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Technik und Informatik
Technique et informatique

Schlussbericht 11. Oktober 2011

Einfluss der Biokomponenten (FAME) auf Emissionen und auf die Abgasnachbehandlungssysteme der Nutzfahrzeug-Dieselmotoren (BioExDi)

Influences of Biocomponents (FAME) on Emissions and on Exhaust Systems of HD-Diesel Engines (BioExDi)

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BFE-Vertrags- und Projektnummer (Verbrennung): 154222/ 103205
BFE-Vertrags- und Projektnummer (Biomasse): 154223/ 103206

Abstract

General objective of the project BioExDi (Biofuels Exhaust Systems Diesel) were to analyze the influences of RME on the functionality of modern aftertreatment systems, like regenerations of DPF, deNOx conversion rate of SCR and DOC light-off.

Also the most important results of other projects with RME are included in this final report:

- influences of RME on injection, combustion and engine-out emissions,
- behaviour of the SCR-systems in different operating conditions,
- potentials of EGR to reduce NO_x,
- unlimited exhaust gas components,
- differential PAH & toxicity equivalence (TEQ) of the particle mass.

The information about actual state of knowledge from literature and about the Swiss quality procedures for DPF (VERT / OAPC) and for SCR (VERTdePN) is given. There also are recommendations for the users of biofuels at the end of report.

Keywords: diesel particle filter, selective catalytic reduction, biofuels, FAMES fatty acid methyl esters, RME rapeseed oil methyl ester, passive DPF regeneration, active DPF regeneration, PAH polycyclic aromatic hydrocarbons, TEQ toxicity equivalence, EGR exhaust gas recirculation, Diesel injection, Diesel combustion, particle filtration efficiency, $deNO_x$ reduction rate, oxidation catalyst light-off with RME.

Die wichtigste Zielsetzung des Projektes BioExDi (Biofuels Exhaust Systems Diesel) war die Erforschung der Einflüsse von RME auf die Funktionalität der modernen Abgasnachbehandlungssysteme, wie Regenerationen von DPF, $deNO_x$-Konvertierungsgrade von SCR und Anspringen von Diesel Oxidationskatalysator.

Auch die wichtigsten Resultate anderer Projekte mit RME wurden in diesen Abschlussbericht einbezogen:

- Einflüsse von RME auf die Einspritzung, Verbrennung und Motor-Rohemissionen,
- Verhalten der SCR-Systeme bei verschiedenen Betriebszuständen,
- NO_x-Reduktionspotentiale der AGR,
- nichtlimitierte Emissionskomponenten,
- differenzierte PAH und Toxizität-Equivalenz der Partikelmasse.

Informationen über den aktuellen Wissenstand aus der Literatur, sowie über die Schweizer Qualitätsprozeduren für DPF (VERT / LRV) und für SCR (VERTdePN) wurden gegeben. Es gibt auch Empfehlungen für die Benützer der Biokraftstoffe am Ende des Berichtes.

Stichworte: Diesel Partikelfilter, selektive katalytische Reduktion, Biokraftstoffe, FAMES fatty acid methyl esters, RME Raps Methylester, passive DPF-Regeneration, aktive DPF-Regeneration, PAH polyzyklische aromatische Kohlenwasserstoffe, TEQ toxicity equivalence, AGR Abgasrückführung, Dieseleinspritzung, Dieselverbrennung, Partikel Abscheidegrad, $deNO_x$ Reduktionsrate, Oxidationskatalysator Anspringen mit RME.

CONTENTS

1. SUMMARY

The use of alternative fuels and among them the biofuels of 1st generation – FAME’s *) and pure plants oils – for propulsion of IC engines is an important objective in several countries in order to save the fossil fuels and to limit the CO_2-production.

The properties of bio-fuels and bio-blend-fuels can vary and this has an impact on the operation and emissions of Diesel engines and on the modern exhaust aftertreatment systems.

The present report summarizes the most important results obtained by AFHB during the project activities, [1, 2, 3, 4], concerning the influences of SCR and DPF on emissions with RME and RME-blended fuels.

Information and knowledge from other projects performed at AFHB are also included in the present report. These are:
- influences of bio-fuels on Diesel injection, combustion and particle emissions, [5],
- emissions with combined systems (DPF+SCR) and standard market fuel (B0), [6, 7],
- influences of EGR on NO_x-and NP-emissions, [8].

At the beginning a literature survey about influences of biofuels on engines operation and emissions is given. There is also information about the Swiss quality verification tests for DPF – VERT / OAPC and for SCR – or combined systems – VERTdePN.

At the end of the report there are some general practical remarks and recommendations, which can be useful for fleet operators with biocomponents.

The most important technical statements basing on the obtained results are:

For injection & combustion:
- RME shortens slightly the injection lag,
- RME offers a rate of heat release similarly like a market fuel, the combustion with RME 100 is slightly advanced (appr. 1°CA at FL),
- this fact and the modified reactivity of RME are the reasons for higher NO_x.

For limited emissions & energy consumption:

RME lowers CO and HC and increases NO_x at all operating points, it lowers PM at higher engine loads and increases PM at lower engine loads. RME has no effect on specific energy consumption.

For EGR & engine parameters:
- At transient operation EGR reduces NO_x approx. in the same range, as B100 increases it (10-20%); SCR is the strongest reduction measure in the range of 72%,
- EGR provokes clearly an increase of NP-emissions. By application of B100, or combinations of B100, SCR & EGR there is a balancing of several influences on NP-production,
- 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,
- reducing NO_x by means of retarding SOI has a disadvantage of higher energy consumption,

EGR and SCR can efficiently reduce NO_x and overcompensate the effect of B100 without drawbacks for: the fuel consumption, for other emission components and nanoparticles. EGR is most advantageous at low load, when SCR is not active. The start of injection SOI is connected with the trade-off between NO_x and fuel consumption and offers for the OEM a limited field of optimization.

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*) Abbreviations see at the end of report

For DPF + SCR:

- the combined dePN systems (DPF+SCR) at transient engine operation efficiently reduce the target emissions with deNO$_x$-efficiencies up to 92% (if operated in the right temperature window) and particle number filtration efficiencies up to 100%,
- 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$_x$ conversion efficiency at transient operation (ETC) strongly depends on the exhaust temperatures which are correlated with the urea-dosing strategy; during low-load operation this efficiency is strongly reduced,
- the nanoparticle filtration efficiency, which is verified at stationary engine operation, is perfectly valid also at transient engine operation,
- in dynamic tests (ETC) with DPF+SCR only higher NO$_x$-emissions with RME 100 are to remark, CO & HC are for all fuels at zero level (catalytic conversion),
- with SCR alone there is usually a small reduction of nanoparticles concentrations (in the range of 10-20%) losses in the mixing tube and in the two in line SCR catalysts; in dynamic operation this reduction is smaller (below 10%),
- with DPF using of pure biofuel B100 lowers the PCFE due to post condensation effects and increased penetration of smallest particles, except of that the lower blends (B7, B20 & B30) have no impact on PCFE.

Passive DPF regenerations with catalytic coatings:

- with the same soot loading procedure the necessary time to load the DPF for Δp = idem increases with the bio-content of fuel,
- the reasons for slower soot charging with biocomponents are:
  - lower engine-out PM-emissions,
  - higher reactivity of PM and partial oxidation during soot loading with DOC,
  - with high bio-content (here B100) lowering of exhaust gas temperature to the temperature-window of the highest NO$_2$-production in DOC, easier NO-NO$_2$ oxidation with B100 and the intensified NO$_2$-continuous regeneration,
- the repeatability of regeneration results and of the instantaneous filtration efficiencies is very good,
- the biocomponents facilitate the passive regeneration procedures.

Active DPF regenerations with standstill burner and fuel injection + DOC:

- the time-courses of emissions and temperatures are closely connected with the regeneration startegy,
- the nanoparticle penetration during the regeneration period is stochastically increased – the equivalent filtration efficiency reduced,
- the biocomponents have little effects on the start of active regeneration procedures.

Comparing the average emission levels of both investigated active regeneration types it can be stated, that the standstill burner has significantly (in 1 range of magnitude) higher CO & HC and lower NO$_x$ & NO$_2$.

DOC light-off with biocomponents

- due to the higher reactivity of RME the fuels with higher bio-content cause an easier light-off of the DOC.

PAH & TEQ

- with increasing bio-content, without DPF, there is a tendency of lowering TEQ at low load and increasing TEQ at high load,
- DPF has a positive effect of reducing PAH & TEQ, higher biofuel content has with DPF no influence on TEQ,
- no differences concerning TEQ could be remarked for catalytic and non-catalytic DPF's.

For VERT

The VERT test procedures for DPF systems and for deNO$_x$ (SCR) systems are widely accepted and they are an important tool to guarantee a satisfactory operation of retrofitted systems.

DPF: Principally the filtration of solid particles (NP) is independent of fuel B-content. Nevertheless with increasing share of bio-components there are more condensates after the DPF, which increase the particle count concentrations and simulate the lower overall PC-filtration efficiency (PCFE) of the DPF.
SCR: Biocomponents have principally no influence on the deNO$_x$-conversion rate. Nevertheless, since the catalytic activity of the SCR-catalyst is a principal effect, care has to be taken for the long life of the catalytic coatings and washcoat materials.

The most important practical recommendations are:

- for long life of catalytic coatings and for sustainable engine operation control periodically the quality of fuel and fuel supply chain,
- for active regeneration systems with high bio-content set down the threshold for starting regeneration to the lower values of backpressure, to prevent the danger of overheating of DPF during the regeneration,
- for burner regeneration, if biofuels are used for the burner, make sure the reliable ignition and operation of the burner,
- consider the general recommendation for the engine: durability of injection system and of lube oil; power reduction with fuels with lower heat value; limits of electronic regulation with changed heat value of fuel,
- generally plan more frequent oil change and inspection/maintenance intervals.

2. INTRODUCTION AND PRELIMINARY INFORMATION

According to the subjects of the presented activities the knowledge from literature and from own research is shortly described about:

- engine operation and emissions with biofuels,
- combined exhaust gas aftertreatment systems DPF+SCR,
- VERT quality testing for DPF,
- VERTdePN quality testing for DPF+SCR,
- experiences about operation of FAME’s and DPF+SCR.

2.1. Application of RME in IC Engines

Rapeseed Oil Methyl Ester (RME), called also bio-diesel is one of many Fatty Acid Methyl Esters (FAME), which can be produced from different primary vegetal oils, like soya oil, palm oil, coconut oil, sunflower oil and others.

RME (FAME) can principally be used in all Diesel engines without changes of injection system. Due to the lower heat value it causes lower full load characteristics of the engine.
RME can be aggressive against different materials, especially sealings, paints, rubber and other synthetics. It provokes a quicker oil dilution and deterioration of oil quality – more frequent oil exchange intervals as well as special oils are recommended.

RME, as all bio-fuels, is bio-degradable and CO$_2$-neutral.
Thanks to the oxygen content (10.7%) RME can lower the emissions of CO, HC including aromats, aldehydes & kethones, [9].

RME produces a lower part of insoluble fraction (INSOF) in the particle mass and it often causes higher particle number concentrations in the nuclei mode (the lowest invisible size range <40nm) due to the spontaneous condensates, [9, 10].

The soluble fraction (SOF) with RME has the lowest mutagenous effects, [9].

The comparison of PM-emissions with RME and standard fuel depends on the working collective of the engine, since the operating regime influences the SOF/INSOF proportion and RME provokes more deposited soluble organic fraction (SOF).

In an extensive study of the US EPA, [11], with blending of 20% soja oil methyl ester (SME), following average changes were found:
NO_x + 2%; PM -10,1%, HC -21,1%; CO -11.0%

In contrary to that a Swiss research program, [12, 13], found no significant improvements of emissions CO, HC & PM with 15% RME blends. The statements about PM-composition and about NP-count concentrations could be confirmed:

- EC share of the PM: significantly less than for diesel fuel, decreasing with increasing RME-content.
- OC share of the PM: much more than with diesel fuel and increasing with RME content.
- Smoke emission: Noticeably diminished black smoke and opacity, both steady-state and transient conditions, improving with larger RME content.
- Particle size distribution: consistent curtailment of particles larger than 80 nm but some increase, at all operating states, of particles smaller than 80 nm.

Further important information about biofuels can be found in [14, 15, 16, 17].

2.2. Combined systems DPF+SCR

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, [18-31].

Several authorities worldwide try to promote the clean technologies by incentives, or creating low emission zones (LEZ). Due to that also the retrofitting market of combined systems (DPF+SCR) is developing.

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 4 catalytic parts:
- precatalyst 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 [29, 31, 32, 33, 34], see [2], annex A1. 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).

Intense further research about the solutions of problems of the present systems and about new developments is going on. To mention are:

- deposits of urea related substances (urea, cyanuric acid, ammonium nitrate), [33, 34, 35],
- measuring accuracy of NO_x in presence of NH_3, [36, 37, 38],
- other reduction agents, [39, 40],
- AdBlue dosing and homogenous distribution [41],
- construction variants of DPF+SCR and their influences on functionality, warm-up, durability etc., [28, 29, 30].

Very rapid and extensive activities about deNO$_X$ and SCR take place actually in academia, in research & development and in industry; this is well demonstrated by the numerous technical conferences, which are organized about this topic in the last years (Vienna, Aachen, Dresden, HDT, TAE, CTI, SAE).

2.3. VERT quality testing for DPF

VERT verification procedure of DPF systems for retrofitting was developed in Switzerland since beginning of 90-ties.

It was a joint project of occupational insurance agencies from Switzerland (SUVA), from Austria (AUVA) and from Germany (TBG) concerning reduction of emissions of real (actual present) machines in tunnel construction, [42, 43, 44].

The objectives of VERT were to create a communication and understanding between Industry, Authorities and Customers and to guarantee the technical quality and efficiency of products, to protect health and environment.
In the initial phase VERT activities were sponsored by the occupational insurances from Switzerland, Austria and Germany and after that it became self supporting.
The quality testing of DPF system consists not only of testing the filtration efficiency, but checking all necessary subsystems, like regeneration systems, control systems, sensors and fulfilment of several general quality requirements.

Additionally to the engine dynamometer tests very important points of the testing procedure are:

- 2000 hours filed test,
- analytics of secondary emissions in justified cases.

It was recognized very quickly in the VERT project, that the retrofitting with DPF is a 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 a 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, [45, 46]. 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, [47, 48, 49].

Since 2001 there were discussions in the international legislative expert groups about possibilities of introducing the NPs as a legally limited parameter – Particulate Measurement Program (PMP) of the UN Working Party on Pollution and Energy (GRPE), [50, 51, 52, 53]. These efforts conducted to introduction of particle count limits for Diesel passenger cars (since 2009, Euro 5), for HD trucks (since 2013, Euro VI) and for DI gasoline cars (since 2014, Euro 6).

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$_x$-systems (SCR, EGR, storage catalysts) in the VERT verification procedures (VERTdePN Programm since 2008).

2.4. VERTdePN for DPF+SCR

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.

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:

- 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:

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

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

2.5. FAME’s and DPF+SCR

Short information about influences of FAME’s on the Diesel exhaust gas aftertreatment from literature survey is given in this section.

DPF regeneration, soot oxidation & structure

The impact of blending 20% SME (soy methyl ester) to Diesel fuel on the regeneration of a catalyzed DPF was investigated in [54] (US) on a Cummins 6 cyl. 5.9 L engine. The used tools were: the traditional engine diagnostics for injection, combustion and limited emissions, as well as analytics of soot composition and structure. It was shown, that biodiesel blending alters the composition of the particulate matter (PM), as well as the nanostructure of the primary soot particles and thereby alters the regeneration behaviour of DPF. The inclusion of biodiesel in the base fuel reduces the temperature required to initiate the regeneration. This is attributed to the changed nanostructure and oxidation reactivity of the primary soot particles, yielding a more amorphous soot structure, which enhances the soot oxidation.

In [55] the same researchers group focused on the mechanisms of oxidation of biofuel soot (B100, SME) and confirmed that due to different structure and oxygen content the B100 soot is more reactive and undergoes a different oxidation process, than the soot derived from Diesel fuel (ULSD & FT). By means of partial oxidations and a detailed analysis of soot structure it was shown that the crucial mechanism by which biodiesel soot enhances oxidation is a structural transformation of the surface of the soot conglomerates in the early stage of oxidation, whereby the initial surface oxygen groups are more important than the initial structure and pore size distribution.

In [56] the effects of biodiesel blends (B20 & B100, SME) were investigated on a Cummins engine 5.9L with a catalyzed CRT (continuously regenerating trap). Significant lowering of the balance point temperature (Δt 45°C with B20 Δt 112°C with B100), as well as an increase of regeneration rate was found. If it would be possible to renounce on active regeneration system due to the use of biofuels, this would mean a supplementary energy saving.

Also finish researchers, [57], investigated B50 & B100 (seed oils methyl ester) on two engines, found differences of morphology (SEM), differences of chemistry and more easy passive regeneration of DPF with biocomponents. It is suggested that potassium contained in the investigated oils might assist in formation of inorganic substances, which would catalytically lower the ignition temperature of the soot.

German researchers, [58], give an extensive overview of different alternative fuels for Diesel engines (except of FAME also dimethyl ether (DME) and synthetic fuels (xTL)). There is also an overview of exhaust gas aftertreatment systems.
Important statements are given about the risks of deactivation of catalysts (thermal, chemical & mechanical deactivation effects), which is known from several experiences with biofuels in the past. The limiting of impurities and phosphorus in b-fuels according to the present standards is an obligatory prerequisite for successful operation.

DeNO$_x$ – selective catalytic reduction (SCR)

Application of biocomponents in fuels was found to modify the conversion rate of a SCR (Ag/Al_2O_3), [59], (Finland).
The NO$_x$-reduction was better at lower exhaust gas temperatures (< 400°C) and worse at higher temperatures (> 400°C).

Detailed mechanisms of chemical deactivation of Vanadia-based SCR catalyst are shown in [60] (PSI Switzerland).
A careful attention about purity and quality of the used biofuels, as well as the choice of the lubricating oil are the best ways to keep the long time activity as high as possible.

Mutagenicity

Mutagenicity of particle mass from RME was investigated in [61] (Germany). It was found that the mutagenous activity with biodiesel is much higher than with base fuel and it is the highest with B20, (nonlinear dependence on biofuel ratio).
In opposite to that another German research group found the mutagenicity of biodiesel much lower, [62].

3. OBJECTIVES of BioExDi

The project "Influences of Biocomponents (FAME) on Emissions and on Exhaust Systems of HD-Diesel Engines" (BioExDi) was initiated to investigate with newer methods the impact of different blend fuels on engine emissions with DPF+SCR.

In the Diesel sector the fatty acid methyl esters (FAME's) – in Europe mostly RME *) (rapeseed oil methyl ester) and in US mostly SME (soja oil methryl ester) – are largely used as blends with the Diesel fuel (B10, B20, Bxx). In Scandinavia FME (fish oil methyl ester) is often used.
The use of low blending ratios, like B5 or B7 is common, but the use of higher ratios (up to B30) is rarer. The use of B100 is a niche, similarly like the use of crude plant oils.
The present project focuses on FAME's being the most important representatives of the biofuels of 1st generation.

There are several open questions and sometimes contradictory opinions about the emissions (especially unregulated components) with these fuels, about the influences on DPF regeneration and about ageing of catalysts (DPF & SCR systems).

Further basic research with the newest analytical tools is performed in this project in collaboration between industry and research institutes.

General objective is to analyze the influences of different FAME's on the functionality of modern exhaust gas aftertreatment, like regeneration of DPF, or deNO$_x$ conversion rate of SCR.

The objective of the present final report is to summarize the most important results obtained by AFHB during the project activities.

The project was performed in 2 moduls with following objectives:

SCR – investigations of influences of FAME's on:

- deNO$_x$ rate
- limited and unlimited emissions, incl. NP, FTIR (during stationary and dynamic operation)
- fouling, distributions of fouling, changes of wash coat (anatomy of the substrate)
  → investigation at EMPA.

DPF – investigations of influences of FAME's on:

- regeneration process (soot loading, light off, speed)
- limited and unlimited emissions, incl. NP, FTIR (during stationary operation and during the regeneration)
- anatomy of filter material → distribution and structure of ash- and soot deposits – influences of FAME's → investigations at EMPA.

In both modules choosen series were investigated on PAH, TEF & TEQ (task sharing collaboration MoU BAFU - JRC).

Additionally several practical remarks and recommendations have to be given, which would help to the user of biofuels FAME's to attain a satisfactory engine operation with possibly lowest exhaust emissions and energy consumption.

4. TEST-ENGINES, FUELS AND LUBRICANTS

4.1. Test engines data

Two Liebherr engines for construction machines were used during the projects with RME. Both of them had identical dimensions of engine block, as well as of the intake and exhaust attachment. Due to the collaboration with the engine manufacturer an access to the engine ECU was given, which enabled the setting of certain parameters and of the full load characteristics. These engines were used for the preliminary research of injection, combustion and emissions as well as for the VERT testing of DPF’s.

For testing of SCR-, or (DPF+SCR) - systems an IVECO engine (Euro 3) was used. This engine, which is without EGR for the E3-version, was transformed in collaboration with the engine manufacturer to the version Euro 4 with EGR. The access to certain engine parameters and switching on/off EGR was enabled. This engine is attached to a dynamic brake, which makes possible all kinds of dynamic testing.

Manufacturer	**Liebherr Machines Bulle S.A., Bulle/Fribourg**	**Liebherr Machines Bulle S.A., Bulle/Fribourg**	**Iveco, Torino Italy**	**Iveco, Torino Italy**
Type	D934 L	D934 S	F1C Euro 3	F1C Euro 4 *)
Displacement	7.01 Liters	6.36 Liters	3.00 Liters	3.00 Liters
RPM	2000 min^{-1}	2000 min^{-1}	max. 4200 rpm	max. 4200 rpm
Rated power	140 kW	111 kW	100 kW @ 3500 rpm	105 [kW] @ 3500 [min^{-1}]
Model	4 cylinder in-line	4 cylinder in-line	4 cylinder in-line	4 cylinder in-line
Combustion process	direct injection	direct injection	direct injection	direct injection
Injection system	Bosch unit pumps	Bosch unit pumps	Bosch Common Rail (CR) 1600 bar	Bosch Common Rail (CR) 1600 bar
Supercharging	Turbocharger with intercooling	Turbocharger with intercooling	Turbocharger with intercooling	Turbocharger with intercooling
Emission control	none (exhaust gas after-treatment according to the requirements)	none (exhaust gas after-treatment according to the requirements)	none	cooled EGR**)
Development period	2005	2005	until 2000	until 2005

*) light duty and heavy duty

**) in present tests engine was used with open E4, or with closed E(4) EGR

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

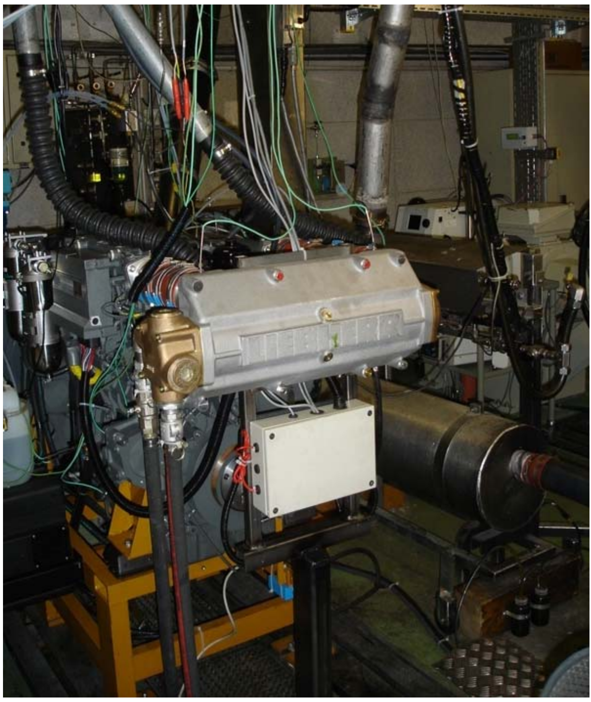


Fig.1a: LIEBHERR engine D934 in the engine room

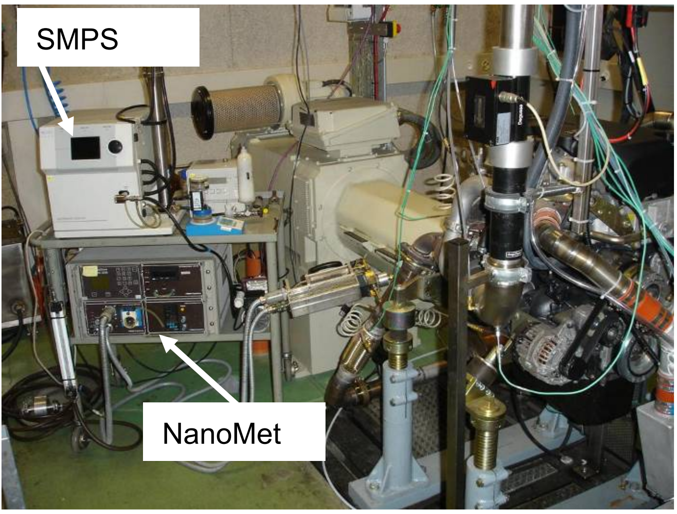


Fig. 1b: Iveco engine F1C and equipment for nanoparticle measurements in the engine room

4.2. 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 from exhaust to the intake collector),
- EGR cooler, (with engine cooling water),
- throttle valve at intake, (after intercooler),
- 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 [63] 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:

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

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%).

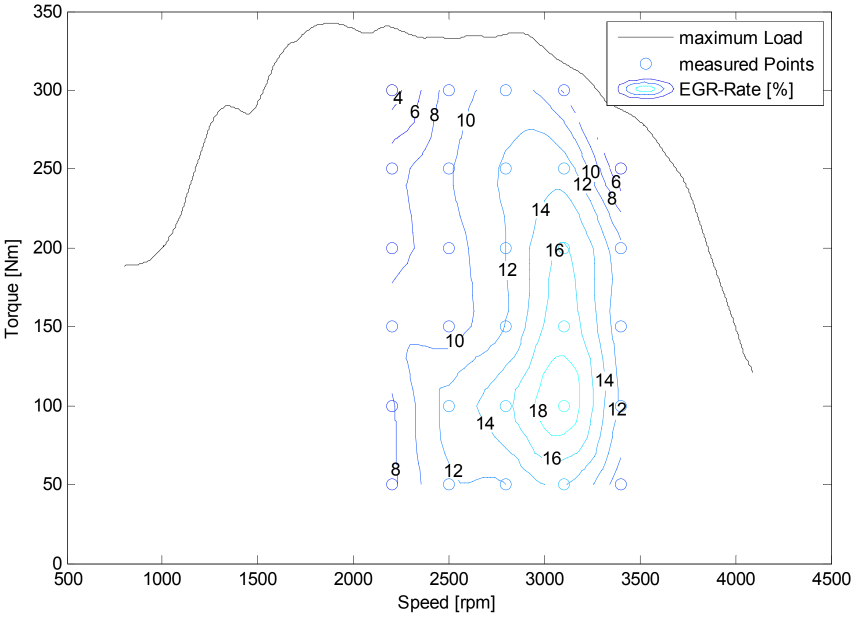


Fig. 2: EGR-Map of the heavy duty IVECO F1C-engine Euro 4, [8]

4.3. 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 are taken into account by the evaluation of measurements. The resulting fuel parameters for the blend fuels are represented in Table 2.

	Diesel	RME
Density at 15°C g/m	0.842*	0.845*
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
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

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

	ρ(20°C) [kg/dm^3]	Hu [MJ / kg]	Air min [kg $_A$ / kg $_F$]
Diesel	0.832	42.70	14.52
RME 7	0.835	42.30	14.38
RME 10$^{*)}$	0.836	42.12	14.32
RME 20	0.842	41.55	14.10
RME 30	0.846	40.98	13.89
RME 100	0.880	37.20	12.49

* only preliminary tests, [5]

Table 2: Principal parameters of the blend fuels

4.4. Lubricants

For the Liebherr engines the Lubrizol research oils, both of ACEA class E4 were used:

Liebherr D 934 L: oil OS No. 164713, red 15W/40,
Liebherr D 934 S: oil OS No. 165108, blue 15W/40.

For the Iveco engine a special lube oil Mobil 1 ESP Formula 5W-30 was used (ACEA classes: C3, A3, B3/B4, API classes: SL / SM; CF).

Table 3 shows the available data of the lube oils.

