ABSTRACT

New Diesel exhaust gas aftertreatment systems, with combined DPF and deNO\(_x\) (mostly SCR) systems represent a very important step towards zero emission Diesel fleet. These combined systems are declared today by the OEM’s as an ultimate solution and are already offered by several suppliers for retrofitting.

Reliable quality standards for those quite complex systems are urgently needed to enable decisions of several authorities.

The Swiss Federal Office of 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 for dePN systems.

The present report informs about the international network project VERT dePN (de-activation, de-contamination, disposal of particles and NO\(_x\)), which was started in Nov. 2006 with the objective to introduce the SCR-, or combined DPF+SCR-systems in the VERT verification procedure.

Examples of results for some of the investigated systems are given. These investigations included parameters, which are important for the VERT quality testing: besides the regulated gaseous emissions several unregulated components such as NH\(_3\), NO\(_2\) and N\(_2\)O were measured. The analysis of nanoparticle emissions was performed with SMPS and NanoMet.

The findings from the tested systems can be summarized as follows:

- the investigated combined dePN systems (DPF+SCR) for dynamic engine application efficiently reduce the target emissions with deNO\(_x\)-efficiencies up to 92\% (if operated in the right temperature window) and particle number filtration efficiency up to 100\%,
- the ammonia slip can be efficiently eliminated by the slip-cat,
during the transient tests there are temporarily increased emission of NO and NH$_3$
due to momentary imbalance of the deNOx stoichiometry,
in the configuration with urea dosing after DPF, a secondary formation of
nanoparticles is detectable with a moderate increase of number concentrations but
no critical impact on the overall filtration efficiency of the system,
the average NO$_x$ conversion rate at transient operation (ETC) strongly depends on
the exhaust gas temperature profile and the resulting urea dosing control,
The particle number 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.

1. INTRODUCTION

Laboratories for IC-Engines and Exhaust Emission Control of the University of
Applied Sciences Biel, Switzerland (AFHB) participate since 1992 at the Swiss
activities about nanoparticle analytics and DPF verification.

The upcoming developments of deNOx (especially SCR) systems and the
combinations with DPF’s offer a large amount of variants and technical complexity,
which represent new challenges not only for the manufacturers, but also for the users
and for the responsible authorities.

In the VERTdePN project AFHB collaborates closely with several Swiss specialists of
chemistry, catalysis, measuring technics and combisystems (EMPA, PSI, SUVA, ME,
UMTEC), as well as European specialist from JRC Ispra, I ; TNO & VROM, NL;
AEEDA, B ; FAD and TÜV D ; AKPF, A.

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

The present paper shows the testing procedures of VERTdePN at the current
development stage and some examples of results from two very advanced combined
retrofitting systems.

2. AVAILABLE TECHNICAL INFORMATION

DPF+SCR

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, [2-16].
The removal of NOx from lean exhaust gas of Diesel engines (also lean-burn gasoline engines) is a challenge. Selective catalytic reduction (SCR) uses a supplementary substance, a reducing agent, which in presence of catalysts produces useful reactions transforming NOx in N2 and H2O.

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

A classical SCR deNOx system consists of four catalytic parts:

- precatalyst converting NO to NO2 (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 NH3)
- selective reduction catalyst (several deNOx reactions)
- oxidation catalyst (minimizing of NH3 slip).

The main deNOx-reactions between NH3, NO and NO2 are widely mentioned in the literature. They have different rates depending on the nature of the catalyst, the exhaust temperature, space velocity and stoichiometry of the reducing agent. This offers a complex situation during transient engine operation.

Additionally to that there exists an optimal temperature window for each catalyst and cut off temperature for the AdBlue-injection to prevent the deposits on the catalyst.

Several side reactions can occur forming secondary pollutants. An objective is to minimize the tail pipe emissions of: ammonia NH3, nitrous oxide N2O, isocyanic acid HNCO and ammonium nitrate NH4NO3 and other secondary nanoparticles, [17-22].

**VERT quality testing**

VERT was in the 1990's a joint project of occupational insurance agencies from Switzerland (SUVA), from Austria (AUVA) and from Germany (TBG) concerning the reduction of emissions of actual machines in tunnel construction, [23, 24, 25].

It was recognized quickly in the VERT project, that the retrofitting with DPF is the most efficient measure to eliminate radically the particle emissions of Diesel engines in underground. To introduce the DPF-systems for retrofitting it was necessary to establish: the quality criteria and quality test procedure, field control and appropriate support to the users.

