Journal of KONES Powertrain and Transport, Vol. 15, No. 3 2008

COMBINED DPF+SCR SYSTEMS FOR RETROFITTING IN THE VERT QUALITY VERIFICATION TESTS.

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Abstract

New Diesel exhaust gas aftertreatment systems, with DPF$^{*)}$ *and deNO*$_x$ *(mostly SCR) inline application are very important step towards zero emission Diesel fleet.Solid quality standards of those quite complex systems are urgently necessary to enable decisions by several authorities.*

The Swiss Federal Office of the Environment BAFU and the Swiss Federal Roads Office ASTRA decided to support further activities of VERT to develop appropriate testing procedures and to define the quality criteria.

The present report informs about the international network project VERT $^{*)}$ *dePN (de-activation, de-contamination, disposal of particles & NO*$_x$*), which was started in Nov. 2006 with the objective to introduce the SCR-, or (DPF+SCR)-systems in the VERT verification procedure. Examples of results with some investigated systems are given. The most important statements are:*

- *the investigated combined aftertreatment systems (DPF+SCR) for dynamic engine application efficiently reduce the target emissions with deNO*$_x$*-efficiency up to 92% (if operated in the right temperature window) and filtration efficiency based on particle count up to 100%,*
- *the average NO*$_x$ *conversion rate at transient operation (ETC) depends strongly on the exhaust gas temperature profile and the resulting urea dosing control,*
- *the NP filtration efficiency, which is verified at stationary engine operation is perfectly valid also at the transient operation.*

The present results will be confirmed in the further project activities with other systems and with different testing cycles. A special attention will be paid to the operational profiles, which are representative for low emissions zones LEZ.

Keywords: *Diesel emission reduction, diesel particle filter, SCR, limited & unlimited emissions, deNO*$_x$

1. Introduction

The combination of particle filtration (DPF) and of the most efficient deNO$_x$ technology (SCR) is widely considered as the best solution, up to date, to minimize the emissions of Diesel engines. Intense developments are on the way by the OEM's and a lot of research is performed, [1-3].

The application of combined systems (DPF+SCR) as retrofits raises different technical and commercial problems. In general opinion, this retrofitting will be possible mostly through the incentives, or restrictions due to the low emission zones LEZ, [4] and decisions of several authorities.

2. Available Technical Information - Dpf+Scr

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 N_2 and H_2O.

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 NH_3, which is the real reduction substance.

A classical SCR deNO_x system consists of four catalytic parts:

- pre-catalyst converting NO to NO_2 (with the aim of 50/50 proportion)
- injection of AdBlue (with the intention of best distribution and evaporation in the exhaust gas flow),
- hydrolysis catalyst (production of NH_3),
- selective catalyst (several deNO_x reactions),
- oxidation catalyst (minimizing of NH_3 slip).

The main deNO_x-reactions between NH_3, NO and NO_2 are widely mentioned in the literature. They have different speeds according to the temperatures of gas and catalysts, space velocity and stoichiometry. This offers a complex situation during the transient engine operation.

Additionally to that there are temperature windows for catalysts and cut off 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 NH_3, nitrous oxide N_2O, isocyanic acid HNCO and ammonium nitrate NH_4 NO_3 (also known as secondary nanoparticles), [5-7].

VERTdePN

Research subjects and objectives

A general objective of VERTdePN is to include the combined systems DPF+SCR in the test procedure, which was previously developed for DPF only. Since the stationary testing of SCR for onroad application will be not sufficient any more, a simplified dynamic test procedure should be found, which nevertheless would be representative for the legal HD transient testing and for LEZ's.

For the VERT DPF quality procedure the research objectives were:

- filtration quality, durability, control - & auxiliary systems, secondary emissions.

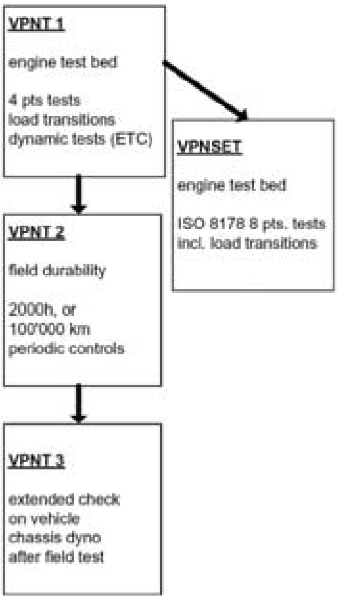

Fig. 1. VERTdePN test procedures for product standards of combined systems (DPF + SCR)

The new objectives for a SCR system in the VERTdePN tests are:

- NO_x reduction
- NO_2- and / or NH_3- slip
- temperature window
- dynamic operation
- field application & durability
- auxiliary systems
- further secondary emissions.