Property		**Lubrizol** oil OS No. 164713, red 15W/40 **Liebherr D 934 L**	**Lubrizol** oil OS No. 165108, blue 15W/40 **Liebherr D 934 S**	**Mobil oil** **Iveco engine**
Viscosity kin 40°C	mm^2/s	104.8	-	72.8
Viscosity kin 100°C	mm^2/s	14.22	13.98	12.1
Viscosity index	(--)	139	-	164
Density 15°C	kg/m^3	-	-	0.850
Pourpoint	°C	-25	- 25	-45
Flamepoint	°C	-	-	254
Total Base Number TBN *	mg KOH/g	13.5	8.4	6
Sulfur ashes *	mg/kg	18‘000	10’770	6’000
Sulfur *	mg/kg	6’500	3’360	2’000
Mg *	mg/kg	< 10	< 10	41
Mo *		-	-	80
Zn *	mg/kg	1’270	1‘200	900
Ca *	mg/kg	4‘730	2‘630	1‘100
P *	mg/kg	1‘160	1‘110	820

Table 3: Data of the utilized oils (* analysis, others: specifications)

5. TEST METHODS AND INSTRUMENTATION

5.1. Engine dynamometers and standard test equipment

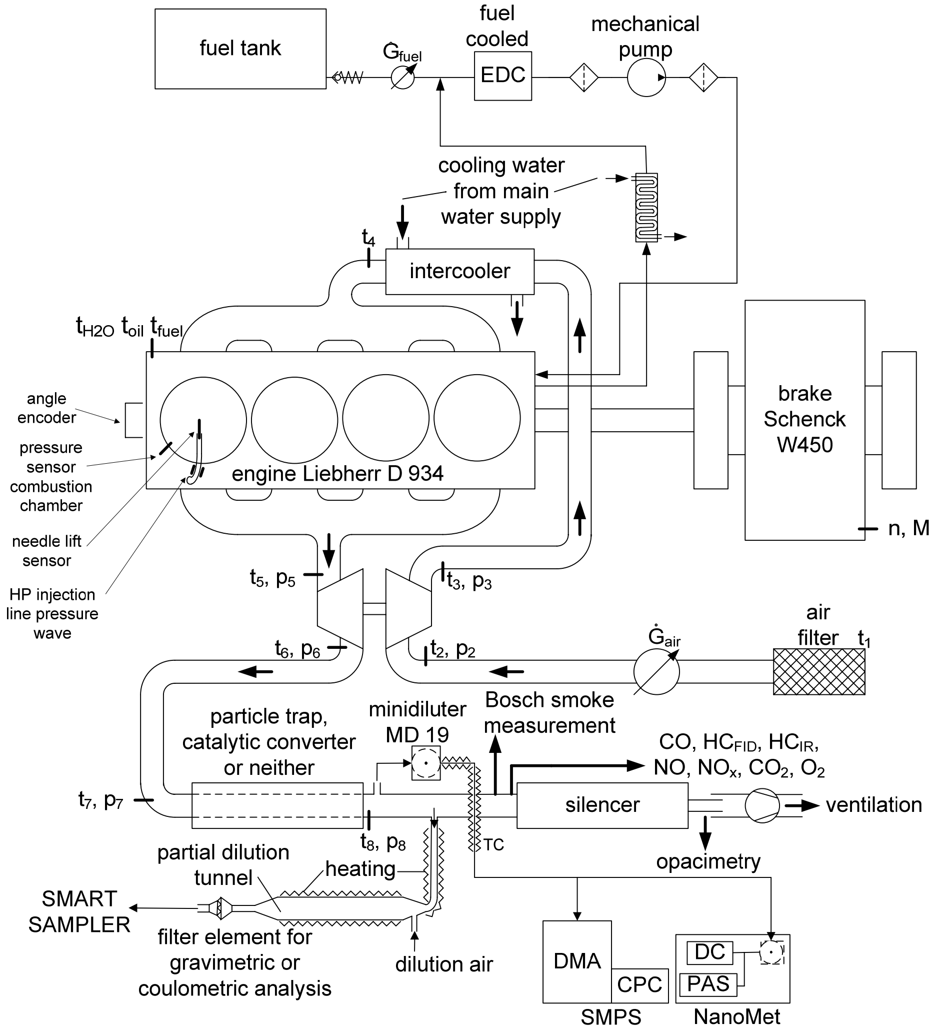


Fig. 3: Engine dynamometer and test equipment for DPF testing on Liebherr engine, [5]

Fig. 3 represents the special systems installed on the engine, or in its periphery for analysis of the limited and unlimited emissions on Liebherr engine. The positions of measured control parameters (p, T) in different positions of the air- and gas path are marked.

For the preliminary research of injection and combustion some sensors were installed in the 1st cylinder to enable a specific diagnostics, [5]. These were:

- sensor for indication of the pressure wave in the HP injection line,
- needle lift sensor in the injector,
- sensor for combustion chamber pressure indication with crank angle encoder.

For VERT testing of DPF systems this diagnostics of injection and combustion is not used. For research of DPF regenerations with active systems (burner, fuel injection) some supplementary adaptations of the exhaust system were performed, [4].

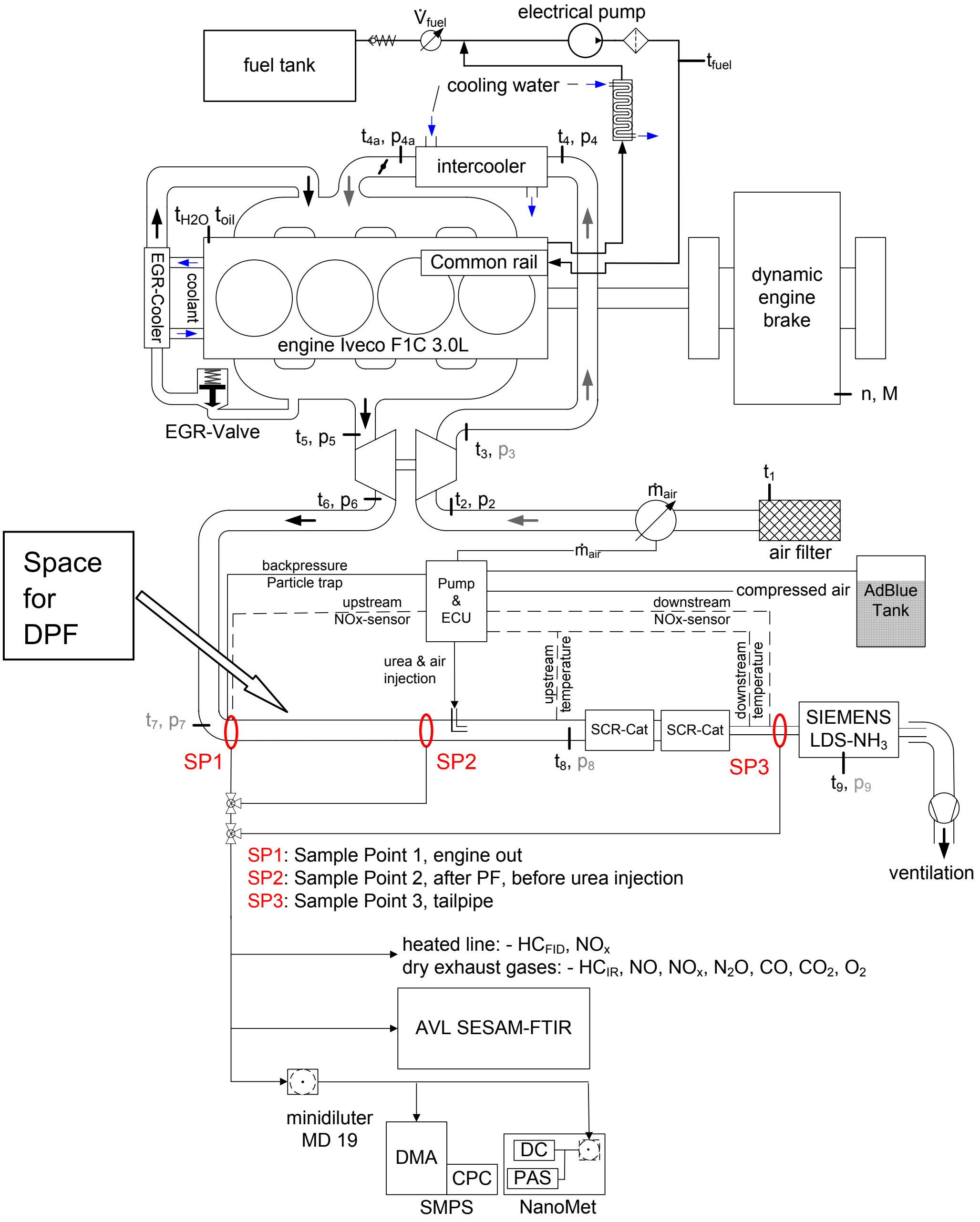


Fig. 4: Engine dynamometer and test equipment for testing of SCR-systems on Iveco engine (engine variant with EGR, [8])

Fig. 4 shows the scheme of installation, the measured parameters and measuring systems in the engine exhaust for the Iveco engine – a version Euro 4 with EGR. The SCR-system has an own ECU and control sensors (NO_x and temperature).
For research different sampling positions (SP) in the exhaust system were used. For combined exhaust aftertreatment systems (DPF + SCR) a DPF is mounted between SP1 and SP2, [6, 7].

The measuring systems for standard- and for non-legislated components are used according to the necessity for both engine dynamometers.

5.2. Test equipment for exhaust gas emissions

Measurements are 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
    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 & N_2O:
  With SCR several unlimited components can be produced. The slip of gaseous components: 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 possibility of simultaneous, time-resolved measurement of approx. 30 emission components – among others: NO, NO_2, NO_x, NH_3, N_2O, HCN, HNCO.

5.3. Particle counts & 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. 1:

- 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) – heated up to 80°C
  - Thermoconditioner (TC) (i.e. MD19 + postdilution sample heating up to 300°C).

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

6. TEST PROCEDURES ON ENGINE DYNOS

According to the different objectives of the respective test series several test procedures were used.

On both engine dynamometers stationary operating points (OP), so called steps-tests were performed. An example is given in Fig. 5, [6]. In VERT Filter Test (VFT) generally 4-points tests are used, [2].

The VERT secondary emissions tests VSET consist of repetitions of 8-points tests, [3]. In other tests certain OP’s were chosen or added according to the research objectives. Particularly to mention is the addition of 3 operating points between OP3 and OP4 to better recognize the urea switch on/off of the SCR-system, [1].

All steps-tests were performed with a warm engine and for each research task always in the same sequence and with the same operating duration of the OP’s.

After analyzing the backpressure of the (DPF+SCR) system at stationary operation in the Iveco engine operation map it was decided to limit the operation range, Fig. 5. In this limited engine map (LEM) different steps-tests were defined.

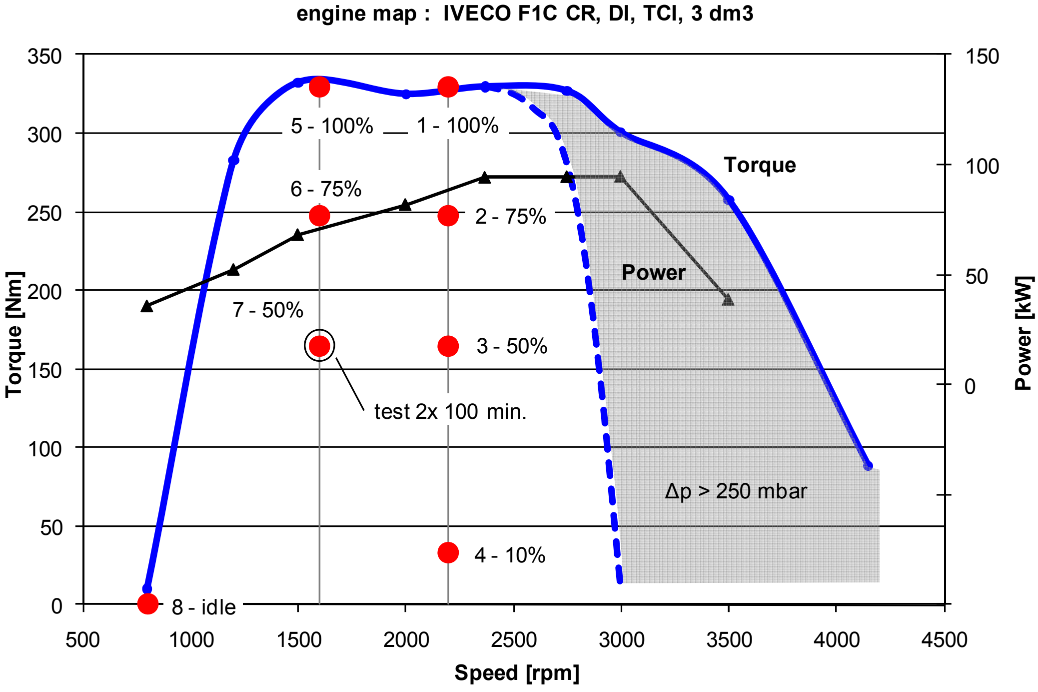


Fig. 5: Limited engine map of the IVECO F1C engine and 8 points test according to ISO 8178

With the biofuels,or bio-blend-fuels the calorific value of the fuel changes and so does the full load torque (FL). In the test programs the part load OP’s were generally driven with the same power (speed & torque) and for the FL OP’s only the required speed was kept (torque resulted from the fuel). The injection characteristics of the engines were not changed, which represents the usual situation in the market application.

For a more detailed investigation of the tested combined systems (DPF+SCR) different sampling positions (SP) were used on the Iveco engine, see Fig. 4.

On Iveco engine the dynamic testing was performed mostly with the ETC (European Transient Cycle), which was defined on the basis of the non limited engine operation map (NEM), for the engine version E3, Fig. 6. The definition of ETC was not changed for the engine version E4 to keep a better comparability with the previous results.

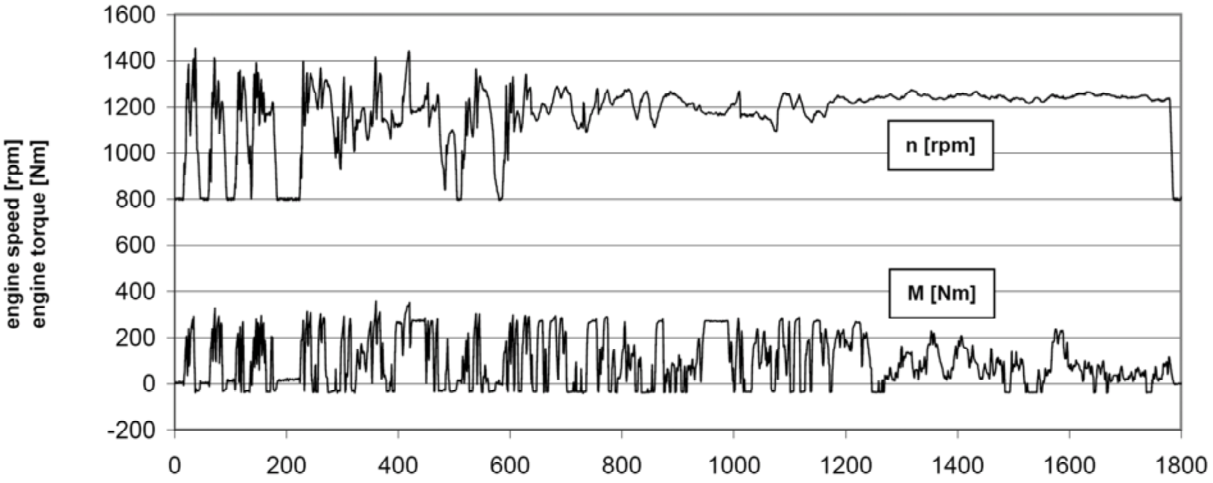


Fig. 6: Torque & speed in ETC IVECO F1C.

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.

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 + 0.5 min idling for ETC & WHTC and 5 min pt. 3 + 0.5 min idling for NYCC & Braunschweig Bus Cycle (both low load).

7. TEST OBJECTS

(DPF+SCR) - systems

The combined exhaust gas aftertreatment system (DPF+SCR) was installed on the IVECO research engine in the ICE-laboratory in Biel, CH, see Fig. 7.

This system is designed for dynamic on-road applications.
The filters and catalysts are exchangeable modules.

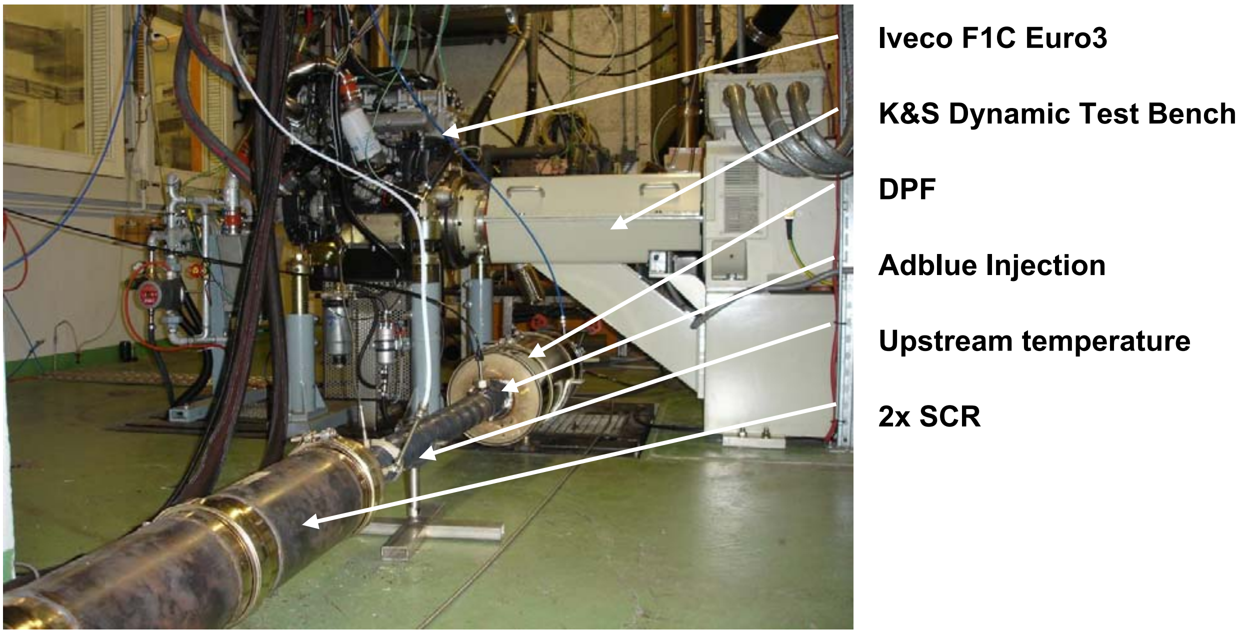


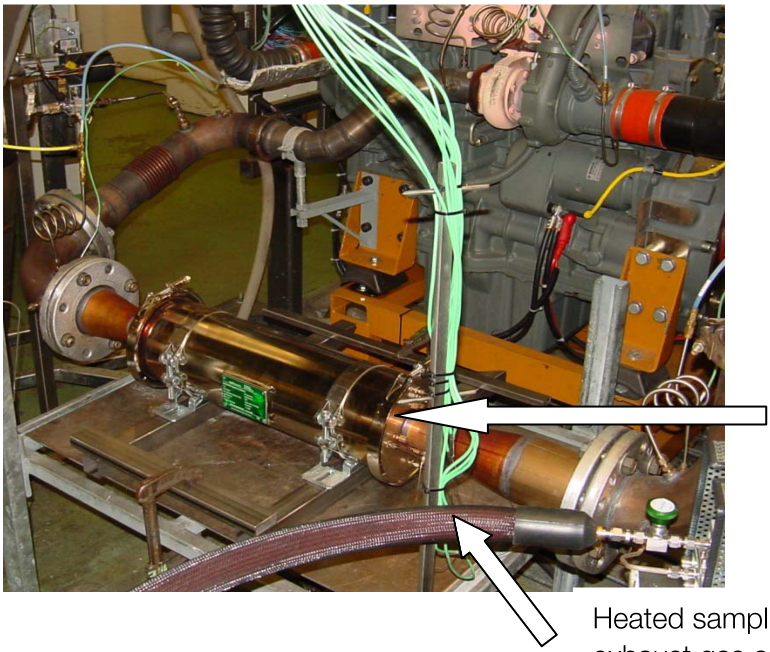
Fig. 7: (DPF+SCR) system on the Iveco research engine, [1, 3, 6, 7]
The investigated combination is: a coated DPF upstream and Vanadium-based SCR catalyst downstream of the urea injection point. For investigations with SCR only the DPF was removed (see Fig. 4).
Additionally to the elements in the engine exhaust system an Ad Blue-tank and Ad Blue injection unit with pump, sensors and electronic control were installed in the laboratory.

DPF-systems

For the research of impacts of the biocomponents on the DPF regeneration following DPF systems were supplied:

- HUG mobiclean RS, DOC+CSF (DPF with catalytic coating), Fig. 8, [2]
- HUG mobiclean RS, CSF only, [2]
- HUSS MK system with standstill burner regeneration, Fig. 9, [4]
- HUSS MD system with fuel injection+DOC, [4]

All applied filter materials were SiC (silicon carbid) with a high average filtration efficiency PCFE > 98% fulfilling the VERT quality criteria.


DPF installed in the exhaust line

Heated sampling line for exhaust gas analysis

Fig. 8: HUG DPF with passive regeneration (DOC+CSF) on the Liebherr engine, [2]

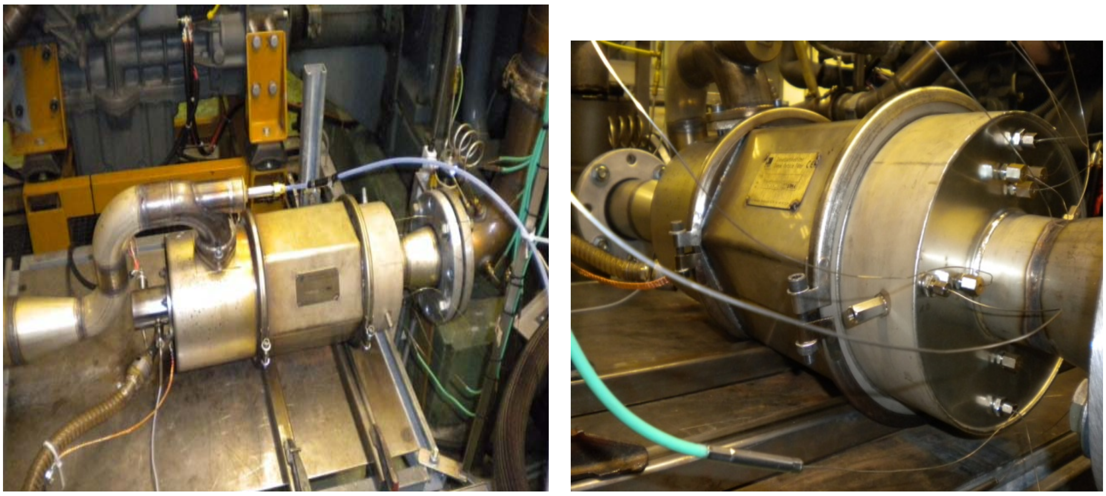


Fig. 9: HUSS DPF-system with active regeneration (burner) on the Liebherr engine, [4]

8. RESULTS

8.1. Preliminary research of injection, combustion and emissions with RME

Tests performed on Liebherr D 934L

Injection and combustion

Fig. 10 represents the signals of injection line pressure p_L, needle lift NL and combustion chamber pressure p_i, which are plotted over the crank angle for all operating points with diesel fuel at 1500 rpm. These signals are taken from representative single working cycles.

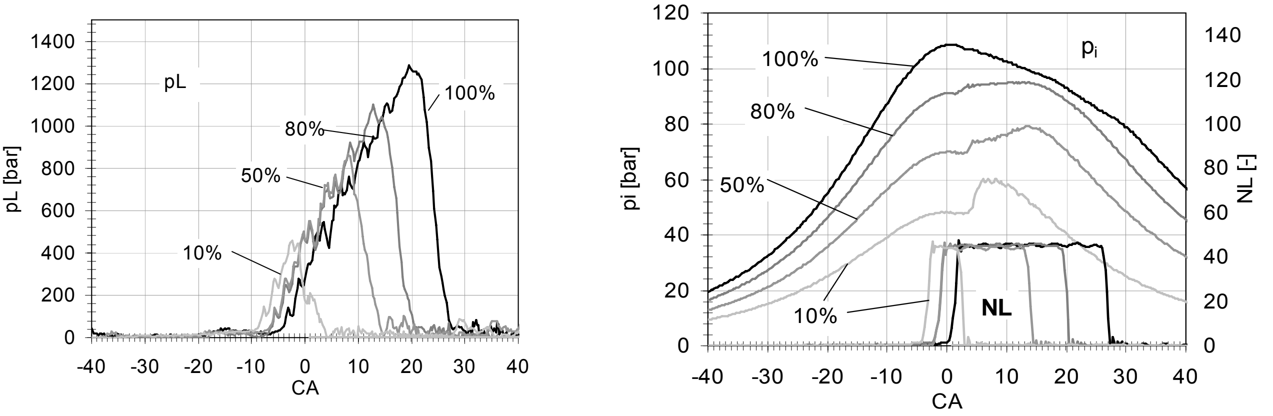


Fig. 10: Injection line pressure pL, needle lift NL and indicated combustion pressure pi, at constant speed (1500 rpm) and increasing load

The usual interaction of these parameters is well depicted: with increasing engine load the injection duration is longer, the injection pressure and the combustion chamber pressure attain higher maximum values.

The pressure wave in the HP-injection line has a typical shape for all cam-driven injection systems with the maximum of injection pressure near to the end of injection event.

It can be remarked, that with increasing load the start of injection (SOI) is moved (by setting of the ECU) to the later position. This injection retard is introduced on purpose to lower NO_x at higher part load and at full load operation (naturally with a drawback of specific fuel consumption). This fact reduces the differences of NO_x by comparison of different fuels at FL.

Fig. 11 puts together the maximum values of injection pressure p_L. The fuel with higher viscosity RME causes higher peak pressures. At nominal power (2000 rpm/FL) with RME the maximum injection pressure attains almost 1600 bar.

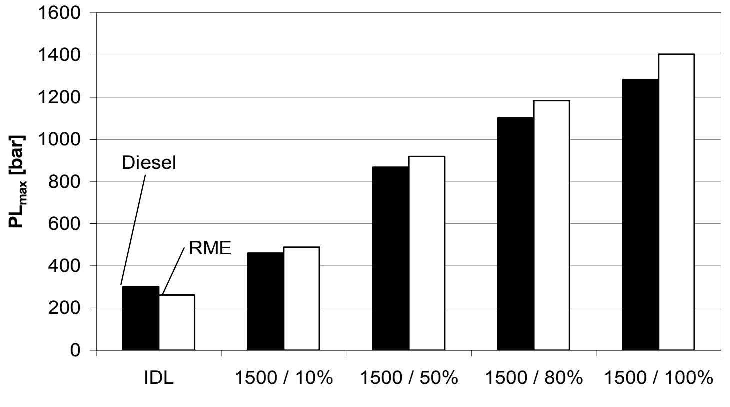


Fig. 11: Maximum injection pressures with 2 fuels

Fig. 12 shows plots of heat release and rate of heat release for Diesel & RME at lower and at higher load.

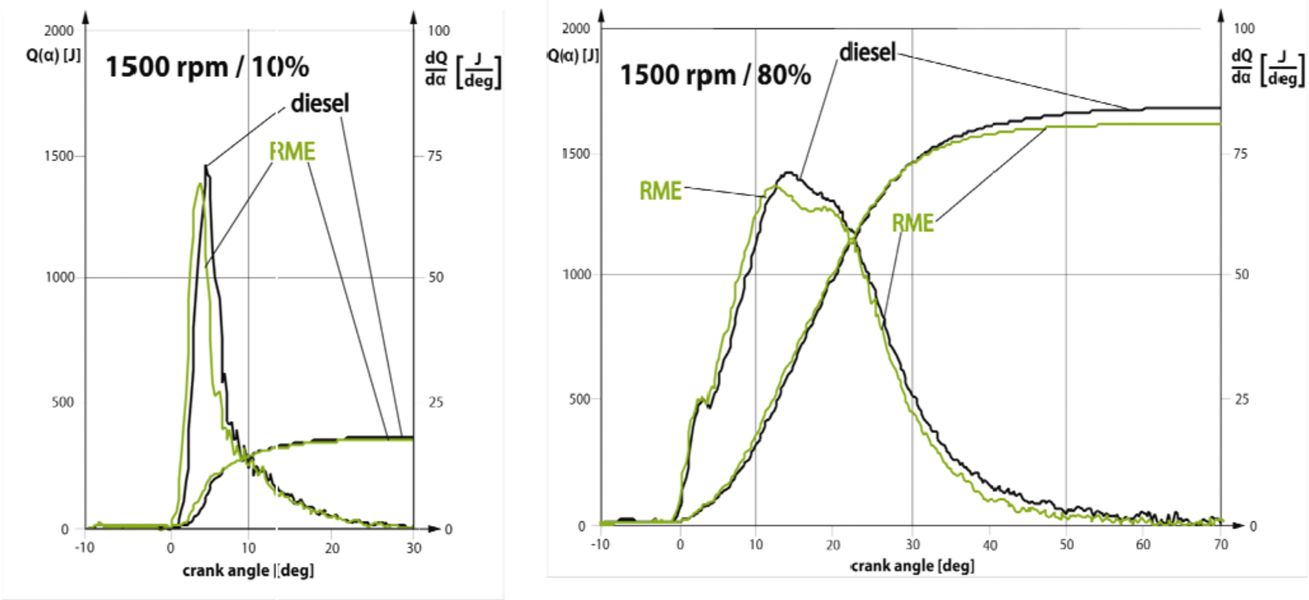


Fig. 12: Heat release with 2 basic fuels

At lower load (1500 rpm / 10%) RME starts as first to burn, but with a slightly slower rate.