One of the most important statements of VERT is, that the validation of filtration efficiency of a DPF by means of particle mass PM (legal parameter up to date) is not sufficient and sometimes misleading. In several cases, particularly with the presence of some catalytic substances in the DPF, sulfates can be produced (only the sulfur from lube oil can be sufficient for that), which pass the DPF as vapor and condensate afterwards on the PM-measuring filter. In an extreme case this can cause, that the DPF, which filters perfectly the solid particles (NP, EC e.g. 98%) seems to double or triple the particle mass (PM).
The filtration efficiency of a DPF can be properly judged only for the solid particles. In this context the nanoparticles are considered in VERT as the most important criterion, [26, 27]. Complementary information is given by a coulometric analysis of elemental carbon (EC) from the collected PM filter residuum.

The nanoparticulates can be measured with different methods and due to the aptitude of penetrating very easily into the living organisms they are regarded as very dangerous for health, [28, 29, 30].

Since 2001 there are discussions in the international legislative gremia about possibilities of introducing the NPs as a legally limited parameter, as recommended by the Particulate Measurement Program (PMP) of the UN Working Party on Pollution and Energy (GRPE), [31, 32, 33].

For some systems, which use catalytic coatings, or fuel additives, or combinations of both of them, a VERT secondary emission test (VSET) has to be performed.

For retrofitting with combined systems (DPF+SCR) quality testing and fulfilment of certain criteria are necessary both: for the user and for the authority.

The Swiss VERT Network started the works to include the deNO\textsubscript{x}-systems (SCR, EGR, storage catalysts) in the VERT verification procedures (VERT dePN Programm).

3. VERTdePN

Research subjects and objectives

A general objective of VERTdePN is to include the combined DPF+SCR systems in the test procedures, which were previously developed for DPF applications 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.

Different variants of catalyst and/or their sequences used for different types of SCR systems, different sequences of DPF and SCR, different possibilities of introduction, homogenization and control of urea and finally different applications offer a large multitude of cases, which will be considered during the tests.

For the VERT DPF quality procedure the research objectives were:

- filtration quality
- durability
- control - & auxiliary systems
- secondary emissions.
The new objectives for a SCR system in the VERTdePN tests are:

- NOx reduction efficiency
- NO2- and / or NH3- slip
- Operating temperature window
- Dynamic operation
- Field application & durability
- Auxiliary systems
- Further secondary emissions.

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

- Quality test and basic investigation on dynamic engine dynamometer on a representative HD-engine,
- Supervised field test 2000h,
- Analyses of toxic and harmful secondary emissions.

When the DPF of the combined system is already approved by VERT, only simplified tests for the SCR-part will be necessary.

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

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

Important questions about: how to use the product standards from VERTdePN to classify the retrofitted vehicles (e.g. for LEZ’s) were raised by the representatives of participating authorities.

The steering committee worked further in several meetings on these problems and elaborated some possible procedures of testing and vehicle admission in Switzerland, see the chart in Fig. 2. A complementary on road vehicle testing SNORB (Swiss NOx Road Benchmarking) was proposed.

It is important to point out, that the expression “vehicle homologation” was replaced by “vehicle benchmarking”, since a strict homologation procedure according to the EU-steps would, due to complexity and costs, eliminate the possibility of retrofitting in-use diesel engines with combined deNOx-DPF systems.

In the present state of discussions the 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,
- VERT procedures offered the quality standards, guidelines and choice of systems for DPF-retrofitting,
- VERTdePN proposes the solutions for DPF+SCR retrofitting,
- important elements of the test procedures are the extensive tests of the product on an 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 VERTdePN activities.

- 6 -
4. TEST-ENGINE, FUEL AND LUBRICANT

Test engine

<table>
<thead>
<tr>
<th>Manufacturer:</th>
<th>Iveco, Torino Italy</th>
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<tbody>
<tr>
<td>Type:</td>
<td>F1C Euro 3</td>
</tr>
<tr>
<td>Displacement:</td>
<td>7.01 Liters</td>
</tr>
<tr>
<td>Rated RPM:</td>
<td>max. 4200 rpm</td>
</tr>
<tr>
<td>Rated power:</td>
<td>100 kW@3500rpm</td>
</tr>
<tr>
<td>Model:</td>
<td>4 cylinder in-line</td>
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</table>

<table>
<thead>
<tr>
<th>Combustion process:</th>
<th>direct injection</th>
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</thead>
<tbody>
<tr>
<td>Injection system:</td>
<td>Bosch Common Rail 1600 bar</td>
</tr>
<tr>
<td>Supercharging:</td>
<td>turbocharger with intercooling</td>
</tr>
<tr>
<td>Emission control:</td>
<td>none</td>
</tr>
<tr>
<td>Development period:</td>
<td>until 2000 (Euro 3)</td>
</tr>
</tbody>
</table>

Fig. 1 shows the engine and the apparatus for nanoparticle analytics SMPS & NanoMet in the laboratory for IC-engines, University of Applied Sciences, Biel-Bienne.

