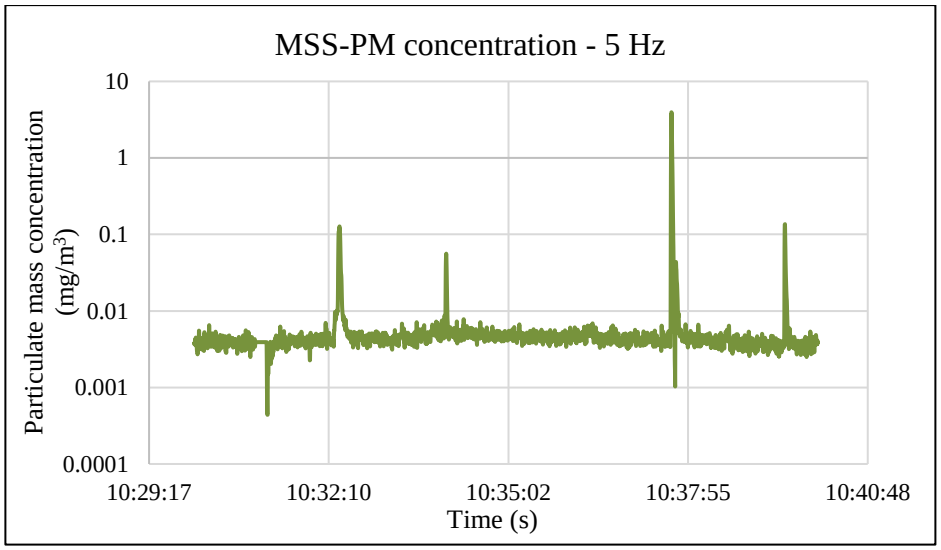

Figure 4.1 Noise level and the measurement signal in the original data of MSS-PM concentration (logarithmic scale)

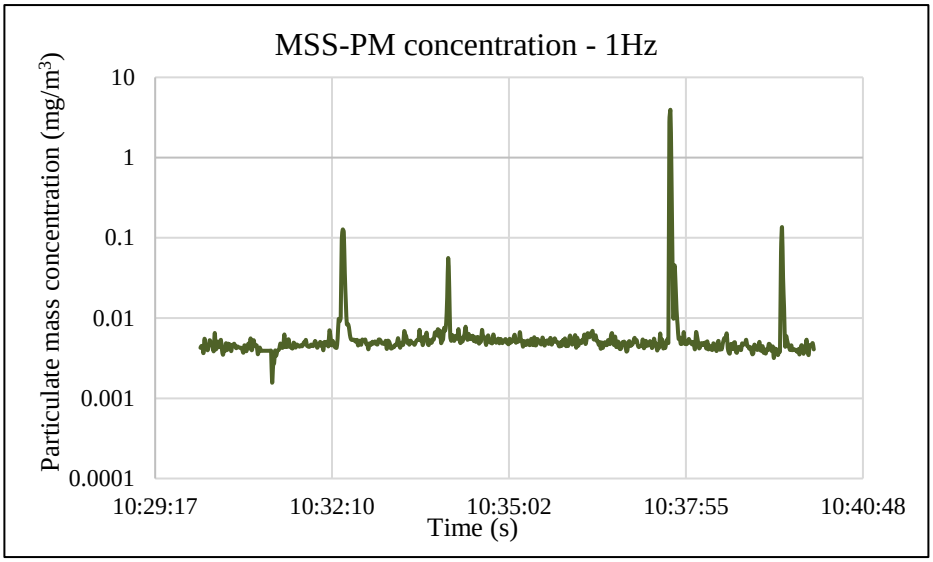

Figure 4.2 Noise level and measurement signal in the resolved data of MSS-PM concentration (logarithmic scale)

4.2 Detection limit of the instruments in this setup

Limit of Detection, the true net concentration or the minimum physically detectable value from the measurement. The detection limit prescribed by the manufacturer will not be the same when the instruments were operated in an open environment. It is critical to evaluate the limit of detection, to know a better understanding about the instruments and to

discriminate between vehicle emission signal and blank sample (which includes the atmospheric concentrations of particles) (Boqué & Heyden, 2009).

The fact that the experiment was conducted in an open environment, makes the detection limit higher than the manufacturer's value. On defining the detection limit, there are two types of error which must be considered. They are: Type I error and Type II error (Boqué & Heyden, 2009).

Type I error, α is the probability of committing a false positive (detect something which is not present) and Type II error, β is the probability of committing a false negative (present but not detected) (Boqué & Heyden, 2009).

In this study, both the Type I error and Type II error were preferred for a fact that the uncertainty in the instruments should be as low as possible. So, it is necessary to choose the value of α and β as low as possible. It was chosen to be 5% ($+2\sigma$ in the one-sided normal distribution curve) which will be a best fit considering the uncertainty in the instrument.

For the above α and β value, the detection limit can be defined as (Boqué & Heyden, 2009),

$$L_D = 3.33\ \sigma_o$$

where, σ_o is the standard deviation of the sample without concentration.

The Detection limit for all the particle concentration measurement instruments used for the analysis (MSS and EEPS) were found and shown in the table 4.2 below,

Particle concentration measurement instrument	**Manufacturer's detection limit**	**Actual detection limit in this setup**
MSS-PM	1 µg/m^3	1.8 µg/m^3
EEPS-PN	200 #/cm^3	8480 #/cm^3
NanoMet3	1000 #/cm^3	1743 #/cm^3

Table 4.2 Detection limit for the different particle concentration measurement instruments (AVL LIST GmbH, 2018) (TSI Incorporated, 2005) (Testo SE & Co. KGaA, 2017)

However, in the atmosphere the concentration of these particles is always present. So, the limit was evaluated on a base assumption that the standard deviation, σ_o corresponds to the sample without the vehicle emission signals.

The sample was chosen in such a way that there was neither an influence of vehicle emission signals nor distortion due to the incoming vehicles.

4.3 Calibration of CO_2 measurement

For FTIR, the value of CO_2 (ppm) detected was lower than the atmospheric level of CO_2 (ppm). The main reason would be the calibration error. So, the data to be analyzed were calibrated with reference to the atmospheric level of CO_2. The gas of interest is only CO_2 from the FTIR measurement. They are calibrated by the relation,

calibration factor = $(CO_{2,\,a}/CO_{2,\,min}) * CO_{2,\,measured}$

where, $CO_{2,\,a}$ is the atmospheric level of Carbon dioxide on the measurement day (400 ppm)

$CO_{2,\,min}$ is the minimum value of Carbon dioxide detected on the measurement day

$CO_{2,\,measured}$ is the measured Carbon dioxide.

From the experimental properties of FTIR, the calibration curve was linear. Hence, this relation was found to be valid. Since the data from FTIR were calibrated, the threshold limit of the instrument can be treated as the detection limit of the instrument. The threshold limit, which is the detection limit of the measurement were assumed for each instrument in the sub-chapter, Threshold limit of the measured emissions.

4.4 Instrument transient response

The evaluation of transient response time for each instrument is an important attribute to be considered for the behavior of the measurement.

“Time, in seconds, a signal takes to rise from 10 % to 90 % of its maximum absolute value is called Rise time” (International Organization for Standardization, 1997). This was a critical parameter for the study of net value and the correction for background, which will be explained in detail in the next sub-chapter. A unit step response was given, the corresponding rise time was calculated. This value will be considered for the window selection. The step response has a peak same as the signal peak and starts when the signal begins to increase steadily from the background. Another important factor considered was the dispersion of the gases. The experiment was carried out in an open environment where the dilution and the local concentration of the gases changes from time to time. The transient response

characteristics were found to be different for each signal. Hence considering the maximum rise time, peak time and the average time taken for the dispersion of gases, the window was assumed. The rise time of the instruments for a data sample where vehicle emission recorded was shown in the figures 4.3 – 4.6 and the table 4.3 below. The data sample chosen was an indication of an average transient response characteristics.

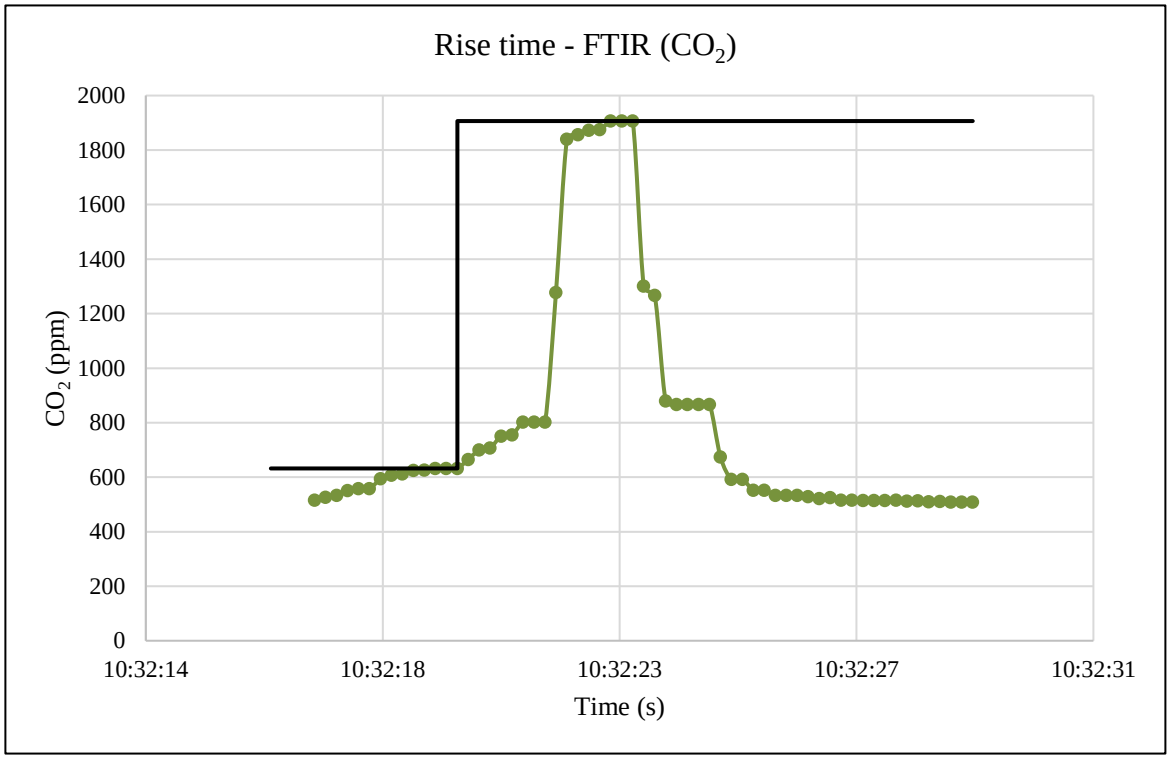

Figure 4.3 Rise time of FTIR (CO_2) for a data sample where vehicle emission was recorded

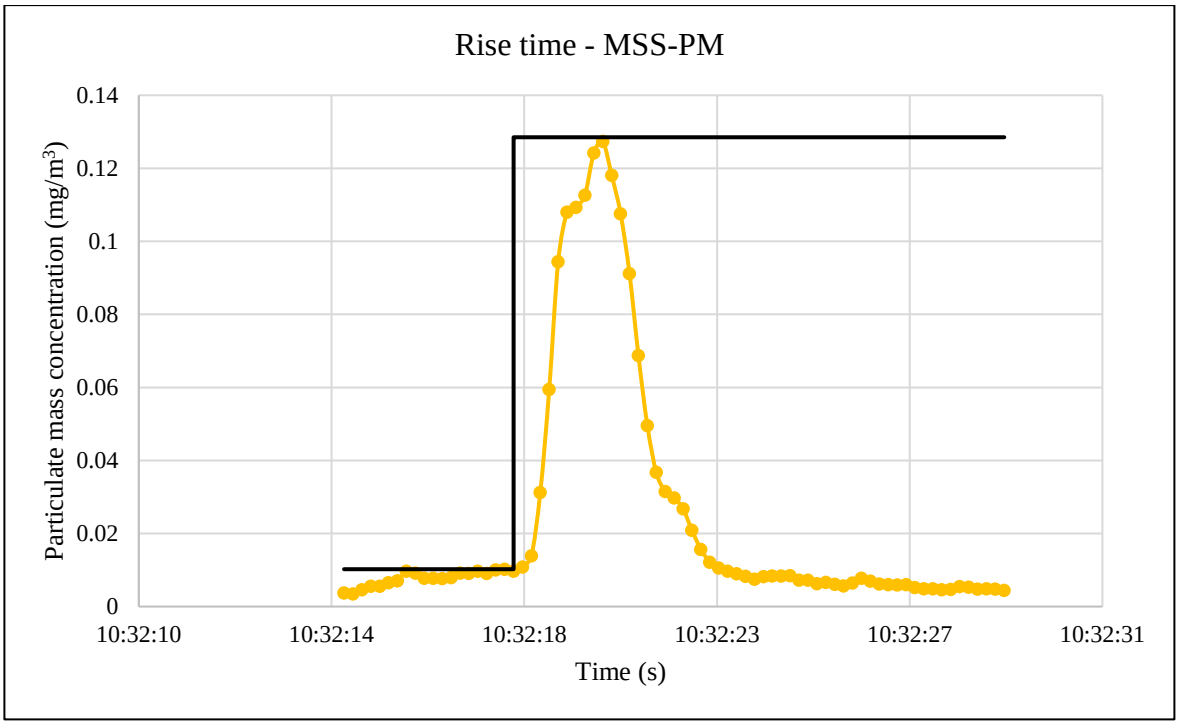

Figure 4.4 Rise time of MSS-PM for a data sample where vehicle emission was recorded

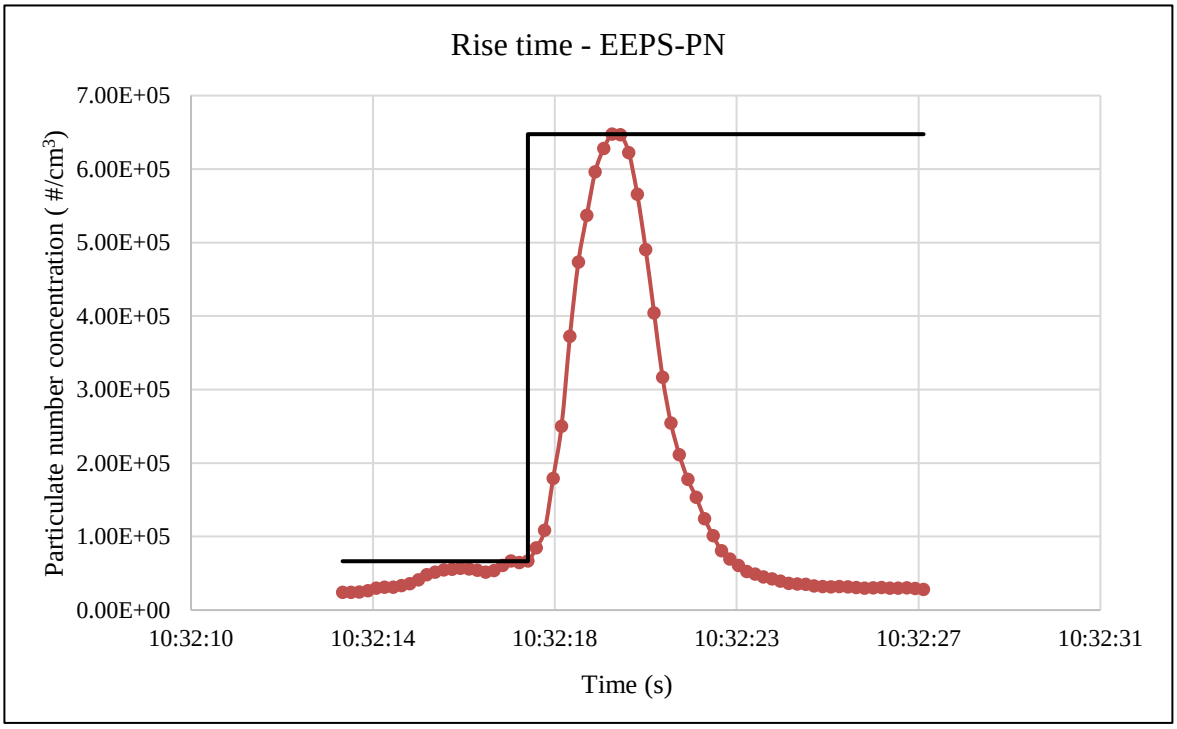

Figure 4.5 Rise time of EEPS-PN for a data sample where vehicle emission was recorded

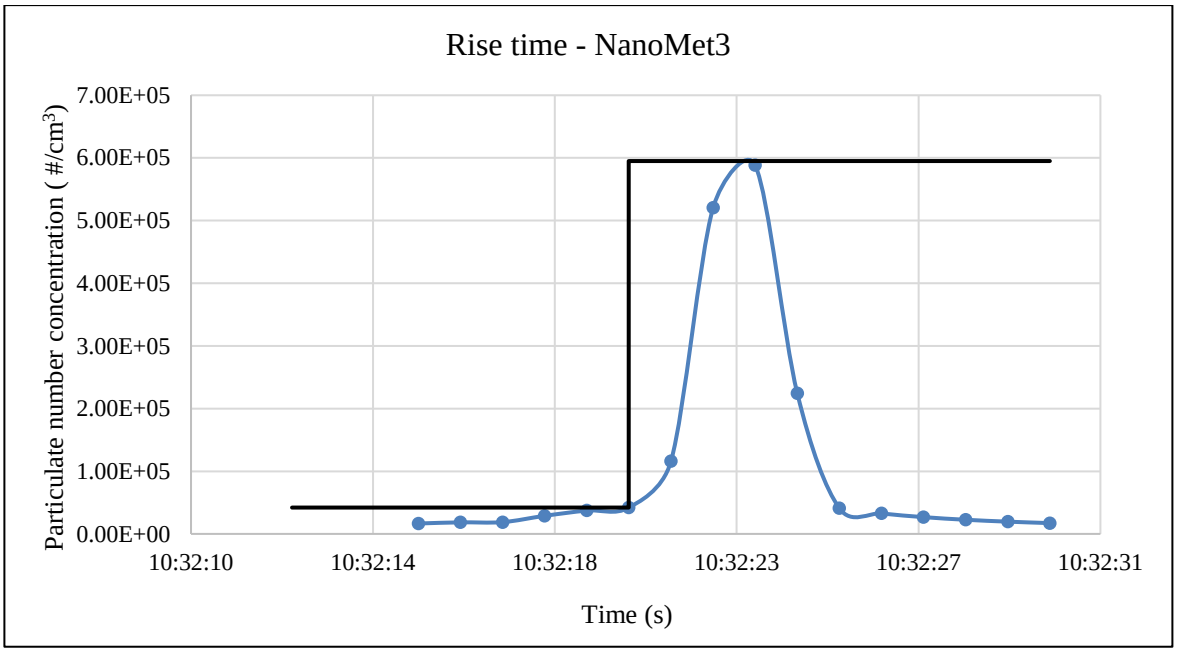

Figure 4.6 Rise time of NanoMet3-PN for a data sample where vehicle emission was recorded

Instrument	Rise time (s) estimated
FTIR (CO_2)	1.4
MSS-PM	1.2
EEPS-PN	1.2
NanoMet3-PN	3.0

Table 4.3 Rise time of the different instruments corresponding to the figures 4.3 – 4.6

4.5 Resolving the measured data

The instruments used in this experiment collects data in different frequencies. To time line all the instrument, it is critical to convert them to a common frequency. Table 4.4 shows the list of instruments and their corresponding frequencies used during the measurement.

