MAGYAR AGRÁR- ÉS
ÉLETTUDOMÁNYI EGYETEM

AFTERTREATMENT OF THE DIESEL EXHAUST GASES

Doctoral (PhD) Thesis

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TABLE OF CONTENTS

LIST OF SYMBOLS, ABBREVIATIONS

Symbols

NO_{xp}	Calculated NO_x concentration	[g/kWh]
NO_p	Calculated NO concentration	[g/kWh]
CO_p	Calculated CO concentration	[g/kWh]
CO_{2p}	Calculated CO_2 concentration	[g/kWh]
CH_p	Calculated CH concentration	[g/kWh]
SPN_{10}	Calculated 10 nm particle concentration	[#/kWh]
SPN_{23}	Calculated 23 nm particle concentration	[#/kWh]

Abbreviations

APC	AVL particle counter	[-]
EEPS	Engine exhaust particle sizer	[-]
SPN	Solid particle number	[#/kWh]
DPF	Diesel particle filter	[-]
PM	Particle mass	[g/kWh]
RDE	Real driving emission	[-]
WHSC	World harmonized steady state cycle	[-]
CPC	Condensation particle counter	[-]
CS	Catalytic stripper	[-]
ET	Evaporation tube	[-]
PN	Particle count	[-]
UNECE	United Nations Economic Commission	[-]
CVS	Constant volume sampling	[-]
DOC	Diesel oxidation catalyst	[-]
SCR	Selective catalytic reduction	[-]
PND	Particle number diluter	[-]
MFC	Mass flow controller	[-]
VPR	Volatile particle remover	[-]

1.INTRODUCTION, OBJECTIVES

1.1. Introduction

Emissions technology represents one of the most rapidly advancing sectors in the automotive industry of the 2000s. Driven by increasingly stringent emissions regulations at both European and global levels, there is a push for the development of newer and more sophisticated exhaust gas aftertreatment systems. Recent events, notably the Volkswagen diesel scandal in 2015, have heightened public attention on the necessity for proper regulation of pollutant emissions, necessitating that all possible scenarios be considered at the design stage to minimize environmental damage. To the lay observer, vehicles equipped with internal combustion engines, particularly those with diesel engines, appear to be on the brink of being replaced by electric propulsion. However, this assumption merits closer examination, as vehicles powered by alternative propulsion systems, namely Battery Electric Vehicle (BEV) and Fuel Cell (F-CELL) vehicles, are not yet, and will not in the foreseeable future, able to replace internal combustion engine technology, especially diesel technology, in the heavy-duty vehicle sector. Humanity's primary energy needs are directed towards the production of electric power (18%), heating (20%), transportation (28%), and other industrial purposes (34%). The total global electric power generation in 2016 was approximately 25 PWh, two-thirds of which originated from fossil fuels, severely damaging the ecosystem through the emission of greenhouse gases and other pollutants. Among currently available energy generation solutions, nuclear power plants represent one of the most crucial carbon-neutral technologies. The 452 operational blocks worldwide have a total electrical capacity of 398 GW, contributing to 10.2% of the world's electricity production in 2018. These data suggest that the electric power, commonly perceived by the public as "clean," is not sourced from carbon-neutral resources in much of the world. Consequently, in further discussions, BEV and F-CELL drives will be referred to as having zero local emissions, though their global emissions are significant, and according to some studies, higher over the full lifecycle than those of internal combustion engines. Building on this premise, there is a justified existence and substantial potential for development for internal combustion engines, as exemplified by the Bosch-Weichai Power diesel engine for heavy-duty vehicles, which achieved a thermal efficiency of over 50% (Bosch-presse, 2020) and has entered serial production. Over the next 10-20 years, the market for passenger car and commercial vehicle engines will see the implementation of Mild Hybrid Electric Vehicle (MHEV) and Plug-in Hybrid Electric Vehicle (PHEV) technologies, along with the optimization of exhaust gas aftertreatment systems, to reduce the unfavorable emission characteristics of both Otto and diesel-powered vehicles.

1.2. Objectives

The primary objective of my doctoral research is to determine the correlations between the two main harmful emission components in diesel engine exhaust, nitrogen oxides (NOx) and particulate matter (PM), with the actuators of diesel engines, through a series of experiments with fixed parameters in an engine brake laboratory environment.

The detailed objectives are as follows:

- To process and understand the relevant emissions technology literature.
- To conduct a comparative evaluation of particle measurement arrangements based on the dilution ratio.
- To develop a new aerosol preparation principle for condensation particle measurement.
- To develop an aerosol preparation unit for a condensation particle measurement system based on the aforementioned principle.
- To write test cell control programs on the PUMA Open TST editor interface.
- To write a program in Visual Basic that controls the engine actuators in a repeatable manner.
- To conduct and thoroughly evaluate a series of fixed-parameter engine brake tests.
- To determine the functional relationship between the emission of 10/23 nm particles and the common rail pressure, as well as the extent of exhaust gas recirculation.
- To determine the functional relationship between NOx emissions and the common rail pressure, as well as the extent of exhaust gas recirculation.

2. MATERIALS AND METHODS

2.1. Test cell infrastructure

Gaseous and liquid media (coolant, oil, intake air, and charge air) significantly influence engine behavior. Conditioning systems are capable of maintaining these media at predetermined temperatures under all operating conditions. The execution of highly accurate and repeatable tests necessitates fixed environmental conditions. Exhaust gas emission measurement tests are conducted with a time delay, following the evaluation of each test, thus conditioning of the media ensures that testing conditions remain comparable. For these reasons, conditioning systems are indispensable for the experiments intended to be carried out. At the research and development center of Ibiden Hungary Ltd. located in Dunavarsány, where I work as an engineer and also conduct my doctoral research, is equipped with the mentioned conditioning devices and complete engine dynamometer test cells. Among these, I used the engine dynamometer test cell containing a heavy-duty vehicle engine, as shown in Figure 1, for my experiments.

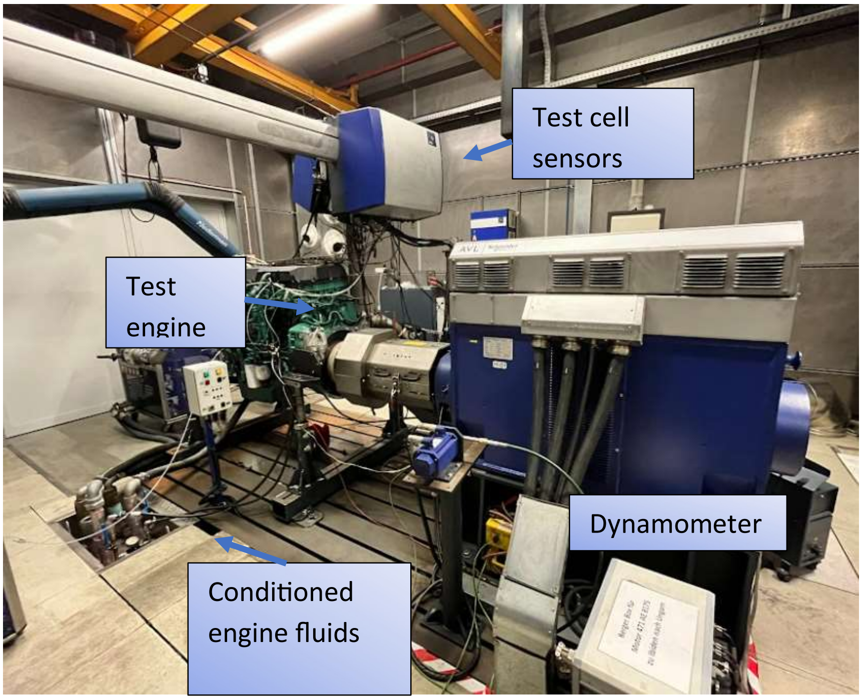


Figure 1. Eengine dynamometer test cell at Ibiden Hungary Ltd.'s facility (Source: Norbert Biró)

For the evaluation of test cycles, appropriate sampling time for data acquisition is also crucial. This data acquisition apparatus includes operational parameters of the engine (such as rotation speed and engine torque), environmental conditions (such as test cell air temperature, intake air pressure, humidity, temperature, engine fluids' temperatures, pressure, etc.), and the specific amounts of gaseous and solid pollutants. Additionally, I had the opportunity to record data from the engine's on-board diagnostics (OBD) sensors, while also having the ability to modify the actuators that are fundamentally regulated by the engine control unit.