Fuel

Following fuel was used for the research:

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

Lubricant

For all tests a special lubeoil 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
Table 1 represents the most important data of this fuel according to the standards.

<table>
<thead>
<tr>
<th>Property</th>
<th>Diesel</th>
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</thead>
<tbody>
<tr>
<td>Density at 15°C</td>
<td>g/m 0.842*</td>
</tr>
<tr>
<td>Viscosity at 40°C</td>
<td>mm²/s 2.0 - 4.5</td>
</tr>
<tr>
<td>Flash point</td>
<td>above 55°C</td>
</tr>
<tr>
<td>Cloud point</td>
<td>max -10°C</td>
</tr>
<tr>
<td>Filterability CFPP</td>
<td>max -20°C</td>
</tr>
<tr>
<td>Ash %</td>
<td>max 0.010</td>
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<tr>
<td>Sulfur ppm</td>
<td>&lt;10</td>
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<tr>
<td>Cetane Number</td>
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</tr>
<tr>
<td>Calorific value</td>
<td>MJ/kg 42.7</td>
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<tr>
<td>C fraction</td>
<td>in % 86.7</td>
</tr>
<tr>
<td>H fraction</td>
<td>in % 13.3</td>
</tr>
<tr>
<td>O fraction</td>
<td>in % 0</td>
</tr>
<tr>
<td>Air / Fuelstoich</td>
<td>kg/kg 14.52</td>
</tr>
<tr>
<td>Boiling range 10-90% °C</td>
<td>180 - 340</td>
</tr>
</tbody>
</table>

Table 2: Data of the applied lubrication oil (EN)

<table>
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<th>Property</th>
<th>Mobil</th>
</tr>
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<tbody>
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<td>Viscosity kin 40°C</td>
<td>72.8 mm²/s</td>
</tr>
<tr>
<td>Viscosity kin 100°C</td>
<td>12.1 mm²/s</td>
</tr>
<tr>
<td>Viscosity index</td>
<td>164 (-- )</td>
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<tr>
<td>Density 15°C</td>
<td>0.850 kg/m³</td>
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<tr>
<td>Pourpoint</td>
<td>-45 °C</td>
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<tr>
<td>Flamepoint</td>
<td>254 °C</td>
</tr>
<tr>
<td>Total Base Number TBN</td>
<td>14.2 mg KOH/g</td>
</tr>
<tr>
<td>Sulfur ashes</td>
<td>6000 mg/kg</td>
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<tr>
<td>Sulfur</td>
<td>7280 mg/kg</td>
</tr>
<tr>
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<tr>
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</tr>
<tr>
<td>Ca</td>
<td>4760 mg/kg</td>
</tr>
<tr>
<td>P</td>
<td>1370 mg/kg</td>
</tr>
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5. MEASURING SET-UP AND INSTRUMENTATION

Engine dynamometer and standard test equipment

Fig. 5 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 with force transducer HBM T10F
- 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

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):
Fig. 5: Engine dynamometer and test equipment

- Volatile components:
  - Horiba exhaust gas measurement devices
    Type: VIA-510 for CO₂, CO, HCIR, O₂.
    Type: CLA-510 for NO, NOₓ (this standard hot analyser with one reactor is marked in this report as “1 CLD”).
  - Amluk exhaust gas measurement device Type: FID 2010 for HC_FID.
• 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 (this analyzer with two reactors is marked in this report as “2 CLD”)

• FTIR (Fourier Transform Infrared) Spectrometer (AVL SESAM) with the possibility of simultaneous, time-resolved measurement of approx. 30 emission components – among those validated are: NO, NO₂, NOₓ, NH₃, N₂O.

**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 number distributions were analysed with following apparatus, **Fig. 4b**:

• 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).

The nanoparticle results represented in this paper are obtained with sampling at tail pipe with MD19 and with thermoconditioner (300°C).

