

Emission Reduction with Diesel Particle Filter with SCR Coating (SDPF)

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Abstract The present paper informs about some results obtained with selective catalytic reduction (SCR) and with SDPF (a diesel particle filter (DPF) with SCR coating) on a medium duty research engine Iveco F1C. This work is a first attempt at evaluating the effects of a SDPF on non-legislated gaseous emissions and on secondary nanoparticles. Beside the limited gaseous emission components, NH₃, NO₂, and N₂O were measured with FTIR, and the analysis of nanoparticle emissions was performed with Scanning Mobility Particle Sizer (SMPS) and condensation particle counter (CPC). The integration of functions of filtration and NO_x reduction in one element of exhaust aftertreatment system offers several advantages and is widely investigated and considered as a market solution. The most important technical statements of the research are as follows:

- The emission behavior of SDPF after urea switch-on (SWON) concerning NO_x reduction speed and NH₃ peak

is always fluctuating even in identical test procedures and with careful conducted conditionings.

- The loaded SDPF, compared with empty one, shows slower NO_x reduction and higher NH₃ after SWON because of use of part of NO₂ for soot oxidation and consequently less NO₂ availability for the deNO_x reactions; the secondary nanoparticle (NP) penetration after SWON is clearly lower with the loaded trap.
- Both investigated systems, SDPF and 2× SCR, attain nearly the same deNO_x efficiency.
- In worldwide heavy duty transient cycle (WHTC) with a lower level of exhaust gas temperature, SDPF causes lower deNO_x values (40–45 against 75 % in European transient cycle (ETC)), but also lower NH₃ emissions.

Further developments of those aftertreatment systems, concerning substrates, coatings, and reduction agent control, open further potentials of improvements.

Keywords Diesel emissions · Diesel particle filter · NO_x reduction · Exhaust after treatment · Non-legislated emissions · SCR coating on filter

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Abbreviations

AFHB	Abgasprüfstelle FH Biel, CH
Air min	Stoichiometric air requirement
ASTRA	Amt für Strassen, CH, Swiss Road Authority
BAFU	Bundesamt für Umwelt, CH (FOEN)
CDI	Common rail diesel injection
cDPF	Catalytic DPF
CFPP	Cold filter plugging point
CLD	Chemoluminescence detector
CNC	Condensation nuclei counter

COND	Conditioning procedure, here: 2200 rpm / 300 Nm	TDC	Top dead center
CPC	Condensation particle counter	TTM	Technik Thermische Maschinen
CR	Common rail	UDS	Urea dosing system
DOC	Diesel oxidation catalyst	ULSD	Ultra low sulfur diesel
DI	Direct Injection	VERT	Verminderung der Emissionen von Realmaschinen in Tunnelbau
DMA	Differential mobility analyzer		Verification of Emissions Reduction Technologies
DPF	Diesel particle filter		
EATS	Exhaust aftertreatment system		
ECU	Electronic control unit		
EGR	Exhaust gas recirculation		
EMPA	Eidgenössische Material Prüf- und Forschungsanstalt		
ETC	European Transient Cycle		
E4	Engine version Euro 4 with EGR		
E(4)	Engine version Euro 4 without EGR		
FE	Filtration efficiency		
FID	Flame ionization detector		
FL	Full load		
FOEN	Federal Office of Environment		
FSN	Filter smoke number		
HD	Heavy duty		
ICE	Internal combustion engines		
INSOF	Insoluble fraction		
K _x	Conversion efficiency of the component "x"		
LD	Low duty		
LDS	Laser diode spectrometer (for NH ₃)		
LRV	Luftreinhalteverordnung		
MD19	Heated minidiluter		
NP	Nanoparticles < 999 nm (SMPS range)		
OEM	Original equipment manufacturer (here: w/o aftertreatment)		
OP	Operating point		
PAH	Polycyclic aromatic hydrocarbons		
PC	Particle counts		
PCFE	Particle counts filtration efficiency		
PM	Particulate matter, particle mass		
PN	Particle number		
PSD	Particle size distribution		
RAI	Reduction agent injection (AdBlue)		
RE	Reduction efficiency		
SCR	Selective catalytic reduction		
SDPF	DPF with SCR coating		
SL	Soot loading procedures		
SMPS	Scanning Mobility Particle Sizer		
SOF	Soluble organic fraction		
SOI	Start of injection		
SP	Sampling position		
SV	Spatial velocity		
SW	Switch on urea		
SWON	Urea switch-on		
TC	Thermoconditioner		

1 Introduction and Objectives

1.1 DPF+SCR

The combination of particle filtration (diesel particle filter, DPF) and of the most efficient deNO_x technology (selective catalytic reduction, SCR) is widely considered as the most efficient solution, up to date, to minimize the emissions of diesel engines. With a DPF a very efficient elimination of solid particles (particle counts filtration efficiency (PCFE) up to 99.99 %) and with SCR a substantial reduction of NO_x (K_{NO_x} over 90 %) are possible. Intense developments are on the way by the original equipment manufacturers (OEMs), and investigations were performed [1–11].

The removal of NO_x from the lean exhaust gases of diesel engines (also lean-burn gasoline engines) is an important challenge. Selective catalytic reduction (SCR) uses a supplementary substance—reduction agent—which in presence of catalysts produces useful reactions transforming NO_x in N₂ and H₂O.

The preferred reduction agent for toxicological and safety reasons is the water solution of urea (AdBlue), which due to reaction with water (hydrolysis) and due to thermal decomposition (thermolysis) produces ammonia NH₃, which is the chemically reacting reduction substance.

A common configuration of SCR deNO_x system consists of four catalytic activities:

- Precatalyst converting NO to NO₂ (with the aim of 50/50 proportion; a part used in the present investigations)
- Injection of AdBlue (with the intention of best distribution and evaporation in the exhaust gas flow)
- Hydrolysis catalyst (production of NH₃)
- Selective catalyst (several deNO_x reactions)
- Oxidation catalyst (minimizing of NH₃ slip)

In the exhaust aftertreatment systems (EATSS) actually in use, several functions can be integrated in one catalyst. In the tested systems, the hydrolysis and the SCR reactions occurred in the SCR catalysts or in the SDPF (DPF with SCR coating). There was no ammonia slip catalyst applied.

The main deNO_x reactions between NH₃, NO, and NO₂ are widely mentioned in the literature [9, 11–14]. Depending on

the temperature of gas and catalysts, space velocity, and stoichiometry, these reactions progress more or less rapidly. During the transient engine operation, a complex situation of reactions is created with varying intensities in time and space.

Additionally, there are temperature windows for catalysts and cutoff of the AdBlue injection at low exhaust gas temperatures to prevent the deposits of residues.

Several side reactions and secondary substances are present. An objective is to minimize the tail pipe emissions of ammonia NH₃, nitrous oxide N₂O, isocyanic acid HNCO, and ammonium nitrate NH₄NO₃ (also known as secondary nanoparticles).

Intense research about the solutions of problems of the present systems and about new developments has been reported. The following can be mentioned:

- Deposits of urea-related substances (urea, cyanuric acid, ammonium nitrate) [13–15]; these deposits create undesirable effects of store-release of reactants, of heterogenous reactivity, and in worst case of plugging the EATS.
- Measuring accuracy of NO_x in presence of NH₃ [16–18]; highly reactive NH₃ may create problems of measuring accuracy and may deteriorate the exactitude of chemoluminescence detector (CLD).
- Other reduction agents [19, 20] were proposed in order to introduce gaseous NH₃ in the exhaust line or to obtain higher storage capacity of NH₃ precursors on board of vehicle.
- AdBlue dosing and homogenous distribution [21]; an attribute of improving the use of urea in the sense: more deNO_x reactivity, less NH₃ slip.
- Construction variants of DPF+SCR and their influences on functionality, warm-up, DPF regeneration, and durability of elements [8–10].

1.2 SDPF

There are efforts and research of integrating the functions of filtration and NO_x reduction in one element, [22–26]. This is designed as SCR on filter (SCRoF) or SCRF, or SDPF.

There are several advantages of this solution:

The flow-through SCR substrate is eliminated and there is, in most cases, a lower volume of the system. Due to the lower volume, there is a reduced thermal capacity and a quicker warm-up. There can also be lower costs of the coatings [25, 27].

