Combinations of Measures for Reduction of NO_x & Nanoparticles of a Diesel Engine.

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ABSTRACT

Reduction of NO_x- and particle emissions of Diesel engines is worldwide an important challenge for the engineers. Some unregulated components, like NO_2, NH_3 and naoparticles NP *) came in the focus of attention in the last years.

Application of EGR and / or SCR can lower NO_x, using RME (Bxx) can increase NO_x. What happens with NP, parameter which enters in some further steps of exhaust gas legislation in Europe?

The present paper informs about the results with EGR, B100 and SCR obtained on a medium duty Diesel engine in the versions: Euro 3 (w/o EGR) & Euro 4 (with EGR), both without particle filter.

The investigations were performed according to the procedures of the international network project VERT *) dePN (de-activation, de-contamination, disposal of particles & NO_x).

The most important findings are:

- the EGR of the new engine version E4 is active at middle load,
- the NO_x reduction potentials in ETC with combinations of the investigated measures are:
  EGR reduces NO_x approx. in the same range, as B100 increases it (17-20%); SCR is the strongest reduction measure in the range of 73%.
  These potentials are similar at middle-load stationary operation.
- the influences on nanoparticles counts emissions (PC) depend on different factors and can partly change between stationary and dynamic operation and with the use of B100.

In summary: EGR and SCR can efficiently reduce NO_x and overcompensate the effect of B100.
EGR is most advantageous at low load, when SCR is not active.

INTRODUCTION & OBJECTIVES

The investigations concerning the reduction potentials of critical emissions NO_x & NP were performed with EGR / B100 / SCR and with limited variation of the injection timing SOI.

The exhaust gas recirculation EGR is commonly used to reduce NO_x. As a drawback the increase of other emissions, like HC, or particle mass & counts can appear with increasing EGR. This risk is extremely reduced with the modern injection systems (common rail CR) with very high injection pressures, so the EGR-rates are very much increased in engines of new generations. The EGR cooling, which brings further advantages of NO_x and the dynamic regulation of EGR give further challenges for developers, [1], [2].

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.

The main deNO_x-reactions between NH_3, NO and NO_2 are often mentioned in the literature [3, 4, 5, 6, 7]. They have different speeds according to the temperatures of gas and catalysts, space velocity and stoichiometry. All these influences cause a complex situation of reactions 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).

Blend fuels with RME (biodiesel Bxx) have impact on emissions, which depends on the engine operating collective. At full load there is a tendency of increased NO_x and reduced CO, HC & PM; at lower part load inversely, [8].

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*) Abbreviations see at the end of this paper

For nanoparticles usually a bimodal particle size distribution (PSD) is produced due to spontaneous condensates in nuclei mode (the lowest size range below 30-40 nm) with biofuels, [9, 10]. Introducing EGR provokes an increase of nanoparticles count concentrations, [11, 12].

For the successful long term operation the limiting of impurities and phosphorus in biofuels according to the present standards, as well as a carefull choice of lubricating oil are strongly recommended.

With SCR alone there are no differences of NO_x and of NO_x reduction rate (K_{NOX}) with increasing RME portion; there is lowering of CO & HC. With SCR catalyst there is usually a small reduction of nanoparticles concentrations (in the range of 10-20%, similar like an usual oxidation catalyst), [13].

The objectives of the present work are to investigate the influences of EGR with Diesel and with B100 and the potentials of the present SCR-system concerning $deNO_x$ rates and nanoparticles.

For comparison of potentials and drawbacks a limited variation of injection timing was performed, as an off-set of +/- 3 degrees CA in the engine map.

The tests were performed at the Laboratories for IC-Engines and Exhaust Emission Control of the University of Applied Sciences Biel, Switzerland (AFHB).

TESTED ENGINE, FUELS, LUBRICANT

Test engine

Manufacturer:	Iveco, Torino Italy
Type:	F1C Euro 3 / Euro 4
Displacement:	3.00 Liters
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)

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.

Fuels

Following base fuels were used for the research (Table 1):

- Shell Formula Diesel fuel Swiss market summer quality (10 ppm S) according to SN EN 590
- Rapeseed Oil Methyl Ester RME from Flamol, Berne, CH

Table 1 represents the most important data of the fuels according to the standards and the analysis certificates.

It can be remarked, that there are differences of density, heat value, stoichiometric air requirement and boiling range, which have influences on the engine operation and especially on the full load parameters. These changing fuel parameters were taken into account by the evaluation of measurements.

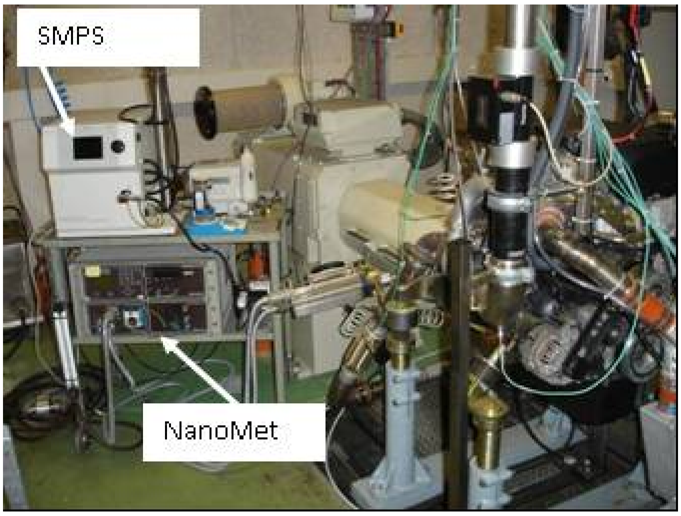


Fig.1: IVECO engine F1C and equipment for nanoparticle measurements in the engine room

		Diesel	RME
Density 15°C	g/m	0.842*	0.885*
Viscosity at 40°C	mm²/s	2.0-4.5	4.6*
Flash point		above 55°C	143°C
Cloud point		max -10°C	-
Filterability CFPP		max -20°C	-15°C
Ash	%	max 0.010	Traces
Sulfur	ppm	<10	1.3*
Cetane number		51	56
Calorific value	MJ/kg	42.7	37.2
C fraction	in %	86.7	77.5
H fraction	in %	13.3	11.8
O fraction	in %	0	10.7
Air_{min}	kg/kg	14.52	12.49
Boiling range 10-90% °C		180-340	315-360

* measured values

Tabel 1: Fuel properties as per EU-standards and further analysis of the test fuels

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

Property	Mobil oil	
Viscosity kin 40°C	72.8	mm²/s
Viscosity kin 100°C	12.1	mm²/s
Viscosity index	164	(--)
Density 15°C	0.85	kg/m³
Pourpoint	-45	°C
Flamepoint	254	°C
Total Base Number TBN*	6	mg KOH/g
Sulfur ashes*	600	mg/kg
Sulfur *	2000	mg/kg
Mg*	41	mg/kg
Mo*	80	mg/kg
Zn*	900	mg/kg
Ca*	1100	mg/kg
P*	820	mg/kg

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

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:

- EGR valve (high pressure EGR), (see sketch Fig. 5)
- EGR cooler, (Fig. 5)
- throttle valve at intake, (Fig. 5)
- air mass flowmeter at intake
- injectors
- new engine calibration (ECU) for modifications of injection timing and injection mode (pre-/post-injections).