Instrument	Frequency of the instrument used during the measurement (Hz)
Fourier Transform Infra-Red spectrometer (FTIR)	5
Micro Soot Sensor (MSS)	5
Engine Exhaust Particle Sizer (EEPS)	5

Table 4.4 List of Instruments and the corresponding frequencies used during the measurement

The above table 4.4 corresponds to the frequency which was employed during the measurement days (17.10.2017 and 27.10.2017). The data collected from Nádraží Veleslavín (Bus terminal Veleslavín) are converted to a frequency of 1 Hz. The reason is, the time intervals between the successive buses were large or in other words the vehicle emission signal can be easily distinguished even with a lower frequency. So, for an Indicative result the data with lower resolution of the measurement was reasonable. The lower resolution of the measurement also results in the reduction of noise level (Keysight Technologies, 2017).

The resolution of measurement of data can be done in two methods:

i. Time averaging of the data. Also, Research work from Hagler G *et al* employs Optimized Noise Reduction Averaging (ONA) – an adaptive time averaging of the data (Hagler, et al., 2011).
ii. Selecting the maximum value in the second's frame – "Maximum approach"

One of the main drawback in time averaging the data was: it shows variation in the data value respective to the maximum value for that time interval of 1 second. On time averaging, variation in data value from the original intended value was high. For different measurement instruments, the variation in percentage of the concentrations were listed in Table 4.5. In the case of FTIR, only CO_2 (ppm) were compared because around 70 % of the vehicles measured were diesel buses in this study. In EEPS only particulate number concentrations were considered whereas, particulate mass was a derived quantity by "Mass-mobility approach" (Park, et al., 2003).

In selecting the maximum value in the second's frame method, the maximum value was chosen instead of the average value. This method was employed in this study as it shows a better correlation with the raw data in the specific emission factors per kg of fuel than the averaging approach and is shown in the sub-chapter 4.12.

Instrument	Percentage of variation of concentrations from the original data when time-averaged
FTIR-CO_2	5 %
MSS-PM	23.5 %
EEPS-PN	24 %

Table 4.5 List of instruments and their percentage of variation of concentrations from the original data when time-averaged (in percentage)

The percentage of average variation of concentrations in the above table 4.5 includes both the days of measurement. However, the variation (in percentage) were comparatively lower in the case of FTIR, but on calculating the soot emission factors and specific emissions they show a large difference in the values. The comparison of the resolution techniques – time-averaging approach and maximum approach with the original data is shown in the subchapter 4.12.

4.6 Time synchronization between the instruments

The data collected from all the instruments are to be time lined to the time recorded for the passing vehicle. One of the technique which was employed was a "Match test". This technique of time synchronization was performed by doc. Michal Vojtíšek *et al* during the measurement days. The test was performed at the beginning or the end of the experiment where the probe connected to the instruments was closed with an HEPA filter i.e., where no plumes could pass through. And few seconds when the data attains steady state, it was removed, and the match stick was lit and kept closed to the opening and the emissions were recorded. And again, it should be closed with an HEPA filter only to differentiate that the peak was due to the match stick.

Based on the known facts, the match stick during the combustion was associated with higher CO_2 and higher Particle concentration. So, the synchronization was done between the instruments based on the above facts. It was seen that the instruments were few seconds lead or lagged between each other.

Some of the reasons for the lead/lag between the instruments includes, Different

i. Time in the computer connected to the instruments,
ii. Travel speed of the plumes to the instruments,
iii. Response time of the instruments

The synchronization of the measured data using "Match test" was shown in the figures below for both the measurement days.

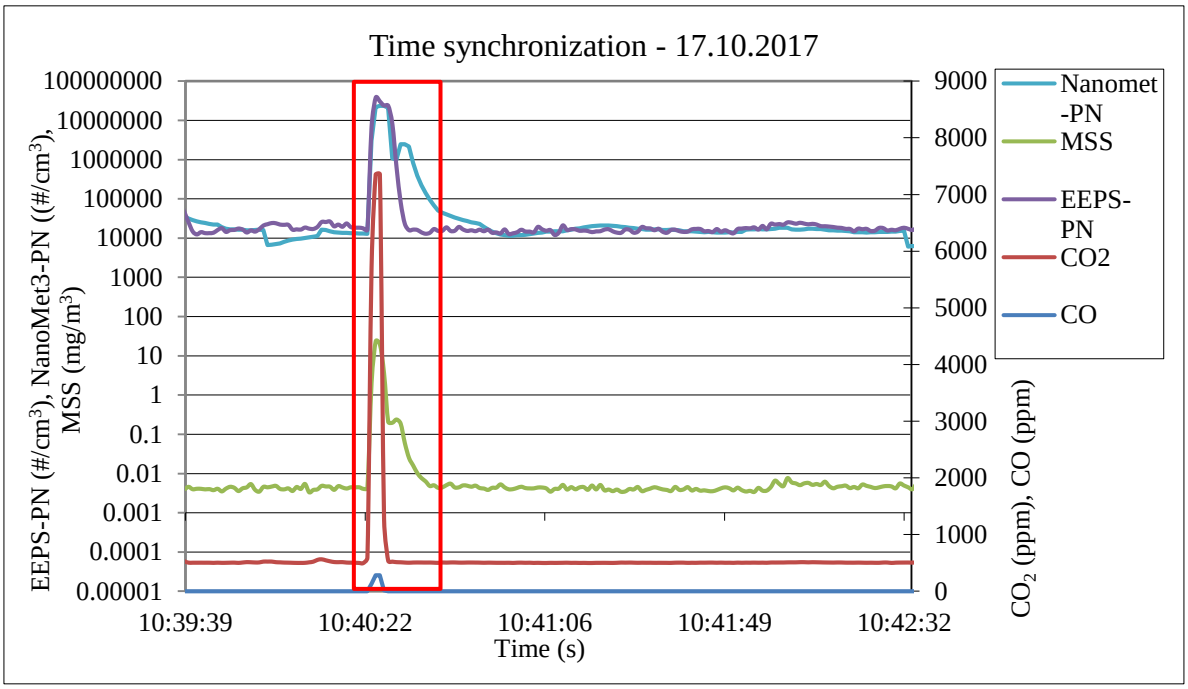

Figure 4.7 Time synchronization – 17.10.2017

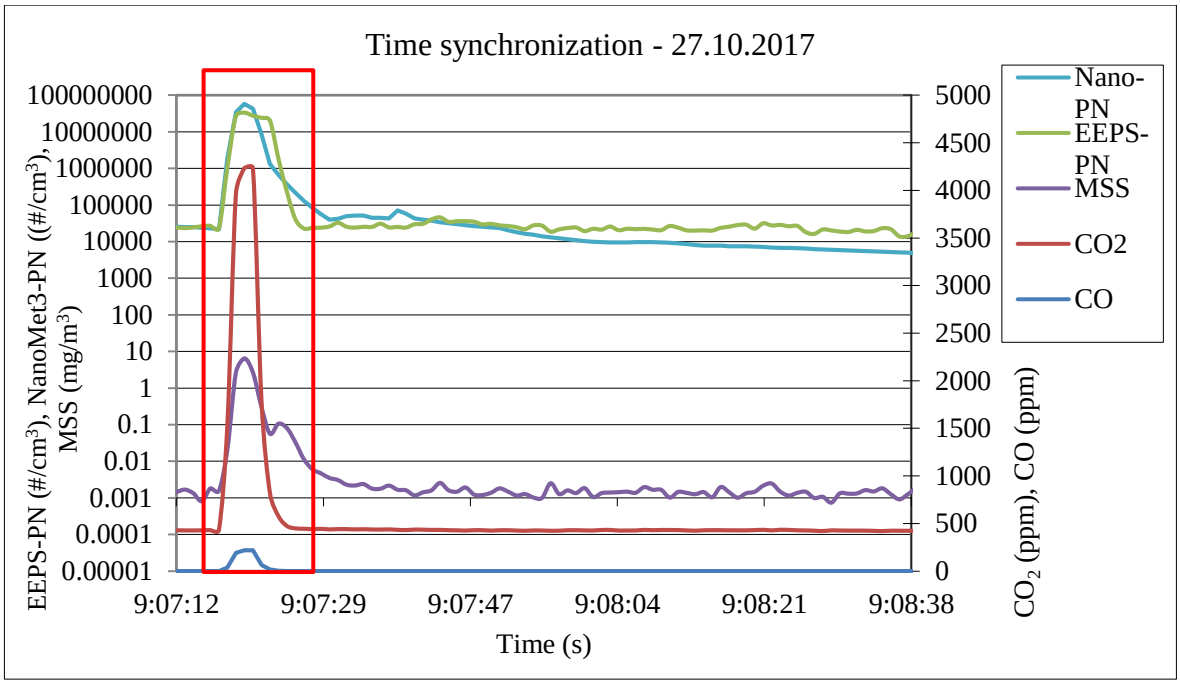

Figure 4.8 Time synchronization – 27.10.2017

The "Match test" didn't correlate with the data from 27.10.2017. The reasons can be improper note-making of the vehicle time and/or the reference time of the vehicle recorded were improper. So, the peaks were matched by moving each instrument forward and backward and the reference time was chosen from one of the instrument. In this case, FTIR was chosen. The corresponding vehicle time was also matched with the peaks and the nearby reference time.

4.7 Correction of background

For a Road-side measurement, the estimation of background is complicated. The background changes from time to time, called as changing background, because of the following factors:

i. Incoming vehicles on the opposite side of the road i.e., in our study, assuming only high emitters affects the measurement.

ii. Change in local dilution ratio, which can be caused by the change in wind speed and direction. This causes the measurement at that time to be less than the usual

background of the gases in atmosphere, called as "Negative emissions". In these cases, during the final calculation, these are assumed to be the threshold value.

iii. Change in the local concentration of the gases.

Keeping these factors in mind the background level for a period was estimated. The background was estimated for three different cases. First one: no change in background before and after the peak. In this case, the window of a specific time frame was chosen to the left of the peak and the 20^{th} percentile value can be assumed to be the background. Another way is to pick the minimum value in the time frame. But, in this technique there will be no significant reduction of the environmental noises or sometimes even the inclusion of them with the background.

The second and the third case will be the difference in the background level before and after the peak. In both the cases, a new specific time frame was chosen. For any values before the peak "the left window" was chosen and any values after the peak "the right window" was chosen. The 20^{th} percentile value in the respective window was assumed to be the background.

In a special case, such as there is a running peak with fluctuating values (pre-assumable noises or change in concentration, etc.) then the peak values before and after that corresponding value was inspected. If the after-peak value is greater than the before peak value, then the right window was chosen. Assuming, that there will be a change in background and that value belongs to the latter changed background and vice versa. The time frame was chosen based on the peak time, rise time and the setting time of the instrument.

The peaks were carefully studied and was found that the different instruments show different peak time and settling time for a different condition. The differences were mainly due to local wind velocity and direction and so on.

Instrument	Time frame window	
	Left window, in s	**Right window, in s**
FTIR	10	15
MSS-PM	5	10
EEPS-PN and PM	5	10
NanoMet3-PN and PM	5	10

Table 4.6 Time frame for the different instruments for correction of the background

It is always seen that the settling time (the time taken to reach the steady state from the peak time) is always greater than the peak time. So, the right window is always chosen a few seconds longer than the left window as shown in table 4.6.

From the estimated background, the net value can be calculated by subtracting the current value with that value. There is also a subsequent noise reduction in this method. The net values for the instruments was shown in the figures below.

From the net value, the maximum as well the area under the curve can also be calculated. Although the area value wasn't used for final calculation, it was useful to find the relation between peak to peak value and area to area value of particulate concentration or particulate number and CO_2. For calculating the maximum and the area value a new term, called as area counter was introduced. Area counter depicts the actual increase or decrease in the net values. For every increase in the CO_2 value (greater than 25 ppm; assumed threshold value, anything less than this value can be discriminated as a noise), it counts or adds "one" and for a decrease, it resets to "zero". The value of "one" will be counted again if the maximum net value in the next 5 seconds will be greater than the above-mentioned threshold value. After every cycle of counts, the peaks and the areas of that cycle were calculated as maximum and sum of the values respectively in that cycle.

For further calculation, the maximum value was chosen as the respective emission concentration, for there will be no drastic changes in the result. It is explained in detail in sub-chapter 4.13.

4.8 Matching the synchronized data with the vehicles

As of the data from the buses the number plate of the buses were noted manually with the time from one of the laptop or the standard local time.

Once all the data were synchronized, a window of data were chosen for every time a vehicle is recorded. In this approach, a window of 9 seconds data was chosen (4 seconds before the vehicle time and 4 seconds after the vehicle time). The main reason for choosing the window was the time drift and dispersion characteristics of the gases.

Time drift refers to several related phenomena where a clock does not run at the same rate to the reference. That is, after some time the clock "drifts apart" or gradually desynchronizes from the other clock. Because, of this reason it can be valid that the value be chosen in front of the expected vehicle time.

The maximum CO_2 net value and their corresponding CO net value, maximum particulate concentration and maximum particulate number were chosen. They were matched with the vehicle and the final calculations were done.

But in the case of data from 27.10.2017, the time synchronization of instruments by "Match test" wasn't sufficient. Therefore, the above-mentioned method cannot be employed. A separate time line should be set between the synchronized data and the vehicle where, the difference in time between the vehicles and the vehicle emission signal was compared and the relation between the difference were found to be correlated and they were used. But, few buses fail to fall within this difference limit. They were compared with the peaks before and after the limit and useful data was documented for further calculation.

4.9 Threshold limit of the measured emissions

The threshold limit can also be termed as the detection limit for the measurement. Threshold limit is used to differentiate the signals from the noises in the measurement. The threshold limit is subjected to be higher than the detection limit of the instruments. If any vehicle produces a value less than the threshold limit, it is either that the vehicle itself produces less emissions or the emission itself wasn't measured. CO_2 measurement is a direct

indication of the vehicle being measured. If the value of CO_2 was less than this threshold limit; it is assumed that the vehicle wasn't measured; uncertainty in the measurement.

Although, noises were drastically reduced from the previous steps, there can still be a certain level which might include the noise associated with the instruments itself. They cannot be completely reduced or deduced. So, this assumption also differentiates the vehicle emission signal from the noises.

To evaluate the threshold value, the net values got from the intermediate calculation were plotted in a graph. An assumption was made to differentiate the signal from all the possible noises. Based on Engineering Judgement, the following values were chosen. The net values below this estimated threshold were rounded off to zero. However, the value closer and lesser than the threshold value can be debated from being a signal or a noise.

In cases the CO_2 was measured (closer to the threshold limit) but has a value lower than the threshold limit, then the threshold value was chosen for the final calculation of soot mass concentration and soot number concentration. The assumed detection limit is shown in the table 4.7 below, for the data on both the days.

Emissions	**Threshold limit**
Net CO (from FTIR)	3 (ppm) for data on 17.10.2017 1 (ppm) for data on 27.10.2017
Net CO_2 (from FTIR)	25 (ppm)
Net particulate mass (from MSS and EEPS)	0.004 (mg/m^3)
Net particulate number (from EEPS)	3.00 E+04 ($\#/cm^3$)
Net particulate number (from NanoMet3)	7.50 E+03 ($\#/cm^3$)
Net particulate mass (from NanoMet3)	0.002 (mg/m^3)

Table 4.7 Threshold limit for the different gaseous and particulate emissions

4.10 Fuel specific emission factor (EF)

Once the threshold value was set, the next step would be to find the specific emissions of all the individual vehicles. In order, to find them a new term called as "Fuel specific emission factor" or simply "Emission factor" was introduced. **Emission factor (EF)**, a

representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. Effective fuel consumption was an important factor for calculating the specific emissions of the vehicle. This effective fuel consumption was a function of the CO_2 released by the vehicle in the atmosphere. Based on the below derivation of effective fuel consumption and emission factors from the CO_2 measurement, an indicative result can be produced. Because the measurements weren't done near the tail pipe where it was supposed to be done. Soot mass factor (mg/kg of fuel) and soot number factor (1 E+15/kg of fuel) an approximate estimate which predicts the behavior of the exhaust emissions near the tail pipe. An assumption was made that, the ratio between the pollutant and the mass of the fuel can be the same at any point near the tail pipe. However, this fact can only be valid if the instruments can be placed in position where it can sense the exhaust plumes. Some of the assumptions made to calculate the effective fuel consumption and soot factors (Hallquist, et al., 2013).

i. The study was ideally done on buses. So, for simplifying the calculation only diesel fuel was considered. Carbon content of diesel fuel, [C] = 0.862 (no unit) (Hallquist, et al., 2013).
ii. Ideal combustion (Vojtíšek, 2017):

$$C_\alpha H_\beta + (\alpha+\beta/4)\, O_2 + (N_2 + \text{inert}) \rightarrow \alpha\, CO_2 + \beta/2\, H_2O + (N_2 + \text{inert})$$

But in real combustion process, the main carbonaceous pollutants were CO, CO2 and soot. The amount of CO and soot are very low compared to CO_2 in diesel combustion. Hence, they are neglected in further calculation. The base relation (4.10.1 and 4.10.2) was suggested by doc. Michal Vojtíšek Ph.D., *et al* and referred from the works of Hallquist *et al* (Hallquist, et al., 2013),

$$N(C) = n(CO_2) \quad (4.10.1)$$

$$m(C) / M(C) = m(CO_2) / M(CO_2)$$

$$m(C) = m(CO_2) * M(C) / M(CO_2)$$

For, 1 m^3 of air,

$$m(\text{fuel}) = m(C) / [C] \quad (4.10.2)$$

Modified form of ideal gas law,

$$PV = mrT$$

$$m = PV/rT$$

$$m(\text{fuel}) = PV/rT * M(C) / M(CO_2) * 1/[C]$$

where,

P	=	Atmospheric pressure `
	=	$101.32 * 10^3$ (N/m^2)
V	=	Volume of CO_2 in $1m^3$ of air (m^3)
	=	CO_2 (ppm)/1.00 E+06 * $1m^3$ of air
r	=	Specific gas constant of CO_2
	=	189 (J/kg/K)
T	=	Atmospheric temperature
	=	(273.15 + 15) K
M (C)	=	Molecular weight of C
	=	12 (g/mol)
M (CO_2)	=	Molecular weight of CO_2
	=	44 (g/mol)
[C]	=	Carbon content in diesel fuel
	=	0.862 (no unit) (Hallquist, et al., 2013)

m (fuel) / 1 m^3 of air (kg/m^3 of air)

= P/rT * M (C) / M (CO_2) * 1/[C] * CO_2(ppm) / 1.00E+06

Substituting the known values,

= 0.5886 * CO_2 (ppm) / 1000000

where, emission factor (kg of fuel/m^3 of air)

= P/rT * M (C)/M (CO_2) * 1/[C]

= 0.5886 (kg/m^3)

Effective fuel consumption, (kg of fuel/m^3 of air)

= Emission factor * CO_2 (ppm) / 1.00E+06

Soot mass factor, (mg/kg of fuel)

= Net value of soot mass/effective fuel consumption

Soot number factor, (1.00 E+15/kg of fuel)

= Net value of soot number / effective fuel consumption / 1.00E+15

In case of Spark Ignition engines, where in this study is typically CNG operated vehicles. The inclusion of Carbon monoxide can be done, for the fact that Carbon monoxide is a principle pollutant for this type of engine. Although only slight changes can be inferred.