In order to increase the NO_x conversion, especially at cold start- and warm-up conditions, a supplementary flow-through SCR catalyst can be applied downstream of SDPF and the last one can be placed nearer to the engine. The more rapid heat-up of SDPF would enable an earlier urea dosing and consequently an improved NO_x control.

The NO₂, which is generated in the oxidation catalyst, is used for both the continuous soot oxidation and the SCR reactions.

One of the biggest challenges of the research is to identify the optimal trade-off between these activities and to be able to adapt the filter component design for specific engine applications.

In the present work, as well as in the cited literature, it has been shown, that similar NO_x reduction rates may be reached with the integrated (SDPF) systems and with the conventional SCR, [23, 25, 26].

1.3 Objectives

A general objective of the paper is to present some specific observations, concerning the urea switch-on (SWON) with different soot loads. These observations are helpful in order to understand better and to compare the emissions and passive regeneration behavior of a conventional (DPF+SCR) system with a SDPF system. The research was performed at certain repeated operating conditions and, consequently, it cannot be generalized for other applications and requirements.

During the project, the dynamic urea dosing was prepared and the tests were performed at steady state (steps-tests) and in dynamic operation (worldwide heavy duty transient cycle, WHTC).

The topics presented in this paper are the following:

- Repetitivity of NO_x/NH₃ emissions after urea switch-on (SWON)
- Nanoparticle emissions after SWON
- deNO_x efficiencies
- Dynamic operation

2 Tested Engine, Fuel, and Lubricant

2.1 Test Engine

Manufacturer:	Iveco, Torino Italy
Type:	F1C Euro 3/Euro 4
Displacement:	3.00 L
RPM: max.	4200 rpm
Rated power:	100 kW @ 3500 rpm
Model:	4 cylinder in-line
Combustion process:	direct injection
Injection system	Bosch Common Rail 1600 bar
Supercharging:	Turbocharger with intercooling
Emission control:	none
Development period:	until 2000 (Euro 3)

Figure 1 shows the engine in the laboratory for IC-engines, University of Applied Sciences, Biel-Bienne, CH.

2.2 Fuel

The following diesel fuel was used for the research (Table 1):

- Shell Formula Diesel fuel Swiss market summer quality (10 ppm S) according to SN EN 590

Table 1 represents the most important data of the fuel according to the standards.

2.3 Lubricant

For all tests, a lube oil according to the manufacturer requirements, Mobil 1 ESP Formula 5W-30, was used.

Table 2 shows the available data of this oil,

ACEA classes: C3, A3, B3/B4,

API classes: SL / SM; CF

2.4 Engine Version Euro 4

In collaboration with the engine manufacturer, the research engine version Euro 3 was upgraded to the version Euro 4. The new engine equipment consisted of the following:

- Exhaust gas recirculation (EGR) valve (high pressure EGR) (see Fig. 2)
- EGR cooler

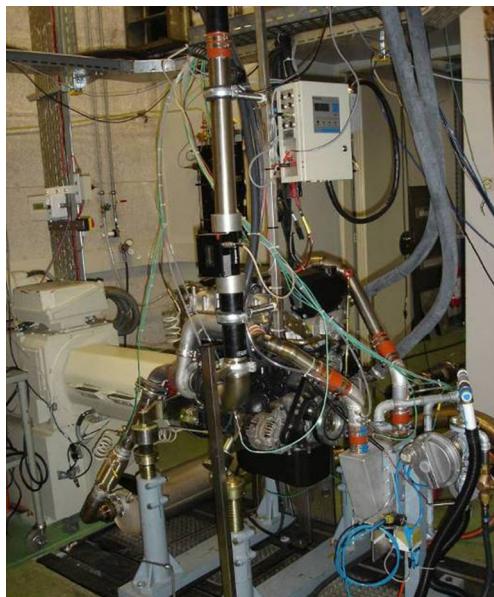


Fig. 1 IVECO engine F1C and dynamic engine dynamometer in the engine room

Table 1 Fuel properties as per EU standards

	Diesel
Density 15 °C	g/mL
Viscosity at 40 °C	mm ² /s
Flash point	above 55 °C
Cloud point	max -10 °C
Filterability CFPP	max -20 °C
Ash	%
Sulfur	ppm
Cetane number	51
Calorific value	MJ/kg
C fraction	in %
H fraction	in %
O fraction	in %
Air _{min}	kg/kg
Boiling range 10–90 °C	14.52 180–340

CFPP cold filter plugging point

- Throttle valve at intake,
- Air mass flowmeter at intake
- Injectors
- New engine calibration (electronic control unit, ECU) for modifications of injection timing and injection mode (pre-/post-injections)

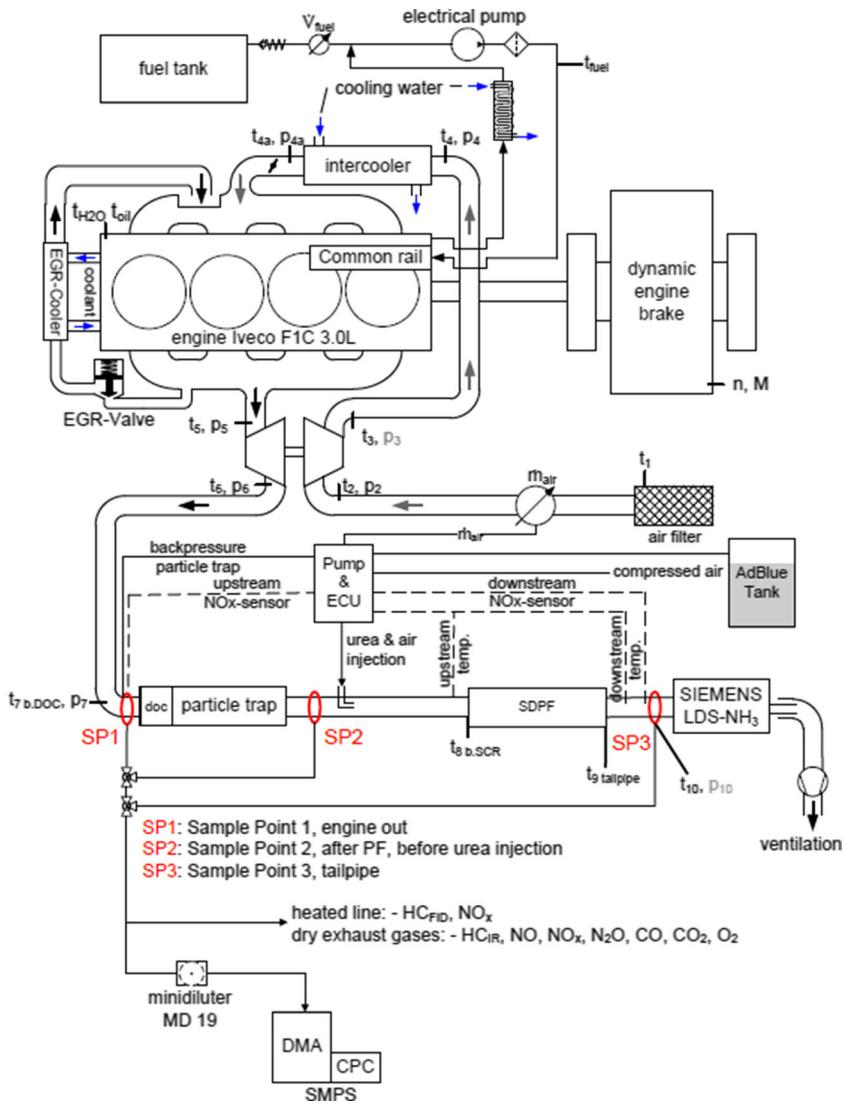
The principal influences on engine combustion and emissions are as follows:

- HP EGR regulated continuously in the engine map

Table 2 Data of the utilized oil (* analysis, others: specifications)

Property	Mobil oil
Viscosity kin 40 °C	72.8
Viscosity kin 100 °C	12.1
Viscosity index	164
Density 15 °C	0.85
Pourpoint	-45
Flamepoint	254
Total base number, TBN*	6
Sulfur ashes*	600
Sulfur*	2000
MG*	41
MO*	80
Zn*	900
Ca*	1100
P*	820

Fig. 2 Engine dynamometer and test equipment



- Further use of potentials of CR injection system (pressure, timing, shaping, strategies)

The EGR is regulated by means of simultaneous positioning of the EGR valve and of the throttle valve with air mass flow as guiding parameter. The total injected fuel quantity is adapted to the air mass flow.

