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HEAVY-DUTY/NON-ROAD VEHICLE ENGINE EMISSIONS

– EU-TUBE-Project



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HEAVY-DUTY/NON-ROAD VEHICLE ENGINE EMISSIONS- EU-TUBE-Project

The focus on this thesis was to study a non-road vehicle exhaust emissions and familiarize oneself with hands-on method of standardized emissions measuring process.

Secondary aim was to collect particulate mass and volatile organic emissions for further microbiological examination at University of Eastern Finland (UEF). Collected particulate will be used to examine the effects of particulate emission on brain health, and to find a link between particulate exposure and the Alzheimer's disease.

The experimental measurements were conducted in VTT's engine laboratory facilities using VTT's own high-speed diesel engine according to the ISO 8178 standard and using RMC-C1 test cycle specified for compression ignition engines.

This thesis was commissioned by Technical Research Centre of Finland VTT and the practical part funding is based on The EU's Horizon 2020 program.

KEYWORDS:

Internal combustion engine, Diesel engine, Exhaust emissions, Carbon dioxide, NOx, Particulate matter

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RASKAAN TYÖKONEMOOTTORIN PÄÄSTÖT JA MITTAAMINEN

- EU-TUBE-Projekti

Opinnäytetyön päätavoite on tutustua työkoneiden dieselmoottorin päästöihin ja käytännön standardipäästömittauksen läpiviemiseen.

Toissijainen tavoite on kerätä pakokaasusta hiukkasmassaa lähetettäväksi jatkotutkimuksiin Itä-Suomen yliopistolle. Kerätyn hiukkasmassan vaikutuksia aivoterveysteen tutkitaan, ja pyritään löytämään yhteys hiukkasaltistumisen ja Alzheimerin taudin välillä.

Tutkimuksen mittaukset toteutetaan Teknologian tutkimuskeskus VTT:n moottorilaboratoriossa VTT:n nopeakäyntisellä dieselmoottorilla mukaillen ISO 8178 -standardin ohjeistusta puristussytytteisen dieselmoottorin mittauksesta RMC-C1- ajosyysin mukaisesti.

Opinnäytetyön toimeksiantajana toimii Teknologian tutkimuskeskus VTT ja käytännön osuuden rahoitus perustuu EU:n Horizon 2020 -ohjelmaan.

ASIASANAT:

Polttomoottori, Diesel-moottori, Pakokaasupäästöt, Hiilidioksidi, NOx, Pienhiukkaset

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LIST OF ABBREVIATIONS

Abbreviation	Abbreviation meaning
D_p	Particle diameter
DR	Dilution rate
ECU	Electronic control unit
FSN	Filter smoke number
GHG	Greenhouse gas
ISO	the International Organization for Standardization
MTS	Maximum test speed
PET	Positron emission tomography
PM	Particulate matter
PN	Particulate number
RMC	Ramped-modal cycle
SCR	Selective catalytic reduction
SMOG	Combination of smoke and fog
SVOC	Semi-volatile organic compound
UEF	University of Eastern Finland

1 INTRODUCTION

Traffic and transportation in its all forms is one of the greatest factors causing air pollution. Even with the increase in the modern engine technology including fully electric cars and hybrids, a major part of the modern road and non-road vehicles still use fossil fuels in some form.

A term fossil fuel covers forms of oil, natural gas and black coal-based compounds that are used as an energy source in vehicle engine. For example, the conventional gasoline, diesel fuel, and natural gas are all fossil fuels. While burning hydrocarbon compounds, more or less hazardous new chemical compounds are generated during the combustion process. In an ideal combustion process, the exhaust gas should only contain carbon dioxide and water. In reality, however, due to incomplete combustion, harmful compounds such as carbon monoxide and oxides of nitrogen are formed along with exhaust emissions.

The only way of reducing global CO₂ emissions is to consume less hydrocarbon containing fossil fuels. However, other hazardous exhaust compounds can be modified by using a catalyst of some sort. This can be conducted using modern exhaust after treatment systems, such as diesel oxidation catalyst (DOC) or a SCR-catalyst system on a vehicle exhaust system. In addition, the usage of renewable fuel components makes the exhaust gas ideally CO₂ neutral.

Vehicle and engine emissions are regulated internationally, however, standards can vary regionally. The regulations are based on an environmental legislation, which sets targets to reduce air pollution and restrains the global warming.

The toxic compounds of engine emissions are known to have a direct cause-effect-relation on the physical health of all people and animals. These health-related problems have commonly been limited to respiratory issues, however, recent studies have shown a worrying link between great exposure to exhaust emissions and cardiovascular and even brain health issues. (UEF.fi) Air pollutant triggered cardiovascular and respiratory issues will be increasingly investigated. The deep body penetrating effect of ultrafine particulates have been noticed widely, yet not that much examined. The recent studies have shown that the people subjected to greater exposure of emissions, mainly in large

cities or coastal areas, will be generally more vulnerable to emission caused neurological issues, most likely the Alzheimer's disease. (UEF.fi)

The EU-TUBE is a project funded by the EU Horizon 2020 research and innovation program. The H2020 is a program with a total funding of nearly €80 billion on promises of breakthroughs, discoveries and innovations for commercial use. The reserved share on the TUBE stands at €5 million. (ec.europa.eu)

The primary aim on the TUBE project is to study an impact of particulate matter pollution on the brain health. The study will be conducted using animal models, human derivate cell models, patient cohorts, PET imaging, omics method, and bioinformatics and systems biology. The objective is to examine the connection between particulate matter exposure and the Alzheimer's disease. (UEF.fi) The project includes numerous national and international participants with their own mandates in their own special fields of research.

The main objective in this thesis is to study regulated emission measurements in heavy-duty diesel engine and collect particulate emission matter in practice for future microbiological examination and emission characterization.

2 ENGINE EXHAUST IN GENERAL

Exhaust emissions are the main pollution sources in the field of transportation.

Exhaust emissions generated by a running engine of a vehicle are a mixture of particulates and different forms of regulated and non-regulated gaseous emission components.

The exhaust emissions tend to reduce the quality of air around us. This is a major factor especially in large cities that usually are congested with all forms of vehicles in a field of transportation. (rac.co.uk, pnnl.gov)

According the rac.co article, carbon dioxide (CO₂) is the greatest media covered pollutant in exhaust gas, even though the total CO₂ concentration in exhaust fumes is the maximum of 15 % of the total exhaust concentration. Most of the exhaust consists of nitrogen along with other varying degrees of harmful compounds at ppm-level. (rac.co.uk, pnnl.gov)

It is a common belief that the combination of exhaust fumes and other airborne particulates forms the greatest factor of global warming. In addition, studies have shown that all forms of air pollution from gas level to larger particulate emissions practically affect every species on earth.

The most common emission-caused problem is related to the respiratory system. It is well proven that the respiratory system of humans and animals reacts quite the same to air pollution. That is the main reason that wildlife is most likely prone to suffer similar symptoms and diseases than humans. (Airgo2.com)

Information on characterizing the short-term emission exposure effects on health is relatively limited. Even so, a number of studies have come to the conclusion that even a short-term exposure tends to irritate the throat and eyes or even cause nausea. (emergency.cdc.gov)

However, in long-term exposure to toxic emission components, such as smog or carbon monoxide, it is proven risk of hazardous compounds penetrating the body and significantly increasing the risk of damaging the lungs and causing a major respiratory problems on animals. This can even lead into increasing lung cancer risk and neurological issues. (UEF.fi)

Greenhouse gases will lead into rising air temperature, which causes increasingly frequent and severe extreme weather events. These events may increase the risk of deaths from dehydration or heat stroke and other forms of injuries from intense weather change. (Canada.ca)

The main concern regarding the environmental perspective is whether greenhouse gases cause the global warming. The greenhouse effect is a natural process that performs a major role in forming the earth's climate. Due to this, the overall global temperature is gradually expected to rise resulting in several different issues in the environment.