The nanoparticulate measurements were performed at constant engine speed (warm) with SMPS and NanoMet. During the dynamic engine operation NanoMet and CPC were used.

**6. 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. 6** shows the limited engine map, the 8-point ISO 8178 cycle in this limited map and the 4-point test, used for VPNT1.
Fig. 6: 8pts. test (ISO 8178) in the limited engine map and setting of the VPNT1
4 pts. test

The 8-points cycle was also used for the secondary emission test VPNSET developed at EMPA. These tests were performed in the present work with three different feed factors $\alpha$.

For the tests concerning: filtration efficiency, deNO$_x$-rate, unregulated parameters, some basic studies on the investigated systems were performed in the 4-points test according to VPNT1 (AFHB).

These operating points are (in the following sequence):
- operating point 7: 50% load, intermediate speed 1, 1600 rpm / 50%,
- operating point 4: 10% load, intermediate speed 2, 2200 rpm / 10%,
- operating point 1: 100% load, intermediate speed 2, 2200 rpm / 100%,
- operating point 3: 50% load, intermediate speed 2, 2200 rpm / 50%,
- operating point 7: repetition.

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

For a more detailed investigation of the tested system different sampling positions (SP) were used (see 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 European Transient Cycle ETC, which was first defined on the basis of the limited engine operation map, Fig. 7.

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

The tests were driven after a warm-up phase, when the engine coolant temperature and lube oil temperature reached their stationary values (stationary points tests). Before the start of each dynamic cycle the same procedure of conditioning was used to stabilize the thermal conditions of the exhaust gas aftertreatment system. This conditioning was: 5 min at point 1 and 0.5 min of idling.

### 7. RESULTS

The results were obtained from a combined system consisting of a coated DPF upstream the urea dosing and a 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\textsubscript{x} before/after system and temperatures before/after SCR modulus.

#### Stationary engine operation

**Fig. 8** shows the time-plots of NO\textsubscript{x} and NH\textsubscript{3} in the 8-points test with different urea feed factors $\alpha$. Increasing the feed factor up to $\alpha = 1.2$ enables a deNO\textsubscript{x} efficiency up to 98%, but also increases the ammonia slip up to 125 ppm. **Table 3** illustrates this at one operating point (2200 rpm / 100%). At low load operation (OP 4 & OP 8) there is no urea feeding and consequently no NO\textsubscript{x}-reduction.

**Table 3:** NO\textsubscript{x} reduction efficiency RE & NH\textsubscript{3} depending on feed factor $\alpha$, (pt. 1 of the 8 pts. test).
Fig. 9 represents emissions at different sampling positions SP in the 4-points test with $\alpha = 0.9$. There are some differences between CO and HCs at SP0 (without aftertreatment system) and SP1 (before aftertreatment system) caused by a slightly higher backpressure with the installed system.

Due to the use of a catalytic DPF there is an efficient oxidation of CO and HCs between SP1 and SP3, except for the low load operation OP4. The verification of conversion rates for CO, HC and NOx as shown in Fig. 10, does not show any significant differences, when refering to engine-out emissions with or without aftertreatment system. The maximum stationary ammonia slip at OP1 is 15 ppm.
Fig. 11 shows the results obtained with FTIR at different sampling positions. Comparing engine-out emissions with those of SP2 (after DPF, before urea dosing) and SP3 (after system).

As expected there is an efficient reduction of nitrogen oxide emissions NO\textsubscript{x}, including NO and NO\textsubscript{2} over the SCR catalysts. Exception is at the low load OP4 with no admission of reducing agent.

The production of NO\textsubscript{2} in the catalytic DPF is demonstrated by the emission differences between SP0 and SP2 (Fig. 11). At OP4 the exhaust gas temperature is too low and consequently no NO\textsubscript{2} is produced.

N\textsubscript{2}O has the tendency to be partially increased in the DPF and in the SCR, nevertheless, the released quantities are small (<1ppm).

Measurements of nanoparticles NP in the 4-points test at different sampling positions are represented in Fig. 12. Particularly interesting is the look on the SP2 (after DPF, before urea dosing) and SP3 (after the combined dePN system). There is some production of secondary nanoparticles due to the presence of urea and of other reaction products of deNO\textsubscript{x}-chemistry. This is indicated by increased CPC- and DC-values between SP2 and SP3.

