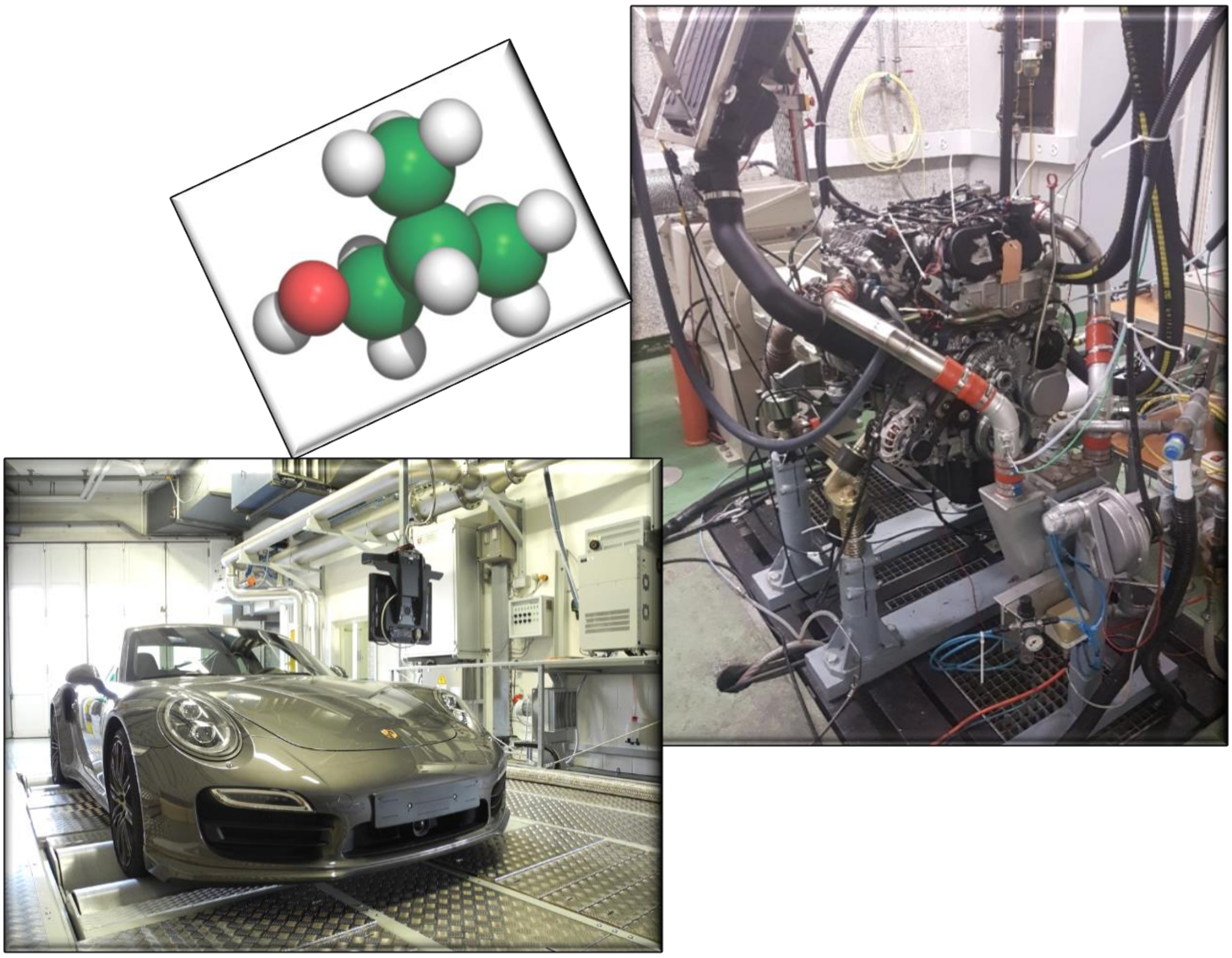
Final report dated February 2020

DiBut

Effects of Diesel-Butanol Blend Fuels on Emissions and Combustion in Diesel-Engines



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Berner Fachhochschule
Technik und Informatik
Automobiltechnik

Abgasprüfstelle und Motorenlabor (AFHB)
Gwerdtstrasse 5
CH-2560 Nidau
Telefon +41 32 321 66 80
Telefax +41 32 321 66 81
www.afhb.bfh.ch

Location: Bern

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Swiss Federal Office of Energy SFOE
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CH-3003 Bern
www.bfe.admin.ch

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Subsidy recipients:
Abgasprüfstelle, Berner Fachhochschule, Biel (AFHB)
Gwerdtstrasse 5, CH-2560 Nidau
www.afhb.bfh.ch

Authors:
J. Czerwinski, AFHB, jan.czerwinski@bfh.ch
P. Comte, AFHB, pierre.comte@bfh.ch
H. Nauroy, AFHB, herve.nauroy@bfh.ch

SFOE project coordinators:
SFOE head of domain: C. Alles, carina.alles@bfe.admin.ch
SFOE programme manager: S. Renz, renz.btr@swissonline.ch
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Zusammenfassung

Butanol kann aus biogenen Quellen hergestellt werden und lässt sich gut mit dem Diesel Kraftstoff mischen. Damit hat Butanol das Potential als Zumisch-Kraftstoff die CO_2-Emissionen von existierenden Fahrzeugen zu senken. Die verbrennungsmotorischen Eigenschaften von Diesel-Butanol-Gemischen (BuXX) wurden an Motor- und an Rollenprüfständen mit folgenden Ergebnissen untersucht.