The rising air temperature causes the sea ice, snow and glacier coverage to decrease resulting in rising sea levels and a significantly increased risk of flooding in coastal areas. Under rising temperatures, the permafrost on the arctic areas will disperse over time and because of a milder weather in winter, the coastal-erosion will be more critical due to the lacking snow coverage. Also due to the global warming, the rising amount of CO₂ absorbed into water leads to ocean acidification as a result of dissolutions. (Canada.ca, Pnel.noaa.gov)

Intense weather changes create a major risk of, for example flooding, heat waves and hurricanes. These will lead to increasing forest fires emitting a large amount of widely spreading wildland fire emission, and the risk of flooding in coastal cities.

Wildlife species also suffer from the raising temperatures. The species will face a difficulty of adapting to greater temperatures, thereby resulting in an additional stress caused by diseases and invasive species. This will eventually lead to an extinction of species as they are not able to cope with the persistently changing climate.

3 EXHAUST GAS REGULATIONS, PARTICULATE AND GASEOUS EMISSIONS

3.1 European engine exhaust gas regulations

The European Union sets up targets in the field of emission control in the European region.

The international emission control is mainly based on the Paris Agreement, the main goal of which is to limit the global climate warming below 2 °C. Europe is aiming to be the first climate-neutral continent by 2050 (Ec.europa.eu).

According to Europa.eu, the EU has set three top priorities reducing pollution caused by all forms of transportation; increasing the efficiency of the transport system, speeding up the deployment of low-emission alternative energy for transport, and moving towards zero-emission vehicles.

These goals may be achieved by making the most of digital technologies, smart pricing of cleaner technologies and encouraging people to shift to lower emission transport modes.

The main issue in achieving these goals is funding. In the current circumstances of rapidly developing technological solutions, people tend to act cautiously on investing in new technological solutions, such as electric or biogas vehicles. Retrofitting an exhaust after treatment systems on the current vehicles could be a quick fix, but also usually an expensive one.

Engine emissions may generally be divided into three parts consisting of regulated emissions, non-regulated emissions and greenhouse gases. Regulated emissions, as the term suggests, include various threshold limit values globally whereas non-regulated do not, even though non-regulated emissions still contain many harmful emission compounds. An example segmentation of engine emissions types is presented in Table 1.

Table 1 European engine emission types

Emissions type	Component examples
Regulated emissions	Carbon monoxide CO Hydro-carbons HC Nitrogen oxides NO _x Particulate matter PM Particulate number PN
Non regulated emissions	Aldehydes Benzene
Greenhouse gases	Carbon dioxide CO ₂ Methane CH ₄ Nitrous oxide N ₂ O

Currently regulated exhaust emissions are carbon monoxide (CO), hydrocarbon compounds (HC), combination of oxides of nitrogen NO and NO₂ (NO_x) and types of particulate emission.

Carbon monoxide is a blank, odorless, toxic gas displacing oxygen in blood. An exposure to carbon monoxide leads to poisoning. A short-term exposure causes dizziness, vomiting, nausea and unconsciousness. A long-term exposure to CO leads to an increased risk of heart diseases and other long-term health issues and also can be fatal. The effect of carbon monoxide emission is local due to the fact that CO tends to react with the surrounding air producing CO₂. (ephtracking.cpc)

Hydrocarbon emissions are unburned fuel components. In the health perspective, the hydrocarbon emissions are relatively harmless. However, hydrocarbons tend to produce smog into the atmosphere and certain forms of HCs, such as many of the polyromantic hydrocarbons, are known carcinogens. (ephtracking.cpc)

The oxides of nitrogen are by-products in the combustion process. NO_x components react with the surrounding hydrocarbons and sunlight causing smog and oxidize producing ozone (O₃) into the atmosphere. In addition, NO_x compounds lead to an increasing risk of breathing difficulties, respiratory issues and acid rain. (ephtracking.cpc)

Particulate matter is a hazardous mixture of organic and inorganic airborne particulates. These particulates vary by their features, such as the diameter or state of the matter. Particulate matter can also include residuals from engine lubricant or fuel. (greenfacts.org)

An example composition of heavy-duty engine particulate emissions in the exhaust gas is presented in the figure below. It should be noticed that modern diesel fuels consist of mainly zero-sulfur-components. Therefore, the share of sulfur and condensated water is zero. (Greenfacts.com)

Typical particle composition for a heavy-duty diesel engine

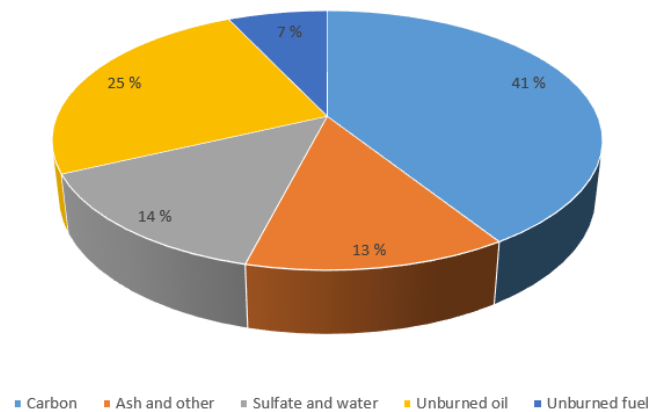


Figure 1 Typical diesel particulate emission composition (Kittelsson)

According to the greenfacts.com article, the major part (90%) of the total mass of particulate matter consists of particulates in the range from D_p 0.1 μm up to 2.5 μm , and also most of the particulate number emitted by engines is in the nanoparticulate range, $D_p < 50$ nm. The remaining 10 percent consists of even smaller ($< 0,1 \mu\text{m}$) ultrafine particulates that tend to have an even deeper body penetrating effect damaging the respiratory system and causing cardiovascular and neurological issues. A typical structure of exhaust particulate emission is presented in Figure 2.

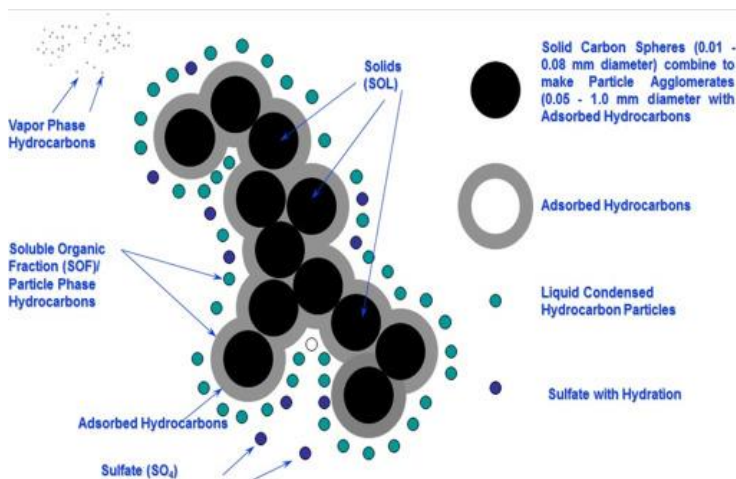


Figure 2 Typical composition and structure of engine exhaust particulates (Mohankumar).

3.2 Non-regulated emission components

Aldehydes are oxidized alcohols. Therefore those are a common by-products using gasoline-ethanol (gasohol) products. A common gasoline engine produces most likely acetaldehydes and diesel-fueled engines produce mainly formaldehydes.

