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PARTICULATE AND NO_X EMISSIONS FROM INTERNAL COMBUSTION ENGINES

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NOMENCLATURE

List of symbols

AH	Absolute humidity	[g/m^3]
NO_x	Nitrogen oxide gas emission	[g/kWh]
PN_{23}	Particle number above 23 nm	[#/kWh]
PN_{10}	Ultrafine particle number below 10nm	[#/kWh]
Rd	Specific gas constant of dry air	[J/kgK]
rpm	Engine speed	[1/min]
T	Ambient temperature	[˚C]
W_{ciklus}	Work performed during a given emission cycle	[kWh]

Abbrevations

ATS	Aftertreatment System
CeO_2	Cerium-oxide
CNG	Compressed Natural Gas
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECE	Economic Committee for Europe Regulation 15
ECE 15	Urban driving Cycle –
EGR	Exhaust Gas Recirculation
EU	European Unio
EUDC	Extra Urban Driving Cycle
HD	Heavy Duty
LD	Light Duty
LNG	Liquid Natural Gas
LPG	Liquefied Petroleum Gas
NEDC	New European Driving Cycle
NO_x	Nitrogen oxides
OBD	OnBoard Diagnostics
PLC	Programmable Logic Controller
PM	Particulate Mass
PC	Personal Car
PN	Particle Number
WHSC	Worldwide Harmonized Stationary Cycle
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
WLTP	Worldwide Harmonized Light Vehicle Test Procedure

1. INTRODUCTION, OBJECTIVES

Air is an indispensable medium for life, and it has undergone significant changes over millions of years.
Its current composition supports the terrestrial environment and ecosystems as we know them. However, these natural periodic variations now appear to be disrupted by large amounts of pollutants released into the atmosphere as a result of human activities.

Many of these substances have existed in the atmosphere for millions of years in varying concentrations. Nitrogen oxides (NO_x), for example, are precursors to ground-level ozone formation, which played a key role in the development of the protective ozone layer essential for life. Yet, due to human activity, NO_x is also responsible for the formation of acid rain and smog. In the transportation sector, diesel engines remain a major source of NO_X emissions (Lee et al., 2013; Reşitoğlu, 2020).

Aerosol particles present in the air—beyond their harmful effects on the respiratory systems of living organisms (Kreyling et al., 2010; Behndig et al., 2006; Mills et al., 2005) demonstrate their destructive potential during major volcanic eruptions. The ash and aerosols released into the atmosphere can cause darkness or significantly reduced sunlight for days or even weeks in affected regions, with possible impacts on the global climate as well.

While modern-day exposure to pollutants is less dramatic, it has become persistent over the long term by human standards. Efforts to reduce emissions now have a history spanning over half a century. The concept of emission reduction has become deeply embedded in modern societies, with vehicle pollutant emissions serving as one of its most visible and representative areas.

1.1. Relevance and sygnificance of the topic

The most tangible and visible segment of transportation is land transport, which is currently on the verge of a paradigm shift. Emerging technologies such as electric drives, fuel cells, and several existing but less widespread solutions—like CNG, LNG, LPG, water injection, emulsions, or variable compression ratio engines (Milojević et al., 2024), often lack a solid technological foundation. As knowledge related to these new propulsion systems expands, it is expected that the emissions generated across the full lifecycle of each technology will become more accurately quantifiable, thus enabling appropriate regulatory control. In this context, the market share of new technologies in transportation is expected to undergo radical changes by the middle of the century. The forthcoming EURO 7 regulation, the strictest to date, is also aligned with this transition, introducing technology-neutral emission limits.

Currently, the most widely understood propulsion system remains the internal combustion engine (ICE), whose emission control technologies have a history spanning over 50 years. Within this category, diesel engines dominate non-road applications and heavy-duty vehicles, where emission control is particularly complex (Kalghatgi, 2019; Ning et al., 2020). Due to the high number of chemical reactions occurring in after-treatment systems, it is inevitable that some emission-reducing processes may act counterproductively. One of the primary challenges is the simultaneous reduction of nitrogen oxides (NO_x) and soot particles, which typically require opposing engine operating conditions and catalyst types. The most common and widespread after-treatment technologies include exhaust gas recirculation (EGR), diesel oxidation catalysts (DOC), and diesel particulate filters (DPF), which—together with advanced engine control—can meet at least the EURO 5 emission standards.

At the end of 2022, the European Commission proposed the new EURO 7 emission regulation. Consistent with the five-decade legacy of emission reduction in internal combustion engines, this new regulatory tightening once again poses major challenges for manufacturers. As anticipated by experts, future standards based on the EURO 7 proposal will also introduce a new element—coverage of particles below 23 nanometers—which further increases the relevance of advanced particle-counting technologies

In addition, the EURO 7 regulation places particular emphasis on enabling as many of the currently operating 1.5 billion vehicles as possible to undergo retrofitted emission reduction modifications.

In the European Union, the average age of vehicles is nearly 12 years, and a significant portion of the existing fleet consists of vehicles compliant with the EURO 5 standard introduced from 2011, which are also included in my research. These retrofits should ideally be as simple and cost-effective as possible. One such potential solution is the retrofitting of vehicles with water injection systems.

In internal combustion engines, water injection on the intake side has so far primarily been applied for performance enhancement. However, its potential for emission reduction has been less thoroughly investigated, largely due to concerns about possible detrimental effects on the engine. These include corrosion—

particularly due to the sulfur content in diesel fuel—lubrication issues, component wear, and the presence of liquid water in the combustion chamber, which could result from certain emulsification or injection techniques (Chybowski et al., 2015; Wróblewski et al., 2018; Holtbecker & Geist, 1998; Vollenweider et al., 1995). With modern technologies and materials, many of these challenges can now be mitigated.

In real-world applications, once water enters the combustion chamber, any excess water exits with the exhaust gases and passes through the entire after-treatment system. This affects all components of the ATS. However, there is currently no concrete data available on how this interaction with various after-treatment technologies influences tailpipe emissions. Clarifying this issue is particularly important in the context of retrofits, which remains a largely unexplored research area.

Under the upcoming EURO 7 standards, in addition to the aforementioned retrofit modifications, special attention is also being directed toward particles smaller than 23 nanometers (PN_{10}), for which there is likewise a lack of literature related to water injection. New developments surrounding EURO 7 suggest that the proposed 2035 ban on internal combustion engine vehicles may be revised (EU proposal 2023). This would align with the fundamentally powertrain-neutral approach of EURO 7 and the European Commission’s position that the EU does not intend to favor specific technologies.

Water used during combustion, as a technological approach, requires reevaluation in the context of today's modern environment—particularly with respect to costs, effectiveness, and benefits. Since retrofitting applies to vehicles already equipped with various levels of emission control systems, studies focusing solely on raw engine emissions—whether for performance or emission reduction—will only be of limited relevance to my research. My work emphasizes practice-based results, and during the literature review, it is essential to differentiate between theoretical and practical aspects and their implementation. Currently, aside from the introduction of EURO 7, there are no suitable regulatory incentives driving retrofitted emission reductions, and consequently, literature on vehicle modifications applying such alternative approaches remains very limited.

1.2. Objectives

In my doctoral research, my primary objective is to reduce typical diesel exhaust emissions, with a particular focus on exploring the emission-reducing potential of water injection into the engine intake manifold.
Based on the facts outlined above, I have defined the following goals for my dissertation, which I intend to achieve in the order presented below:

1. Review the relevant literature on water injection and emission control systems in the context of modern technological and regulatory environments.
2. Develop and assemble the measurement systems required for the experimental investigations.
3. Examine the exhaust system temperatures and the chemical reactions taking place within it, in order to establish a baseline reference without water injection.
4. Investigate the effects of humidity on pollutant emissions, drawing important preliminary conclusions prior to conducting the water injection experiments.
5. Study the impact of water injection on the overall emission control system and on pollutant outputs.
6. Assess the feasibility and necessity of integrating water injection with existing emission control systems, especially in the context of retrofit potential under the EURO 7 regulation.
7. Conduct further investigations to enhance the effectiveness of water injection, focusing on:
   - The impact of water injection on diesel particulate filter (DPF) regeneration,
   - The effect on fuel consumption.
8. Evaluate the feasibility of real-world system implementation.
9. Assess the overall effectiveness of water injection as a technology capable of achieving simultaneous NOx and particulate matter reduction, aiming to:
   - Demonstrate that under modern conditions, with ongoing technological advancement and evolving transport paradigms, water injection can be effectively applied,
   - Prove that water injection does not negatively impact the performance of after-treatment systems,
   - Show that exhaust gas recirculation (EGR) and water injection can be operated in a complementary manner within real-world systems.