Ein höherer Butanol-Anteil bewirkt einen tieferen Heizwert des Kraftstoffes und somit ein tieferes Vollast-Drehmoment. Im Teillastbetrieb wurden bei höheren Butanol-Zumischraten folgende Einflüsse auf die Entflammungsphase festgestellt: schwächere Selbstzündungsfähigkeit (wegen tieferer Cetanzahl) und ein höherer Anteil der vorgemischten Verbrennung. Bu30 ist beim ungeregelten Motor eine obere Grenze. Der Motorbetrieb wird bei Teillast instabil. Bei modernen Motoren (Euro VI) ist die Steuerung (ECU) imstande die niedrigere Cetanzahl und die anderen veränderten Kraftstoffparameter bis zu Bu30 grösstenteils zu kompensieren.

Die motorischen Roh-Emissionen von CO, HC und NO_X sind im WLTC und bei Teillast mit Bu30 höher als mit Bu00. Die PM- und PN-Emissionen sind hingegen geringer. Moderne Abgasnachbehandlungs-systeme (DOC/DPF/SCR/EGR) können diese Unterschiede (Bu30-Bu00) weitgehend kompensieren und am Auspuffende kaum feststellbar machen. Für die Elemente der Abgasnachbehandlung wurde für höhere Butanol-Anteile folgendes festgestellt: DOC: höhere light-off Temperatur mit geringfügig tieferen Konvertierungsraten; DPF: durch die geringere PM-Entstehung längere Russbeladungsintervalle, keine Änderung des Regenerationsverhaltens; SCR – keine Einflüsse auf Funktionalität und deNOx-Wirkungsgrad.

Bei älterer Fahrzeugtechnologie steigert ein höherer Butanol-Anteil die Emissionspicks von Acetaldehyd (MeCHO) und Formaldehyd (HCHO) beim Kaltstart beträchtlich. Bei neuerer Technologie ist diese Tendenz ebenfalls sichtbar, dies jedoch bei sehr tiefem und nicht signifikantem Niveau der absoluten Emissionen.

Für die Marktanwendung der Butanol-Diesel Mischkraftstoffe können folgende vereinfachte Empfehlungen formuliert werden:

Mit dem Dieselkraftstoff ergibt Butanol eine dauerhafte Mischung, die einen verminderten Heizwert, einen erhöhten Sauerstoffgehalt, eine tiefere Cetanzahl und keine korrosiven oder aggressiven Eigenschaften aufweist. Mit kleineren Butanol-Anteilen (<10%) sind im Fahrzeug unabhängig vom Stand der Technologie keine Betriebsunterschiede zu bemerken. Höhere Butanol-Anteile bewirken ein schlechteres Kaltstartverhalten, höhere Laufunruhe und eine schlechtere Dynamik bei Teillast. Die Emissionen, insbesondere mit der modernen Abgasnachbehandlung bleiben unverändert. Beim dauerhaften Betrieb mit höheren Butanol-Anteilen sind Abklärungen und Massnahmen bezüglich der Dauerhaltbarkeit der Einspritzanlage und des Schmieröls zu treffen.

Mit Beachtung der notwendigen Vorkehrungen und Grenzen kann Butanol einen positiven Beitrag zur Kohlenstoff-freien Mobilität leisten. Zurzeit ist dieser Alkohol noch zu teuer, um den kommerziellen Durchbruch zu schaffen.

Résumé

Le Butanol peut être produit à partir sources biogènes et se mélange durablement avec le carburant Diesel. Comme un carburant additionnel, il a le potentiel de réduire les émissions CO_2 des véhicules existants. Des recherches sur les caractéristiques de combustion avec différents pourcentages de Butanol dans le carburant Diesel (BuXX) ont été exécutées sur les bancs d'essai moteur et sur le banc d'essai à rouleaux.

Avec une teneur plus élevée en Butanol, le pouvoir calorifique du carburant et le couple du moteur à pleine charge sont plus faibles. En opération à charge partielle, les influences suivantes sur la phase d'inflammation avec l'augmentation du taux de Butanol ont été trouvées : aptitude à l'auto-inflammation affaiblie (indice de cétane plus bas) et phase pré-mélangée de la combustion plus intense.

Bu30 est considéré comme le taux limite de l'addition de Butanol au carburant diesel. Au-delà de ce taux, le fonctionnement du moteur en charge partielle deviendra instable. L'ECU du moteur moderne (EuVI) est capable de compenser les influences de l'indice de cétane diminué ainsi que d'autres paramètres du carburant modifié.

Les émissions de CO, HC et NO_X du moteur durant le cycle WLTC et en charge partielle sont plus élevées avec Bu30 qu'avec Bu00. Avec les systèmes modernes de traitement des gaz d'échappement (DOC/DPF/SCR/EGR) et avec le niveau d'émissions considérablement plus faible (à la sortie du pot d'échappement) ces différences (Bu30 - Bu00) sont moindres ou inexistantes. Une teneur plus élevée en Butanol réduit les émissions de PN. Néanmoins, avec l'utilisation du FAP (DPF) l'influence du carburant sur les PN est négligeable.

Les systèmes de traitement des gaz d'échappement sont influencés par la proportion plus élevée du Butanol de la manière suivante : DOC – température d'amorçage plus élevée et taux de conversion légèrement inférieur ; DPF – intervalle entre les régénérations allongé en raison d'une production de particules plus faible, aucun changement de la régénération ; SCR – aucune d'influence sur la fonctionnalité et sur l'efficacité de la réduction des NO_X.

Lors du démarrage à froid d'un véhicule avec une technologie plus ancienne, la teneur plus élevée en Butanol augmente considérablement les pics d'émissions d'acétaldéhyde (MeCHO) et de formaldéhyde (HCHO). Avec les nouvelles technologies, cette tendance est également visible. Toutefois, elle se reflète à un niveau très bas et insignifiant des émissions absolues.