The PAS (photoelectric aerosol sensor) is sensitive to the surface of particulates and to the chemical properties of the surface. It indicates solid carbonaceous particles. The PAS-signals decrease between SP2 and SP3 (Fig. 12), indicating that some of the PAS-active particle surface must be chemically changed in the deNO\textsubscript{x} system.

The DC (diffusion charging sensor) measures the total particle surface independent of the chemical properties of the particles. It indicates both solid particles and condensates.
As known from the literature, secondary pollutants such as cyanuric acid, ammonium nitrate and others can form during the deNOx process. In addition, unreacted urea can also be released. The chemical composition of these secondary aerosols will be studied in further phases of the project.

The increase of NP number concentration (CPC) or of the total surface of the aerosol (DC) over the SCR-system (SP2-SP3) is small compared with the reduction of NP in the DPF (SP0-SP2). Therefore, the secondary formation of nanoparticles does not impact the overall filtration efficiency of the system (notice the logarithmic scale in Fig. 12). Exception is the operating point OP1 with the highest space velocity and an intense secondary formation of nanoparticles.

**Fig. 11:** FTIR results in 4-points test at different SP’s

**Fig. 12:** Secondary nanoparticles in the 4-points test (w/o slip cat.)

Commentary [nvh3]: I do not trust these data and would therefore not publish them at this stage. There is enough data in this article that seems to be very reasonable. Especially the 30'000 ppm of isocyanic acid emissions seem to be very unhealthy.
A summary of reduction efficiencies $RE$ in the 4-points test is represented in Table 4. NO$_x$ and NO$_2$- values of CLD and FTIR, as well as all NP-values (CPC, PAS, DC) are given.

At operating points 7, 1 and 3 the SCR system is working in the optimal temperature window and deNO$_x$-efficiencies are in the range of 86 - 91%.

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<tbody>
<tr>
<td>339</td>
<td>100</td>
<td>113.97</td>
<td>3</td>
<td>4</td>
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<td>143</td>
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<td>35</td>
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<td>2.7E+05</td>
</tr>
</tbody>
</table>

Table 4: Integral average values and reduction efficiencies of NO$_x$, NO$_2$ and NP in the 4-points test.

Concerning the NO$_2$ reduction rates there are some open questions: why is the NO$_2$ efficiency so high at OP4 with no urea dosing and why is it so low at OP3, when the urea injection and temperature range are optimal? These questions can be at least partly explained by the dynamic response of the aftertreatment system in the preceding, load transitions. There are on the one side the thermal memory effects of the different components (DPF, SCR) in the range of 10 min and on the other side the chemical memory due to store / release effects and secondary reactions.

The presented nanoparticle filtration efficiencies (Table 4) are excellent and confirm the required high quality of the DPF part of the system (except of OP1 with highest space velocity and intense secondary NP formation).

**Load transitions**

The emissions over the time were monitored for transitions A,B,C and D of the 4-points test (Fig. 6). Fig. 13 shows as an example the transition B with a load increase from 10% (OP4) to 100% (OP1) at 2200 rpm and with urea switching on.

NO$_2$ levels measured before the combined dePN system (SP1) decline at 100% load, as expected, because of thermal NO$_2$ decomposition at temperatures up to 490 °C (Table 4).

Measured after the system (SP3) quite long response times, in the range of 90 sec, are noticed. In this time, exhaust temperatures increase and the urea dosing starts.
According to the conditions of flow, space velocity, temperature and urea stoichiometry ($\alpha$) different SCR reactions proceed. An increase of nanoparticles concentrations is clearly indicated by both, the CPC and the DC.

Load transitions between two stationary engine conditions are very indicative to study in detail the instationary changes in the combined system. Nevertheless for some specific purposes longer operation times at the final stationary state are recommended as well. 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 up to 20 min.

**Fig. 13:** Load transition B: from 2200 rpm / 10%L to 2200 rpm / 100%L with measurements before and after DPF + SCR

**Fig. 14:** Comparison of 2 ETCs (ETC1-ETC3), with & w/o slip catalyst at $\alpha = 0.9$
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 stabilized by repetitive conditioning (see Test Procedures).

**Fig. 14** compares emissions during two ETC’s with and without slip catalyst. During both tests, exhaust temperatures at the tailpipe decreased below 200 °C and in the second part of the test NOx emissions increased because of stopped urea dosage.

The ammonia slip catalyst reduced NH3 emissions, most efficiently in the first phase of the test (until approx. 200 s).