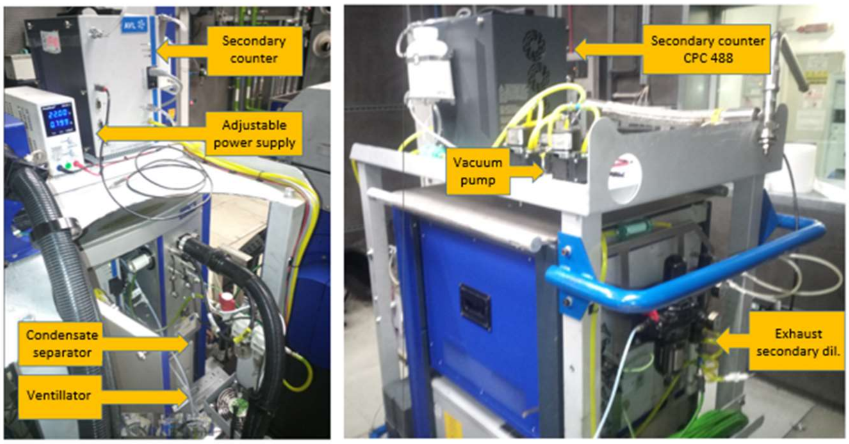
2. MATERIALS AND METHODS

As emission regulations came into force, the need arose for equipment and procedures that allow for the measurement of pollutants emitted by vehicle engines in a repeatable and comparable manner across the world.
In the following, I will describe those instruments and methods that were used during my investigations. In all cases not otherwise specified, I employed currently valid standardized measurement procedures for particle number (PN) measurement, primarily in accordance with Regulation (EC) No. 595/2009, as well as its annexes and the "Common Technical Specifications", including the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) and the New European Driving Cycle (NEDC). These are further supplemented and specified by Commission Regulation (EU) 2017/1151.
My related measurements were also carried out using these instruments, along with additional R&D-grade measurement devices commonly used in the automotive industry, in a documented and repeatable manner, as detailed in the following chapters.

2.1. Measurement equipments used

The device used to measure the filtration efficiency of the Diesel Particulate Filter (DPF) counts the number of particles (PN – Particle Number) emitted by the vehicle. This equipment is the Particle Counter Plus manufactured by AVL List GmbH. It is a Condensation Particle Counter (CPC), which is a widely used instrument for determining aerosol particle concentrations in automotive research and development (Kangasluoma and Attoui, 2019).
In the CPC, solid aerosol particles are enlarged by condensing liquid butanol onto them. As the sample gas passes through the detection chamber, the enlarged particles interrupt a laser detection mechanism, generating measurable signals that enable the accurate and reliable counting of particles in the aerosol sample and the determination of their number concentration (#/cm^3).
My measurements are performed using a proportional partial-flow dilution system. During testing, I used a dilution ratio of 10,000 for raw exhaust gas and 100 after the full aftertreatment system, in order to prevent clogging of the particle counter.

To achieve the desired measurement objectives, it was necessary to enable parallel 10-nanometer measurements alongside the standard 23-nanometer particle counting.
For this purpose, I connected a second particle counter (PNC External – CPC 488) to the “Exhaust Secondary Dilution” output of the particle counter system (APC 489), which is specifically designed for connecting a particle size distribution measurement device. This setup allows the secondary device to use pre-conditioned and properly diluted sample air (see Figure 2.1).
The accumulation of water in different parts of the device can cause serious issues and damage. To ensure safe operation and prevent any related problems, an air filter and a moisture separator were installed upstream of the particle counter's exhaust gas inlet. The main criteria for selection were ease of monitoring (the condensate level can be visually observed) and ease of emptying and cleaning.



2.1. figure: Main elements of new layout (Source: Szőllősi Dániel)

Most of the exhaust gas components regulated by the “Euro” vehicle emission directives consist predominantly of gaseous pollutants. To measure these in the test laboratories, we use two multi-channel, continuous emission measurement systems: the AMAi60 manufactured by AVL List GmbH, and the HORIBA MEXA 7500.
These systems utilize two independent sampling channels, allowing simultaneous measurement of NO_x emissions at two different points within the exhaust system.

2.2. Types of measurements

During my investigations, the AVL and HORIBA engine test cells used were fully integrated systems. These systems manage the control of the conditioning units, engine dynamometers, the engine itself, emission measurement equipment, fuel supply system, data acquisition system, and the programmable logic controllers (PLCs) applied at an operational level—all via a central computer located outside the test cells.
Each individual experiment is executed by the control software in the exact same sequence and steps, thereby ensuring the reliability and reproducibility of the results. The use of standardized, procedural instruction-based operation during test cycles has enabled direct comparability and repeatability of experiments—crucial for obtaining trustworthy outcomes and drawing valid conclusions.
Emission test cycles are designed to simulate typical vehicle operating conditions in a controlled laboratory (test bench) environment. As emission regulations have become increasingly strict, more official test cycles have been introduced. The type of cycle used depends on whether the vehicle is a light-duty (LD), heavy-duty (HD), or passenger car (PC), as well as the region of the world in which the tests are conducted. In addition, a distinction must be made between on-road and off-road use. In my research, the following test cycles were applied:

- ECE 15 (Urban Driving Cycle – PC/LD),
- EUDC (Extra Urban Driving Cycle – PC/LD),
- NEDC (New European Driving Cycle – PC/LD),
- WLTC (Worldwide Harmonized Light Vehicles Test Cycle – PC/LD),
- WHSC (Worldwide Harmonized Stationary Cycle – HD).

Since 2017, the European Union has implemented the Worldwide Harmonized Light Vehicle Test Procedure (WLTP), along with its corresponding test cycle, the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) (Varella et al., 2018).
The new standard was developed to better reflect real-world and modern driving conditions, thereby ensuring that fuel consumption and emission values measured under laboratory conditions more accurately correspond to those experienced during real on-road driving.
The World Harmonized Steady State Cycle (WHSC) is an engine dynamometer test cycle consisting of steady-state operating conditions, defined under Global Technical Regulation (GTR)

No. 4 (EUR-LEX, 2007). Unlike the NEDC and WLTC cycles, the WHSC consists solely of fixed engine operating points and was developed to represent typical driving behavior in the European Union, the United States, Japan, and Australia. Accordingly, this cycle was chosen in the present study for the humidity-related measurements, as it allows for straightforward comparability with manufacturer data and results from other research efforts.

When aiming to load soot into the DPF (Diesel Particulate Filter), several methods can be applied. If access to the engine control unit (ECU) is unavailable and its parameters cannot be modified, the most soot-producing operating condition must be selected from the engine's performance map. However, if modifications to engine operation are possible, injection strategies can be adjusted to deliberately increase soot generation. A commonly applied technique is lowering the common rail pressure.

During engine operation, soot particles gradually accumulate in the DPF. As the DPF traps particulate matter (PM), the exhaust gases experience increasing flow resistance when passing through the growing soot layer, which results in a pressure drop. As more soot is filtered out, this pressure loss begins to affect engine performance, potentially leading to reduced power output and increased fuel consumption. Consequently, removal of the accumulated soot via oxidation (regeneration) becomes necessary.

One of the main challenges in this process is providing sufficient energy to reach the required regeneration temperature, approximately 600 °C, which is necessary for soot oxidation. The technologies used to achieve this temperature tend to increase the complexity and size of the exhaust aftertreatment system.