Pour l'application sur le marché des carburants mélangés Butanol-Diesel les recommandations simplifiées suivantes peuvent être formulées :
Le mélange Diesel, Butanol reste stable durablement. Le pouvoir calorifique en est réduit, la teneur en oxygène est plus élevée, l'indice de cétane est plus faible et aucune propriété agressive ou corrosive n'est constatée. Avec un pourcentage de Butanol plus modéré (<10%), aucune différence n'est remarquée dans le fonctionnement d'un véhicule. Une teneur plus élevée en Butanol entraîne une détérioration du démarrage à froid, des irrégularités de fonctionnement et une moins bonne dynamique à charge partielle. Les émissions, notamment avec les systèmes de traitement des gaz d'échappement, restent inchangées. Pour le fonctionnement à long terme avec des taux de Butanol plus élevés, les clarifications et les mesures concernant la longévité du système d'injection et de l'huile de lubrification sont nécessaires.

En tenant compte de certaines précautions et limites, le Butanol peut très bien contribuer à la mobilité sans carbone. Actuellement, cet alcool est encore trop cher pour être largement commercialisé avec succès.

Summary

Butanol can be produced from biological sources and it can easily be blended with the Diesel fuel. As a drop-in additional fuel, it has the potential of reducing the CO_2-emissions of the present vehicles. The investigations of combustion properties with different Butanol portions in Diesel fuel (BuXX) were performed on the engine and on chassis dynamometers.

With higher Butanol content there is a lower heat value of the fuel and there is lower torque at full load. At engine part-load operation, the influences of increased Bu-rate on the inflammation phase were observed: lower self-ignition aptitude (due to lower CN) and higher portion of premixed combustion. Bu30 is considered as a limit blending ratio: the operation of the engine becomes instable at part load. The ECU of the modern engine (EuVI) is able to compensate nearly the effects of low CN and of the other modified fuel parameters up to Bu30.

The “engine out” emissions of CO, HC and NO_X with Bu 30 in WLTC and at engine part load are higher than with Bu00. With the modern exhaust aftertreatment technology (DOC / DPF / SCR / EGR), with a significantly lower emission level (at tailpipe), these differences (Bu30 - Bu00) are smaller or not existing. Higher Bu-content lowers the PN-emissions. With DPF nevertheless, the influence of fuel on PN is insignificant.

With higher Bu-content it was found for the exhaust aftertreatment elements: higher light-off temperature of DOC with slightly lower conversion rates; lower PM-production, longer DPF soot loading intervals and no difference of regeneration behavior; no influences on SCR efficiency and functionality.

At cold start with an older car technology, the higher Bu-content in fuel increases significantly the emission peaks of Acetaldehyde (MeCHO) and Formaldehyde (HCHO). With a newer technology, this tendency is also present but at a very low and insignificant absolute emission level.

For the application of Butanol blend fuels on the market following simplified recommendations can be given:

Together with Diesel fuel, Butanol produces durable blends with a reduced heat value, with increased Oxygen content, with the lower Cetane number and with no aggressive or corrosive properties.

With the lower Butanol blending ratios (<10%) no operating differences are noticeable in the vehicle.

Higher Butanol contents in fuel result in: worse cold start behavior, higher irregularity of engine running and less dynamic at part load operation. The emissions, especially with the modern exhaust aftertreatment systems, are unchanged. For the long-life operation with higher Butanol rates, clarifications and measures concerning the durability of injection system and lube oil are necessary.

With consideration of certain precautions and limits, Butanol can contribute very well to the carbon-free mobility. At present, this alcohol is still too expensive to be commercially successful on a large scale.

Wichtigste Ergebnisse

- Maximum 30% Butanol Anteil ist zu gebrauchen
- Geringer Einfluss auf Verbrennung (Entflammungsphase)
- Mit den aktuellsten Abgasnachbehandlungssystemen kein Einfluss auf Emissionen
- Massnahmen zu Dauerhaltbarkeit des Schmieröls und des Einspritzsystems abzuklären. (Keine Fragestellung des vorliegenden Projektes).

Principales conclusions

- Teneur maximale en Butanol à utiliser fixée à 30%
- Faible influence sur la combustion (phase d'auto-inflammation)
- Avec les systèmes actuels de post-traitement des gaz d'échappement, aucune influence significante n'est constatée sur les émissions
- Les mesures à entreprendre pour la longévité de l'huile de lubrification et du système d'injection sont à définir. (Dans ce projet, le sujet n'était pas concerné).

Main findings

- Use maximal 30% Butanol blend fuel
- With last-date exhaust aftertreatment no influence on emissions
- Little influence on combustion (inflammation phase)
- Clear up the measures for durability of lube oil and of the injection system. (Not investigated in the present project).