Aldehydes are hazardous to living cells. A Sciencedirect article states that “Formaldehyde irreversibly cross-links protein amino acids, which produces the hard flesh of embalmed bodies”. In enclosed space, it is possible to suffer from nose bleeding, respiratory distress, lung diseases and constant headaches caused by formaldehyde exposure. (Sciencedirect.com)

Benzene is an organic compound with the molecular formula C_6H_6 . Benzene in room temperature is a sweet-smelling, colorless, highly flammable fluid.

Symptoms of long-term exposure to benzene are drowsiness, dizziness, rapid heartbeat, headaches, tremors and confusion. In extreme cases, benzene exposure is proven fatal. (emergency.cdc.gov).

4 REQUIREMENTS ON MEASUREMENTS ACCORDING TO ISO 8178

4.1 Test cell, engine and dynamometer

The calibration of all measuring instruments must be traceable to national standards. Engine and dynamometer must meet the criteria set up in the ISO 8178-4 standard, including the appropriate cycle validation criteria, if relevant. The authorized dynamometer types are either eddy-current, water-brake, alternating current, or direct current motoring dynamometer.

Requirements on the dynamometer input and output measurements are listed in the standard. There are numerous property demands set on, for example shaft work, speed and torque calculation. These demands are set on the system rise-time, recording frequency, accuracy, repeatability and noise. An example of the measurement device specifications is shown in Table 2 below.

Table 2 Performance specifications for measurement instruments (ISO 8178).

Measurement Instrument	Measured quantity symbol	Complete System Rise time (t_{10-90}) and Fall time (t_{90-10}) ^a	Recording update frequency	Accuracy ^b	Repeatability ^b	Noise ^b
Engine speed transducer	n	1 s	1 Hz means	2,0 % of pt. or 0,5 % of max.	1,0 % of pt. or 0,25 % of max.	0,05 % of max
Engine torque transducer	T	1 s	1 Hz means	2,0 % of pt. or 1,0 % of max.	1,0 % of pt. or 0,5 % of max.	0,05 % of max
Electrical work (active-power meter)	W	1 s	1 Hz means	2,0 % of pt. or 0,5 % of max.	1,0 % of pt. or 0,25 % of max.	0,05 % of max
General pressure transducer (not a part of another instrument)	p	5 s	1 Hz	2,0 % of pt. or 1,0 % of max.	1,0 % of pt. or 0,50 % of max.	0,1 % of max
Atmospheric pressure meter used for PM-stabilization and balance environments	p_a	50 s	5 times per hour	50 Pa	25 Pa	5 Pa
General purpose atmospheric pressure meter	p_a	50 s	5 times per hour	250 Pa	100 Pa	50 Pa
^a The performance specifications identified in the table apply separately for rise time and fall time.						
^b Accuracy, repeatability, and noise are all determined with the same collected data as described in 5.3, and based on absolute values. "pt." refers to the overall flow-weighted mean value expected at the standard; "max." refers to the peak value expected at the standard over any test interval, not the maximum of the instrument's range; "meas" refers to the actual flow-weighted mean measured over any test interval.						
^c The procedure for accuracy, repeatability and noise measurement described in Clause 3 may be modified for flow meters to allow noise to be measured at the lowest calibrated value instead of zero flow rate.						

4.2 Measuring of particulate matter emissions

According to the ISO 8178, the dilution system is mandatory when determining particulates. Exhaust gas dilution can be executed either in a full flow dilution tunnel, such as the constant volume sampler (CVS) system (commonly used for regulatory testing), or in a partial flow dilution system.

The partial flow dilution system is designed to extract a proportion of raw exhaust sample from the engine exhaust stream. It is essential that the dilution ratio (r_d) or the sampling ratio (r_s) be determined such that the specified accuracy limits will be fulfilled.

Demands set on the dilution system are large enough flow capacity to eliminate the water condensation in the dilution and sampling system, dilution air temperature between 20 and 52 °C, and the constant diluted sample temperature between 42 and 52 °C.

4.3 Measuring of gaseous emission

The amount of gaseous emissions can be determined by using a mass-based procedure or molar-based calculation.

The measuring probes must be fitted either $> 2^{-1}$ m or three times the diameter of the exhaust pipe (whichever is larger) upstream of the exit of the exhaust system, although close enough to the engine to ensure a minimum exhaust gas temperature of 70 °C at the measuring probe.

This guidance applies only to single-branch exhaust systems. Guidance on the multi-branch systems (as in V-type engines) is further introduced in the standard.

Evaluating the gaseous emissions, the raw HC, CO and NO_x concentrations and the exhaust gas mass flow must be recorded and stored with the minimum of 2 Hz frequency in data-logging according to the standard.

When using analogue analyzers, the response signals can be recorded and the calibration data can be added online or offline during the data evaluation.

4.4 Emission test cycles

The types of non-road test cycles are steady-state and transient state (NRSC and NRTC).

The test cycle is a sequence of test points with a defined speed and torque to be followed by the test engine under steady-state or transient operating conditions. (ISO 8178)

The transient test cycle is a second-by-second sequence of normalized speed and torque values.

The transient state test speeds must be determined according to the test cycles to be used. In certain cases, a rated speed will be used to represent 100 % speed, as declared by the manufacturer. In other cases, the maximum test speed (MTS) and an intermediate speed will be determined from the curve of engine speed versus power. If the intermediate speed is not used, the needed test speeds will be determined as a percentage of the rated speed or MTS.

The following figure shows the definitions of the system response during the test sequences.

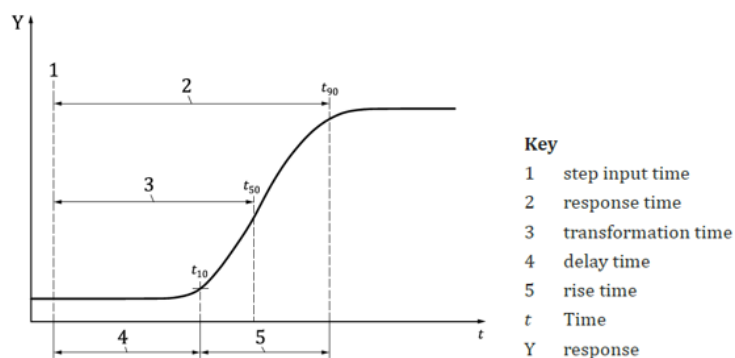


Figure 3 Definitions of system response: delay time, response time, rise time, and transformation time (ISO 8178).

A steady-state test cycle contains a list of discrete modes (operating points). Each point includes a certain value set for speed and torque. Steady-state cycles must be performed with a warmed-up engine based on the manufacturer's guidance.

Based on the manufacturer's choice, a steady-state cycle may be performed as a discrete mode cycle or ramped-modal cycle (RMC).

Selected RMC-cycles vary depending on the engine application. The C1 is used for measurements in compression ignited heavy-duty engines (alternatively in spark ignited engines >56 kW) whereas RMC-C2 is meant to be used generally in spark ignited non-road engines.

The decision between the possible test cycles is made considering the test engine specifications and application. Further listing of the ISO 8178-cycles can be found in Appendix C.

While running the RMC test where second-by-second speed and torque values are not available, the validation criteria as follows shall be applied according to the ISO 8178.

At each mode the requirements for the speed and torque tolerances the maximum deviation of the measured speed to reference speed shall be ± 1 % of rated speed (maximum full load speed allowed by the engine governor function) or ± 3 min⁻¹, whichever is greater besides the idle speed which is defined by the engine manufacturer (ISO 8178).

According to ISO 8178 tolerances in linear speed and torque transitions between different RMC test modes the speed must be held linear within ± 2 percentage of the rated speed and the torque within ± 5 percentage of the maximum torque at the rated speed.

In the NRTC sequence of normalized speed and torque values vary relatively quickly with time as for the NRSC the ramp time between different measurement points is significantly longer, thus the measurement equipment and engine-dynamometer combination specifications determine the selection between the NRSC cycles in addition to the NRTC cycle.