The European Emission norms prescribes the limit with respect to per kilo Watt-hour (kWh) for M3 class vehicles (Buses and Trucks >5 tons) (DieselNet, 2016). To calculate the specific emissions, the brake specific fuel consumption (bsfc) was assumed to be 250 g/kWh. The value was chosen after considering the facts that the experiment was carried out when the vehicle was accelerating, so the bsfc would be a higher than the optimum value.

Specific particulate mass (g/kWh)

= Soot mass factor / 1000 / 1000 * bsfc

Specific particulate number (1.00E+15/kWh)

= Soot number factor / 1000 * bsfc

4.11 Comparison of specific particulate emissions among instruments

NanoMet3 gives a very low soot emission factors per kg of fuel comparing with MSS and EEPS. NanoMet3 collects only non-volatile particles and between the range 10-700 nm. But, on comparing them with MSS, which measures soot particles, the difference in the soot emission factors between them were higher and not correlated. The lower soot emission factors per kg of fuel gives a very low specific emission. This can be due to the different methods employed by the instruments.

On comparing the calculated specific particulate emissions among these instruments as shown in the figure 4.9 and 4.10, Nanomet3 doesn't identify any high emitters, instead gives a different result against the result obtained from both MSS and EEPS (the result indicates high emitters or not). Buses, AKA 7298, 2AE 8019 and 5J2 7127 were high emitters (from the MSS data; EEPS data wasn't used for it includes volatile fractions, sulphates in the measurement) and didn't show any significant result in the NanoMet3 data.

Hence, the results from NanoMet3 weren't compared further in the study and only the data from MSS for the specific particulate mass and EEPS for specific particulate number were approached.

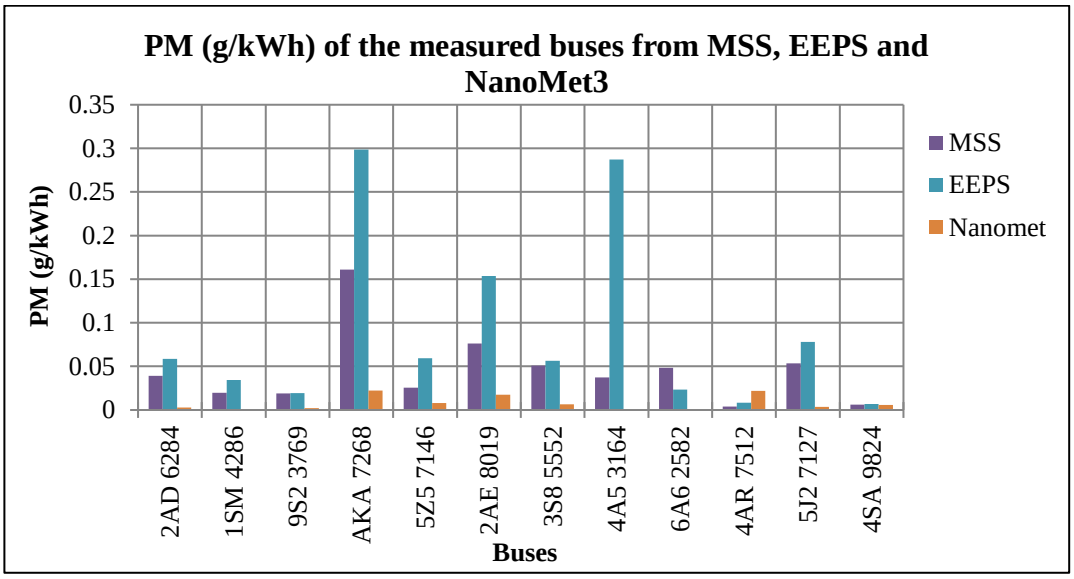

Figure 4.9 Comparison of PM (g/kWh) of the measured buses from MSS, EEPS and Nanomet3 (27.10.2017)

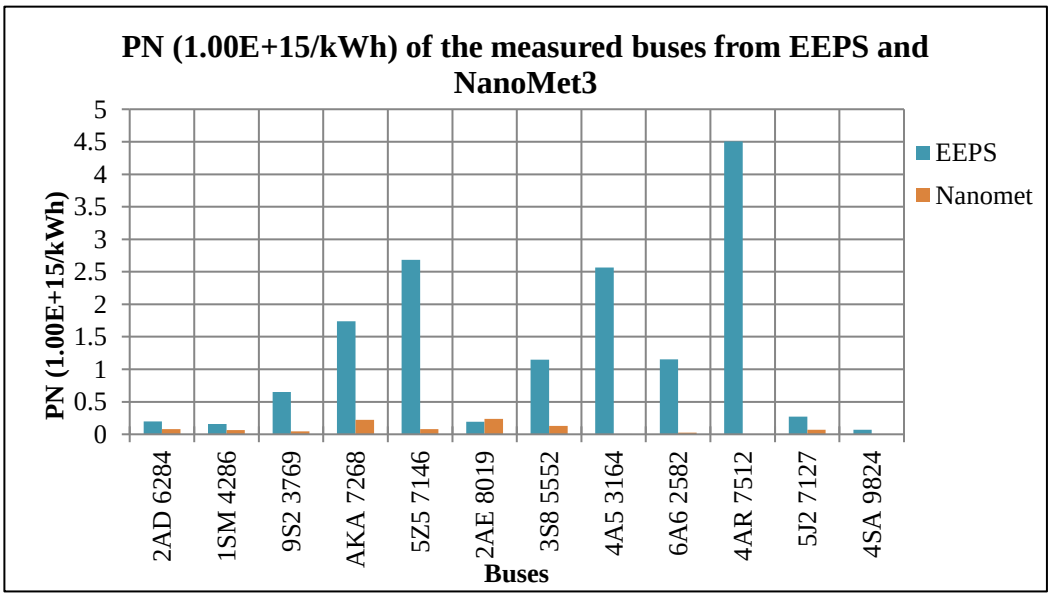

Figure 4.10 Comparison of PN (1.00E+15/kWh) of the measured buses from EEPS and Nanomet3 (27.10.2017)

In the figure 4.11, the specific particulate mass was from the MSS data (for it will be used to find the high emitters) and specific particulate number as from the EEPS data. There

were correlations found between the specific particulate mass and specific particulate number for some of the measured vehicles and some shows discrepancies. These discrepancies can be that the corresponding data point has large number of nanoparticles which accounts for a very low mass. The chart was plotted for the vehicles which were measured (Carbon dioxide detected, which is an indication that the instrument captures the vehicle's emissions).

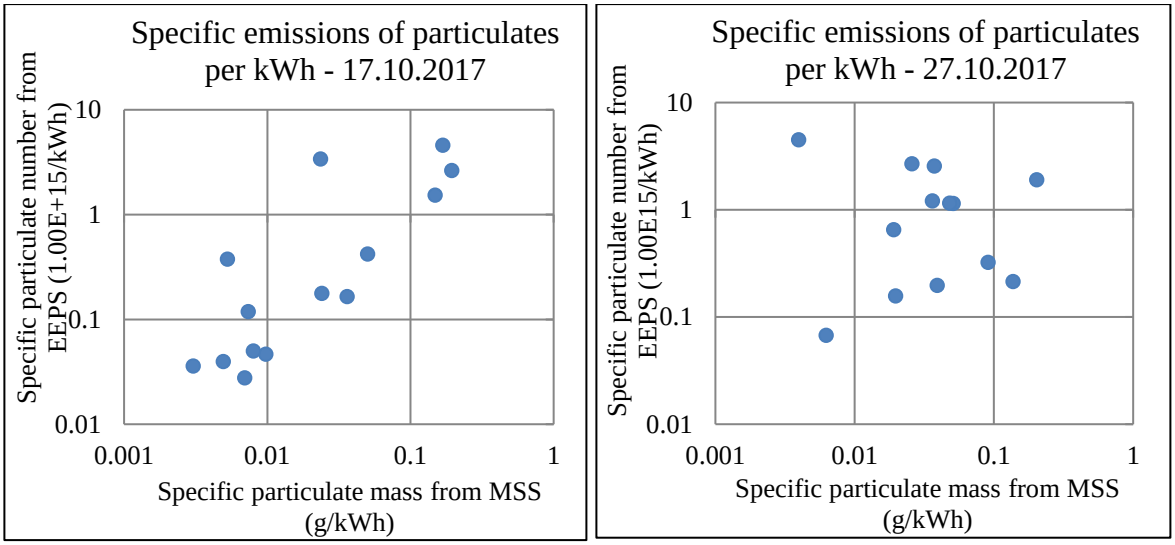

Figure 4.11 Logarithmic scale of specific emissions of particulates per kWh – 17.10.2017 and 27.10.2017

4.12 Comparison of fuel specific emission factors among different resolution techniques

The fuel specific emission factors were compared with the raw data (5 Hz data) and the resolved measurement of data (1 Hz – maximum and averaging). Table 4.8 – 4.10 shows the fuel specific emission factors calculated from the raw data, resolved data for 1 Hz – by maximum approach and averaging approach for the high emitters. The blue box in the below tables interprets that the instrument didn't measure for that bus.

Vehicle	Soot mass factor, (mg/kg of fuel) from MSS data		
	Raw data (from MSS - 5Hz)	Resolved measurement of data (1 Hz) from MSS by Maximum	Resolved measurement of data (1 Hz) from MSS by Averaging
AKA 7268	808	810	644
5S6 6474	595	596	514
2AE 8016	588	548	305
5AE 7908	356	341	102
5J2 7127	364	363	214

Table 4.8 Soot mass factor (mg/kg of fuel) compared by calculating using Raw data, Maximum approach and averaging approach for the MSS data

Vehicle	Soot mass factor, (mg/kg of fuel) from EEPS data		
	Raw data (from EEPS - 5Hz)	Resolved measurement of data (1 Hz) from EEPS by Maximum	Resolved measurement of data (1 Hz) from EEPS by Averaging
AKA 7268	1195	1195	1022
5S6 6474	1347	1358	1259
2AE 8016	608	630	446
5AE 7908	0	0	0
5J2 7127	382	391	312

Table 4.9 Soot mass factor (mg/kg of fuel) compared by calculating using Raw data, Maximum approach and averaging approach for the EEPS data

Vehicle	Soot number factor, (1.00E+15/kg of fuel) from EEPS data		
	Raw data (from EEPS - 5Hz)	Resolved measurement of data (1 Hz) from EEPS by Maximum	Resolved measurement of data (1 Hz) from EEPS by Averaging
AKA 7268	8.9	8.7	7.9
5S6 6474	7.0	6.9	6.7
2AE 8016	1.1	1.0	0.9
5AE 7908	0	0	0
5J2 7127	1.5	1.5	1.2

Table 4.10 Soot number factor (1.00E+15/kg of fuel) compared by calculating using Raw data, Maximum approach and averaging approach for the EEPS data

Therefore, from the tables 4.8 - 4.10, Maximum approach shows better correlation to the Original raw data than the averaging approach. Hence, selecting the maximum value approach was chosen in this study.

4.13 Comparison of specific particulate emissions among maximum and area value

Another factor to be investigated is that: the peaks were continuous. So, the basic assumption for employing the maximum value rather than the area value calculated by the area counter from the window was to be justified. It was seen that the specific particulate mass calculated using area value is always less than using max value. Hence, the vehicles other than the high emitters are also assumed to have a lower specific PM value when calculated using area values. So, for easier calculation the maximum value was chosen.

The values of the specific emissions closer to the limits can be argued of being a high emitter or not. Hence, the vehicles with specific emissions closer to the limit were not treated as a high-emitter. Based on the Vehicle Technical data, the recorded vehicles were categorized according to the classes and the Euro limits. The final vales were compared with the limits and the high emitters were deducted. The specific particulate number also includes the SOF and other volatile particles. So, the comparison with the specific particulate mass is

more preferred and the high emitters were found by using the data from MSS. They are 5J2 7127, 5AE 7908, 2AE 8019, 5S6 6474, AKA 7268.

The high emitters were detected by using the maximum value in the area counter. However, these high emitters are essentially checked, by using the area value from the area counter and comparison was made between them and found that the result were the same, except the value found using area value were always lower than the value found by using max value. This is due to low area value of the soot concentrations. This satisfies the condition of not picking the vehicles which were closer to the limit.

Vehicle	Euro Stage	MSS-PM [Using Area] (g/kWh)	MSS-PM [Using Max] (g/kWh)
AKA 7268	II	0.154	0.202
5S6 6474	III	0.119	0.149
2AE 8016	V	0.088	0.137
5AE 7908	VI	0.016	0.084
5J2 7127	VI	0.049	0.09

Table 4.11 Comparison of the result of the high emitters calculated using area and maximum values

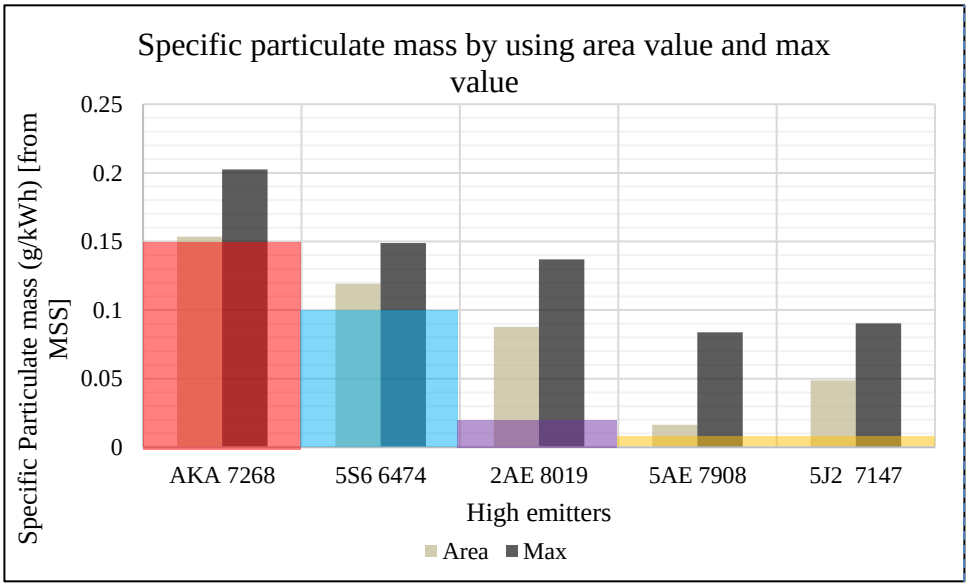

Figure 4.12 Specific particulate mass calculated from MSS by using area and max value

The larger squares are the nominal value of the applicable EURO limit in the figure 4.12.

4.14 Automation of the calculations using Visual Basics for Applications (VBA)

The calculations done in this chapter was automated using Visual Basic for Applications (VBA). The main reason for automating the calculations of the data was to save the time. The particle size distributions which will be discussed in the next chapter and the other attributes of the instruments weren't automated as it is subjective to change to the analyst's interest.

There are certain conditions which was to be presumed and practiced in the Macros:

i. Before the measurement was to be done, the time in the laptops connected to the instruments should be synchronized.
ii. The vehicle should be listed keeping the time from any of the laptop connected to the instruments as a reference time.
iii. For synchronizing the instruments, "Match test" should be performed only once and should have only one significant peak (or continuous peak) and not multiple peak
iv. For analysis, a new file should be opened and must name as "VBA~practice(1).xlsm" or the name of the file used should be changed directly in the VBA coding.
v. The file should already have the time in column A, the data from FTIR i.e., CO in column B and CO_2 in column C, MSS-PM in column D and EEPS-PN in column E.
vi. The coding was done only to 1 Hz data.
vii. The values: fuel C content was already set, [C] = 0.862 because most of the buses were running on diesel fuel, brake specific fuel consumption (bsfc) = 250 g/kWh. The atmospheric pressure and atmospheric temperature on the date of measurement was to be selected by the analyst.

On considering these facts, macros code was written. The macros code was attached in Appendix D.

5 Particle size distributions

5.1 Properties of size distributions

Monodisperse particles are particles having a uniform diameter and mass

Polydisperse particles are particles having different diameter and mass

The size of the particles of a monodisperse was completely defined by a single parameter; particle diameter. The physical properties of the particles were strongly dependent on their sizes. Hence, it was critical to characterize by statistical means (Hinds, 1982, p. 69).

The Engine Exhaust Particle Sizer (EEPS) provides the particles number based on the segregation by mobility diameter. Electrical mobility is the ability of charged aerosol particles to move through a medium in response to an electric field that is pulling them. It was inversely proportional to the effective radius of the charged ion (TSI Incorporated, 2017). Based on this, separation was done into 32 classes. This effective radius was called as mobility diameter. Herein after, it will be referred simply as particle diameter.

The statistical approach was done to the vehicles which exceeds the European emission limit of the stage it belongs. The distribution of the particle numbers used were from the raw data. The analysis was done only to show the trends of the distribution.

5.2 Particle size distribution

The statistical approach was explained in detail to 5J2 7127.

Vehicle Number	**Measured date and Time**	**First year of registration and Euro stage**	**PM (data from MSS)**	**PM (data from EEPS)**	**PN (data from EEPS)**
5J2 7127	27.10.2017 10:07:30.0	2014 (EURO VI)	0.09 g/kWh	0.098 g/kWh	0.32 * 10^{15} /kWh

Table 5.1 Vehicle details and calculated result of PM and PN for 5J2 7127 by different instruments

In Figure 5.1, the basic histogram was used to plot between particle diameter (in nm) and their corresponding number of particles (Particle number distribution was analyzed from data of Engine Exhaust Particle Sizer) (Hinds, 1982, p. 70).