Contents

Appendices see at the end of this report

Abbreviations

AFHB	Abgasprüfstelle FH Biel, CH
ASET	Aerosol Sampling and Evaporation Tube
ATS	aftertreatment system
BAFU	Bundesamt für Umwelt, (Swiss EPA)
BD	combustion duration (α 90% - α 5%)
BfE	Bundesamt für Energie
Bu	Butanol
Bu30	30% vol Butanol in Diesel
BuXX	Butanol portion in fuel XX vol %
CA	crank angle (α)
CLD	chemoluminescence detector
CN	cetan number
CO	carbon monoxide
CO_2	carbon dioxide
COV	coefficient of variance
CPC	condensation particle counter
CrS	crankshaft
CS	cold start
CVS	constant volume sampling
DC	Diffusion Charging sensor
DI	Direct Injection
DiBut	Diesel – Butanol project
DOC	Diesel oxidation catalyst
DPF	Diesel Particle Filter
DMA	differential mobility analyser
Ds	downstream
E1, E2	engine 1, engine 2
ECU	electronic control unit
EGR	exhaust gas recirculation
EO	engine out
ETC	European Heavy Duty Transient Cycle
FBC	Fuel Borne Catalyst = Fuel Additive = Regeneration Additive

FE	filtration efficiency
FID	flame ionization detector
FL	full load
FMO	fuel mass observer
FOEN	Federal Office of Environment (BAFU), CH
FPT	Fiat Powertrain Technologies
FTIR	Fourier Transformation Infra-Red Analyzer
HC	unburned hydrocarbons
HCHO	Formaldehyde
HCOOH	Formic Acid
HD	heavy duty
HNCO	Isocyanic Acid
Hu	lower heat value
ICE	internal combustion engines
IMEP	indicated mean effective pressure
INCA	integrated calibration / application tool
K_x	conversion rate of the component “x”
M	torque
MD19	heated minidiluter
MeCHO	Acetaldehyde
MFB	mass fuel burned
NDIR	non-dispersive infrared
N_2	nitrogen
N_2O	nitrous oxide
NH_3	Ammonia
NO	nitrogen monoxide
NO_2	nitrogen dioxide
NO_x	nitric oxides
NP	nanoparticles < 999 nm (SMPS – range)
nSMPS	nano SMPS
NRTC	non-road transient cycle
OBD	on board diagnosis
OEM	original equipment manufacturer
OP	operating point

PCFE	particle count filtration efficiency
PM	particle mass
p_{max}	maximum combustion pressure
PMFE	particle mass filtration efficiency
PN	particle number
PSD	particle size distribution
$[\dot{Q}(\alpha)]$	rate of heat release (ROHR)
RAI	reduction agent injection
ROHR	rate of heat release $[\dot{Q}(\alpha)]$
RR	reduction rate
SCR	selective catalytic reduction
SD	standard deviation
SOF	soluble organic fraction
SP1	sampling position 1 (tailpipe)
SMPS	Scanning Mobility Particle Sizer
SSC	steady state cycle
SWOFF	urea switch-off
SWON	urea switch-on
TC	thermo conditioner
TDC	top dead center
T_{exh}	exhaust temperature
TP	tailpipe
ULSD	ultra low sulfur Diesel
Us	upstream
V1, V2	vehicle 1, vehicle 2
VTG	variable turbine geometry
WHTC	Worldwide Heavy Duty Transient Cycle
WLTC	world harmonized light duty test cycle
α	crank angle [deg CA]

1 Introduction & objectives of DiBut

1.1 Background information and current situation

Using Bioalcohols as renewable energy source to substitute a part of fossil energy in traffic and increasing the sustainability of individual transportation are important objectives in several countries. The global share of Bioethanol used for transportation is continuously increasing. Butanol, a four-carbon alcohol, is considered in the last years as an interesting alternative fuel, both for Diesel and for Gasoline application. Its advantages for engine operation are: good miscibility with gasoline and diesel fuels, higher calorific value than Ethanol, lower hygroscopicity, lower corrosivity and possibility of replacing aviation fuels. Further information about Butanol, its application and perspectives of market are given in annexes 1 & 2.

The project DiBut focused on the application of Butanol-blends in Diesel-engines only. The project consisted of three parts.

Part 1: investigations of emissions, of DPF and of DOC functionality on engine dynamometer.

This research is conducted on a Liebherr D 934 S engine with a cam-driven injection system. This engine is equipped with a programmable control unit, which allows variations of certain parameters in order to promote the soot loading of DPF. The test bench with eddy-current dynamometer is equipped with analysis of limited exhaust gas components.

The most important objectives of the research with different Butanol content are:

- full load (FL) characteristics,
- influences on catalytic conversion rates of DOC,
- influences on charging / regeneration of DPF.

Part 2: Investigations of combustion and of SCR on engine dynamometer.

This research is conducted on an Iveco F1C engine with a common rail injection system. The test bench is equipped with 4-quadrant dynamic dynamometer, which allows performing any transient cycles. The exhaust system can be set up with DOC / DPF / SCR in modular way. There is also a possibility of analysing the limited and non-legislated exhaust gas components.

The most important objectives of the research with different Butanol content are:

- full load characteristics (FL)
- investigation of injection/combustion by means of high-pressure-indication
- performance of different transient cycles
- influences on SCR deNOx-efficiency
- influences on gaseous non-legislated emissions and on nanoparticles

On this engine, is installed a combustion chamber pressure indication with data acquisition and processing, which allows an accurate and dynamic combustion diagnostic.

With this research and working packages, it is possible to investigate the influences of fuel quality on engine internal processes as well as on the actual exhaust aftertreatment systems.

The proposed research was with Bu0, (B15), Bu30.

Part 3: Investigations of emissions in legal driving cycle on chassis dynamometer.

This research is performed on two cars:

An older one (Euro 2), with traditional concept of injection (distributor pump) and exhaust after-treatment (DOC) and a newer one (Euro 6c), with common rail injection and exhaust after-treatment (DPF + $deNO_x$).

The test vehicles are driven in WLTC cold & warm, as well as at a steady state cycle (SSC). The measurements of legislated and non-legislated emissions (NP & FTIR) are attached.

Special attempts of cold starts are conducted and compared with the equivalent results with Bu0 & BuXX. The tests are performed with Bu0, (B15), Bu30.