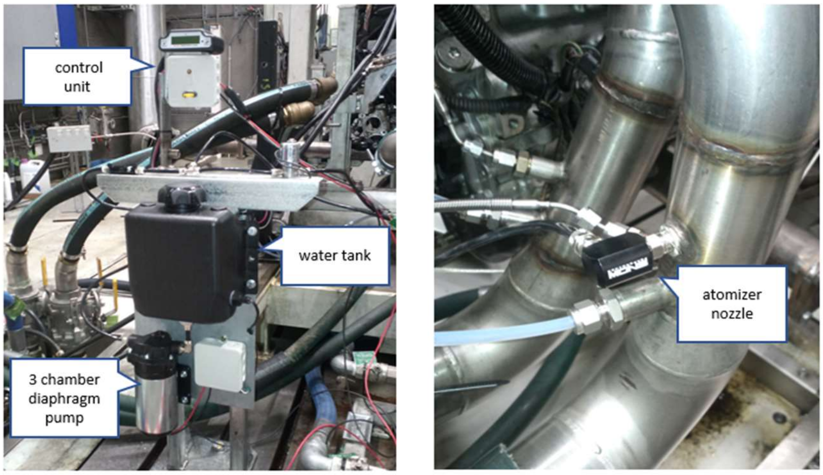
There are two primary strategies to reach the required regeneration temperature: passive regeneration and active regeneration.

In my current measurement setup, I used a catalyst-coated DPF, combined with active regeneration. In an active system, the heat required for regeneration originates from the in-cylinder combustion temperature, which can exceed 2200 °C. To utilize this thermal energy effectively, a technique known as post-injection regeneration was employed, where multi-phase fuel injection is used inside the engine's combustion chamber.

The combination of a catalyst-coated DPF and active regeneration ensures that the necessary conditions for soot oxidation are achieved.

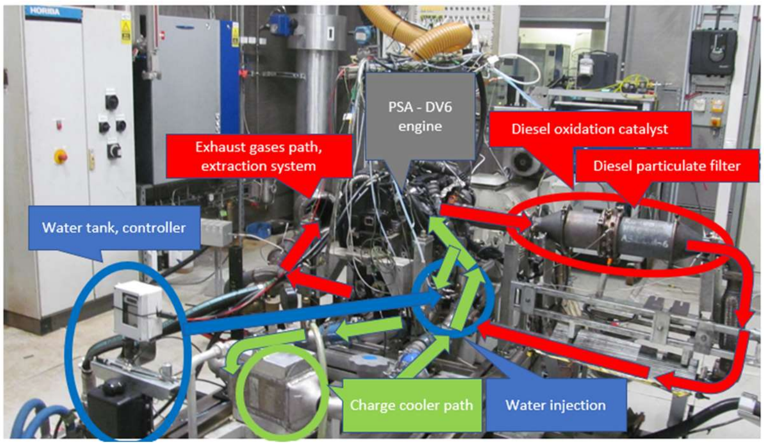
2.3. Water injection

When selecting the water injection system, an important criterion was its easy availability on the commercial market, ensuring its suitability for retrofit applications. For this purpose, a "Snow Performance Stage 3 TD MPG-MAX" system was selected, which performs injection across the full performance range. The layout of the injection system is shown in Figure 2.2.



2.2. figure: The installed intake manifold water injection system

The full system configuration is presented in Figure 2.3, mounted on a DV6 passenger car engine. For all tests, purified and deionized water was utilized.



2.3. figure: Engine test cell with the complete measurement system

2.4. Engines used in the investigations

An important aspect of my research is that the obtained results are reproducible and independent of the engine type, ensuring the generalizability and scientific validity of the study. Accordingly, the engines used during the research are parameterizable, meaning their key characteristics can be modified arbitrarily. This allows for the application of individual settings on each powertrain regardless of engine type, while ensuring that every engine subsystem operates with uniform, fixed parameters during the measurements. Meanwhile, the parameter under investigation can be purposefully varied.
During the experiments, I used two passenger car engines, one light commercial vehicle engine, and one heavy-duty diesel engine (Table 2.1). The current configuration of the measurement system is presented in the results chapter for each test.

2.1. table: Summary table of test engines

Engine type	**PSA DV6**	**PSA DW10**	**OM926LA**	**Volvo D13TC**
Number of cyl. [-]	4	4	6	6
Bore, stroke [mm]	75 x 88.5	85 x 88	106 x 136	131 x 158
Displacement [cm^3]	1560	1997	7201	12800
Horspower [kW]	80	103	210	372
Torque [Nm]	260	340	1120	2840
Compression ratio [-]	16.0:1	17.3:1	17.5:1	18.0:1

2.5. Brake test benches, auxiliary and fuel supply systems

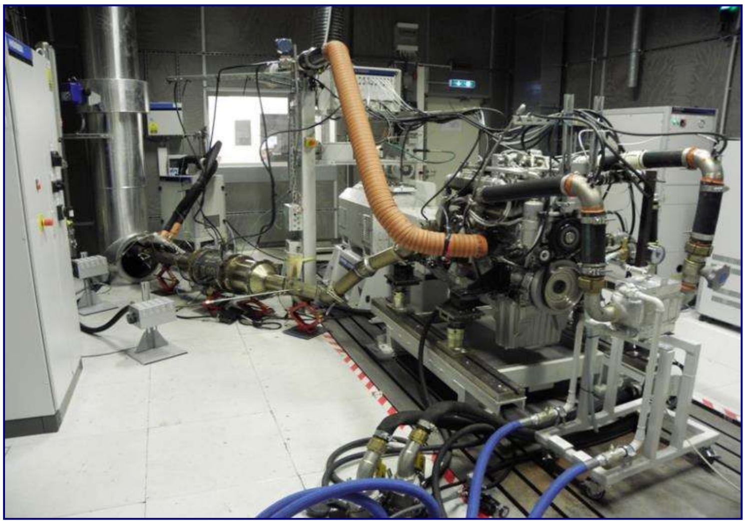
The tests were conducted on AVL and Horiba passenger car test benches, a Horiba light commercial vehicle test bench, and an AVL heavy-duty truck test bench. These include complete conditioning systems for controlling fluids (coolant, chilled water, fuel) and air. Engine test cells, also known as engine dynamometers, are specialized test systems that enable the precise measurement of various operating parameters of internal combustion engines, such as power, torque, and fuel consumption, under controlled conditions. The advantage of engine dynamometers is that they provide laboratory accuracy while simulating realistic engine operation (Steiber, et al., 2006). A summary of the testing equipment is provided in Table 2.2.
The experiments were carried out at the research and development center of Ibiden Hungary Ltd. in Hungary, where the above-

mentioned conditioning equipment and full engine dynamometer test cells are available (Figure 2.4).

2.2. table: Summary table of engine test benches

	HORIBA TITAN T250	AVL Load System 220 kW	HORIBA TITAN T460	AVL Load System 500 kW
Dynamometer	Dynas3 HT250	DynoRoad 204/8	Dynas3 HT460	DynoRoad 504/4.6
Max. speed [1/min]	10 000	8000	8000	5000
Max. torque [Nm]	700	934	1500	3000
Max power [kW]	250	220	460	500
Control system	STARS 1.6	Puma Open 1.5.1	STARS 1.6	Puma Open 1.5.1
Coolant conditioner	CM 15-200	ConsysCool	CM 30-400	ConsysCool
Lubricant cond.	CM 15-200	ConsysLube	CM 30-400	ConsysLube
Combustion air cond.	Comb. Air	ConsysAir	Comb. Air	ConsysAir
Charge air cond.	Charg. Air	ConsysBoost	Charg. Air	ConsysBoost
Fuel system	KMA 4000	KMA 4000	KMA 4000	KMA 4000
Particle counter	APC 489/488	APC 489/488	APC 489/488	APC 489/488
Gas analyser	MEXA 7500	AMA i60	MEXA 7500	AMA i60

To evaluate the test cycles, it is essential to know the exact timing of the recorded measurement data. The recorded data included the engine’s operating parameters (such as engine speed and torque), environmental conditions (such as the test cell’s air temperature, intake air pressure, humidity, etc.), as well as the quantities of gaseous and solid pollutants.

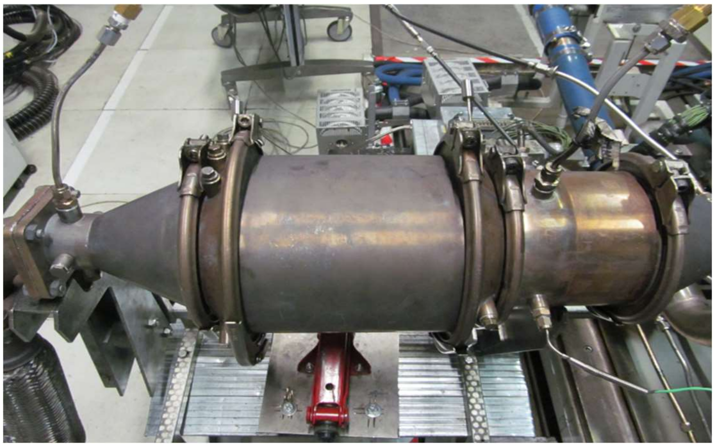


2.4. figure: HORIBA MD Titan T460 engine test bench

In addition, it is also possible to record data from the engine’s onboard diagnostic (OBD) sensors and to modify the actuators that are fundamentally controlled by the engine control unit (ECU).