The RMC-C1 is a NRSC type test cycle containing seven engine load modes and two idle modes. Mode durations vary from 126 s to 248 s along with the 20 s response period.

The RMC-C1 test cycle begins and ends with the idle mode where the engine speed shall be in the range defined by the manufacturer. The idle speed shall be the lowest possible engine speed with the minimum engine load (greater than or equal to zero load), where an engine governor function controls the engine speed.

The intermediate test speed and load points are determined based on the engine specifications. The desired intermediate test points needed for the test are calculated as a percentage in the following procedure.

The percentage load for each test mode of the chosen test cycle derive from Table 3.

Comparing Tables 3 and 4 explains the differences between a steady-state discrete-mode C1-test cycle and the RMC-type C1 cycle. The basic C1 cycle lacks the idle mode at the beginning of the cycle, and also the arrangement of the cycle modes varies. The C1 cycle begins with 100% load modes as for the RMC-cycle begins with with idle followed by intermediate load modes. Also, the minimum mode length in discrete-mode cycle stands at 10 minutes.

In terms of calculation, the weighing factors in steady-state, discrete-mode cycle are presented by modes in the ISO 8178, as for the RMC-C1 there are no specific weighting factors due to varying mode lengths.

Also during the calculations the 100 % value at a given test speed is the measured or declared value taken from the mapping curve expressed as power (kW). The engine setting for each test mode is calculated by the following formula:

Equation 1 Engine load

$$S = \left((P_{100\%} + P_{AUX}) * \frac{L}{100} \right) - P_{AUX}$$

Where:

S is dynamometer setting in kW;

$P_{100\%}$ is 100 % value of measured or declared power at the specified test speed in kW;

L is % torque;

P_{AUX} is the sum of the declared total power absorbed by auxiliaries that are to be removed for the test but which are installed minus the declared total power absorbed by auxiliaries that should be fitted for the test but were not installed.

Table 3 Table of cycle C1 test modes and weighting factors (ISO 8178-4)

Mode number	1	2	3	4	5	6	7	8
Speed ^a	100%				Intermediate			Idle
Torque ^b (%)	100	75	50	10	100	75	50	0
Weighting factor	0,15	0,15	0,15	0,1	0,1	0,1	0,1	0,15
^a See 7.2, 7.4 and 7.7 for determination of required test speeds.								
^b The % torque is relative to the maximum torque at the commanded engine speed.								

Table 4 RMC-C1 Test cycle (ISO 8178-4).

RMC Mode Number	Time in mode (s)	Engine speed	Torque (%)
1a Steady state	126	Idle	0
1b Transition	20	Linear transition	Linear transition
2a Steady state	159	Intermediate	100
2b Transition	20	Intermediate	Linear transition
3a Steady state	160	Intermediate	50
3b Transition	20	Intermediate	Linear transition
4a Steady state	162	Intermediate	75
4b Transition	20	Linear transition	Linear transition
5a Steady state	246	100%	100
5b Transition	20	100%	Linear transition
6a Steady state	164	100%	10
6b Transition	20	100%	Linear transition
7a Steady state	248	100%	75
7b Transition	20	100%	Linear transition
8a Steady state	247	100%	50
8b Transition	20	Linear transition	Linear transition
9 Steady state	128	Idle	0

5 IMPLEMENTED MEASUREMENTS

The main objective during the measurement period was to produce diesel particulate emission matter to be used in future microbiological examination and emission characterization.

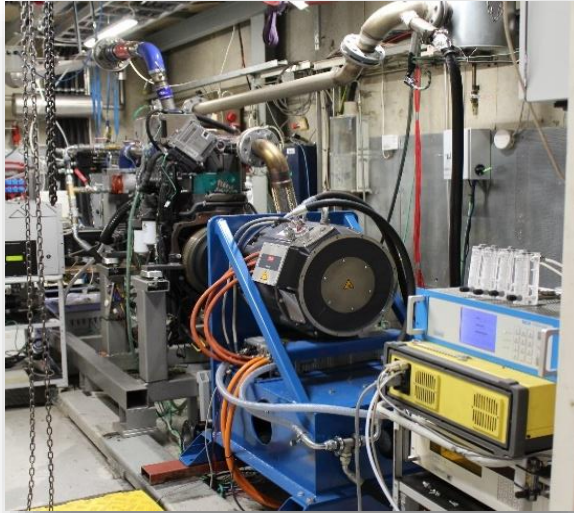
The collected particulate matter will be used in in-vitro cell exposure studies by the UEF determining the link between ultrafine particulates and brain health and possible mutations.

Numerous gaseous emissions were also monitored and recorded during the measurements mostly in order to observe the stability of the test engine.

5.1 Measurement infrastructure

The term measurement infrastructure stands for the entirety that includes the engine, a possible after-treatment system, and measurement devices needed for the measurements.

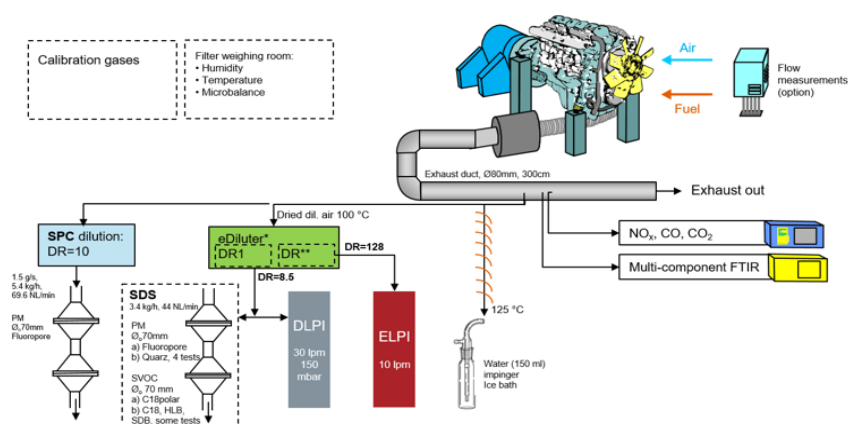
In this case, the arranged space for the engine and measurement devices was only about 15 m². The majority of the available space was reserved for engine and exhaust piping. The efficiency of the space available had to be considered when assembling the test set-up in order to keep the area clear for safe repairs and measurement device operation by the side of constantly hot exhaust lines and rotating engine.



Picture 1 Measurement infrastructure (VTT)

The safe operation of the devices was conducted by leaving the test cell entirely for the engine and devices. PC's those were controlling the engine and dynamometer parameters and numerous functions on measurement devices were placed outside the test cell in external control room, although some device calibration related functions and repairs could only be performed inside the test cell.

A conceptual graph of the instrumentation used during the second measurement period is shown below.



Picture 2 Tube test set-up (Aakko-Saksa et al.)

5.1.1 Engine and dynamometer

The test motor was a turbocharged, high-speed diesel engine produced by AGCO. The engine was equipped with an electrically controlled common-rail fuel injection system, which makes it less sensitive to in-fuel properties, such as density and viscosity, than older engines equipped with a mechanical fuel injection system.



The dynamometer used a Danfoss manufactured, heavy-duty electric motor unit producing the torque needed for the test.

The engine and dynamometer cooling system was open-circulated using common tap water as coolant. The intercooling of the engine was also water-cooled to keep the inlet air temperature leading to the engine steady.



Picture 3 Dyno control room (VTT)

Table 5 Test engine (VTT).