2.2. Test engine

For the experiments, I utilized a Volvo-manufactured, common rail, direct injection diesel engine designed for heavy-duty vehicles, which is shown in Figure 2. The engine used in my research is parametrizable, allowing for modifications in its key characteristics. This enables the application of specific settings on the engine, regardless of the engine type, thereby ensuring that the engine subsystems operate with fixed parameters while the parameter under examination is varied. As a result, I am capable of conducting reproducible measurements independent of the engine type, which facilitates the generalizability and repeatability of my research findings. The engine data can be found in Table 1.

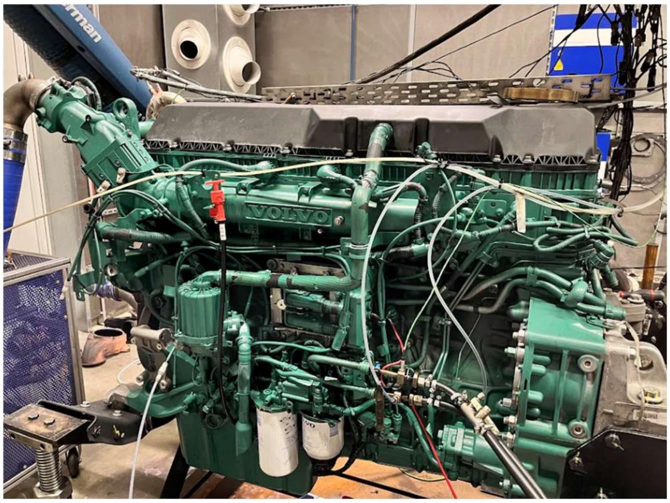


Figure 2: Volvo D13-TC installed on an AVL HD 500 kW engine dynamometer at the Ibiden Hungary Technical Center in Dunavarsány. (Source: Norbert Biró)

Table 1. Test engine specifications

Engine specifications	
Denomination	D13TC TURBO-TC
Type	Direct injection diesel
Bore × stroke	131 [mm] × 158 [mm]
Displacement	12800 [cm^3]
Firing order	1-5-3-6-2-4
Peak performance	372 [kW] @1300-1600 [1/min]
Peak torque	2840 Nm @900-1300 [1/min]
Compression ratio	18:1

2.3. Experiment planning

2.3.1. WHSC cycle

The World Harmonized Steady State Cycle (WHSC) is a constant state engine dynamometer test cycle defined by Regulation No. 4 of the Global Technical Regulation (GTR). The WHSC, which includes steady-state engine conditions, was developed to cover the characteristic driving habits of the EU, USA, Japan, and Australia. The WHSC test cycle is a key part of the complex certification framework aimed at harmonizing heavy-duty vehicle emissions on a global scale. Therefore, I chose the WHSC cycle for my research because it allows my results to be easily comparable with data from manufacturers and other researchers.

The so-called normalized values define the percentages of the maximum engine speed and torque. In contrast, denormalized values are derived specifically for the given engine. I determined the denormalized engine speed and torque for the test engine I used with the help of Equation 1.

Denormalization calculation

$$n_{ref} = n_{norm} \cdot \left(0{,}45 \cdot n_{lo} + 0{,}45 \cdot n_{pref} + 0{,}1 \cdot n_{hi} - n_{idle}\right) \cdot 2{,}0327 + n_{idle} \qquad (1)$$

Where:

n_{lo} The lowest rotational speed at which the engine's output reaches 55 percent of its maximum power.

n_{pref} The engine speed at which the integral of the mapped torque between nidle and n95h constitutes 51 percent of the total integral. This speed indicates the most favorable torque characteristics within the operational range.

n_{hi} The highest speed at which the engine's performance achieves 70 percent of its maximum power, marking an upper limit of efficient power output.

N_{idle} The idle speed of the engine,

n_{95h} The highest speed at which the engine's output reaches 95 percent of its maximum power, defining the upper performance limit under high load conditions.

2.3.2. AVL PUMA programming environment

The AVL PUMA software is associated with test cells manufactured by AVL GmbH. The entire system adheres to the "single software principle," meaning that control of the previously described conditioning systems, the engine dynamometer, the engine itself, emission measuring equipment, the fuel system, data acquisition, and the control of PLCs (Programmable Logic Controllers) found at the facility operation level is accessible from a control computer located in front of the test cells. This integration facilitates comprehensive management and synchronization of test cell operations, enhancing efficiency and precision in the testing processes.

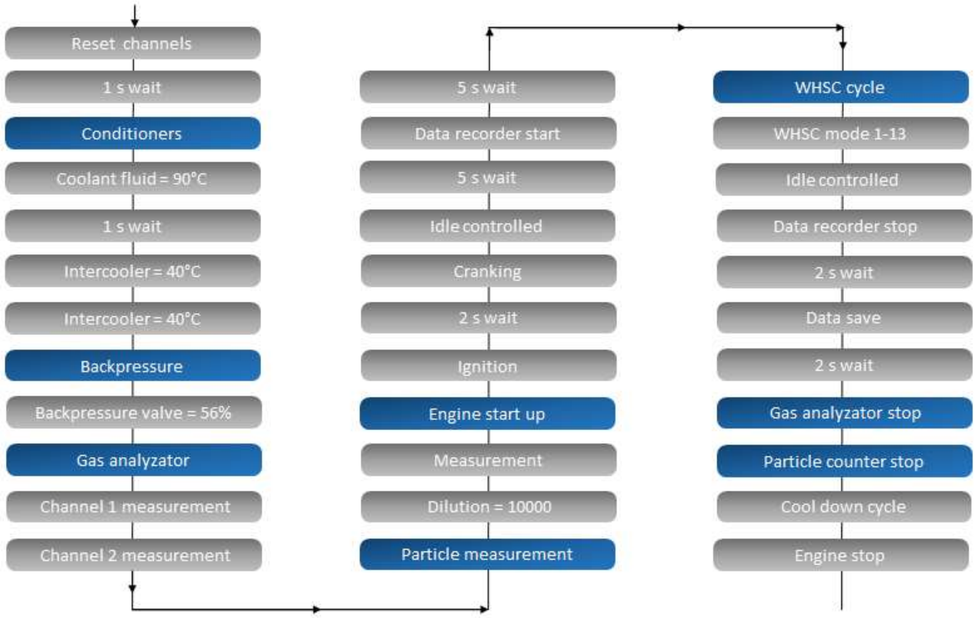


Figure 3. Steps of the WHSC program on the AVL Puma programming interface (Source: Norbert Biró)

The WHSC mode 9 and WHSC test programs I developed provide strictly fixed parameters during experiments. Each experiment is executed by the control program in exactly the same sequence and steps (as shown in Figure 3), ensuring the reliability and repeatability of the results. Achieving this level of precision with manual control would be impossible. Through the use of consistent and standardized procedures during the test cycles, the experiments are comparable and reproducible, which is crucial for obtaining reliable results and conclusions in engine testing.