2.6. Design of the measurement system

The two components of the emission aftertreatment system I used are the DOC and the DPF.
For the measurements, I used a 1.8 dm^3 coated catalyst (DOC) containing the noble metals platinum and palladium. To increase the surface area, it also includes a gamma-alumina (γ-Al_2O_3) washcoat, and cerium oxide (CeO_2) to promote catalysis.
The diesel particulate filter (DPF) is a 3.8 dm^3 ceramic filter from Renault (RSA), provided by Johnson Matthey, and is coated with catalytic material.



2.5. figure: Exhaust system with quick-release coupling design

Both the DOC and the DPF were pressed into metal housings wrapped with vibration-damping and insulating material.
These housings were designed to be easily removable and re-installable into the exhaust system (Figure 2.5).

3. RESULTS

I conducted my measurements using the equipment, materials, and methods presented in Section 2. The large number of planned tests were carried out on modern EURO 5–6 classified diesel engines from passenger cars, light commercial vehicles, and heavy-duty trucks. Each engine was selected in accordance with the specific objectives of the investigation.

I present my results in chronological and logical order, also including the problems encountered during the research and the corresponding solutions—thus making originally unplanned tests comprehensible as well.

3.1. Results of humidity-related investigations

During the operation of internal combustion engines, the main components of the combustion process are the fuel and the air. While the possibilities and effects of fuel composition have been widely studied, significantly less attention has been given to the other component, air. It is often considered a fixed parameter, but at least one of its constituents—humidity—can vary greatly depending on environmental conditions and can have a major impact on engine performance.

For the experiments, I selected the static WHSC cycle previously introduced in Chapter 2, which ensures better comparability of the results. To calculate absolute humidity, relative humidity, temperature, and pressure were recorded at the engine intake manifold.

From August 2022 to June 2023, I ran the above-described three-step cycle a total of 18 times. This allowed for the tracking of potential humidity values over the course of an entire year, which are representative of Hungary's temperate climate. Hungary, while predominantly continental, is also influenced by oceanic and Mediterranean weather patterns.

Analysis of variance (ANOVA) was used to verify the relevance of the model (Table 3.1), based on which the PN_{10}, PN_{23}, and NO_x models are deemed applicable. As expected, correlation analysis showed a sufficiently strong correlation between humidity and PN_{10}, PN_{23}, and NO_x (Table 3.2).

3.1. table: Variance analysis between humidity and particle and gaseous emissions

	PN_{10}	PN_{23}	NO_x
p significance level	0,0085	0,0090	0,0000

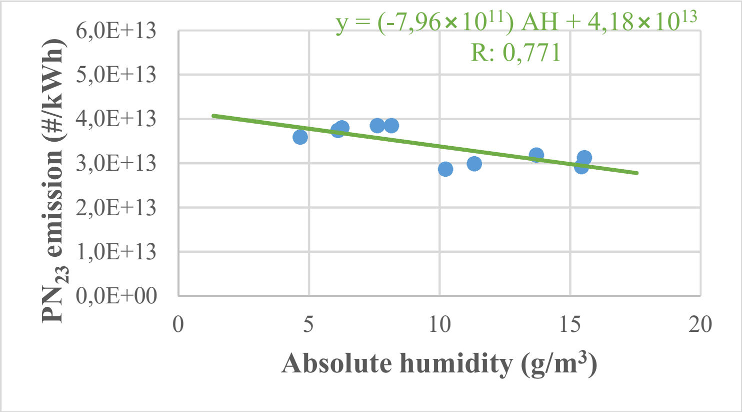
3.2. table: Correlation analysis between humidity and particulate/gaseous emissions

	Humidity	***PN_{10}***	***PN_{23}***	***NO_x***
R value	1,000	-0,718	-0,771	-0,897

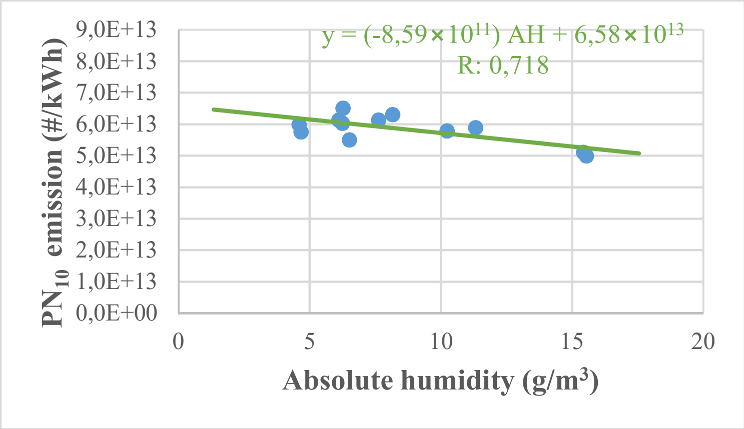
Based on the regression analyses, a linear functional relationship exists between the variables. The results can be seen in Figures 3.1, 3.2, and 3.3.

The established regression models and their goodness of fit are as follows:

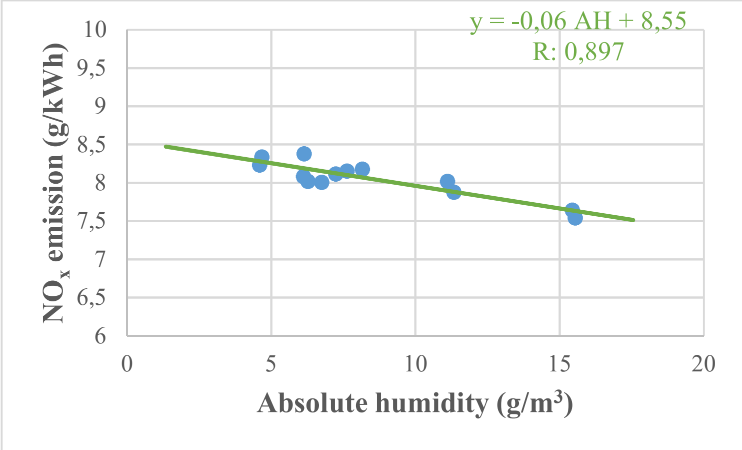
- particles larger than $PN_{23} = (-7{,}96 \times 10^{11})\ AH + 4{,}18 \times 10^{13}$,
- particles larger than $PN_{10} = (-8{,}59 \times 10^{11})\ AH + 6{,}58 \times 10^{13}$,
- for nitrogen oxides, $NO_x = -0{,}06\ AH + 8{,}55$.



3.1. figure: PN_{23} emission in relation to humidity



3.2. ábra: PN_{10} emission in relation to humidity



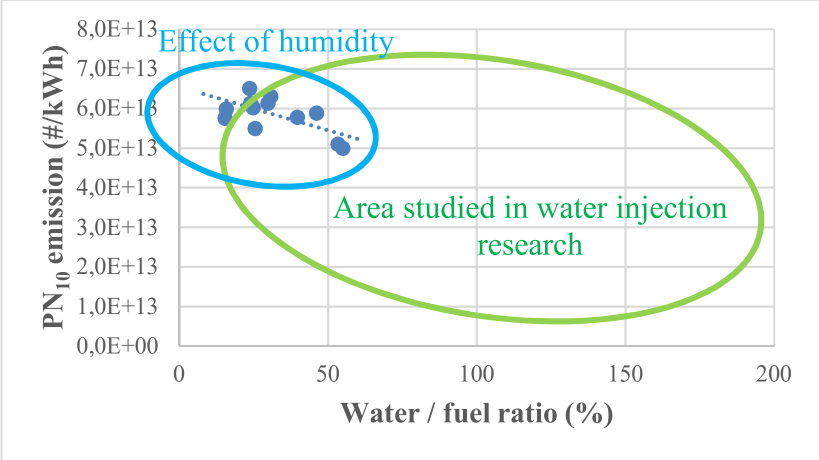
3.3. figure: NO_x emission in relation to humidity

Based on the results, we can conclude that with an increase in absolute humidity, the emissions of the three main diesel engines show a decreasing trend. The differences in emissions measured between the lowest (2.34 g/m^3) and highest (15.55 g/m^3) humidity levels throughout the year, as well as the greatest observed emission reduction, are shown in Table 3.3.