The ECU engine calibration is given in two versions: for HD and for LD application. In the present work, only the HD version was used.

The research laboratory received access to the ECU with the possibility of switching on/off EGR.

The engine version Euro 4 with EGR is abbreviated to E4 in this paper and the same version with EGR switched off is called E(4).

3 Measuring Setup and Instrumentation

3.1 Engine Dynamometer and Standard Test Equipment

Figure 2 represents the special systems installed on the engine, or in its periphery for analysis of the regulated and unregulated emissions.

Laboratory equipment employed:

- Dynamic test bench Kristl & Seibt
- Tornado Software Kristl & Seibt
- Fuel flow measurement AIC 2022
- Air mass meter ABB Sensiflow P
- Pressure transducers Keller KAA-2/8235, PD-4/8236
- Thermo-couples Type K.

3.2 Test Equipment for Exhaust Gas Emissions

Measurement is performed according to the exhaust gas emission regulations for heavy duty vehicles which are in force in Switzerland (Directive 2005 / 55 / CE & ISO 8178):

- Volatile components:
- Horiba exhaust gas measurement devices
Type: VIA-510 for CO₂, CO, HCIR, O₂,
Type: CLA-510 for NO, NO_x
- Amluk exhaust gas measurement device Type:
FID 2010 for HCFID,
- NH₃ and N₂O:
With SCR, several unregulated and secondary pollutants can be produced. The slip of gaseous components such as ammonia NH₃ and nitrous oxide N₂O was measured by means of
 - Siemens LDS 6 Laser Analyzer 7MB 6021, NH₃
 - Siemens ULTRAMAT 6E 7MB2121, N₂O
 - Eco physics CLD 822 CM hr with hot line for NO, NO₂, NO₃, NH₃

3.3 Particle Size Analysis

The distribution of the particle size and number was analyzed with the following apparatus:

- SMPS – Scanning Mobility Particle Sizer, TSI (DMA TSI 3081, CPC TSI 3010 A)
- NanoMet – dilution system consisting of
- MD19 tunable minidiluter (Matter Eng. MD19-2E) – heated up to 80 °C
- thermoconditioner (TC) – heated up to 300 °C.

The nanoparticle results represented in this paper are obtained with sampling at tail pipe with MD19 and with thermoconditioner. The nanoparticulate measurements were performed at constant engine speed (warm) with SMPS and in dynamic cycles with CPC.

4 Test Procedures on Engine Dynamometer

The stationary testing is performed by different constant operating points (OPs) of the engine. These OPs are chosen at 2200 rpm (intermediate speed) and at different loads; see Fig. 3. The sequence of OPs with increasing load and with

increasing exhausts gas temperature is called regeneration steps-test.

In the first part of the works, the step duration was 20 min per step. This caused a total oxidation of the particle matter (PM) loading in the highest steps. For investigations of regeneration efficiency by mass with different changed conditions (like soot load, or reduction agent injection (RAI) on/off), it was decided in the further works to apply a shorter step duration of 10 min, to enable a better differentiation of the results.

At lower load, with exhaust temperature before SCR lower than 200 °C, the urea dosing is stopped.

As conditioning (COND) a constant OP, 2200 rpm/300 Nm was used to purge the SDPF concerning the soot load and the ammonia storage.

DPF soot loading (SL) was performed according to a fixed schedule at part load OP of the engine, 2200 rpm/50 Nm and with adapted engine parameters (ECU load mode)—lower injection rail pressure, earlier injection timing, and activated EGR. An example of this setting at one OP is given in Table 3.

DPF fully pre-loaded means the increase of mass (weight at 140 °C) by 20.9 g (3.5 g/L) in average; half pre-loaded means the one half of this PM charge and “filter empty” is after the conditioning (COND).

The urea dosing system (UDS) consists of an AdBlue tank, a pump, an ECU, and an injector. The injector is attached to the pressurized air and the injection jet is air-shrouded to minimize the deposits. The dynamic dosing of AdBlue was performed by means of the control units: of the engine dynamometer and of the Albonair dosing system with the input of the NO_x sensor “engine out” signals; see scheme Fig. 4.

For dynamic testing, the cycles WHTC and ETC were used (Fig. 5).

5 Exhaust Aftertreatment Systems

The exhaust aftertreatment systems (EATSS) were set in modular way in the exhaust line of the engine.

Table 4 shows the EATSS, which are presented in this paper. The elements diesel oxidation catalyst (DOC), catalytic DPF (cDPF), and SCR were placed for the research in the straight in-line configurations, and this Table 4 replaces a possible scheme representation. The material of substrates of DOC, cDPF, and SDPF is cordierite.

Table 5 shows some data of the investigated elements. The SCR coatings were Fe-based. There is no further information about all applied coatings.

For research of SCR efficiencies with SDPF in some test series, a cDPF was used upstream of SDPF in order to eliminate any influence of particles on the SDPF NO_x reduction rate. This test system is called SYS05.

Due to equal active volumes of 2× SCR and SDPF elements, similar spatial velocities result in the engine operation.

Fig. 3 Engine map of the Iveco F1C engine and tested OPs

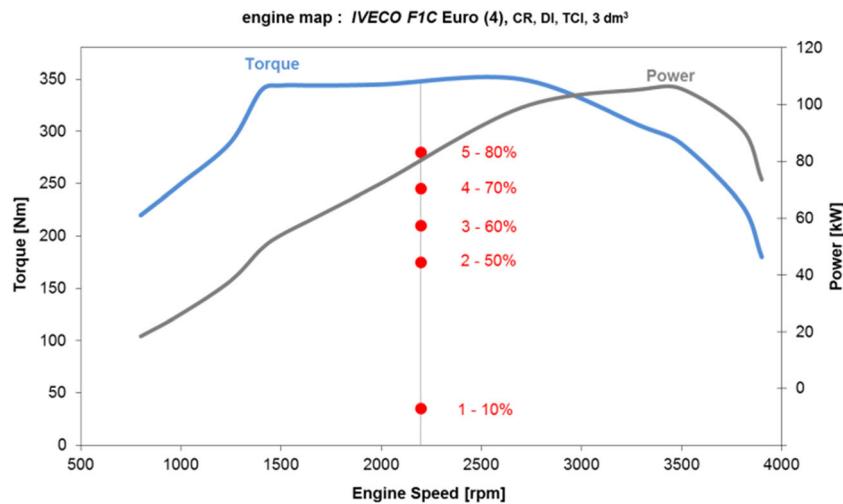


Table 6 summarizes the spatial velocities (SVs) in the steps-test with consideration of different exhaust gas temperatures.

6 Results

Below, the results of some specific research subjects are presented. These subjects are chosen out of many results of a 2-year project. Even if these results are connected with the given test material of EATS and with the test procedures of this work, the authors believe that they may complete or enlarge the present state of knowledge.

6.1 Repetitivity of NO_x/NH₃ Emissions After Erea Switch-on

Figure 6 shows the first comparison of emissions in steps-tests with different soot loadings of the SDPF (full, half, empty) and with active RAI. After urea switch-on (SWON), there is a reduction of NO_x concentration and a peak of NH₃. This NH₃ peak declines to a lower average value in further steps. With higher soot load, this average NH₃ concentration increases. The reduction speed of NO_x after SWON correlates with the

soot load in the sense: more soot load, lower reduction rate of NO_x. This is to explain with less NO₂ production on the soot-loaded catalytic surface (DOC) and more NO₂ consumption for the soot oxidation. Less availability of NO₂ in the deNO_x reactions causes more NH₃.

The NH₃ peaks in Fig. 6 do not follow the sequence of soot load, and it was not clear if the NH₃ peaks after SWON are repetitive or varying from test to test. Most probably, they are extremely influenced by the initial state of the SDPF (local distribution and amounts of soot load, urea, and NH₃ storage). This question was considered in further tests (see Fig. 7).