2.4. Eperiment schedule

The experiments were conducted at the Technical Center located at the Ibiden Hungary facility, utilizing the equipment described in previous chapters. I employed motor control programs I developed in Visual Basic to forcibly modify different actuator values of the engine. It's crucial to note that during the operation of the engine, all parameters were fixed, meaning that only the actuator values modified for the specific experiments deviated from their baseline state. This was guaranteed by the uniquely created dynamometer and engine control automated programs I developed, ensuring that each experiment was perfectly consistent in terms of the desired parameters. I produced 24 different variants of the experiments, each repeated 3 times, resulting in a total of 72 test series. Moreover, since each test series comprised one WHSC mode 9 and one WHSC main program, a total of 144 separate engine dynamometer measurements were conducted. A single test series took exactly 4.08 hours, meaning the entire measurement process spanned 296.76 hours, which, calculated over 8-hour workdays, extended over more than 7 weeks.

2.5. Emission measurement devices

2.5.1. Particle counter (APC 489)

Condensation Particle Counting (CPC) is the most widely used method for determining the particle number concentration of an aerosol (sample gas). This technique involves the treatment of the aerosol's solid particles with liquid butanol, causing them to enlarge. These enlarged particles pass through an extremely sensitive sensing chamber, equipped with laser light and sophisticated photodetection optics, designed for precise particle analysis and quantification. This method enables the accurate detection and counting of particles, even at very low concentrations, making it indispensable for assessing air quality, environmental monitoring, and compliance with emissions standards.

2.5.2. Gas analyzer (AMA i60)

The majority of exhaust gas components regulated by the Euro vehicle emission directives consist predominantly of gaseous pollutants. The analyzers used during the AMA i60 experiments have a wide measurement range and are capable of accurately measuring gaseous pollutants such as THC, $NO/NO_2/NO_X$, CO, CO_2, O_2, N_2O, CH_4, SO_2, NH_3, and H_2O. Since the measurement principles of various gaseous emission components differ from one another, aerosols must be analyzed using different analyzers, which are separated from a common measurement tube. From a research perspective, NO_X as an emission component is of particular importance, with its associated analyzer based on the principle of chemiluminescence measurement. This method is critical for the accurate detection and quantification of NO_X emissions, offering valuable insights into the environmental impact of vehicle exhaust.

2.6. Data analysis with linear and polynomial regression

I analyzed the dataset, cleansed of outliers, using polynomial and linear regression. During the regression process, the removal of outliers aided in enhancing the stability and reliability of the model. This method allowed for a detailed examination of the interactions between variables and their impact on the dependent variable, minimizing the potential distorting effect of outliers on the analysis. By employing these regression techniques, it was possible to better understand the underlying relationships within the data, providing insights that are critical for accurate predictions and interpretations in the context of the research.

3. RESULTS

3.1. Analysis of particle counting lab equipment

The topic of particle number measurement was of paramount importance during the experiments. For this purpose, before starting the series of experiments, I tested the two particle counter setups I had designed. The focus of the conducted measurements was the simultaneous examination of the measurement range between 10 and 23 nanometers. This became particularly important since the current Euro VI standard mandates counting particles in exhaust gas starting from a 23-nanometer particle diameter. However, the upcoming Euro VII standard will also require the counting of particles with diameters between 10 and 23 nanometers. This development was an important step because it ensures that my research findings not only comply with current standards but also remain relevant and useful following the introduction of

Euro VII. Measuring particles as small as 10 nanometers helps guarantee that my research results and information related to particle concentration will continue to be valuable and applicable in the future, with the emergence of new standards and requirements. Due to the inherently different measurement principles of the Advanced Particle Counter (APC) and the Electrical Low-Pressure Impactor (EEPS), initial tests were necessary to verify that the two devices could measure together accurately. The validating measurements were conducted with the WHSC cycle, the results of which are visible in Table 2 and presented in Figure 4, where I related the dilution factor to the final particle number result calculated for each WHSC measurement.

Table 2 Results of experiments conducted with APC and EEPS particle counters, with varying dilution factors

Test nr.	APC dilution factor [-]	Calculated particle count [#/kWh]	EEPS dilution factor [-]	Calculated particle count [#/kWh]
1	100	$5\cdot10^{12}$	5	$5\cdot10^{12}$
2	5000	$5\cdot10^{13}$	50	$5\cdot10^{13}$
3	15000	$5\cdot10^{13}$	1000	$5\cdot10^{13}$
4	100	$1\cdot10^{9}$	5	$8\cdot10^{10}$
5	5000	$1\cdot10^{9}$	50	$5\cdot10^{11}$
6	15000	$1\cdot10^{11}$	1000	$1\cdot10^{13}$

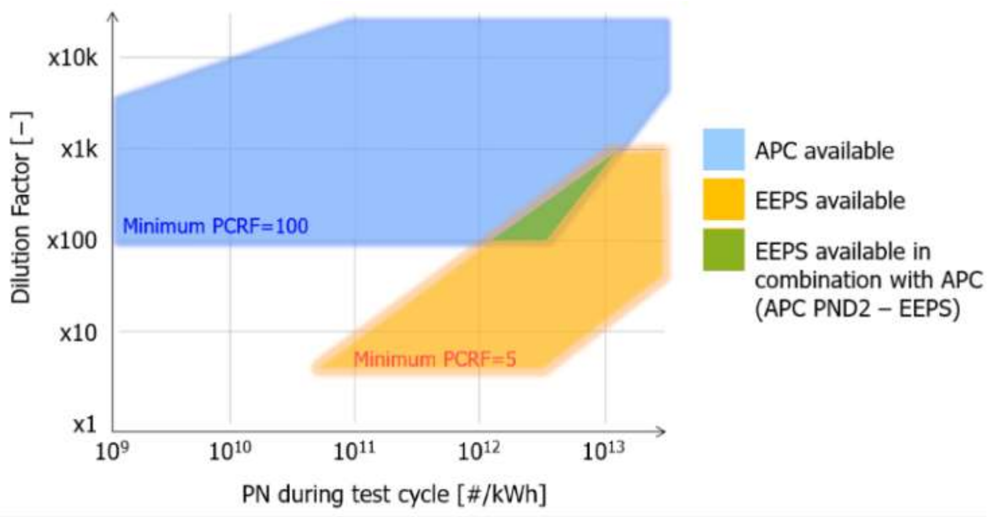


Figure 4 illustrates the results of particle number measurements with the APC and EEPS as a function of the dilution factor. APC = AVL Particle Counter, CPC = Condensation Particle Counter, and EEPS = Exhaust Emission Particle Sizer.