AGCO 44 AWI			
Nominal power, kW	94 @ 2200 min ⁻¹		
Nominal torque, Nm	550 @ 1500 min ⁻¹		
Number of cylinders	4		
Displacement, L	4.4		
Compression ratio	16.5		
Fuel injection	Common-rail		
Additional info	Turbocharged, intercooled		

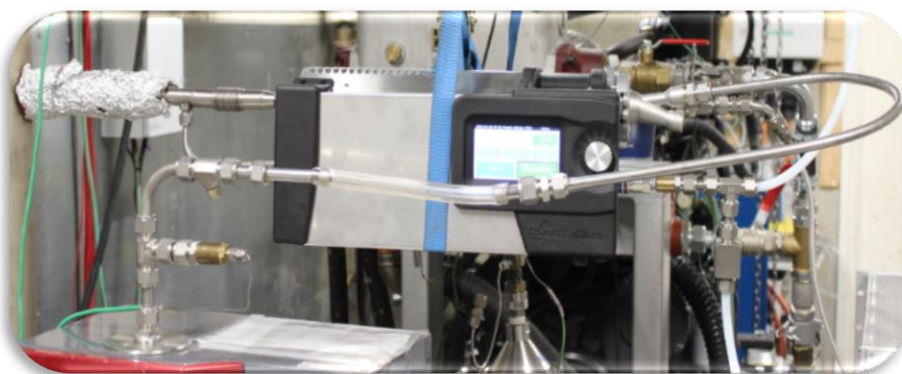
5.1.2 Exhaust gas dilution systems

Most of the measurement devices are too sensitive to handle raw exhaust gas. The devices have their own specific demand on sample gas conditions and the conditions were achieved using numerous different methods, such as external diluter systems or dryer/cooler units.

The dilution of the exhaust sample for the SDS-system, ELPI and CPCs was produced using Dekati eDiluter, and the secondary dilution with Dekati manufactured engine exhaust diluter (DEED), also for CPCs.

The Dekati manufactured eDiluter is a two-stage combined sample dilution and condition system, which is used for particulate measurements. eDiluter enables particulate measurements from high concentrations, temperatures, and humid conditions for a long period. The construction with two sheath air ejector diluters allows the heating of the dilution air up to 400°C at the first stage of the dilution. The temperature at the first stage of the dilution is controlled with an integrated control panel. The control panel includes also two additional controls, which allow controlling the temperature of two heated sampling lines.

The dilution rate in eDiluter is adjustable by the stage. The first stage allows setting df 5, 10 or 15. The second stage contains dilution factor options from five to 15. The total df on the outputs leading to the measurement devices is available anywhere between 25 and 225.



Picture 4 Dekati eDiluter (VTT).

The DEED is a EURO 5b/6 requirement of volatile particle remover (VPR) fulfilling dilution system. The system is designed to minimize user-generated errors, and maximize the repeatability of the results. The inlet sample gas is kept at $>150^{\circ}$ in the particulate number diluter 1 (PND1). PND1 dilutes the sample with a constant dilution factor of 10. After the PND1, the sample passes into $> 350^{\circ}\text{C}$ evaporation tube (ET). The ET evaporates all volatile particulates from the sample. The evaporation efficiency for $dp > 30\text{nm}$ tetracontane particulates is higher than 99%. After evaporation, the sample passes through t-branch diluter that dilutes the sample with the df of 10. The t-branch can be set on/off representing the selection of high or low dilution rate. After the t-branch, the sample is led to the secondary dilution stage at PND2. This operates at ambient temperature and cools down the sample. PND2 operates also at df 10. After the secondary dilution, the sample is led out to the measurement instruments, in this case to the CPCs.



Picture 5 Dekati DEED (VTT).

5.1.3 Particulate measuring devices

Particulate matter (PM) sampling was conducted using two partial flow dilution systems (AVL smart sampler and in-house SDS system) meeting the ISO 8178.

The smart sampler is an AVL manufactured partial flow dilution system used for gravimetric sampling of exhaust particulates. The system can be used under steady state or transient conditions. The SPC uses calibrated mass flow meters.

The ISO 8178 requires $DR > 4$, temperature on filter $< 52^{\circ}\text{C}$, and face velocity on filter 35-100 cm/s.

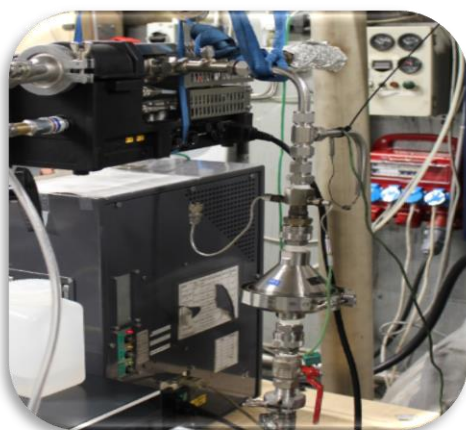
A partial flow from the raw exhaust gas was directed for the dilution. The filtered and dried air diluted sample flow is conducted through a pair of filters to collect particulates.

The smart sampler is approved for steady state testing of particulate matter emission by the EU under the ISO 16183 and therefore, fulfills the requirements of the ISO 8178 test cycle. The ISO 8178 requires $DR > 4$, temperature on filter $42 - 52^{\circ}\text{C}$, and face velocity on filter $35-100 \text{ cm/s}$. According to the standard, the minimum loading on 70mm filter stands at 0.25 mg and the recommended loading is around 1.3 mg.



Picture 6 AVL SPC smart sampling system (VTT).

eDiluter was used for the dilution on SDS's PM & SVOC collection. DR on the first dilution stage of eDiluter was set on five, and the dilution air was set up to 100°C .



Picture 7 SDS filter retainer (VTT).

The particulate number distributions were measured using an Airmodus CPC and Dekati Ltd. manufactured ELPI.

Airmodus manufactured butanol condensation particulate counter (CPC) is a measurement equipment measuring small airborne aerosol particulates up from one nm diameter. Two types of CPCs were used during the measurements; one with the size range up from five nm and one with the range up from 23 nm.

The operation principle of the CPC is to condensate butanol on airborne particulates to increase the size of the particulates that are impossible to detect as they enter into the device. After condensation, the particulates are at their optimal size for optical detection.



Picture 8 Airmodus CPC 5 & 23nm (VTT).

The particulate number distributions were measured with the Dekati Ltd. manufactured ELPI. The measuring principle is based on particulate charging, inertial size classification in a cascade impactor, and electrical detection of the aerosol particulates. The ELPI is a real-time particulate size spectrometer measuring airborne particulate size distribution in the size range of 30 nm – 10 μm . When using a Filter Stage, the lowest size range can be potentially extended up from seven nm.



Picture 9 Dekati Ltd. ELPI (VTT).

The mass of impure carbon was measured using the AVL Micro soot sensor (MSS).

The AVL MSS is a measurement system measuring the concentration of mass of impure carbon particulates directly without cross-sensitivity to other exhaust components. MSS operates based on the photoacoustic measurement principle. With this measurement method, the sample gas is exposed to modulated light. The periodical warming and cooling and the resulting expansion and contraction of the gas can be regarded as a soundwave and detected by microphones.

The construction of a test cell in MSS allows a particularly low detection limit of one $\mu\text{g}/\text{m}^3$ with reduced signal noise.

Automated thermophoretic loss compensation (TLC) allows using the MSS as an extension of dilutor or to measure soot straight out of raw exhaust gas. TLC compensates particulate losses.



Picture 10 AVL Micro soot sensor (VTT).

5.1.4 Gaseous measuring devices

The sampling and analysis of gaseous regulated pollutants were performed in accordance to the international standard ISO 8178-1.

FTIR technology was used as a main gaseous emissions measuring system. Additional gaseous emissions analyzer by SICK Maihak was used backing up the FTIR data.

Fourier transform infrared spectroscopy (FTIR) is a gas measurement technology for simultaneous measurements of multiple gases.