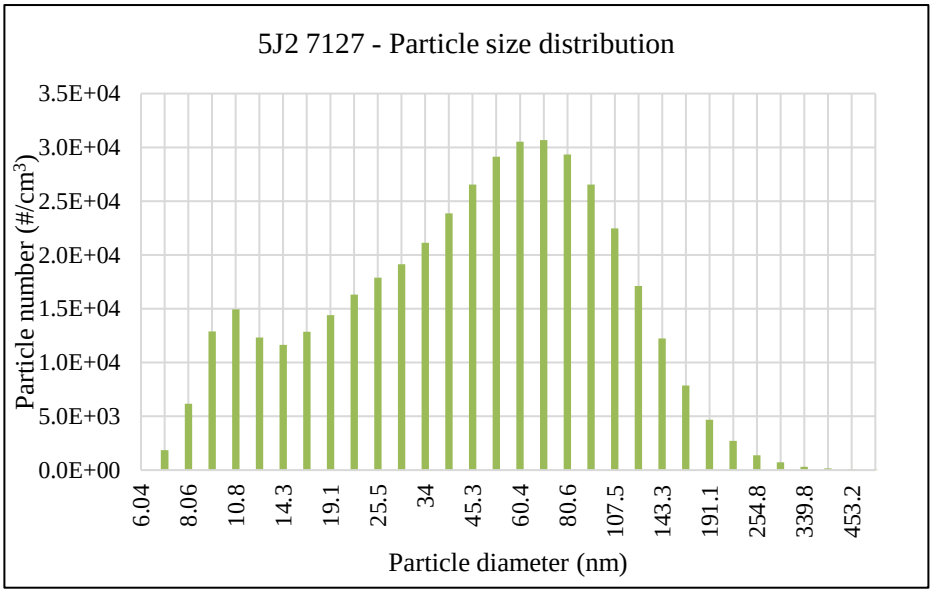

Figure 5.1 Particle size distribution of 5J2 7127 (from EEPS data)

The total number of particles in the sample, N was the sum of all the particles in the sample.

$$N = \sum_i n_i$$

where, n_i was the number of particles in that size range, i

The fraction of the total number of particles per unit of size interval (Hinds, 1982, p. 71) , f_i is,

$$f_i = n_i / N$$

$$\sum_i f_i = 1$$

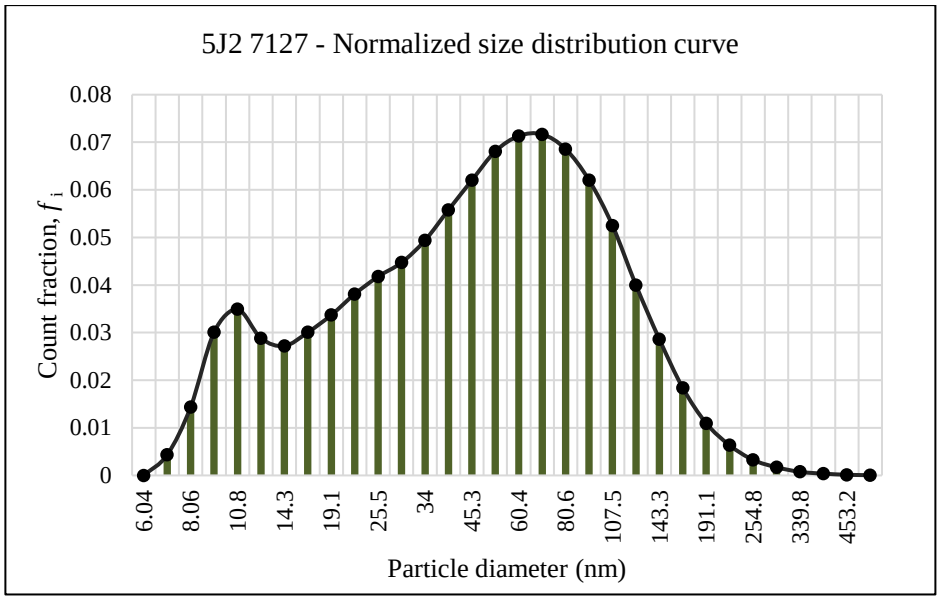

Figure 5.2 Normalized size distribution curve of 5J2 7127(from EEPS data)

The particle frequency distribution curve was the graphical representation of the frequency function or the probability density function. It was also an important way of characterizing the distributed quantities. It was plotted against the particle size in Figure 5.2.

Another important parameter was Count Mean Diameter (CMD) (Hinds, 1982, p. 75). It was the diameter that divides the graphical representation of the numbers into two equal area segments. This value of CMD was also helpful in predicting the presence and inefficiency of filtering in the Diesel Particle Filter.

$$\text{CMD} = \sum_i (n_i * d_i) / N$$

where, d_i was the particle diameter in that size range

The value of CMD for 5J2 7127 was 60 nm. It means half the number of the total particles lies before this value and the remaining half after this value.

The Engine Exhaust Particle Sizer (EEPS) provides the number of particles. The mass of the particle can be calculated by the general formula of density of the particle multiplied by its volume. The shape of the particle was assumed to be sphere. But generally, particles were polydisperse. So, this assumption can be compensated by taking an effective density of the particles according to their sizes. The default particle density used in EEPS was 1 g/cm^3 (TSI Incorporated, 2017). The effective density can be calculated by two different techniques: Mass mobility technique and Aerodynamic size technique (TSI Incorporated, 2017).

Mass mobility technique was employed by Park, *et al.,* (2003), who found that the effective density of soot particles generated by a diesel engine decreased as particle size increased, ranging from 1.2 g/cm^3 at 50 nm, down to 0.3 g/cm^3 at 300 nm. Aside from particle size, density was also affected by engine load and fuel consumption.

Another experimental method was to combine electrical mobility sizing with aerodynamic sizing. This technique called as Aerodynamic size technique was employed by Maricq and Xu (2004) (Maricq & Xu, 2004). The experiment was carried out in LDD (Light Duty Diesel) and GDI (Gasoline Direct Injection). The effective particle density decreases with the increase in particle size, correlates with the Park *et al* work (Park, et al., 2003).

The mass mobility approach was chosen because, the experiment done by Park *et al* was for general diesel engines and the instrument EEPS works on the principle of Electrical mobility.

The volume of the particles was assumed to be the volume of the sphere.

Volume of the particle, $V = 1/6 * \pi * d^3$

where, d was the particle diameter

Mass of the particle, $m = \rho_{eff} * V$

where, ρ_{eff} was the effective density of the particle (Park, et al., 2003) and V was the volume of the particle

The total mass of the particles measured from the EEPS data was calculated as follows

$$M = \sum_i (n_i * m_i)$$

where, m_i was the mass of the particle in that size range, i

The mass estimated or calculated from EEPS size distributions was used to calculate the specific particulate mass. However, the mass value from EEPS and MSS were found to be different. This is because EEPS measures the soot particles along with the Soluble Organic Fractions (SOF's), Sulphate particles or other Volatile particles. Hence, theoretically the value of EEPS should be greater than the value of MSS. But, there were certain uncertainties which is discussed in the next chapter.

In Figure 5.3, the basic histogram was used to plot between particle diameter (in nm) and their corresponding mass of particles (Hinds, 1982, p. 70).

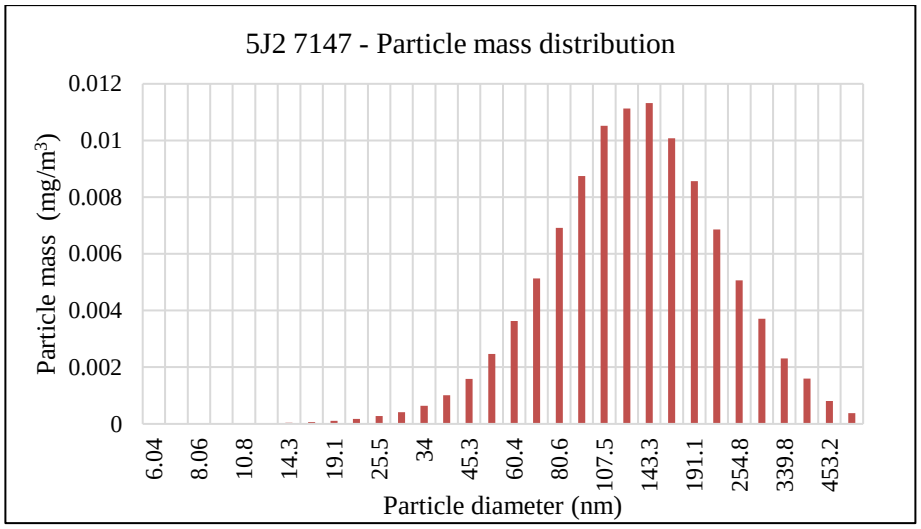

Figure 5.3 Particle mass distribution of 5J2 7127 (from EEPS data)

The fraction of the total mass of particles per unit of size interval (Hinds, 1982, p. 79), g_i was,

$$g_i = m_i / M$$

$$\sum_i g_i = 1$$

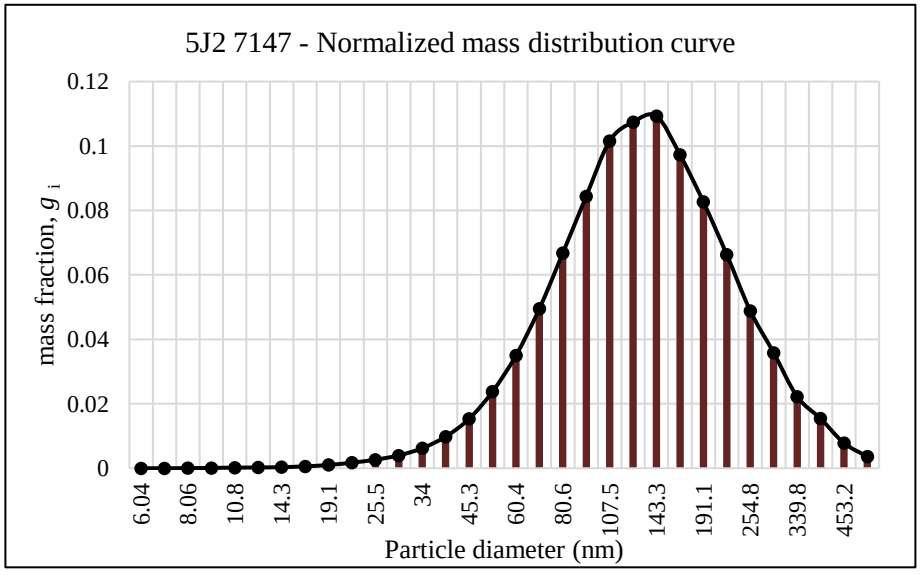

Figure 5.4 Normalized mass distribution curve of 5J2 7127 (from EEPS data)

Mass Mean Diameter (MMD) (Hinds, 1982, pp. 78,79) was the diameter that divides the graphical representation of the masses into two equal area segments.

$$MMD = \sum_i (m_i * d_i) / M$$

where, d_i was the particle diameter in that size range

The value of MMD for 5J2 7147 was 150 nm. It means half the mass of the total particles lies before this value and the remaining half after this value.

5.3 Vehicles with/without DPF (High emitters)

A Diesel Particulate Filter (DPF) is a filter that physically captures and stores the exhaust soot particles. It must be remembered that traps may have limited effectiveness, or be totally ineffective, in controlling the non-solid fractions of PM, such as the SOF or sulfate particulates. Particulate filters tend to increase the formation of nanoparticles through nucleation. In effect, DPFs reduce the numbers of mostly solid agglomeration mode particles, replacing them by mostly liquid nuclei mode nanoparticles (Majewski, 2001).

The presence of DPF can be inferred by the distributions of the particle size. For vehicles without DPF, the peak number of particles can be seen around the particle diameter of greater than 60 nm (Majewski, 2001). This inference was shown for the vehicle which was measured and not a high emitter. 4AR 7512, First year of registration: 2015, EURO V. It has a DPF. And to a high emitter 2AE 8019 and 5AE 0660, which is a EURO VI Diesel M1 type vehicle. The Particle size and mass distribution, Count Mean Diameter (CMD) and Mass Mean Diameter (MMD) were also mentioned below. But two high emitters have a Count Mean Diameter (CMD) of around 50 nm (which is 10 nm less than threshold value of CMD for vehicles without DPF).

5.3.1 Vehicle with DPF

4AR 7512 has a Count Mean Diameter (CMD) of 10 nm and Mass Mean Diameter (MMD) of 84 nm.

Vehicle Number	Measured date and Time	First year of registration and Euro stage	PM (data from MSS)	PM (data from EEPS)	PN (data from EEPS)
4AR 7512	27.10.2017 10:06:35	2015 (EURO V)	0.004 g/kWh	0.008 g/kWh	$4.5 * 10^{15}$ /kWh

Table 5.2 Vehicle details and calculated result of PM and PN for 4AR 7512 by different instruments

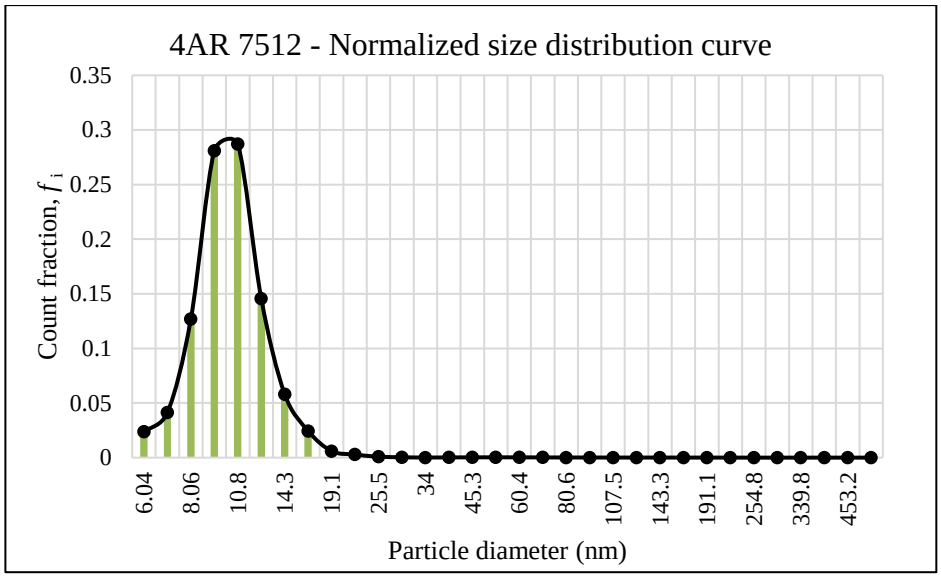

Figure 5.5 Normalized size distribution curve of 4AR 7512 (from EEPS data)

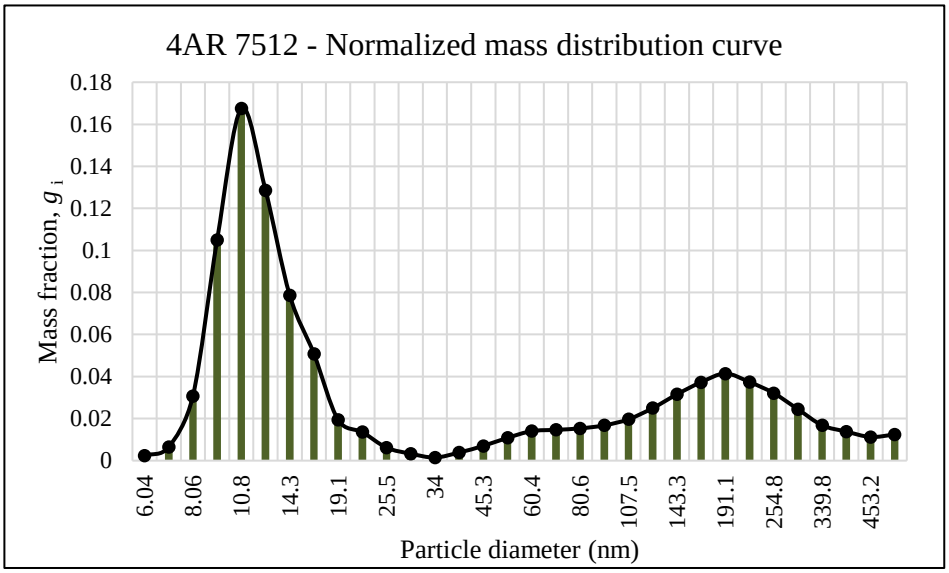

Figure 5.6 Normalized mass distribution of 4AR 7512 (from EEPS data)

The high numbers in the specific particulate number was due to the formation of nanoparticles through nucleation. DPF reduces the solid agglomeration mode particles, replacing them by mostly liquid nuclei mode nanoparticles. These particles are non-volatile particles. European emission standards prescribe only for the non-volatile particles and on comparing the specific particulate mass from MSS and EEPS, they are not a high emitter.

5.3.2 Vehicles without DPF

The high emitter 2AE 8019 has a CMD of 72 nm and MMD of 202 nm.

Vehicle Number	Measured date and Time	First year of registration and Euro stage	PM (data from MSS)	PM (data from EEPS)	PN (data from EEPS)
2AE 8019	27.10.2017 09:33:05	2011 (EURO V)	0.14 g/kWh	0.15 g/kWh	0.21 * 10^{15} /kWh

Table 5.3 Vehicle details and calculated result of PM and PN for 2AE 8019 by different instruments

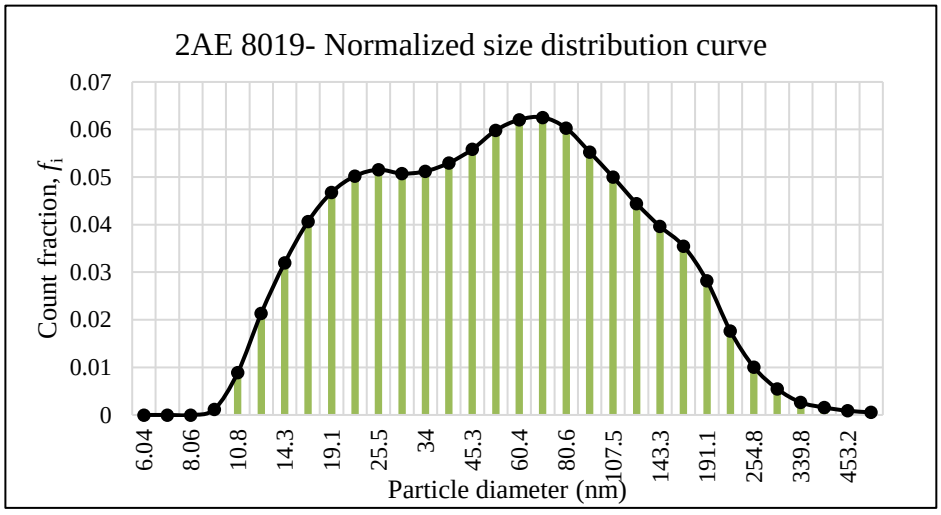

Figure 5.7 Normalized size distribution curve of 2AE 8019 (from EEPS data)

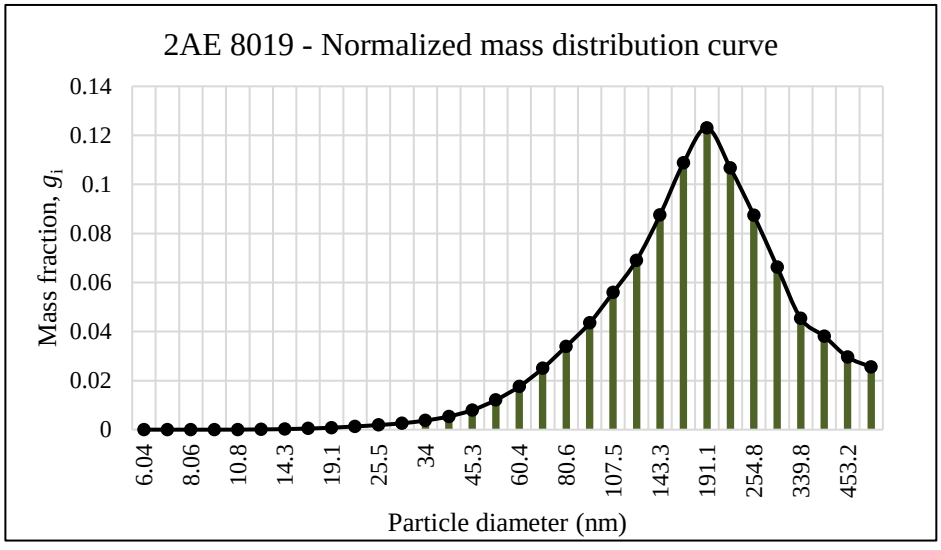

Figure 5.8 Normalized mass distribution curve of 2AE 8019 (from EEPS data)

But, 5AE 0660 belongs to class M1 (Vehicles used for carriage of passengers, not more than eight seats in addition to driver's = 9; Typically, a car) and EURO VI vehicle, which should typically have a DPF. But, it was listed in the sub-chapter, Vehicles without DPF for the particle size distributions for this vehicle 5AE 0660 behaves like a vehicle without DPF. It has CMD of 70 nm and MMD of 203 nm. The specific emissions were calculated on terms of per km. PM = 0.146 g/km (It was calculated by multiplying soot mass factor with fuel density, ρ = 0.832 kg/l (DieselNet, 2012) and an assumed fuel consumption value of 4 l/100 km). This vehicle wasn't listed in the results of detecting high emitters as the results were dedicated only to the buses but the trends in the particle size distributions was shown in the figures below.