The green area on the chart indicates where the two devices are able to measure effectively in conjunction. The overlap, where the counting efficiency of both devices is acceptable, is quite small and not deemed suitable for extensive experimental work, leading me to conclude that the first particle counting setup was not optimal. In contrast, the second setup, where the two devices operate almost entirely with a matching measurement methodology, allows for efficient measurement across the entire blue field. Additionally, as subsequent experiments are based on the measurement of raw exhaust gas, a higher aerosol dilution is necessary to protect the particle counting equipment. Furthermore, the dilution capacity of the EEPS below 100 becomes entirely unnecessary, further reinforcing the use of the second setup. While the use of the EEPS would have provided a more comprehensive picture of particle formation by determining the distribution of particles across different size classes, I ultimately decided against its further application in my experiments based on my analysis. The experiment and its results were also published in an international journal with an impact factor.

3.2. Development of a particle counter for research

Before launching my planned series of engine dynamometer emission measurement experiments, I meticulously addressed the challenges associated with condensation particle measurement. Specifically, in lengthy experimental series that occur in measurement environments with significant particle number concentrations and high relative humidity - typically situations where the emission measuring systems operate without aftertreatment devices - clogging of the aerosol (sample gas) flow paths and condensate formation can occur. These phenomena can lead to the malfunctioning of measuring equipment, hindering the smooth execution of the planned nearly 300-hour experimental series. To avoid this, I designed a new aerosol preparation unit aimed at preventing the clogging of sample lines and the formation of condensate, thereby ensuring the successful completion of the experimental series. This approach underscores the importance of addressing operational challenges to maintain the integrity and accuracy of long-duration emission measurement studies.

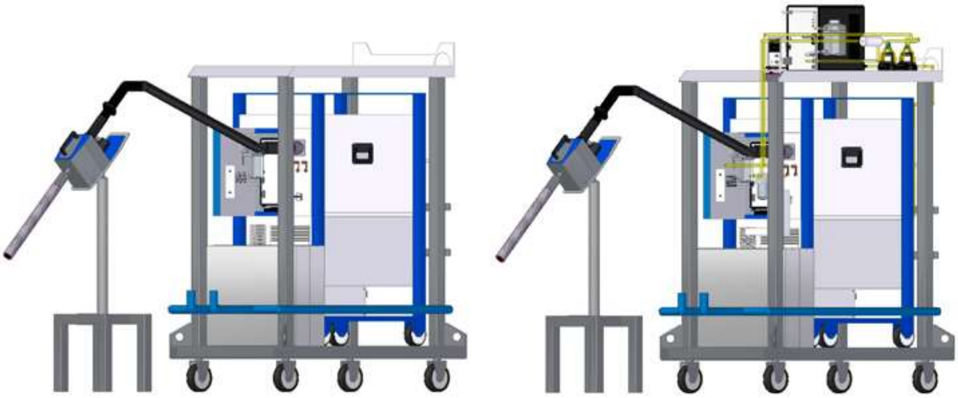


Figure 5 CAD models of the original (left) and developed (right) aerosol preparation units for a condensation particle counter.

The developed aerosol preparation unit incorporates new components and subunits, including a condensate drainage unit, a dedicated container for collecting condensed liquids, a high-efficiency particulate air (HEPA) filter, an adjustable power supply, and a membrane pump, as shown in Figure 5. The flow of sample gas through the developed unit is illustrated in Figure 6. This enhanced design aims to address the challenges of aerosol preparation in environments with high particle concentrations and humidity, ensuring reliable measurement performance and preventing equipment malfunction through innovative engineering solutions.

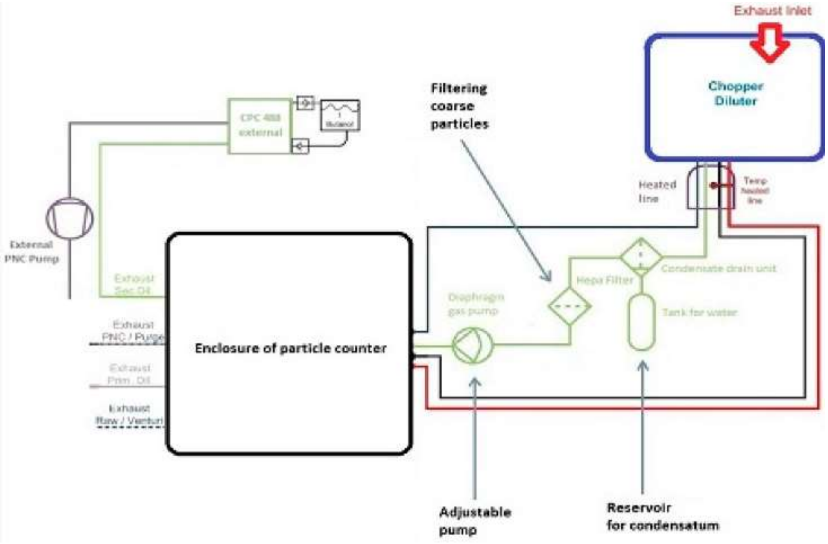


Figure 6 shows the process diagram of the APC 489, featuring the developed N-configuration (Source: Norbert Bíró).

3.3. Evaluation of experiments

Within the framework of classification analysis, I recorded the cleaned experimental data. Adjustments to the exhaust gas recirculation and common rail pressure parameters were made symmetrically in relation to the baseline conditions, ranging from -30% to +30%, with 10% increments. In the following sections of the chapter, I will analyze the remaining experimental data. Given that a single WHSC cycle captures approximately 160,000 data points, the 12 experiments required the processing of nearly 2 million data points in total. To manage the data reliably, I employed an automated data processing method, which I developed in Microsoft Excel format. To maintain the readability of the document and reduce its length, I will present in detail only one of the 12 experiments.

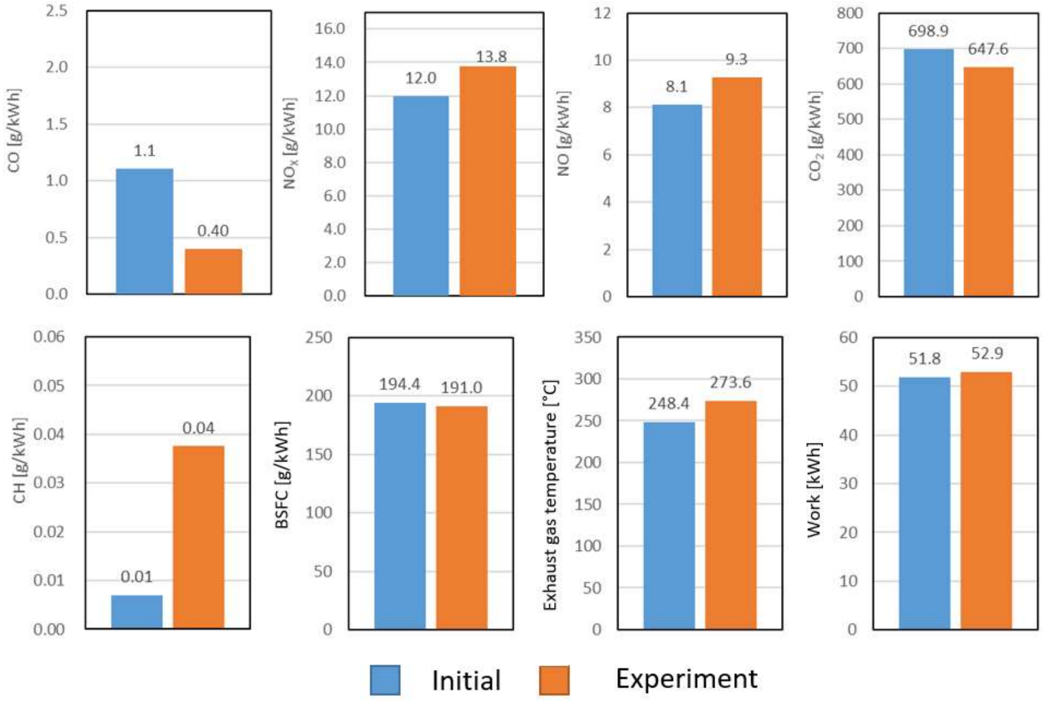


Figure 7 Calculated carbon monoxide, nitrogen oxides, nitrogen monoxide, carbon dioxide, hydrocarbons, specific fuel consumption, exhaust gas temperature, and work performed during the experimental WHSC cycle, compared with the baseline (Source: Norbert Bíró).