3.3. table: Emission reductions based on the models with annual humidity fluctuations

	PN_{23}	PN_{10}	NO_x
Case of yearly max. humidity	2,94E+13	5,24E+13	7,63
Case of yearly min. humidity	3,99E+13	6,38E+13	8,41
Emission difference	**26,35 %**	**17,80 %**	**9,29 %**

The most significant difference in emissions was observed for particles larger than 23 nm, amounting to 26.35 %. This was followed by ultrafine particles with a difference of 17.80%, and nitrogen oxides showing a 9.29 % variation.
The results were converted to the water-to-fuel ratio, which is used as a unit of measure in studies related to water injection to determine the amount of water introduced into the combustion chamber. Alongside the typically examined injection quantities (Hadidi, et al., 2023; Pamminger, et al., 2020; Wei, et al., 2022), the results derived from humidity measurements are also shown in Figure 3.4, demonstrating a significant overlap.

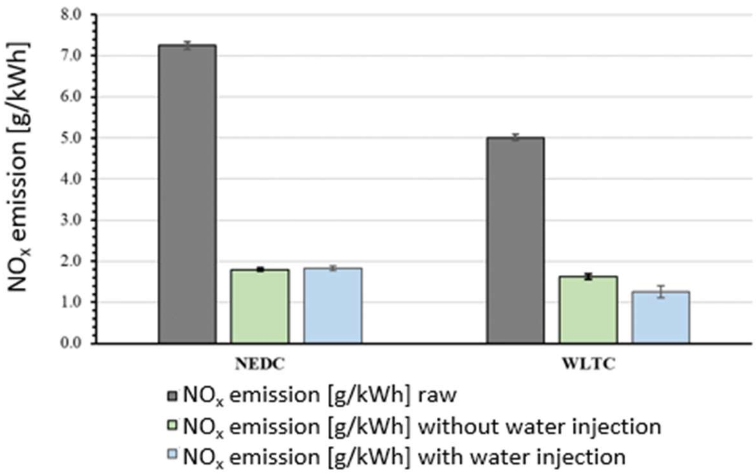


3.4. figure: Particle number results as a function of the water/fuel ratio, within the typical range of water injection tests

Without accounting for humidity, the variable amount of moisture present in the air can cause significant distortions in the results.

3.2. Impact of water injection on the emission control system

In Figures 3.5 and 3.6, alongside the raw emissions, we can see the effect of water injection within the full emission control system during the NEDC and WLTC cycles. Summarizing these results, it is evident that alongside the reduction of NOx, the number of emitted particles also decreases in the PN_{23} size range.

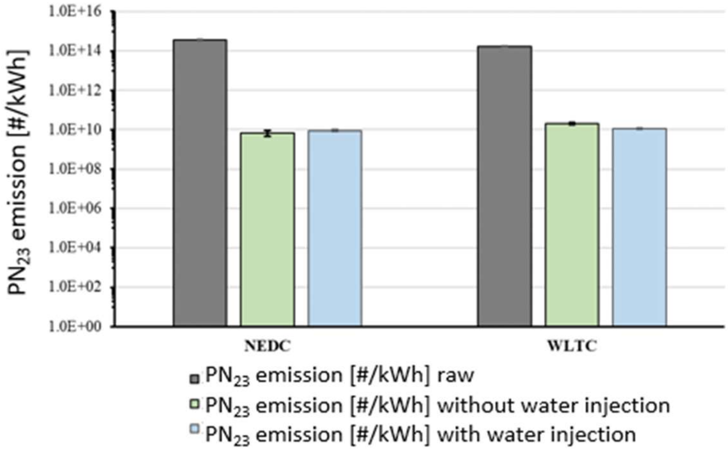


3.5. figure: Change in NO_x emissions during cycles with increasing load from left to right

3.4. table: Reduction of NO_x emissions in the complete system, with and without water injection, compared to raw emissions

	Complete system	*Complete system and water injection*
NEDC	-75,23 %	+ 1.75 %
WLTC	- 67,46 %	- 22,95 %

As seen in Table 3.4, within the complete system without water injection, the emission reduction decreases by approximately 8%, from -75.2 % to -67.5 % compared to the raw emissions. With the addition of water injection, initially, there was no significant emission change in the low-load NEDC cycle. However, for the WLTC cycle, the emissions were approximately 23 % lower compared to measurements without water injection. Compared to the NEDC cycle, this represents a 24.7 % change.



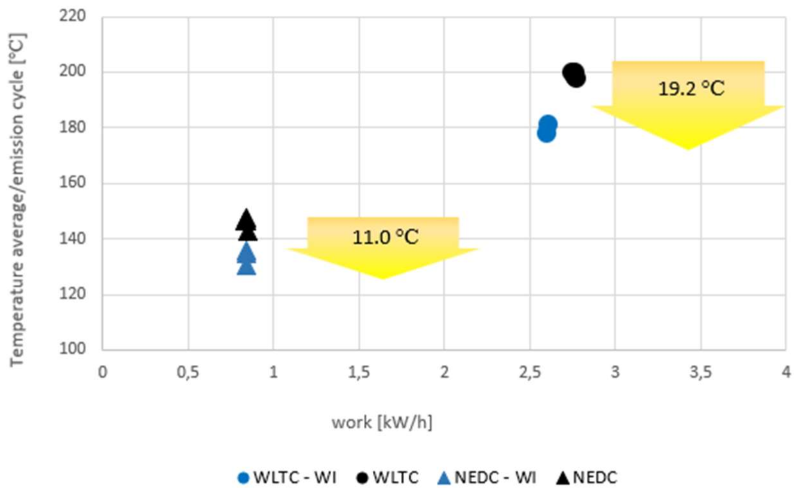
3.6. ábra: PN_{23} kibocsátás változása balról jobbra növekvő terhelésű ciklusok esetén

As seen in Table 3.5 and Figure 3.6, in the complete system without water injection, the emission reduction is practically 100 % due to the presence of the particulate filter.

3.5. table: PN_{23} emission reduction in the complete system, with and without water injection, compared to raw emissions.

	Complete system	*Complete system and water injection*
NEDC	-100,00 %	33,02 %
WLTC	-99,99 %	-46,76 %

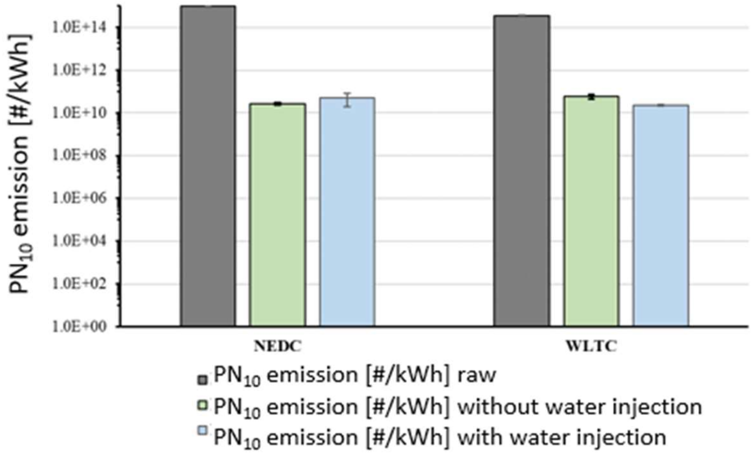
Compared to this, a further significant 47 % reduction is observed with the latest high-load WLTC cycle, which is currently in effect. This corresponds to a 79.8 % change compared to the NEDC.
As shown clearly in Figure 3.7., the achieved temperature decrease during the WLTC cycle is 60 % greater, which strongly demonstrates that at higher loads and in cycles with higher specific power, the temperature-reducing effect of water injection is significantly larger.