At higher load (1500 rpm / 80%) RME starts to burn a little earlier and at higher rate, than Diesel. Nevertheless the differences between the plots are very little (e.g. differences of $\alpha_{50\%}$ in the range of 1°CA).

Fig. 13 shows the time-progress of injection and combustion for Diesel and RME in function of engine load at constant speed (1500 rpm).
RME causes also a shorter ignition lag. It burns as quickly, as Diesel, so that $\alpha_{50\%}$ for RME follows 1-2°CA earlier (reason for higher NO_x).

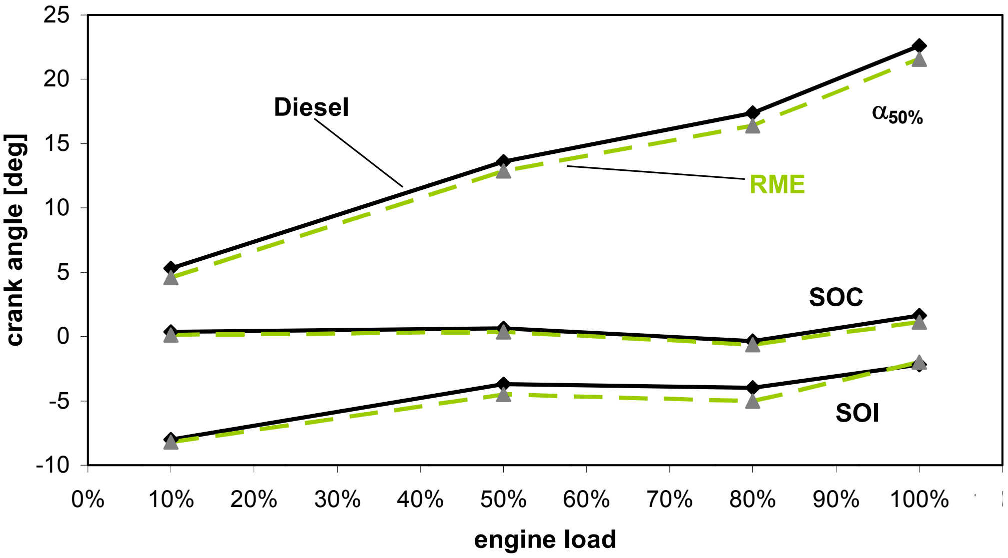


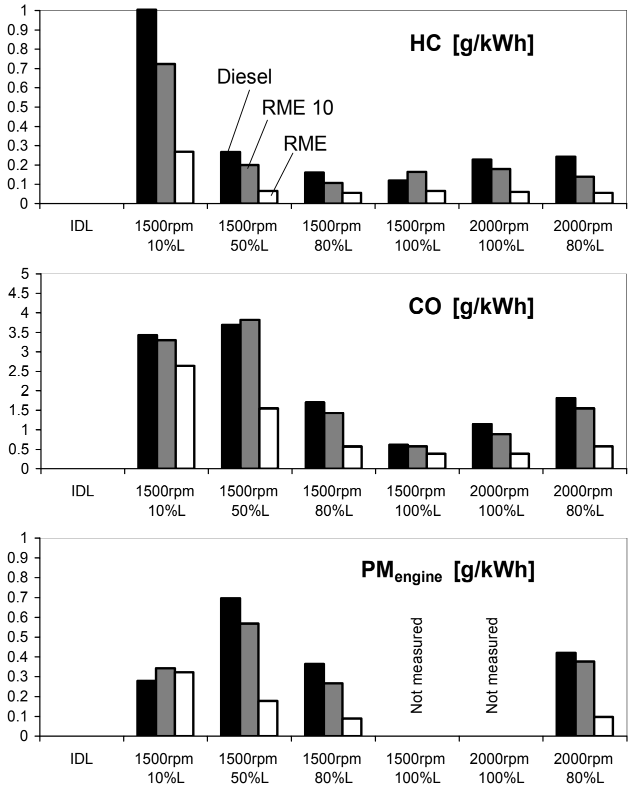
Fig. 13: Injection and combustion progress with different fuels at 1500 rpm

It can be said, that the biofuel RME has no draw-backs of inflammation and combustion in contrary it can offer a quicker energy conversion in the first period of combustion.

The results represented in Figures 12 & 13 are averages of 50 cycles.

Limited emissions & nanoparticles

Figures 14 & 15 summarize the results of limited emissions (CO, HC, NO_x, PM) and of specific energy consumption for all performed measuring series and all operating points. It can be remarked:



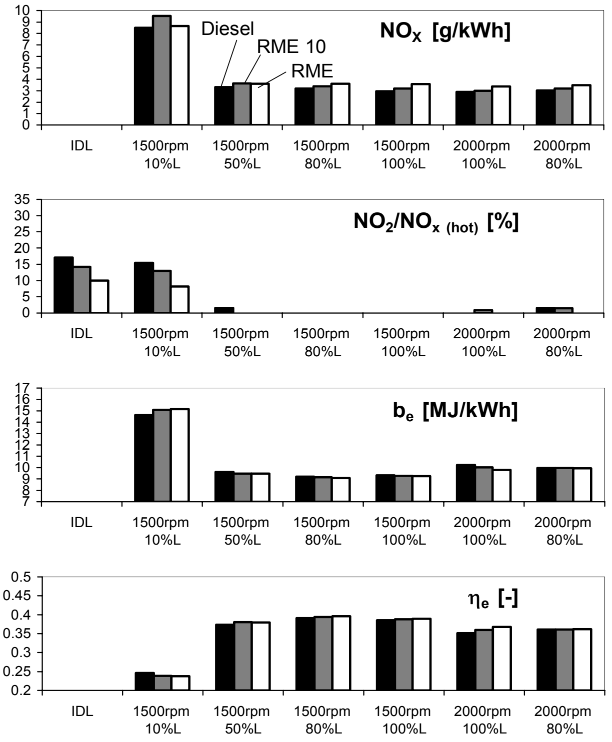


Fig. 14: Comparison of gaseous and particle emissions with different fuels

Fig. 15: Comparison of NO_x emissions and specific energy consumption with different fuels

RME lowers CO and HC and increases NO_x at all operating points, it lowers PM at higher engine loads and increases PM at lower engine loads. RME has no significant effect on specific energy consumption.

The blend with 90% vol Diesel fuel shows usually results, which are between the results for both pure fuels.

Generalizing it can be said, that:
The investigated RME fuel is advantageous for CO, HC and PM with a penalty for NO_x.
The effects of slightly lower energy consumption are in the range of measuring dispersion.

These tendencies can reverse at low-load-operation, which explains that comparisons at different part load driving cycles may yield different results.

It was shown (Fig. 10), that the injection timing at high- and full-load of this engine is set quite late (power limitation and minimizing NO_x for this engine version). Due to that the higher NO_x-emissions with RME are not so much pronounced, like they use to be for modern HD trucks.
A representation of particle emissions with the investigated fuels at operating points 1500/10% and 1500/80% is given in the Figures 16 & 17.

In this representation the comparisons of particle mass PM, summary aerosol surface DC and SMPS number concentration integrated in the size-range 20-300nm are included.

With RME the maximum of PSD (accumulation mode) at high load is moved to smaller sizes (approx. 50-60 nm) and the nuclei mode starts to appear already at high load. At low load (idling & 10%) the nuclei mode is much more pronounced than for Diesel. This is caused by more spontaneous condensates (more SOF) with RME.

The NP-emissions with RME10 are similar to those with Diesel.

There are lower particle emissions with RME at high load and higher emissions at low load. As already known from other research these higher emissions at low load are caused principally by the condensated substances (increased SOF-content), which is depicted by a part with increased nuclei mode.

Regarding the integrated SMPS particle numbers in the range 20-300nm for all measuring series and all operating points it can be stated, that there are no influences of RME, or RME10, on the summary nanoparticles counts, because there is a balancing effect between the higher nuclei mode and lower accumulation mode with RME.

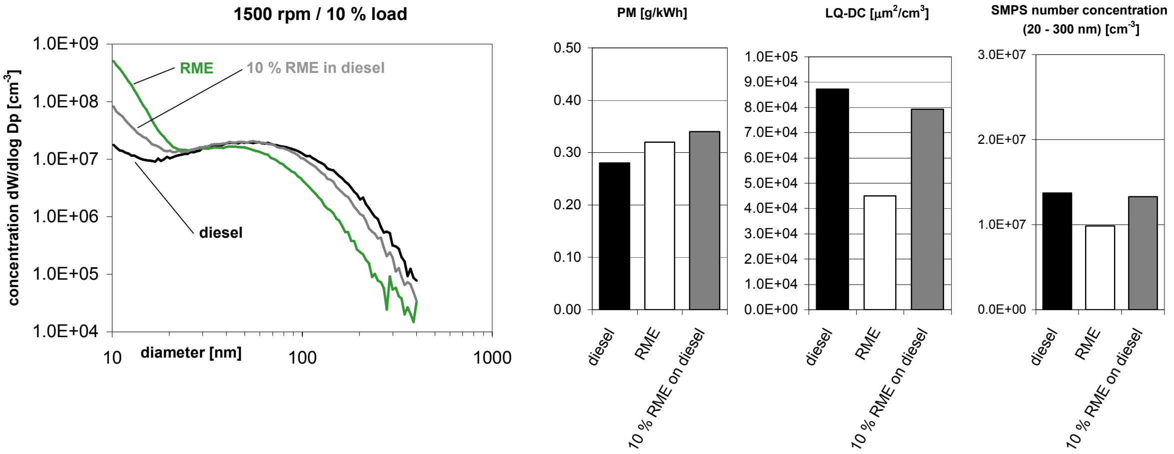


Fig. 16: Particle mass and nano-particles; comparison of different fuels at low load

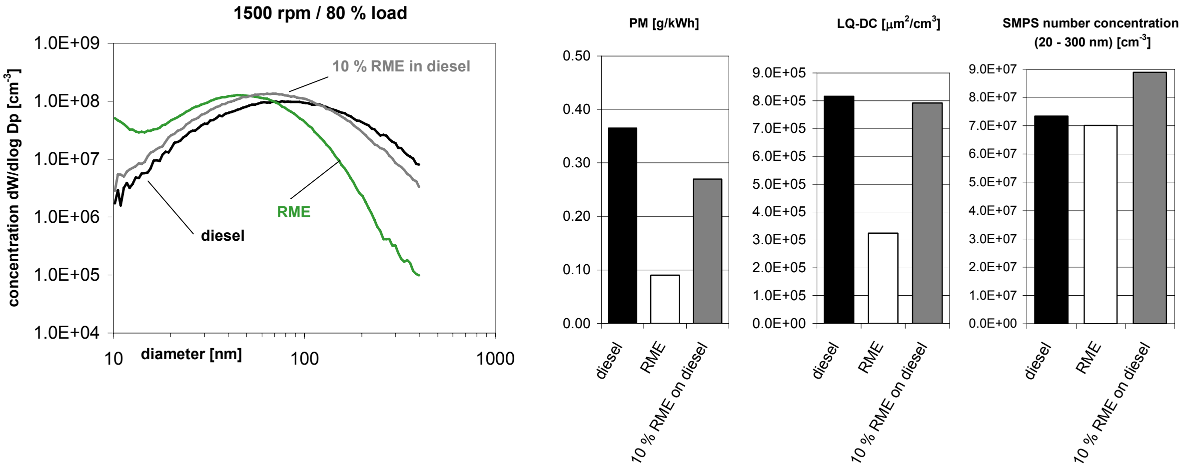


Fig. 17: Particle mass and nano-particles; comparison of different fuels at high load

Coulometry EC&OC

At the operating points: pt. 2. 1500 rpm / 10% and pt. 4. 1500 rpm / 80% single samples of particulate matter for coulometry were taken for Diesel and RME. The coulometric analysis of filter residuum was performed by the SUVA analytical laboratory.
The standard procedure consists of thermal extraction of SOF with N_2 at 500°C during 8 min and after that of the EC-oxidation with O_2 at 650°C.
Since RME is a fuel, which produces higher portion and heavier SOF, it was decided to increase the temperature of the first thermal N_2-extraction to 800°C for all samples.

The coulometric results EC, OC & TC – all values responding to 3 min sampling time on the entire measuring filter and to the same sampling conditions – are represented in Fig. 18.

It can be remarked, that:

- higher engine load produces less OC and more EC, i.e. "dryer" soot
- RME causes higher portion of OC (lower portion of EC), which is particularly pronounced at lower engine load
- RME reduces the total PM at higher engine load, especially due to the reduction of EC.

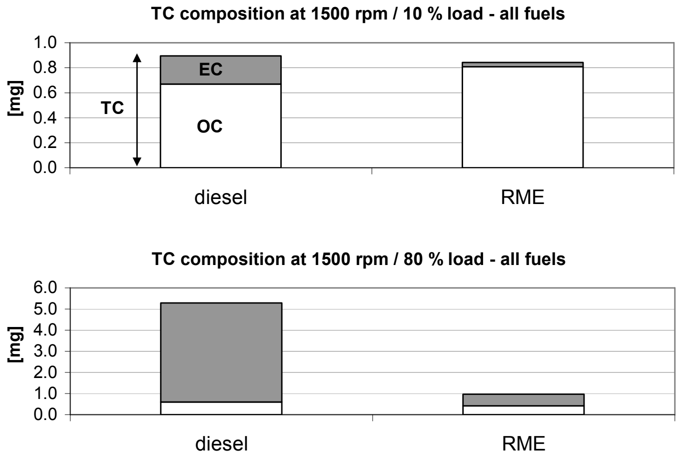


Fig. 18: Influences of engine load on EC/TC-ratio for different fuels

Conclusions

The most important influences of the investigated alternative fuels on the Liebherr D 934L engine can be summarized as follows:

Limited emissions & energy consumption:

RME lowers CO and HC and increases NO_x at all operating points, it lowers PM at higher engine loads and increases PM at lower engine loads. RME has no effect on specific energy consumption.

Nanoparticle emissions:

- RME moves the PSD spectra to smaller sizes and increases the nuclei mode due to spontaneous condensates,
- RME causes lower particle emissions at high load and higher emissions at low load,
- with RME there is a higher portion of condensates (SOF) at low load and idling,
- the results with 10% blends are between the results with respective pure fuels.

Elemental & organic carbon EC/OC:

- higher engine load produces less OC and more EC, i.e. “dryer” soot
- RME causes higher portion of OC (lower portion of EC), which is particularly pronounced at lower engine load
- RME reduces the total PM at higher engine load, especially due to the reduction of EC.

8.2. Influences of EGR and engine control parameters on emissions with RME

Tests performed on Iveco F1C Euro 3 & Euro 4.

8.2.1. Influences of EGR on emissions with SCR and RME

Comparisons of engine versions Euro 3 – Euro 4

The different variants of engine setting were shortly designed as: E3 (Euro 3 without EGR), E4 (Euro 4 with specific equipment, chap. 4.2. and with EGR active) and E (4) (engine version Euro 4, but with deactivated, closed EGR).

EGR lowers generally the NO_x-emissions, with almost no influence on CO & HC. 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.

The differences between the variants E3 and E(4) (EGR valve closed) result mainly from the changed injection parameters (injectors, geometry, pressure, rate shaping, timing) and influences on boost pressure (intake collector, intercooler, operating conditions of the turbocharger).

Fig. 19 demonstrates an example of an EGR switch off at OP3 (50%).

Looking on these plots from right to left it can be summarized that:

- 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.

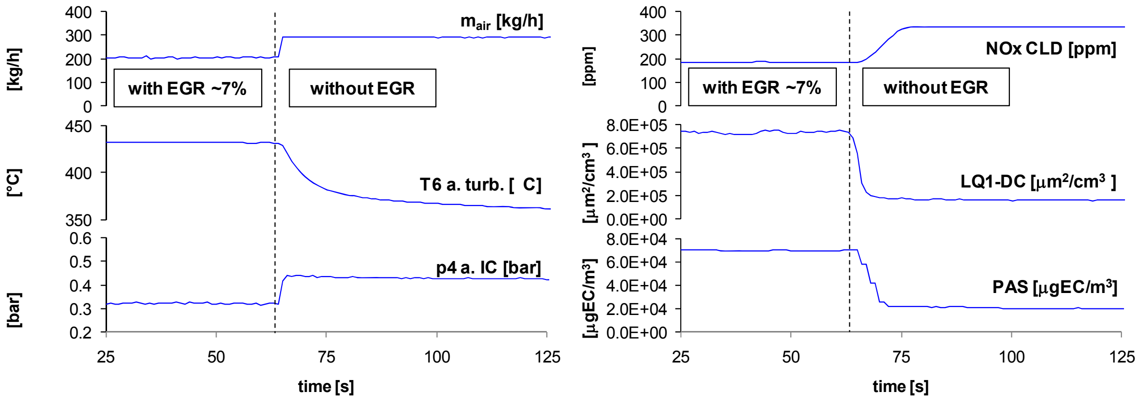


Fig. 19: Switch off EGR mode at 2200 rpm / 162 Nm Iveco F1C E4; Diesel; w/o exhaust gas aftertreatment system

Fig. 20 shows the SMPS PSD-spectra with the different engine variants at middle load (OP3, 50% load).

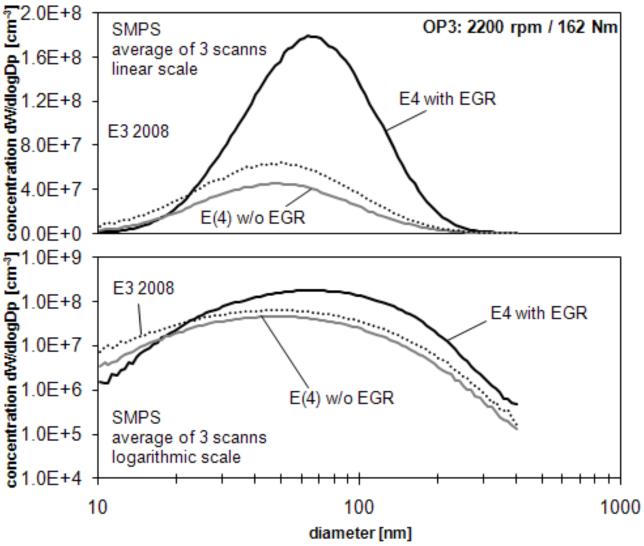


Fig. 20: Influence of EGR on nanoparticle emissions Iveco F1C E4; Diesel; w/o exhaust Gas aftertreatment system

At low load the switching in EGR has a marginal (or none) influence on NP's (E(4)-E4). The other type of injection parameters yielded a clearly higher NP-concentration level for the older version E3.

At middle load the versions E3 and E(4) have nearly the same level of NP count concentrations, the switching in of EGR provokes a clear increase of NP.

The findings concerning the impact of EGR on NP's can be summarized as follows:
- no influence of EGR on NP at low load
- clear increase of NP with EGR at middle load
- no EGR (EGR closed) at full load.

Research with EGR at stationary operation

Except of influences of EGR this research shows also the influences of B100 (RME) and of SCR.

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.

Gaseous emissions – an example of results (with EGR, B100 & SCR) is represented in Fig. 21. The resulting average EGR rates for both fuels are noted in this figure. They are different for Diesel and for B100 because of different injection duration and air consumption.

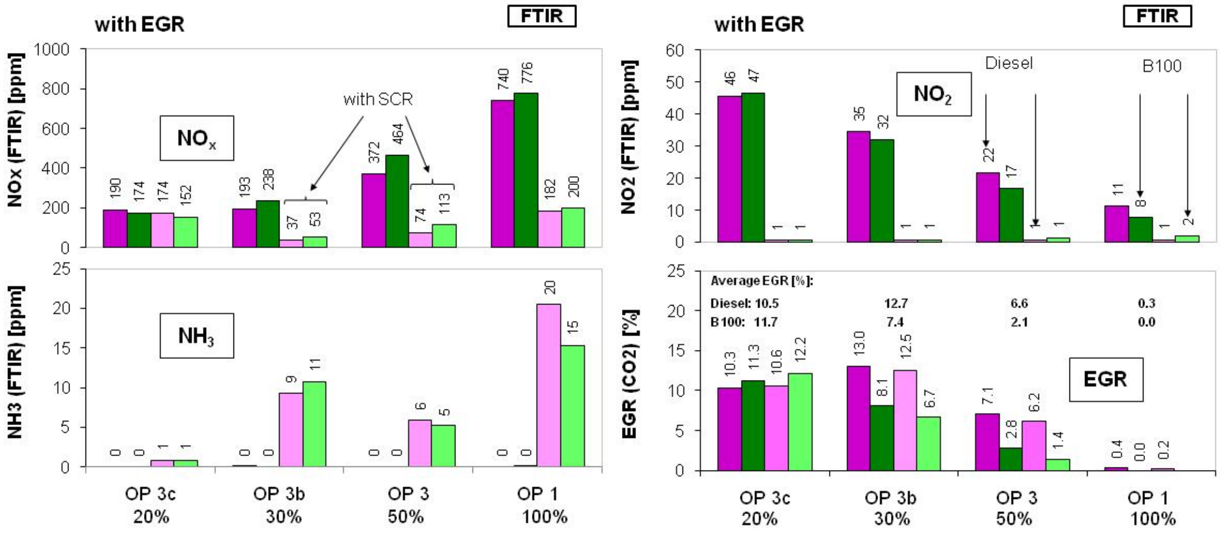


Fig. 21: Influences of B100 & SCR on NO_x emissions in 4 ptstest
Iveco F1C E4; 2200 rpm

From all results with/without EGR, [4], can be concluded:

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) and increases CO & HC,

B100: increases NO_x at higher part load and full load in the range of 10-15%, reduces strongly HC and increases CO,

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

Regarding the potentials of NO_x-reduction with combinations of the represented measures it can be stated that (in parenthesis are the values from FTIR relative changes):

- at lowest load OP3c EGR reduces NO_x by up to 30% (25%), B100 does not increase NO_x and SCR has no effect due to urea switched off,
- at middle load (OP3) EGR reduces NO_x approx. in the same range 20-25% (12%) as B100 increases it (26%), SCR is the strongest reduction tool in the range of 80% (79%),
- at full load (OP1) there is no EGR, B100 increases NO_x by 4% (2%) and SCR reduces it by 78% (76%).

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.

Fig. 22 gives a summary of relative changes of NO_x-emissions measured with FTIR, as averages of 4 pts.

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 IR …increase rate with B100 RR …reduction rate with SCR

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

Fig. 22: Relative changes of NOx-emissions (FTIR), average of 4 pts

Nanoparticle emissions are influenced by the applied measures EGR, B100, SCR. An example of NP-increase caused by EGR is given in Fig. 20. A typical influence of B100 & SCR on NP represents Fig. 23:

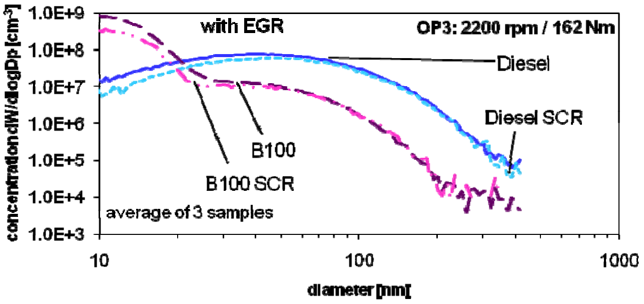


Fig. 23: Influences of B100 & SCR on nano-particle (SMPS-PSD) Iveco F1C E4; OP 3: 2200rpm / 50% load

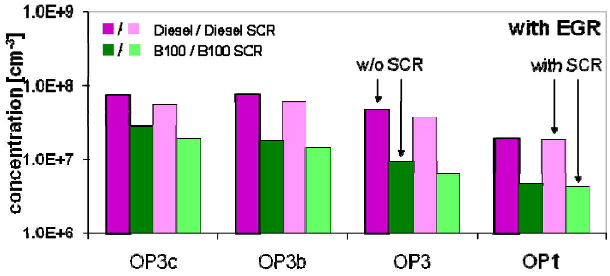


Fig. 24: Integrated counts of particles in the size spectrum 20-300nm Iveco F1C E4; with Diesel & B100; with and w/o SCR

- there is a slight tendency of reduction of the NP count concentrations with SCR – diffusion loses in the SCR catalysts,
- there is a typical and repetitive influence of B100 on NP PSD's: increase of nuclei mode and reduction of accumulation mode with B100.

Fig. 24 shows a sample of comparisons of the integrated particle counts in the size spectrum 20-300 nm. It can be remarked that the average NP-concentration level decreases with increasing engine load and both: B100 & SCR reduce the NP counts.

The relative changes of particle counts [20-300 nm], as averages of 4 pts are represented in Fig. 25.

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

$$IR = \frac{NP_{with\_EGR} - NP_{w/o\_EGR}}{NP_{w/o\_EGR}} \cdot 100\%$$

$$RR = \frac{NP_{Diesel} - NP_{B100}}{NP_{Diesel}} \cdot 100\%$$

$$RR = \frac{NP_{w/o\_SCR} - NP_{with\_SCR}}{NP_{w/o\_SCR}} \cdot 100\%$$

Fig. 25: Relative changes of particle counts (PC) in the size range [20-300nm], average of 4pts

Research with EGR at transient operation

Fig. 26 – shows examples of NO_x-traces in the first part of ETC, comparing the effects of: EGR, EGR+SCR, B100 and B100+EGR+SCR – the NO_x-differences caused by the different measures are well demonstrated.

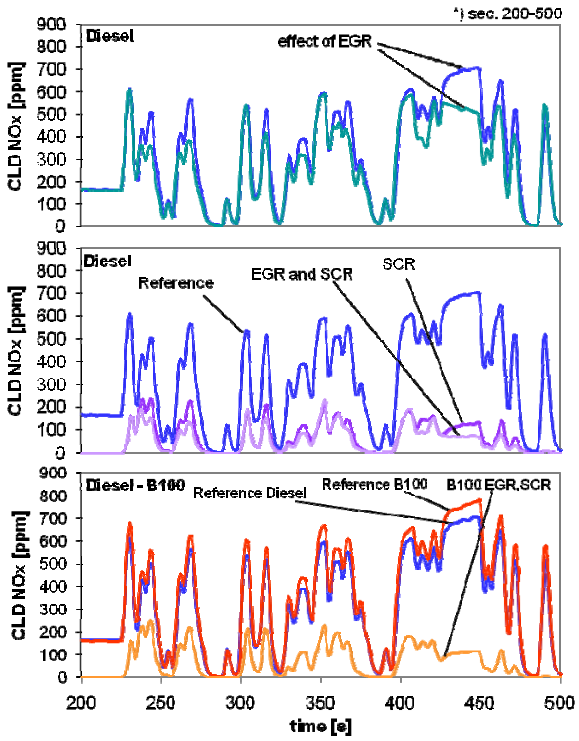


Fig. 26: Influences of EGR, B100 & SCR on NO_x-traces in ETC*) Iveco F1C E4

In general it can be remarked:

- due to the conditioning at full load the tailpipe temperature at the beginning of cycle is higher than the average value resulting from the cycle itself,
- the NO_x-traces depend strongly on the driving cycle and are very repetitive and similar to each other.

Fig. 27 shows average emissions in ETC (NO_x, NO_2, NH_3 & CPC).

There is a clear reduction of NO_x & NO_2 and appearance of NH_3 with SCR. B 100 increases slightly NO_x (w/o SCR) and reduces CPC (summary NP-counts).
Table in Fig. 28 summarizes the relative changes of NO_x in ETC.