The principal influences on engine combustion and emissions are given trough the:

- HP EGR regulated continuously in the engine map,
- 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 and influencing the start of injection (SOI) of the main injected quantity (if preinjection is present it stays always at the same distance from the main injection event).

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

In a study work [14] the EGR-rate in the engine map was estimated by means of CO_2-measurements in the exhaust ($CO_{2\,high}$) and in the intake collector ($CO_{2\,low}$). The EGR-rate is calculated:

$$\mathrm{EGR}\ \% = \frac{CO_{2low} - CO_{2room}}{CO_{2high} - CO_{2room}} \bullet 100\%$$

Fig. 2 shows the EGR engine map for HD application. It can be remarked, that by the mostly investigated engine speed 2200 rpm there are the highest EGR-rates in the part load domain below approx. 130 Nm (36%).

In the same study the influence of HD-EGR on the turbocharging system was demonstrated by means of energy flow diagrams (Sankey-diagrams) for some operating points of the engine.
Figures 3 & 4 show the examples with / without EGR at 30% load. The zero-point for enthalpy in these representations is put on 0°C and the specific heat capacity of gas as function of temperature is considered.
It can be seen, that with EGR the enthalphy flow to the turbine of the turbocharger is clearly lower, which provokes also the lower boost pressure (in this OP3b $\Delta p \approx$ 60 mbar).
The turbine has fix geometry.

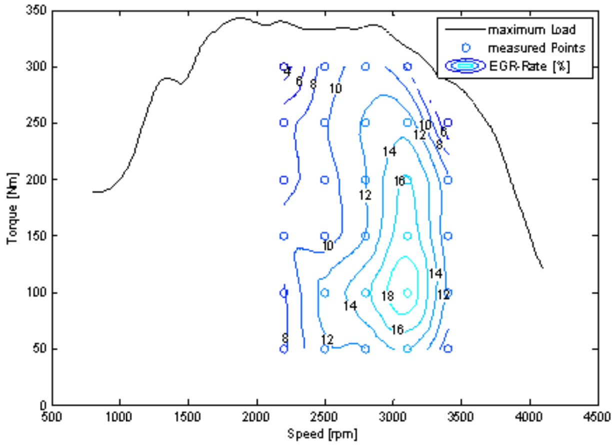


Fig. 2: EGR-Map of the heavy duty IVECO F1C-Engine Euro 4

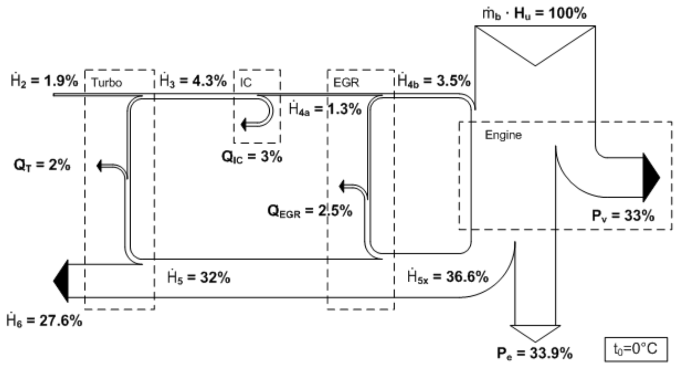


Fig. 3: Sankey-Diagram of the IVECO F1C Engine with 13% EGR at 2200rpm and 106Nm (30%)

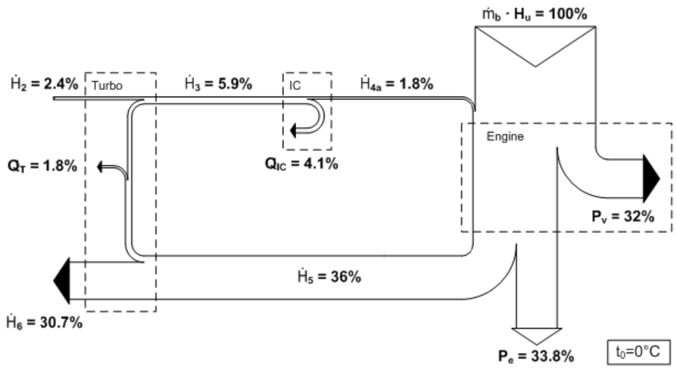


Fig.4: Sankey-Diagram of the IVECO F1C Engine without EGR at 2200rpm and 106Nm (30%)

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.

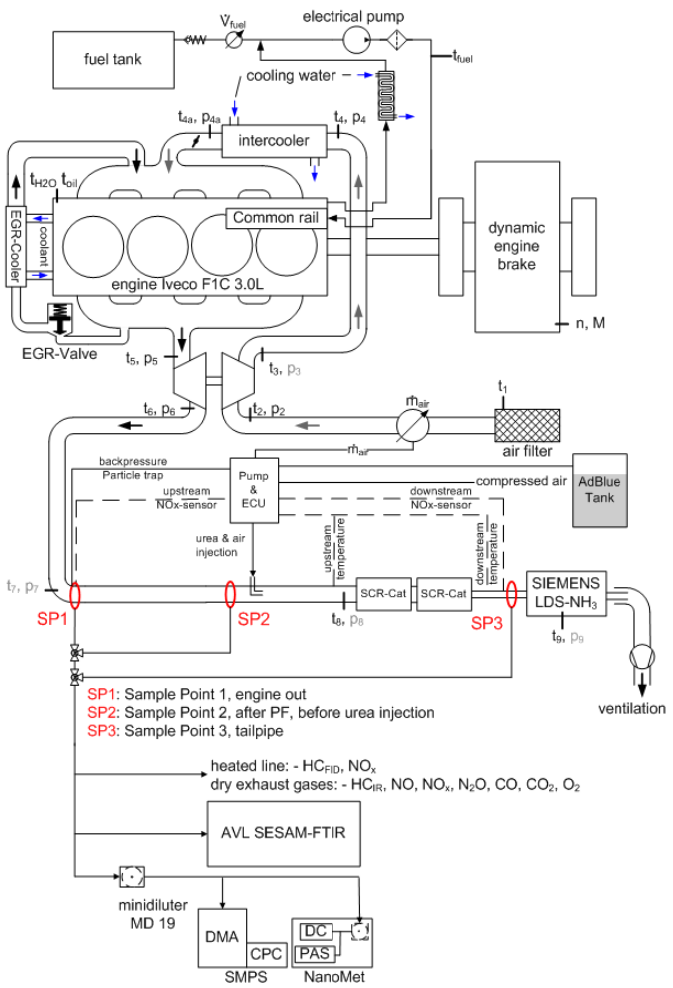


Fig.5: Engine dynamometer and test equipment

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 exhaust gas emissions regulations for heavy duty vehicles which are also in force in Switzerland (Directive 2005 / 55 / CE & ISO 8178):