Figure 7 illustrates that reducing the extent of exhaust gas recirculation (EGR) resulted in a significant increase in the values of nitrogen oxide (NO) and nitrogen dioxide (NO_x), while the level of carbon dioxide (CO_2) decreased. This is attributed to the fact that the EGR method used for NO_x reduction adversely impacts the engine's thermal efficiency. Therefore, when the EGR rate is reduced by 30% in this experiment, CO_2 emissions and consequently fuel consumption decrease, while the work output increases, as identified by Needham.

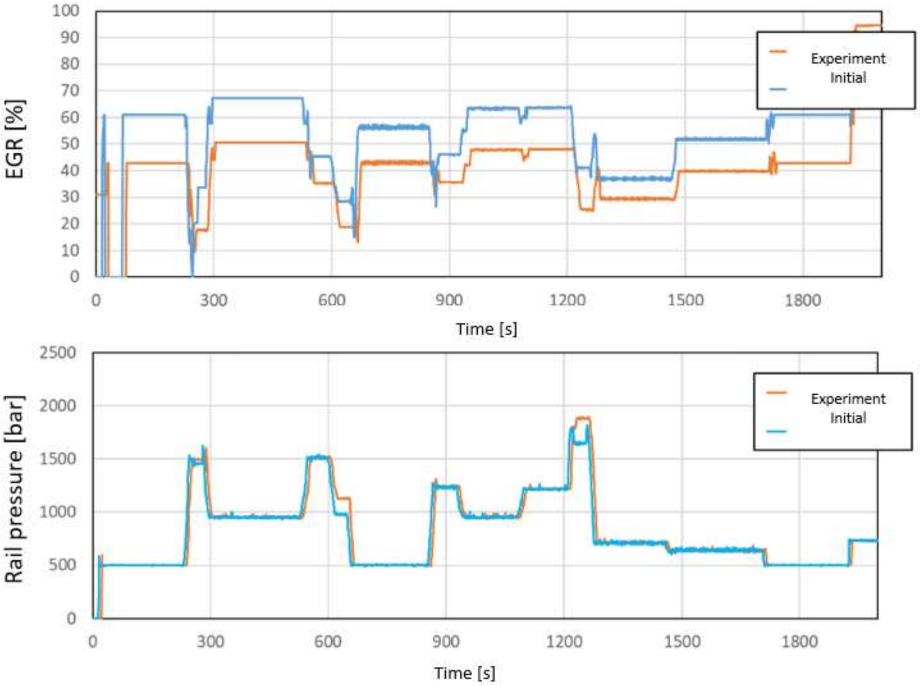


Figure 8 Transient exhaust gas recirculation ratio (EGR) and common rail pressure during the experimental WHSC cycle, compared with the baseline (Source: Norbert Bíró).

In the final phase of the evaluation, I examine the pressure in the common rail system and the extent of exhaust gas recirculation (EGR) throughout the cycle. These parameters are controlled through the engine management system with the help of the program code I developed. In this experiment, the EGR opening value was reduced by 30%, which can be clearly followed in Figure 8.

3.4. Functional Relationship between the Emission of 10/23 nm Particles and Common Rail Pressure

The aim of this part of my research was to investigate the number of solid particles in the exhaust gas of a diesel engine as a function of changes in the common rail pressure. During the study, I distinguished between two particle sizes: those 10 nanometers and larger, and those 23 nanometers and larger. For modeling the relationship, I chose polynomial regression because a quadratic relationship could be observed between the data, a point also referenced in Siebers' research. The polynomial regression model allows for the description of non-linear patterns as well. Furthermore, it meets my predefined objective of at least a 97% fit to the experimental data points, based on preliminary calculations. The regressions are presented in Figure 9.

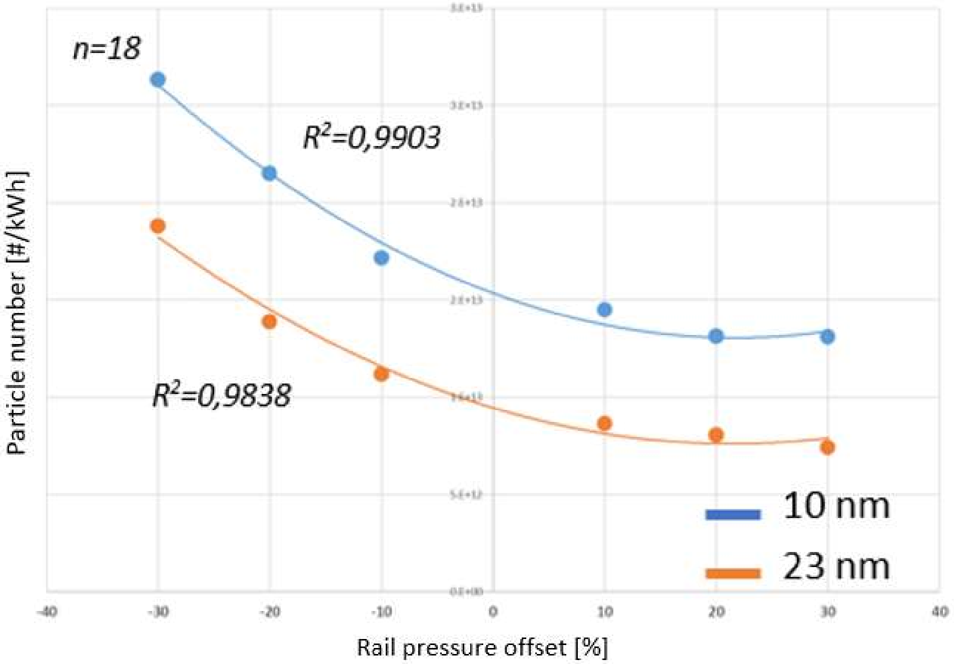


Figure 9 Particle number of 10 and 23 nm as a function of common rail pressure changes during the WHSC cycle. (Source: Norbert Bíró)

3.5. Functional relationship between the emission of 10/23 nm particles and the extent of exhaust gas recirculation

The aim of this part of my research was to investigate the number of solid particles found in the exhaust gas of a diesel engine as a function of the percentage adjustment of exhaust gas recirculation (EGR). During the study, two particle sizes were distinguished: those 10 nanometers and larger, and those 23 nanometers and larger. For modeling the relationship, I opted for polynomial regression, but in this case, linear regression would work as a good approximation based on my preliminary study, however, it could not meet the set error margin of 3%.

The functions and measurement points are illustrated in Figure 10.