The main structure of VERTdePN tests for SCR is similar, as the preceding VERT activities for DPF, Fig. 1:

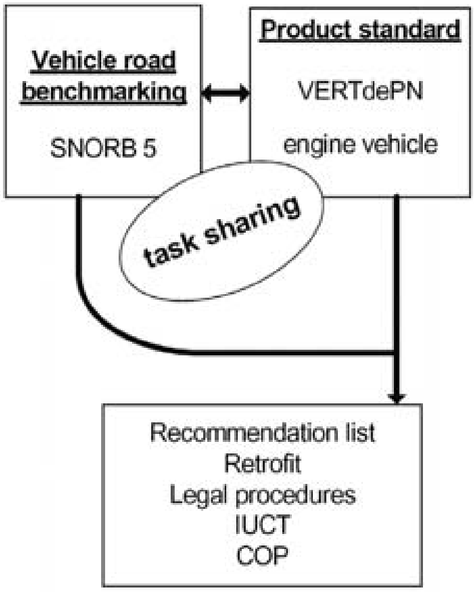

Fig. 2. VERTdePN test procedures for product standards and legal admission of combined systems (DPF + SCR)

Quality test and basic investigation on dynamic engine dynamometer on a representative HD-engine,

- Supervised field test 2000h,
- Analytics of unlimited- and secondary emissions.

Standards for retrofitted vehicles

Important questions on the applicability of the product standards from VERTdePN to classify the retrofitted vehicles (e.g. for LEZ's) were raised by the representatives of participating authorities. As a result of these discussions some possible procedures of testing and vehicle admission in Switzerland were proposed, see the chart in Fig. 2a complementary on road vehicle testing SNORB (Swiss NO_x Road Benchmarking) was proposed.

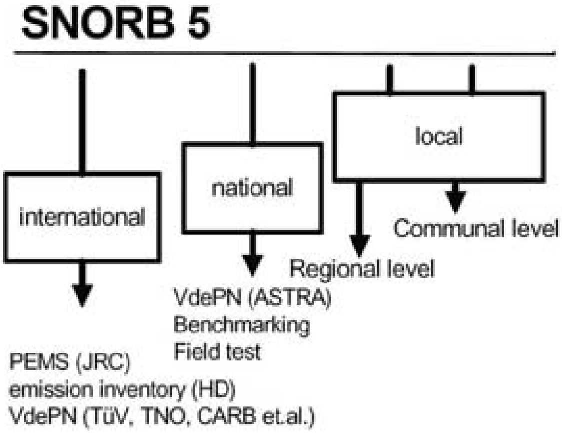

Fig. 3. Swiss NO_x Road Benchmarking EU 5 - validation of retrofitting on different political levels

It is important to point out, that the strict homologation procedures according to the EU-steps would, due to complexity and costs, eliminate the possibility of retrofitting.In the present state of discussions following main points can be remarked:

- retrofitting, as a quicker and more efficient measure to reduce consequently the air pollution, makes much sense for the society,
- if any authority wants to support retrofitting it has to do it among others by means of more flexible requirements and procedures; this flexibility can and should be adapted to the different levels of political decisions, Fig. 3,
- important elements of the test procedures are the extensive tests of the product on engine dynamometer connected with different kind of vehicle testing,
- there are three kinds of on road testing proposed:
- on road real world vehicle benchmarking and comparison with OE vehicles with similar technology (proposed project SNORB to be started during 2008),
- field test with intermediate and final control on the chassis dynamometer (VPNT2 & VPNT3),
- simplified acceptance test (vehicle stand still).

Further details of these procedures will be elaborated in the coming VdePN activities.

3. Test-Engine

Tab.1.Test Engine Specification

Manufacturer:	Iveco, Torino Italy	Combustion process:	direct injection
Type:	F1C Euro 3	Injection system:	Bosch Common Rail 1600 bar
Displacement	7.01 Liters	Supercharging:	turbocharger with intercooling
Rated RPM:	max. 4200 rpm	Emission control:	none
Rated power:	100 kW@3500rpm	Development period:	until 2000 (Euro 3)
Model:	4 cylinder in-line		

Fig. 4 shows the Iveco engine on a dynamic dynamometer in the laboratory for IC-engines, University of Applied Sciences, Biel-Bienne.

Fig. 4. IVECO engine F1C with the dynamic dynamometer

Measuring set-up and instrumentation

Fig. 5 represents the special systems installed on the engine, or in its periphery for analysis of the limited and unlimited emissions.

Test equipment for exhaust gas emissions

Measurement is performed according to the Swiss exhaust gas emissions regulation for heavy duty vehicles (Directive 2005 / 55 / ECE & ISO 8178:

Volatile components: Horiba exhaust gas measurement devices: CO_2, CO, HC_{IR}, O_2, CLD (hot), NO, NOx, FID HC_{FID}, NH_3 LDS 6 Laser Analyzer, N_2O infrared analyzer.

FTIR (Fourier Transform Infrared) Spectrometer (AVL SESAM) with possibility of simultaneous, time-resolved measurement of approx. 30 emission components - among others: NO, NO_2, NO_x, NH_3, N_2O, HCN, HNCO.

Particle size analysis

To estimate the filtration efficiency of the DPF, as well as to detect the possible production of secondary nanoparticles, the particle size and counts distributions were analysed with following apparatus, Fig. 4:

- SMPS - Scanning Mobility Particle Sizer, TSI (DMA TSI 3071, CPC TSI 3025 A),
- NanoMet - System consisting of:
- PAS - Photoelectric Aerosol Sensor (Eco Chem PAS 2000),
- DC - Diffusion Charging Sensor (Matter Eng. LQ1-DC),
- MD19 tunable minidiluter (Matter Eng. MD19-2E),
- Thermoconditioner (TC) (i.e. MD19 + postdilution sample heating until 300°C).