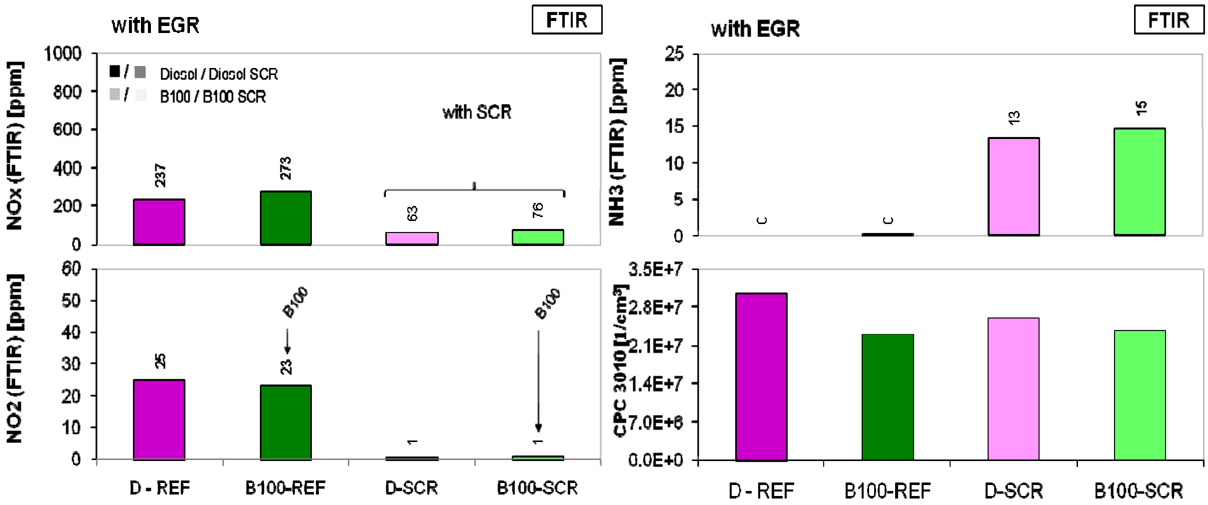


Fig. 27: Average emissions in ETC with Diesel & B100, with and w/o SCR Iveco F1C E4

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

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

Fig. 28: Reduction rates of NO_x in ETC

From all investigations (with/without EGR) it can be remarked, that:

EGR: reduces NO_x (with Diesel) by 23%, with B100 by 12%,
B100: increases NO_x by 10%,
SCR: reduces NO_x in average of all variants by 72% and eliminates nearly NO_2 (by 95-100%); with SCR there are: an average NH_3-emission up to 12 ppm (LDS), reduction of Formaldehydes and slight increase of Hydrocyanic Acid.

Regarding the potentials of NO_x-reduction with combinations of the represented measures, similar statement, like for the stationary operation can be made:
EGR reduces NO_x approx. in the same range, as B100 increases it (10-20%); SCR is the strongest reduction measure in the range of 72%.

By means of different measuring methods used for NP-emissions – CPC for summary particle counts and NanoMet (PAS & DC) for summary active aerosol surface – some controversus influences of B100 on NP could be found:

B100 increases the NP-counts (CPC) w/o EGR and reduces the NP-counts with EGR; in both cases nevertheless the NanoMet-signals indicate a strong reduction of summary aerosol surface.
This can be explained by the bimodality of PSD’s with B100 (see Figure 23) – higher nuclei mode and lower accumulation mode:
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.
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. 29 represents relative changes of CPC-particle counts in ETC with different applied measures EGR / B100 / SCR.

EGR		**B100**		**SCR**	
ETC [%]	CPCIR $[1/cm^3]$	ETC [%]	CPCRR $[1/cm^3]$	ETC [%]	CPCRR $[1/cm^3]$
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

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

Fig. 29: Relative changes of summary particle counts (PC) in ETC

It can be stated that:

EGR: increases the PC with Diesel by approx. 44%, with B100 this increase is small (even reduction w/o SCR),
B100: reduces PC w/o SCR (~ 6%) and increases PC with SCR (~ 6%),
SCR: reduces PC with Diesel (~ 15%); with B100 there is lower reduction w/o EGR (2.6%) and a slight increase with EGR (not shown in this table).

Finally it can be stated, that the effects of EGR, B100 and SCR on NP’s counts and surface are superimposed (especially for B100) by the balancing of PC-concentrations between nuclei and accumulation modes, by the changing composition of aerosol (more/less SOF) and by the increased diffusion losses, stronger oxidation and possibility of secondary NP’s with SCR.

For a low-load driving cycle NYCC there are little effects on NO_x-reduction: EGR (1%), SCR (22%).

Conclusions

From the 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:

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).

The differences between engine variants E3 and E(4) (EGR valve closed) result mainly from the changed injection parameters (injectors, geometry, pressure, rate shaping, timing) and influences on boost pressure (intake collector, intercooler, operating conditions of the turbocharger).

At stationary engine operation the NO_x reduction potentials with combination of EGR, B100 & SCR are:

- at lowest load OP3c EGR reduces NO_x by up to 30%, B100 does not increase NO_x and SCR has no effect due to urea switched off,
- at middle load (OP3) EGR reduces NO_x approx. in the same range (20-25%) as B100 increases it, SCR is the strongest reduction tool in the range of 80%,
- at full load (OP1) there is no EGR, B100 increases NO_x by 4% and SCR reduces it by 78%.

At transient engine operation the NO_x reduction potentials with combination of EGR, B100 & SCR are:

EGR reduces NO_x approx. in the same range, as B100 increases it (10-20%); SCR is the strongest reduction measure in the range of 72%.

EGR provokes clearly an increase of NP-emissions. By application of B100, or combinations of B100, SCR & EGR there is a balancing of several influences on NP-production:

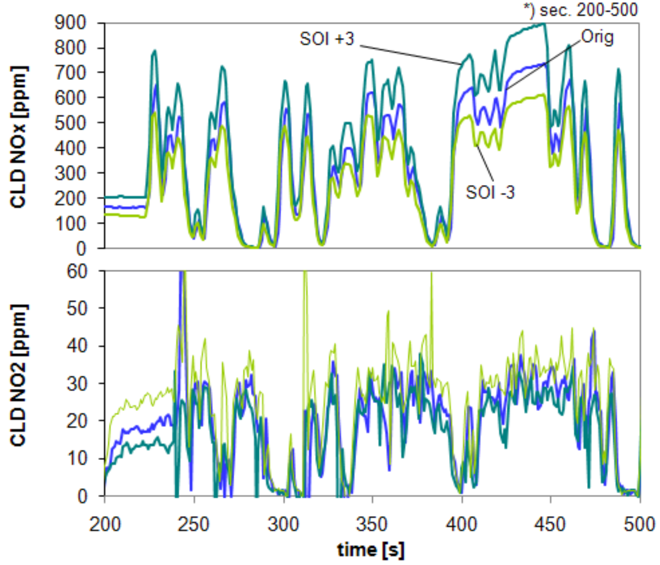
Changes between nuclei and accumulation modes, the changing composition of aerosol (more/less SOF), increased diffusion losses, stronger oxidation and possibility of secondary NP’s with SCR.

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.

8.2.2. Influences of engine control parameters on emissions with RME

The main engine control parameter, which influences NO_x-emissions is the injection timing (SOI). Tests with variations of SOI at stationary and transient engine operation were performed in [5].

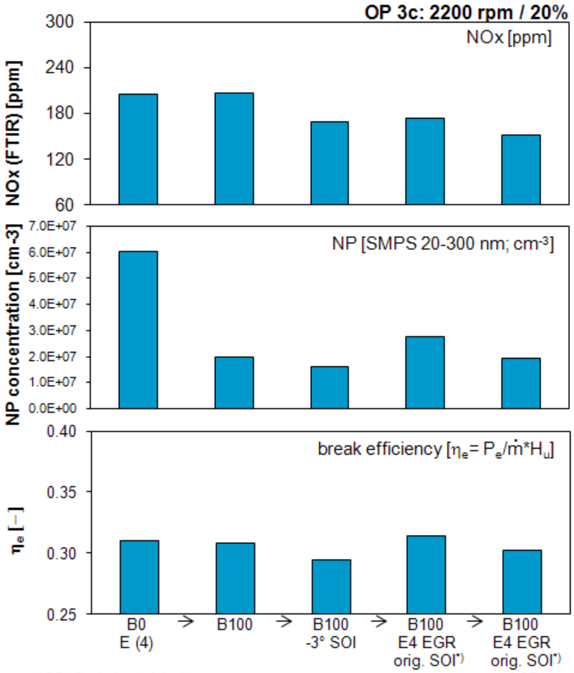
The SOI-variations were +/- 3 deg CA took place with Diesel (ULSD) and B100, without EGR and without exhaust gas aftertreatment. For dynamic cycles (ETC) the SOI-variation was an SOI-offset in entire engine operation map.



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

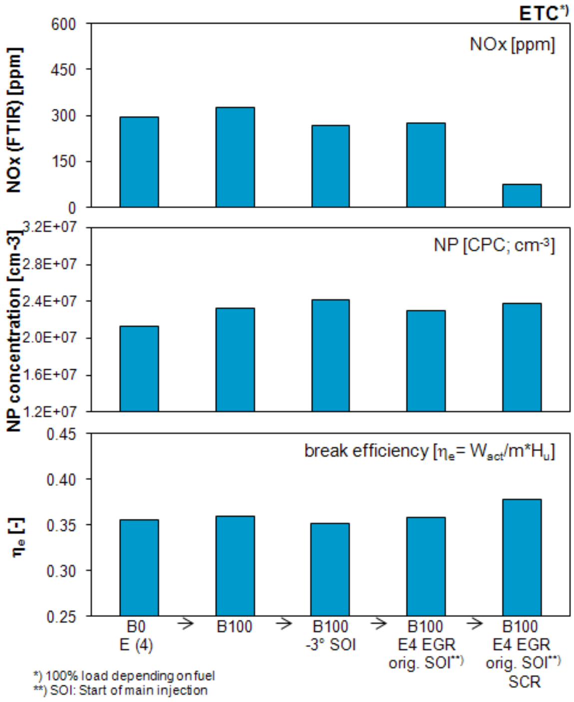
**) SOI: Start of main injection

Fig. 30: Variation of start of injection (SOI) - NO_x-plots in ETC*)
Iveco F1C E(4); Diesel; w/o exhaust gas aftertreatment system



*) SOI: Start of main injection

Fig. 31: Influence of combinations of measures on emissions NO_x & NP and on the effective engine efficiency Iveco F1C E4; EGR, B100, SOI, SCR



*) 100% load depending on fuel
**) SOI: Start of main injection

Fig. 32: Influence of combinations of measures on emissions NO_x & NP and on the effective engine efficiency Iveco F1C E4; EGR, B100,SOI, SCR

At stationary part load OP, SOI is different for both fuels (Diesel & B100), because of differences of injection duration for the same power. Due to lower heat value B100 needs longer injection duration and causes another setting of SOI by the control unit.

At full load there are the same maximum injection durations for both fuels, B100 yields less torque and the values of SOI are equal.

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

The break specific fuel consumption in [g/kWh] is higher for B100 due to the lower calorific value.

Fig. 30 – shows examples of NO_x and NO_2-traces in the first part of ETC with varying SOI. This representation demonstrates clearly higher NO_x-values with more advanced SOI.

Some results from [4] were used to show the potentials of SOI-variation, or its combinations with EGR & SCR.

At low load (OP3c), Fig. 31, 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.

At full load (OP1), (not represented here) there is a little increase of NO_x with B100, EGR is closed and SCR is the most efficient NO_x-reduction measure. Reducing NO_x by means of late SOI is little attractive because of deteriorating effective engine efficiency. All variants with B100 are nearly at the same NP-level, which is significantly lower, than with Diesel.

At transient operation (ETC), Fig. 32, 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.

Conclusions

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:
    - at lower OP3c there is a tendency of increasing NP with advancing SOI,
    - at higher OP1 the NP with Diesel decrease with advancing SOI, with B100 there is no influence of SOI,
    - at dynamic operation (ETC) the nanoparticles emissions are not influenced by the SOI,
- at stationary operation B100 reduces the PC by (in average) 67%, in ETC B100 increases the PC in the range of 15%,
- 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.

8.3. Influences of SCR and DPF on emissions with RME

Tests performed on Iveco F1C Euro 3.

Both systems SCR (deNO_x) and DPF were developed and can be applied separately for reduction of NO_x, or reduction of particle emissions. Nevertheless, the best exhaust gas cleaning can be achieved with the inline combination of both systems (DPF+SCR), which exists in OEM-application and in retrofitting.
In BIODEG project all variants: SCR, DPF and (DPF+SCR), were investigated [2, 3, 6, 7, 8] and the most important results were published in [64] & [65]. Here the most important messages:

8.3.1. Emissions with SCR

Stationary engine operation (CSF+SCR)

Fig. 33 shows the time-plots of NO_x and NH_3 in the 8-points test with different urea feed factors α. Increasing the feed factor up to α = 1.2 enables a deNO_x efficiency up to 98%, but also increases the ammonia slip up to 125 ppm. Table 5 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_x-reduction.

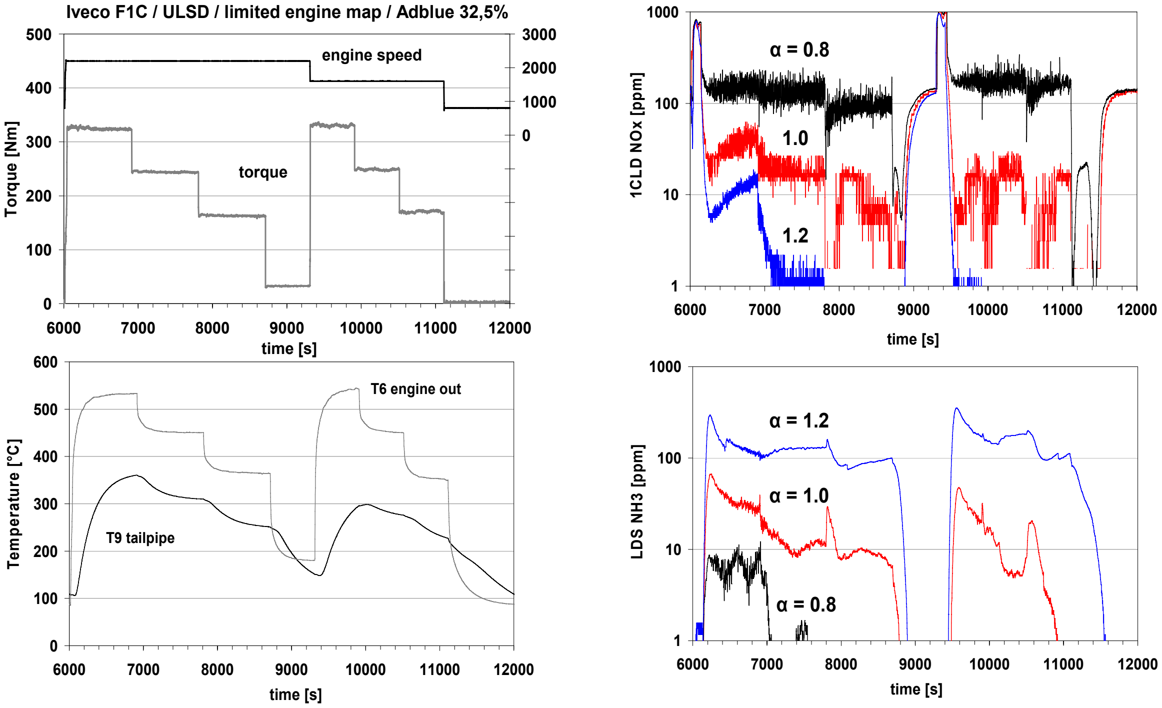


Fig. 33: Comparison of results at 8 points-test with different feed factors α

	w/o	with DPF + SCR		
2200 rpm / 100 %	DPF + SCR	α =0.8	α = 1.0	α = 1.2
NO_X 1CLD [ppm]	782.0	159.0	42.0	14.0
RE $_{NOX}$ [%]	-	80.0	95.0	98.0
NH_3 LDS [ppm]	-	6.0	31.0	125.0

Table 5: NO_x reduction efficiency RE & NH_3 depending on feed factor α, (pt. 1 of the 8 pts. test).

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 NO_x as shown in Fig. 34, does not show any significant differences, when referring to engine-out emissions with or without aftertreatment system. The maximum stationary ammonia slip at OP1 is 15 ppm.
At OP4 there is no urea injection and the NO_x-conversion rate is very low.

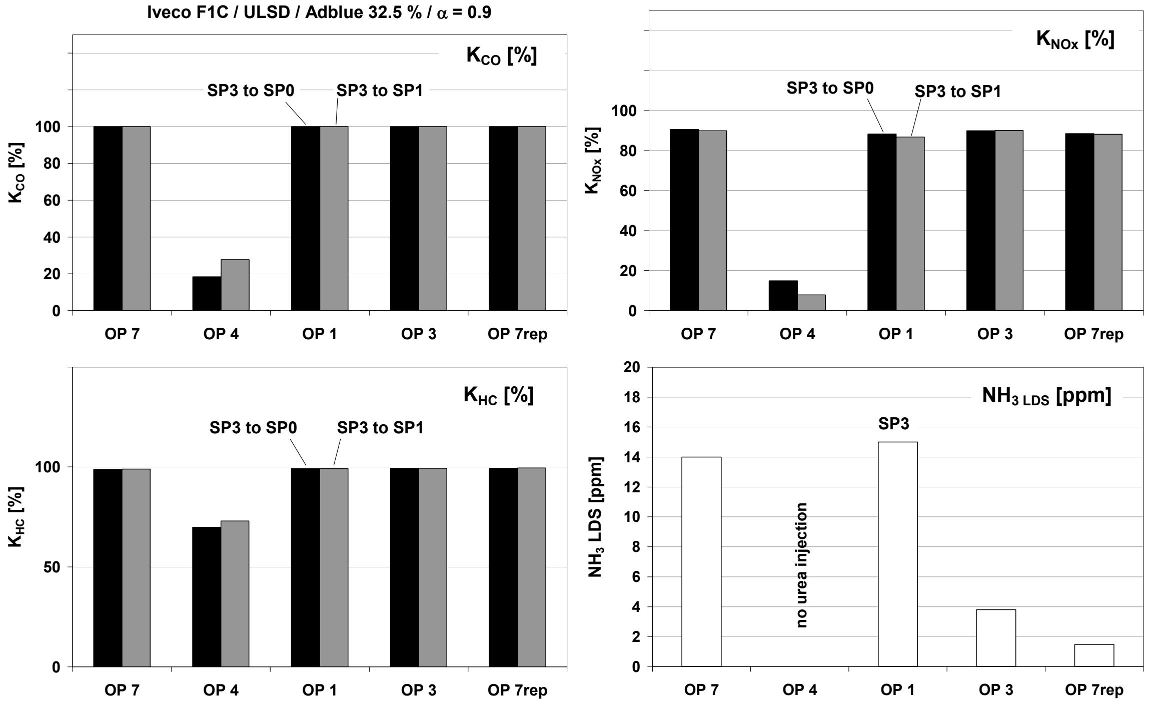


Fig. 34: 4 points test: conversion rates with different SP's & NH_3 tail pipe

Measurements of nanoparticles NP in the 4-points test at different sampling positions are represented in Fig.35. 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_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, (indicating that some of the PAS-active particle surface must be chemicaly changed in the deNO_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 and therefore it correlates well with the total nanoparticle counts (CPC).

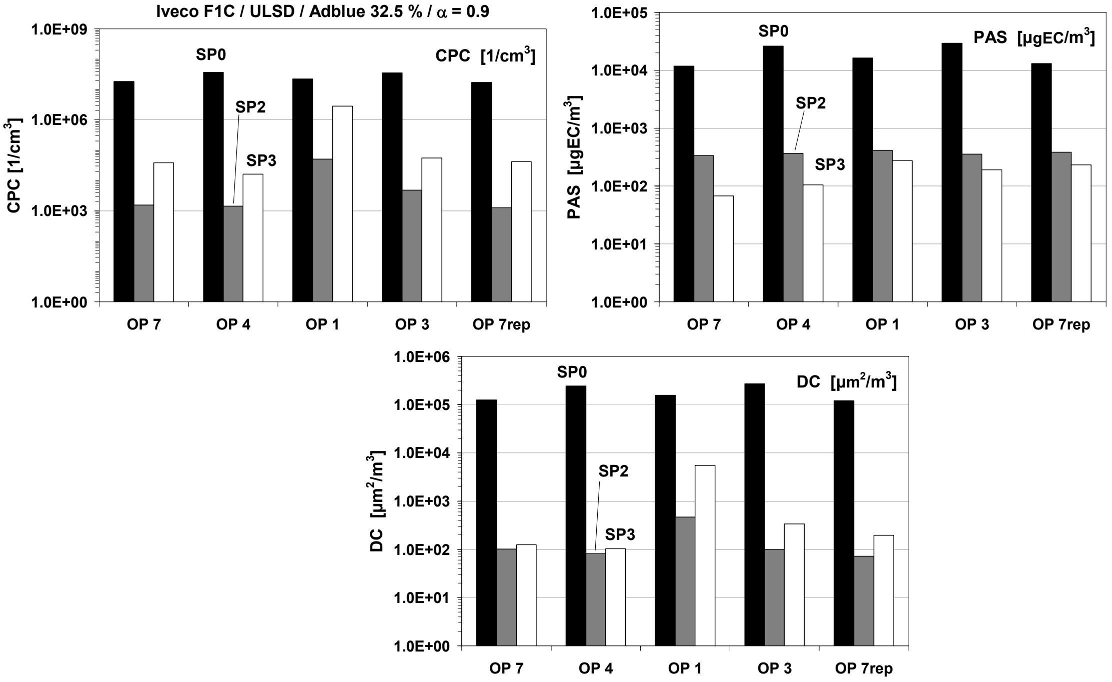


Fig. 35: Secondary nanoparticles at 4pts, test (w/o slip cat.) indicated with total NP counts (CPC) and surface measuring sensors PAS & DC

As known from the literature, secondary pollutants such as cyanuric acid, ammonium nitrate and others can form during the deNO$_x$ process. In addition, unreacted urea can also be released.

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. 35). Exception is the operating point OP1 with the highest space velocity and an intense secondary formation of nanoparticles.

Dynamic engine operation (CSF+SCR)

These tests were performed in the ETC with limited engine map (LEM).
Following results will be shown:

- ETC1 & ETC2 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. 36 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 NO$_x$ emissions increased because of stopped urea dosage.
The ammonia slip catalyst reduced NH$_3$ 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, Fig. 37, which are an effect of the highly in stationary 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.

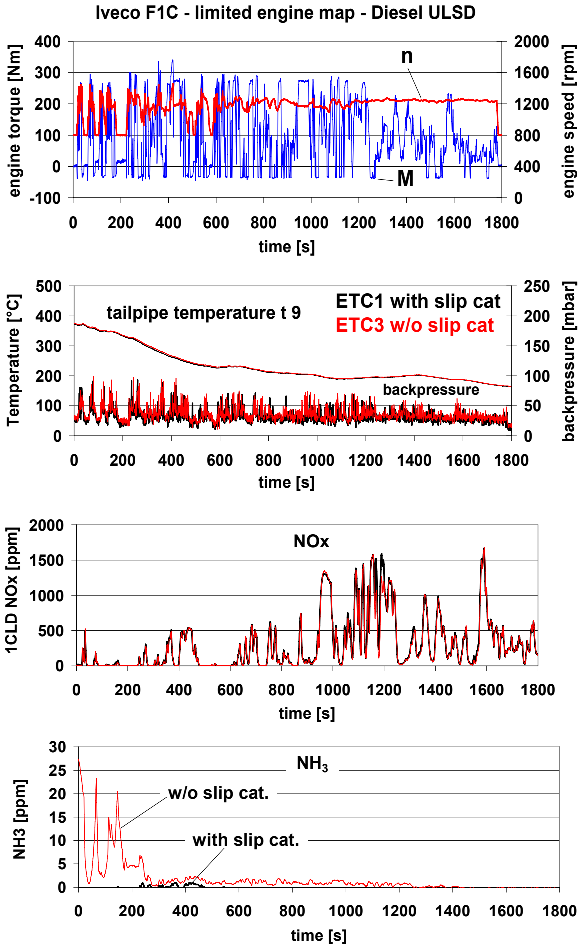


Fig. 36: Comparison of 2 ETC’s (ETC1-ETC3), with & w/o slip catalyst α=0.9

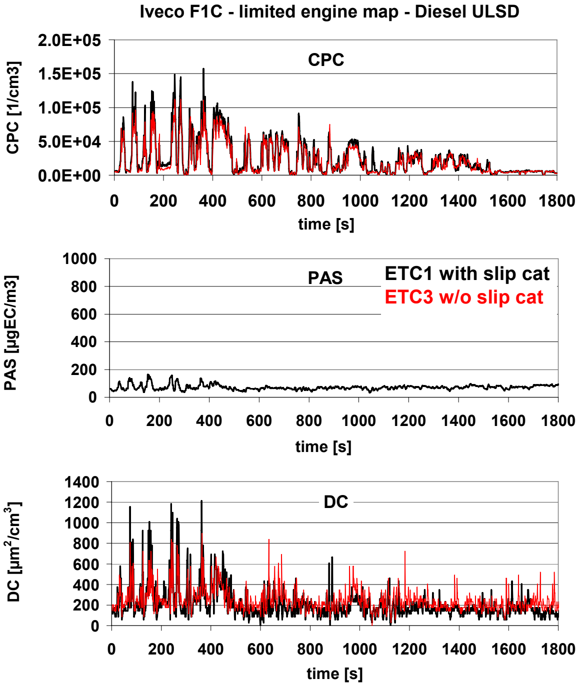


Fig. 37: Comparison of NP-emissions in ETC1 – ETC3, with & w/o slip catalyst α=0.9

Fig. 38: compares filtration efficiencies of the combined dePN system (DPF+SCR) in stationary and in 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 fullfills 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.

Further tests were performed with different driving cycles with non limited engine map (NEM).

The conditioning of the engine and exhaust system was for ETC and WHTC identical, as for the previous tests with LEM (see Test Procedures): after warm-up 5 min 2200 rpm / FL and 0,5 min idling.

For the low-load cycles (NYCC and Braunschweig) the conditioning was: 5 min 1600 rpm / 165 Nm and 0,5 min idling.

Fig. 39 represents the time-plots of tailpipe temperature over the cycle duration for other investigated test cycles.

The New York City Cycle (NYCC) and the Braunschweig-Cycle are low-load cycles, which were developed in those cities and represent the city bus driving.

It can be seen, that the exhaust temperatures in the low load cycles are too low to enable the full working potential of the SCR-system.

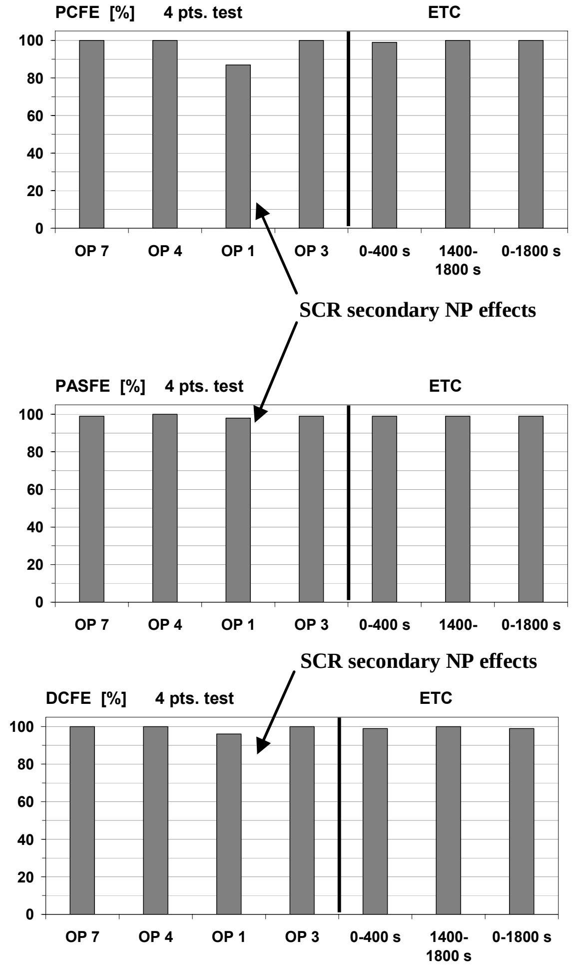


Fig. 38: Filtration efficiencies of the combi-system after SCR – catalyst in stationary and dynamic engine operation

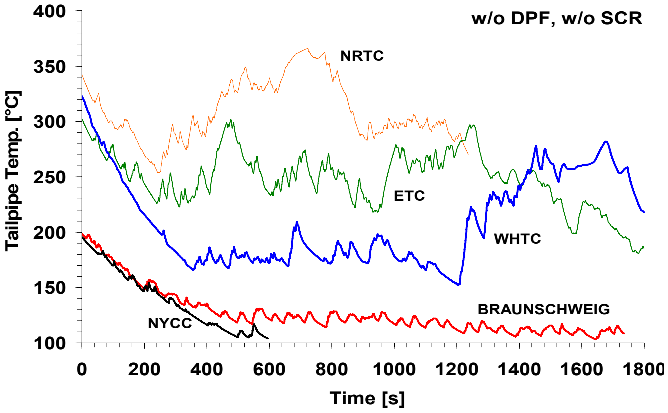


Fig. 39: Engine tailpipe temperature in different cycles (w/o exhaust gas after treatement, NEM).