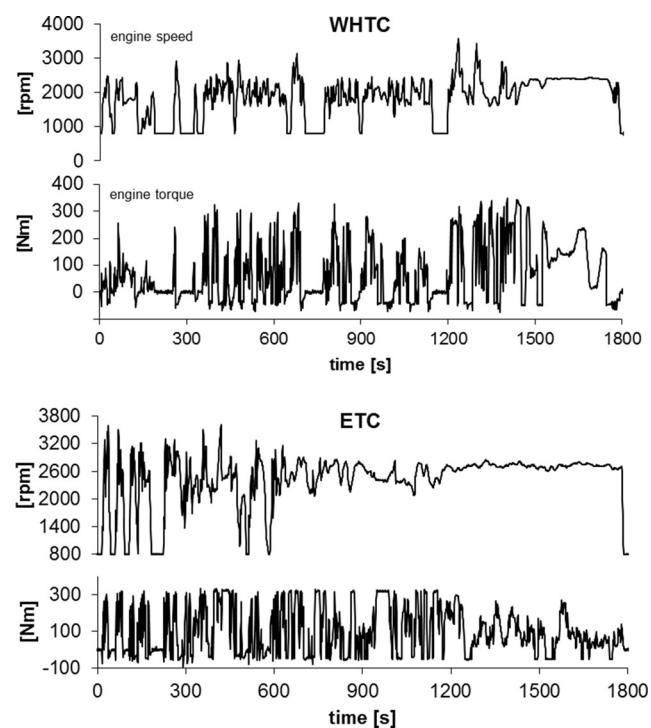


Fig. 4 Implementation of AdBlue dosing control over the engine test bench

Table 3 Adaptation of engine parameters for quicker soot loading

2200 rpm/50 Nm	Original (reference)	Adapted
FSN [-]	0.5	2.2
T. b. cDPF (°C)	197	243
Rail pressure (bar)	600	300
Inj. b. TDC (°CA)	5.7	9.5
Air flow (mg/hub)	750	500
EGR	Closed	Active

cDPF catalytic diesel particle filter, TDC top dead center, EGR exhaust gas recirculation

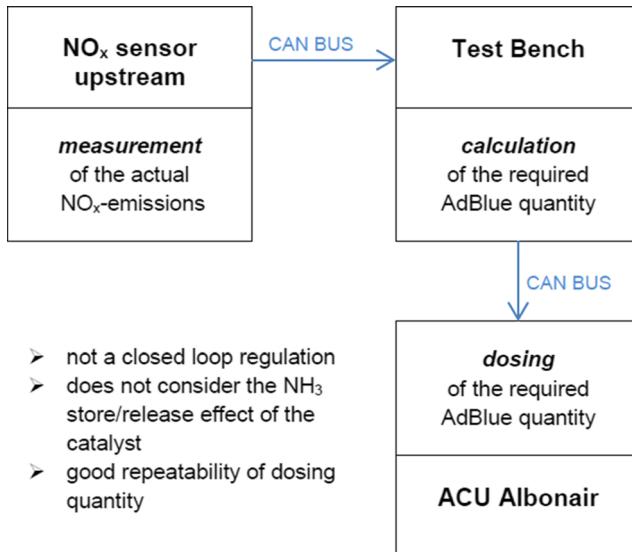


Fig. 5 Engine torque and speed in the WHTC and ETC (Iveco F1C, 3.0 l)

With active RAI, the nanoparticle (NP) emissions increase after the start of urea injection, indicating the contribution of urea products to the emission. With loaded trap, the NP filtration efficiency is as usually increased and the emitted concentrations of secondary NP, which pass the trap, are lower.

The additional tests about emissions after SWON were performed with the empty SDPF (always after conditioning procedure). Figure 7 shows in the higher part the magnified representation of NO_x and NH₃ courses from Fig. 6 with addition of another repetition with empty SDPF. The repetition shows a slower drop of NO_x and a higher peak value of NH₃, than the previous attempt with not pre-loaded filter.

In the lower part of Fig. 7, three successive switch-on attempts with not pre-loaded filter are represented. These results confirm the tendency that the cases with quicker NO_x drop after SWON have also a lower NH₃ emission.

In the presented example of three SWON attempts with empty filter, there is a sequence of results (d), (e), and (f) indicating an increasing deNO_x reactivity. This in turn can be explained with more complete oxidation of residual soot from the filter in the later attempts.

If the filter soot load is added, then the amount of soot and the distribution of soot residues in the filter volume have an

Table 4 Variants of exhaust aftertreatment systems

System	Elements
SYS01	DOC cDPF _Δ SCR SCR
SYS03	DOC _Δ SDPF
SYS05	DOC cDPF _Δ SDPF

Δ position of RAI, DOC diesel oxidation catalyst, cDPF catalytic diesel particle filter, SCR selective catalytic reduction

Table 5 Data of investigated elements

Element	Porosity	Wall thickness	Dimensions
DOC	400 cpsi	4.3 mil	6.77×3.5 in
SCR	400 cpsi	4.3 mil	6.77×5 in
cDPF	300 cpsi	12 mil	6.77×10 in
SDPF	300 cpsi	12 mil	6.77×10 in

DOC diesel oxidation catalyst, cDPF catalytic diesel particle filter, SCR selective catalytic reduction, SDPF DPF with SCR coating

influence on the chemical reactions, their speed, stoichiometry, and local availability of reactants, especially of NO₂.

In general, the differences of reactivity between the SWON attempts can be a result of heterogeneous distribution of urea and soot in the SDPF volume, which causes the variances of NO₂ availability at the same operating conditions with identical history of the precedent operating collectives.

According to the investigations with filter weighing (not represented in this paper), there are indications of soot load being heterogeneously distributed and causing different relationships between backpressure and the stored soot mass in diverse identical soot loading procedures. This has an impact on the local NO₂ availability and consequently on the deNO_x reactions and on the possible NH₃ slip. This local impact is supposed to be similar, as the global influence (see Fig. 8): more soot → less availability of NO₂ for deNO_x, slower rate of NO_x reduction, and higher probability of ammonia slip.

In summary, we can assert that the emission behavior of SDPF after urea SWON concerning NO_x reduction speed and NH₃ peak is always fluctuating even after identical procedures of soot loading and/or conditioning.

As per the presented results and their explanations, the authors declare that the reasons of this dispersion are the inhomogeneity of urea (and urea products) distribution and the varying initial state of filter in respect of soot loading and soot distribution in the filter volume.

Figure 9 represents the results with not pre-loaded (empty) SDPF with RAI.

Table 6 Spatial velocities in SCR and SDPF during the steps-test

M (Nm)	m _{exh.} (kg/h)	Spatial velocities			
		DOC (1/s)	SDPF (1/s)	cDPF (1/s)	2xSCR (1/s)
35	223	38	13	13	13
175	293	67	24	24	23
210	312	74	26	27	26
245	334	83	29	30	28
280	355	92	32	33	31

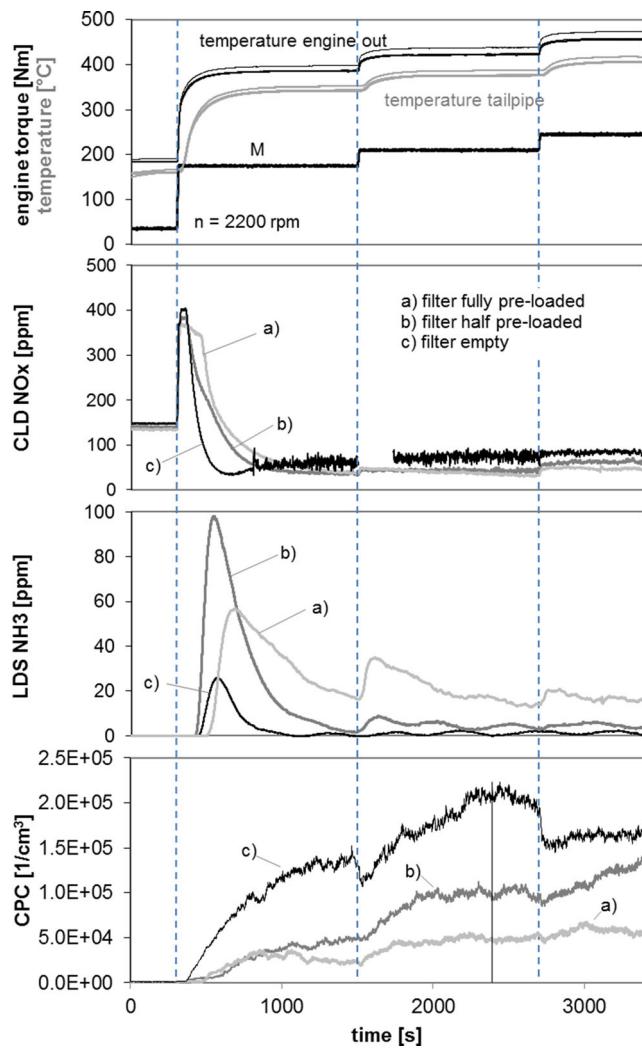


Fig. 6 Comparison of emissions in steps-tests with SDPF at different loadings; SYS03; dosing $\alpha=0.9$