4. Test Procedures

According to the different objectives of the project several test procedures were used. After analyzing the backpressure of the system in the entire engine operation map it was decided to limit the operation range.

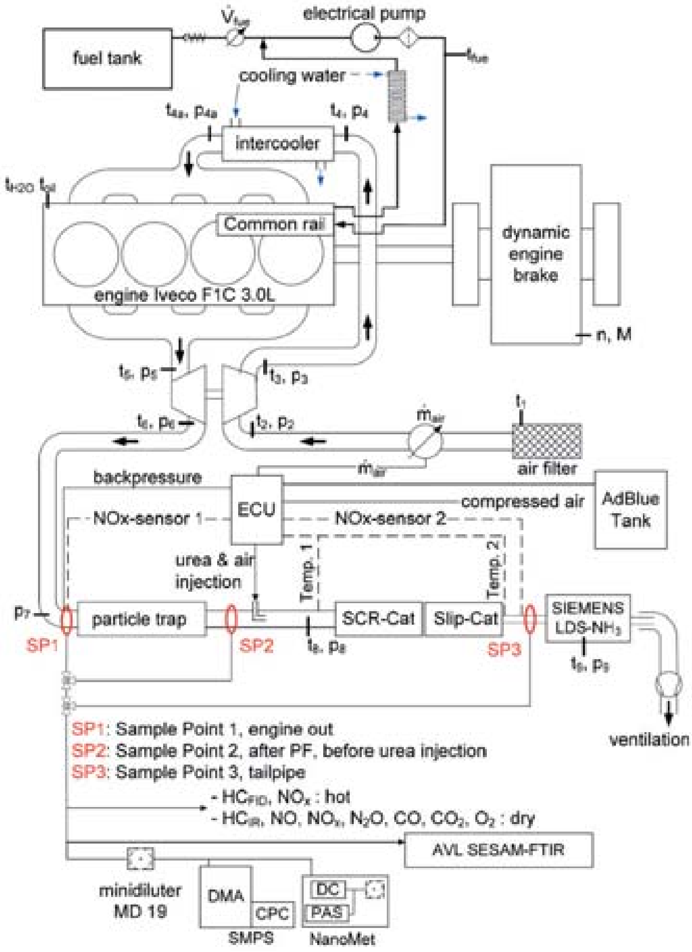

Fig. 5. Engine dynamometer and test equipment

Fig. 6 shows the limited engine map, the ISO 8178 8 points in this limited map and the 4 points test, which was fixed for VPNT1. 8 pts. tests were used for the secondary emission tests VPNSET with EMPA with different feed factors α.

For the tests concerning: filtration efficiency, deNO$_x$-rate, unlimited parameters, some basic studies about the investigated systems and about the test procedures 4 pts. tests were used according to VPNT1 (AFHB).

The four operating points were chosen in such way, that the switching „of" and „on" of the urea-dosing is included in the tests (pt. 7 → pt. 4 and pt. 4 → pt. 1).

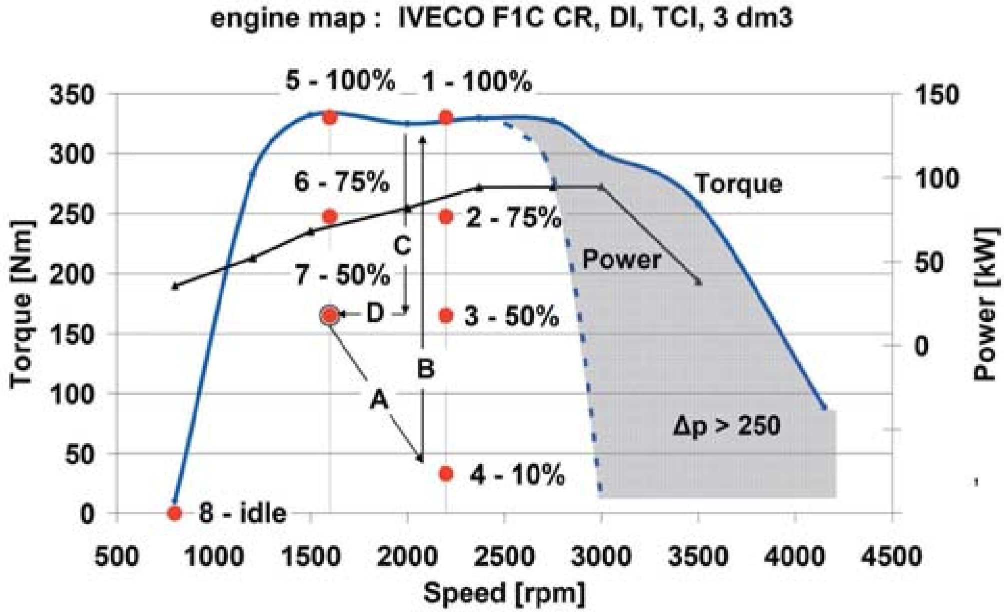

Fig. 6. 8pts. test (ISO 8178) in the limited engine map and setting of the VPNT1 4 pts. test

For a more detailed investigation of the tested system different sampling positions (SP) were used (Fig. 5):

SP 0 - sampling engine out w/o aftertreatment system,
SP 1 - sampling engine out with aftertreatment system,
SP 2 - sampling engine after DPF (before urea dosing) with aftertreatment system,
SP 3 - sampling engine at tailpipe with aftertreatment system.