Table 6 depicts the integral average conversion rates in different driving cycles measured with different methods.
In the Braunschweig-Cycles there are the lowest NO_x conversion rates.

$RE_X = \frac{X_{w/o} - X_w}{X_{w/o}} \cdot 100$	RE [%]			
	ETC	WHTC	NYCC	BRAUN
NO_x 2CLD [ppm]	91	65	42	16
NO_x FTIR [ppm]	90	64	40	14
NO_2 2CLD [ppm]	93	33	87	76
NO_2 FTIR [ppm]	91	35	98	92

Table 6: Integral average conversion rates of NO_x & NO_2 in different driving cycles ETC, WHTC,NYCC & Braunschweig-Cycle, $\alpha = 0.9$, (NEM)

Finally it must be followed, that the investigated SCR-system in the present configuration is a little efficient NO_x reduction measure in the low-load city driving.

SCR and RME blend fuels

Fig. 40 shows the results of interesting NOx-components in function of exhaust gas temperature with BO, B30 & B100 for SCR alone.

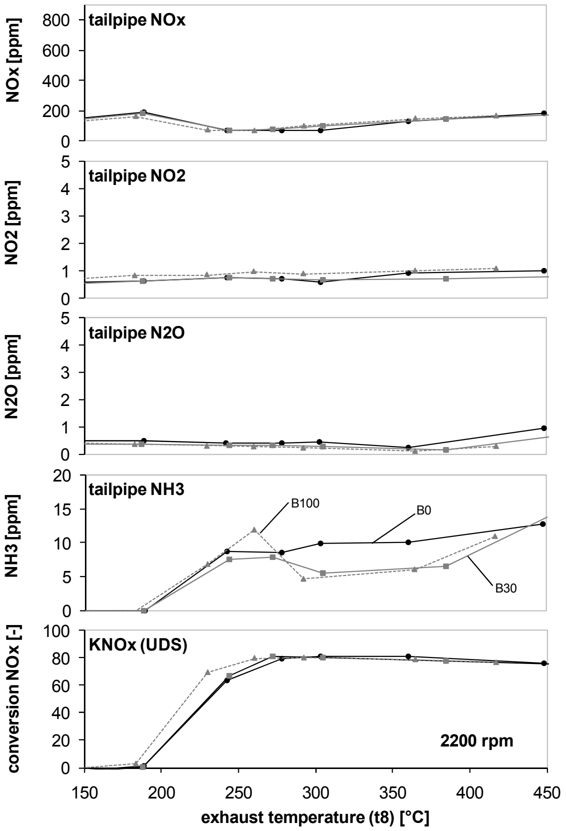


Fig. 40: Comparison of emissions in steps-tests with SCR and B0, B30 &B100; $\alpha=0.9$; FTIR

In steps-tests there is no clear influence of RME portion on NO_x. There is reduction of CO at higher load and general reduction of HC (not represented here). There are very little influences on NO_2 & NH_3.

The light-off of the SCR alone is with RME 100 at a slightly lower temperature, than with B0 & B30 ($\Delta t \sim$ 10-20°C).
Except of that there are no other clear effects of the RME-content on the presented parameters.

In dynamic operation (ETC), Fig. 41, there are no differences of NO_x, NO_2 & NH_3 and there is lowering of CO & HC with higher RME content.

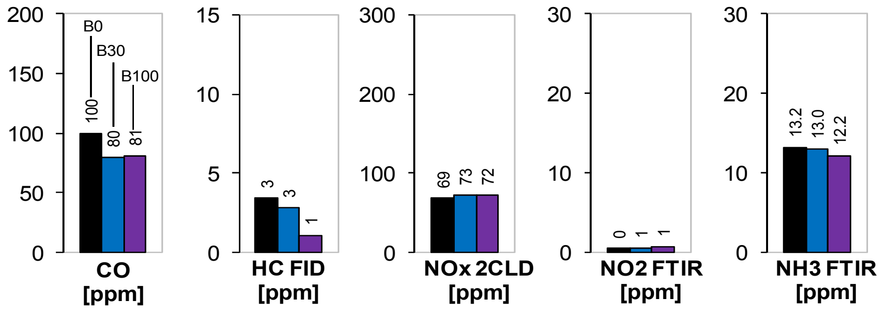


Fig.41: Emissions in ETC with different fuels with SCR

The influence of RME on NO_2 with DPF+SCR which was remarked at stationary operation (more NO_2 with more RME in certain t_{exh}-range) is no more present or even inversed at transient operation. Similarly for NH_3, which was reduced by RME (with DPF+SCR) in stationary steps-tests and is not reduced or even increased in the dynamic test.

In general, it can be said, that some relationships of results, which are remarked at stationary operation can disappear or even be inverted at transient operation. This is to explain with the running chemical reactions in the aftertreatment system, which meet quite different changing conditions (p, T) during the transients.

Different exhaust aftertreatment systems

Fig. 42 represents the nitric emissions in function of exhaust gas temperature, with Diesel base fuel, for the three investigated variants:

- reference case (Ref.) without exhaust gas aftertreatment,
- combined aftertreatment system (DPF+SCR) and
- SCR alone.

With the catalyzed DPF there is a production of NO_2 in the temperature range 250°C – 350°C. With the combined system (DPF+SCR) there is a slight emission of N_2O (up to 4ppm) in the lowest temperature range and there are lower NH_3- values, than with SCR alone.
The increase of NO_x conversion rate K_{NOX} is with the combined system at a slightly lower temperature (Δt ~ 10-20°C)

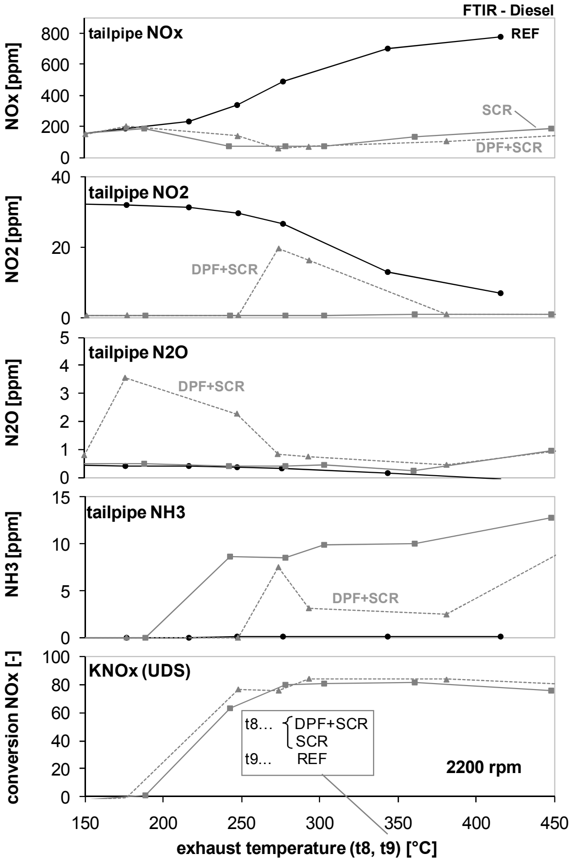


Fig. 42: Comparison of emissions in steps-tests with DPF+SCR and SCR, with the base fuel; α=0.9; FTIR

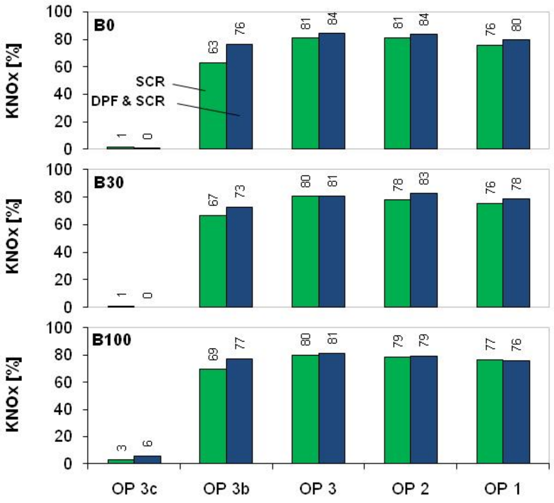


Fig. 43: NO_x conversion rates with different exhaust aftertreatment systems at stationary operation; α=0.9; UDS-sensors; 2200 rpm

Fig. 43: summarizes the conversion rates K_{NOX} resulting from datalogging with OEM-UDS-sensors with B0, B30 & B100 in stationary steps-tests. The remarkable NO_x-conversion takes place at OP 3b and all higher operating points. With DPF+SCR K_{NOX}-values are slightly higher due to the production of NO_2 in the catalytic DPF (upstream of SCR).

There are principally no significant differences of K_{NOX} with different fuels, except of more reduction of NO_x with B100 at the lowest OP3c (easier light-off with B100).

Nanoparticles emissions

The particle filter of the combined system had the filtration efficiency, which fulfilled the actual VERT quality requirements (PCFE > 99 %). I was interesting to state if there are some influences of biocomponents on the filtration resp. reduction efficiency of NP's of the combined system (DPF+SCR) and how is the influence of SCR alone on NP's ?

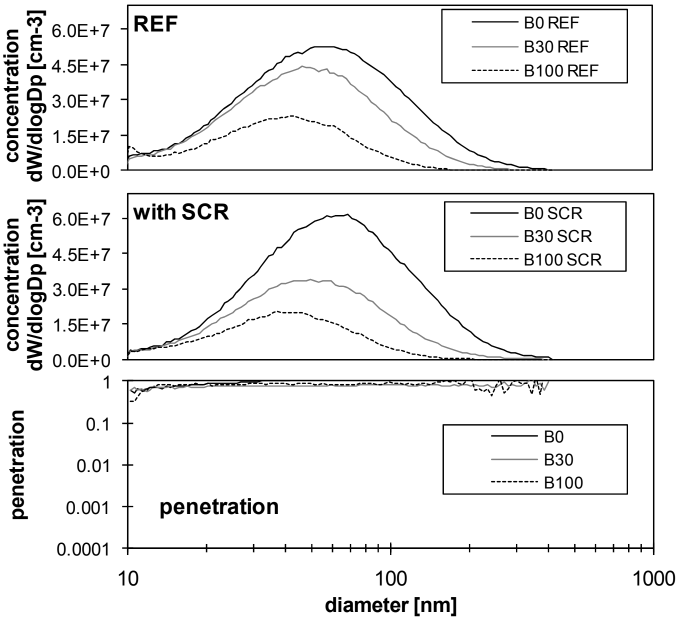


Fig. 44: SMPS-PSD spectra with B0, B30 &B100 and SCR; α= 0.9; 2200rpm/100% load

Fig. 44 shows the SMPS particle size distribution spectra without and with SCR at OP1 with B0, B30 & B100. There is a reduction of NP count concentration due to increasing B-content. This is in accordance with the other research results which generally state lower PM emissions with FAME's at full load (higher O_2-content in fuel, lower accumulation mode).

The penetration nevertheless stays similar for all fuel variants at approx. 90%. This small reduction of nanoparticles concentration represents the diffusion losses in the mixing tube and in the SCR catalyst.

Penetration is a parameter representing the portion of particulates passing through the aftertreatment device; it is a ratio of down – to upstream concentrations.

With DPF+SCR and B100 it has been stated at full load operation, that there is a higher PC-concentration after the system. These effects are due to the high exhaust gas temperature (production of sulfates, evaporation of higher boiling HC) and to the interaction of the gas after DPF with the injected Ad Blue and with the SCR-system (secondary NP after SCR).

The most important findings of this section are:

- excellent particle reduction in the (DPF+SCR) system at part load and increase of nanoparticles penetration with growing RME portion (interaction of biocomponents and secondary NP),
- little particle reduction rates with SCR alone, in the range of 10%; store-release-effects with SCR.

Conclusions

For SCR- and (DPF+SCR) - systems with B0 can be summarized:

- the combined dePN systems (DPF+SCR) at transient engine operation efficiently reduce the target emissions with deNO$_x$-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$_x$ 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$_x$ conversion efficiency at transient operation (ETC) strongly depends on the exhaust temperatures which are correlated with the urea-dosing strategy; during low-load operation this efficiency is strongly reduced,
- the nanoparticle filtration efficiency, which is verified at stationary engine operation, is perfectly valid also at transient engine operation.

For SCR- and (DPF+SCR) - systems with RME blend fuels the conclusions are:

- the increased share of RME w/o aftertreatment causes an increase of NO$_x$ by higher engine load and reduction of CO & HC; at transient operation (ETC) these tendencies are less pronounced and only B100 shows an increase of NO$_x$,
- with DPF+SCR in the stationary conditions, where NO$_2$ is produced RME causes higher NO$_2$ –values and in the conditions, where NH$_3$ is produced RME causes lower NH$_3$ –values,
- in dynamic tests (ETC) with DPF+SCR only higher NOx-emissions with RME 100 are to remark, CO & HC are for all fuels at zero level (catalytic conversion),
- with SCR alone there are no differences of NO$_x$ and of NOx reduction rate (K_{NOX}) with increasing RME portion; there is lowering of CO & HC,
- in dynamic tests (ETC) with SCR there are no differences of NO$_x$ and there is lowering of CO & HC with RME,
- there are generally no influences of RME-portion in fuel on the conversion values K_{NOX} & K_{NO2},
- the light-off of the SCR alone is with RME 100 at a slightly lower temperature, than with B0 & B30 ($\Delta t \sim 10$-20°C),
- with DPF+SCR K_{NOX}-values are slightly higher, than with SCR alone, due to the production of NO$_2$ in the catalytic DPF (upstream of SCR),
- with DPF+SCR the CO- and HC-emissions are mostly eliminated,
- with DPF+SCR in certain range of the exhaust temperature there are higher NO$_2$-values than with SCR alone; these NO$_2$-values are further increased with RME,
- with DPF+SCR the NH$_3$-emissions are lower than for SCR,
- the reduction efficiencies in ETC with the combined system DPF+SCR, are for NO$_x$ higher and for NO$_2$ lower,
- with DPF+SCR there is excellent filtration efficiency of DPF, up to 99.96%,
- at stationary full load operation with DPF+SCR and with RME 100 there is an intense production of secondary nanoparticles from the SCR part; this effect lowers remarkably the overall NP-reduction efficiency; it is almost not visible at dynamic operation,
- with SCR alone there is usually a small reduction of nanoparticles concentrations (in the range of 10-20%) losses in the mixing tube and in the two in line SCR catalysts; in dynamic operation this reduction is smaller (below 10%),
- with SCR at full load there is a slight increase of NP-counts due to the secondary NP-production.

8.3.2. Emissions with DPF

Tests performed on Liebherr D934 S and Iveco F1C Euro 3.

Diesel particle filters (DPF) reduce, or eliminate efficiently the solid particles from exhaust gas of engine. The collected soot and SOF have to be periodically burned away to prevent the pluging of the filter and an excessive backpressure for the engine. These regenerations of DPF's are enabled by different methods:

- passive – using catyltic coatings, regeneration additives to the fuel (fuel borne catalysts FBC), oxidation catalyst (DOC) upstream of the filter with regeneration support by exothermy and NO_2;
- active (or semiactive) – using supplementary sources of heat, like burner, electrical heating elements, or glow plugs and fuel injection with DOC (fuels processors, evaporators, fuel aerosol generators, etc.)
- for OEM applications the connection of DPF regeneration system to the engine ECU and OBD opens further important possibilities, like CR fuel post injection, actions on engine throttling, EGR and turbocharging system.

All those regenerations helps as well as the regeneration procedures have some influences on emissions.
By following the most important experiences of VERT and some actual results from BIODEG are given.

VERT experiences

PM / PN – measurement: Gravimetry is not an appropriate parameter to characterize the DPF quality. The right metric is the nanoparticles count concentration. This is because some substances like sulfates or heavy HC can pass DPF as vapors and condensate afterwards on the PM-measuring filter, simulating a worse PM-filtration efficiency. By NP measuring methods (SMPS, CPC, DC, PAS) this danger does not exist due to appropriate dilution and thermoconditioning of the sample.

Emissions during regeneration: There are sometimes increased emissions of gaseous and particulate components during the regeneration period. This depends of the DPF system and the regeneration conditions.

With passive, catalytically supported regenerations CO & HC are usually strongly reduced, or eliminated, there is NO_2-increase at certain operating conditions and due to a less intense regeneration there are hardly increases of NP-emissions (pass-through).

With active regeneration systems less catalytic coatings are used (more CO, HC, no NO_2) and the regeneration may be intensly emitting more NP.

Results about emissions during regeneration are shown in the next chapter 8.3.3

NO_2/NO-ratio when using noble metal coatings: The ratio of NO_2/NO where NO is the less toxic component of NO_x, is usually < 0,1 at engine-out conditions. When using noble metal coatings on high specific-surface substrates however NO can be oxidized to NO_2 which is 6 times more toxic based on MAK-threshold values.

In case of DPF regeneration the conversion of NO to NO_2 is performed on purpose to support a soot oxidation process at very low temperatures. This process however is obviously not very well controlled, resulting in high NO_2-slip levels. The same could happen with Pt-containing additives.
It was remarked during several investigations, that the fuel additives (FBC) and some special filter coatings don't produce the higher NO_2-level.

Secondary gaseous emissions with traps and fuel-additives: Since traps provide an ideal environment for generation of new substances from the many educts supplied by fuel, lube-oil, combustion and engine wear it must be expected, that such chemical processes can be accelerated by catalysis if catalytically active materials are also present. Fuel additive substances are by definition catalytically active. Examples from earlier VSET’s demonstrate how strong such effects may be thus supporting the need of this kind of test:

Fig. 45 represents the formation of Dioxins in a particulate trap with different fuel additives (FBC). The worst case is simulated by means of doping the fuel with chlorine.

Generation of PCDD/F when using a Copper-Additive

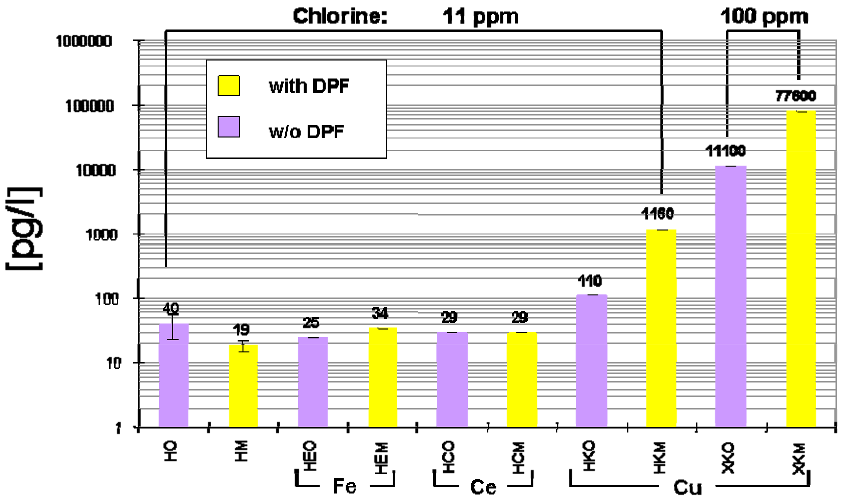


Fig. 45: Formation of Dioxins in a catalytic active particulate trap (O... w/o DPF, M ... with DPF), [source: EMPA, VERT reporting]

When using the copper additive the trap immediately became active, increasing the PCDD/F-emission by about one order of magnitude at limited chlorine content but by more than 3 orders of magnitude for increased chlorine whereas in the case of the Fe- and Ce-additives the PCDD/F-concentration was not influenced with the trap-system.

Actual results

Fig. 35 shows with the CPC-values at sampling positions SP0 & SP2 a high filtration efficiency of the used DINEX-DPF on the Iveco engine.

Fig. 38 demonstrates, that the high filtration efficiency of a DPF, which fulfils the VERT quality requirements does not change at dynamic operation of the engine.

With a passively regenerating DPF system HUG coated with DOC, series of 4 pts test (VFT1) were performed with different bio-blend fuels (B0, B7, B20, B30 & B100), [2].
This DPF was also used for regeneration tests and was chosen on purpose smaller, than necessary for the research engine to enable a quicker soot loading. Thanks to that it was possible to approach the limit of maximum spacial velocity of this filter, when the NP-blow through starts to take place. The operating points of the 4 pts. test were adequately set at lower engine speeds 900 rpm and 1100 rpm.

The comparisons of emissions with different fuel blends and with / without DPF, Fig. 46, show:

Without DPF lowering of CO, HC and lowering of PM at high-load OP’s with increasing bio-content. The NO_x-values increase with Bxx, which is a fact generally confirmed by the own and foreign research.

With DPF there are: elimination of CO, strong reduction of HC and an increase of the NO_2 / NO_x-ratio. With increasing bio-content this NO_2 / NO_x -ratio decreases at part-load OP’s. There is a clear catalytic influence of the tested DPF (DOC + CSF).

The investigated DPF shows a very good reduction of particle mass PM.

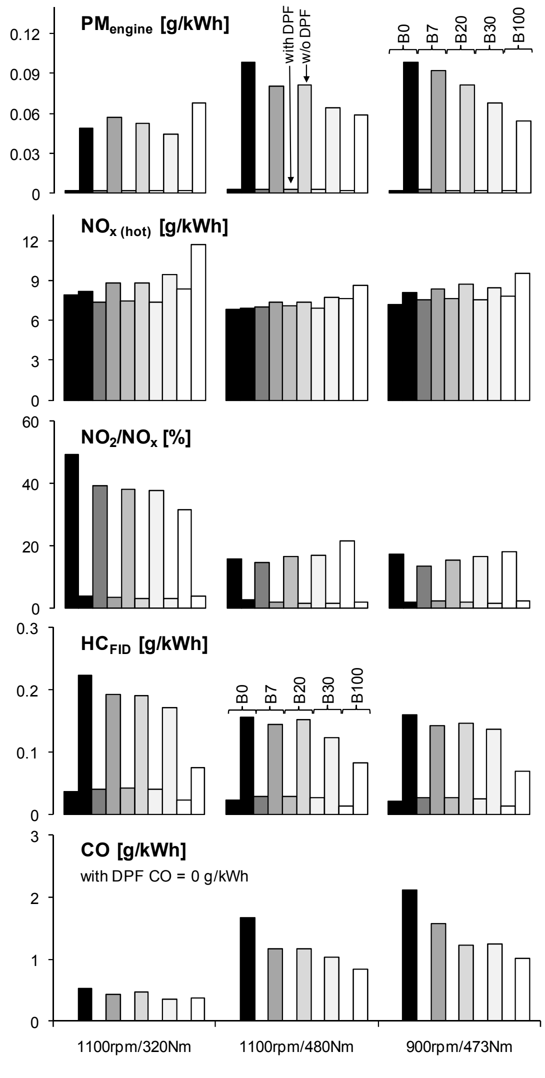


Fig. 46: Comparison of emissions with different fuel blends and with / without DPF HUG coated with DOC, engine: Liebherr D 934 S

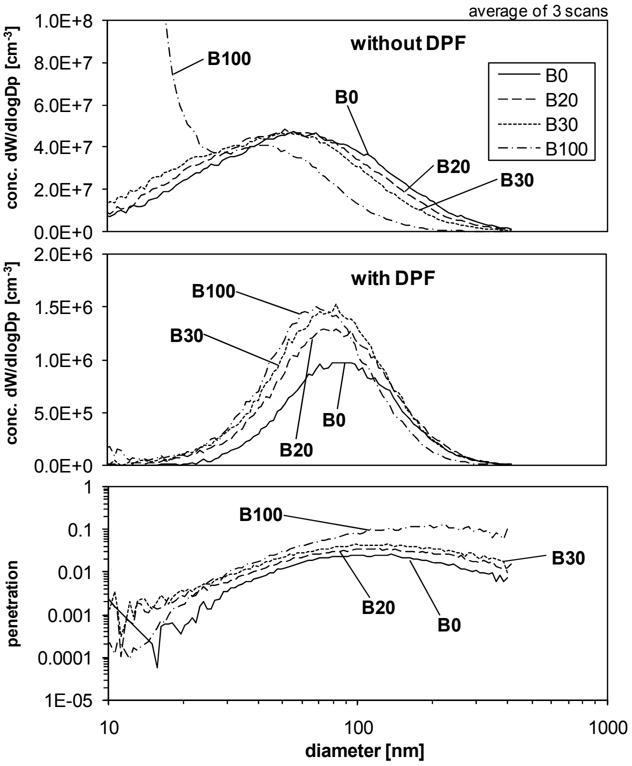


Fig 47: SMPS PSD - spectra & penetration values with different fuel blends at OP 2b (1100rpm/480Nm), with/without DPF HUG coated with DOC, engine: Liebherr D934S

Fig. 47 shows the comparisons of SMPS PSD-spectra with all fuel blends (except of B7 for graphical clarity) at OP 2b (high load).

There is a tendency (w/o DPF) especially with B100, to emit high PC in nuclei mode (size spectrum below 30 nm) and lower PC-concentrations in accumulation mode (30-300 nm).

With DPF there are also higher PC-concentrations and higher values of penetration with B100 – more spontaneous condensates.

These tendencies are similar for other OP’s and there is also a certain logical sequence of curves with increasing share of biocomponents.

Tables 7 summarize the filtration efficiencies for counts (PCFE) and summary particle surface (DCFE) filtration of the used DPF HUG. The results of DC-sensor correspond closely to the PC’s. The tendency of lower filtration efficiency at OP’s 6b & 2b (high gas flow), as well as the tendency of lower filtration efficiency with B100 (more spontaneous post condensation) are confirmed. The filtration material of the investigated DPF fulfills the highest quality requirements of VERT and the requirements of Swiss LRV (OAPC).
Operation above the limit of spacial velocity provokes the NP-break-through and deteriorates the filtration efficiency PCFE & DCFE.

PCFE [%]						
operating point	6b	7b	3b	2b	6b (r.)	
speed	900	900	1100	1100	900	rpm
torque	473	315	320	480	473	Nm
ulsd	**98.63**	**99.99**	**100.00**	**98.55**	**98.95**	%
average of all points	99.22					
RME7	**98.09**	**99.92**	**99.94**	**97.83**	**98.30**	
average of all points	98.82					
RME20	**98.95**	**99.97**	**99.98**	**97.98**	**98.11**	
average of all points	99.00					
RME30	**97.40**	**99.97**	**99.98**	**97.62**	**97.65**	
average of all points	98.52					
RME100	**95.45**	**99.75**	**99.78**	**97.06**	**96.90**	
average of all points	97.79					

DCFE [%]						
operating point	6b	7b	3b	2b	6b (r.)	
speed	900	900	1100	1100	900	rpm
torque	473	315	320	480	473	Nm
ulsd	**98.56**	**99.98**	**100.00**	**98.35**	**98.80**	%
average of all points	99.14					
RME7	**97.85**	**99.92**	**99.94**	**97.07**	**98.24**	
average of all points	98.61					
RME20	**98.95**	**99.97**	**99.98**	**97.15**	**98.09**	
average of all points	98.83					
RME30	**96.85**	**99.96**	**99.99**	**96.80**	**97.29**	
average of all points	98.18					
RME100	**93.25**	**99.66**	**99.74**	**94.75**	**94.86**	
average of all points	96.45					

Table 7: comparison of trapping efficiencies of counts 20-300 nm (PCFE) and aerosol summary surface (DCFE) with different fuel blends, with / without DPF HUG coated with DOC, engine: Liebherr D 934 S; fuels: B0, B7, B20, B30 & B100

Conclusions

The VERT Filter Tests (VFT1) with catalytic DPF system and different bio-blend fuels showed following influences on emission:

- with increasing bio-content in fuel without DPF the limited components CO, HC and PM (at high load) are reduced and NO_x are increased,
- with DPF there is a clear catalytic influence: elimination of CO, strong reduction of HC and increase of the NO_2 / NO_x-ratio,
- the tested DPF reaches the nanoparticle counts filtration efficiency PCFE up to 99.99%,
- using the DPF at too high gas flow – over the limit of maximum spacial velocity – deteriorates the PCFE due to the NP-break-through,
- the filtration efficiency according to mass PMFE is always lower, than PCFE due to the post condensation artefacts in the PM-measuring line (in the present work the differences of both values are little),
- using of pure biofuel B100 also lowers the PCFE due to post condensation effects and increased penetration of smallest particles, except of that the lower blends (B7, B20 & B30) have no impact on PCFE.

The investigated DPF-system HUG coated with DOC is introduced in the recommendation lists of VERT Association and of the Swiss LRV (OAPC).

8.3.3. Impact of bio components on DPF regeneration

The research of regeneration procedures with different biofuels and with online measurements of limited and unlimited exhaust components was conducted on Liebherr engine D 934 S with four types of regeneration:

- passive regenerations of HUG DPF’s, [2], DOC + CSF and CSF,
- active regenerations of HUSS DPF’s, [4], standstill burner and fuel injection + DOC.

Passive regenerations, HUG

The results of soot loading procedures give important information about the effects of biocomponents.