Vehicle Number	Measured date and Time	First year of registration and Euro stage	PM (data from MSS)	PM (data from EEPS)	PN (data from EEPS)
5AE 0660	17.10.2017 08:27:40	2016 (EURO VI)	0.19 g/km	0.26 g/km	0.39 * 10^{15} /km

Table 5.4 Vehicle details and calculated result of PM and PN for 5AE 0660 by different instruments

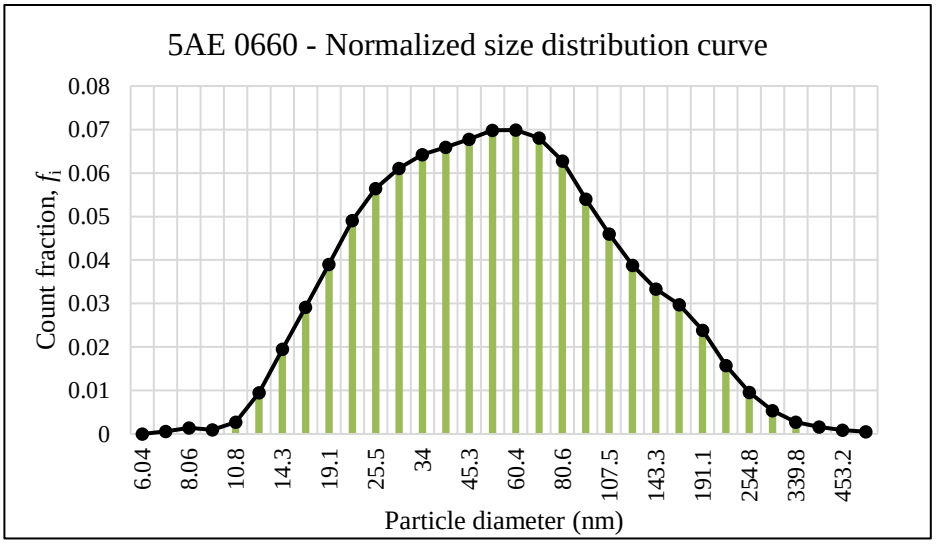

Figure 5.9 Normalized size distribution curve of 5AE 0660 (from EEPS data)

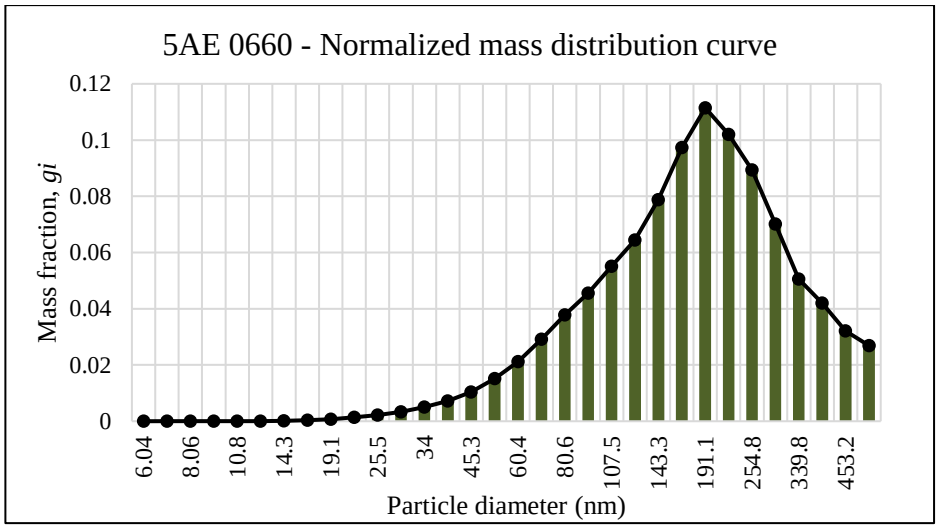

Figure 5.10 *Normalized mass distribution of 5AE 0660 (from EEPS data)*

6 Emission factors of buses

Out of 120 vehicles (including the multiple occurrences of the same vehicle) recorded, only 58 buses were measured. It means that carbon dioxide traces were found only for 58 buses in the data subset. The distribution of the measured vehicles according to the EURO stages they belong are shown in the table 6.1.

EURO Stage	Number of measured vehicles
I	0
II	4
III	8
IV	1
V	11
VI	34

Table 6.1 Distribution of the number of measured vehicles - by EURO Stages

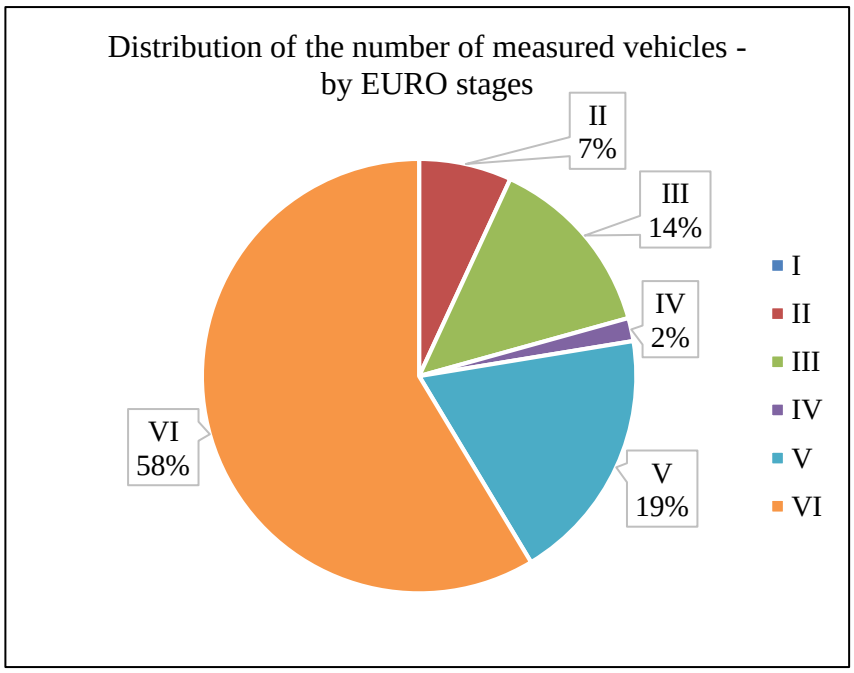

Figure 6.1 Distribution of the number of measured vehicles – by EURO stages

The measurement result of the buses on 17.10.2017 and 27.10.2017 were shown in detail in the tables 6.2 and 6.3. The particulate mass was calculated from MSS data and EEPS

data. The particulate mass from the EEPS data was a derived quantity (Park, et al., 2003). The specific particulate emissions from EEPS data includes the non-volatile fractions, sulphates, etc. in their measurement. Hence, the high emitters were detected only from the MSS data and was shown in the figure 6.2. Figure 6.3, shows the distribution of the overall particulate mass emissions based on the EURO stages.

From the measurement, 5 of them were detected as high emitters, i.e., 9% of the buses measured. They are 5J2 7127, 5AE 7908, 2AE 8019, 5S6 6474, AKA 7268. They are also represented in bold letters in the table 6.2 and 6.3.

Time of measurement	Vehicle Registration number, first year of registration, EURO stage and Vehicle type				MSS-PM (g/kWh)	EEPS-PM (g/kWh)	EURO PM LIMIT (g/kWh)	EEPS-PN (1E+15/kWh)
8:04:30.0	ALC 1225	2001	IIB	M3-D	0.082	0.138	0.15	3.406
8:43:20.0	3B5 4537	2005	III	M3-D	0.024	0.130	0.10	3.406
8:43:35.0	4AI 8782	2014	VI	M3-D	0	0.005	0.01	0.115
8:46:35.0	4SA 7848	2017	VI	M3-D	0.003	0.010	0.01	0.036
8:48:25.0	5AE 5124	2016	VI	M3-D	0	0	0.01	0
8:49:50.0	2AD 7690	2011	V	M3-D	0.031	0.039	0.02	0
8:51:40.0	4AR 8026	2015	VI	M3-D	0	0	0.01	0.494
9:07:27.0	4AR 8025	2015	VI	M3-D	0	0	0.01	0
9:10:30.0	5J2 1489	2013	V	M3-D	0	0.013	0.02	0.094
9:11:25.0	4AR 8024	2015	VI	M3-D	0	0	0.01	0
9:16:28.0	4AI 8630	2014	VI	M3-D	0	0.008	0.01	0.102
9:20:27.0	5AB 6129	2015	VI	M3-D	0	0.010	0.01	0.013
9:21:45.0	4AR 7510	2015	VI	M3-D	0	0	0.01	0.347
9:25:45.0	3J9 0188	2010	V	M3-D	0	0	0.02	0
9:26:26.0	4AR 7509	2015	VI	M3-D	0	0	0.01	0.369
9:36:40.0	5Z5 7146	2003	III	M3-D	0.066	0.060	0.10	0.369
9:38:15.0	4AR 8023	2015	VI	M3-D	0.010	0	0.01	0.047
9:41:40.0	3AH 5486	2010	V	M3-D	0.050	0.057	0.02	0.422
9:44:08.0	**5S6 6474**	**2006**	**III**	**M3-D**	**0.149**	**0.339**	**0.10**	**1.538**
9:45:02.0	4AS 3373	2015	VI	M3-D	0.015	0	0.01	0
9:47:10.0	4AR 8026	2015	VI	M3-D	0	0	0.01	0.313
9:51:25.0	5AE 8353	2016	VI	M3-D	0	0	0.01	0
9:56:55.0	4AS 3372	2015	VI	M3-D	0.007	0	0.01	0.119
10:01:40.0	4AR 7511	2015	VI	M3-D	0.007	0	0.01	0.028
10:03:40.0	ALC 1225	2001	IIB	M3-D	0.098	0.152	0.15	0.701
10:07:00.0	4AI 8782	2014	VI	M3-D	0.005	0.007	0.01	0.376
10:09:00.0	4SA 9824	2017	VI	M3-CNG	0	0	0.01	0
10:16:35.0	4AI 8630	2014	VI	M3-D	0	0	0.01	0.171
10:17:20.0	2AD 6291	2011	V	M3-D	0	0.039	0.02	0.157

10:21:25.0	4AR 7510	2015	VI	M3-D	0	0	0.01	0.224
10:26:35.0	**5AE 7908**	**2016**	**VI**	**M3-D**	**0.084**	**0**	**0.01**	**0**
10:32:25.0	2AD 7690	2011	V	M3-D	0.036	0.089	0.02	0.166
10:33:00.0	4AR 8025	2015	VI	M3-D	0	0.024	0.01	0.052
10:34:05.0	4SA 7848	2017	VI	M3-D	0.005	0.010	0.01	0.040
10:36:20.0	4AS 3374	2015	VI	M3-D	0	0	0.01	0
10:40:09.0	4E5 2247	2011	V	M3-D	0	0	0.02	0
10:48:57.0	3S1 3536	2004	III	M3-D	0.019	0	0.10	0

Table 6.2 Measurement result – 17.10.2017 (Bold letters indicate high emitters)

Time of measurement	Vehicle Registration number, first year of registration, EURO stage and Vehicle type				MSS-PM (g/kWh)	EEPS-PM (g/kWh)	EURO PM LIMIT (g/kWh)	EEPS-PN (1E+15/kWh)
9:01:00	4E5 2250	2011	V	M3-D	0	0	0.02	0
9:02:20	2AD 6284	2011	V	M3-D	0.039	0.059	0.02	0.224
9:09:30	4AR 7512	2015	VI	M3-D	0	0	0.01	0
9:10:30	4SA 9822	2017	VI	M3-CNG	0	0	0.01	0
9:12:00	1SM 4286	2011	V	M3-D	0.020	0.034	0.02	0.179
9:15:50	4AS 3372	2015	VI	M3-D	0	0	0.01	0
9:16:35	9S2 3769	2009	IV	M3-D	0.019	0.019	0.02	0.740
9:17:40	**AKA 7268**	**2000**	**IIB**	**M3-D**	**0.203**	**0.292**	**0.15**	2.168
9:24:00	4AS 3373	2015	VI	M3-D	0	0	0.01	0
9:31:55	4AR 7509	2015	VI	M3-D	0.036	0	0.01	1.382
9:32:50	5Z5 7146	2003	III	M3-D	0.026	0.059	0.1	3.051
9:33:05	**2AE 8019**	**2011**	**V**	**M3-D**	**0.137**	**0.147**	**0.02**	0.244
9:36:05	3S8 5552	2005	III	M3-D	0.051	0.056	0.1	1.306
9:41:40	4A5 3164	1999	IIB	M3-D	0.037	0.287	0.15	2.914
9:48:50	5AS 0165	2003	III	M3-D	0	0	0.1	0
9:56:20	4AR 8024	2015	VI	M3-D	0	0	0.01	0
10:03:45	6A6 2582	2006	III	M3-D	0.048	0.023	0.1	1.309
10:06:35	4AR 7512	2015	VI	M3-D	0.004	0.008	0.01	5.121
10:07:30	**5J2 7127**	**2014**	**VI**	**M3-D**	**0.091**	**0.098**	**0.01**	0.367
10:08:00	4AS 3372	2015	VI	M3-D	0	0.017	0.01	1.527
10:09:00	4SA 9824	2017	VI	M3-CNG	0.006	0.007	0.01	0.077

Table 6.3 Measurement result – 27.10.2017 (Bold letters indicate high emitters)

	Not measured
	Measured; but below threshold limit

M3 - Bus; >5 tonnes

D, CNG - Diesel, Compressed Natural Gas

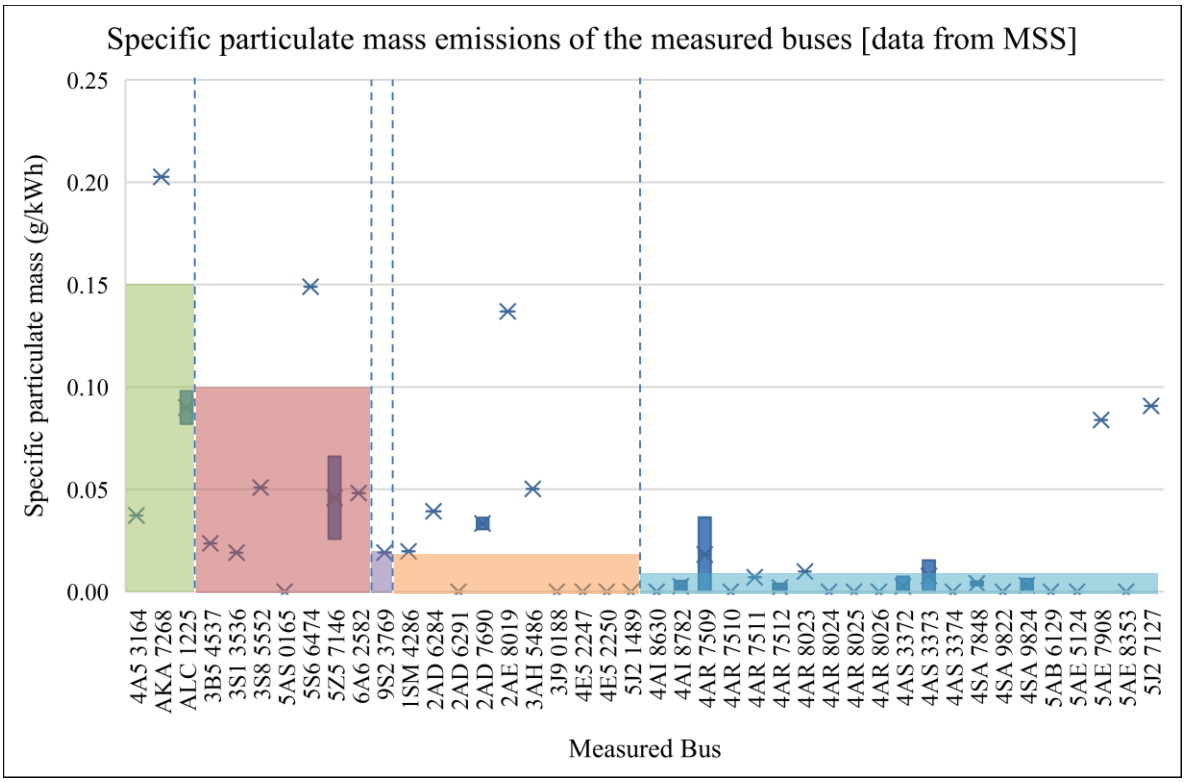

Figure 6.2 Specific particulate mass emissions of the measured buses [data from MSS]

The larger squares are the nominal value of the applicable EURO limit in the figure 6.2.

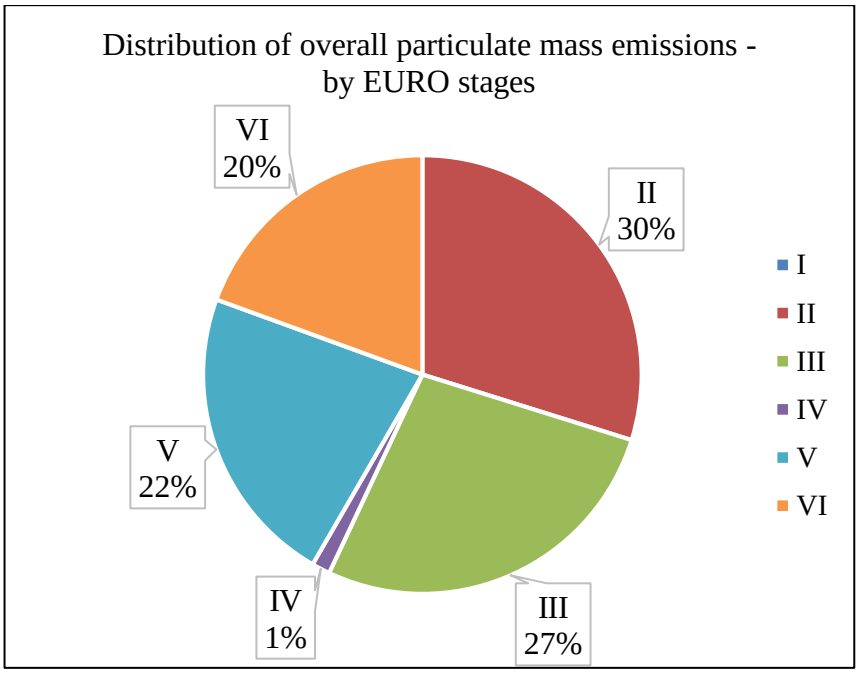

Figure 6.3 Distribution of overall particulate mass emissions – by EURO stages

These 9% of the buses contributes 47 % of the overall vehicle emissions during the measurement (the percentages were inclusive of only the specific particle mass emissions of the buses calculated from MSS). In figure 6.4, rest of the vehicles refers to the rest of the measured vehicles.