This research enables a complete insight in the non-legislated emissions at cold start and in repetitive transient operation with quite different state of the art Diesel cars.

2 Research on engine dynamometers

2.1 Test engines, fuels and lubricants

2.1.1 Test engines

The tested engine (E1), Liebherr D934 S for construction machines is represented in Fig. 1 and with its data in Table 1.

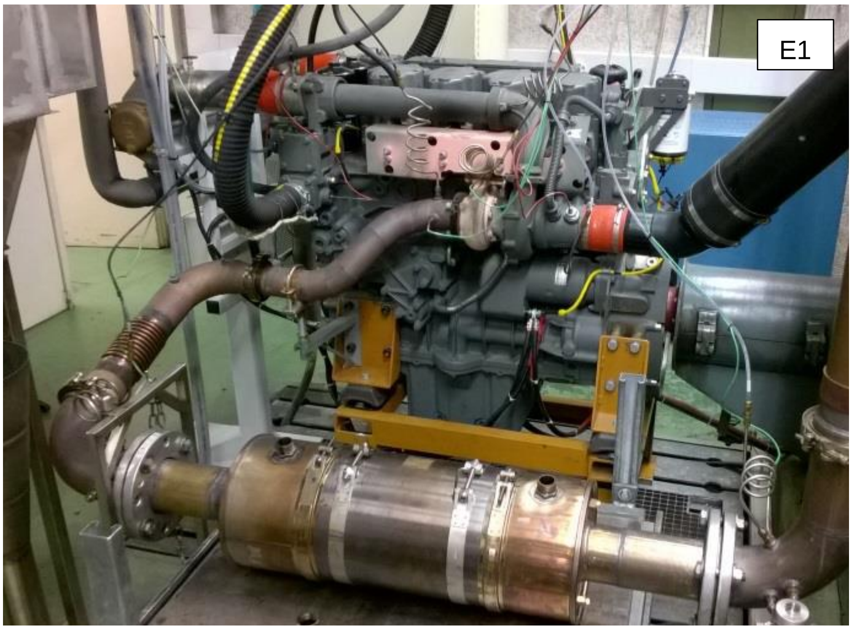


Fig. 1: Test engine (E1) Liebherr D934S on the engine dynamometer¨

The engine (E2), Iveco F1C is represented in Fig. 2 and in Table 2.

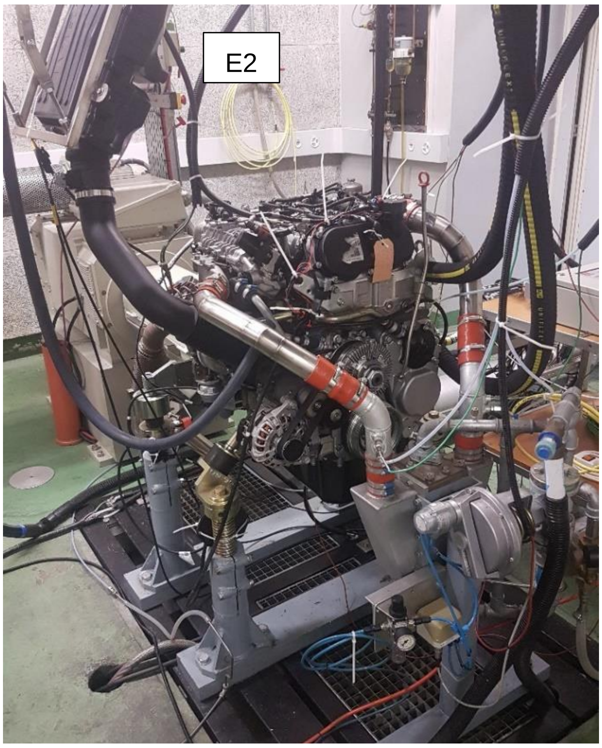


Fig. 2: Iveco F1C engine (E2) on the engine dynamometer

Manufacturer/type	Liebherr Machines Bulle S.A. / D 934 S
Emission level	97/68/EG step 3A; EPA/CARB Tier 3
Cylinder number and configuration	4 cylinders in-line
Rated power / Rated speed (present EDC setting)	105 [kW]@2000 [min^{-1}]
Low idle speed / high idle speed	800 [min^{-1}]; 2170 [min^{-1}]
Overall displacement	6.36 [dm^3]
Compression ratio	17 [-]
Year of manufacturer	2005
Cooling medium	water
Combustion process	direct injection
Fuel system type	unit pump Bosch
Speed governor	EDC
Method of air aspiration	turbo charging
Charge air cooling system	intercooler

Table 1: Engine specifications Liebherr D 934 S (E1)

Manufacturer	IVECO Torino Italy
Type, emission level	F1C Euro VI
Displacement	3.0 liters
Cylinder number and configuration	4 cylinders in-line
Engine speed	Max. 4200 rpm
Rated power	107kW@3500 rpm
Combustion process	direct injection
Fuel system type	Common Rail Bosch LWR-20
Method of air aspiration	turbo charging
Charge air cooling system	intercooler

Table 2: Engine specifications Iveco F1C Euro VI (E2)

The most important equipment of this new engine (E2) consists of:

- single stage turbocharging system with VTG
- EGR valve (high pressure EGR)
- EGR cooler
- throttle valve at exhaust
- air mass flowmeter at intake
- common rail injection system
- exhaust aftertreatment system (ATS: DOC+DPF+SCR)

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 engine was equipped with a glow plug with integrated pressure sensor for the high-pressure indication.

For research purposes, in order to observe the influences of varied fuel quality on untreated emissions, the engine was enabled to operate without exhaust aftertreatment system (ATS) and without EGR.