In the first phase of the test (until approx. 500 s) there are also higher emission peaks of NP-emissions CPC & DC, which are an effect of the highly instationary chemistry, production of secondary nanoparticles and store/release phenomena. In the second part of the measuring cycle with less fluctuating engine speed there are also less fluctuations in the CPC- and DC-plots.

**Fig. 15** depicts the decreasing NOx conversion efficiency caused by the cooling of the exhaust system during the test and the respective shut-off of urea dosage. It can be concluded, that with better insulation of the exhaust system, or placing the dePN system closer to the engine, or extending the engine operation range, the deNOx reduction rates can be influenced. Some of these measures will be tested in further works.

The results of target emission were integrated for different test periods:
- initial period 0-400 s
- final period 1400-1800 s
- overall test 0-1800 s.

The obtained average emission concentration and the reduction efficiencies are summarized in **Table 5**.

The NOx- and NO2-conversion rates decrease during the test, as previously discussed. The NOx concentrations obtained from CLD and FTIR correspond very well. NOx levels are rather low, therefore discrepancies are larger. Again, very high filtration efficiencies of 99 - 100% were noticed despite of some secondary NP-formation in all periods of the ETC.
**Table 5**: Average concentrations and reduction efficiencies of NO\(_x\), NO\(_2\) and nanoparticle emissions in different parts of the ETC.

**Fig. 16**: Filtration efficiencies of the combisystem after SCR – catalyst in stationary and dynamic engine operation.

In the operating point OP1 of the stationary 4-points test, the influence of the secondary formation of nanoparticles is visible. In the dynamic test, such effects are hardly detectable, due to overlapping and blurring of all transient effects.

In the dynamic ETC test, the DPF which fulfills VERT quality standards, is as efficient as in stationary tests. Moreover, in stationary testing it is possible to observe phenomena, which are not visible in the transient tests. Such effects can be: storage/release of sulfates in the exhaust system, influences of additive particles, or secondary SCR nanoparticles. The stationary testing of DPFs according to the VERT procedures can be confirmed as the best solution.
8. CONCLUSIONS

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

- the combined dePN systems (DPF+SCR) at transient engine operation efficiently reduce the target emissions with deNO\textsubscript{x}-efficiencies up to 92\% (if operated in the right temperature window) and particle number filtration efficiencies up to 100\%,
- with increasing feed factor (up to overstoichiometric urea dosing) NO\textsubscript{x} conversion efficiencies increase (up to 98\%), but also the ammonia slip rises up to 125 ppm,
- with the recommended feed factor \( \alpha = 0.9 \), without slip catalyst, and there is only a moderate average slip of ammonia up to 7 ppm in the ETC and there is a release of small amounts of nitrous oxide of up to 3 ppm,
- the ammonia slip can be efficiently eliminated by a slip-cat,
- during transients there are temporarily increased emissions of nitrogen-containing components, due to momentary imbalanced deNOx reactions,
- in the investigated configuration with urea dosing after the DPF, a secondary formation of nanoparticles is detectable, however with little impact on total number concentrations and overall filtration efficiency of the system,
- the average NO\textsubscript{x} conversion efficiency at transient operation (ETC) strongly depends on the exhaust temperatures which are correlated with the urea-dosing strategy,
- the nanoparticle filtration efficiency, which is verified at stationary engine operation, is perfectly valid also at transient engine 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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10. LITERATURE

[1] www.lowemissionzones.eu


[23] Particulate traps for heavy duty vehicles. Environmental Documentation No. 130, Swiss Agency for Environment, Forests and Landscape (SAEFL, since Jan. 06 BAFU), Bern 2000