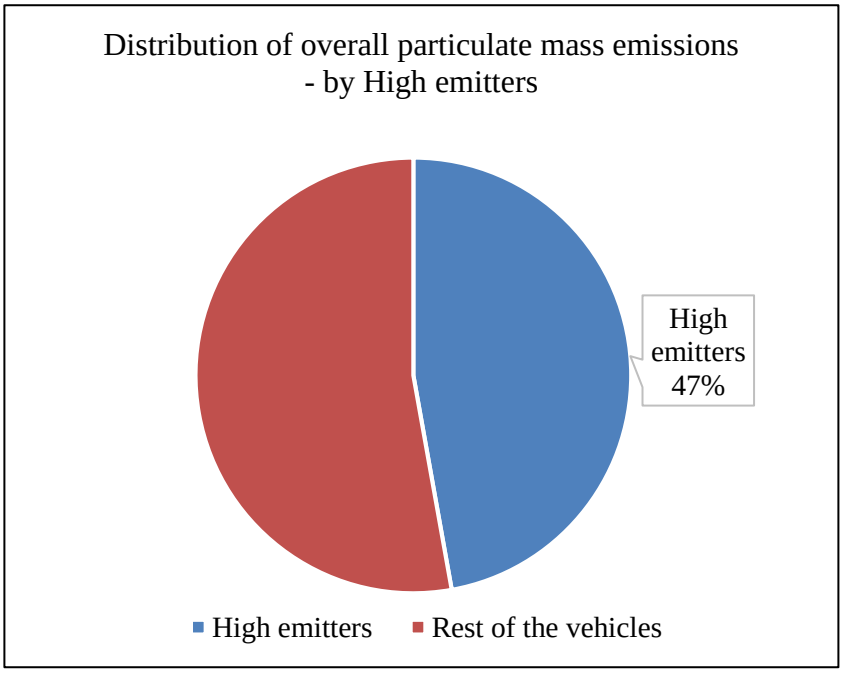

Figure 6.4 Distribution of overall particulate mass emissions – by High emitters

7 Test-to-test variances and uncertainty in the experiment

29 buses were found to be recorded multiple times on the same day of measurement as well as on the other day. These buses were shown in the table 7.1 along with the calculated specific particulate mass (from both the instruments; MSS and EEPS) and specific particulate number (from EEPS). Out of 29 buses, only 10 of them can be used to study the Test-to-test variances (if all the instruments are less than the detection limit for all the times was also included, i.e., 3 vehicles) where in rest of them, either CO_2 wasn't measured (or less than the detection limit) or all the gases or particles of interest weren't measured or less than the detection limit. In these 6 buses produces the same result, but not a consistent one. The calculated specific particulate mass between the measurements of the multiple passes: from MSS has the variability, up to 40 % and from EEPS, up to 50 % and the variability in specific particulate number from EEPS was even greater than 90 %. The variations in the value of the specific particulate emissions, if lesser and didn't affect the result then they weren't analyzed in detail. The main reason for not analyzing was the lack of operating history. So, the fact that the vehicles were operating under different conditions or load was assumed. And one of these buses gives a contradicting or a different result.

Vehicle	Measured date	Measured time	PM (data from MSS) (g/kWh)	PM (data from EEPS) (g/kWh)	PN (data from EEPS) (1E+15/kWh)
2AD 7690	17.10.2017	8:49:50	0.031	0.039	0
	17.10.2017	10:32:25	0.036	0.089	0.166
2ST 7861	17.10.2017	8:18:20			
	17.10.2017	10:46:40	CO_2, MSS, EEPS-PN, EEPS-m were below threshold values		
3AH 5486	17.10.2017	9:41:40	0.050	0.057	0.422
	17.10.2017	8:25:10	CO_2, MSS, EEPS-PN, EEPS-m were below threshold values		
3S1 3536	17.10.2017	8:30:30	CO_2 wasn't measured		
	17.10.2017	10:48:57	0.019	0	0
4A5 3164	17.10.2017	9:41:40	CO_2, MSS, EEPS-PN, EEPS-m were below threshold values		
	27.10.2017	9:41:40	0.037	0.287	2.914
4AI 8630	17.10.2017	8:25:00	CO_2 wasn't measured		
	17.10.2017	9:16:28	0	0	0.171

	17.10.2017	10:16:35	0	0.008	0.102
4AI 8782	17.10.2017	8:43:35	0	0.005	0.115
	17.10.2017	10:07:00	0.005	0.007	0.376
4AR 7509	17.10.2017	8:33:15	CO_2 wasn't measured		
	17.10.2017	9:26:26	0	0	0.369
	27.10.2017	9:31:55	0.036	0	1.382
4AR 7510	17.10.2017	8:29:10	CO_2 wasn't measured		
	17.10.2017	9:21:45	0	0	0
	17.10.2017	10:21:25	0	0	0
4AR 7511	17.10.2017	8:37:00	CO_2, MSS, EEPS-PN, EEPS-m were below threshold values		
	17.10.2017	10:01:40	0.007	0	0.028
	27.10.2017	9:10:10	CO_2, MSS, EEPS-PN, EEPS-m were below threshold values		
4AR 7512	27.10.2017	9:09:30	MSS, EEPS-PN, EEPS-m were below threshold values		
	27.10.2017	10:06:35	0.004	0.008	5.121
4AR 8023	17.10.2017	8:40:05	CO_2, MSS, EEPS-PN, EEPS-m were below threshold values		
	17.10.2017	9:38:15	0.010	0	0.047
4AR 8024	17.10.2017	8:17:20	CO_2, MSS, EEPS-PN, EEPS-m were below threshold values		
	17.10.2017	9:11:25	0	0	0
	27.10.2017	9:56:20	0	0	0
4AR 8025	17.10.2017	8:15:40	CO_2, MSS, EEPS-PN, EEPS-m were below threshold values		
	17.10.2017	9:07:27	0	0	0
	17.10.2017	10:33:00	0	0.024	0.052
	27.10.2017	9:38:25	CO2, MSS, EEPS-PN, EEPS-m were below threshold values		
4AR 8026	17.10.2017	8:51:40	0	0	0.494
	17.10.2017	9:47:10	0	0	0.313
	17.10.2017	10:47:35	CO2 wasn't measured		
4AS 3372	17.10.2017	9:56:55	0.007	0	0.119
	27.10.2017	9:15:50	0	0	0
	27.10.2017	10:08:00	0	0.017	1.527
4AS 3373	17.10.2017	8:22:35	CO2, MSS, EEPS-PN, EEPS-m were below threshold values		
	17.10.2017	9:31:30	0	0	0
	17.10.2017	9:45:02	0.015	0	0
	27.10.2017	9:24:00	0	0	0
4AS 3374	17.10.2017	8:06:30	CO2, MSS, EEPS-PN, EEPS-m were below threshold values		
	17.10.2017	10:36:20	0	0	0
	27.10.2017	9:00:00	CO2 wasn't measured		
4E5 2250	17.10.2017	8:33:05	CO2, MSS, EEPS-PN, EEPS-m were below threshold values		
	27.10.2017	9:01:00	0	0	0
4S8 3331	17.10.2017	9:22:30	0	0	0
	27.10.2017	9:21:15	CO2 wasn't measured		

4SA 7848	17.10.2017	8:46:35	0.003	0.010	0.036
	17.10.2017	10:34:05	0.005	0.010	0.040
4SA 9817	17.10.2017	9:45:35	0	0	0
	27.10.2017	9:45:46	CO2 wasn't measured		
4SA 9824	17.10.2017	10:09:00	0	0	0
	27.10.2017	10:09:00	0.006	0.007	0.077
4SA 9826	17.10.2017	9:43:30	CO2, MSS, EEPS-PN, EEPS-m were below threshold values		
	27.10.2017	9:30:40	CO2, MSS, EEPS-PN, EEPS-m were below threshold values		
5AE 5124	17.10.2017	8:48:25	CO2, MSS, EEPS-PN, EEPS-m were below threshold values		
	17.10.2017	9:31:40	CO2 wasn't measured		
5AE 8353	17.10.2017	8:03:00	CO2, MSS, EEPS-PN, EEPS-m were below threshold values		
	17.10.2017	9:51:25	0	0	0
5S6 6474	17.10.2017	9:44:08	0.149	0.339	1.538
	27.10.2017	9:43:40	0.089	0.110	1.395
5Z5 7146	17.10.2017	9:36:40	0.066	0.060	0.665
	27.10.2017	9:32:50	0.026	0.059	3.051
ALC 1225	17.10.2017	8:04:30	0.082	0.138	8.776
	17.10.2017	10:03:40	0.098	0.152	0.617

Table 7.1 Test-to-test variance of all the buses recorded along with specific particulate emissions and comments

	Not measured
	Measured; but below threshold limit

Instruments and Measurements has their own detection limit and uncertainties. However, these parameters are related with each other. In the above table 7.1, there were 9 occurrences stated that the "CO_2 wasn't measured". The measurement of Carbon dioxide is a direct indication of whether the vehicle was measured. Out of these occurrences, in three of them the instrument was turned off for transferring of the data. Whereas in the rest, the instrument didn't pick any signal which can be either too low within the uncertainty in the instrument.

Another case in the table 7.1, 18 occurrences were depicted as "CO_2, MSS, EEPS-PN, EEPS-m were below threshold values". It means that all the gases and the particle concentrations weren't measured and within the uncertainty in the experiment. Or else, the vehicle by itself doesn't emit particles. This criterion can be accepted if there were some traces of CO_2 measured, but wasn't.

7.1 Detection of variations

Again, from the table 7.1, most of the vehicles which were detected for multiple times were measured only once. In the case of the vehicle, 5S6 6474 both the times the measurement was done and in the first occurrence it was a high emitter and in the second occurrence, it wasn't a high emitter. The vehicle details and the calculated result of PM and PN for 5S6 6474 for both the occurrence is shown in the table 7.2 below.

Occurrence	**Measured date and time**	**First year of registration and Euro stage**	**PM (data from MSS)**	**PM (data from EEPS)**	**PN (data from EEPS)**
1	17.10.2017 09:44:08	2006 (EURO III)	0.15 g/kWh	0.3 g/kWh	$1.5 * 10^{15}$ /kWh
2	27.10.2017 09:43:40		0.089 g/kWh	0.11 g/kWh	$1.4 * 10^{15}$ /kWh

Table 7.2 Vehicle details and calculated result of PM and PN for 5S6 6474 recorded at 09:44:08 on 17.10.2017 and 09:43:40 on 27.10.2017 by different instruments

From the table 7.2, the vehicle exceeds the emission limits in the first occurrence and was slightly below the limit in the second occurrence. On comparing the net CO_2 values, it was 156 ppm and in the second occurrence, net CO_2 value was 27 ppm. This can be due to the difference in dilution in the atmosphere.

The figure 7.2 (left) below, also shows that the mass distribution curve is leaned towards the particles of greater size and has a fraction of higher magnitude. This vehicle was treated as a high emitter.

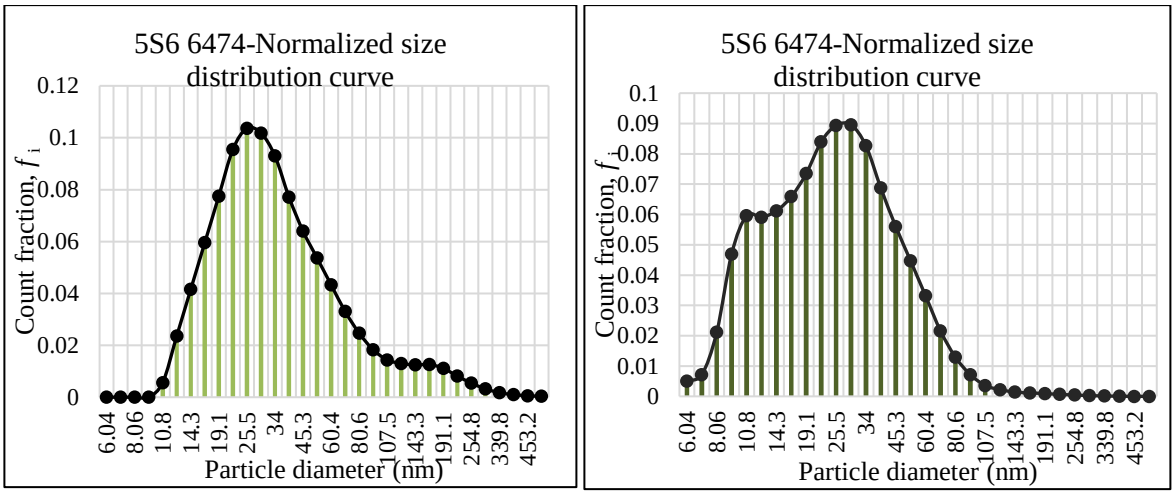

Figure 7.1 Normalized size distribution curve of 5S6 6474 recorded at 09:44:08 on 17.10.2017 (left) and 09:43:40 on 27.10.2017 (right)

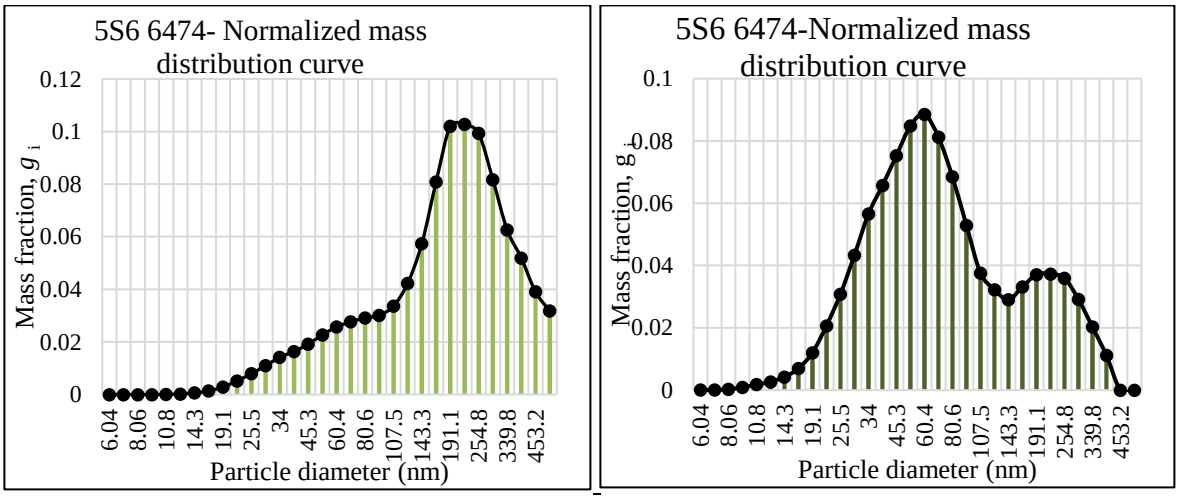

Figure 7.2 Normalized mass distribution curve of 5S6 6474 recorded at 09:44:08 on 17.10.2017 (left) and 09:43:40 on 27.10.2017 (right)

7.2 Difference between the instruments

There were many uncertainties recorded during the measurement and they were discussed in this chapter. Another main uncertainty between the instruments was the discrepancy in the Particulate mass measured data (from MSS) and the derived data (from EEPS). The derived data was found from the particulate number measurement from EEPS, which was already discussed in the above chapter.

From the Manufacturer's point, Micro Soot Sensor measures only the soot particles by employing Photoacoustic measurement method. Engine Exhaust Particle Sizer measures all particles. But, however particles were a mixture of soot, sulphates and other volatile compounds. So, ideally the derived particulate mass from EEPS should be greater than the measured particulate mass from MSS. But, it showed an opposite result for the three vehicles: 5Z5 7146, 6A6 2582 and 9S2 3769

Vehicle	Measured date and time	First year of registration and Euro stage	Particulate mass (by MSS), g/kWh	Particulate mass (by EEPS), g/kWh
5Z5 7146	17.10.2017 9:36:40	2003 (EURO III)	0.066	0.060
9S2 3769	27.10.2017 9:16:35	2009 (EURO IV)	0.019	0.018
6A6 2582	27.10.2017 10:03:45	2006 (EURO III)	0.048	0.023

Table 7.3 Inconsistency between the instruments for the particulate mass measurement

This inconsistency can be due to the difference in methods used by each instrument and can also be due to the concentration of the gases inside the sample line tube during the time when the plumes were distributed.

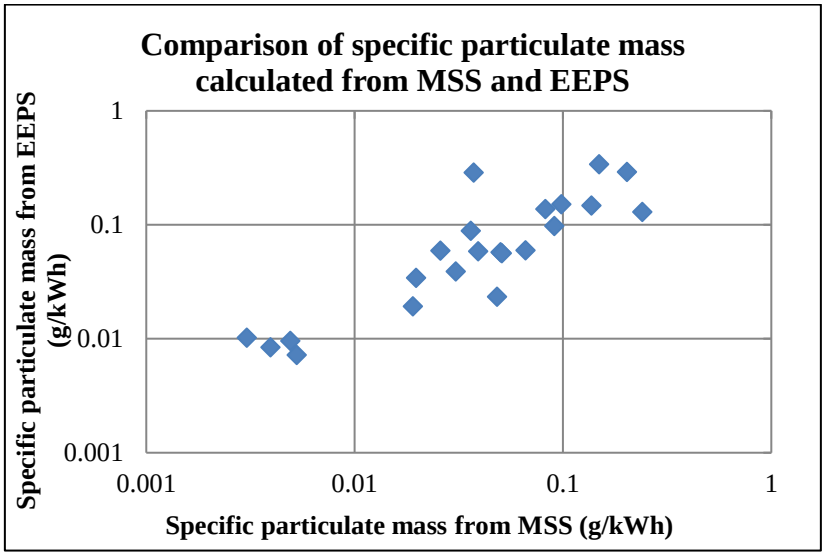

Figure 7.3 Comparison of specific particulate mass calculated from MSS and EEPS (logarithmic scale)

Figure 7.3, shows the correlation between the specific particulate mass calculated from MSS and derived EEPS. The results from both the instruments were correlated to a reasonable scale. Except in come of the cases, which were already discussed before.

Discussion

In resolution of the measurement of data, the Maximum approach (selecting the maximum value in the second's frame) was used for they show better correlation with the raw data. Soot emission factors were compared between the measurement resolution approaches – maximum approach and averaging approach. The reduction in the soot emission factors between the maximum approach (max PM or PN/max CO_2) and the averaging approach (average PM or PN / average CO_2) accounts, even up to 28 % in the averaging approach and not more than 3 % in the maximum approach when compared with the Raw data. Hence, resolution of measurement was done by maximum approach.