Results of a repeated comparison between fully loaded and empty SDPF are demonstrated again in Fig. 8, which confirms the findings that with higher soot loading of the trap, there are after SWON

- Lower reduction speed of NO_x
- Higher NH_3 -peak and higher NH_3 -average values
- Less penetration of secondary nanoparticles

In one test, the SDPF is applied without DOC. Absence of DOC upstream of SDPF deteriorates strongly the deNO_x efficiency due to the lack of NO_2 , but also strongly increases the NH_3 concentrations (more than double). Since there is little availability of NO_2 and consequently less reactivity of urea, there is a slight increase of secondary (nitric) nanoparticles [28–30].

In another test, the lower AdBlue dosing not only reduces the deNO_x efficiency and eliminates NH_3 but also causes less NP after SWON.

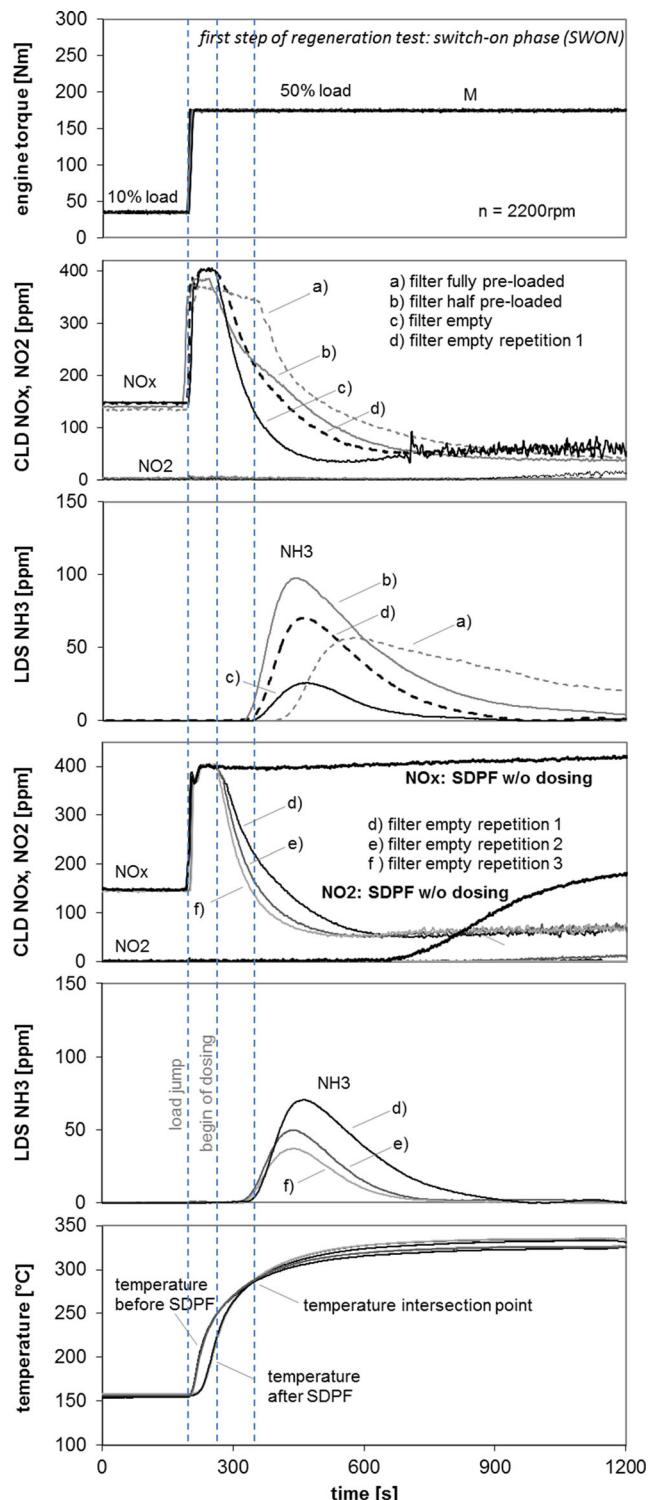


Fig. 7 Repetition of switch-on behavior with empty SDPF; SYS03; dosing $\alpha=0.9$

Table 7 shows the accumulated mass (PM) after the test for those trials. With higher urea dosing, higher mass is accumulated, but without DOC (without NO_2 production), there is the highest mass, which could not be oxidized during the steps-test.

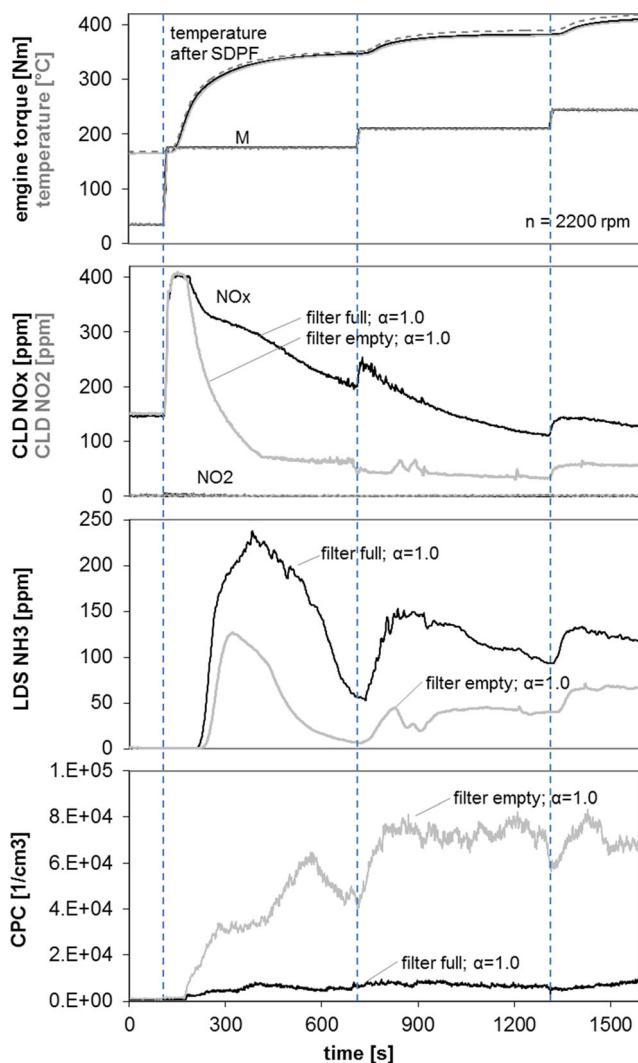


Fig. 8 Repeated comparison of emissions in steps-tests with full and empty SDPF; SYS03; dosing $\alpha=1.0$

6.2 Nanoparticle Emissions After Urea Switch-on

As already demonstrated, the NP values (CPC) start to increase after SDPF at the moment of SWON; this is, nevertheless, at a very low level.

The zoomed representation of CPC traces in diverse steps-tests, Fig. 10, shows the details of PC increase with different SDPF loadings and with/without RAI.

With more filter pre-loading, the NP counts increase later and attain lower values in the steps-test.

With RAI, PCs increase directly after SWON and stay at a similar level up to the highest (fifth) step.