3.7. figure: The temperature-reducing effect of water injection

The fact that water injection in the intake manifold operates effectively over a wider load range aligns with the current trend of “downsizing,” which involves reducing engine size but results in higher load levels on the engines (Figures 3.5 and 3.6).
As I have demonstrated, the pollutant-reducing efficiency of intake manifold water injection increases with engine load, which also coincides with the typical operating range of injection systems used in real-world applications mainly for power enhancement.
Based on all of the above and in line with my original objectives (see in objectives point 5), the effective applicability of intake manifold water injection has been proven in a typical EURO 5 diesel emission system under current traffic conditions. Considering how traffic conditions have evolved over the past 30–35 years, the future outlook for the use of water injection is increasingly favorable.

There are currently no results available in the literature regarding the emissions of ultrafine particles below 23 nm in relation to water injection. This is because the necessity and capability to measure these particles is very recent.
Water injection achieves its optimal operation for ultrafine particles as well during the higher-load WLTC cycle. As can be seen in Table 3.6 and Figure 3.8, in the full system without water injection, the emission reduction is practically 100 % due to the presence of the particulate filter. Compared to this, a further significant 62 % reduction is observed with the latest currently valid high-load WLTC cycle.



3.8. figure: PN_{10} emission changes in cycles with increasing load from left to right

3.6. table: Reduction of PN_{10} emissions in the full system, with and without water injection, compared to raw emissions

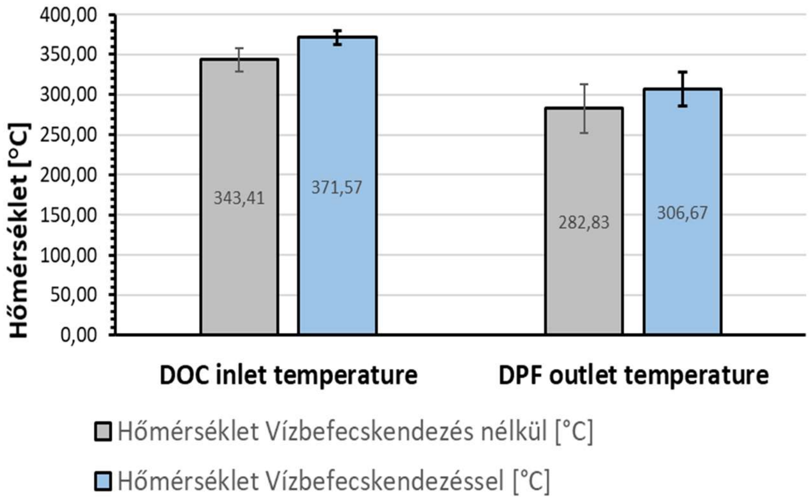
	Complete system	***Complete system and water injection***
NEDC	-100,0 %	+ 78,19 %
WLTC	-99,98 %	- 62,35 %

Based on my current results, the particle emissions at the end of the EURO 5 full emission control system of the passenger car internal combustion diesel engine also show a significant decrease with the currently valid WLTC test cycle and water injection.
By measuring particle numbers after each element of the emission control system, it becomes possible to determine where the particle number reduction occurs. Since I already have results regarding humidity without the emission control system, I subsequently examined the raw emissions after each element of the emission control system: EGR, DOC, and DPF.

3.7. table: PN_{10} particle emissions reduction after individual components of the emission aftertreatment system (NEDC cycle)

	W.o water injection	With water injection	Difference
EGR	1,28E+15	1,45E+15	13,04 %
DOC	1,24E+15	1,15E+15	- 7,10 %
DPF	2,76E+10	4,91E+10	78,19 %

Based on the NEDC results, it can be observed that PN_{10} particle emissions increase after the EGR, similar to PN_{23} according to the literature (Table 3.7).
Although the DOC does not reach the "light off" temperature during the NEDC cycle, a significant reduction in PN_{10} emissions is still evident (Table 3.7). No significant changes can be stated for the DPF. Based on these observations, any emission reduction mechanism, agglomeration, or other processes certainly occur at least in the DOC as a result of water injection.
Using water injection, I also verified the temperatures of the individual aftertreatment system components. With both NEDC and WLTC cycles, the emission aftertreatment system can operate optimally, both with and without water injection (Figure 3.9). The temperature changes during WLTC are approximately +8 % at both the DOC inlet and the DPF outlet when water injection is used.



3.9. figure: Temperature maximum on EURO 5 emission control system components during the WLTC test cycle

In this chapter, in accordance with point 5 of my objectives, I have established the emission-reducing effect of water injection on ultrafine PN_{10} pollutant emissions. Additionally, through further investigations, I identified the specific location of the emission reduction. These findings are novel contributions to the literature on water injection and are particularly significant in the context of EURO 7 regulations.

3.3. Effect of water injection on particulate filter regeneration

During the operation of the engine, soot continuously accumulates in the particulate filter. The accumulated amount of soot must be removed periodically by soot oxidation (Chapter 2.2).
Based on the pressure drop and mass measurement, an efficiency increase of 3–7 % is observed during regeneration performed in the presence of water (Table 3.8).

3.8. table: Regeneration efficiency with and without water injection

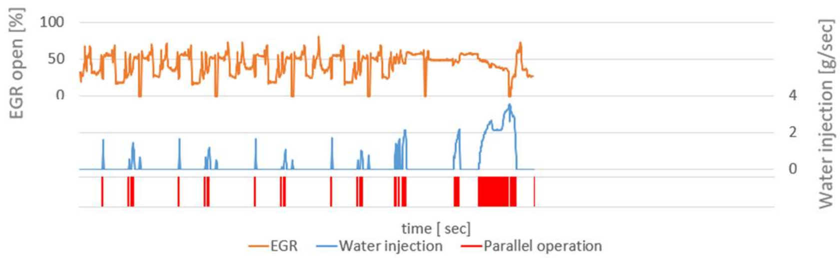
	Complete system	Complete system and water injection
Pressure drop difference	-61,6 %	-68,8 %
Soot mass difference	-84,3 %	-87,6 %

In this chapter, in accordance with the 7th point of my objectives, I conducted investigations aimed at extending the efficiency of water injection. The results obtained for particulate filter regeneration demonstrate the increased efficiency of regeneration occurring in the presence of water, which can lead to significant fuel savings over the vehicle's lifetime and directly improve the competitiveness of the particulate filter.

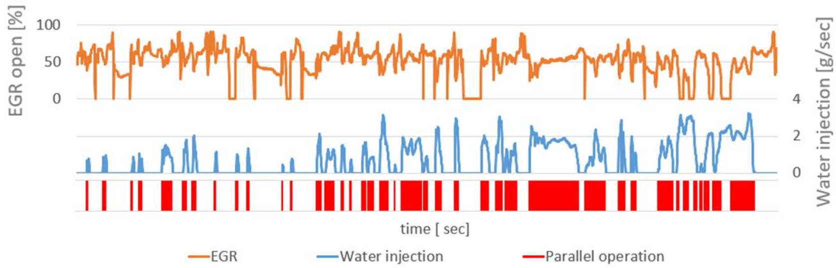
3.4. Simultaneous operation of EGR and water injection

Based on the publications, the system becomes overregulated, and the combination of water injection and EGR leads to a decrease in efficiency. In the literature, under experimental conditions—typically at fixed parameters—the two devices are operated together (constant EGR valve opening and water injection) using experimental water injection systems. EGR typically operates at lower loads by reducing temperature through combustion deterioration, while water injection generally functions at higher loads by the heat capacity and heat absorption effect of phase change. When the vehicle operates at higher loads, the amount of water injection increases, while the EGR valve opening decreases. This finding is definitely new compared to the existing literature.

The fact that water injection operates effectively in a higher load range aligns with the current trend of “downsizing,” which entails increased engine load levels due to engine size reduction. The increase in traffic speed is also observable, which the EURO regulations attempt to track with newer emission cycles characterized by a more aggressive driving style involving intense load shifts, also at higher power levels. Accordingly, I conducted supplementary measurements with the newer WLTC (Worldwide Harmonized Light Vehicles Test Cycle).
I examined this phenomenon, particularly the points where water injection and EGR operate simultaneously, which is assumed to reduce each other’s efficiency. Figures 3.10 and 3.11 show how much more water injection operates during WLTC compared to the NEDC cycle, yet a decrease in harmful emissions is observed.