2.1.2 Fuels

As a base Diesel fuel with Swiss market quality was used, see Tab. 3.

Base fuel (without additive)			
Type	Diesel fuel Swiss market quality		
Manufacturer	BP		
Property	**Method**	**Unit**	
Density (at 15°C)	ISO 3675	kg/l	0.820 – 0.845
Viscosity (at 40°C)	ISO 3104	mm²/s	2.2 – 2.8
Cetane number	ISO 5165	-	52 - 54
Cetane index	ISO 4264	-	49 - 51
Sulphur content	ISO 4260 / 8754	mg / kg	max. 10
Cloud point	ISO 3015	°C	max. -10
Pour point (CFPP)	ISO 3016	°C	max. -20
Flash point	ISO 2719	°C	min. 62
Heating value		MJ/kg	min. 42.5
Aromatic hydrocarbons	ISO 3837	% vol	max. 2
Conradson at 10% test residue			max. 0.02 g/100g
Boiling analysis (at 1013 mbar, 340°C)			min. 98 vol%

Table 3: Data of Swiss market Diesel fuel according to the norm

As blend fuels different rates of n-Butanol in Diesel (BuXX) were used, see Tab. 4. As example: Bu30 i.e. 30% vol n-Butanol with 70% vol Diesel fuel.

	Ref. Diesel	**Bu05**	**Bu15**	**Bu30**	**Bu50**	**Bu100 Butanol**
Density at 15°C in kg/m³	833-837	833	832	828	822	806
Net calorific value in MJ/l	35.3	34.9	34.0	32.8	31.4	26.7
Stoichiometric air/fuel ratio	14.6	14.4	14.0	13.5	12.9	11.2
Oxygen content in wt.-%	<0.03	1.1	3.1	6.4	10.7	21.6
H:C ratio (molar)	0.157	0.160	0.165	0.170	0.179	0.208
Cetane number	52-54	≈ 51	≈ 48	≈ 43	≈ 35	≈ 20

Table 4: Data of Diesel fuel, Butanol and their blends (annex A1).

2.1.3 Lubricants

The lubricating oils are used according to the requirements of manufacturers. The most important data of the lube oils are given in the Tab. 5 for engine E1 (Liebherr) and in Tab. 6 for engine E2 (Iveco).

Manufacturer / specification	Motorex Focus 10W40	
ACEA or API category	E9-12, E7-12, E6-12	
Viscosity kin 40°C	97.51	mm²/s
Viscosity kin 100°C	14.8	mm²/s
Viscosity index	159	(--)
Density 20°C	859	kg/m³
Pourpoint	- 36	°C
Flamepoint	> 200	°C
Total Base Number TBN	9.9	mg KOH/g
Sulfur residue content	< 1.0	% by weight
Sulfur	1997	mg/kg
Mg	85	mg/kg
Zn	8635	mg/kg
Ca	2168	mg/kg
P	703	mg/kg

Table 5: Data of the used lube oil for engine E1.

Manufacturer / specification	Petronas Urania Daily SAE 0W30, FPT FPI.LUBR002 class SC1 LV-16
Physical state	Liquid
Appearance	Viscous
Initial boiling point	>300°C
Flash point	>200°C
Density	0.846 G/CM3
Solubility in water	Insoluble
Kinematic viscosity at 100°C	9.7 CST

Table 6: Data of the used lube oil for engine E2

2.2 Test methods and instrumentation

2.2.1 Engine dynamometers and emission test equipment

Engine E1 is attached to an eddy current dynamometer (a scheme of the set-up, see in annex A3). For investigations of DOC conversion and of DPF soot loading and regenerations following instrumentation was used:

- PN measurements - the particle size and counts distributions were analysed with following apparatus:
- SMPS – Scanning Mobility Particle Sizer, TSI (DMA TSI 3081, CPC TSI 3010 S)
- NanoMet – System consisting of:
  - DC – Diffusion Charging Sensor (Matter Eng. LQ1-DC)
  - MD19 tunable minidiluter (Matter Eng. MD19-2E).
  - Thermoconditioner (TC) (i.e. MD19 + postdilution sample heating until 300°C)

DPF weighing, Fig. 3 – the DPF element was quickly disassembled from the exhaust line and weighed. The temperature of the substrate was measured by a thermocouple and the fluctuations of weight with varying temperature could be indicated.