This designation of sampling positions is used in the presented Figures and in the discussion of results. The dynamic testing was started with the ETC (European Transient Cycle), which was first defined on the basis of the limited engine operation map, Fig. 7.

The tests were driven after a warm-up phase. Before the start of each dynamic cycle the same procedure of conditioning was used to fix as well as possible the thermal conditions of the exhaust gas aftertreatment system. This conditioning was: 5 min pt. 1 and 0.5 min idling.

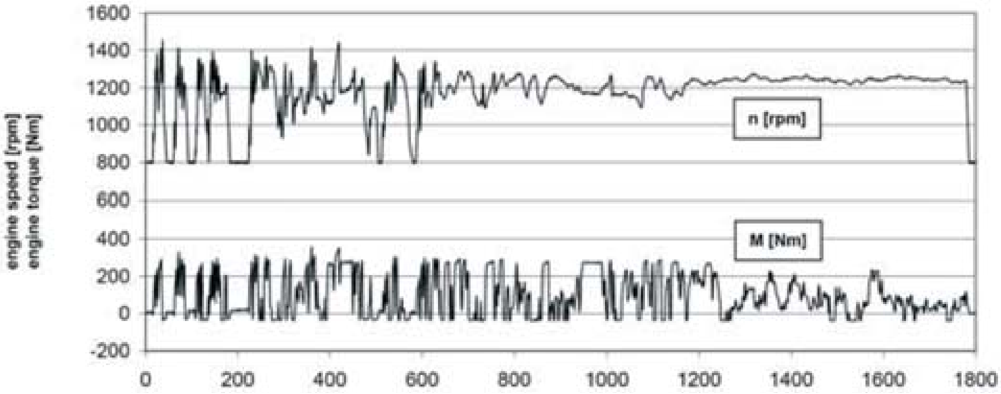

Fig. 7. ETC for the limited version of engine map, IVECO F1C

5. Results

The results are obtained with a combined system consisting of a coated DPF upstream, urea dosing and SCR catalyst downstream (as in Fig. 5). Sometimes an ammonia slip catalyst was used as a modulus at the end of the system. This (DPF+SCR) system is designed for transient application. It has an electronic control unit, which uses the signals of: air flow, NO_x before/after system and temperatures before/after SCR modulus.

Stationary engine operation

Fig. 8 shows the time-plots of NO_x and NH_3 in the 8 pts. test with different feed factors α. The increasing feed factor up to $\alpha = 1.2$ enables the deNO_x efficiency up to 98%, but with increased ammonia slip up to 125 ppm.

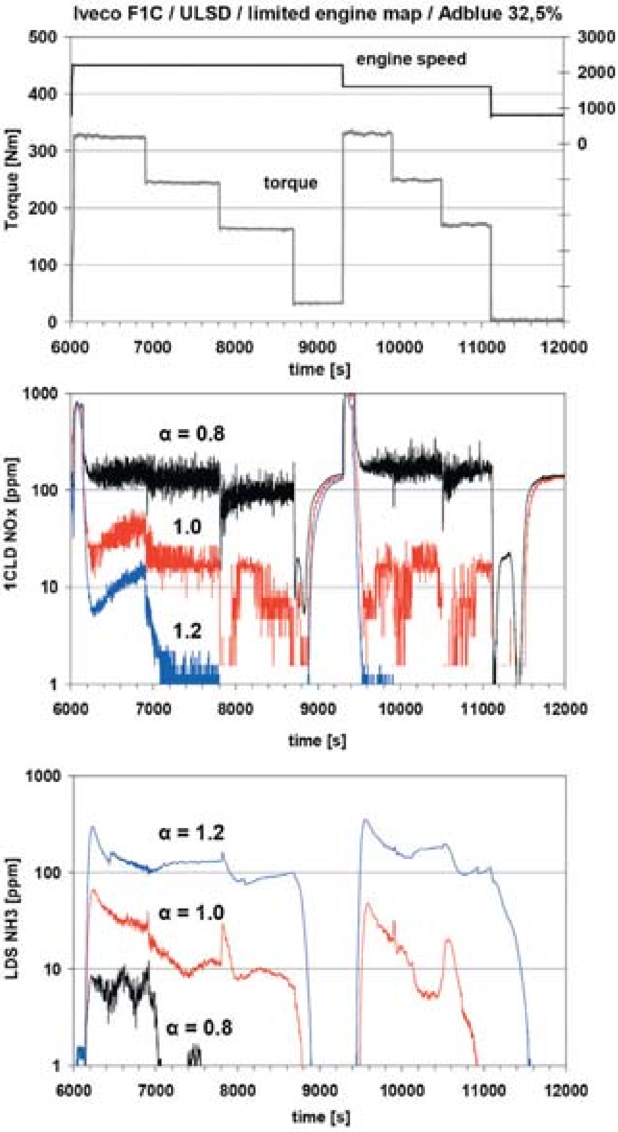

Fig. 8. Comparison of results at 8 points-test with different feed factors α

Fig. 9 shows the results obtained with FTIR at different sampling positions. This time there is a direct comparison between SP2 (after DPF, before urea dosing) and SP3 (after system).