- Volatile components:
  - Horiba exhaust gas measurement devices
    Type: VIA-510 for CO_2, CO, HC_{IR}, O_2,
    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},
- NH_3 and N_2O:
  With SCR several unregulated and secondary pollutants can be produced. The slip of gaseous components such as ammonia NH_3 and nitrous oxide N_2O was measured by means of:
  - Siemens LDS 6 Laser Analyzer 7MB 6021, NH_3
  - Siemens ULTRAMAT 6E 7MB2121, N_2O
  - Eco physics CLD 822 CM hr with hot line for NO, NO_2, NO_3, NH_3 (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, NO_2, NO_x, NH_3, N_2O.

Particle size analysis

The particle size and number distributions were analysed with following apparatus, Fig. 1:

- SMPS – Scanning Mobility Particle Sizer, TSI (DMA TSI 3071, CPC TSI 3025 A)
- NanoMet – System consisting of:
  - PAS – Photoelectric Aerosol Sensor (EcoChem PAS 2000) indicates the carbonaceous total surface of the aerosol
  - DC – Diffusion Charging Sensor (Matter Eng. LQ1-DC) indicates the totale surface of the aerosol independently of the chemical properties
  - MD19 tunable minidiluter (Matter Eng. MD19-2E)

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.

TEST PROCEDURES

Several test procedures were used.

After analyzing the backpressure of the system at stationary operation in the entire engine operation map in the previous parts of research with DPF, it was decided to limit the operation range. In this limited engine map (LEM) different steps-tests were defined. In the present work a 4 steps-test at 2200 rpm was used, Fig. 6.

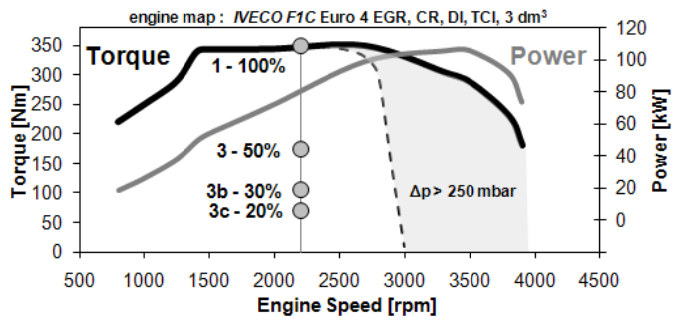


Fig.6: Limited engine map of the IVECO F1C engine and 4 points test for SCR-investigations

Fig. 6 shows the limited engine map and the 4 points steps-test.

- operating point OP 3c, 20% load, 2200 rpm / 65 Nm
- operating point OP 3b, 30% load, 2200 rpm / 98 Nm
- operating point OP 3, 50% load, 2200 rpm / 162 Nm
- operating point OP 1, 100% load, 2200 rpm / FL

These operating points were chosen in such way that the urea switch-on was included in the test (between 20% and 30% load).
The denomination of the OP's from other measuring series was not changed in order to keep comparability with other projects and new OP's were named by adding a letter 3b, 3c).

For a more detailed investigation of the tested system different sampling positions (SP) were used in previous research, see Fig. 5. In the present works only SP 3, sampling position at tailpipe with and without aftertreatment system was used.

The dynamic testing was performed with the ETC (European Transient Cycle), which in this work was defined on the basis of the non limited engine operation map (NEM), for the engine version E3, Fig. 7. The definition of ETC was not changed, to keep a better comparability with the previous results.

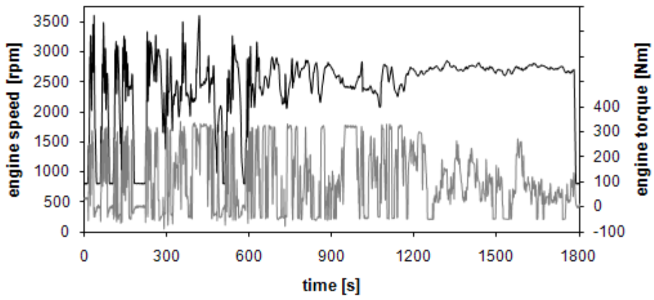


Fig.7: Torque & speed in ETC IVECO F1C

The tests have shown that the backpressure at dynamic operation is generally lower, as at stationary operation and therefore the dynamic tests were performed with ETC adapted to the entire engine operation map.

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 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.

The test program consisted of:

- test procedures: steps-tests at 2200 rpm and ETC (NEM);
- aftertreatment systems: without, with SCR only;
- fuels: Diesel (ULSD) & B100;
- with/without EGR (engine versions E4 / E(4))

TESTED SCR SYSTEM

The SCR exhaust gas aftertreatment system was installed on the IVECO research engine in the ICE-laboratory in Biel, CH.
This system is designed for dynamic on-road applications.
The filters and catalysts are exchangeable moduls, for SCR alone the DPF modulus was removed.

The investigations in the present work were performed without DPF, with the Vanadium-based SCR catalyst downstream of the urea injection point (see scheme Fig. 5).
Additionally to the elements in the engine exhaust system an Ad Blue-tank and Ad Blue injection unit with pump, sensors and electronic control were installed in the laboratory.

There are following sensors, which enable the open-loop control of urea dosing:

- 2x Temperature sensors (PT200)
- 1x AdBlue level sensor
- 1x Mass Air Flow sensor
- 2x NO_x sensors (upstream & downstream DPF)

Optional: 1x NO_x sensor downstream SCR catalysts for monitoring of performance.

Urea dosing and control unit has an open loop control.

Optional: GPRS Flight recorder enables:

- data logging of system performance, state and alarms on a remote server/database
- changing and checking of configuration parameters of urea dosing unit via internet.

The SCR-system, which was investigated in the present work is without mixer (only mixing tube 1.0 m).

RESULTS

Steady state operation, 4 pts-test

In this research 4 operating points (OP) were used.