Without RAI, PCs start to increase in the second or third step, which can be visible according to the representing scale even in the fourth step. In the last step, the PCs w/o RAI increase continuously indicating the increasing penetration through the SDPF. AdBlue dosing clearly inhibits this increased penetration in the two highest steps—the reasons

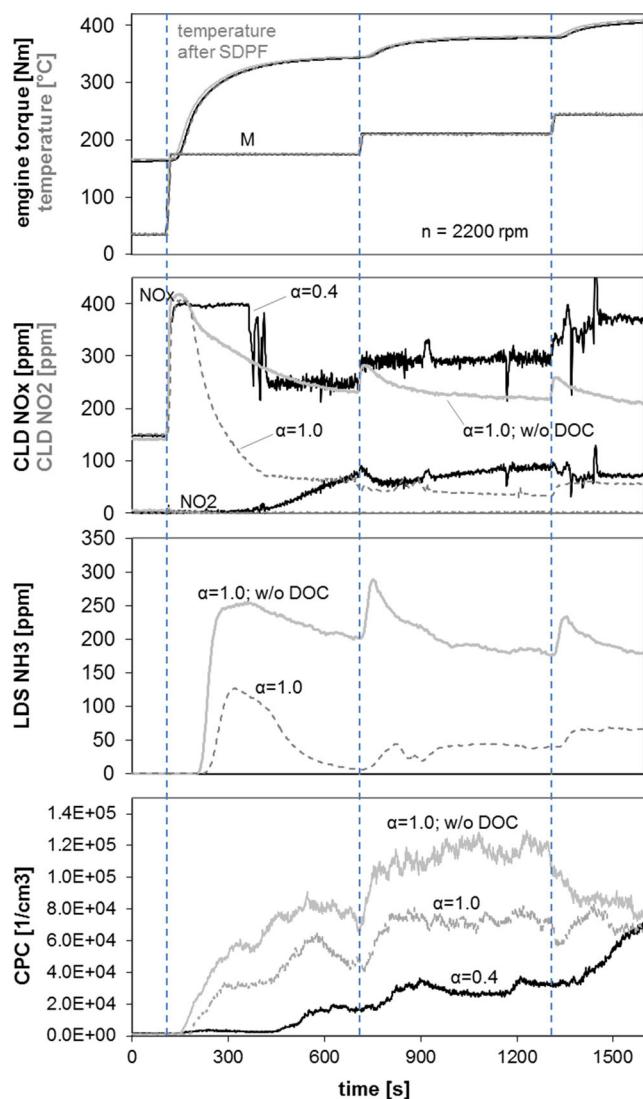


Fig. 9 Comparison of emissions in steps-tests with empty SDPF with and without DOC; SYS03; dosing $\alpha=0.4/1.0$

can be reduction of the average temperature of the substrate surface and impact on NP filtration mechanism, like the surface adhesion forces independently on increasing spacial velocity in these higher steps. Since this is a question of secondary (nitric) nanoparticles, which consist mostly of urea and ammonium nitrate crystals, there is an open question of

Table 7 Influence of urea dosing on accumulated mass in empty SDPF during the steps-tests

Measurement name	α [-]	Accum. mass (g)	Remarks
REGSTEPS21	0.4	0.1	
REGSTEPS22	1	6.9	w/o DOC
REGSTEPS23	1	1.9	

DOC diesel oxidation catalyst

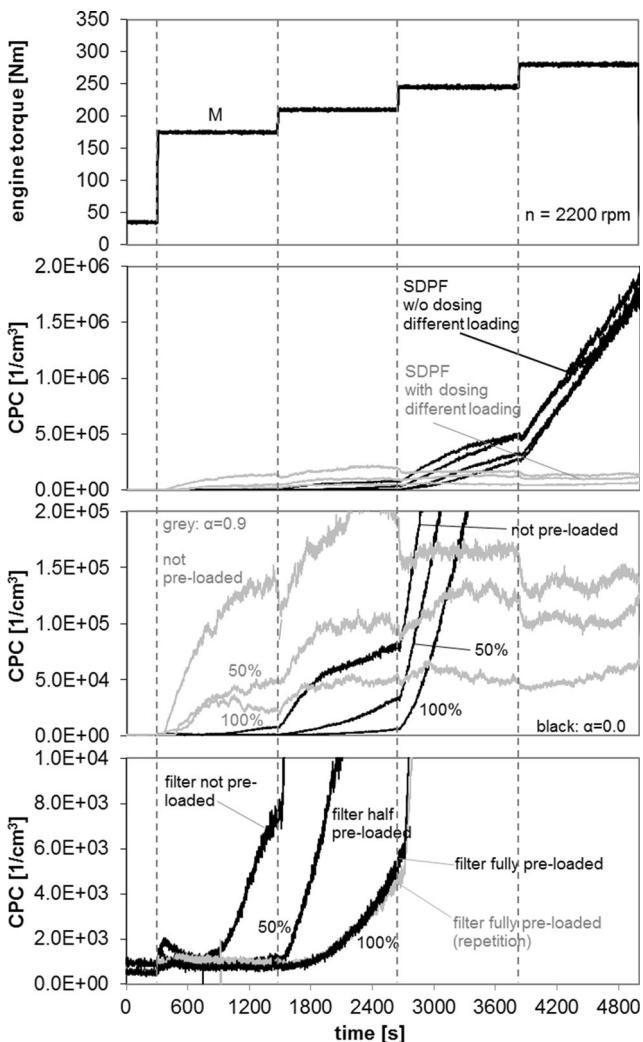


Fig. 10 Nanoparticle emissions in steps-test with SDPF, with/without dosing (zoomed representation); SYS03; dosing $\alpha=0.9$

implication of these nanoparticles or their precursors in the chemical reactions.

Measurements of SMPS particle size distributions (PSDs) were performed with cDPF and SDPF (systems 1 and 3) at three operating points: 2200 rpm and 35/175/245 Nm, to visualize the effects of secondary nanoparticles with urea dosing.

At the lowest load, urea dosing was not active and, at the highest OPs, it was varied for research.

The performance of tests was according to the identical schedule: starting the engine, heating up at the lowest OP, measurements, and progressing to the middle and after to the highest OP. In this way, the exhaust system was either thermally stabilized or heated up.

Figure 11 shows the example of results with cDPF (system 1) not pre-loaded at 175 Nm. The feed factor α was varied. With increasing urea dosing (after cDPF), the secondary NPs are visible, and the penetration values of entire system increase in the size ranges below 35 nm and above 250 nm.

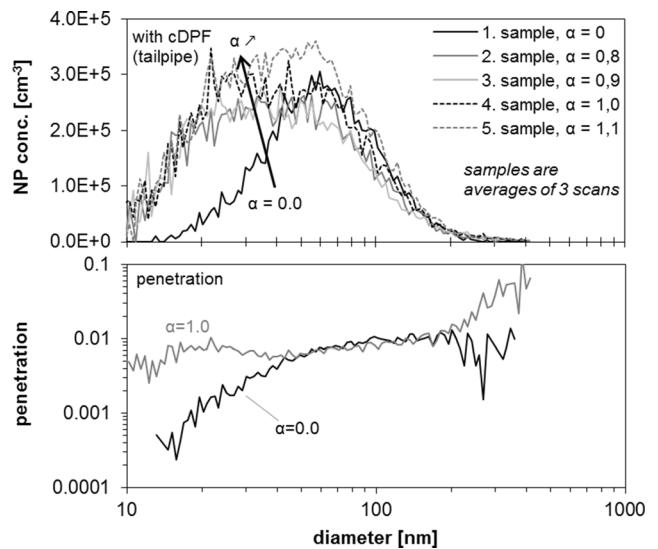


Fig. 11 NP size spectra with conventional DPF+SCR at stationary OP 2200 Nm/175 Nm; SYS01; not pre-loaded

Figure 12 shows the results for SDPF (system 3) not pre-loaded at 175 Nm. The effect of secondary NPs from RAI is clearly demonstrated. The secondary NPs can be seen, even if the RAI is placed upstream of the filter (by cDPF, RAI is downstream of the filter). The urea dosing with α varying from 0.8 to 1.1 has no influence on the concentrations of these secondary NPs.

The maximum values of PC concentrations are with cDPF significantly higher, than with SDPF. This is due to the fact that with cDPF (SYS 01), the urea dosing is placed downstream of DPF. Nevertheless, in both cases (cDPF and SDPF), the secondary NPs are negligible comparing with the engine-out emissions.