All loading procedures, except of B100, were performed in identical way. For B100, which yielded very difficult conditions of soot loading, periodical switch-off’s for cool-down were necessary.

The soot loading with increased bio-content needed always a longer time period. This is represented for (DOC + CSF) and for CSF in Fig. 48.

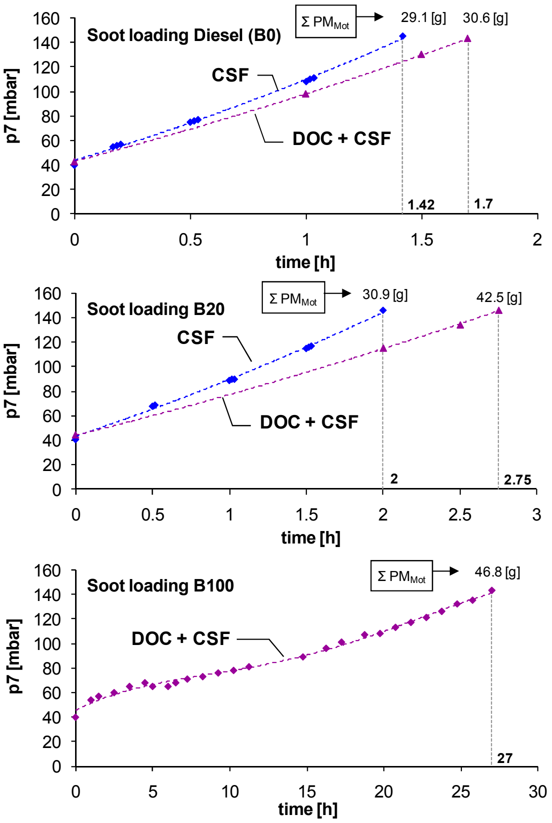


Fig. 48: Backpressure during soot loading cycle

The final particle mass, as product of engine-out emission and time, increases. Nevertheless the oxidized portion of PM during the soot loading procedure and the PM remaining in the DPF at the end of soot loading procedure are unknown.

The reasons for slower soot charging with biocomponents are:

- lower engine-out PM-emissions,
- higher reactivity of PM and partial oxidation during soot loading with DOC,
- with high bio-content (here B100) lowering of exhaust gas temperature to the temperature-window of the highest NO_2-production in DOC, easier NO-NO_2 oxidation with B100 and the intensified NO_2-continuous regeneration.

In Fig. 49 – the comparison of regenerations 7, 11 & 10 (B0, B20 & B100 with DOC + CSF) shows with B100 following tendencies, which would not be visible with B20:

- there is more NO_2 with B100 because of lower t_{exh} (near to the maximum of NO_2-production), more NO_x and more easy NO-NO_2 oxidation,
- the intensity of regeneration with B100 from 5th step (approx. 300°C) is higher; the drop of backpressure quicker than with the other fuels,
- the increase of NP-emissions due to regeneration with B100 starts in the 4th step - spontaneous condensates after DPF and/or break-through of smallest size NP nuclei mode, (represented in [6]),
- there is a transitory postoxidation effect with B100 at 4200s, visible as CO-peak (represented in [6]),
- with B100 the N_2O peak in 2nd step is a little bit higher, than with B20 (7ppm / 5ppm) and after start of regeneration NH_3 increases with B100 up to 6ppm (during 1/2h), while with B20 it stays at zero-level.

Figure 50 gives the comparisons of the instantaneous NP filtration efficiencies (CPC & DC) for the test variants with (DOC + CSF) and B0, B20 & B100.

With the stronger catalytic system (DOC + DPF) B100 causes a drop of FE during the regeneration because of spontaneous condensation of heavy HC-compounds before and/or after DPF and a partially increased penetration of “thermodenuded” nuclei mode (PASFE not represented here).

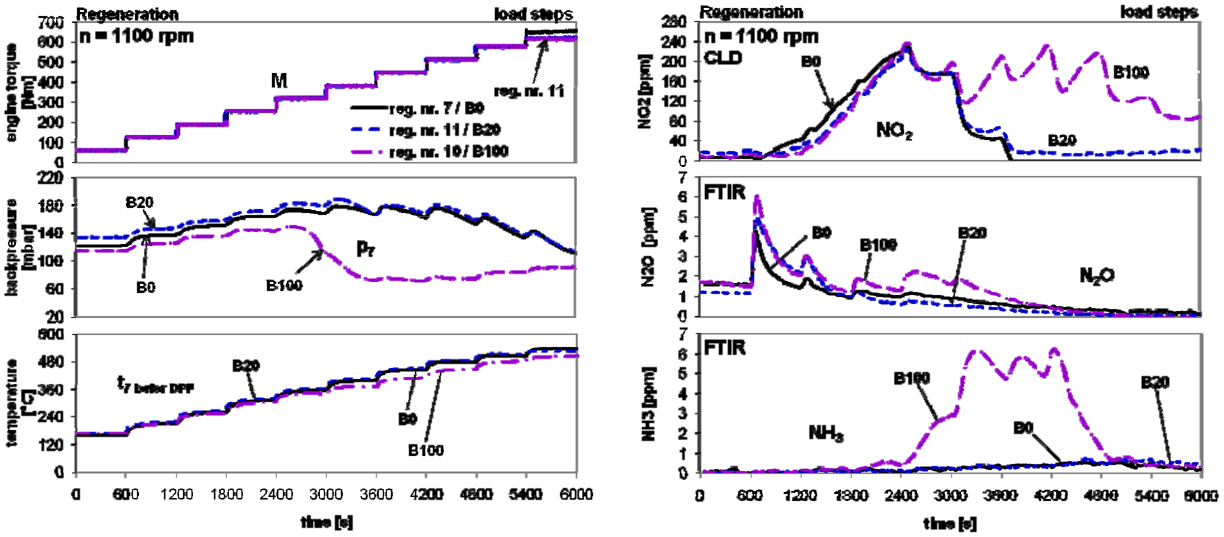


Fig. 49: Regenerations with (DOC + CSF) & B0, B20 & B100

Fig. 51 – the comparison of regenerations 7, 11 (B0 & B20 with DOC + CSF) and 18, 16 (B0 & B20 with CSF) shows for the DPF-system with weaker catalytic activity (CSF only) following tendencies:

- start of regeneration later – in steps 6 & 7 (instead of step 5 like for the other system) at exhaust gas temperature approx. 100°C higher,
- higher values of CO and HC (little oxidation),
- no production of NO_2,
- no production of N_2O peak in the 2nd step (represented in [2]),
- increased NP-values with B20 comparing to B0 (this is not the effect with strongly catalytic system DOC+CSF),
- the DPF with DOC oxidizes more the precursor substances of spontaneous condensates yielding lower NP-concentrations since the DOC-light-off in the 2nd step (approx. 240°C).

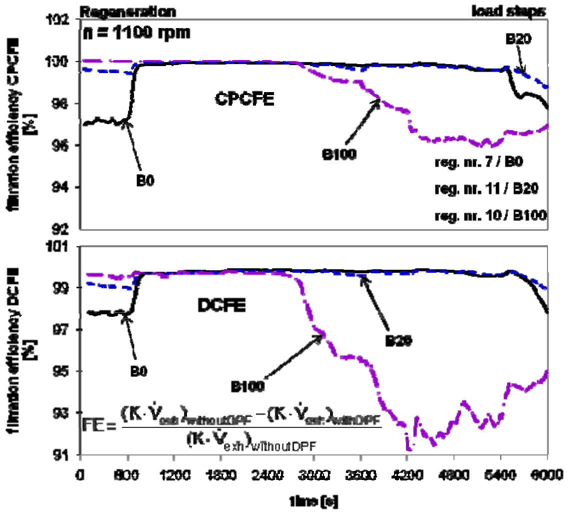


Fig. 50 Instantaneous nanoparticle filtration efficiency during the regeneration procedures with (DOC + CSF) & B0, B20, B100

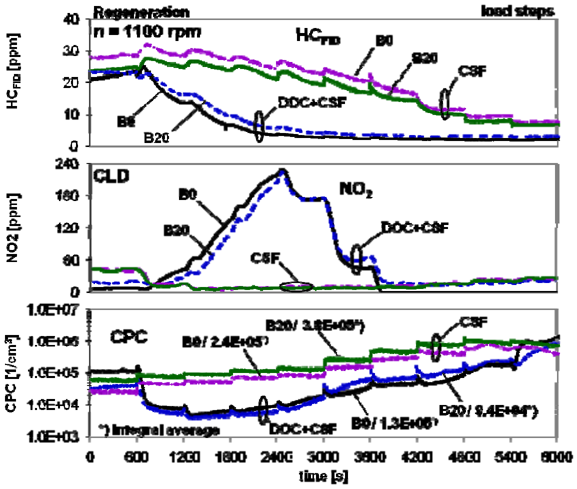


Fig. 51 Regeneration with (DOC + CSF) vs. (CSF) with B0 & B20

Table 8 summarizes the domains of balance point temperatures for the investigated regeneration variants. There are higher balance point temperatures with less catalytic activity and they decrease with growing bio-content in fuel.

DOC + CSF			CSF	
B0	B20	B100	B0	B20
356-368°C	356-363°C	342°C	454-464°C	447-455°C
at step 5	at step 5	at step 5	at step 7	at step 7

Table 8: Domains of the balance point temperatures of the investigated regeneration cases.

It can be summarized:

for regenerations with (DOC + CSF):

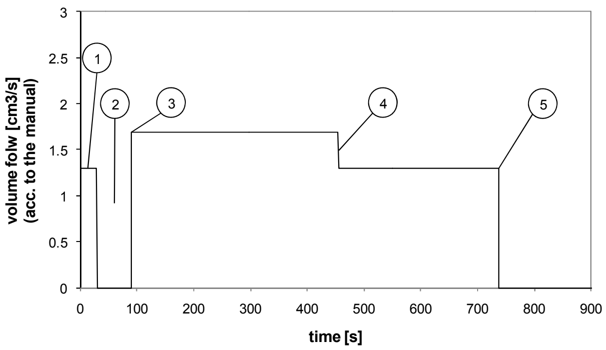
- with the same soot loading procedure the necessary time to load the DPF for Δp = idem increases with the bio-content of fuel (here for $\Delta p \approx$ 100 mbar: B0 1,7h; B20 2,5h; B100 27h),
- the reasons for slower soot charging with biocomponents are:
  - lower engine-out PM-emissions,
  - higher reactivity of PM and partial oxidation during soot loading with DOC,
  - with high bio-content (here B100) lowering of exhaust gas temperature to the temperature-window of the highest NO_2-production in DOC, easier NO-NO_2 oxidation with B100 and the intensified NO_2-continuous regeneration.
- there is a production of NO_2 with maximum in the steps 4 & 5 of the regeneration procedure,
- with unloaded DPF there is a clearly higher production of NO_2,
- the NP-signals (CPC, PAS, DC) give increased values in the last two steps due to intensified regeneration and higher spacial velocity (increased NP-break-through),
- the results of FTIR confirm the NO_x-results of CLD and give some further information: little N_2O-peak in the 2nd step (DOC light-off) and no significant emissions of NH_3,
- the repeatability of regeneration results and of the instantaneous filtration efficiencies is very good, except for the 1st step,
- the differences in the 1st step can be explained with the dispersion of the preliminary state of soot loading at the beginning of respective regeneration,
- with B100 there are some effects, which would not be detectable with B20:
  - there is more NO_2 with B100 because of lower t_{exh} (near to the maximum of NO_2-production), more NO_x and more easy NO-NO_2 oxidation,
  - the intensity of regeneration with B100 from 5th step (approx. 340°C) is higher; the drop of backpressure quicker than with the other fuels,
  - the increase of NP-emissions due to regeneration with B100 starts in the 4th step - spontaneous condensates after DPF and/or break-through of smallest size NP nuclei mode,
  - with the stronger catalytic system (DOC + DPF) B100 causes a drop of FE during the regeneration because of spontaneous condensation of heavy HC-compounds before and/or after DPF and a partially increased penetration of “thermodenuded” nuclei mode (PASFE).

for regenerations with (CSF):

- soot loading with B20 needs longer time (2h), than with B0 (1,4h),
- soot loading with CSF takes a little shorter time, than with (DOC+SCF),
- the regeneration procedures and emissions are well repeatable. The pressure curves p_7 indi cate the start of regeneration from step 7 (t_7 approx. 460°C),
- the plots of instantaneous filtration efficiency show the starting regeneration activity already from the 6th step (t_7 approx. 400°C) – NP are a more sensitive parameter,
- NO_2 is reduced, due to the Vanadium coating (Δ NO_2 negative nearly in all test),
- there is lower dispersion of curves of instantaneous FE and of temperature traces in step 8 with B20, than with B0.

<u>Active regenerations, HUSS</u>

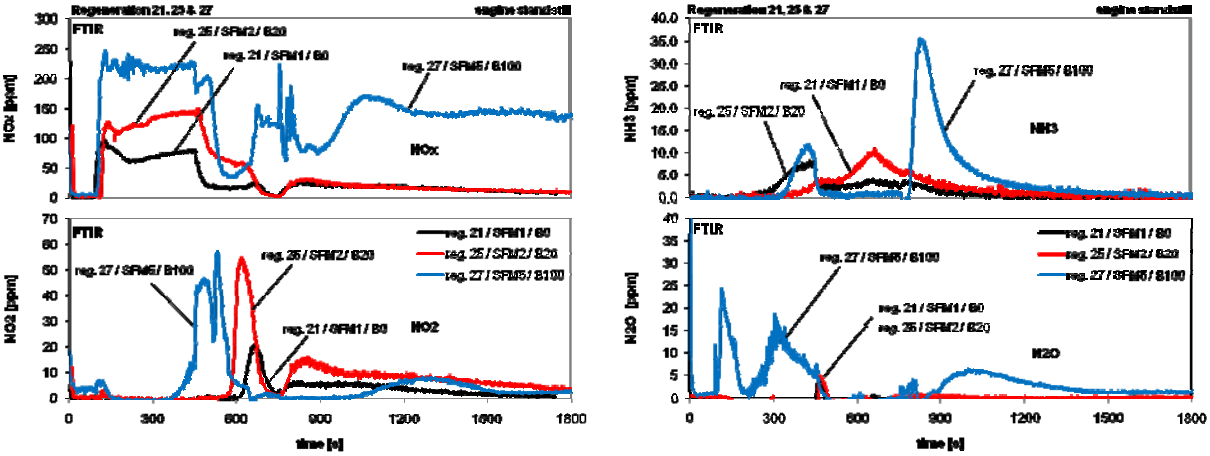
The regeneration procedure **with standstill burner** (system MK) is represented in <u>Fig. 52</u>. The represented points① to ⑤ are fixed in the ECU of the system and are a repetitive procedure. The air supply by the air pump is an important necessity at engine standstill.



1. glow plug precooling, air pump on
2. glow plug start (no air pump)
3. start of fuel & air supply, ignition, flame
4. switch off fuel (air pump on)
5. switch off air pump

<u>Fig.52</u>: Regeneration procedure with standstill burner (system MK)

<u>Fig. 53</u> shows the comparison of regenerations with B0, B20 and B100.
Regeneration 27 (B100) developed too much heat from the burning particle mass and destroyed the filter and the thermocouples.
There are tendencies of higher peak value of NO_x, NO_2, N_2O and NH_3 with B100. Nevertheless it must be supposed that some of these results are due to the extreme overheating and not only to the chemistry connected with B100.

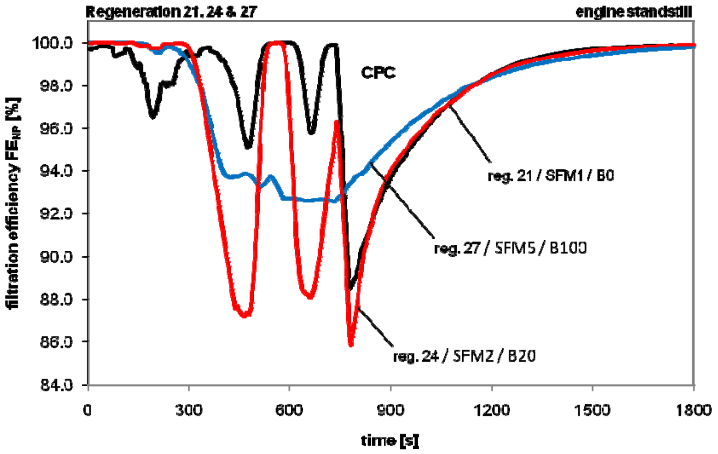


<u>Fig. 53</u>: Influence of B20 & B100 on the standstill burner regeneration DPF HUSS

The DPF overheating with B100 produced a high number of bigger nanoparticles, which increased stronger the summary active surface DC & PAS, than the count concentrations CPC. This provokes a considerable reduction of the equivalent FE_{DC} and FE_{PAS}, ([4], Fig. 16).

A definition of DPF filtration efficiency during engine standstill is not possible, since there is no engine-out emission entering the DPF.
Since the NP-values (CPC, DC & PAS) were measured during all regeneration procedures it was decided to calculate the instantaneous relative reduction rate of them as an equivalent of filtration efficiency. As reference the average concentrations of CPC, DC & PAS in the regeneration steps, [6], and engine without DPF were considered.
This equivalent filtration efficiency compares only the NP-concentrations [#/cm^3]. A comparison of absolute particle counts as product of concentration [#/cm^3] and volumetric flow [cm^3/s] makes no sense, since the volume flow of the regeneration air supply is negligible comparing to the engine volume flow.

Figure 54 shows some comparisons of instantaneous equivalent CPC- reduction rates with B0 / B20 & B100. It can be generally remarked, that the nanoparticle penetration during the flame period is stochastically increased – the equivalent filtration efficiency reduced. No influence of bio component content can be remarked.



$$FE_{NP} = \frac{(K)_{withoutDPF} - (K)_{withDPF}}{(K)_{withoutDPF}}$$

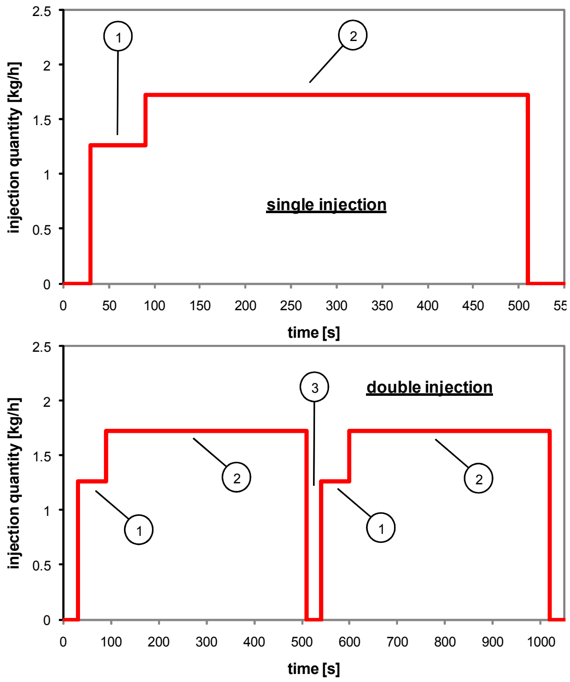
*) all reg. with burner fuel B0 except reg. 24 with B20

Fig. 54: Comparison of instantaneous equivalent CPC-reduction rates during the standstill burner regeneration with different bio-contents (burner fuel B0 & B20)*)

for the standstill burner regeneration HUSS MK it can be concluded:

- the time-courses of emissions and temperatures are closely connected with the regeneration startegy,
- the earlier switch-off of regeneration and air-flow is clearly visible – the soot burning stops,
- the nanoparticle penetration during the flame period is stochastically increased – the equivalent filtration efficiency reduced,
- the biocomponents increase the NO_x - & NO_2 - values, as well as the NP-emissions during the flame period,
- higher peak-values of NH_3 & N_2O are possible with increased bio-content,
- B20 can cause more difficult ignition of the burner,
- the filter loaded quickly with B100 was overheated and destroyed during the regeneration,
- definition of filtration efficiency for engine standstill is problematic.

The regeneration procedure with **fuel injection and DOC** consists of injecting the same amount of fuel during the same time at a constant operating point of the engine. This operating point can be chosen, but it should be in any case over the light-off of the DOC.



1. preinjection
2. main injection
3. pause

Fig. 55: Fuel injection strategies for regenerations of system Huss MD

Fig. 55 shows the fuel injection strategies for regeneration of the HUSS DPF, system MD. It can be programmed in the ECU of this DPF-system, that after the first FI-period, if the backpressure does not fall below a certain value, a second FI-period will be automatically activated.

In the present investigations some regenerations were performed with single, or with double FI.

The 1st two regenerations with each fuel (28 & 29 with B0; 31 & 32 with B20) were performed at engine operating point 900 rpm / 250 Nm / t_7 approx. 285°C.
The last regenerations (30 with B0; 33 with B20) were performed at 900 rpm / 330Nm / t_7 approx. 335°C.

By engine operation with B0 the same fuel was used for the FI (fuel aerosol generator).
By engine operation with B20 also B20 was used for FI.

Fig. 56 shows a part of the comparison of emissions of regenerations 28, 29 & 30, all with B0.
The second fuel injection in regeneration 28 is visible by the higher values of T_8, CO, HC, NP (CPC, DC) and NH_3 in the time interval 600-1100s.
Regeneration 30 was conducted at higher OP – higher levels of CO, HC and DC in the time interval of FI 200-500s and continuously higher NO_x-values.
After stopping the FI the temperature before DOC (T_8) decreased to the range of high NO_2-production, which causes a considerable increase of NO_2 concentrations. With double FI (reg. 28) this effect is respectively retarded.
During the fuel injection (FI) there is a production of ammonia NH_3 up to 3 ppm and a production of nitrous oxide N_2O in the range of 10 ppm with considerable peaks (up to 100 ppm) at the FI-start.

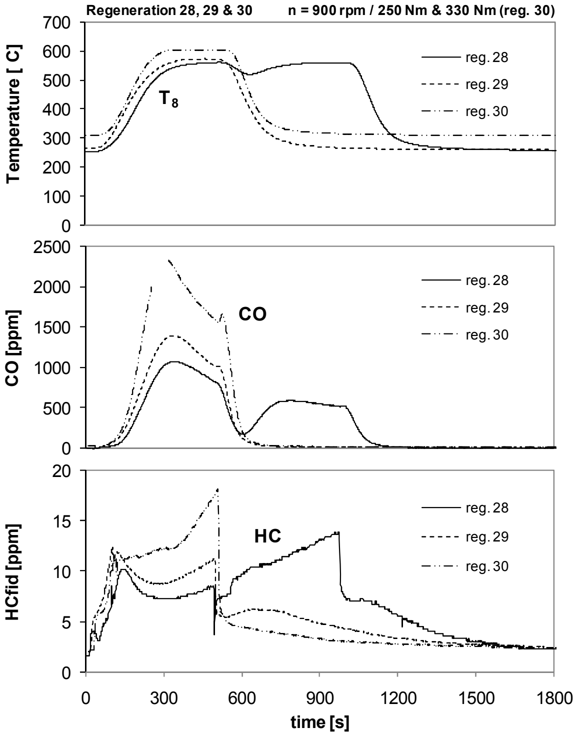


Fig. 56a: Fuel aerosol generator regenerations with B0

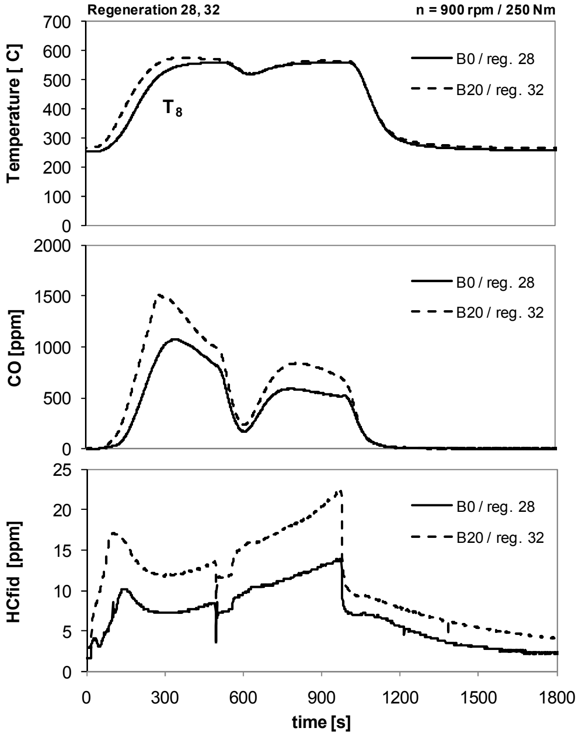


Fig. 57: Influence of B20 on fuel aerosol generator regeneration

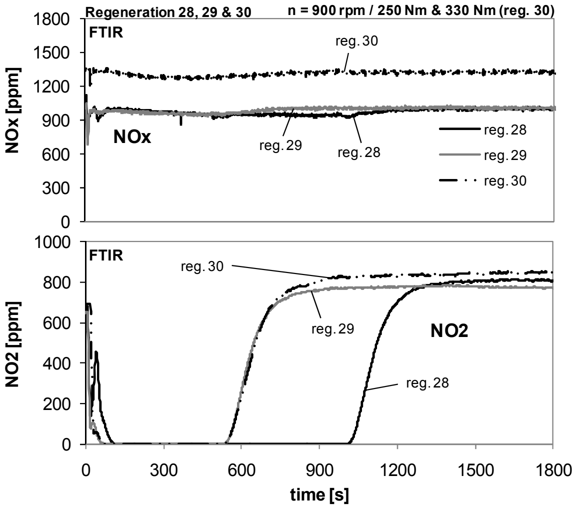


Fig. 56b: Fuel aerosol generator regenerations with B0

Fig. 57 shows the comparisons of some emission parameters with B0 and B20 and with double fuel injection (2xFI).

There are higher CO and HC with B20. There is a little influence of B20 on NO_x, NO_2, N_2O & NH_3.

In the 1st phase of regeneration process, during the period of increase of the exhaust gas temperature (T_8) there are significantly higher NP-emissions with B20; after this period the NP-values become equal, as with B0.

This observation can be explained with the fact, that the fuel injection is also conducted with B20 for the DPF, which was charged with B20. At the beginning of FI, when there is no oxidation in DOC the different HC-matrix from B20 (from both: DOC & DPF) enables more condensates after DPF. In the further phase, when the oxidation in DOC and in DPF becomes more intense, the influences of the products of this oxidation become similar for both fuels B0 & B20 and so they give origin to similar condensation effects afterwards.

Fig. 58 represents the comparison of the instantaneous CPC-filtration efficiency B0 & B20. It is confirmed that with B20 there is a significantly lower CPC FE in the first phase of regeneration procedure up to approx. 700s.

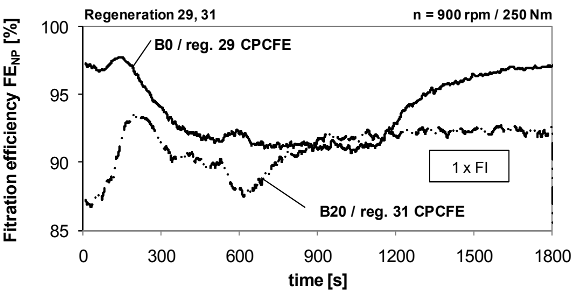


Fig. 58: CPC filtration efficiency during regeneration with B0 & B20

for the regeneration with fuel injection + DOC, HUSS MD it can be summarized, that:

- longer duration of fuel injection (double FI) prolongs respectively the period of high temperature level for the regeneration,
- the longer regeneration period is depicted with the higher emissions of CO, HC, DC & NH_3, in the respective time interval,
- at higher OP there is a higher level of exhaust temperature and of NO_x,
- after stopping the fuel injection there is an intense production of NO_2 due to t_{exh} decreasing into the level of NO_2-maximum,
- during the period of FI there is a production of NH_3 (up to 3 ppm) and of N_2O (in the range of 10ppm)
- during the regeneration period (period of FI) there is a break-down of NP-filtration efficiency, which correlates with the single, or double FI-period and which is more intense for DC,
- with B20 there is a lower NP-filtration efficiency in the first phase of regeneration procedure – this is an effect of stronger artefact of condensates after DPF, due to the changed HC-matrix of B20.

Comparing the average emission levels of both investigated active regeneration types it can be stated, that the standstill burner has significantly (in 1 range of magnitude) higher CO & HC and lower NO_x & NO_2.

8.3.4. Emissions of unlimited exhaust gas components

Results from engines: Liebherr D 934 S and Iveco F1C Euro 3 & 4.

With increasing analytical possibilities and increasing knowledge about different harmful substances it became necessary to get a more differentiated look at the emissions of engines. There is a general opinion of specialists and authorities, that the legally limited parameters from the past are no more sufficient to prevent the dangers resulting from the last technical developments and from the increasing traffic.
There is a necessity to consider the non-legislated (so called unlimited) components and to introduce them, if necessary, into the legislation.