At the lowest load (20%, OP3c) SCR is not active due to lower exhaust gas temperatures and urea cut off.

All part load operating points (OP3c, OP3b, OP3) were realized at exactly the same speed & torque. In contrary the full load points (OP1) were driven at different torques according to the used fuel (same engine speed).

With the used EGR map at full load (OP1) EGR is almost switched off with Diesel and completely closed with B100. Therefore, in the variant "with EGR" the full load point (OP1) is de facto without EGR.

Except of influences of EGR the following figures show also the influences of B100 (RME) and of SCR.

Effect of EGR at middle engine load (OP3, 50%) on some control- and emissions parameters is demonstrated in Fig. 8. Looking on these plots from right to left it can be summarized that EGR lowers the NO_x-emissions and increases the NP-emissions (PAS & DC) (comparison E(4)-E4). With EGR there is less gas flow through the engine, lower boost pressure and lower backpressure. At higher engine loads there are also higher engine out exhaust gas temperatures with EGR.

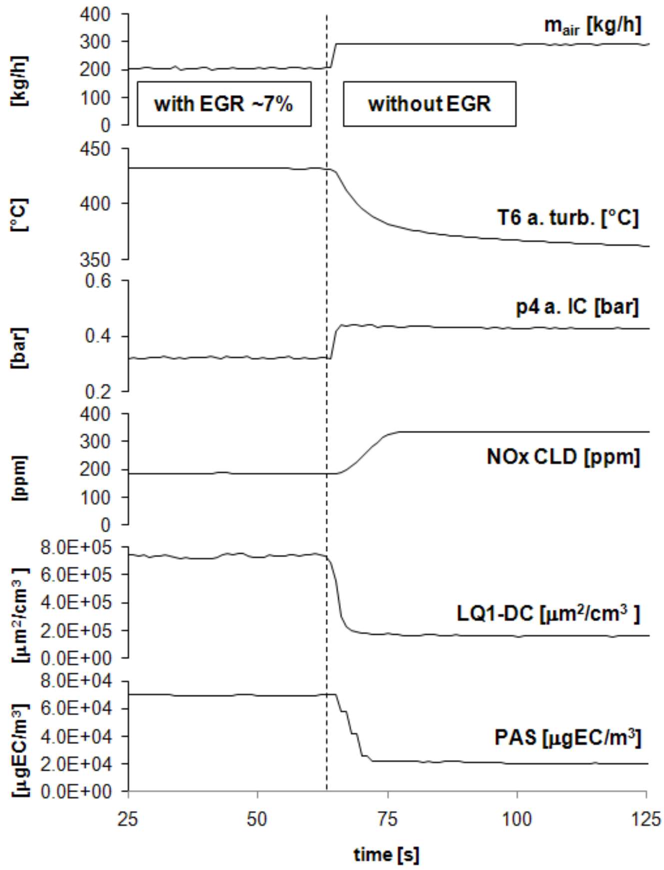


Fig.8: Switch off EGR mode at 2200 rpm / 162 Nm, Iveco F1C E4; diesel; w/o exhaust gas after-treatment system

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

All signals of PAS and DC in this figure are converted to the values responding to the undiluted volume concentrations in the exhaust gas.

The NanoMet results usually confirm the findings from SMPS and are regarded, especially DC, as parameters substituting the NP-count concentration measurement.

Fig. 9 gives an example of some NO_x-related emission values depending on B100 and SCR, all with EGR.
It can be remarked, that:

B100: increases NO_x at higher part load and full load in the range of 10-15%, reduces strongly HC and increases CO (not represented here).

SCR: reduces strongly NO_x & NO_2, is source of NH_3 in the range up to 20 ppm at full load, reduces HC.

The resulting average EGR rates for both fuels are represented in this figure. They are different for Diesel and for B100 because of different injection duration and air consumption and different settings of the present EGR control system.

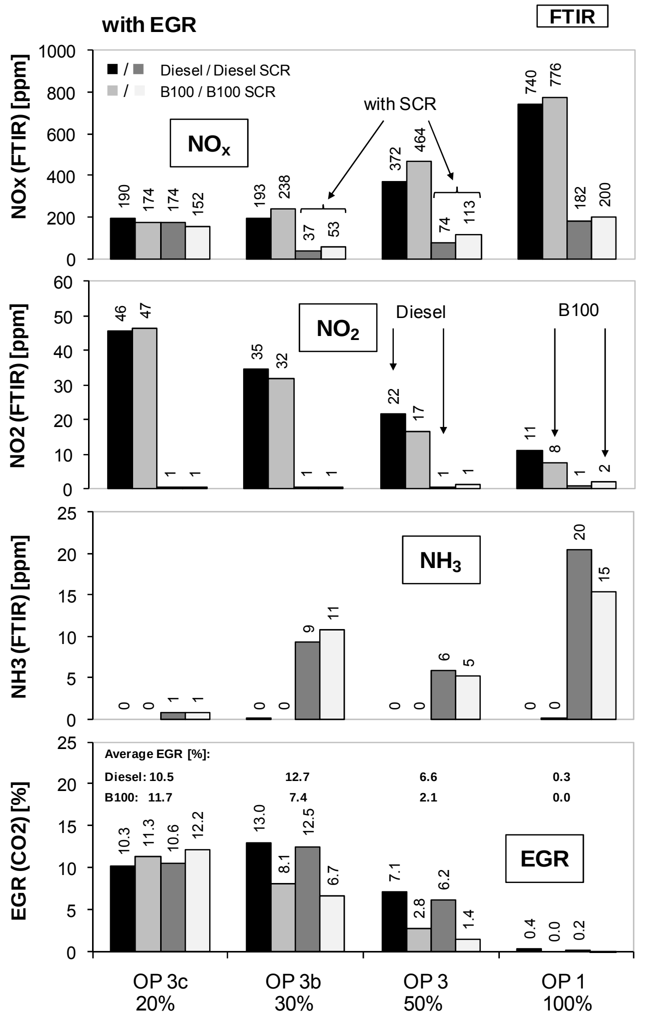


Fig.9: Influences of B100 & SCR on NOx emissions in 4pts.-test, Iveco F1C E4; 2200rpm

Identical tests were also performed without EGR.

Table 3 summarizes the relative changes of NO_x-emissions, as averages of 4 points. It results, that EGR reduces NO_x approximately in the same range (15%) as B100 increases it (12%). SCR is the strongest reduction tool in the range of 60% (by averaging only OP's with SCR active 80%).