As expected there is an efficient reduction of nitric emissions NO_x, NO & NO_2 by passing the SCR catalysts. Exception is at low load OP4 where there is no admission of reduction agent.

The production of NO_2 in the catalyzed DPF is demonstrated by the differences between SP0 and SP2. At OP4 the exhaust gas temperature is to low and no NO_2 is produced.

N_2O has the tendency to be increased partly in the DPF, partly in the SCR - nevertheless the quantities of it are negligible.

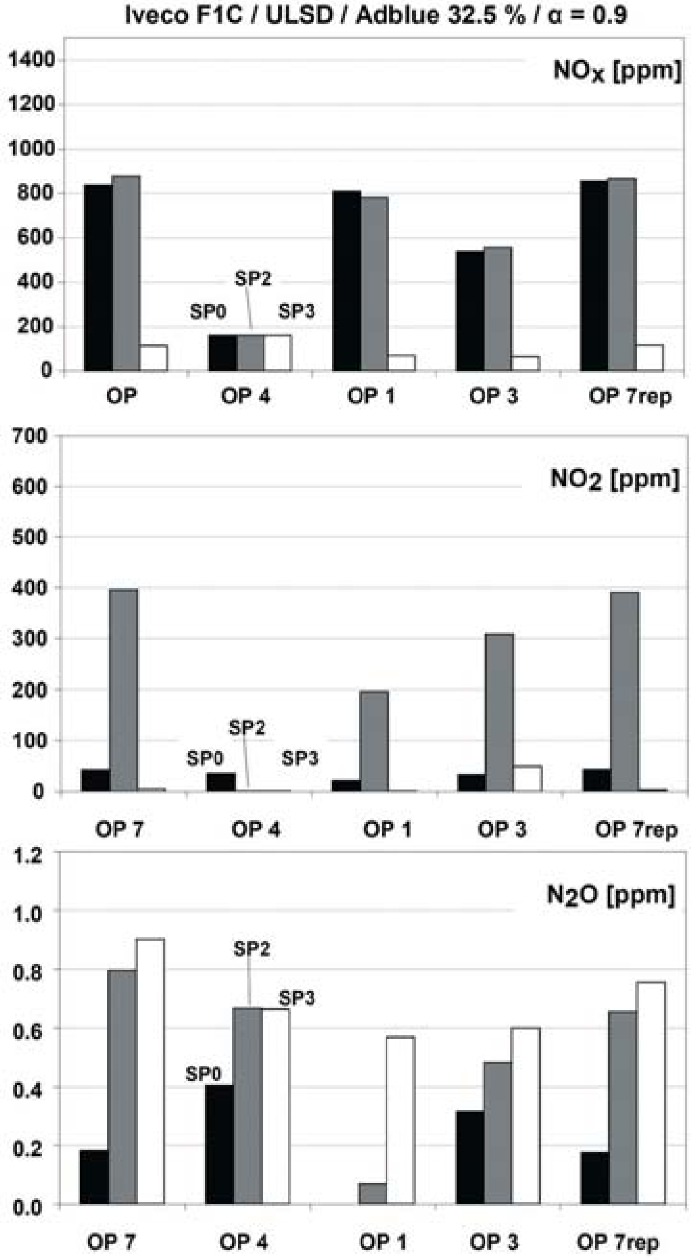

Fig. 9. FTIR results in 4 pts. test at different SP's

Measurements of nanoparticles NP in the 4 pts. test at different sampling positions are represented in Fig. 10. Particularly interesting is the look on the SP2 (after DPF, before urea dosing) and SP3 (after the system). There is some production of secondary nanoparticles due to the presence of urea and the other products of deNO$_x$-reactions. This is indicated by increased CPC- and DC-values between SP2 and SP3.

DC (diffusion charging sensor) measures the total particle surface independent of the chemical properties. It indicates the solids and the condensates.

PAS (photoelectric aerosol sensor) is sensitive to the surface of particulates and to the chemical properties of the surface. It indicates the solid carbonaceous particles. The PAS-values between SP2 and SP3 (Fig. 10) decrease, because there is less carbonaceous summary aerosol surface - the previously present carbonaceous particles are enveloped by other products (in liquid, or solid form) and the new particles have definitely no carbon.