4.10. figure: Overlaps between EGR and water injection operation during the NEDC cycle



4.11. figure: Overlaps between EGR and water injection operation during the WLTC cycle

During the WLTC cycle, which more closely reflects current driving conditions, higher loads result in significantly higher temperatures, preventing overcooling in the system.
This is also confirmed by my investigation, where I compared oxygen consumption in the oxidation catalyst and, indirectly, gained insight into the occurrence of the following reactions within the oxidation catalyst. Based on the oxygen content exiting the engine and after the catalyst, oxygen consumption during the

WLTC cycle is 56 %, and with water injection it is also 56 %. This indicates that the conversion efficiency of the oxidation catalyst is adequate during the WLTC cycle. As a result, the performance of the oxidation catalyst does not degrade, and therefore the conversion of hydrocarbons—which is also responsible for particle emissions—does not deteriorate.
In this chapter, according to objectives 6 and 9, I concluded that the efficiency of the aftertreatment systems does not deteriorate, and the operation of EGR and water injection can complement each other in real-world systems. Based on all this, there is no need for separate software coordination between the emission control system and the water injection system.

4. NEW SCIENTIFIC RESULTS

1. Thesis

Based on emission engineering measurements, I established that **intake manifold water injection positively influences the overall emission efficiency of the EURO 5 emission control system.** This beneficial effect can be tracked in the examined emission control system as follows:

- The temperature of the emission control system does not degrade, which is essential for the necessary reactions to take place. The gas temperature changes at typical system points—both at the DOC inlet and the DPF outlet—show an increase of +8 % with water injection (Chapter 3.2.).
- The conversion efficiency of the oxidation catalyst remains unchanged; the pollutant conversion efficiency is 56 % both with and without water injection (Chapter 3.4.).
- Water injection, when operating alongside the EGR in full emission control systems, consistently causes further emission reductions of approximately ~45 % for PN_{23}, ~60 % for PN_{10}, and 23 % for NO_x (Chapter 3.2.).

The investigation was carried out using a direct-injection, turbocharged passenger car diesel engine and a commercially available intake manifold water injection system, applying the WLTC (Worldwide Harmonized Light Vehicles Test Cycle).

2. Thesis

Based on my measurements (Chapter 3.1.), I established that **the humidity of the intake air during the operation of diesel engines favorably influences the level of pollutant emissions according to the following relationships.** With the increase of absolute humidity, the particle number emissions of PN_{10} and PN_{23} as well as NO_x emissions decrease — related to the annual humidity fluctuations — with magnitudes of approximately 17-18 %, 26 %, and 9 %, respectively, which can be described by the following equations:

- for particles larger than 23 nm: $PN_{23} = (-7{,}96 \times 10^{11})\ AH + 4{,}18 \times 10^{13}$,
- for particles larger than 10 nm: $PN_{10} = (-8{,}59 \times 10^{11})\ AH + 6{,}58 \times 10^{13}$,
- for nitrogen oxide emissions: $NO_x = -0{,}06\ AH + 8{,}55$.

Where AH is the absolute humidity [g/m^3].

These findings are valid considering the full load range of the WHSC (World Harmonized Stationary Cycle). The pollutant emission values were determined based on cumulative data for the entire cycle. The investigation was carried out with a direct-injection, turbocharged passenger car diesel engine and a commercially available intake manifold water injection system.

3. Thesis

During my measurements, I found that **with the use of water injection, at the end of an EURO 5 complete emission control system and using the currently valid high-load WLTC emission cycle, there is approximately a 45 % reduction in PN_{23} particle emissions and a 23 % reduction in NO_x emissions.** Compared to water injection measurements performed with the previously used NEDC cycle, which was in use for 45 years, this corresponds to an improvement of approximately 25 % for NO_x and 80 % for PN_{23}.

The investigation was carried out using a direct-injection, turbocharged passenger car diesel engine and a commercially available intake manifold water injection system (Chapter 3.2.).

4. Thesis

During my measurements, I found that with the use of water injection, at the end of an EURO 5 complete emission control system and using the currently valid high-load WLTC emission cycle, approximately a 60 % reduction in PN_{10} particle emissions was observed.

The investigation was conducted using a direct-injection, turbocharged passenger car diesel engine and a commercially available intake manifold water injection system (Chapter 3.2.).

5. Thesis

Based on my measurements, I established that **the emission reduction effect induced by water injection can be localized within certain components of the EURO V emission control system, primarily acting in the diesel oxidation catalyst (DOC)** (Chapter 3.2.). According to measurements performed using the NEDC cycle, with water injection:

- the PN_{10} ultrafine particle count increased by approximately 13 % **after the EGR**,

- a reduction of about 7 % was observed **after the DOC** due to the catalytic effect of water on combustion, despite the catalyst not reaching its "light-off" temperature,
- no measurable change was detected in particle count **after the DPF.**

The investigation was carried out using a direct-injection, turbocharged passenger car diesel engine and a commercially available intake manifold water injection system. These findings represent novel results in the literature on water injection regarding ultrafine particles emerging in the context of EURO 7.

6. Thesis

During load tests conducted with a direct-injection, turbocharged engine in a EURO 5 emission system, I performed active regeneration both with and without water injection (Chapter 3.3). Based on the results obtained, I established that **the regeneration efficiency of the diesel particulate filter (DPF) can be increased by 3–7 % when using water injection-assisted active regeneration compared to the conventional method (without water injection).**

Based on pressure drop and mass measurements, the presence of water catalyzed the oxidation process, significantly improving the regeneration efficiency:

	Complete system	Complete system and water injection	Efficiency change
Pressure drop difference	-61,6 %	-68,8 %	7,2 %
Soot mass change	-84,3 %	-87,6 %	3,3 %

The regeneration was more complete, as confirmed by the visual analysis of the particulate filter's frontal surface. The more efficient regeneration achieved through water injection may contribute to reduced fuel consumption and enhance the competitiveness of particulate filters.

5. CONCLUSIONS AND SUGGESTIONS

5.1. Direct and indirect costs and benefits of water injection

In this chapter, in accordance with objective no. 7, I examined changes in fuel consumption as part of investigations aimed at extending the efficiency of water injection. I conducted measurements with a complete emission control system, both with and without water injection, using the NEDC and WLTC cycles. The summarized results are presented in Table 5.1.

5.1. table: Change in Fuel Consumption with Water Injection

	Without water injection [kg/h]	**With water injection [kg/h]**	**Change [%]**
NEDC	1512,26	1538,24	1,72
WLTC	3249,63	3196,25	-1,64
Fuel consumption change	**-**	**-**	**-3,36**

Based on the results, with high-performance test cycles, the previously observed additional fuel consumption appears to reverse: under the NEDC cycle, a 1.72 % increase in fuel consumption was observed, while under the WLTC cycle, fuel consumption was already 1.64 % lower with water injection.

5.2. Combination of water emulsion and intake manifold injection

In this chapter, in line with objective point 8 of my research goals, I examine the possibilities for real-world implementation.
As previously discussed, intake manifold water injection is most effectively used under higher engine loads, where the EGR’s diluting, oxygen-reducing effect can cause significant performance loss and, in real systems, is usually deactivated. In contrast, water injection – due to its high specific heat capacity, phase-change enthalpy, and chemical effects – can achieve significant nitrogen oxide reduction even at high engine loads, without compromising performance.
At lower loads, compared to EGR, another water-injection-based technique, the fuel-water emulsion (FWE), is shown in the literature to be more favorable both for emission reduction and for its effects on engine performance and fuel consumption. It

requires only minimal modification and investment if used with the engine's original injector system. Its main limitation, however, stems from this: it can only be used in limited concentrations (20–25 vol % relative to fuel) and mainly under low-load conditions. In contrast, EGR still retains the advantage of not requiring an additional tank, and once installed, it doesn't need continuous monitoring or refilling.

However, if the emulsion is used in combination with intake manifold water injection – supplied from a common tank and premixed before injection – this advantage is negated in light of the fact that such a system can reduce both nitrogen oxides and particulate emissions across the engine's full operating range, even in diesel emission control. It is suitable for retrofitting, and there is no risk of catalyst poisoning. The limitation of the emulsion system (i.e. limited use with the engine's own injectors) does not apply here, as intake manifold injection would take over at higher loads, where it already operates most effectively.