11. ABBREVIATIONS

AEEDA  Association Europeenne d’Experts en Dépollution des Automobiles  CDI  Common Rail Diesel Injection
AFHB  Abgasprüfstelle FH Biel, CH  CFPP  cold filter plugging point
AKPF  Arbeitskreis der Partikelfilterhersteller  CLD  chemoluminescence detector
Air min stoichiometric air requirement  CNC  condensation nuclei counter
ASTM  American Society for Testing Materials  COP  conformity of production
ASTRA  Amt für Strassen, CH, Swiss Road Authority  CPC  condensation particle counter
AUVA  Austria Unfallversicherung-Anstalt  dePN  de Particles + deNOx
BAFU  Bundesamt für Umwelt, CH (Swiss EPA)  DI  Direct Injection
CARB  Californian Air Resources Board  DMA  differential mobility analyzer
DPF  Diesel Particle Filter  ECU  electronic control unit
ELPI electric low pressure impactor
EMPA Eidgenössische Material Prüf- und Forschungsanstalt
EPA Environmental Protection Agency
ETC European Transient Cycle Förderkreis
FAD European Transient Cycle Förderkreis Abgasnachbehandlungs-technologien für Dieselmotoren, Dresden
FBC fuel borne catalyst (regeneration additive)
FE filtration efficiency
FID flame ionization detector
FTIR Fourier Transform Infrared Spectrometer
GRPE UN Groupe of Rapporteurs Pollution & Energie
HD heavy duty
ICE internal combustion engines
IUCT in use compliance test
JRC EU Joint Research Center
LDS Laser Diode Spectrometer (for NH₃)
LEZ low emission zones
LRV Luftreinhalteverordnung
ME Matter Engineering
MD19 heated minidiluter
NanoMet NanoMet nanoparticle summary surface analyser (PAS + DC + MD19)
NP nanoparticles < 999 nm (SMPS range)
OEM original equipment manufacturer
OP operating point
PAS Photoelectric Aerosol Sensor
PC particle counts
PCFE particle counts filtration efficiency
PM particulate matter, particle mass
PMFE particle mass filtration efficiency
PMP Particulate Measurement Program of GRPE
PSD particle size distribution
PSI Paul Scherrer Institute
RD relative difference
RE reduction efficiency
SCR selective catalytic reduction
SMPS Scanning Mobility Particle Sizer
SNORB Swiss NO Retrofit Benchmark
SP sampling position
SUVA Schweiz. Unfallversicherungs-Anstalt
TBG Tiefbaugenossenschaft
TC thermoconditioner. Total Carbon
TNO Netherland National, Laboratories
TÜV Technischer Überwachungsverein, D
ULSD ultra low sulfur Diesel
UMTEC Umwelttechnik Institut FH Rapperswil, CH
US-EPA US – Environmental Protection Agency
VERT Verminderung der Emissionen von Realmaschinen in Tunelbau
VERTdePN VERT DPF + VERT deNOₓ
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
VROM Netherlands EPA
VSET VERT Secondary Emissions Test
VERTdePN – quality verification of combined DPF+SCR systems for retrofitting.

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Network-Project „VERT dePN-Verification for HD-Retrofitting with combined systems DPF+SCR“

**Working laboratories**:
AFHB, ME, EMPA, SUVA, UMTEC
Leading:: TTM, AFHB, BAFU

**Financial support**
BAFU
SUVA
ASTRA

**Working packages**
- **Engine**
  - Partner 1
  - Partner 2
  - Partner 3
- **Field**
  - Partner 1
  - Partner 2
  - Partner 3

**Industrial partners**
- HUG,
- UMTEC Technologie
- DINEX,
- EMINOX,
- HJS,
- Johnson Matthey

*Open for further partners*

**Consulting**
- PSI (CCEM, NEADS)
- EMPA
- LAV-ETHZ
- VITO, Belgium
- AVL MTC, Sweden

**Collaborations**
- FAD, AKPF, AECC
- CARB
- SWRI
- TNO / VROM

**Technical details**
- TTM, AFHB, BAFU

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

**VPNT 1**
- engine test bed
- 4 pts tests
- load transitions
- dynamic tests (ETC)

**VPNT 2**
- field durability
- 2000h, or 100'000 km
- periodic controls

**VPNT 3**
- extended check on vehicle
- chassis dyno
- after field test

**VPNSET**
- engine test bed
- ISO 8178 8 pts. tests
  - incl. load transitions
VERTdePN test procedures for product standards and legal admission of combined systems (DPF + SCR)
Swiss NOx Road Benchmarking EU 5 – validation of retrofitting on different political levels

SNORB 5

- International
- National
- Local
  - Communal level
  - Regional level

PEMS (JRC)
emission inventory (HD)
VdePN (TüV, TNO, CARB et.al.)
VdePN (ASTRA)
Benchmarking Field test
Measuring
Set-up
TEST ENGINE

Manufacturer: Iveco, Torino Italy
Type: F1C Euro3
Cylinder volume: 3.00 Liters
Rated RPM: 3500 min⁻¹
Rated power: 100 kW
Model: 4 cylinder in-line
Combustion process: direct injection
Injection system: Bosch Common Rail
Supercharging: Turbocharger with intercooling
Exhaust line prepared for adaptation of dePN-systems and special exhaust gas analysis

DPNSET-Sampling  LDS
Measuring set-up (1)
Measuring set-up

Investigated (DPF+SCR) system
Test Procedures
8pts. test (ISO 8178) and the VPNT1 4pts. test

engine map: IVECO F1C CR, DI, TCI, 3 dm3
ETC for the limited version of engine map, IVECO F1C
Stationary engine operation
8-points test

Comparison of results with different $\alpha$
$\text{NO}_x$ conversion at different SP’s & NH3 tail pipe
Secondary nanoparticles at 4pts. test (w/o slip cat.)