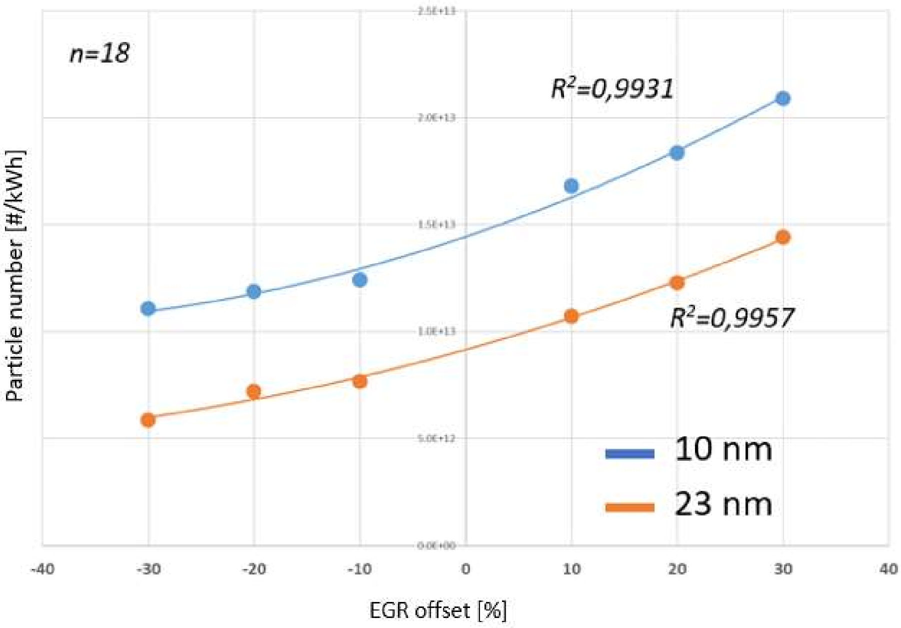


Figure 10 Particle number of 10 and 23 nm as a function of changes in exhaust gas recirculation during the WHSC cycle. (Source: Norbert Bíró)

3.6. Functional relationship between NO_x emissions and the amount of exhaust gas recirculation

In this part of my research, the objective was to examine the relationship between changes in the opening value of EGR and the nitrogen oxide emissions (NO_x) of a diesel engine. I adjusted the opening settings of the tested engine by a fixed amount: from -30% to +30%, in 10% intervals. Concurrently, I recorded the NO_x emission levels in g/kWh. For the mathematical modeling of the relationship, I performed a linear regression analysis. I fitted a regression model to the data, which describes the linear relationship between the independent variable (x) and the dependent variable (y).

The function is visually depicted in the figure below, shown in Figure 11.

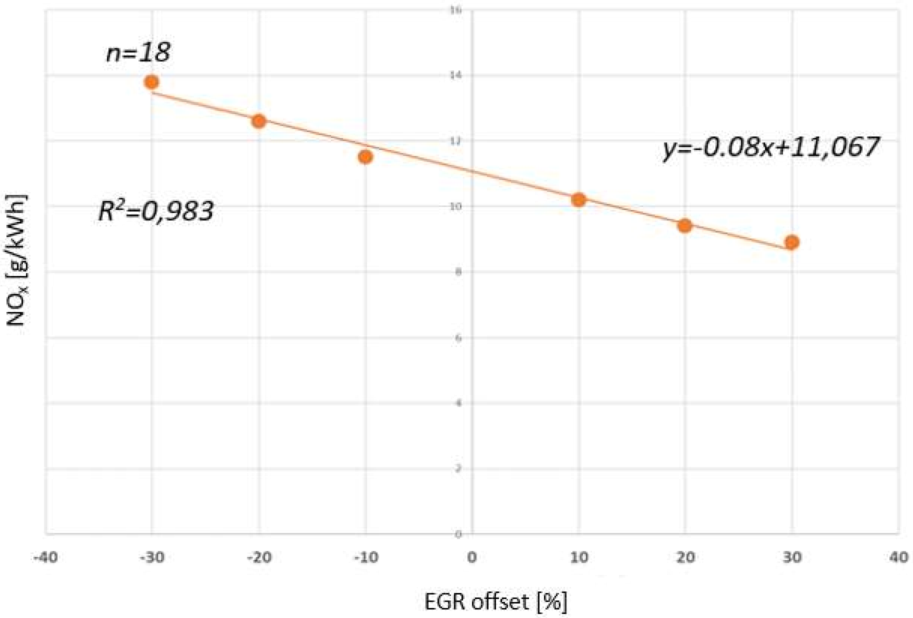


Figure 11: NOx concentration as a function of changes in exhaust gas recirculation during the WHSC cycle. (Source: Norbert Bíró)

3.7. Functional relationship between NO_x emissions and common rail pressure

In this part of my research, my objective was to examine the relationship between changes in common rail pressure and the nitrogen oxide emissions (NO_x) of a diesel engine. I adjusted the pressure settings of the tested engine by a fixed amount: from -30% to +30%, in 10% intervals. Concurrently, I recorded the NO_x emission levels in g/kWh. For the mathematical modeling of the relationship, I performed a linear regression analysis. The regression is presented in Figure 12.

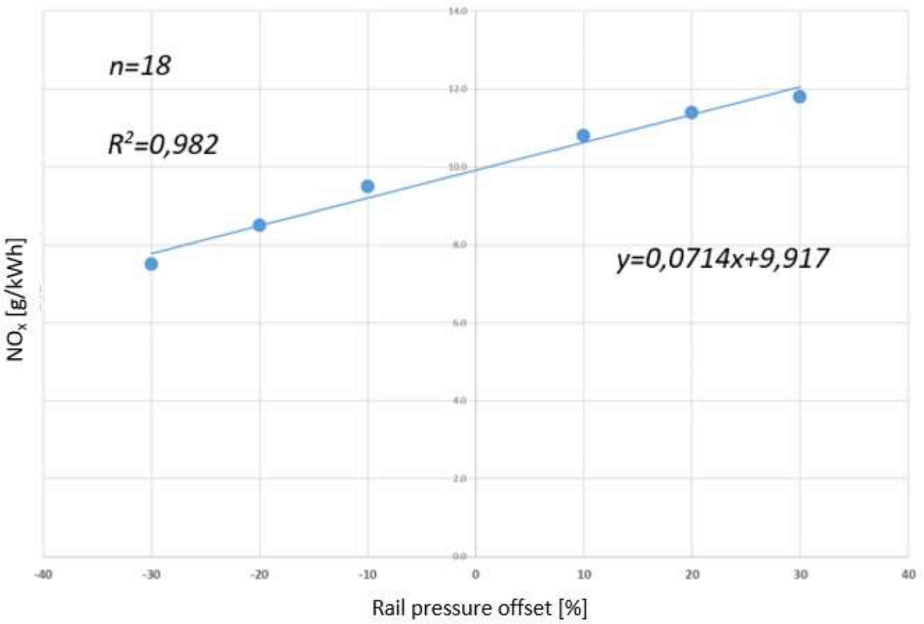
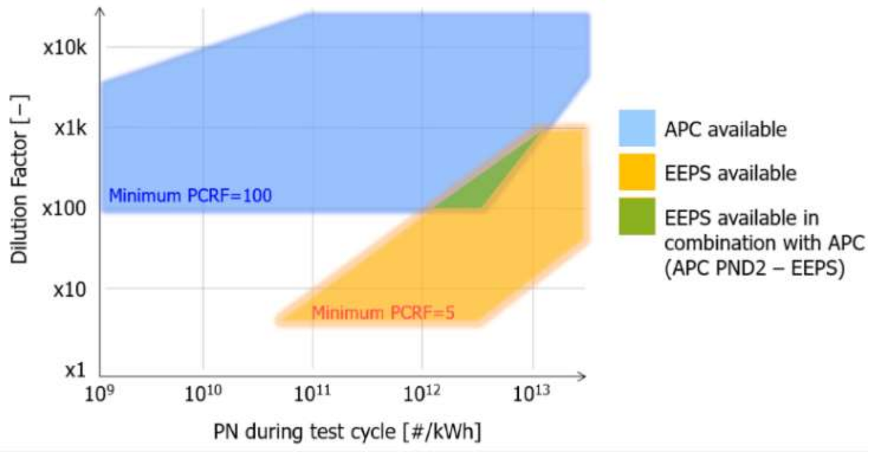