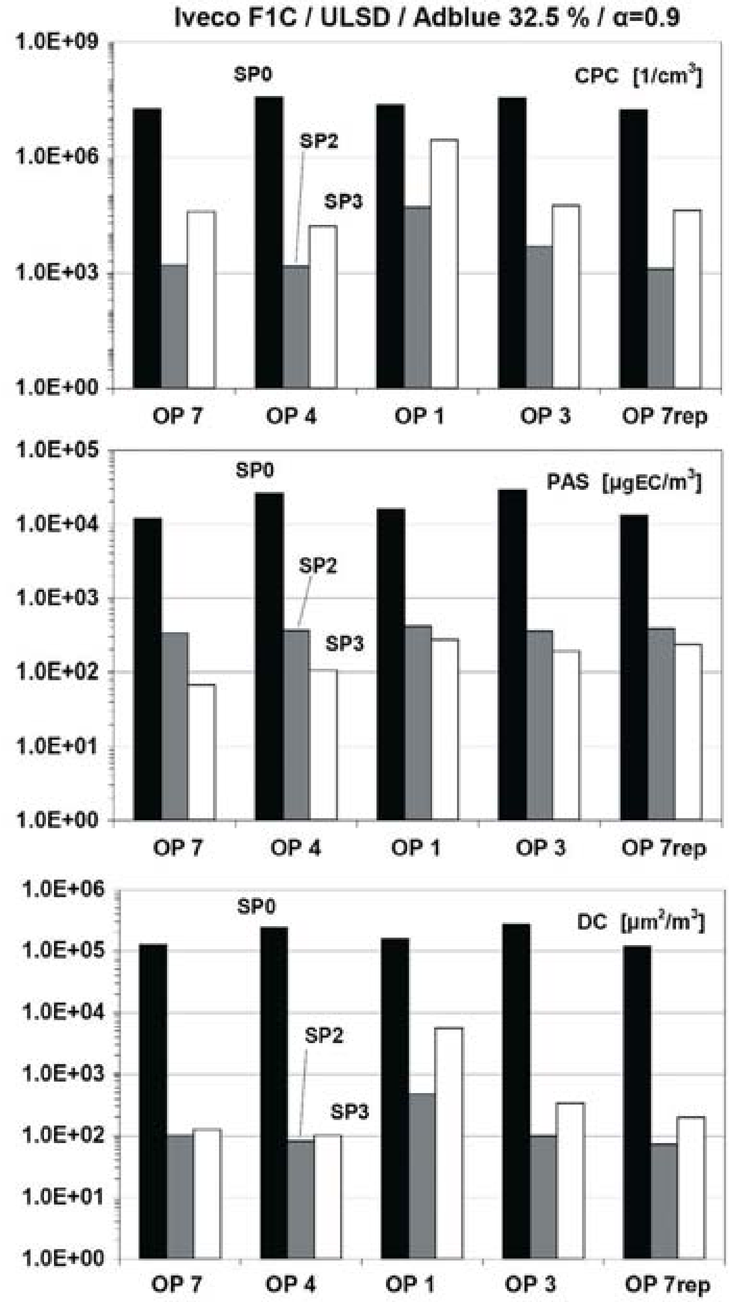

Fig. 10. Secondary nanoparticles at 4pts. test (w/o slip cat.)

As already known from the literature these new substances can be: urea, cyanuric acid and ammonium nitrate.

The increase of NP count concentration or of the summary surface of the aerosol (DC) in the SCR-part (SP2-SP3) is little in comparison with the reduction of NP in the DPF-part of the system (SP0-SP2). Therefore the secondary NP-production does not impact the overall filtration efficiency of the system (see logarithmic scale of the ordinate). Exception is the operating point OP1 with the highest space velocity and intense secondary NP production.

Load transitions

The emissions over the time in all transitions A,B,C & D of the 4 pts. test (Fig. 6) were registered.

Fig. 11 shows as example the transition B with load increase from 10% to 100% at 2200 rpm and with urea switching on. The NO_2 measured before the system (SP1) declines at the high operation point because of thermal decomposition ($t_{exh.gas} = t_7$, Tab. 4). Measured after the system (SP3) quite long response times, in the range of 1.5 min, are visible. In this time the exhaust temperature increases and the urea dosing starts.