Iveco F1C / ULSD / Adblue 32.5 % / a=0.9
Quasi dynamic engine operation → Load transitions
Load transition: 2200 rpm 10%L to 100%L

Adblue injection switch on

Load transition B:
from 2200 rpm / 10%L to 2200 rpm / 100%L
with measurements before and after DPF + SCR
Dynamic engine operation

ETC
ETC’s with limited engine map

<table>
<thead>
<tr>
<th>ETC 1 with slip</th>
<th>ETC 3 w/o slip cat</th>
<th>ETC 4 Ref. w/o DPF + SCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>with cat</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Conditioning before ETC**

5 min → pt. 1  2200 rpm / 100 % Load

0.5 min → idle
Comparison of 2 ETC’s (ETC1-ETC3), with & w/o slip catalyst, \( \alpha = 0.9 \)

Iveco F1C - limited engine map - Diesel ULSD

- Engine torque [Nm]
- Engine speed [rpm]
- Backpressure [mbar]
- Temperature [°C]

ETC1 with slip cat
ETC3 w/o slip cat
Comparison of 2 ETC’s (ETC1-ETC3), with & w/o slip catalyst, $\alpha = 0.9$
Comparison of 2ETC’s (ETC1-ETC3), with & w/o slip catalyst 

\( \alpha = 0.9 \)
Comparison of 2 ETC’s (ETC3-ETC4), reference & w/o slip catalyst, $\alpha = 0.9$

Iveco F1C - limited engine map - Diesel ULSD

![Graph showing engine torque, engine speed, and NOx conversion over time.](image)
Filtration efficiencies of the combisystem after SCR – catalyst in stationary and dynamic engine operation
Conclusion (1)

• $\alpha \uparrow \rightarrow \text{NO}_x \downarrow \rightarrow \text{NH}_3 \uparrow$ (w/o slip cat)

• urea switch on/off at lower $t_{\text{Exh}}$

• $\text{NO}_x$ conversion rate in ETC dependent strongly on urea dosing = $f(t_{\text{Exh}})$

further research and evaluations in course
Conclusion (2)

• in ETC with $\alpha = 0.9$
  - average NH3 $\leq$ 7 ppm
  - average N2O $\leq$ 3 ppm

• secondary NP

• DPF filtration efficiency up to 100%
  stationary = dynamic

further research and evaluations in course
SCR, V-HSO System

- Pre (Vor)-Catalyst
- Hydrolysis, SCR and Oxidation Catalyst

\[ \text{HNCO} \quad \text{isocyanic acid} \]

Thermolysis

\[ \text{oxidation catalyst (O)} \]

\[ 2\text{NO} + \text{O}_2 \rightleftharpoons 2\text{NO}_2 \]

\[ \text{HCNO} + \text{H}_2\text{O} \quad k_5 \quad \text{NH}_3 + \text{CO}_2 \]

\[ 4\text{NH}_3 + 3\text{O}_2 \quad k_4, k_9 \quad 2\text{N}_2 + 6\text{H}_2\text{O} \]

\[ 4\text{NH}_3 + \text{NO} + \text{O}_2 \quad k_1, k_8 \quad 4\text{N}_2 + 6\text{H}_2\text{O} \]

\[ 4\text{NH}_3 + 2\text{NO} + 2\text{NO}_2 \quad k_2 \quad 4\text{N}_2 + 6\text{H}_2\text{O} \]

\[ 8\text{NH}_3 + 6\text{NO}_2 \quad k_3 \quad 7\text{N}_2 + 12\text{H}_2\text{O} \]

\[ (\text{NH}_2)_2\text{CO} \quad \rightleftharpoons (\text{NH}_2)_2\text{CO(s)} + 7.1\text{H}_2 \quad \text{g} \]

\[ (\text{NH}_2)_2\text{CO(s)} \quad \rightarrow \text{NH}_3 + \text{HCNO} \]

normal rapid slow

Thank you for your attention!