EGR		B100		SCR	
4 pts [%]	NOx RR	4 pts [%]	NOx IR	4 pts [%]	NOx RR
average Diesel	18.9	average w/o SCR	7.2	average Diesel	60.8
average B100	10.5	average with SCR	16.1	average B100	59.0
average	14.7	average	11.6	average	59.9

RR ...reduction rate with EGR $\quad$ IR ...increase rate with B100 $\quad$ RR ...reduction rate with SCR

$$RR = \frac{NOx_{w/o\_EGR} - NOx_{with\_EGR}}{NOx_{w/o\_EGR}} \cdot 100\% \qquad IR = \frac{NOx_{B100} - NOx_{Diesel}}{NOx_{Diesel}} \cdot 100\% \qquad RR = \frac{NOx_{w/o\_SCR} - NOx_{with\_SCR}}{NOx_{w/o\_SCR}} \cdot 100\%$$

Tabel 3: Relative changes of NOx-emissions (FTIR), average of 4 pts.

Fig. 10 gives example of SMPS PSD-specta with different engine variants at middle load (OP3, 50% load). The PSD are represented in linear and in logarithmic scale to

demonstrate the appearance of different kind of representations.
The NP count concentrations show a little difference between the engine versions E 3 2008 (Euro 3 w/o EGR) and E (4) (Euro 4 with closed EGR). The opening of EGR (version E4) causes a clear increase of NP numbers, with a maximum in the size range 70-80 nm.

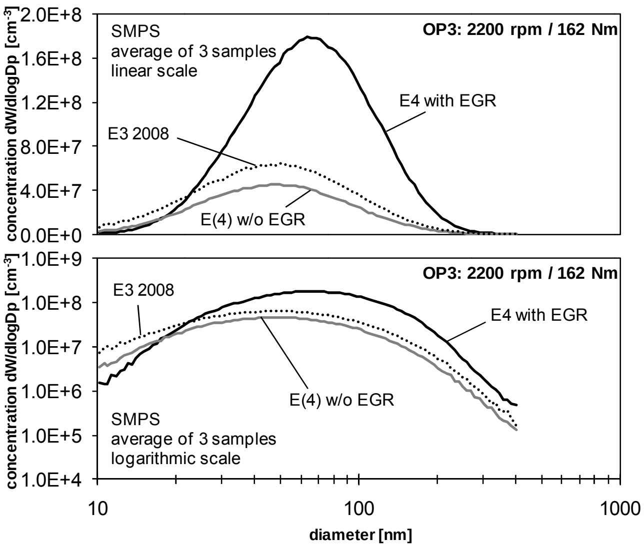


Fig.10: Influence of EGR on nanoparticle emissions, Iveco F1C E4; diesel; w/o exhaust gas after treatment system

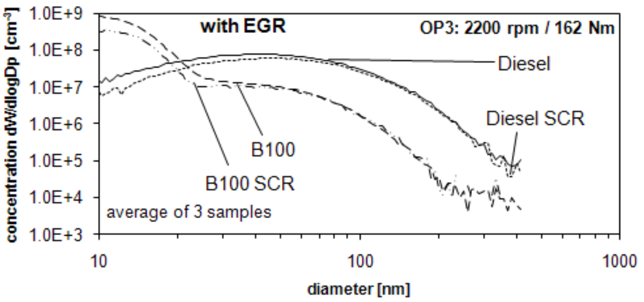


Fig.11: Influences of B100 & SCR on nanoparticles (SMPS-PSD), Iveco F1C E4; OP 3: 2200rpm / 50% load

Fig. 11 shows the influences of B100 and of SCR on the SMPS PSD at the same operating point (OP3, 50% load).

With SCR there is a slight tendency of reduction of the NP count concentrations – diffusion loses in the SCR catalysts.

With B100 there is a typical and repetitive influence on NP PSD's: increase of nuclei mode (size approx. < 30 nm) and reduction of accumulation mode (size approx. 30-300 nm) comparing with the standard Diesel fuel.

Thanks to parallel measurements of nanoparticles counts concentrations with SMPS and of the summary active surface of the nanoaerosol with DC it could be found, that the balancing between the two modes influences differently those two parameters (NP & DC). This may be explained in following way considering a stationary case:

If the same summary particle number will be produced more by nuclei and less by accumulation mode, than the summary surface of aerosol decreases (with 3rd power of equivalent particle diameter).
It is well possible, that passing from Diesel to B100 the CPC NP-counts increase due to increased nuclei mode, but in the same time the summary surface of aerosol decreases due to a lower accumulation mode.
The balancing of particle number (PN) between these two modes (nuclei & accumulation) is linear and independent of particle size, while the balancing of summary surface follows the "3rd power law" depending on particle size.

For dynamic engine operation additionally to these reflections founding on results from the stationary engine operation, the dynamic changes of aerosol due to the transient driving cycle have to be considered. The summary time-average balancing of the effects discussed above is dependent on the used driving cycle.

Fig. 12 summarizes the integrated particle numbers in the size range 20-300 nm at 4 operating points and confirms a slight reduction of NP with SCR and a stronger reduction of NP with B100.
The NP size range 20-300 nm is used for estimate of reduction rates, or filtration efficiencies in the Swiss procedures of quality verification of Diesel exhaust gas aftertreatment systems VERT & OAPC.

Table 4 gives an overview of average relative changes of particle counts (PC) in 4 pts-test by means of EGR, B100 and SCR.

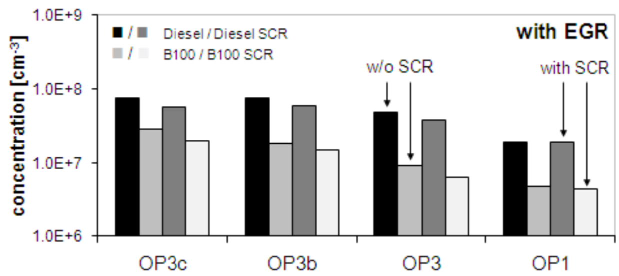


Fig.12: Integrated counts of particles in the size spectrum 20-300 nm, Iveco F1C E4; with diesel & B100; with and w/o SCR

EGR		B100		SCR	
4 pts [%]	PCIR [20-300 nm]	4 pts [%]	PCRR [20-300 nm]	4 pts [%]	PCRR [20-300 nm]
average Diesel	43.1	average w/o SCR	72.2	average Diesel	15.7
average B100	15.7	average with SCR	71.3	average B100	14.0
average	29.4	average	71.8	average	14.9

IR ...increase rate with EGR RR ...reduction rate with B100 RR ...reduction rate with SCR

$$IR = \frac{NP_{with\_EGR} - NP_{w/o\_EGR}}{NP_{w/o\_EGR}} \cdot 100\% \quad RR = \frac{NP_{Diesel} - NP_{B100}}{NP_{Diesel}} \cdot 100\% \quad RR = \frac{NP_{w/o\_SCR} - NP_{with\_SCR}}{NP_{w/o\_SCR}} \cdot 100\%$$

Tabel 4: Relative changes of particle counts (PC) in the size range [20-300nm], average of 4 pts.