Figure 12 NO$_x$ as a function of changes in common rail pressure during the WHSC cycle. (Source: Norbert Bíró)

3.8. New scientific results

1.Thesis

In my research, I examined particle counters based on various measurement principles and determined their operational ranges as a function of the dilution factor. The relationship between particle concentration and dilution factor uncovered is illustrated in the figure below.



During the investigations, I uncovered a significant, previously unknown relationship between particle measurement and dilution factor, which is of practical importance. The results were published in a Q1 journal with an impact factor and cited in both Q1 and Q2 journals.

2.Thesis

In my engine dynamometer studies, I established the relationship between the pressure in the common rail and the number of particles measured and calculated for diameters of 10 and 23 nm, described by polynomial regression analysis. I was able to fit the function to my measurement data with a 3% error margin using the polynomial regression model and also avoided overfitting. The test engine used during the experiments is a motor with parametrizable settings, which allows for the generalization and reproducibility of the results. The derived relationships are applicable to compression ignition, common rail fuel supply system-equipped, EURO VI-compliant heavy-duty vehicle engines.

Polynomial regression equation for 10 nm.

$$\hat{y}_{Rail;10nm} = 1{,}54 \cdot 10^{13} - 2{,}11 \cdot 10^{11}x + 4{,}87 \cdot 10^{9}x^{2}$$

Polynomial regression equation for 23 nm.

$$\hat{y}_{Rail;23nm} = 9{,}46 \cdot 10^{12} - 1{,}72 \cdot 10^{11}x + 4{,}02 \cdot 10^{9}x^{2}$$

Where:

$\hat{y}_{Rail;10nm}$ is the number of 10 nm particles [#/kWh];

$\hat{y}_{Rail;23nm}$ is the number of 23 nm particles [#/kWh];

x is the percentage displacement of the common rail pressure [%].

3.Thesis

During my engine dynamometer investigations, I described the relationship between the exhaust gas recirculation (EGR) level and the number of particles measured for diameters of 10 and 23 nm using polynomial regression analysis. The primary reason for choosing polynomial regression analysis was its ability to allow for a 3% error margin. To avoid overfitting, I selected a model that was flexible enough to accurately fit complex measurement data structures, yet general enough to be effectively applied to new data. The test engine used in the experiments, having parametrizable settings, enables the generalization and reproducibility of the results. The findings can be applied to compression ignition, electronically controlled exhaust gas recirculation system-equipped, EURO VI-compliant heavy-duty vehicle engines.

Polynomial regression equation for 10 nm.

$$\hat{y}_{EGR;10nm} = 1{,}44 \cdot 10^{13} + 1{,}67 \cdot 10^{11}x + 1{,}71 \cdot 10^{9}x^{2}$$

Polynomial regression equation for 23 nm.

$$\hat{y}_{EGR;23nm} = 9{,}16 \cdot 10^{12} + 1{,}39 \cdot 10^{11}x + 1{,}16 \cdot 10^{9}x^{2}$$

Where:

$\hat{y}_{EGR;10nm}$ is the number of 10 nm particles [#/kWh];

$\hat{y}_{EGR;23nm}$ is the number of 23 nm particles [#/kWh];

x is the percentage shift in exhaust gas recirculation opening [%].

4.Thesis

In my investigations, I described the relationship between the level of exhaust gas recirculation and the concentration of NO_x in the exhaust gas using linear regression analysis. This method was chosen because it allows for accurate and reliable model construction within a 3% error margin, avoiding overfitting. While ensuring simplicity and a high R^2 value, the linear regression model was capable of describing the general trends of the data without excessively adapting to the minimal noise found in the measurement data. The test engine used in the experiments, having parametrizable settings, enables the generalization and reproducibility of the results. The findings are relevant and applicable to compression ignition, electronically controlled exhaust gas recirculation system-equipped, EURO VI-compliant heavy-duty vehicle engines.

$$\hat{y}_{EGR;NOx} = -0{,}08x + 11{,}06$$

Where:

$\hat{y}_{EGR;NOx}$ is the NO_x concentration [g/kWh];

x is the percentage shift in exhaust gas recirculation opening [%].

5.Thesis

During my engine dynamometer investigations, I established the relationship between the pressure in the common rail and the concentration of NO_x in the exhaust gas using linear regression analysis. By controlling model complexity and adhering to a 3% error margin, I created a stable, generalizable model that not only showed exceptional fit to the measured data but also retained its predictive accuracy for new data. The test engine used in the experiments, having parametrizable settings, enables the generalization and reproducibility of the results. The derived relationship can be applied to compression ignition, common rail fuel supply system-equipped, EURO VI-compliant heavy-duty vehicle engines.

$$\hat{y}_{Rail;Rail} = 0{,}0714x + 9{,}917$$

Where:

$\hat{y}_{Rail;NOx}$ is the NOx concentration [g/kWh];

x is the percentage of offset in common rail pressure [%].

4. CONCLUSIONS AND SUGGESTIONS

My research work carries new scientific results that are highly applicable across various fields, providing practical support for particle emission measurement experiments in selecting particle counting equipment uniquely based on the dilution factor. These results have been published in an international scientific journal with an impact factor to contribute to the field of emission measurement research. My work was cited by the president of the Particle Measurement Programme (PMP) at the European Commission's own automotive research and development center (Joint Research Center – JRC), serving as a benchmark in their research. These organizations propose limits for emission standards, such as the upcoming Euro 7 directive. This positive feedback suggests that my work has created value for the scientific community.

I developed a new principle for sample gas preparation for particle counting systems, initially creating a model followed by practical implementation. At my workplace, Ibiden Hungary Ltd., which focuses on automotive emission research, the equipment is now officially used not just for my doctoral research but also for live experiments based on this innovative principle. My scientific publication detailing this principle was also cited by a leading researcher at the European Commission. Due to the positive feedback, I decided to initiate a patent registration, which is currently in process. Based on the regression equations obtained from the engine dynamometer experiments, I made forecasts for NO_x and 10/23 nanometer particle emissions across various exhaust gas recirculation and common rail pressure shift values. These forecasts allowed me to quantify the effects of these two actuators on NO_x and particle emissions, which emission technology currently considers the two most critical components of exhaust gas.The analysis confirmed my research hypothesis that changes in common rail pressure and EGR opening value significantly influence diesel engine NO_x and particle emissions. The high level of the R^2 value of the regression models enables the optimization of engine operational parameters to reduce emissions. Thorough analysis of the statistical and mathematical details is essential in such research, allowing for accurate and well-founded conclusions. The data and calculations were meticulously documented to make the research process transparent and reproducible. Future analyses plan to extend the data to ensure results are based on more data points, eliminating the possibility of distortions caused by random variations or unrepresentative data. Future research plans include creating multivariable models that consider the simultaneous changes of multiple engine parameters, further refining the accuracy of NO_x and particle emission forecasts.