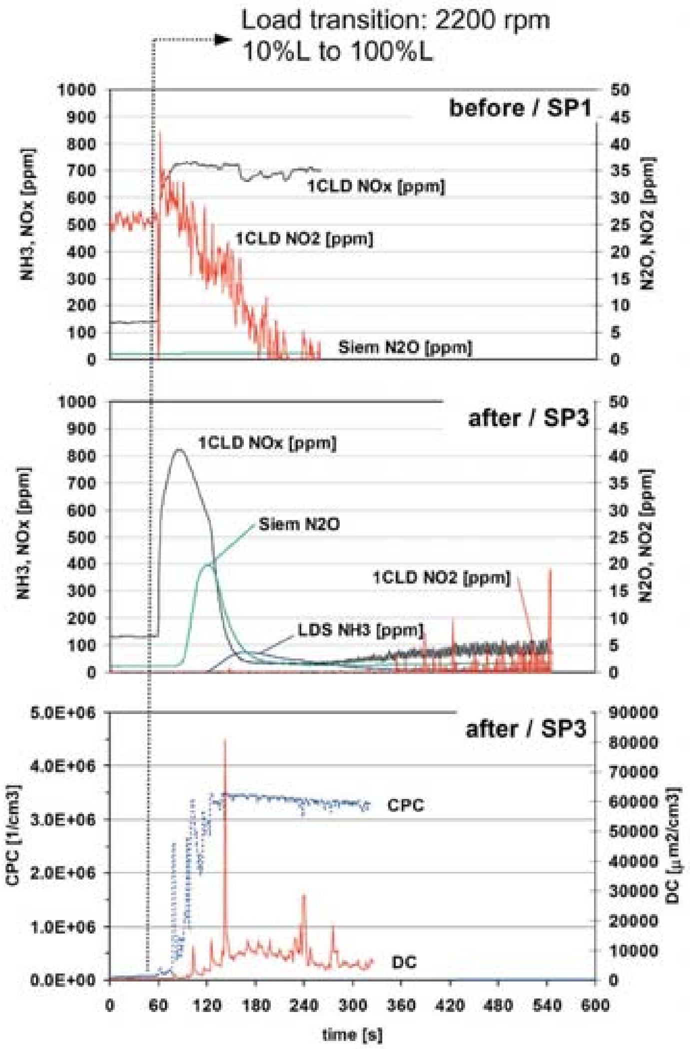

Fig. 11. Load transition B: from 2200 rpm /10%L to 2200 rpm/100%L with measurements before and after DPF + SCR

According to the conditions of flow, spacial velocity, temperature and stoichiometry (α) different reactions are running in the SCR parts.

The increase of nanoparticles concentrations is indicated clearly by CPC & DC.

Load transitions between two stationary engine conditions are the best tool of research of the instationary changes in the combined system. Nevertheless for some specific purposes longer operation times at the final stationary state can be recommended. By extreme load changes (from 0% to 100%) the time necessary for thermal and chemical stabilization of the system can be in the range of 20 min.

Dynamic engine operation

These tests were performed in the ETC with limited engine map.

Following results will be shown:

- ETC1 with DPF+SCR+slip cat,
- ETC3 with DPF+SCR without slip cat,
- ETC4 reference (w/o DPF+SCR).

Before starting each test the thermal condition of the exhaust system was fixed by a repetitive conditioning (see chap. Test Procedures).

Fig. 12 represents the comparison of two ETC's with and without slip catalyst. During the test the exhaust gas temperature at tailpipe decreases and in the second half of the test there is an increase of NO_x due to urea cut off.