The FTIR system used was a Gasmet produced portable DX4000 FTIR system. This system is usually set up to measure H₂O, CO₂, NO, NO₂, N₂O, SO₂, NH₃, CH₄, HCL, HF and different VOCs and is able to measure up to 50 gases simultaneously.

Raw exhaust sample was led into the portable measuring cell by a heated sampling line, which heated the raw gas up to 180 °C in order to prevent the sample gas cooling down before the measuring cell.

FTIR measuring unit had continuous zero calibration gas flow of 2-1 l/min inlet in order to prevent condensation during any unwanted circumstances. The heated sample gas was led into the measuring unit (DX4000) for analyzing.

Sidor is a gaseous emission analyzer for measurement of up to two infrared components. Oxygen can be additionally measured by integration of an electrochemical or paramagnetic measuring cell.

The sampling line was tapped into the raw exhaust gas line. The sample was dried and cooled down to approx. 3 °C before led into the main measuring device. Sidor measured CO₂, NO, and O₂ on paramagnetic cell.



Picture 11 Gasmet DX4000 & SICK Sidor (VTT).

5.2 Test cycle and fuels

5.2.1 ISO 8178 RMC-C1 and daily measurement protocol

A ramped-modal cycle (RMC) Type C1 cycle is used in compression-ignition engine powered non-road machinery.

The selection of the RMC-C1 test procedure was based on the ISO 8178-4 international standard. The test running time is 1800 s per cycle. The normal procedure contains only

one test cycle. In this case, however, to maximise the collected PM-mass 3 to 6 cycles were driven in a row.

Emission measurements for two different types of diesel fuels were conducted with the defined protocol.

The daily protocol is presented in Table 5, and the more specific RMC-C1 test cycle description in Table 3. The cycle was run 3-6 times in a row per filter combination and was completed 2-4 times per day.

The repeatability of the collected engine ECU data and gaseous emissions were monitored daily by examining the data collected from the engine control unit in order to ensure the stability of the engine between the cycles.

Table 6 Daily protocol & measurements during measurement period (VTT).

Daily measurement protocol	
Engine warm-up:	30 minutes at 75% load (15+ minutes between various test runs)
Test cycle ISO 8178 C1 NRSC (RMC weighted by load mode durations)	<ul style="list-style-type: none"> Parameters: Intake air flow, fuel mass flow calculated collections Filter collections concurrently implemented on SPC & SDS <ul style="list-style-type: none"> PM collections: Fluoropore & TX40 filters (SPC & SDS) SVOC collections: HLB filters (SDS) Gaseous emissions: FTIR (Gasmeter DX4000) & SICK Maihak Sidor Mass of impure carbon particulates (AVL Micro soot sensor) Non-volatile PN above 5nm & above 23nm (Airmodus CPC) Particulate number distribution (ELPI)
Fuel change	ISO 8178-C1 + 120 minutes at 75% load.

5.2.2 High aromatic and non-aromatic test fuels

The test cycles were conducted using two different types of diesel fuels. The main difference in the fuels was their aromatic content.

EN590 specified diesel fuel with 20-weightpercentage total aromatic fuel was used as an “A20” high aromatic fuel and Neste MY-diesel containing 0.1 weightpercentage total aromatics as low aromatic “A0” fuel.

The fuel samples were analyzed beforehand by ASG Analytik-Service GmbH. The analytical results of the test fuel properties are shown in Appendix A.

5.3 Measurement preparations

The team leader introduced the project goals, mandates, and individual tasks for the team members on a PowerPoint presentation.

The engine was prepared and serviced for the test period. Samples of the engine lubricant and test fuels were taken and sent for analysis at Fluidlab. The lubricant properties after the test period are presented in Appendix B.

In order to prevent the contamination of the samples, everything that was in direct contact with the sample filters, such as sample containers, sample filters, tweezers and sample retainers were soaked carefully in methanol according to the guidelines set by the UEF.

The measurement infrastructure was built in the test cell conforming to the standards and measurement plan.

The engine lubricant was aged and the test cycle was driven numerous times to make sure there were no issues with the engine, mechanics and dynamometer.

The measurement devices and sampling lines were installed, calibrated, checked, and isolated for any leaks or contact to the surrounding cold air. Any exposed parts in the heated measurement lines produces so-called “cold spots”, which would cause condensation in the lines and an unwanted effect on the measurement results.

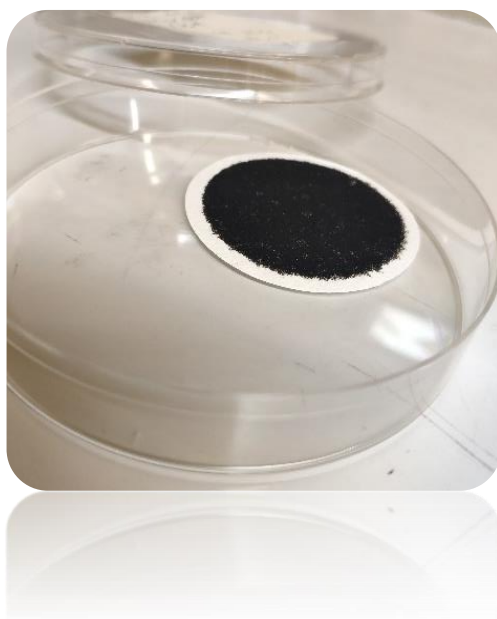
Methanol soaking for sample filters and equipment was performed, and sample filters and a number of reference filters of each type were weighed and concealed.

5.4 Measured exhaust emission components

5.4.1 PM-, PN-, SVOC measuring

Particulate matter collections were conducted using an AVL smart sampler and an in-house SDS-system. The particulate mass was collected on 70 mm diameter filters.

During the measurement period, PM was collected on Fluoropore and TX40- type filters and SVOCs were collected on HLB-type filter.



Picture 12 Particulate matter collected on TX40-filter (VTT).

PN and particulate size distribution was measured using two CPCs with different measuring ranges and ELPI. A micro soot sensor was used for measuring black carbon. Each device had their own internal data logging.

5.4.2 Gaseous emissions measuring

The in-test measured gaseous emissions were carbon dioxide, oxides of nitrogen and oxygen. The measured gaseous emissions were used mainly as monitors for sequence repeatability and equivalence for previously run tests on the same test set-up.

Maihak manufactured Sidor was connected into the in-house data logging system and the Gasmet FTIR had an internal data logging on Calcmnet-software on PC.

The measurement data was recorded daily, exported into Excel form and the desired charts were made.

6 RESULTS

6.1 Particulate matter

Particulate matter samples were collected in two campaigns between September 2019 and April 2020 (Aakko-Saksa 2020).

Relatively low PM concentrations of $<5 \text{ mg/m}^3$ were noticed during the measurements although the collected PM mass was relatively high. Using both test fuels the PM concentration averages appeared to be lower in the second measurement period. PM concentrations were higher in the exhaust from the diesel engine when using A20 than A0 fuel in two periods.

The total mass of the collected particulate emission on the primary Fluoropore filter was 65.95 mg on A0-fuel (39.4 m³ raw exhaust gas) and 76.96 mg on A20-fuel (30.8 m³ raw exhaust gas). The standard deviation of the collections stands at 0.72 on A0-fuel and 0.71 on A20-fuel.

Figure 5 shows a mass of collected particulate emission along with the collected mass of SVOC emission in mg.