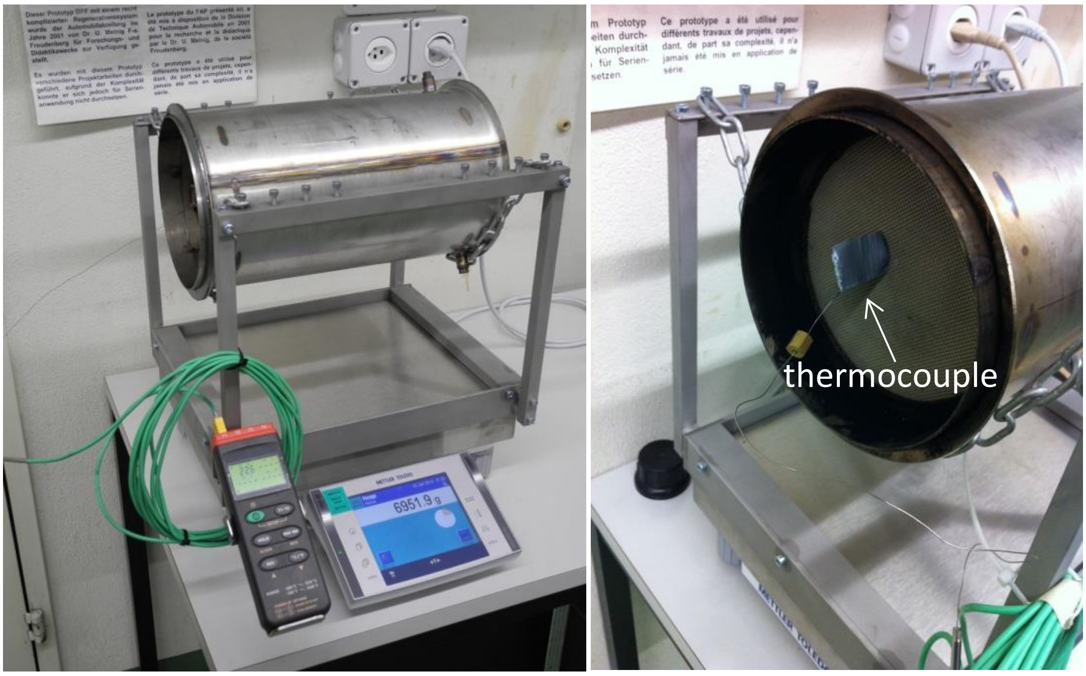


Fig. 3: Measuring the weight of DPF in function of the temperature

Engine E2 is attached to a 4-quadrant dynamic test bench which enables the performance of transient cycles. This engine was operated with and without exhaust aftertreatment system (ATS). A scheme of the dynamometer set-up with ATS is represented in annex A4.

During the investigations of SCR-system on the engine E2 several non-legislated gaseous emission components were analyzed with FTIR (Fourier Transform Infrared). FTIR Spectrometer (AVL SESAM) offers the possibility of simultaneous, time-resolved measurement of approx. 30 emission components – among others: NO, NO_2, NO_x, NH_3, N_2O, HCN, HNCO, HCHO, HCOOH, MeCHO (measured parameters of FTIR see separate description annex A5).

For measurements of standard (legally limited) gaseous exhaust emission components both engine stands used the same apparatus: Horiba exhaust gas analyzers: Type VIA-510 for CO_2, CO, HC_{IR}, O_2; Eco Physics CLD 822 EL ht for NO, NO_x and Amluk exhaust gas measurement device Type FID 2010 for HC_{FID}.

2.2.2 Combustion diagnostics – pressure indication

On the engine E2, high pressure indication system was installed in order to perform a standard combustion diagnostic. The pressure sensor is integrated in the glow plug of 1st cylinder. The pressure signal is processed by means of KISTLER KiBox with integrated signal conditioner and with the “KiBox Cockpit” software. The time basis in [deg. CA] is obtained and used by the KiBox from the engine ECU. With KiBox it is possible to perform the pressure indication on more cylinders and also in the dynamic operation of the engine.

2.3 Test procedures on engine dynamometers

Different test procedures were applied for different investigated subjects:

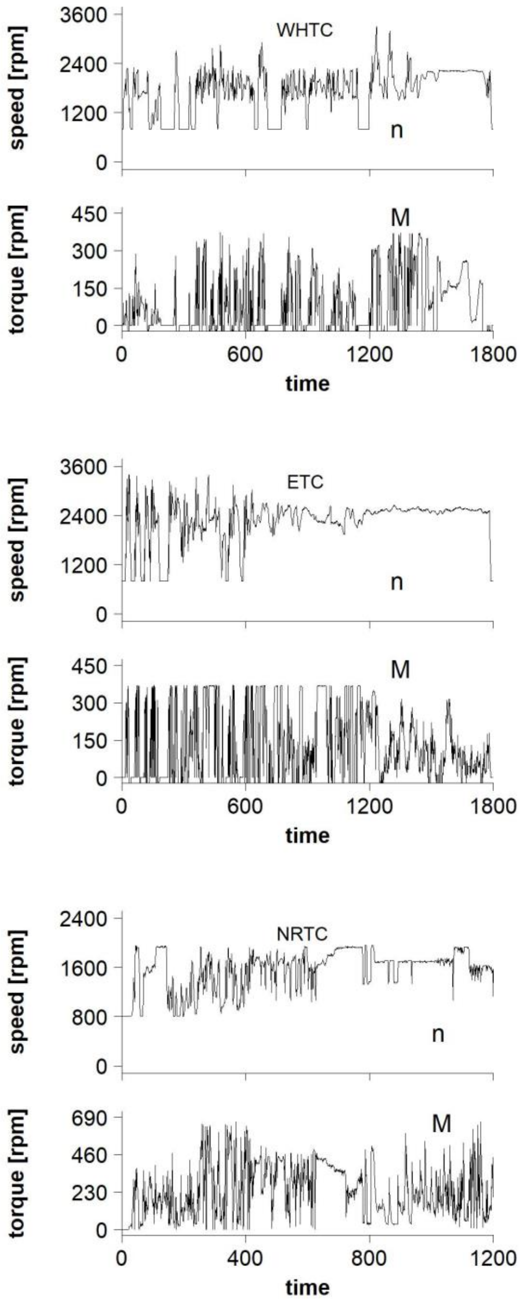


Fig. 4: Dynamic cycles

- for soot loaded DPF, regeneration was performed by stepwise increasing the engine torque at constant, nominal engine speed; the duration of each step was 10 min (according to SN 277206); E1,
- for DOC light-off and conversion, slow load ramps (0-300 Nm, 45 min) at constant air mass flow were performed up and down fixing by this procedure the influences of thermal inertia of the exhaust system; E1,
- for DOC efficacity dynamic cycles NRTC (warm) were performed on engine E1,
- on both engines different constant operating points (OP's) were used for comparisons of fuels effects; these OP's are represented in the results,
- for SCR-testing constant OP's were used on engine E2 to indicate the effects of urea SWON/SWOFF and the dynamic cycles WHTC and ETC were performed in order to represent the "real world" operation of the engine,
- for the tests with dynamic pressure indication (from cycle to cycle) sudden load increases (load jumps) at 1500 rpm were used on engine E2,
- for conditioning and purifying the ATS forced regenerations (of DPF) were performed on engine E2.