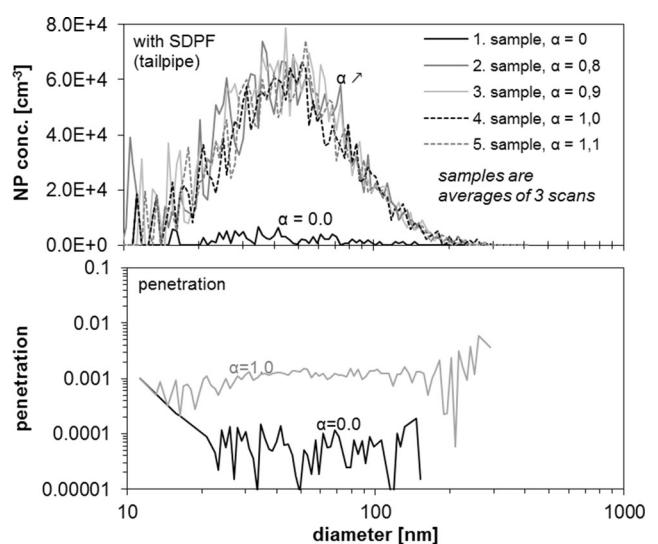


Fig. 12 NP size spectra with SDPF at stationary OP 2200 Nm/175 Nm; SYS03; not pre-loaded

At the highest OP (2200 rpm/245 Nm), both systems showed the increased particle counts due to spontaneous condensates of sulfates [31] (see Fig. 13).

The exhaust gas temperature before (DOC + cDPF / SDPF) being at this high OP is at 433 °C, which is well sufficient for intense sulfur oxidation in the catalytic system. The sulfates pass in the form of vapors through the trap and then condense after it, creating increased NP count concentrations. This effect overlaps with the secondary NPs from RAI, which contribute to the seeding effect.

Figure 13 summarizes the NP count concentrations integrated in the size spectrum 20–300 nm and the resulting particle counts filtration efficiencies (PCFEs).

It can be stated that

- The investigated SDPF has a slightly higher PCFE than the cDPF.
- The urea dosing produces secondary NPs which, nevertheless, have negligible impact on the overall PCFE.
- At high OP (with high t_{exh}), there are spontaneous condensates of sulfates, an artifact, which lower the estimated value of PCFE.

6.3 DeNO_x Efficiency

The deNO_x efficiency (K_{NO_x}) and some interesting emission components (NO_x, NO₂, N₂O, and NH₃) were estimated in steps-tests with cDPF (SYS01) and with SDPF (SYS03). The SDPF was tested with different states of soot loadings.

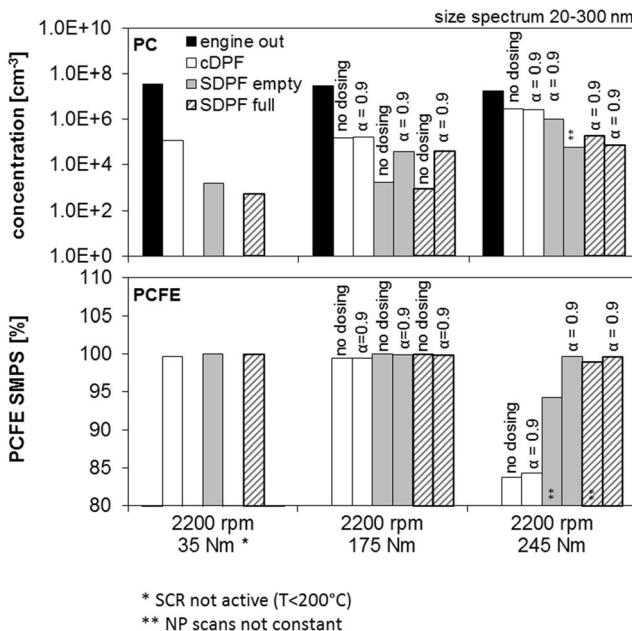


Fig. 13 Particle counts and particle counts filtration efficiency with cDPF and SDPF at stationary OPs; cDPF SYS01 and SDPF SYS03

Figure 14 represents the results at two steps with 175 and 280 Nm.

The SDPF with no soot loading has the lowest K_{NO_x} values (in average 85 %). This seems to contradict the earlier results (Figs. 6, 7 and 8) showing the quickest NO_x drop after SWON and the lowest level of NH₃ with empty filter. However, in the presented experiments, the engine-out NO_x level varies; being higher for the empty and lower for the fully-loaded SDPF (see Fig. 6, load jump from the first to the second step). This fact influences the calculated K_{NO_x} values.

With increased soot loading of SDPF (Fig. 14), the K_{NO_x} increases to 90 % (average), which is in the same magnitude as for (cDPF + 2× SCR).

The increase of NH₃ with soot load and active RAI is confirmed for SDPF. The average N₂O values for SDPF are all below 5 ppm. The higher N₂O value with cDPF was registered only in the first load-jump and it must be associated with a random situation of urea or deposit distribution.

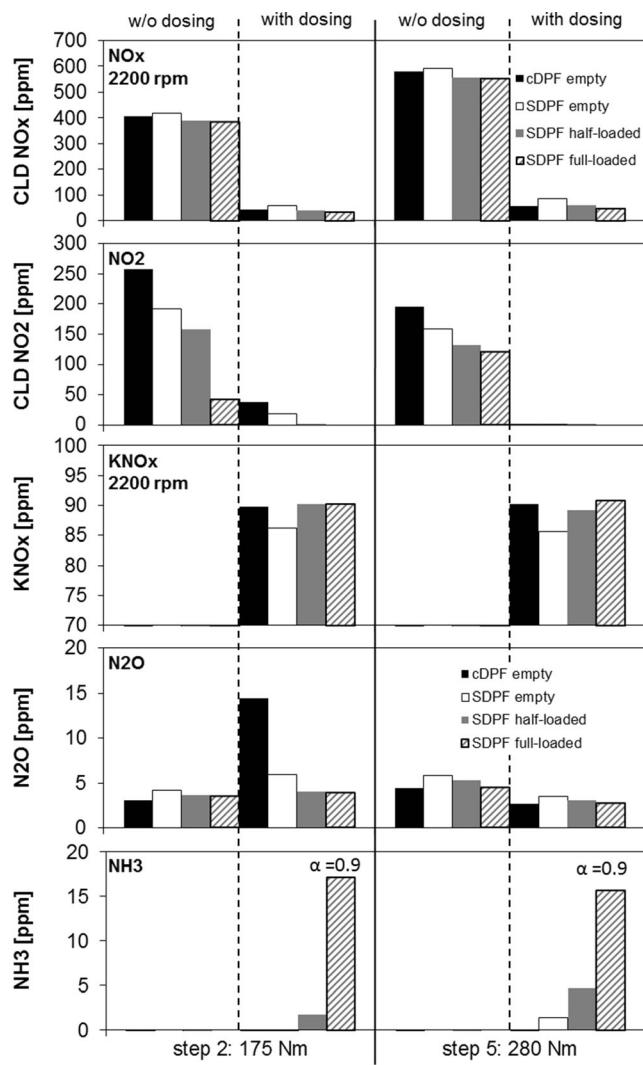


Fig. 14 Average emissions and K_{NO_x} values in steps 2 and 5; SYS01 and SYS03; filter not pre-loaded; with and w/o dosing $\alpha=0.9$

In another experiment, the SCR efficiency (K_{NO_x} , NO_x conversion, de NO_x efficiency, NO_x reduction rate) was tested with both systems SYS05 with SDPF and SYS01 with 2× SCR at three different engine loads such as 2200 rpm/87/175/280 Nm, with variation of feed factor α . It was confirmed in these tests that both investigated systems, SDPF and 2× SCR, attain similar values or de NO_x efficiency.

6.4 Dynamic Operation

After the preparation and testing of the dynamic AdBlue dosing, three WHTC and two ETC tests were performed with SDPF, SYS03, both without and with RAI.

Figure 15 represents the time plots of engine and emission parameters in a part of WHTC, in which a remarkable NH_3 peak occurred.