EGR increases PC by 29%. Looking separately on the two fuels this increase is much stronger with Diesel fuel, than with B100.
B100 reduces PC for this engine and test procedure by 72% and SCR reduces PC by 15%,

Dynamic operation, ETC

Fig. 13 – shows examples of NO_x-traces in a part of ETC, comparing the effects of:
EGR, SCR, EGR+SCR, B100 and B100+EGR+SCR – the NO_x-differences caused by the different measures are well demonstrated.

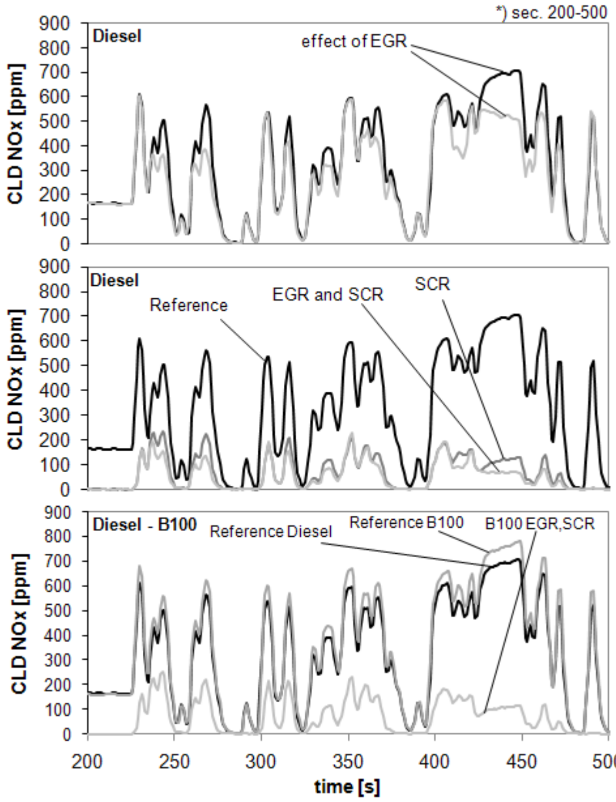


Fig.13: Influences of EGR, B100 & SCR on NOx-traces in ETC*), Iveco F1C E4

Fig. 14 represents the average emissions in ETC of: NO_x, NO_2, NH_3 and CPC (all with EGR).
Again it is confirmed, that:

- B100: increases NO_x, but reduces NO_2 and NP (CPC)
- SCR: reduces strongly NO_x & NO_2, increases NH_3, reduces slithly CPC with Diesel (no reduction with B100).

Identical tests have also been performed without EGR.

Table 5 summarizes the average reduction or increase rates of NO_x in ETC with the investigated measures.

Similar statements like for the stationary operation can be made for the results in ETC:
EGR reduces NO_x approx. in the same range (17%), as B100 increases it (10%); SCR is the strongest reduction measure in the range of 72%.

Table 6 gives an analogous information for CPC – increase, or CPC-reduction rates in ETC.

With EGR the total NP-counts are much less increased with B100, than with standard Diesel fuel. This is very plausible, since B100 produces lower total particle numbers with more spontaneous condensates in nuclei mode, which are much more lost, or agglomerated on the way from engine exhaust to the engine intake.

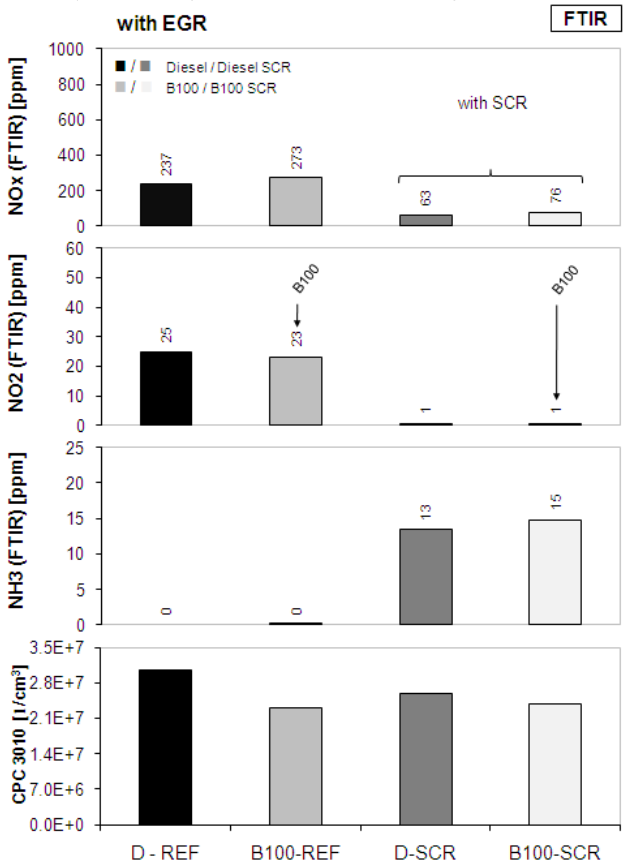


Fig.14: Average emissions in ETC, Iveco F1C E4; with diesel & B100; with and w/o SCR

EGR		B100		SCR	
ETC [%]	NOx RR	ETC [%]	NOx IR	ETC [%]	NOx RR
average Diesel	22.6	average w/o SCR	10.5	average Diesel	72.3
average B100	12.4	average with SCR	10.1	average B100	72.5
average	17.5	average	10.3	average	72.4

RR ...reduction rate with EGR IR ...increase rate with B100 RR ...reduction rate with SCR

$$RR = \frac{NOx_{w/o\_EGR} - NOx_{with\_EGR}}{NOx_{w/o\_EGR}} \cdot 100\% \quad IR = \frac{NOx_{B100} - NOx_{Diesel}}{NOx_{Diesel}} \cdot 100\% \quad RR = \frac{NOx_{w/o\_SCR} - NOx_{with\_SCR}}{NOx_{w/o\_SCR}} \cdot 100\%$$

Tabel 5: Reduction rates of NOx in ETC

With B100 the NP-emissions are reduced w/o SCR, but increased with SCR. The reason for that is the interaction of secondary nanoparticles from SCR with the aerosol coming from the engine.
With B100 the exhaust gas contains much more heavy HC's, which are ready for spontaneous condensation and the secondary NP's from SCR give a "seeding effect" for that, [13].