In the so-called FWE (Fuel-Water Emulsion Injection) system, a separate water tank and standard fuel tank are used to generate the emulsion. Water is injected at high pressure into the fuel system and homogenized. The resulting emulsion is then immediately injected into the combustion chamber, while any excess is recirculated. I plan to integrate intake manifold water injection into this system, resulting in a setup that operates optimally across the full engine load range. In applications where raw emissions need to be reduced, this could be a particularly effective technique. If implemented, it would be worthwhile to compare it against full emission control systems as well.

6. SUMMARY

My PhD topic, on future mobility, concentrates on reducing the environmental impacts of land transport, in particular on mitigating the emissions of diesel internal combustion engines. As such, water injection, as an after-treatment emission reduction technique, proved to be a less promising solution in the 2000s, based on a consideration of the potential risks and achievable results at the time's technological level. With the current technical and technological background, I have re-evaluated water injection and its applicability in my research. In the literature review, I discussed harmful substance emissions, air quality protection, emission standards, and the efforts made so far to reduce emissions. I identified key issues in after-treatment emission reduction research and its absence, as well as the placement of water injection within internal combustion engine emission control systems, which is also lacking in current studies. My thesis examines the literature on water injection into the combustion of diesel engines in chronological order, focusing on the changes that have occurred over the past three decades. It then analyzes and reevaluates water injection in the context of current technology and the upcoming Euro 7 regulations, comparing the findings with current automotive applications and mobility trends to highlight potential benefits and future research directions in this field.

In order to properly address these gaps, I needed to conduct extensive preliminary investigations, which allowed me to confidently present and support my novel findings. The processes occurring in the emission after-treatment system – specifically within the vehicle’s exhaust system – are closely related to the exhaust gas temperature. Accordingly, I conducted measurements to determine the typical temperatures of the planned emission after-treatment system components. I compiled the significant reactions taking place here, including those on the Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF), and summarized these in tables. This greatly aided in the understanding of our later results.

Before starting the water injection tests, I assessed the effect of the water already entering the combustion chamber through humidity and concluded that the reactions occurring in the combustion chamber shift towards more complete combustion when the air has a higher water content due to humidity. As a result, during the emission reduction process, we observed a new outcome: a decrease in PN_{10} particle size, which is one of the new elements of the emerging EURO 7 emission regulations.

I conducted measurements to determine the effect of water injection on temperature, both after the engine and along the emission after-treatment system. I found that the oxidation catalyst conversion was adequate and that the temperatures did not degrade across the various emission treatment components.
In my research, I demonstrated that, within the current technological environment, "downsizing" and the high-load cycles that reflect modern transportation (WLTC) allow intake manifold injection to perform well. Under real-world conditions, exhaust gas recirculation is capable of reducing typical diesel pollutant emissions, such as NO_x and PN_{23}. A key new finding regarding the upcoming EURO 7 regulations is that it also has a positive impact on PN_{10} particle size emissions, and I have determined the location of this reduction too.
As a result of using practical and real-world applications in materials and methods, my findings can be easily transferred and applied to after-treatment retrofitting modifications involving water injection. The results of my investigations show that, without costly modifications to the engine control system, intake manifold water injection can still demonstrate positive emission effects. In addition, we did not observe any increased fuel consumption when using water injection alongside the complete emission treatment system. However, due to the positive catalytic effect on the regeneration of the diesel particulate filter — specifically the combustion of soot — the post-injection duration is reduced, which in turn lowers fuel consumption.

7. KEY PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign language

1. **Szőllősi, D**., Kiss, P. (2024): Effects of Water Injection in Diesel Engine Emission Treatment System—A Review in the Light of Euro 7. *Energies,* 17 (20), Paper: 5107, 29 p., https://doi.org/10.3390/en17205107 (Scopus: Q1, IF = 3.0)
2. Bíró, N., Kiss, P., **Szőllősi, D**. (2024): The Emission of off-Road Vehicles and Their Reduction Options. *IOP Conference Series: Materials Science and Engineering,* 1311 (1), Paper: 012010, 9 p., https://iopscience.iop.org/article/10.1088/1757-899X/1311/1/012010
3. Biró, N., **Szőllősi, D**., Kiss, P. (2024) Evaluation of NO_x and PN Emission in Relation to Actuator Control. *Sensors*, 24 (14), Paper: 4430, https://doi.org/10.3390/s24144430 (Scopus: Q1, IF = 3.4)
4. Bíró, N., **Szőllősi, D**., Kiss, P. (2023) Particle Counter Design Upgrade for Euro 7. *Atmosphere*, 14 (9), Paper: 1411, https://doi.org/10.3390/atmos14091411 (Scopus: Q2, IF = 2.9)
5. **Szőllősi, D**., Kiss, P., (2023): Reactions on the typical temperatures of the diesel aftertreatment system. *Mechanical Engineering Letters: R and D: Research and Developement*, Vol. 24, pp. 179-198., 20 p., HU ISSN 2060-3789
6. **Szőllősi, D**., Kiss, P. (2023): Soot accumulation in the diesel particulate filter and its effect on the filtration efficiency. *Mechanical Engineering Letters: R and D: Research and Developement*, Vol. 22, pp. 61-69., 9 p., HU ISSN 2060-3789
7. Biró, N., Pillinger, Gy., Kiss, P., **Szőllősi, D**., Ohira, A. (2021): Reducing nitrogen oxides in ICE R&D laboratory environment. *Mechanical Engineering Letters: R and D: Research and Developement*, Vol. 20, pp. 50-58., 9 p., HU ISSN 2060 3789
8. Bíró, N., Pillinger, Gy., Kiss, P., **Szőllősi, D**., Ohira, A. (2020) Experimental SCR System for Engine Dynamometer Applications. *Hungarian Agricultural Engineering*, Vol. 38, pp. 56-62. 7 p., http://doi.org/10.17676/HAE.2020.38.56

Lektorált cikk magyar nyelven

9. 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., ISSN 0026-1890
10. Csankó, Cs., **Szőllősi, D**., Biró, N., Kiss, P. (2021) Dízelmotor NO_x Kipufogógáz-Emissziójának Mérése. *MEZŐGAZDASÁGI TECHNIKA*, 62 (9), pp. 2–5., 4 p., ISSN 0026-1890
11. **Szőllősi, D**., Biró, N., Kiss, P. (2020) A Dízel Részecskeszűrő (DPF) Koromszűrési Hatékonyságának Megállapítása.

MEZŐGAZDASÁGI TECHNIKA, 61 (9), pp. 2–5. 4 p., ISSN 0026-1890

International conference proceeding

12. **Szőllősi, D.**, Kiss, P. (2024): The combination of exhaust gas recirculation and water injection in a modern diesel engine, *21st International and 12th Asia-Pacific Regional Conference of the ISTVS*, Paper 1902., 9 p., https://doi.org/10.56884/XAK8652F, Yokohama, Japán, 2024, October 28-31.
13. **Szőllősi, D**., Kiss, P. (2023): Effects of Humidity on the emissions of the diesel engines, *16th European-African Regional Conference of the ISTVS*, Paper 4816., 6 p., https://doi.org/10.56884/IGQO3531, Lublin, Lengyelország, 2023, October 11-13.

International conference abstract

14. 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, https://sciforum.net/event/WSF-10, Basel, Svájc, 2023, Szeptember 14.

Citations

The Publication **Particle counter design upgrade for EURO 7** cited in:

15. Giechaskiel, B.; Melas, A.; Broekaert, S.; Gioria, R.; Suarez-Bertoa, R. (2024): Solid Particle Number (SPN) Portable Emission Measurement Systems (PEMS) for Heavy-Duty Applications. Appl. Sci. 2024, 14, 654., ISSN: 2076-3417, https://doi.org/10.3390/app14020654 **IF 2.7, Scopus Q2**

The Publication **Effects of Water Injection in Diesel Engine Emission Treatment System—A Review in the Light of EURO 7** cited in:

16. Sharkey, A.; Zare, A.(2024) The Impact of Water Injection and Hydrogen Fuel on Performance and Emissions in a Hydrogen/Diesel Dual-Fuel Engine. Energies 2024, 17, 5838. https://doi.org/10.3390/en17235838 **IF 3.0, Scopus Q1**
17. Başaran, B.Ü. (2025) Advanced Technologies to reduce nitrogen oxide emissions in diesel engine systems, Makine Mühendisliği Konuları 2025, pp.1-21, 22 p., E ISBN, 978-625-5547-75-0 (mtmt-ben még nem jelent meg)