5. SUMMARY

Automotive emission industry underwent a rapid development in the 2000s, driven by increasingly stringent emission standards at both European and global levels. These standards spurred the development of new, more complex exhaust gas treatment systems. Recent events have highlighted the importance of effective pollutant emission regulation to the public, demanding even greater attention to innovative solutions in engineering design to minimize environmental impacts.

The primary goal of my doctoral research, through a series of fixed-parameter experiments conducted in a dynamometer laboratory environment, is to determine the correlations between the two main harmful emission components found in the exhaust gas of diesel engines, namely nitrogen oxides and particulate matter, in relation to the actuators of modern diesel engines, such as the common rail fuel system and the exhaust gas recirculation (EGR) valve. In this endeavor, I was aided by the study of relevant literature and knowledge of emission technology research. Additional objectives included the development of a unique experimental system that encompasses the creation of a program in Visual Basic programming language for the repeatable control of engine actuators, writing control programs for the test cell on the PUMA Open TST editor interface, and enhancing the measurement reliability of the AVL 489 particle counter machine, enabling its use throughout numerous experiments. Furthermore, I aimed to compare different particulate measurement procedures based on the dilution factor.

This research was conducted at the Research and Development Center of Ibiden Hungary Kft. in Dunavarsány, where I work as an engineer. The experiments were performed in a motor test bench laboratory environment using a Volvo D13 Euro VI-d emission standard compliant heavy-duty diesel engine. Gaseous and liquid media significantly affect the emissions of internal combustion engines. Therefore, to ensure the fidelity of fixed-parameter experiments, I also employed fuel, lubricating oil, charge air, and coolant conditioning systems.

Special attention was given to the complex analysis of these factors throughout my research. I encountered several challenges at the start, including understanding the selection and dilution-dependent operation of particle counters, designing an aerosol preparation unit that ensures reliable particle measurements during long test series, and developing program codes for actuators to allow precise control. Innovative procedures developed in response to these challenges enabled me to commence over 300 hours of experiments on the motor test bench, the results of which can be described by regression models with high determination coefficients ($R^2 > 0.97$).

These results accurately approximate the two main emission components, NO_x and PN, of new development heavy-duty vehicles equipped with compression ignition, common rail fuel injection systems, electronically controlled exhaust gas recirculation systems meeting the Euro VI standard, as related to changes in common rail pressure and the extent of exhaust gas recirculation. With regressions determined for particulate number concentrations across measurement ranges of 10 and 23 nm, these can be utilized in upcoming research related to the soon-to-be-introduced EURO VII standard. Thus, the model I developed serves not only the current research objectives but also provides a solid foundation for the creation of more complex models. These advanced models can offer deeper and more comprehensive insights into the emission dynamics and behavior of diesel engines, enabling the scientific community and engineering practice to refine and optimize engine performance while complying with environmental regulations.

6. IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Peer-reviewed article in foreign language

1. Bíró, N., Pillinger, Gy., Kiss, P., Szőllősi, D., Akihiro, O. (2020): Experimental SCR system for engine dynamometer applications, Hungarian Agricultural Engineering 38 pp. 56-62., 7 p.
2. Bíró, N., Pillinger, Gy., Kiss, P., Szőllősi, D., Akihiro, O. (2020): Reducing nitrogen oxides in ICE R&D laboratory environment, Mechanical Engineering Letters: R and D, Vol. 20, 20 pp. 50-58., 9 p.
3. Bíró, N., Kiss, P., (2021): Reviewing ICE soot filtration in EATS laboratory environment, Mechanical Engineering Letters: R and D, Vol. 21, 21 pp. 85-95., 11 p.
4. Bíró, N., Kiss, P., (2022): Comparing pressure hysteresis of DPF filters, Mechanical Engineering Letters: R and D, Vol. 22, 22 pp. 109-115., 7 p.
5. Biró, N., Szőllősi, D., Kiss, P., (2023): Particle Counter Design Upgrade for Euro 7, Atmosphere, 14, 1411. https://doi.org/10.3390/atmos14091411- ***IF 2,9***
6. Biró, N., Kiss, P., (2023): Emission Quantification for Sustainable Heavy-Duty Transportation. Sustainability, 15, 7483. https://doi.org/10.3390/su15097483 ***- IF 3,9***
7. Biró, N., Kiss, P., (2023): Euro VI-d Compliant Diesel Engine’s Sub-23 nm Particle Emission. Sensors, 23, 590. https://doi.org/10.3390/s23020590- ***IF 3,9***

Peer-reviewed article in hungarian language

8. Bíró, N., Pillinger, Gy., (2020): Adblue-adagoló fejlesztése kipufogógáz-kezelő rendszer optimalizálásához, Mezőgazdasági Technika 61: 5 pp. 2-5., 4 p.
9. Szőllősi, D., Bíró, N., Kiss, P., (2020): A dízel részecskeszűrő (DPF) koromszűrési hatékonyságának megállapítása, Mezőgazdasági Technika 61: 9 pp. 2-5., 4 p.
10. Csankó, Cs., Szőllősi, D., Biró, N., Kiss, P., (2021): Dízelmotor NOx kipufogógáz-emissziójának mérése, Mezőgazdasági Technika 62: 9 pp. 2-5., 4 p.
11. Csankó, Cs., Biró, N., Szőllősi, D., Kiss, P., (2021): Belső égésű motor részecskeszűrési hatékonyságának változása az üzemóra függvényében, Mezőgazdasági Technika 62:12 pp. 2-5., 4 p.

International conference proceedings

12. Bíró, N., Kiss, P., (2023): Evaluating the pressure performance of DPF filters using engine bench analysis, Proceedings of the 16th European-African Regional Conference of the ISTVS. ISBN:9781942112556

International conference abstracts

13. Bíró, N., Szőllősi, D., (2023): Emission Quantification for Sustainable Heavy-Duty Transportation, The 10th World Sustainability Forum: Basel Hub - Sustainable Transition
    p. 31 Paper: sciforum-073454

Citations

14. Milojević, S.; Glišović, J.; Savić, S.; Bošković, G.; Bukvić, M.; Stojanović, B. Particulate Matter Emission and Air Pollution Reduction by Applying Variable Systems in Tribologically Optimized Diesel Engines for Vehicles in Road Traffic. Atmosphere 2024, 15, 184. **(Hivatkozás a 7. számú publikációmra)**
15. Giechaskiel, B.; Melas, A.; Broekaert, S.; Gioria, R.; Suarez-Bertoa, R. Solid Particle Number (SPN) Portable Emission Measurement Systems (PEMS) for Heavy-Duty Applications. Applied Sciences 2024, 14, 654. **(Hivatkozás az 5. és 7. számú publikációimra)**
16. Gade, C.R.; Wahab, R.S. Conceptual Framework for Modelling of an Electric Tractor and Its Performance Analysis Using a Permanent Magnet Synchronous Motor. Sustainability 2023, 15, 14391. **(Hivatkozás a 6. számú publikációmra)**