Regarding the CPC RR with SCR (Tab. 6) the difference between Diesel and B100 is also extremely pronounced.

EGR		B100		SCR	
ETC [%]	CPCIR [1/cm³]	ETC [%]	CPCRR [1/cm³]	ETC [%]	CPCRR [1/cm³]
average Diesel	43.9	average w/o SCR	5.8	average Diesel	14.9
average B100	2.2	average with SCR	-6.6	average B100	2.6
average	23.1	average	-0.4	average	8.8

IR ...increase rate with EGR   RR ...reduction rate with B100   RR ...reduction rate with SCR

$$IR = \frac{NP_{with\_EGR} - NP_{w/o\_EGR}}{NP_{w/o\_EGR}} \cdot 100\% \qquad RR = \frac{NP_{Diesel} - NP_{B100}}{NP_{Diesel}} \cdot 100\% \qquad RR = \frac{NP_{w/o\_SCR} - NP_{with\_SCR}}{NP_{w/o\_SCR}} \cdot 100\%$$

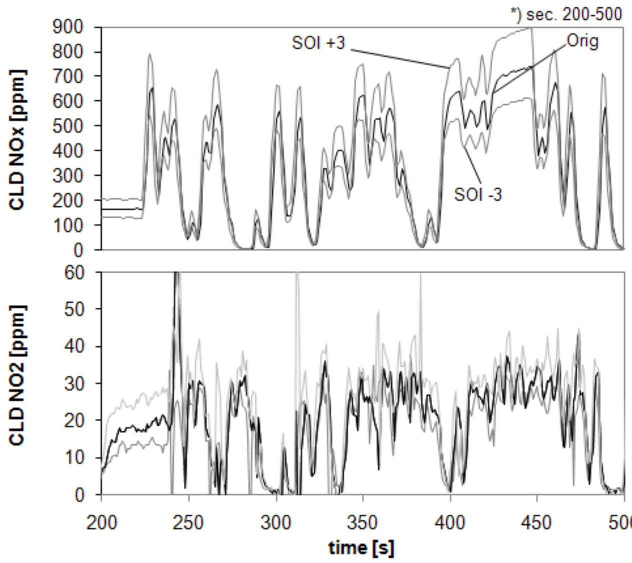
Tabel 6: Relative changes of summary particle counts (PC) in ETC

In summary regarding the Diesel fuel only it can be stated, that EGR increases NP /CPC by 44% and SCR reduces it by 15%.

Variation of start of injection SOI +/- 3°CA was performed to show the magnitude of positive and negative effects. This was done by introducing an offset in the engine operation map.

SOI is the start of main injection quantity. If there is a preinjection, it is always kept at the same distance from the main injectors.

The name SOI was introduced to simplify the understanding. In fact this is the start of energizing the injectors.



Average values over all ETC:				
SOI**)	[°CA]	-3	Orig	+3
NOx	[ppm]	233	280	348
NO2	[ppm]	19	21	26

**) SOI: Start of main injection

Fig.15: Variation of start of injection (SOI): Comparison of NOx-plots in ETC*), Iveco F1C E(4); diesel; w/o exhaust gas aftertreatment system

Fig. 15 shows the NO_x- and NO_2 plots in an interval of ETC with different SOI. As usual the earlier injection timing results in higher NO_x.

The way to reduce NO_x is the late injection, which in turn causes higher fuel consumption.

Other test with B100 at stationary and dynamic engine operation were performed with variation of SOI. They are not further described here, but the findings are included in conclusions.

Combinations of measures

In Figures 16 & 17 the effects of the investigated measures (B100, SOI, EGR, SCR) on NO_x, NP and ηe are summarized. The effective engine efficiency ηe is inversely proportional to the fuel consumption.

At low load (OP3c), Fig. 16, there is no influence of B100 on NO_x.
Reducing NOx by retarding SOI is disadvantageous for the effective efficiency (higher fuel consumption).
EGR reduces NO_x in the same magnitude, like retarded SOI, but without the draw-back of efficiency. SCR has a little effect on NO_x because of urea cut-off. All variants with B100 have lower NP-emissions than Diesel and there are only little differences between them concerning NP's.

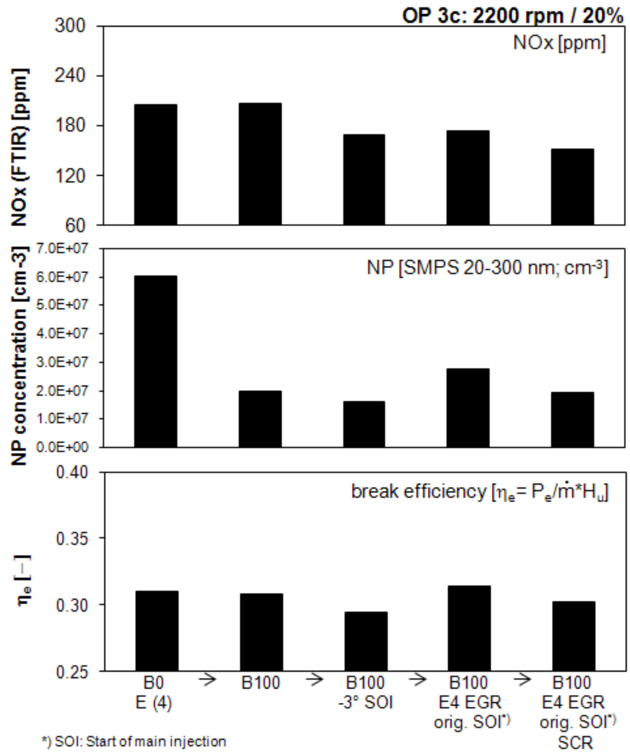


Fig.16: Influences of combinations of measures on emissions NOx & NP and on the effective engine efficiency, Iveco F1C E4; EGR, B100; SOI*), SCR

At transient operation (ETC), Fig. 17, the influences on NO_x are similar as at stationary points: slight increase of NO_x by B100, reduction by EGR and significant reduction by SCR. The NP-emission level (CPC) with B100 is higher than with Diesel.