According to the technical developments and analytical possibilities the unlimited components can be divided into 3 groups:

a) Nanoparticles (NP) came into the focus of attention as parameter of verification of DPF-systems. Today NP (>20 nm) are to be fixed as a legal parameter and the research on metal oxides particles (< 20nm) will continue.
   In all parts of the present tests the nanoparticles were measured with different methods: particle size and counts distributions with SMPS at stationary operation, summary particle counts at dynamic operation (CPC) and summary active surface of the nanoaerosol (carbonaceous PAS and total DC).

b) Nitric - and FTIR - components especially connected with the SCR-technology.
As nitric components are called:
  - nitrogen dioxide NO_2, much more toxic then NO, particularly produced in the catalytic after-treatment systems, very critical parameter being limited in some regulations for retrofitting, measured with CLD and with FTIR;
  - nitrous oxide N_2O, undesired greenhouse gas (greenhouse potential approx. 300 x CO_2), measured with IR-analyzer and with FTIR;
  - ammonia NH_3, prohibited to be emitted from SCR; in CARB regulation maximum ammonia - slip 20 ppm, measured with LDS, with CLD and with FTIR.

The application of FTIR opened the possibility of on-line measurements of 30 components (see annexes [6,7]). Among them the traditional gaseous components, some control values (CO_2, H_2O) and differential hydrocarbons, which are recalculated in “total Diesel HC’s”.
As FTIR components are called in this report some substances, which result from the $deNO_x$-chemistry and which can have a toxicological relevance. These are: isocyanic acid HNCO, hydrocyanic acid HCN, formic acid HCOOH and formaldehyde HCHO.

c) Secondary emissions and traces are investigated as a part of VERT / LRV quality verification procedure for DPF- and SCR-systems. The sampling and analytics are performed by a specialized team of EMPA Analytical Laboratory for Organic Chemistry. There are 3 groups of secondary emissions, which are known as very carcinogen and toxic and which can be found in [3], annex A3, p. 43-48:
  - Polycyclic Aromatic Hydrocarbons PAH, 12 substances, [μg/L],
  - Nitro-PAH, 22 substances, [μg/L],
  - Polychlorinated Dibenzodioxins PCDD and Polychlorinated Dibenzofurans PCDF, 33 substances, [pg/L].

In following some specific results with unlimited emissions are presented and discussed.

Nanoparticles

Typical influences of biofuels-blends on the nanoparticle emissions (SMPS-PSD) are represented in Figures 16, 17 and 23. Fig. 20 shows an example of the impact of EGR on NP PSD. Effects of biofuels with SCR on NP are represented in Fig. 44 and effects of biofuels on the emissions with DPF are depicted in Fig. 47.
The author refers to the comments and conclusions concerning these figures.

Regarding the emissions with SCR and DPF it can be said that:

- SCR catalyst reduces the NP count concentrations in the range of 10%. This is due to the diffusion loses, similarly, like in any straight-channel catalyst.
- SCR-system can produce secondary nanoparticles (crystals of: urea, isocyanic acid, cyanuric acid, nitrates, sulfates). The count concentration of secondary NP is negligible comparing to the engine-out-NP.
- DPF – if with the VERT / OAPC quality – eliminates efficiently the NP (PCFE>99%).
- With B100 a seemingly lowering of PCFE due to increased spontaneous condensation after DPF can be observed.
- With a combined system DPF (upstream) and SCR (downstream), at full load with B100 there is an artefact of “seading” the spontaneous condensation of bio-components from B100 by the secondary NP’s from SCR. As an effect the NP-penetration increases up to 25%.

Nitric components & FTIR

Useful information about reactions running in a SCR-system during engine load transitions, or urea switch-on tests can be obtained from the time-plots of the unlimited components (FTIR).

Fig. 59 shows as an example the load transition B, [6], 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.

Measured after the system (SP3) quite long response times of NO_x-reduction, 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 (α) different SCR reactions proceed.

An increase of nanoparticles concentrations is clearly indicated by both, the CPC- and the DC-signals.

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.

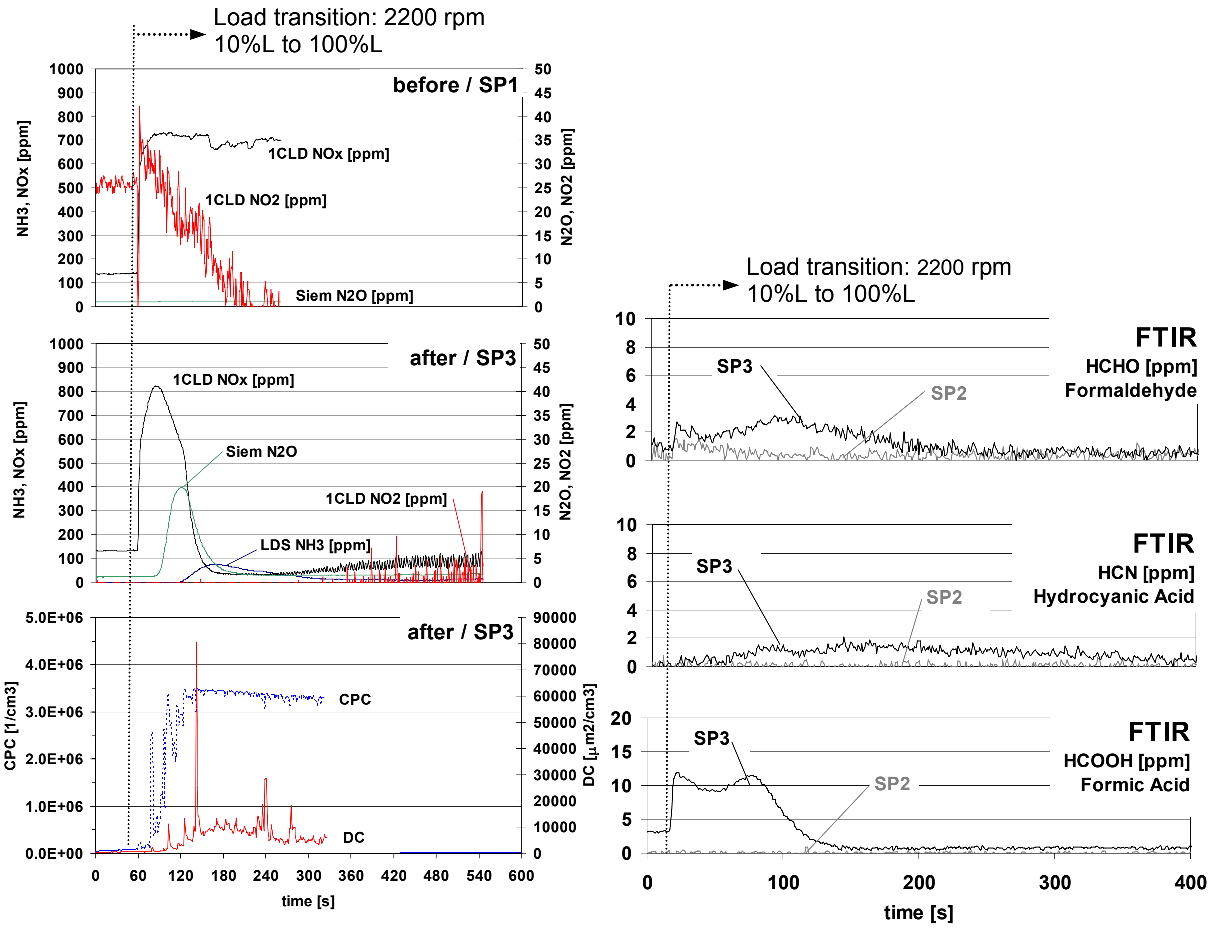


Fig. 59: Load transition B: from 2200 rpm / 10%L to 2200 rpm / 100%L with measurements before and after DPF + SCR, α=0.9, B0, Iveco F1C E3

The **urea switch-on test** (SW) was developed to study effects during the SCR light-off. Engine and exhaust system in this test are warmed up at a low load OP (e.g. 1200 rpm / 60 Nm) without urea injection. After a jump to higher engine loads OP (e.g. 1600 rpm / 165 Nm), urea injection is activated.

In the 1st operating point the engine slowly warms up, but the exhaust gas temperature is still too low to allow urea injection. After a jump to higher loads, the 2nd operating point, urea injection is activated after certain time after the exhaust temperature t_{exh} has increased.

Measurements were started shortly before the load jump to register the changes of exhaust concentrations during the urea activation period.

Fig. 60 shows the repeatability of several switch-on trials (SW12, 13, 14).

During SW12 temperatures were higher at the beginning. This may be a reason for lower concentrations of NO_2, formaldehyde, and formic acid in this period. Also the history of the SCR-catalyst can influence its chemistry by variable amounts of residues, or adsorbed substances.

The time period from "load on" to "urea on" varied in the range of 20s in these tests.

The NO_x reduction efficiencies K_{NOX} during the urea switch-on are also quite repetitive. This procedure can be regarded as a simple check of the SCR system on the HD chassis dynamometer.

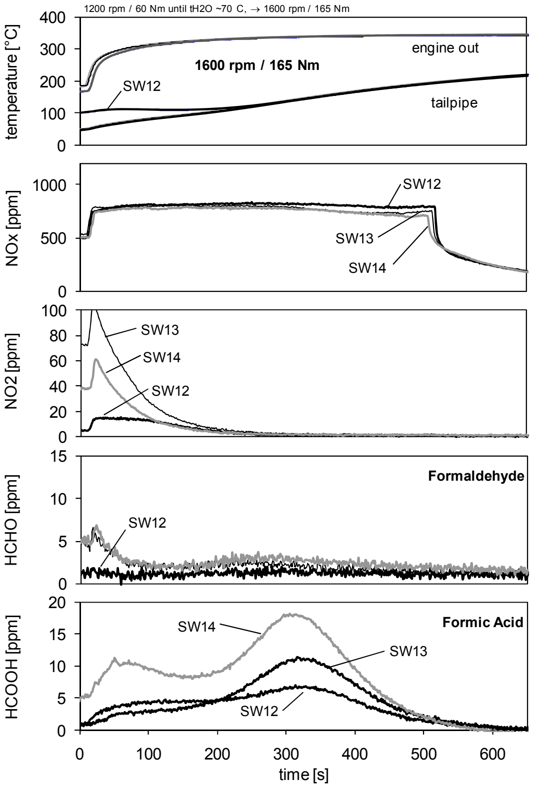


Fig. 60: Repeatability of switch-on tests, α=0.9, B0

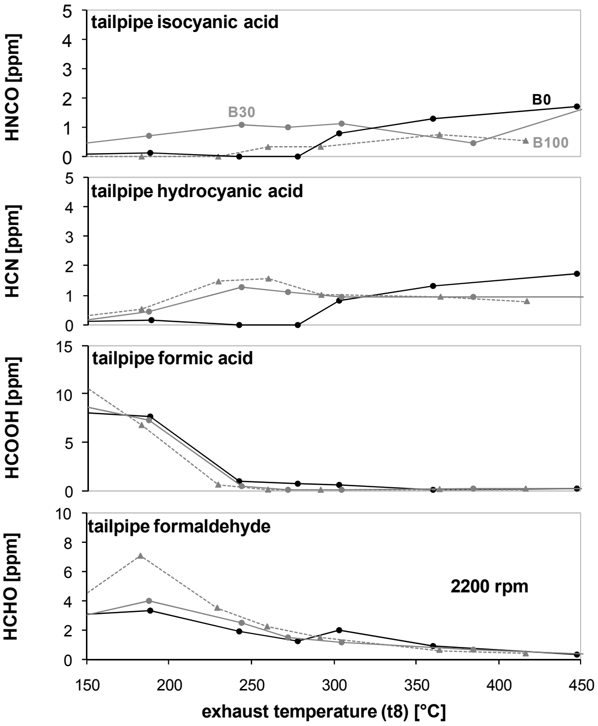


Fig. 61: Comparison of emissions in steps-test with SCR and B0, B30 & B100

Fig. 61 shows the emissions of FTIR components (isocyanic, hydrocyanic and formic acids and formaldehyde) with SCR and with different bio-contents B0, B30 & B100. This representation is a supplement to Fig. 40 and is a result of stationary steps tests at constant engine speed 2200 rpm and with stepwise increasing torque.

All represented components have very low absolute values which rarely pass over 2 ppm.
By the lowest operating points with the lower exhaust gas temperature (t_8) there is an increase of formic acid (up to 10 ppm) independently of B-content. In these low-load conditions there is also an increase of formaldehyde, which is clearly more pronounced with B100 (up to 8 ppm).
The increase of formaldehyde with B100 at the lowest OP was confirmed in [8]. It was found, that this increase roughly doubles (up to 16 ppm) with EGR. In dynamic operation of the engine (ETC) this tendency is no more visible (see Fig. 62).

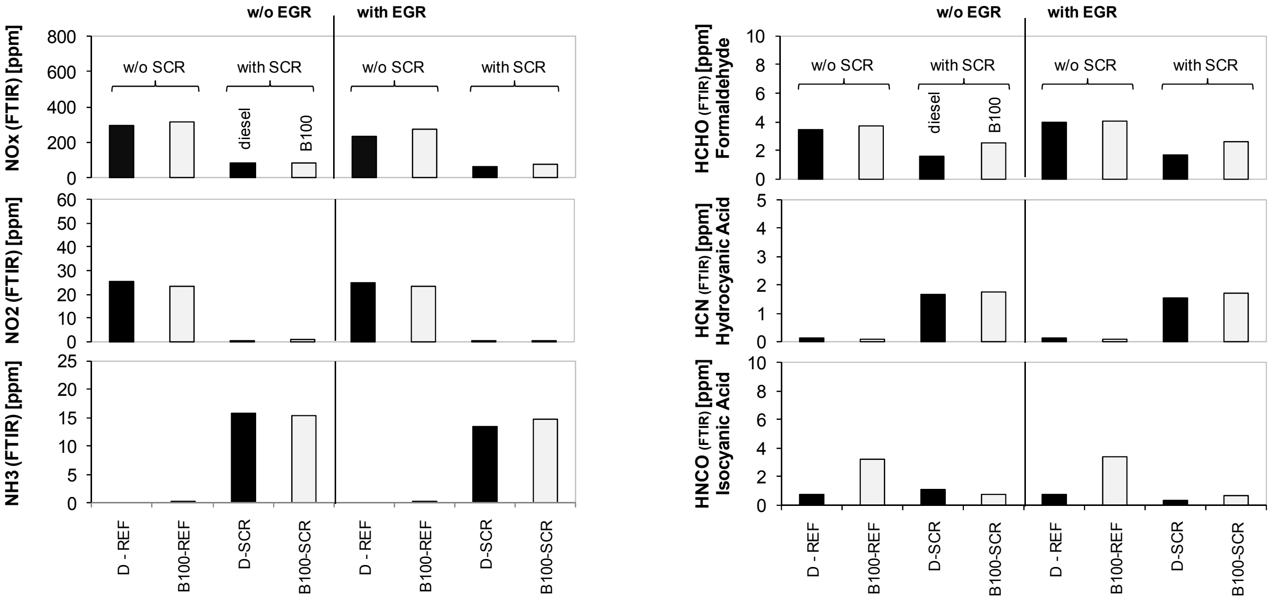


Fig. 62: Average emissions in ETC with Diesel and B100 with and w/o EGR, SCR; Iveco F1C E4

Fig. 62 represents the integral average values of nonlimited components (FTIR) in the ETC: with/without EGR, with/without SCR and with B0 & B100. This is an extended representation of Fig. 27. It can be remarked, that:

- EGR has no influence on the represented emissions (except of reduction of NO_x in the range of 17.5%, see Fig. 28);
- SCR is a most efficient measure to reduce NO_x & NO_2, it increases ammonia NH_3 and has effects on the other FTIR-components, but regarding the absolute values these effects are negligible;
- B100 has no influences on the represented emissions (except of some negligible increase of isocyanic acid w/o SCR).

The variations of SOI showed no influences on the unlimited components (FTIR).

In the research of DPF regenerations with biofuels the unlimited components (FTIR) indicated some transitory effects of running reactions (see examples in Fig. 49 & 53). Considering the high reactivity and the little amount of these substances it must be assumed, that most of these effects are not significant.

Summarizing it can be stated:

- the most important nitric components are: NO_2 and NH_3,
- NO_2 increase from catalytic aftertreatment systems is in the course of becoming limited at different places,
- NH_3, which is the reduction agent of SCR is limited actually by careful industrial developments; a follow-up in the respective legislations is most probable,
- other components: isocyanic acid, hydrocyanic acid, formic acid and formaldehyde (FTIR) are present in very low quantities; they are a very good indicator for the running chemical reactions, transient effects and store-release-effects of reactants, but as emissions they are insignificant.

Secondary emissions and traces

A VERT Secondary Emissions Test was performed with biofuels B100 and B30 and urea based SCR as well as with combinations of SCR and biofuels. Particle emissions were not analysed since respective data are already available from earlier test, [3]. This time the focus was on gaseous trace compounds and secondary emissions which were analysed following the VSET test protocol.

Samples were taken continuously proportional to the actual gas flow (aliquot) from the undiluted hot exhaust gas. A volume of typically 5-8 Nm3 was collected through a validated sampling arrangement over 200 Minutes driving cycle time (2 full ISO 8178/4 C1-cycles).
The sampling device consists of a sampling sonde, energy cooler, condensate separator, filter stage and two-stage adsorber unit (XAD-2). The sampling apparatus, made from glass is extensively cleaned and heated to high temperatures prior to each sampling. Using marked PCDD-standards in this investigation the recovery was found to be 65 ± 10 %.

The same sample was used to determine the PCDD/F as well as the PAH

PCDD/F-analysis was performed by separating the toxicologically relevant PCDD/F isomers using gas chromatography followed by high resolution mass spectrometry.

After chromatographic work-up quantitative analysis of the PAH and Nitro-PAH were also performed using capillary gas chromatography high resolution mass spectrometry.

PCDD/F- Analysis:

Aliquot exhaust gas samples were taken over the full length of the test (2 cycles, 200 minutes) with an isokinetic sampling unit which was designed to collect the gaseous components proportional to gas flow as well as the particle-bound species. Back home in the laboratories of EMPA/Dübendorf these samples were analysed with respect of the 17 toxicologically relevant polychlorinated dibenzodioxin/furan (PCDD/F) isomers.

The following graph, Fig. 63, shows the overall results.

There seems to be a slight indication of increase when biofuels are used, which is more pronounced with some individual compounds like the Seveso Dioxin but when SCR is used these toxic substances are clearly reduced with both fuels.

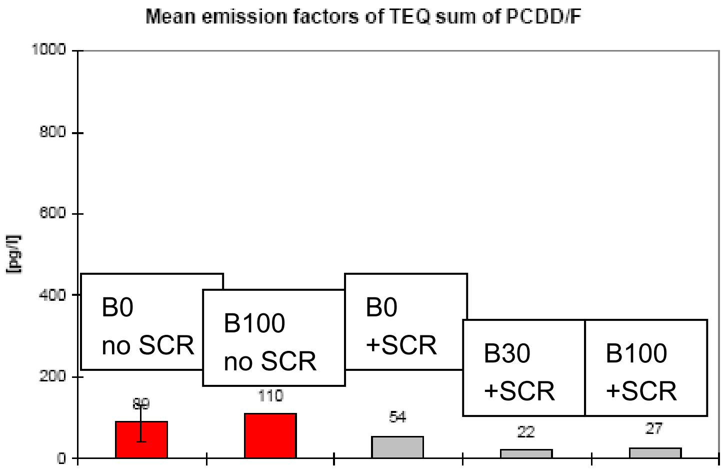


Fig 63: Emission factors for the weighed sum of 2, 3, 7, 8-substituted PCDD/F (TEQ-sum) in pg per liter fuel.

PAH-Analysis:

PAH were analysed from the same sample as the PCDD/F.
The following graph, Fig. 64, summarizing the data for the carcinogenic PAH according to the IARC-definition shows the overall results.

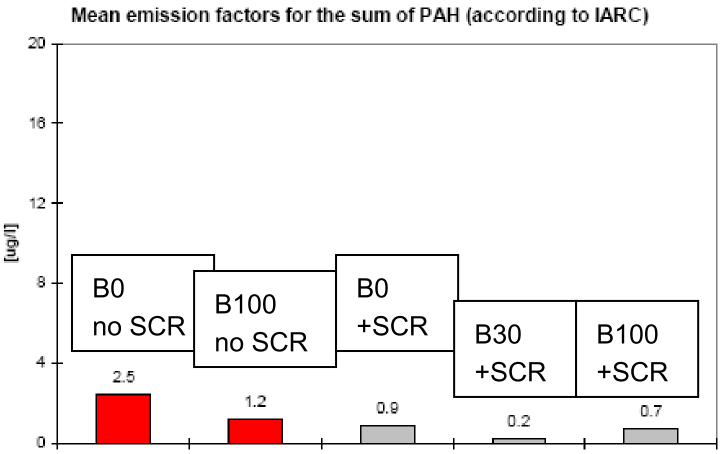


Fig. 64: Emission factors for the sum of carcinogenic PAH (IARC) in µg per liter fuel

The following results were obtained:

- Biofuels B100 and B30 had little influence on NO_x, NO_2/NO_x, CO, CO_2 and consumption of fuel, however they reduced HC by about 50 %, PAH by 80-90 % and Nitro-PAH by 50-70 %
- The Urea based SCR reduced NO_x on average by about 85 % and eliminated NO_2
- SCR also reduced HC, PAH and Nitro-PAH very effectively but had no influence on CO
- The side effects of the SCR technology can be emissions of NH_3, N_2O and HNCO. These were visible but not very pronounced
- Formation of dioxines and furanes was visible but not promoted by these technologies
- The combination of SCR and biofuels had no negative side effects – on the opposite a further reduction of PAH and PCDD/F could be observed.

8.3.5. DOC light-off with biocomponents

In order to investigate the DOC light-off load steps were performed at different engine speeds (900, 1100 & 1300 rpm) with B0, B20 & B100. These load steps with 5 min step duration were conducted up and down to see the possible effects of hysteresis.

Following findings can be pointed out:

With increased bio-content there is a higher NO_x- and lower HC-emission.
During the load jump from the 1st to the 2nd step, there are:

- elimination of CO, equal for all fuels,
- lowering of HC with B100, while increasing with B0 in the 2 minutes after load jump – most probably due to the starting oxidation of HC with B100,
- quicker increase of NO_2 with B100 (see also in the zoomed representation, Fig. 30-3), which indicates an easier light-off with B100.

Similar tendencies are also visible at higher engine speeds.
The differences are less pronounced due to higher flow velocities through the catalyst.
The representation in function of exhaust temperature, Fig. 65, confirms that there is light-off for NO_2 starting with B0 at approx. 220°C, with B20 at 200°C and with B100 at 170°C.
For HC the lowering in the 1st step with B100 is confirmed, which indicates the light-off for HC at approx. 170°C. (As light-off in this context is understood the visible start of reaction).

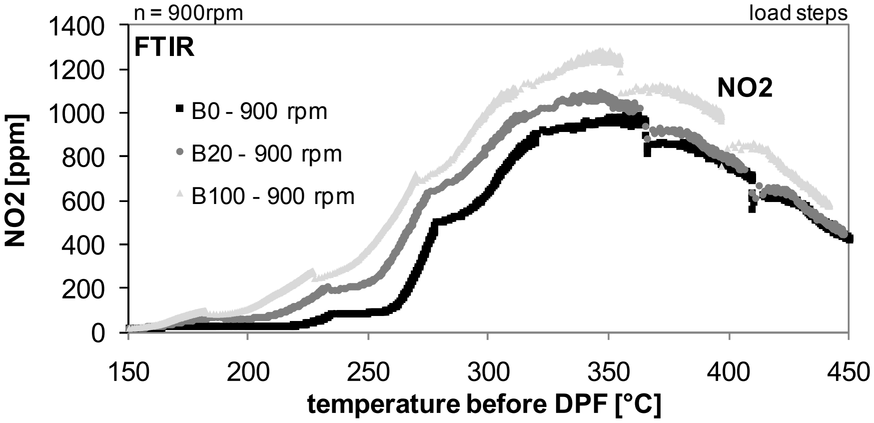


Fig.65: Influences of fuels B0, B20 & B100 on DOC light-off for NO_2 in steps tests;
Liebherr D 934S A6

The consideration of NO_2- and HC-plots in function of exhaust gas temperature at increasing engine speed, allows to remark, that there is a little influence of increasing gas flow and increasing spacial velocity (SV) on the light-off. With higher engine speed the start of increasing NO_2, or decreasing HC is moved to higher exhaust gas temperature (in the range of $\Delta t \approx 10°C$).

With the chosen duration of steps (5 min) there were differences of results between the tests with increasing or decreasing load.

It can be generally remarked, that during the down-steps there is higher temperature level, which causes the more intense catalytic conversion of CO, HC & NO_2 in the lower steps.
These temperature differences caused by different ways of conducting the tests are due to the thermal inertia of the system.

The resulting statement is that the results in all steps tests (like ISO 8178, or ESC) are connected to the time-schedule of the test procedure.

8.3.6. PAH & TEQ with biofuels

Particle matter (PM) emitted by the engine at different operating points (OP), with different fuels (B0, B30 & B100) and with different exhaust gas aftertreatment was sampled and analyzed at the JRC laboratories.
14 Polycyclic Aromatic Hydrocarbons (PAH) were determined in the filter samples by means of the High Pressure Liquid Chromatography (HPLC) and the toxicity equivalence (TEQ) according to the EPA method was estimated. Details of procedures are described in the supplements to [1] & [2].

The analyzed PAH and their toxicity equivalence factors are represented in the following Table 9:

Compound	TEF
Fluorene	0,001
Phenanthrene	0,001
Anthracene	0,001
Fluoranthene	0,010
Pyrene	0,001
Benzo[a]anthracene	0,100
Chrysene	0,010
Benzo[b]fluoranthene	0,100
Benzo[k]fluoranthene	0,100
Benzo[e]pyrene	0,002
Benzo[a]pyrene	1,000
Indeno[1,2,3-CD]pyrene	0,100
Dibenz[a.h]anthracene	1,000
Benzo[ghi]perylene	0,010
Coronene	0,010

Table 9: Toxicity equivalence factors of different PAH’s (according to US EPA 1994)

The tests consisted of two parts.
- part 1 including SCR – and (DPF+SCR) – systems on Iveco engine,
- part 2 including two types of DPF’s on Liebherr engine.

Part 1

Particle matter was sampled on the Iveco F1C engine at a part load (PL) and full load (FL) operating points according to the following matrix:

	B0	**B30**	**B100**
w/o aftertreatment	PL / FL	PL / FL	PL / FL
DPF + SCR	PL / FL	PL / FL	PL / FL
SCR only	PL / FL	PL / FL	PL / FL

PL (part load): 2200 rpm / 32 Nm OP4, 7.4 kW
FL (full load): 2200 rpm / 300-330 Nm OP1, 74 kW

The comparison of TEQ in [ng / mg PM] for all investigated variants of fuel, of aftertreatment and operating points is represented in Fig. 66.

It can be remarked:

- there is generally a lower TEQ at higher OP1,
- with increased bio-content there is a tendency of lovering TEQ at lower OP4 and of increasing TEQ at higher OP1; (some exceptions – especially SCR B0 & SCR B30 at OP4 – are attributed to the measuring and emitting dispersion),
- the SCR alone produces at low load generally higher TEQ as (DPF+SCR),
- at high load with higher bio-content the TEQ of (DPF + SCR) is higher, than of SCR alone – this can be attributed to the condensation effects after DPF, which are promoted by the presence of bio-components and a seeding effect of the secondary NP from SCR.

The view on TEQ-comparisons in [µg / kWh], (not represented here), allows further statements:

- SCR has a tendency to slightly lower the TEQ-values, comparing with no aftertreatment,
- DPF is the best method to eliminate PAH and to minimize TEQ.