High emitters were identified from the MSS data, for which it calculates only the soot particles. Hence, the buses with high specific particulate mass on comparing with the limits prescribed for each EURO stage by European emission standards were identified as a high emitter. The data from EEPS which gives particulate number was also used to derive the particulate mass with the aid of effective particulate densities (Park, et al., 2003). However, EEPS detects both the volatile and non-volatile fractions, the data was not used for identifying the high emitters as the distribution of the non-volatile and volatile fractions weren't known. Hence, the data from EEPS was used for comparison of the data between MSS and to find differences between the instruments.

NanoMet3 measures only the non-volatile fractions between the diameter 10-700 nm, but it also gives a very low soot emission factors when compared to the factors from MSS and EEPS data. It didn't identify any high emitters. Hence it wasn't useful for this set-up and wasn't discussed in the study.

High emitters don't have an active Diesel Particulate Filter. The presence of Diesel Particulate Filter (DPF) was inferred by using the Count Mean Diameter (CMD) and the trend in the particle size distributions, for which the vehicle with DPF has its CMD in the range of 10 or 20 nm and without DPF (high emitters) has a range of greater than 60 nm. But two high emitters have a Count Mean Diameter (CMD) of around 50 nm (which is 10 nm less than threshold value of CMD for vehicles without DPF).

Theoretically, specific particulate mass emissions from the EEPS should be greater than the specific particulate mass emissions from MSS, for it measures both the volatile and

non-volatile fractions. In certain cases, it was less compared to MSS. For, a successful measurement or in other words the vehicle was measured, was identified if the instrument can pick the CO_2 measurement. The CO_2 should be greater than the threshold limit. In such cases, the fuel specific emission factors cannot be calculated. If all the measurements were below the threshold limit, except the CO_2 then the vehicle is identified as clean.

Conclusion

In a pilot study conducted in Prague, roadside measurements of exhaust plumes left by individual passing vehicles were analyzed by high time resolution instruments – Fourier Transform Infra-Red spectrometer (FTIR) for measuring CO and CO_2, Micro Soot Sensor (MSS), Engine Exhaust Particle Sizer (EEPS) and NanoMet3 for particle concentrations. The goal of the thesis was to analyze a representative subset of the data from the buses measured in Nádraží Veleslavín on 17.10.2017 and 27.10.2017.

First, the signal strength which is the discrimination between the signals and noises is studied by calculating the Signal to Noise Ratio (SNR). It is defined as the ratio of the mean of the signal to the standard deviation of the noises. The range of the calculated $(SNR)_{dB}$ for all the instruments were 25 ± 5 dB.

The actual detection limit (L_D) in this setup was not the same as the detection limit quoted by the manufacturer, because the experiment was conducted in an open environment. L_D is 3.33 times the standard deviation of the sample without concentration. It is approximately 1.8 times greater than the manufacturer's value for MSS and NanoMet3, whereas EEPS has an L_D of 8480 #/cm^3 and manufacturer's value is 200 #/cm^3.

In resolution of the measurement of data, the Maximum approach (selecting the maximum value in the second's frame) was used for they show better correlation with the raw data. The variations in the fuel specific emission factors between the maximum approach and the raw data were 3 % and between averaging approach and raw data were 28 %.

From the data sets, 5 buses were identified as high emitters i.e., 9% of the measured buses. The high emitters were identified only for the specific particulate mass calculated from MSS. The specific particulate number and the derived specific particulate mass from EEPS includes the SOF and other volatile particles. NanoMet3 measures only the non-volatile fractions between the diameter 10-700 nm, but it gives a very low soot emission factors (average PM or PN / average CO_2) when compared to the factors from MSS and EEPS data. NanoMet3 didn't identify any high emitters. So, the evaluation using the specific particulate mass of MSS is more preferred.

Out of 120 vehicles (including the multiple occurrences of the same vehicle) recorded, 58 buses were measured. The vehicles were termed as measured, if the instrument picks the

CO_2 emissions (CO_2 was above the detection limit). In that, 29 buses were found to be recorded multiple times and only 10 buses can be used to study the Test-to-test variances where in rest of them, either CO_2 wasn't measured or too low within the uncertainty in the instrument. In these 10 buses, 9 of them were classified as clean or as high emitters both the times. One bus was identified once as high emitter, with a difference of tens of percent between the measurements.

The high emitters detected by MSS were 5J2 7127, 5AE 7908, 2AE 8019, 5S6 6474, AKA 7268. These 9 % of the measured vehicle fleet contributes 47 % of the overall vehicle emissions measured. These high emitters contribute excess emissions than the average emissions of the measured buses in their respective EURO stage. With a maximum excess percentage occurring in EURO VI stage, where the average emission from the buses measured were 0.009 g/kWh and the high emitters (average of the two buses identified as high emitters in EURO VI stage together) contributes 0.09 g/kWh (10 times more than the average emissions produced by buses in EURO VI). Subsequent repair or removal of these high emitters from the fleet can reduce 35 % of the fleet emissions (the percentage was obtained by removing the high emitters and substituting them with the average emissions and the percentages correspond to the data from MSS).

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Appendix

A. Technical data of Micro Soot Sensor plus

Measuring unit	
Measuring range: Measured value concentration of soot (mg/m^3, $\mu g/m^3$)	0.001 – 50 mg/m^3
Display resolution	0.01 mg/m^3
Detection limit	1 $\mu g/ m^3$
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)
Blow by amount of the pressure reduction unit depending on pressure	~ 40 l/min at 1,000 mbar exhaust gas pressure and 25°C
Weight conditioning unit	~15 kg

Technical data of Micro Soot Sensor ^{plus} (AVL LIST GmbH, 2018)

B. Technical data of Engine Exhaust Particle Sizer Spectrometer

Specifications	**Range**
Particle size range	5.6 to 560 nm
Particle size resolution	16 channels per decade (32 total)
Charger mode of operation	Unipolar diffusion charger
Time resolution	10 size distributions/sec
Flow rates Sample flow	10 l/min
Sheath air	40 l/min
Inlet sample temperature	10 to 52°C
Operating temperature	0 to 40°C
Storage temperature	-20 to 50°C
Atmospheric pressure correction range	70 to 103 kPa (700 to 1034 mbar)
Humidity	0 to 90% RH (noncondensing)
User interface	Rotary knob and display; EEPS software
Computer requirements	Pentium® 4 processor, 2 GHz speed or better, at least 512 MB RAM

Operating system required	Windows® XP or better
Weight	32 kg
Sample inlet	3/8-in. Outer diameter (without inlet cyclone)
Cyclone inlet	3/8-in. Outer diameter
Exhaust/Outlet	3/8-in. Outer diameter
Power requirements	100 to 240 VAC, 50/60 Hz, 250W

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

C. Technical data of NanoMet3

Specifications	**Range**
Aerosol	Primarily diluted exhaust gases or air which contains nanoparticles
Concentration range	Sensor: 1E3 to 1E6 #/cm^3; Diluted: 1E4 to 3E8 #/cm^3
Particle size	10 to 700 nm = 0.01 to 0.70 µm
Average particle size range (mode diameter)	10 to 300 nm = 0.01 to 0.30 µm
Inlet gas flow	4.0 l/min, actively fed to the diluter by internal pump
Dilution factor	Standard: 10, 100, 300; Optional one custom DF
Measuring gas	1.0 l/min measuring gas
Power supply	12-24 VDC, max. 60A. 90-240 VAC 50/60 Hz
Power consumption	nominal 650W; 300 W under standard ambient conditions
Evaporation tube temperatures	Ambient to 300 °C / 572 °F; accuracy ±3 °C / 5.4 °F
Assembly	19" case with handles
Weight	approx. 18 kg;

	with complete connections: ca. 23 kg
Operating conditions	Tamb: 5 to 35 °C; 0 to 80%RH, max. 80%@30 °C, linearly degrading to 50%@35 °C, non-condensing
Sensor calibration	standard calibration with NaCl particles
System calibration	Against PMP-System with soot from CAST @GMD 60 nm and 85 nm

Technical data of NanoMet3 (Testo SE & Co. KGaA, 2017)