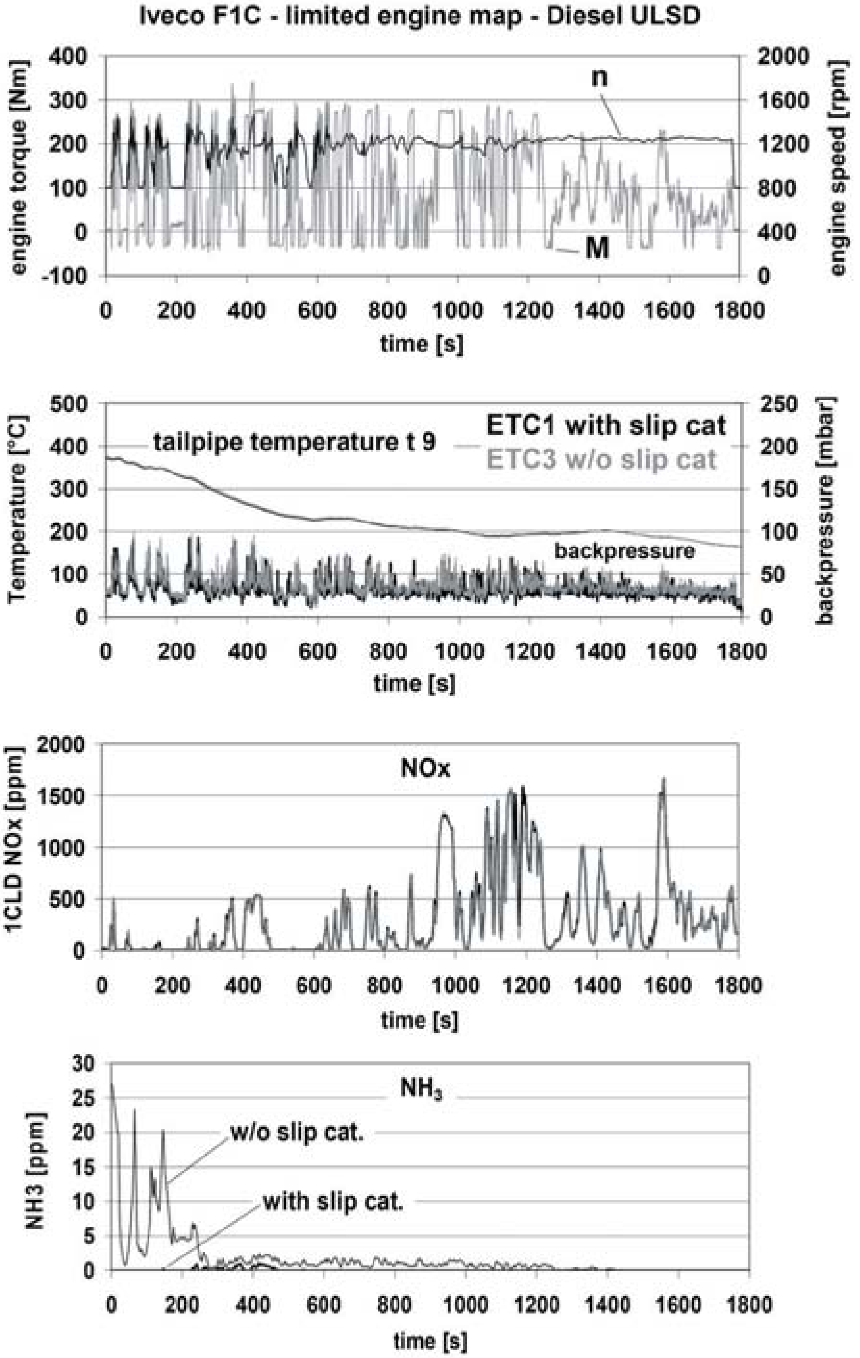

Fig. 12. Comparison of 2 ETC's (ETC1-ETC3), with & w/o slip catalyst α = 0.9

The ammonia slip catalyst eliminates efficiently NH_3 in the first phase of the test (until approx. 200 s). The second part of the test depicts the decreasing NO_x reduction efficiency caused by the cooling down the exhaust system during the test and the respective urea shortage.

The results of target emission were integrated in different periods of the test:

- initial period 0-400 s,
- final period 1400-1800 s,
- total test duration.

With the obtained integral average emission values the reduction rates were estimated. They are summarized in Tab. 1.

The NO_x- and NO_2-conversion rates decrease in course of the test, as previously demonstrated.

For the filtration part there is very good filtration efficiency in spite of the secondary NP-production in all periods of the ETC.

Tab. 1. *Reduction efficiencies of NO_x, NO_2 & NP in different parts of the ETC*

$RE_X = \frac{X_{w/o} - X_w}{X_{w/o}} \cdot 100$	**RE [%]**		
	0-400s	1400-1800 s	0-1800 s
NO_x [ppm]	92	23	59
NO_2 [ppm]	92	13	26
CPC [$1/cm^3$]	99	100	100
PAS [$\mu gEC/m^3$]	99	99	99
DC [$\mu m^2/cm^3$]	99	100	99

6. Conclusions

The most important results about the investigated combined DPF+SCR system for transient application can be summarized as follows:

- the investigated combined aftertreatment systems (DPF+SCR) for dynamic engine application reduce efficiently the target emissions with deNO$_x$-efficiency up to 92% (if operated in the right temperature window) and particle count filtration efficiency up to 100%,
- the ammonia slip can be efficiently eliminated by the slip-cat,
- during the transients there are temporary increases of the undesired emission components due to momentary imbalance of the reactions,
- in the investigated configuration - urea dosing after DPF - secondary nanoparticles are detectable; they have little count concentrations and no critical impact on the overall filtration efficiency of the system,
- the average NO_x conversion rate at transient operation (ETC) depends strongly on the exhaust gas temperature profile and the resulting urea dosing control,
- the NP filtration efficiency, which is verified at stationary engine operation is perfectly valid also at the transient operation.

The present results will be confirmed in the further project activities with other systems and with different testing cycles. A special attention will be paid to the operational profiles, which are representative for low emissions zones LEZ.

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Abbreviation

AEEDA	Association Europeenne d'Experts en Dépollution des Automobiles
AFHB	Abgasprüfstelle FH Biel, CH
AKPF	Arbeitskreis der Partikelfilterhersteller Air min stoichiometric air requirement
ASTRA	Amt für Strassen, CH, Swiss Road Authority
BAFU	Bundesamt für Umwelt, CH (Swiss EPA)
CLD	chemoluminescence detector
COP	conformity of production
CPC	condensation particle counter
DC	Diffusion Charging Sensor
dePN	de Particles + deNO_x
DMA	differential mobility analyzer
DPF	Diesel Particle Filter
ETC	European Transient Cycle
FE	filtration efficiency
FID	flame ionization detector
FTIR	Fourrier Transform Infrared Spectrometer
IUCT	in use compliance test
LDS	Laser Diode Spectrometer (for NH_3)
LEZ	low emission zones
MD19	heated minidiluter
NanoMet	NanoMetnanoparticle summary surface analyser (PAS + DC + MD19)
PAS + DC	sampling & dilution unit
OP	operating point
PAS	Photoelectric Aerosol Sensor
RE	reduction efficiency
SCR	selective catalytic reduction
SMPS	Scanning Mobility Particle Sizer
SNORB	Swiss NO Retrofit Benchmark
SP	sampling position
VERT	Verminderung der Emissionen von Realmaschinen in Tunelbau
VERTdePN	VERT DPF + VERT deNO_x
VPNT1	VERTdePN Test 1 - engine dyno
VPNT2	VERTdePN Test 2 - field durability 2000h
VPNT3	VERTdePN Test 3 - check after field test chassis dyno
VPNTSET	VERTdePN secondary emissions test - engine dyno
VSET	VERT Secondary Emissions Test