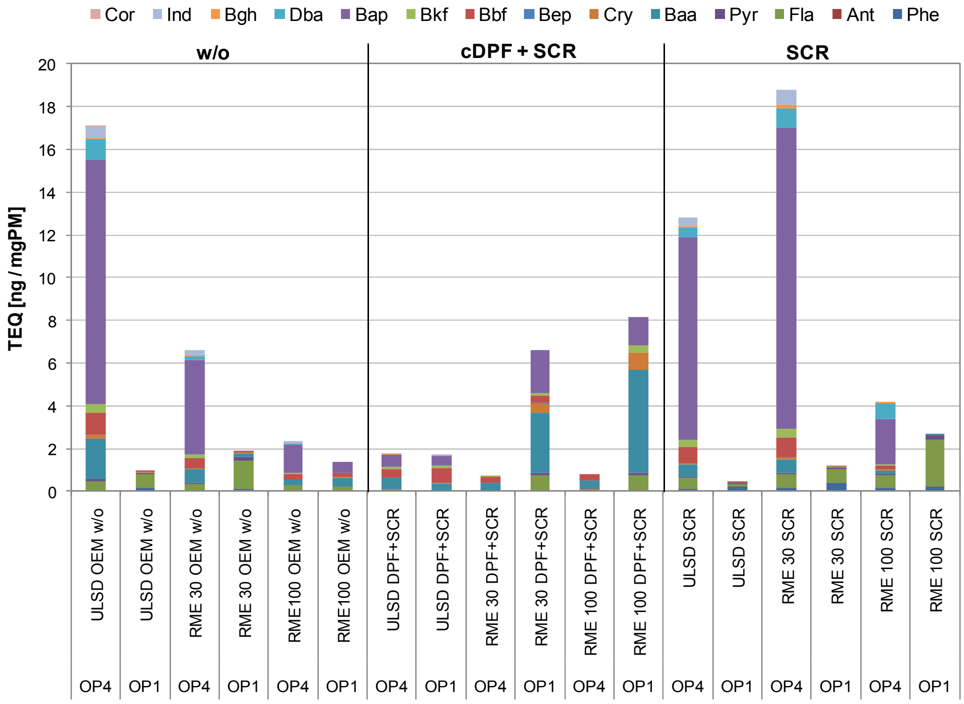


Fig. 66: Toxicity Equivalence TEQ [ng / mgPM] with biocomponents (RME), SCR and DPF, Iveco F1C E3

Part 2

Particle matter was sampled on the Liebherr D 934 S engine at a part load (PL) and full load (FL) operating points according to the following matrix:

	B0	**B30**	**B100**
w/o DPF	PL / FL	PL / FL	PL / FL
with DPF (no coating, burner)	PL / FL	PL / FL	PL / FL
with DOC + DPF (coated)	PL / FL	PL / FL	PL / FL

PL (part load): 900 rpm / 315 Nm OP7b, 29.7 kW
FL (full load): 1100 rpm / 480 Nm OP2b, 55.3 kW

The comparison of TEQ in [ng / mg PM] for all investigated variants of fuel, of aftertreatment and operating points is represented in Fig. 67.

It can be remarked:

- the highest values of TEQ are at the low load OP7b, without exhaust gas treatment, mostly due to the presence of B(a)P; with B100 at this OP there is a clearly lower TEQ,
- at the higher OP2b, without aftertreatment the TEQ-values are lower and there is a tendency of highest TEQ for B30,
- with DPF's the TEQ is clearly lower, than without DPF,
- in the average for the results with DPFs there is no clear tendency of TEQ for different fuels, different operating points or DPF-types; a more differentiated look reveals a tendency of lower TEQ at part load operating points with biofuels and with catalytic DPF.

Regarding the comparisons of TEQ expressed in [μg / kWh], (not represented here), the high efficiency of DPF to reduce TEQ is demonstrated. This with no regard, if catalytic or no catalytic DPF is used.

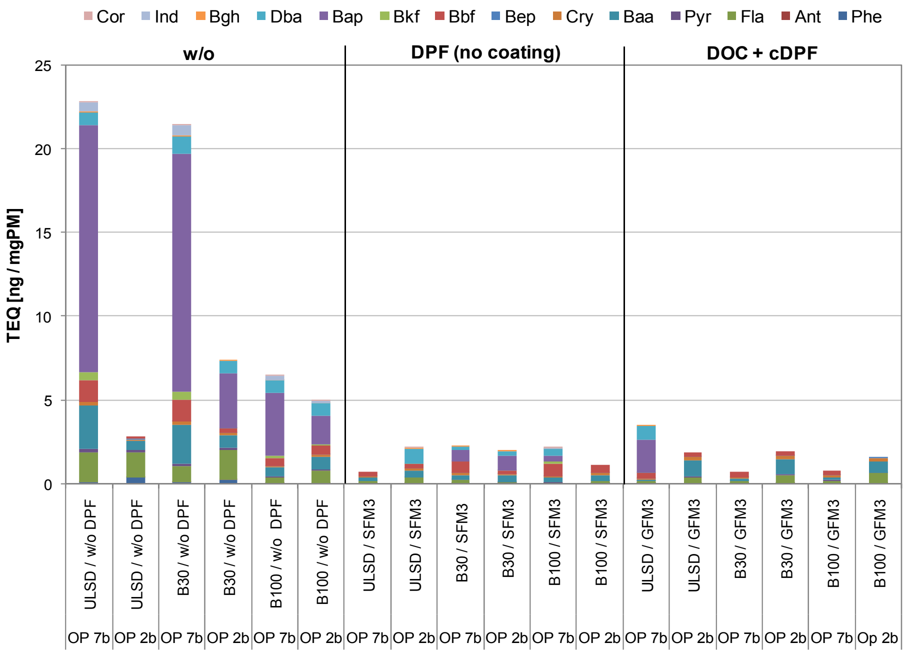


Fig. 67: Toxicity Equivalence TEQ [ng / mgPM] with biocomponents (RME) and DPF, Liebherr D 934 S A6

Conclusions

- DPF has a positive effect of reducing PAH & TEQ.
- At low-load operating conditions without DPFthere is a tendency of higher TEQ (due to presence of B(a)P).
- Higher biofuel content has with DPF no influence on TEQ.
- Without DPF there is a tendency of lowering TEQ at low load and increasing TEQ at high load. The tendency of maximum TEQ in the range of B30 at high load, which is reported in literature, [61], is confirmed.
- No differences concerning TEQ could be remarked for catalytic and non-catalytic DPF's. This result nevertheless must be limited to the present engine and the present operating conditions.
- SCR alone has no influence on TEQ.

The investigated TEQ considers only the PAH, which were deposited in the PM. The PAH from gaseous phase are not considered.

8.4. Swiss quality verification tests VERT / OAPC

Formal situation

General information about the VERT quality testing of DPF-systems for retrofitting is given in chap. 2.3. More details about the tests, requirements and the recommendation list of tested products can be found on the homepage of VERT ® - Association: www.vert-certification.eu, or www.vert-dpf.eu.

Swiss legislation for the workplace [66] and offroad [67] where traps are now mandatory on Diesel engines is based on VERT-results and requires exclusive use of systems which have successfully passed VFT and VSET. These test protocols are also approved by several foreign authorities.

The VERT measuring procedures were carefully reconsidered and described in the Swiss Norm SNR 277205 (Sept. 2007), [68] which, after several improvements became a definitive norm SN 277206, since the beginning of 2011.

In the amendment to the Clean Air Ordinance (OAPC/LRV) from Sept. 19th, 2008, (part 4a and appendix 4, paragraph 3) [67], the Swiss Federal Office of Environment established new legal base for the approval of construction machines and DPF systems for retrofitting.
These procedures, here simply called LRV are based on VERT test procedures and SN 277206. There are some simplifications of quality requirements and a change of administrative procedure, which became a conformity testing and conformity certification, like for different other products, according to the federal law.

LRV offers two options to control the emission quality of construction machines (both OEM and retrofit).

- fulfilling of nanoparticles counts limit value of 10^{12} 1/kWh in the NRSC and NRTC according to the guideline 97/68/EG (possibility for OEMs),
- using of DPF system, which fulfils the LRV-requirements.

Since January 2009, the Federal Office BAFU transformed the VERT Filter List in a LRV List, which recommends the DPF systems suitable for retrofitting.

The Association of Retrofit Manufacturers (AKPF) decided to create a VERT Association, which owns the legally protected label "VERT" and will continue to take the worldwide responsibility for BAT- VERT procedures and of VERT Filter List. In this way, a regular attention will be paid to: additional quality requirements (which are not included in LRV), activities of knowledge transfer, consulting and support for the users and for industry and a control of the aftermarket service.

There is a close and continuous collaboration between the committees of VERT verification procedures and LRV conformity.

The actual BAFU-LRV DPF List can be found at: www.umwelt-schweiz.ch/filterliste.

Further information about formal procedures and main differences between VERT & LRV can be found at: www.afhb.bfh.ch (under: VERT/LRV).
It can be stated, that the technical tests procedures for both quality systems are the same (with exception of durability field test 1000h for LRV & 2000h for VERT). Main differences are in the administrative procedures.

VERTdePN, as already explained in chap. 2.4., has the objective of including the deNO$_x$ systems (mainly SCR) into the verification procedure.
The VERTdePN procedures are (to date May 2011) in the end phase of development and will be most probably implemented by the responsible authorities 2012.

Results & recommendations

The used equipment and procedures in the present project are those of VERT. There are several results concerning the use of bio-fuels.

DPF: Principally the filtration of solid particles (NP) is independent of fuel B-content. Nevertheless with increasing share of bio-components there are more condensates after the DPF, which increase the particle count concentrations and simulate the lower overall PC-filtration efficiency (PCFE) of the DPF. This means, that to prevent the mistakes resulting from this artefact it is better to test the DPF with standard fuel. Typical results of PCFE with increasing content of RME in 4 pts tests are presented in the Table 7.
The soot loading with biofuel, or biofuel-content, Fig. 48, needs longer time because of less PM-emission of the engine and also because of stronger soot oxidation during the loading procedure. The regeneration is easier to ignite with Bio-content, Table 8. In case of a stronger soot loading up to the limit of the capacity of the DPF, there is a danger of overloading DPF and getting too much heat value of the SOF deposited in the DPF. This effect with B100 caused, in one case of a non-catalytic DPF with an active regeneration help, an overheating and destruction of the filter material.

An important part of VERT quality testing procedure is the field durability test (2000h for VERT, 1000h for LRV). This was not an objective of investigations in present part of project, since the results concerning exhaust aftertreatment are well known:

- the biofuels have historically a bad reputation concerning poisoning of catalytic coatings; this is true, if the content of sulphur, phosphorus and dirt is above the quality norm,
- the presence of biofuels quality norms and the fuels, which fulfil these norms are guarantee for satisfactory long life of catalytic coatings,
- the questions of lube oil durability and degradation with application of biofuels is always to consider and it was a subject of the part of investigations of INIG.

The fulfilment of biofuel quality requirements depends on supplier, transport, stocks conditions and time of storage.

Bio components have limited durability (validity) time because of oxidative degradation, water absorption and possible bacteria befall [69, 70, 71]. For these reasons the user of biofuel is recommend to periodically control the quality of supply chain and of the fuel.

A recently published study of a US industrial consortium, [72], about the impact of biodiesel impurities on the long-term behaviour of exhaust aftertreatment elements showed, that due to diffusion of Alcali Metals (K, Na, Ca) into the ceramic materials of DOC, DPF and SCR, the material resistance of these elements is reduced significantly during the long duration operation.

Following recommendations can be given for the use of biofuels with DPF systems:

- the filtration efficiency is not influenced by the biofuel, but there can be artefacts of spontaneous condensates after DPF,
- performing VERT/LRV tests part 1 & 3 is recommended with a standard fuel,
- for long life of catalytic coatings and for sustainable engine operation control periodically the quality of fuel and fuel supply chain,
- for active regeneration systems with high bio-content set down the threshold for starting regeneration to the lower values of backpressure, to prevent the danger of overheating of DPF during the regeneration,
- for burner regeneration, if biofuels are used for the burner, make sure the reliable ignition and operation of the burner,
- consider the general recommendation for the engine: durability of injection system and of lube oil; power reduction with fuels with lower heat value; limits of electronic regulation with changed heat value of fuel.

<u>SCR</u>: Biocomponents have principally no influence on the deNO$_x$-conversion rate. Nevertheless, since the catalytic activity of the SCR-catalyst is a principal effect, care has to be taken for the long life of the catalytic coatings and washcoat materials.
Therefore, the consideration of biofuel quality (sulfur, phosphorus), as above mentioned is very important.

The recommendations for the users of SCR systems with biofuels concern the fuel quality and the sustainability of the engine operation and are the same, as mentioned above for DPF.

- for long life of catalytic coatings and for sustainable engine operation control periodically the quality of fuel and fuel supply chain,
- consider the general recommendation for the engine: durability of injection system and of lube oil; power reduction with fuels with lower heat value; limits of electronic regulation with changed heat value of fuel.

With Vanadium based SCR it was confirmed that the unregulated components N_2O, NH_3 & HCN are in a low and negligible level. There is also no production of undesired trace-substances, like dioxins and furans.

9. CONCLUSIONS, REMARKS & RECOMMENDATIONS

9.1. Conclusions

The most important conclusions, according to the investigated topics and the performed working packages, can be listed as follows:

<u>Injection & combustion:</u>

- RME shortens slightly the injection lag,
- RME offers a rate of heat release similarly like a market fuel, the combustion with RME 100 is slightly advanced (appr. 1°CA at FL),
- this fact and the modified reactivity of RME are the reasons for higher NO$_x$.

<u>Limited emissions & energy consumption:</u>

<u>RME</u> lowers CO and HC and increases NO$_x$ at all operating points, it lowers PM at higher engine loads and increases PM at lower engine loads. RME has no effect on specific energy consumption.

Nanoparticle emissions with RME:

- RME moves the PSD spectra to smaller sizes and increases the nuclei mode due to spontaneous condensates,
- RME causes lower particle emissions at high load and higher emissions at low load,
- with RME there is a higher portion of condensates (SOF) at low load and idling.

Elemental & organic carbon EC/OC:

- higher engine load produces less OC and more EC, i.e. "dryer" soot
- RME causes higher portion of OC (lower portion of EC), which is particularly pronounced at lower engine load
- RME reduces the total PM at higher engine load, especially due to the reduction of EC.

EGR, B100 & SCR:

At stationary engine operation the NO_x reduction potentials with combination of EGR, B100 & SCR are:
- at lowest load OP3c EGR reduces NO_x by up to 30%, B100 does not increase NO_x and SCR has no effect due to urea switched off,
- at middle load (OP3) EGR reduces NO_x approx. in the same range (20-25%) as B100 increases it, SCR is the strongest reduction tool in the range of 80%,
- at full load (OP1) there is no EGR, B100 increases NO_x by 4% and SCR reduces it by 78%.

At transient engine operation the NO_x reduction potentials with combination of EGR, B100 & SCR are:
EGR reduces NO_x approx. in the same range, as B100 increases it (10-20%); SCR is the strongest reduction measure in the range of 72%.

EGR provokes clearly an increase of NP-emissions. By application of B100, or combinations of B100, SCR & EGR there is a balancing of several influences on NP-production.

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.

SOI & B100:

- 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,
- 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.

SCR- and (DPF+SCR) - systems with B0:

- the combined dePN systems (DPF+SCR) at transient engine operation efficiently reduce the target emissions with deNO$_x$-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$_x$ conversion efficiencies increase (up to 98%), but also the ammonia slip rises up to 125 ppm,
- with the recommended feed factor α = 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$_x$ conversion efficiency at transient operation (ETC) strongly depends on the exhaust temperatures which are correlated with the urea-dosing strategy; during low-load operation this efficiency is strongly reduced,
- the nanoparticle filtration efficiency, which is verified at stationary engine operation, is perfectly valid also at transient engine operation.

SCR- and (DPF+SCR) - systems with RME blend fuels:

- in dynamic tests (ETC) with DPF+SCR only higher NOx-emissions with RME 100 are to remark, CO & HC are for all fuels at zero level (catalytic conversion),
- with SCR alone there are no differences of NO$_x$ and of NOx reduction rate (K_{NOX}) with increasing RME portion; there is lowering of CO & HC,
- the light-off of the SCR alone is with RME 100 at a slightly lower temperature, than with B0 & B30 ($\Delta t \sim$ 10-20°C),
- at stationary full load operation with DPF+SCR and with RME 100 there is an intense production of secondary nanoparticles from the SCR part; this effect lowers remarkably the overall NP-reduction efficiency; it is almost not visible at dynamic operation,
- with SCR alone there is usually a small reduction of nanoparticles concentrations (in the range of 10-20%) losses in the mixing tube and in the two in line SCR catalysts; in dynamic operation this reduction is smaller (below 10%).

Emissions with DPF:

The VERT Filter Tests (VFT1) with catalytic DPF system and different bio-blend fuels showed following influences on emission:

- with increasing bio-content in fuel without DPF the limited components CO, HC and PM (at high load) are reduced and NO$_x$ are increased,
- with DPF there is a clear catalytic influence: elimination of CO, strong reduction of HC and increase of the NO$_2$ / NO$_x$-ratio,
- the tested DPF reaches the nanoparticle counts filtration efficiency PCFE up to 99.99%,
- using the DPF at too high gas flow – over the limit of maximum spacial velocity – deteriorates the PCFE due to the NP-break-through,

- the filtration efficiency according to mass PMFE is always lower, than PCFE due to the post condensation artefacts in the PM-measuring line (in the present work the differences of both values are little),
- using of pure biofuel B100 also lowers the PCFE due to post condensation effects and increased penetration of smallest particles, except of that the lower blends (B7, B20 & B30) have no impact on PCFE.

Regenerations with (DOC+CSF):

- with the same soot loading procedure the necessary time to load the DPF for Δp = idem increases with the bio-content of fuel (here for $\Delta p \approx 100$ mbar: B0 1,7h; B20 2,5h; B100 27h),
- the reasons for slower soot charging with biocomponents are:
    - lower engine-out PM-emissions,
    - higher reactivity of PM and partial oxidation during soot loading with DOC,
    - with high bio-content (here B100) lowering of exhaust gas temperature to the temperature-window of the highest NO_2-production in DOC, easier NO-NO_2 oxidation with B100 and the intensified NO_2-continuous regeneration.
- the repeatability of regeneration results and of the instantaneous filtration efficiencies is very good, except for the 1st step,
- the differences in the 1st step can be explained with the dispersion of the preliminary state of soot loading at the beginning of respective regeneration,
- with B100 there are some effects, which would not be detectable with B20:
    - there is more NO_2 with B100 because of lower t_{exh} (near to the maximum of NO_2-production), more NO_x and more easy NO-NO_2 oxidation,
    - the intensity of regeneration with B100 from 5th step (approx. 340°C) is higher; the drop of backpressure quicker than with the other fuels,
    - the increase of NP-emissions due to regeneration with B100 starts in the 4th step - spontaneous condensates after DPF and/or break-through of smallest size NP nuclei mode,
    - with the stronger catalytic system (DOC + DPF) B100 causes a drop of FE during the regeneration because of spontaneous condensation of heavy HC-compounds before and/or after DPF and a partially increased penetration of “thermodenuded” nuclei mode (PASFE).

Regenerations with (CSF):

- soot loading with B20 needs longer time (2h), than with B0 (1,4h),
- soot loading with CSF takes a little shorter time, than with (DOC+SCF),
- the regeneration procedures and emissions are well repeatable,
- there is lower dispersion of curves of instantaneous FE and of temperature traces in step 8 with B20, than with B0.

Regeneration with standstill burner:

- the time-courses of emissions and temperatures are closely connected with the regeneration startegy,
- the nanoparticle penetration during the flame period is stochastically increased – the equivalent filtration efficiency reduced,
- the biocomponents increase the NO_x - & NO_2 - values, as well as the NP-emissions during the flame period,
- B20 can cause more difficult ignition of the burner,
- the filter loaded quickly with B100 was overheated and destroyed during the regeneration.

Regeneration with fuel injection + DOC:

- longer duration of fuel injection (double FI) prolongs respectively the period of high temperature level for the regeneration,
- the longer regeneration period is depicted with the higher emissions of CO, HC, DC & NH_3, in the respective time interval,
- at higher OP there is a higher level of exhaust temperature and of NO_x,
- after stopping the fuel injection there is an intense production of NO_2 due to t_{exh} decreasing into the level of NO_2-maximum,
- during the regeneration period (period of FI) there is a break-down of NP-filtration efficiency, which correlates with the single, or double FI-period and which is more intense for DC,
- with B20 there is a lower NP-filtration efficiency in the first phase of regeneration procedure – this is an effect of stronger artefact of condensates after DPF, due to the changed HC-matrix of B20.

Comparing the average emission levels of both investigated active regeneration types it can be stated, that the standstill burner has significantly (in 1 range of magnitude) higher CO & HC and lower NO_x & NO_2.

Nanoparticles with SCR & DPF:

Regarding the emissions with SCR and DPF it can be said that:

- SCR catalyst reduces the NP count concentrations in the range of 10%. This is due to the diffusion loses, similarly, like in any straight-channel catalyst.
- SCR-system can produce secondary nanoparticles (crystals of: urea, isocyanic acid, cyanuric acid, nitrates, sulfates). The count concentration of secondary NP is negligible comparing to the engine-out-NP.
- DPF – if with the VERT / OAPC quality – eliminates efficiently the NP (PCFE>99%).
- With B100 a seemingly lowering of PCFE due to increased spontaneous condensation after DPF can be observed.
- With a combined system DPF (upstream) and SCR (downstream), at full load with B100 there is an artefact of “seeding” the spontaneous condensation of bio-components from B100 by the secondary NP’s from SCR. As an effect the NP-penetration increases up to 25%.

Nitric components & FTIR:

- the most important nitric components are: NO_2 and NH_3,
- NO_2 increase from catalytic aftertreatment systems is in the course of becoming limited at different places,
- NH_3, which is the reduction agent of SCR is limited actually by careful industrial developments; a follow-up in the respective legislations is most probable,
- other components: isocyanic acid, hydrocyanic acid, formic acid and formaldehyde (FTIR) are present in very low quantities; they are a very good indicator for the running chemical reactions, transient effects and store-release-effects of reactants, but as emissions they are insignificant.

Secondary emissions & traces with SCR:

- Formation of dioxines and furanes was visible but not promoted by these technologies,
- The combination of SCR and biofuels had no negative side effects – on the opposite a further reduction of PAH and PCDD/F could be observed.

DOC light-off with biocomponents

- due to the higher reactivity of RME the fuels with higher bio-content cause an easier light-off of the DOC,

- with B100 the NO-NO_2-oxidation and the HC-conversion start already at approx. 170°C,
- with higher engine speed (higher spacial velocity) the start of increasing NO_2, or decreasing HC is moved to higher exhaust gas temperature (here $\Delta t \approx 10°C$),
- due to the thermal inertia of the engine-exhaust-system there are differences of emission results by conducting the steps test with increasing or with decreasing engine load,
- the emissions results in all steps test are connected to the time-schedule of the test procedure.

PAH & TEQ with RME (of PM)

- DPF has a positive effect of reducing PAH & TEQ of the PM.
- At low-load operating conditions without DPFthere is a tendency of higher TEQ (due to presence of B(a)P).
- Higher biofuel content has with DPF no influence on TEQ.
- Without DPF there is a tendency of lowering TEQ at low load and increasing TEQ at high load. The tendency of maximum TEQ in the range of B30 at high load, which is reported in literature, [61], is confirmed.
- No differences concerning TEQ could be remarked for catalytic and non-catalytic DPF’s. This result nevertheless must be limited to the present engine and the present operating conditions.
- SCR alone has no influence on TEQ.

9.2. Remarks & recommendations

The present investigations did not concern the long term effects:

- possible coinfluences of bio-fuels with lubricating oil,
- possible deactivation of catalytic activity in case of too high content of sulphur, phosphorus and dirt if the bio-fuel quality does not correspond to the actual norms,
- possible influences on deposits and material degradation in fuel system and in combustion chambers of the engine.

Following recommendations can be given for the use of biofuels with DPF systems:

- the filtration efficiency is not influenced by the biofuel, but there can be artefacts of spontaneous condensates after DPF,
- performing VERT/LRV tests part 1 & 3 is recommended with a standard fuel,
- for long life of catalytic coatings and for sustainable engine operation control periodically the quality of fuel and fuel supply chain,
- for active regeneration systems with high bio-content set down the threshold for starting regeneration to the lower values of backpressure, to prevent the danger of overheating of DPF during the regeneration,
- for burner regeneration, if biofuels are used for the burner, make sure the reliable ignition and operation of the burner,
- consider the general recommendation for the engine: durability of injection system and of lube oil; power reduction with fuels with lower heat value; limits of electronic regulation with changed heat value of fuel.

The recommendations for the users of SCR systems with biofuels concern the fuel quality and the sustainability of the engine operation and are the same, as mentioned above for DPF.

- for long life of catalytic coatings and for sustainable engine operation control periodically the quality of fuel and fuel supply chain,
- consider the general recommendation for the engine: durability of injection system and of lube oil; power reduction with fuels with lower heat value; limits of electronic regulation with changed heat value of fuel.

Generally plan more frequent oil change and inspection/maintenance intervals.

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11. ABBREVIATIONS

AFHB	Abgasprüfstelle FH Biel, CH
Air min	stoichiometric air requirement
ASTRA	Amt für Strassen, CH, Swiss Road Authority
AUVA	Austria Unfall Versicherung-Anstalt
BAFU	Bundesamt für Umwelt, CH (Swiss EPA, FOEN)
CA	crank angle
CARB	Californian Air Resources Board
CDI	Common Rail Diesel Injection
CFPP	cold filter plugging point
CLD	chemoluminescence detector
CNC	condensation nuclei counter
CPC	condensation particle counter
CPCFE	CPC filtration efficiency
CR	common rail
CSF	Catalytic Soot Filter

CTI	Car Training Institute
DC	Diffusion Charging Sensor
DCFE	DC filtration efficiency
dePN	de Particles + deNO$_x$
DI	Direct Injection
DiSC	Diffusion Charge Size Classifier
DMA	differential mobility analyzer
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particle Filter
EC	Elemental Carbon (VDI 2465) / European Community
ECU	electronic control unit
EGR	exhaust gas recirculation
ELPI	Electric low pressure impactor
EMPA	Eidgenössische Material Prüf- und Forschungsanstalt
EPA	Environmental Protection Agency
ETC	European Transient Cycle
E4	engine version Euro 4 with EGR
E(4)	engine version Euro 4 without EGR
FAME	Fatty Acid Methyl Ester
FBC	fuel borne catalyst (regeneration additive)
FE	filtration efficiency
FI	fuel injection (fuel aerosol generator)
FID	flame ionization detector
FL	full load
FOEN	Federal Office of Environment
FTIR	Fourrier Transform Infrared Spectrometer
GRPE	UN Groupe of Rapporteurs Pollution & Energie
HD	heavy duty
HDT	Haus der Technik Essen
HP	high pressure
IARC	International Association of Research on Cancer
ICE	internal combustion engines
INSOF	insoluble fraction
IR	increase rate, infrared
JRC	EC Joint Research Center
K$_x$	conversion efficiency of the component “x”
LD	low duty
LDS	Laser Diode Spectrometer (for NH$_3$)
LEM	limited engine map
LEZ	low emission zones
LRV	Luftreinhalteverordnung (engl: OAPC)
MAK	mittlere Arbeitsplatz Konzentration
MD19	heated minidiluter
	NanoMetnanoparticle summary surface analyser (PAS + DC + MD19)
MoU	memorandum of understanding
NanoMet	PAS + DC + sampling & dilution unit
NEM	nonlimited engine map
NP	nanoparticles < 999 nm (SMPS range)
NRTC	Non Road Transient Cycle
NYCC	New York City Cycle
OAPC	Ordinance on Air Pollution Control (germ. LRV)

OBD	on board diagnostics
OC	Organic Carbon (VDI 2465)
OEM	original equipment manufacturer
OP	operating point
PAH	Polycyclic Aromatic Hydrocarbons
PAS	Photoelectric Aerosol Sensor
PASFE	PAS filtration efficiency
PC	particle counts
PCDD/F	Polychlorinnated Dibenzodioxins/Furans
PCFE	particle counts filtration efficiency
PM	particulate matter, particle mass
PMFE	particle mass filtration efficiency
PMP	Particulate Measurement Program of GRPE
PN	particle number
PSD	particle size distribution
RD	relative difference
RE	reduction efficiency
Ref	reference (here: w/o aftertreatment)
RME	rapeseed methyl ester
RR	reduction rate
SAE	Society of Automotive Engineering
SCR	selective catalytic reduction
SiC	silicium carbid
SMPS	Scanning Mobility Particle Sizer
SOF	soluble organic fraction
SOI	start of injection
SP	sampling position
SUVA	Schweiz. Unfallversicherungs-Anstalt
SW	switch on urea
TAE	Technische Akademie Esslingen
TBG	Tiefbaugenossenschaft
TC	thermoconditioner. Total Carbon
TEF	toxicity equivalence factor
TEQ	toxicity equivalence
TTM	Technik Thermische Maschinen
UDS	urea dosing system
ULSD	ultra low sulfur Diesel
VERT	Verminderung der Emissionen von Realmaschinen in Tunelbau Verification of Emissions Reduction Technologies
VERTdePN	VERT DPF + VERT deNO$_x$
VFT1	VERT Filter Test 1
VPNT1	VERTdePN Test 1 - engine dyno
VPNSET	VERTdePN secondary emissions test - engine dyno
VSET	VERT Secondary Emissions Test (for DPF systems)
WHTC	Worldwide Heavy Duty Transient Cycle

12. PUBLICATIONS

During the project duration two technical papers concerning the AFHB-activities were published, [64, 65]. The third paper about the influences of bio-blends-fuels on the DPF regeneration is submitted for the SAE World Congress, Detroit April 2012.