D. Macros (VBA)

```
Sub Analysis()

Dim Lastcolumn As Long
Dim Lastrow As Long
Dim b As Long

        Lastrow = ActiveSheet.Cells(Rows.Count, 1).End(xlUp).Row
        b = Lastrow / 5
        Lastcolumn = ActiveSheet.Cells(1, Columns.Count).End(xlToLeft).Column

        Range("F1").Select
        ActiveCell.FormulaR1C1 = "Frequency"
        Range("H1").Select
        ActiveCell.FormulaR1C1 = "CO~1Hz"
        Range("I1").Select
        ActiveCell.FormulaR1C1 = "CO2_low~1Hz"
        Range("J1").Select
        ActiveCell.FormulaR1C1 = "MSS~1Hz"
        Range("K1").Select
        ActiveCell.FormulaR1C1 = "PN~1Hz"
        Range("L1").Select
        ActiveCell.FormulaR1C1 = "Time~1Hz"

        Range("F3").Select
        ActiveCell.FormulaR1C1 = Application.InputBox("Enter 5", "Frequency")

Dim n As Long
Dim m As Long
Dim i As Long
Dim a As Long
Dim c As Long
Dim d As Long
Dim e As Long
Dim f As Long

        Range("H2").Select
```

```
For g = 2 To Lastcolumn

        For c = 1 To b

                m = ActiveCell.Row
                e = (5 * (m - 1)) – 2
                f = (5 * m) - 3
                MyRange = Sheets(1).Range(Cells(e, g), Cells(f, g))
                ActiveCell.FormulaR1C1 = Application.max(MyRange)
                ActiveCell.Offset(1, 0).Select
                Selection.NumberFormat = "general"

        Next c

                Range("H2").Select
                ActiveCell.Offset(0, g - 1).Select

Next g

        Range("L2").Select

For a = 1 To b

        n = ActiveCell.Row
        i = 5 * (n - 1) + 1
        ActiveCell.FormulaR1C1 = Application.small(Range("A2:A" & Lastrow), i)
        ActiveCell.Offset(1, 0).Select
        Selection.NumberFormat = "hh:mm:ss.0"

Next a

Dim cLastcolumn As Long
Dim cmax As Double
Dim cn As Double

        Range("L1").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        Range("N2").Select
        Range(Selection, Selection.End(xlDown)).Select
        ActiveSheet.Paste
        Columns("N:N").EntireColumn.AutoFit
        Range("H1").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        Range("O2").Select
        Range(Selection, Selection.End(xlDown)).Select
        ActiveSheet.Paste
        Range("I1").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        Range("Q2").Select
        Range(Selection, Selection.End(xlDown)).Select
        ActiveSheet.Paste
        Range("L2").Select
        Range(Selection, Selection.End(xlDown)).Select
```

```
        Selection.Copy
        Range("T3").Select
        Range(Selection, Selection.End(xlDown)).Select
        ActiveSheet.Paste
        Columns("T:T").EntireColumn.AutoFit
        Range("J1").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        Range("U2").Select
        Range(Selection, Selection.End(xlDown)).Select
        ActiveSheet.Paste
        Range("L2").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        Range("X3").Select
        Range(Selection, Selection.End(xlDown)).Select
        ActiveSheet.Paste
        Columns("X:X").EntireColumn.AutoFit
        Range("K1").Select
        Range(Selection, Selection.End(xlDown)).Select
        Application.CutCopyMode = False
        Selection.Copy
        Range("Y2").Select
        Range(Selection, Selection.End(xlDown)).Select
        ActiveSheet.Paste
        Range("H" & Rows.Count).End(xlUp).Select
        ActiveCell.Offset(2, -1).Select
        ActiveCell.FormulaR1C1 = "Max Value"
        ActiveCell.Offset(1, 0).Select
        ActiveCell.FormulaR1C1 = "Time"

        cy = ActiveCell.Offset(-1, 1).Select

For cc = 1 To 2

        cn = ActiveCell.Column
        cLastrow = ActiveSheet.Cells(Rows.Count, cn).End(xlUp).Row
        cMyRange = Sheets(1).Range(Cells(2, cn), Cells(cLastrow, cn))
        cmax = Application.max(cMyRange)
        ActiveCell.FormulaR1C1 = Application.max(cMyRange)
        Selection.NumberFormat = "General"

        ActiveCell.Offset(1, 0).Select

        cRng = Sheets(1).Range(Cells(2, cn), Cells(cLastrow, 12))
        cd = Application.VLookup(cmax, cRng, 6 - cc, 0)
        ActiveCell.FormulaR1C1 = Application.VLookup(cmax, cRng, 6 - cc, 0)
        Selection.NumberFormat = "h:mm:ss.0"

        ActiveCell.Offset(-1, 1).Select

Next cc

For ci = 1 To 2

        Range("H" & Rows.Count).End(xlUp).Select
```

```
        ActiveCell.Offset(-1, 1 + ci).Select
        cn = ActiveCell.Column
        cLastrow = ActiveSheet.Cells(Rows.Count, cn).End(xlUp).Row
        cMyRange = Sheets(1).Range(Cells(2, cn), Cells(cLastrow, cn))
        cmax = Application.max(cMyRange)
        ActiveCell.FormulaR1C1 = Application.max(cMyRange)
        Selection.NumberFormat = "General"

        ActiveCell.Offset(1, 0).Select
        cRng = Sheets(1).Range(Cells(2, cn), Cells(cLastrow, 12))
        ce = Application.VLookup(cmax, cRng, 4 - ci, 0)
        ActiveCell.FormulaR1C1 = Application.VLookup(cmax, cRng, 4 - ci, 0)
        Selection.NumberFormat = "h:mm:ss.0"

        Range("T2").Select
        ActiveCell.Offset(0, 4 * ci - 4).Select

        If cd > ce Then

                ActiveCell.FormulaR1C1 = cd - ce
                cp = cd - ce

                For cq = 1 To cLastrow

                        ActiveCell.Offset(1, 0).Select
                        ActiveCell.FormulaR1C1 = ActiveCell.Offset(0, -6 - 4 * (ci - 1)) + cp

                Next cq

        Else

                ActiveCell.FormulaR1C1 = ce - cd
                cr = ce - cd

                For cs = 1 To cLastrow

                        ActiveCell.Offset(1, 0).Select
                        ActiveCell.FormulaR1C1 = ActiveCell.Offset(0, -6 - 4 * (ci - 1)) - cr

                Next cs

        End If

        Selection.NumberFormat = "h:mm:ss.0"

Next ci

Dim nb As Long
Dim nc As Long

        Range("P2").Select
        ActiveCell.FormulaR1C1 = "CO~1Hz_net"
        Range("R2").Select
        ActiveCell.FormulaR1C1 = "CO2_low~1Hz_net"
        Range("V2").Select
        ActiveCell.FormulaR1C1 = "MSS~1Hz_net"
```

```
        Range("Z2").Select
        ActiveCell.FormulaR1C1 = "PN~1Hz_net"

        Range("O3").Select
        nn = ActiveCell.Column
        nLastrow = ActiveSheet.Cells(Rows.Count, nn).End(xlUp).Row

        ActiveCell.Offset(0, 1).Select

For nc = 1 To nLastrow

        ActiveCell.FormulaR1C1 = _
        "=IF(ISNUMBER(RC[-1]),IF(RC[-1]>R[-1]C[-1],RC[-1]-MIN(OFFSET(RC[-1],MAX(-10,5-
        ROW(RC)),0):R[-1]C[-1]),IF(MAX(OFFSET(RC[-1],MAX(-5,5-ROW(RC)),0):R[-1]C[-
        1])>MAX(R[1]C[-1]:OFFSET(RC[-1],MIN(5,12000-ROW(RC)),0)),(RC[-1]-MIN(R[1]C[-
        1]:OFFSET(RC[-1],MIN(15,12000-ROW(RC)),0))),RC[-1]-MIN(OFFSET(RC[-1],MAX(-10,5-
        ROW(RC)),0):R[-1]C[-1])))"

        ActiveCell.Offset(1, 0).Select

Next nc

        Range("Q3").Select
        nn1 = ActiveCell.Column
        nLastrow1 = ActiveSheet.Cells(Rows.Count, nn1).End(xlUp).Row

        ActiveCell.Offset(0, 1).Select

For nd = 1 To nLastrow1

        ActiveCell.FormulaR1C1 = _
        "=IF(ISNUMBER(RC[-1]),IF(RC[-1]>R[-1]C[-1],RC[-1]-MIN(OFFSET(RC[-1],MAX(-10,5-
        ROW(RC)),0):R[-1]C[-1]),IF(MAX(OFFSET(RC[-1],MAX(-5,5-ROW(RC)),0):R[-1]C[-
        1])>MAX(R[1]C[-1]:OFFSET(RC[-1],MIN(5,12000-ROW(RC)),0)),(RC[-1]-MIN(R[1]C[-
        1]:OFFSET(RC[-1],MIN(15,12000-ROW(RC)),0))),RC[-1]-MIN(OFFSET(RC[-1],MAX(-10,5-
        ROW(RC)),0):R[-1]C[-1])))"

        ActiveCell.Offset(1, 0).Select

Next nd

        Range("U3").Select

        nn2 = ActiveCell.Column
        nLastrow2 = ActiveSheet.Cells(Rows.Count, nn2).End(xlUp).Row

        ActiveCell.Offset(0, 1).Select

For ne = 1 To nLastrow2

        ActiveCell.FormulaR1C1 = _
        "=IF(ISNUMBER(RC[-1]),IF(RC[-1]>R[-1]C[-1],RC[-1]-MIN(OFFSET(RC[-1],MAX(-10,5-
        ROW(RC)),0):R[-1]C[-1]),IF(MAX(OFFSET(RC[-1],MAX(-5,5-ROW(RC)),0):R[-1]C[-
        1])>MAX(R[1]C[-1]:OFFSET(RC[-1],MIN(5,12000-ROW(RC)),0)),(RC[-1]-MIN(R[1]C[-
        1]:OFFSET(RC[-1],MIN(15,12000-ROW(RC)),0))),RC[-1]-MIN(OFFSET(RC[-1],MAX(-10,5-
        ROW(RC)),0):R[-1]C[-1])))"
```

```
        ActiveCell.Offset(1, 0).Select

Next ne

        Range("Y3").Select

        nn3 = ActiveCell.Column
        nLastrow3 = ActiveSheet.Cells(Rows.Count, nn3).End(xlUp).Row

        ActiveCell.Offset(0, 1).Select

For nf = 1 To nLastrow3

        ActiveCell.FormulaR1C1 = _
        "=IF(ISNUMBER(RC[-1]),IF(RC[-1]>R[-1]C[-1],RC[-1]-MIN(OFFSET(RC[-1],MAX(-10,5-
        ROW(RC)),0):R[-1]C[-1]),IF(MAX(OFFSET(RC[-1],MAX(-5,5-ROW(RC)),0):R[-1]C[-
        1])>MAX(R[1]C[-1]:OFFSET(RC[-1],MIN(5,12000-ROW(RC)),0)),(RC[-1]-MIN(R[1]C[-
        1]:OFFSET(RC[-1],MIN(15,12000-ROW(RC)),0))),RC[-1]-MIN(OFFSET(RC[-1],MAX(-10,5-
        ROW(RC)),0):R[-1]C[-1])))"

        ActiveCell.Offset(1, 0).Select

Next nf

        Range("AC2").Select
        ActiveCell.FormulaR1C1 = "Time~1Hz"
        Range("AD2").Select
        ActiveCell.FormulaR1C1 = "CO~1Hz_net"
        Range("AE2").Select
        ActiveCell.FormulaR1C1 = "CO2_low~1Hz_net"
        Range("AF2").Select
        ActiveCell.FormulaR1C1 = "MSS~1Hz_net"
        Range("AG2").Select
        ActiveCell.FormulaR1C1 = "PN~1Hz_net"
        Range("N3").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        Range("AC3").Select
        Range(Selection, Selection.End(xlDown)).Select
        ActiveSheet.Paste

        sn = ActiveCell.Column
        sLastrow = ActiveSheet.Cells(Rows.Count, sn).End(xlUp).Row

        Range("AD3").Select

For si = 1 To sLastrow

        sa = ActiveCell.Offset(0, -1)
        sRng1 = Range("N3", "R" & sLastrow)
        sSync1 = Application.VLookup(sa, sRng1, 3, 0)
        ActiveCell.FormulaR1C1 = sSync1
        sSync2 = Application.VLookup(sa, sRng1, 5, 0)
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = sSync2
        ActiveCell.Offset(1, -1).Select
```

```
Next si

        Range("AF3").Select

For si = 1 To sLastrow

        sa = ActiveCell.Offset(0, -3)
        sRng2 = Range("T3", "V" & sLastrow)
        sSync3 = Application.VLookup(sa, sRng2, 3, 0)
        ActiveCell.FormulaR1C1 = sSync3
        ActiveCell.Offset(1, 0).Select

Next si

        Range("AG3").Select

For si = 1 To sLastrow

        sa = ActiveCell.Offset(0, -4)
        sRng3 = Range("X2", "Z" & sLastrow)
        sSync4 = Application.VLookup(sa, sRng3, 3, 0)
        ActiveCell.FormulaR1C1 = sSync4
        ActiveCell.Offset(1, 0).Select

Next si

File = Application.GetOpenFilename(, , "Browse for file")
Workbooks.Open (File)
Sheets(1).Select

Windows("VBA~practice(1).xlsm").Activate
Sheets("Sheet2").Activate
pkLastrow1 = ActiveSheet.Cells(Rows.Count, 2).End(xlUp).Row

        Range("C1").Select
        ActiveCell.FormulaR1C1 = "Vehicle Class"
        Range("D1").Select
        ActiveCell.FormulaR1C1 = "Fuel NM - DIESEL BA - PETROL"
        Range("E1").Select
        ActiveCell.FormulaR1C1 = "Engine size"
        Range("F1").Select
        ActiveCell.FormulaR1C1 = "Power"
        Range("G1").Select
        ActiveCell.FormulaR1C1 = "First Registration"
        Range("B2").Select

For pki = 2 To pkLastrow1

        pkb = ActiveCell.Value

        Windows("Bus_registration.xlsx").Activate
        pkLastrow = ActiveSheet.Cells(Rows.Count, 1).End(xlUp).Row
        pkLastcolumn = ActiveSheet.Cells(1, Columns.Count).End(xlToLeft).Column
        pkMyRange = Range(Cells(1, 1), Cells(pkLastrow, pkLastcolumn))
        pkpck = Application.VLookup(pkb, pkMyRange, 5, 0)
```

```
        Windows("VBA~practice(1).xlsm").Activate
        Sheets("Sheet2").Activate

        Range("C" & pki).Select
        ActiveCell.FormulaR1C1 = pkpck
        ActiveCell.Offset(1, -1).Select

Next pki

        Range("B2").Select

For pki = 2 To pkLastrow1

        pkc = ActiveCell.Value

        Windows("Bus_registration.xlsx").Activate
        pkLastrow = ActiveSheet.Cells(Rows.Count, 1).End(xlUp).Row
        pkLastcolumn = ActiveSheet.Cells(1, Columns.Count).End(xlToLeft).Column
        pkMyRange = Range(Cells(1, 1), Cells(pkLastrow, pkLastcolumn))
        pkpck1 = Application.VLookup(pkc, pkMyRange, 8, 0)

        Windows("VBA~practice(1).xlsm").Activate
        Sheets("Sheet2").Activate

        Range("D" & pki).Select
        ActiveCell.FormulaR1C1 = pkpck1
        ActiveCell.Offset(1, -2).Select

Next pki

        Range("B2").Select

For pki = 2 To pkLastrow1

        pkd = ActiveCell.Value

        Windows("Bus_registration.xlsx").Activate
        pkLastrow = ActiveSheet.Cells(Rows.Count, 1).End(xlUp).Row
        pkLastcolumn = ActiveSheet.Cells(1, Columns.Count).End(xlToLeft).Column
        pkMyRange = Range(Cells(1, 1), Cells(pkLastrow, pkLastcolumn))
        pkpck2 = Application.VLookup(pkd, pkMyRange, 9, 0)

        Windows("VBA~practice(1).xlsm").Activate
        Sheets("Sheet2").Activate

        Range("E" & pki).Select
        ActiveCell.FormulaR1C1 = pkpck2
        ActiveCell.Offset(1, -3).Select

Next pki

        Range("B2").Select

For pki = 2 To pkLastrow1

        pke = ActiveCell.Value
```

```
        Windows("Bus_registration.xlsx").Activate
        pkLastrow = ActiveSheet.Cells(Rows.Count, 1).End(xlUp).Row
        pkLastcolumn = ActiveSheet.Cells(1, Columns.Count).End(xlToLeft).Column
        pkMyRange = Range(Cells(1, 1), Cells(pkLastrow, pkLastcolumn))
        pkpck3 = Application.VLookup(pke, pkMyRange, 10, 0)

        Windows("VBA~practice(1).xlsm").Activate
        Sheets("Sheet2").Activate

        Range("F" & pki).Select
        ActiveCell.FormulaR1C1 = pkpck3
        ActiveCell.Offset(1, -4).Select

Next pki

        Range("B2").Select

For pki = 2 To pkLastrow1

        pkf = ActiveCell.Value

        Windows("Bus_registration.xlsx").Activate
        pkLastrow = ActiveSheet.Cells(Rows.Count, 1).End(xlUp).Row
        pkLastcolumn = ActiveSheet.Cells(1, Columns.Count).End(xlToLeft).Column
        pkMyRange = Range(Cells(1, 1), Cells(pkLastrow, pkLastcolumn))
        pkpck4 = Application.VLookup(pkf, pkMyRange, 12, 0)

        Windows("VBA~practice(1).xlsm").Activate
        Sheets("Sheet2").Activate

        Range("G" & pki).Select
        ActiveCell.FormulaR1C1 = pkpck4
        ActiveCell.Offset(1, -5).Select

Next pki

        Windows("VBA~practice(1).xlsm").Activate
        Sheets("Sheet2").Activate

        Range("H1").Select
        ActiveCell.FormulaR1C1 = "CO~1Hz_net"
        Range("I1").Select
        ActiveCell.FormulaR1C1 = "CO2_low~1Hz_net"
        Range("J1").Select
        ActiveCell.FormulaR1C1 = "MSS~1Hz_net"
        Range("K1").Select
        ActiveCell.FormulaR1C1 = "PN~1Hz_net"

For wy = 2 To 11

        wa = Application.Worksheets("Sheet2").Range("A" & wy)
        Selection.NumberFormat = "hh:mm:ss.0"
        wLastrow = Worksheets("Sheet3").Cells(Rows.Count, 29).End(xlUp).Row

        For wi = 3 To wLastrow
```

```
wb = Worksheets("Sheet3").Cells(wi, "AC").Value
Selection.NumberFormat = "hh:mm:ss.0"

If wa = wb Then

        Sheets("Sheet3").Activate
        Range("AC" & wi).Select
        ActiveCell.Offset(0, 1).Select
        Selection.NumberFormat = "general"

        wm = ActiveCell.Row
        wn = ActiveCell.Column

        If wm - 4 = 0 Then

                wp = 1

        Else

                wp = wm - 4

        End If

        wq = wm + 4

        With Worksheets("Sheet3")

        wMyRange = Range(Cells(wp, wn), Cells(wq, wn))

        End With

        Worksheets("Sheet2").Activate
        Range("H" & wy).Select
        ActiveCell.FormulaR1C1 = Application.max(wMyRange)
        Selection.NumberFormat = "general"

        Sheets("Sheet3").Activate
        Range("AC" & wi).Select
        ActiveCell.Offset(0, 2).Select
        Selection.NumberFormat = "general"

        wm1 = ActiveCell.Row
        wn1 = ActiveCell.Column

        If wm1 - 4 = 0 Then

                wp1 = 1

        Else

                wp1 = wm1 - 4

        End If

        wq1 = wm1 + 4
```

```
With Worksheets("Sheet3")

        wMyRange1 = Range(Cells(wp1, wn1), Cells(wq1, wn1))

End With

Worksheets("Sheet2").Activate
Range("I" & wy).Select
ActiveCell.FormulaR1C1 = Application.max(wMyRange1)
Selection.NumberFormat = "general"

Sheets("Sheet3").Activate
Range("AC" & wi).Select
ActiveCell.Offset(0, 3).Select
Selection.NumberFormat = "general"

wm2 = ActiveCell.Row
wn2 = ActiveCell.Column

If wm2 - 4 = 0 Then

        wp2 = 1

Else

        wp2 = wm2 - 4

End If

        wq2 = wm2 + 4

With Worksheets("Sheet3")

        wMyRange2 = Range(Cells(wp2, wn2), Cells(wq2, wn2))

End With

Worksheets("Sheet2").Activate
Range("J" & wy).Select
ActiveCell.FormulaR1C1 = Application.max(wMyRange2)
Selection.NumberFormat = "general"

Sheets("Sheet3").Activate
Range("AC" & wi).Select
ActiveCell.Offset(0, 4).Select
Selection.NumberFormat = "general"

wm3 = ActiveCell.Row
wn3 = ActiveCell.Column

If wm3 - 4 = 0 Then

        wp3 = 1

Else
```

```
                    wp3 = wm3 - 4

                End If

                wq3 = wm3 + 4

                With Worksheets("Sheet3")

                    wMyRange3 = Range(Cells(wp3, wn3), Cells(wq3, wn3))

                End With

                Worksheets("Sheet2").Activate
                Range("K" & wy).Select
                ActiveCell.FormulaR1C1 = Application.max(wMyRange3)
                Selection.NumberFormat = "general"

                Sheets("Sheet3").Activate
                Range("AC1").Select

                Else

                Sheets("Sheet3").Select
                Range("AC1").Select
                ActiveCell.Offset(wi, 0).Select

                End If
        Next wi

Next wy
With Sheets("Sheet2").Activate

        Range("R1").Select
        ActiveCell.FormulaR1C1 = "Fuel C content [1]"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = "0.862"

        ActiveCell.Offset(1, -1).Select
        ActiveCell.FormulaR1C1 = "Molar weight C (g/mol)"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = "12"

        ActiveCell.Offset(1, -1).Select
        ActiveCell.FormulaR1C1 = "Molar weight CO2 (g/mol)"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = "44"

        ActiveCell.Offset(1, -1).Select
        ActiveCell.FormulaR1C1 = "Molar weight CO (g/mol)"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = "28"

        ActiveCell.Offset(1, -1).Select
        ActiveCell.FormulaR1C1 = "Atmopheric pressure (N/m2)"
        ActiveCell.Offset(0, 1).Select
```

```
        ActiveCell.FormulaR1C1 = Application.InputBox("Enter the atmospheric pressure (in N/m2)
        on the measuring day", "Atmospheric Pressure")

        ActiveCell.Offset(1, -1).Select
        ActiveCell.FormulaR1C1 = "Atmospheric Temperature (K)"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = Application.InputBox("Enter the atmospheric temperature in (K)
        on the measuring day", "Atmospheric Temperature")

        ActiveCell.Offset(1, -1).Select
        ActiveCell.FormulaR1C1 = "Specific gas constant, CO2 (J/kg/K)"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = "189"

        ActiveCell.Offset(1, -1).Select
        ActiveCell.FormulaR1C1 = "Specific gas constant, CO (J/kg/K)"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = "297"

        ActiveCell.Offset(2, -1).Select
        ActiveCell.FormulaR1C1 = "Emission factor, K (kg/m3)"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = "=(R[-5]C/R[-3]C/R[-4]C*R[-8]C/R[-7]C/R[-9]C)"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = "=(R[-5]C[-1]/R[-2]C[-1]/R[-4]C[-1]*R[-8]C[-1]/R[-6]C[-1]/R[-9]C[-
        1])"

        ActiveCell.Offset(2, -2).Select
        ActiveCell.FormulaR1C1 = "CO threshold (ppm)"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = Application.InputBox("Enter the threshold CO value (in ppm)",
        "CO threshold")

        ActiveCell.Offset(1, -1).Select
        ActiveCell.FormulaR1C1 = "CO2 threshold (ppm)"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = Application.InputBox("Enter the threshold CO2 value (in ppm)",
        "CO2 threshold")

        ActiveCell.Offset(1, -1).Select
        ActiveCell.FormulaR1C1 = "MSS threshold (mg/m3)"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = Application.InputBox("Enter the threshold MSS value (in
        mg/m3)", "MSS threshold")

        ActiveCell.Offset(1, -1).Select
        ActiveCell.FormulaR1C1 = "PN threshold (#/cm3)"
        ActiveCell.Offset(0, 1).Select
        ActiveCell.FormulaR1C1 = Application.InputBox("Enter the threshold PN value (in #/cm3)",
        "PN threshold")

        Columns("R:R").EntireColumn.AutoFit

End With

        Range("L1").Select
```

```
        ActiveCell.FormulaR1C1 = "Fuel kg/m3"
        ktr = ActiveCell.Offset(11, 7).Value
        ktr2 = ActiveCell.Offset(12, 7).Value
        ktr3 = ActiveCell.Offset(13, 7).Value
        ktr4 = ActiveCell.Offset(14, 7).Value
        kk = ActiveCell.Offset(9, 7).Value
        kk2 = ActiveCell.Offset(9, 8).Value
        kv = ktr2 / 1000000 * kk

        kLastrow = ActiveSheet.Cells(Rows.Count, 1).End(xlUp).Row

For ki = 1 To kLastrow - 1

        Range("L1").Select
        ka = ActiveCell.Offset(ki, -3).Value
        kb = ActiveCell.Offset(ki, -4).Value

        If ActiveCell.Offset(ki, -8).Value = "NM" Then

                If ka > ktr2 Then

                        ActiveCell.Offset(ki, 0).Select
                        ActiveCell.FormulaR1C1 = ka / 1000000 * kk

                Else

                        ActiveCell.Offset(ki, 0).Select
                        ActiveCell.FormulaR1C1 = "0"

                End If

        Else

                If ka > ktr2 And kb > ktr Then

                        ActiveCell.Offset(i, 0).Select
                        ActiveCell.FormulaR1C1 = (ka / 1000000 * kk) + (kb / 1000000 * kk2)

                Else

                        ActiveCell.Offset(ki, 0).Select
                        ActiveCell.FormulaR1C1 = "0"

                End If

        End If

Next ki

        Columns("L:L").EntireColumn.AutoFit

        Range("M1").Select
        ActiveCell.FormulaR1C1 = "Soot mass factor (mg/kg of fuel)"

For ki = 1 To kLastrow - 1
```

```
        Range("M1").Select
        kc = ActiveCell.Offset(ki, -3).Value

        If kc > ktr3 Then

                If ActiveCell.Offset(ki, -1).Value = 0 Then

                        ActiveCell.Offset(ki, 0).Select
                        ActiveCell.FormulaR1C1 = kc / kv

                Else

                ActiveCell.Offset(ki, 0).Select
                ActiveCell.FormulaR1C1 = kc / ActiveCell.Offset(0, -1)

                End If

        Else

        ActiveCell.Offset(ki, 0).Select
        ActiveCell.FormulaR1C1 = "0"

        End If

Next ki

        Columns("M:M").EntireColumn.AutoFit

        Range("N1").Select
        ActiveCell.FormulaR1C1 = "Soot number factor (#1E+15/kg of fuel)"

For ki = 1 To kLastrow - 1

        Range("N1").Select
        kd = ActiveCell.Offset(ki, -3).Value

        If kd > ktr4 Then

                If ActiveCell.Offset(ki, -2).Value = 0 Then

                        ActiveCell.Offset(ki, 0).Select
                        ActiveCell.FormulaR1C1 = kd / kv / 1E+15 * 1000000

                Else

                        ActiveCell.Offset(ki, 0).Select
                        ActiveCell.FormulaR1C1 = kd / ActiveCell.Offset(0, -2) / 1E+15 * 1000000

                End If

        Else

                ActiveCell.Offset(ki, 0).Select
                ActiveCell.FormulaR1C1 = "0"

        End If
```

```
Next ki

        Columns("N:N").EntireColumn.AutoFit

        Range("O1").Select
        ActiveCell.FormulaR1C1 = "PM (g/kWh)"
        Columns("O:O").EntireColumn.AutoFit

        Range("P1").Select
        ActiveCell.FormulaR1C1 = "PN (#1E+15/kWh)"
        Columns("P:P").EntireColumn.AutoFit

        Range("O1").Select
        fLastrow = ActiveSheet.Cells(Rows.Count, 1).End(xlUp).Row

For fi = 1 To fLastrow - 1

        ActiveCell.Offset(1, 0).Select
        ActiveCell.FormulaR1C1 = ActiveCell.Offset(0, -2) / 1000 / 1000 * 250
        Selection.NumberFormat = "general"

Next fi

        Range("P1").Select

For fi = 1 To fLastrow - 1

        ActiveCell.Offset(1, 0).Select
        ActiveCell.FormulaR1C1 = ActiveCell.Offset(0, -2) / 1000 * 250
        Selection.NumberFormat = "general"

Next fi

End Sub
```

E. Effective particle density values for different approaches

Electrical mobility midpoint (nm)	Maricq & Xu (g/cm^3)	Park *et al* (g/cm^3)	EEPS default (g/cm^3)
	GDI & LDD	Diesel, engine dyno	
6.04	2	2	1
6.98	2	2	1
8.06	2	2	1
9.31	2	2	1
10.75	2	2	1
12.41	2	2	1
14.33	2	2	1
16.55	2	2	1
19.11	2	2	1
22.07	1.87	1.94	1
25.48	1.69	1.77	1
29.43	1.53	1.62	1
33.98	1.38	1.48	1
39.24	1.25	1.35	1
45.31	1.13	1.23	1
52.33	1.02	1.13	1
60.43	0.92	1.03	1
69.78	0.83	0.94	1
80.58	0.75	0.86	1
93.05	0.68	0.78	1
107.45	0.62	0.72	1
124.08	0.56	0.65	1
143.29	0.50	0.60	1
165.47	0.46	0.54	1

191.08	0.41	0.50	1
220.66	0.37	0.45	1
254.81	0.34	0.42	1
294.25	0.31	0.38	1
339.80	0.28	0.35	1
392.39	0.25	0.32	1
453.13	0.23	0.29	1
523.26	0.20	0.26	1

Effective density values (ρ_{eff}) from two different techniques: Aerodynamic approach (Maricq & Xu, 2004), Mass-mobility approach (Park, et al., 2003) and EEPS default (TSI Incorporated, 2017)