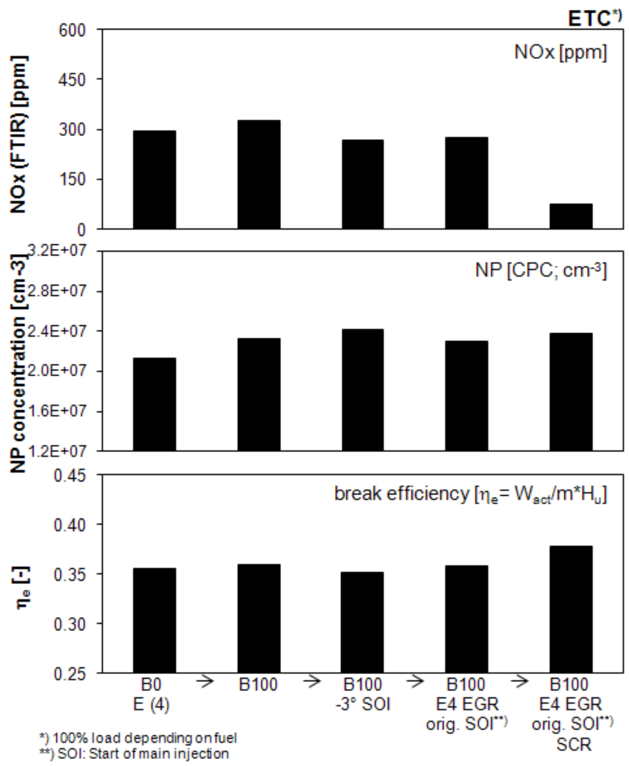


Fig.17: Influences of combinations of measures on emissions NOx & NP and on the effective engine efficiency, Iveco F1C E4; EGR, B100; SOI**), SCR

CONCLUSIONS

From the present tests performed at stationary engine operation in steps-tests and at dynamic engine operation in ETC several results can be remarked. The most important are:

General influences of EGR

EGR, which is active at middle load of version E4 has following effects:

- EGR lowers NO_x and increases CO, PAS & DC (NP),
- EGR reduces the gas throughput through the engine,
- EGR lowers the boost pressure and the backpressure,
- EGR increases the exhaust gas temperature.

These effects are confirmed in dynamic operation (ETC).

Stationary engine operation, 4 pts tests, EGR, B100, SCR

EGR: lowers NO_x, but does not impact NO_2 (NO_2/NO_x-ratio increases), lowers slightly NH_3 (which is present only with SCR), increases the NP counts in average of 4 pts 43% with Diesel & 16% with B100,

B100: increases NO_x at higher part load and full load in the range of 10-15%, reduces the NP counts in average of 4 pts by 72%.

SCR: reduces strongly NO_x & NO_2, is source of NH_3 in the range up to 20 ppm at full load, reduces HC, reduces the NP counts in average of 4 pts by 15%.

The average NO_x reduction potentials with EGR, B100 & SCR are: EGR reduces NO_x approximately in the same range (15%) as B100 increases it (12%). SCR is the strongest reduction tool in the range of 60% (by averaging only OP's with SCR active 80%).

Transient engine operation, ETC, EGR, B100, SCR

EGR : reduces NO_x (with Diesel) by 23%, no clear influence on NO_2 increases the NP counts in average by 44% (with Diesel),

B100: increases NO_x by 10%; no clear influence on NO_2 reduces PC with Diesel by 6%,

SCR: reduces NO_x (in average of all variants) by 73% and eliminates nearly NO_2 (by 95-100%); with SCR there are: an average NH_3-emission up to 12 ppm (LDS), reduces PC with Diesel (~ 15%); with B100 there is lower reduction, (~ 3%).

The NO_x reduction potentials with combination of EGR, B100 & SCR are:

EGR reduces NO_x approx. in the same range (17%), as B100 increases it (10%); SCR is the strongest reduction measure in the range of 72%.

Variation of SOI & combinations

After the tests with Diesel and B100 with variation of SOI following statements can be made:

- for fuels with different heat values, like Diesel and B100, there are different injection durations for the same power and the ECU sets differently the injection timing map,
- NO_x-emissions generally increase with advancing the SOI. At full load NO_x-values are clearly higher for B100,
- the influence of SOI on the integrated NP-emissions depends on engine load:
    - o at lower OP3c there is a tendency of increasing NP with advancing SOI,
    - o at higher OP1 the NP with Diesel decrease with advancing SOI, with B100 there is no influence of SOI,
    - o at dynamic operation (ETC) the nanoparticles emissions are not influenced by the SOI,
- with combination of different measures the increase of NO_x caused by B100 can be compensated by EGR & SCR,
- EGR is particularly useful at lower load, when SCR is still inactive,
- reducing NO_x by means of retarding SOI has a disadvantage of higher energy consumption.

Finally it can be stated, that the combination of EGR and SCR is a very important way to reduce NO_x without drawbacks for: the fuel-consumption, for other emission components and nanoparticles.

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ABBREVIATIONS

AFHB	Abgasprüfstelle FH Biel, CH
Air min	stoichiometric air requirement
BAFU	Bundesamt für Umwelt, CH (Swiss EPA)
Bxx	blend fuel with biocomponent share xx%
CFPP	cold filter plugging point
CLD	chemoluminescence detector
CNC	condensation nuclei counter
CPC	condensation particle counter
DC	Diffusion Charging Sensor
dePN	de Particles + deNO_x
DI	Direct Injection
DMA	differential mobility analyzer
DPF	Diesel Particle Filter
E3	engine version Euro3 w/o EGR
E4	engine version Euro4 with EGR
E(4)	engine version Euro4 closed EGR
ECU	electronic control unit
EGR	exhaust gas recirculation
EPA	Environmental Protection Agency
ETC	European Transient Cycle
FAME	Fatty Acid Methyl Ester
FE	filtration efficiency
FID	flame ionization detector
FL	full load
FOEN	Federal Office of Environment (BAFU)
FTIR	Fourrier Transform Infrared Spectrometer
HD	heavy duty
Hu	lower calorific value

ICE	internal combustion engines
IR	increase rate
K_x	conversion rate of “x”
LDS	Laser Diode Spectrometer (for NH_3)
LEM	limited engine map
LRV	Luftreinhalteverordnung
MD19	heated minidiluter
NanoMet	NanoMet nanoparticle summary surface analyser (PAS + DC + MD19)
NEM	nonlimited engine map
NP	nanoparticles < 999 nm (SMPS range)
OAPC	Ordinance on Air Pollution Control
OP	operating point
PAS	Photoelectric Aerosol Sensor
PC	particle counts
PM	particulate matter, particle mass
PSD	particle size distribution
RE	reduction efficiency
RME	rapeseed oil methyl ester
RR	reduction rate
SCR	selective catalytic reduction
SMPS	Scanning Mobility Particle Sizer
SOI	start of injection
SP	sampling position
TC	thermoconditioner.
ULSD	ultra low sulfur Diesel
VERT	Verminderung der Emissionen von Real maschinen in Tunelbau Verification of Emission Reduction Tech nologies
VERTdePN	VERT DPF + VERT deNO$_x$
α	feed factor of urea dosing; ratio: urea injected / urea stoichio-metric; calculated by the ECU. here α = 0.9