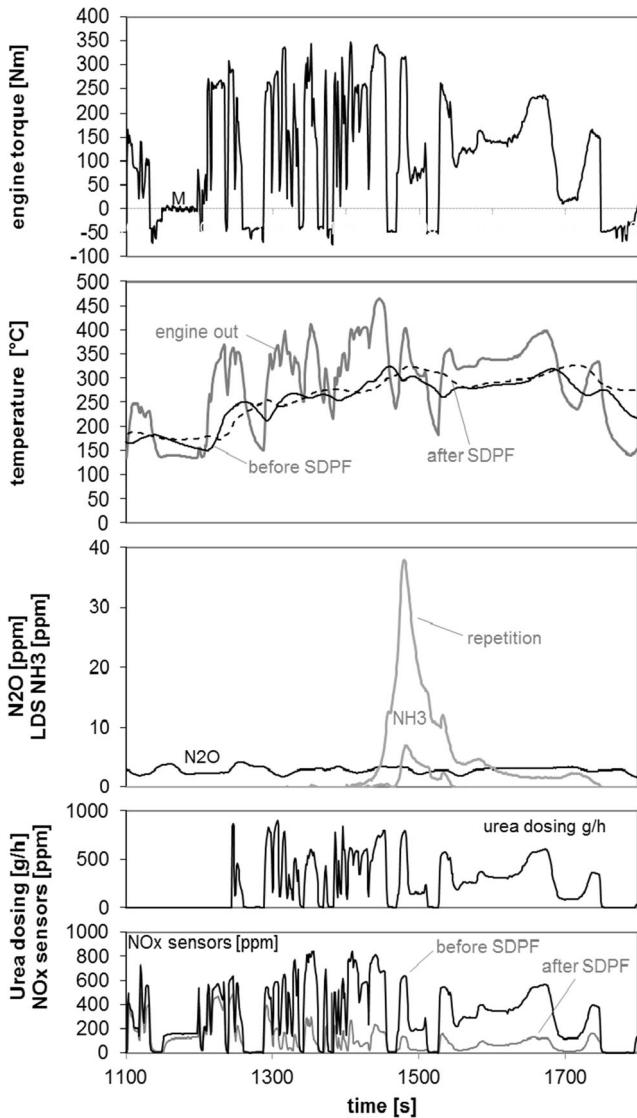


Fig. 15 NH_3 dispersion in two WHTCs with SDPF; SYS03; not-pre-loaded; with dosing, $\alpha=0.9$

The precedent operation was conditioning (COND) and $3 \times$ WHTC without urea dosing. Afterward, the two represented WHTC with urea dosing followed directly.

In the identical operation profiles of two WHTCs with RAI, there are different peak values of NH_3 . These confirm that NH_3 emissions depend not only on the operating conditions but also on the state of deposits, soot, nitric deposits, and especially ammonia storage, in the filter.

The average values of results from the performed dynamic driving cycles are represented in Fig. 16.

It can be pointed out that the WHTC with a lower level of exhaust gas temperature has lower K_{NO_x} values (40–45 % against 75 % in ETC). In ETC with a higher exhaust temperature level, higher NH_3 values can be observed.

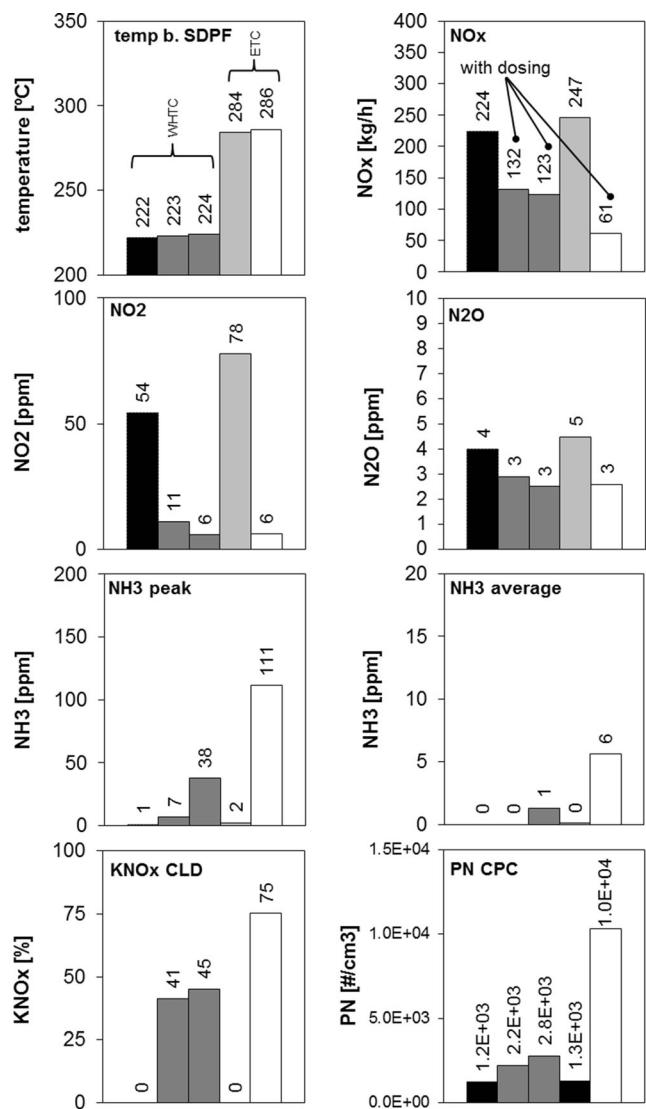


Fig. 16 Average emission and control parameters in dynamic cycles; SYS03; not-pre-loaded; with dosing, $\alpha=0.8$

7 Conclusions

Several observations and conclusions result from the presented work.

For emissions after SWON, the following can be stated:

- In both systems SCR and SDPF with RAI, there is a reduction of NO_x and NO_2 in the second step.
- With active urea dosing, there are peaks of N_2O and NH_3 , as well as a better oxidation of CO and HC in the second step, SDPF.
- The emission behavior of SDPF after urea SWON concerning NO_x reduction speed and NH_3 peak is always fluctuating.
- This fluctuation can be explained with the inhomogeneity of urea (and urea products) distribution and the varying initial state of filter in respect of soot loading and soot distribution in the filter volume.
- There is a tendency that the cases with quicker NO_x drop after SWON have also a lower NH_3 emission.

The presence of secondary nitric nanoparticles (NPs) with urea dosing is a known effect, but it has a negligible impact on the particle counts filtration efficiency (PCFE) of the entire system. With RAI upstream of SDPF, the level of secondary particle counts is 1 order of magnitude lower, than with RAI downstream of cDPF. Some specific points concerning NP can be remarked:

- The emissions of secondary NP counts CPC start to increase with SDPF from the instant of SWON even with a very low level.
- With more filter pre-loading, the NP counts increase later and bring down values in the steps-test.
- At high OP (with high t_{exh}), there are spontaneous condensates of sulfates, which lower the estimated value of PCFE.

The most important remarks concerning the de NO_x efficiency (NO_x conversion rate K_{NO_x}) are as follows:

- Operation without DOC upstream of SDPF (no NO_2 production) deteriorates the NO_x conversion, increases the NH_3 emissions, and reduces the portion of PM, which is oxidized in the SDPF.
- The loaded SDPF, compared with empty one, shows slower NO_x reduction and higher NH_3 after SWON due to the use of part of NO_2 for soot oxidation and consequently less NO_2 availability for the de NO_x reactions; the secondary NP penetration after SWON is clearly lower with the loaded trap.
- Both investigated systems, SDPF and 2× SCR, attain nearly the same de NO_x efficiency (K_{NO_x}).

- The highest K_{NO_x} values are to be obtained at stoichiometric urea dosing, but to minimize the NH_3 slip, it is recommended to avoid passing over feed factor of $\alpha=0.9$.

In dynamic operation in the WHTC with a lower level of exhaust gas temperature, lower K_{NO_x} values (40–45 % against 75 % in ETC) and also lower NH_3 emissions with SDPF are resulting.

Different NH_3 peaks (with RAI at WHTC) in the identical operation profiles indicate that NH_3 emissions depend not only on the operating conditions but also on the state of deposits in the filter.

The presented observations and results warrant further research in the future, specifically aimed at the following:

- Studying in more detail the interaction of urea/ NH_3 , NO_2 , and the accumulated soot
- Further analysis of reasons for fluctuating results after SWON
- Explaining of lower penetrations of secondary NP with active RAI and SDPF
- The ash and soot loading and the regeneration in different dynamic test cycles

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