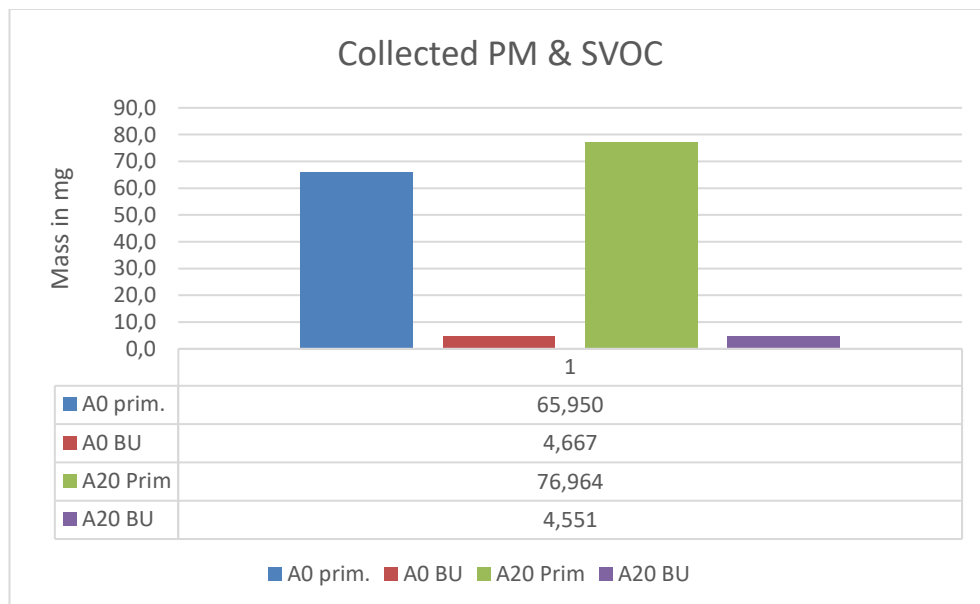


Figure 4 Collected PM & SVOC emission

6.2 Gaseous emissions

Along with PM, gaseous emissions were monitored. The result data collected from the Sidor was exported in Excel form whereas the data collected by FTIR was saved internally as a special spectrum form every 20 seconds.

As an example, the figure below represents nitrogen repeatability between the various test runs measured by Sidor. The total running time of one test cycle corresponds to 1800 s, therefore, the figure demonstrates in total of 3x3 cycle runs (5400 s each).

During the idle mode at the beginning and end of the cycle, the NO value stands at approximately 200 ppm. The maximum value of NO concentration of 1050 ppm (90 % increase in concentration from the lowest concentration on mode 6) was discovered unpredictably on mode 2 of the maximum engine load value of 520 Nm at 1450 rpm.

The lowest NO concentration of approximately 100 ppm was discovered on mode 6 (2200 rpm / 39 Nm load); the concentrations on the other modes vary from 200-800 ppm (50 -88 %) increase compared to the lowest concentration.

Figure 6 shows mode by mode alteration of measured NO emission value during three RMC-C1-cycles.

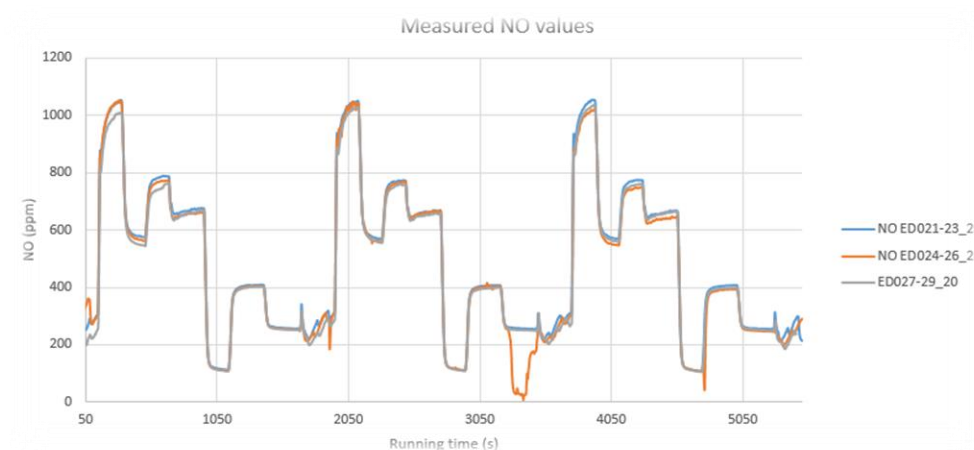


Figure 5 Measured NO values on test run #21-29 (VTT)

All the gaseous emissions act the same pattern during the measurements. For instance, in case of CO₂ (%) the increase in percentage between the lowest value of 1.6 % (at mode 6) and the highest concentration value of 8.4 % (at mode 2) was approximately 81% whereas the increase in other mode values varies from 55-70 % from the lowest concentration.

Conclusions based on FTIR data must be drawn cautiously for the reason that FTIR provided an average result of the measured gaseous components during every 20-second measurement period due to the choice of the measurement interval. This creates an unwanted effect where the true maximum and minimum values in relatively short measurement points (modes) may never be reached, therefore, never discovered if only using the FTIR.

7 SUMMARY

Conventional diesel fuel is currently the most common energy source in the field of transportation even though the environmental legislation is constantly placing pressure on consumers to shift into lower emission transportation forms.

Toxic gaseous and particulate pollutants emitted from engines using conventional fuels will slowly impair the air quality around us. Exhaust gas pollutants are known to have a varying influence on the human health and environment.

Many recent studies have shown a connection between particulate emissions and more severe health issues, such as respiratory and neurological issues.

The EU H2020 TUBE project concentrated on investigations in finding a link between deep penetrating ultrafine particulate emissions and Alzheimer's disease. In the practical part of the thesis, a certain amount of particulate matter was collected from a diesel engine and was delivered to the UEF for further investigation.

The project measurements will be continued in fall 2020.

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Appendix A Fuel properties

Parameter	Method	Unit	EN590 "A20"	Arom-free "A0"
Density (15 °C)	DIN EN ISO 12185	kg/m ³	834.4	779.6
Kin. viscosity (40 °C)	DIN EN ISO 3104	mm ² /s	3.1	2.9
Carbon residue (10 % D.)	DIN EN ISO 10370 DIN EN ISO 6245	% (m/m)	<0.10	<0.10
Ash content		% (m/m)	<0.001	<0.001
Total contamination	DIN EN 12662	mg/kg	<12	<12
Water content	DIN EN 12937	mg/kg	<30	<30
Monoaromatics	DIN EN 12916	% (m/m)	17.8	0.1
Diaromatics		% (m/m)	1.6	<0.1
Triaromatics		% (m/m)	0.1	<0.1
PAH content		% (m/m)	1.7	<0.1
Total aromatics		% (m/m)	19.6	0.1
Flash point	DIN EN ISO 2719	°C	73	73
CFPP	DIN EN 116	°C	-18	-43
Cloud point	DIN EN 23015	°C	-4	-33
Cetane number	DIN EN 17155		52.8	69.6
Cetane Index	DIN EN ISO 4264	-	55.5	92.8
% (V/V) recovery 250°C	DIN EN ISO 3405	°C	28.5	6.6
% (V/V) recovery 350 °C		°C	95.6	>98
95 % (V/V) recovery		°C	347.9	294.0
Sulphur content	DIN EN ISO 20884	mg/kg	6.2	<5
Oxidation stability	DIN EN ISO 12205	mg/m ³	<1	<1
HFRR (Lubricity)	DIN EN ISO 12156-1	µm	300	380
Copper strip corrosion	DIN EN ISO 2160	Corr.degree	1	1
FAME content	DIN EN 14078	%(V/V)	<0.1	<0.1
Calorific value, lower	DIN 51900-2 mod.	MJ/kg	42.86	43.62
HFRR (60 °C)	DIN EN ISO 12156	µm	300	380
Carbon content	ASTM D 5291	%(m/m)	85.8	85.1
Hydrogen content		%(m/m)	13.9	15.1
Oxygen content	DIN 51732	%(m/m)	<0.5	<0.5
Electrical conductivity	DIN 51412-1	pS/m	186	349
Silver (Ag)	ASG 1917-ICP-	mg/kg	<0.01	<0.01
Copper (Cu)	OES/MS	mg/kg	<0.01	<0.01
Aluminium (Al)		mg/kg	<0.05	<0.05
Cadmium (Cd)		mg/kg	<0.01	<0.01
Sodium (Na)		mg/kg	<0.05	<0.05

Potassium (K)	mg/kg	<0.05	<0.05
Chromium (Cr)	mg/kg	<0.01	<0.01
Manganese (Mn)	mg/kg	<0.01	<0.01
Nickel (Ni)	mg/kg	<0.01	<0.01
Iron (Fe)	mg/kg	<0.01	<0.01
Molybdenum (Mo)	mg/kg	<0.01	<0.01
Barium (Ba)	mg/kg	<0.5	<0.5
Boron (B)	mg/kg	<0.01	<0.01
Calcium (Ca)	mg/kg	<0.05	<0.05
Magnesium (Mg)	mg/kg	<0.05	<0.05
Lead (Pb)	mg/kg	<0.01	<0.01
Vanadium (V)	mg/kg	<0.01	<0.01
Tin (Sn)	mg/kg	<0.5	<0.5
Zinc (Zn)	mg/kg	<0.01	<0.01
Silicon (Si)	mg/kg	<0.5	<0.5
Titanium (Ti)	mg/kg	<0.01	<0.01
Phosphorous (P)	mg/kg	<0.5	<0.5
Cobalt (Co)	mg/kg	<0.01	<0.01
Lithium (Li)	mg/kg	<0.01	<0.01

Appendix B Lubricant properties after test period

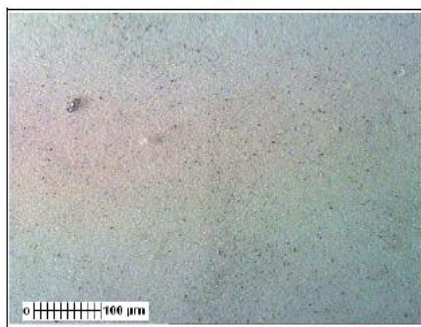
KOMMENTIT JA DIAGNOOSI

Öljyn kunto: Öljyn merkkiä/tyyppiä ei ilmoitettu, mutta mitatut arvot ovat tyypilliset Shell Rimula R5 LE 10W-40 öljylle.
Kuluminen: Kulumametallipitoisuudet olivat yleisesti ottaen alhaiset (huom! molybdeeni on osa öljyn lisäaineistusta) eikä mikroskooppitarkastelussa havaittu isoja metallihiukkasia.
Öljyn puhtaus: Moottoriöljyssä ei ollut merkittäviä määriä epäpuhtauksia (esim. vesi, glykoli, noki, polttoaine tms.)

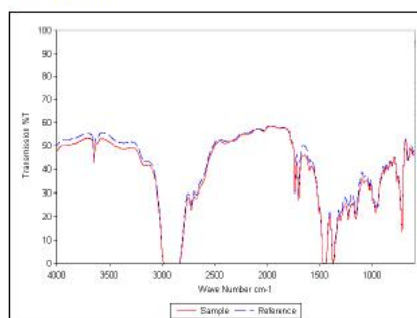
TULOKSET

Näytteenottopäivä	29.4.2020			
Öljyn käyttötunnit	143			
Laboratorionumero	H72001			
ÖLJYN KUNTO		Menetelmä		
Viskositeetti	+40 °C	cSt	ASTM D445	89,94
	+100 °C			13,44
Viskositeetti-indeksi	-			151
TBN	-		ISO 3771	9,23
TAN				
Öljyn hapettuminen	A / cm			1
Öljyn nitrautuminen	A / cm			1
Öljyn sulfatoituminen	A / cm			3
Dispergoituvuus	%			98
Lisäaineet - ICP	ppm	ASTM D5185		
Kalsium				2007
Magnesium				420
Boori				115
Sinkki				1221
Fosfori				1043
Barium				0
Rikki				2941

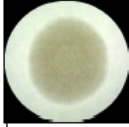
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FT-IR-spektri



TULOKSET

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Öljyn käyttötunnit	143			
Laboratorionumero	H72001			
JÄRJESTELMÄN KULUMINEN JA ÖLJYN KONTAMINAATIO		Menetelmä		
Kulumametallit - ICP	ppm	ASTM D5185		
Rauta			6	
Kromi			0	
Tina			0	
Alumiini			0	
Nikkeli			0	
Kupari			7	
Lyijy			1	
Molybdeeni			59	
PQ-indeksi	-		OK	
Kontaminantit - ICP		ppm		
Pii			4	
Kalium			8	
Natrium			3	
Vesipitoisuus	ppm	ASTM D6304 C	390	
Glykoli	-		negat.	
Polttoainelaimentuma	%		<0,30	
Biodieselpitoisuus (FAME)	%		<0,30	
Nokipitoisuus	%		<0,1	
Puhtausluokka	ISO4406	ISO4407		
Hiukkaslaskenta (A=autom., M=mikrosk.)			-	
ISO4406:1999	ISO4406			
> 4 µm	(> 2 µm)	kpl / 100 ml		
> 6 µm	(> 5 µm)			
> 10 µm	(> 10 µm)			
> 14 µm	(> 15 µm)			
> 21 µm	(> 20 µm)			
> 25 µm	(> 25 µm)			
> 38 µm	(> 50 µm)			
> 70 µm	(> 100 µm)			
Paperikromatografinen täpläkoe				
				

Appendix C ISO-8178 Test cycles

RMC test cycle	Ignition type	Example application
C1	Compression (spark)	<ul style="list-style-type: none"> - Industrial drilling rigs, compressors etc.; - Construction equipment including wheel loaders, bulldozers, crawler tractors, crawler loaders, truck-type loaders, dumpers, hydraulic excavators etc.; - Agricultural equipment, rotary tillers; - Forestry equipment; - Self-propelled agricultural vehicles (including tractors)
C2	Spark	<ul style="list-style-type: none"> - Fork-lift trucks; - Airport equipment; - Material handling equipment; - Road maintenance equipment;
Type D 1&2 (constant speed)	Compression / Spark	<ul style="list-style-type: none"> - Power plants; <p>cycle D2:</p> <ul style="list-style-type: none"> - Gas compressors, irrigation pumps; - Generating sets with intermittent load including generating sets on board of ships and trains (not for propulsion), welding sets; - Turf care, chippers, snow removal equipment, sweepers.

Type E 1-5 (Marine)	Compression / Spark	<ul style="list-style-type: none"> - Cycle E1: compression ignition engines for propulsion of craft less than 24 m in length excluding tug boats and push boats; - Cycle E2: constant-speed heavy duty engines for propulsion of ships of any length including diesel-electric drive and variable-pitch propeller applications; - Cycle E3: propeller-law heavy duty engines for propulsion of ships of any length; - Cycle E4: spark ignition engines for propulsion of craft less than 24 m in length except tug boats and push boats; - Cycle E5: compression ignition engines for propulsion of craft less than 24 m in length when operated on a propeller law except for tug boats and push boats.
Type F (Rail traction)	Compression	<ul style="list-style-type: none"> - locomotives; rail cars, shunting locomotives (C1 may also be used)
Type G 1-3 (Utility, law, garden)	Compression / Spark	<ul style="list-style-type: none"> - Rotary tillers, edge trimmers, lawn sweepers, waste disposers, sprayers, snow removal systems, golf carts
Type H	Spark	<ul style="list-style-type: none"> - Snowmobiles
Type I		<ul style="list-style-type: none"> - Transport refrigeration units