Fig. 4 represents for the performed dynamic cycles the time-courses of engine speed and engine torque (NRTC for E1; WHTC and ETC for E2).

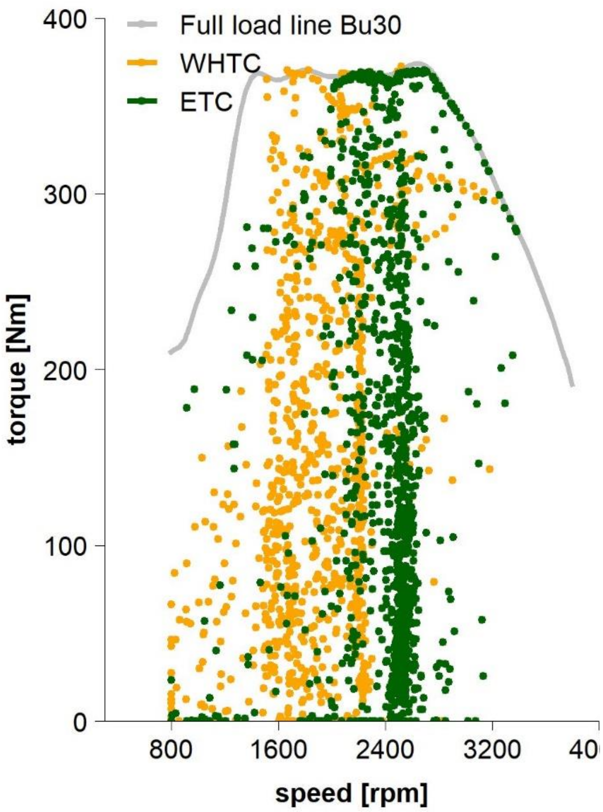


Fig. 5: Operating profiles at transient cycles; engine E2 Euro VI, EGR closed

Fig. 5 shows the operating collectives (in WHTC & ETC) in the engine map of E2.

The definition of the full load line of the engine considered always the fuel with the highest Bu-content (lowest heat value) used in the given comparison test. In this way the results with all fuels were given at the same cycle-work.

2.4 Results

In this section, some examples of results according to the performed working packages on engines are presented and commented.

2.4.1 DPF, [1]

For investigations of DPF soot-loading on the engine (E1) a Dinex DiSiC uncoated filter was used. To promote the regeneration a ferocen FBC with dosing 20 ppm Fe was applied. For the tests of each fuel quality (Bu0; Bu30), the DPF was ash-cleaned by an external specialized provider. The regeneration tests were performed at nominal engine speed (2000 rpm) with stepwise increased torque, according to SN 277206.

Fig. 6 compares the emissions in regeneration steps with Bu0 and with Bu30. The two lowest steps with Bu30 were skipped due to instabilities of engine operation (caused by the low Cetane number of Bu30). This is also the reason for higher values of CO and HC at engine part load with Bu30. In the 4th step, NO_x with Bu30 increases significantly over the level of Bu0. With Bu30, the injected fuel quantity is higher since the steps are driven at the same torque (except for the last step at FL). Additionally, due to more volatile components in the fuel, the premixed part of combustion is more intense. These facts have an impact on NO_x and the other emission components.

The NP-level after DPF is very low (near to ambient level), so the represented differences are not significant. Nevertheless, the increased values of NP with Bu30 in the lowest steps can be explained with the mentioned instabilities and the increased NP in the highest steps – with the different interaction with the wall oil layer in combustion chamber.

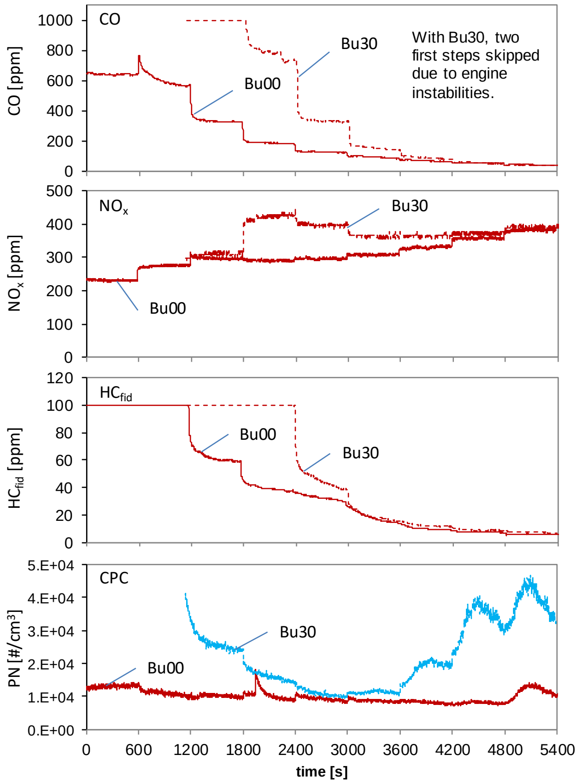


Fig. 6: Comparison of emissions in regeneration steps Bu00 & Bu30 (w DPF Dinex DiSiC), E1, 2000 rpm

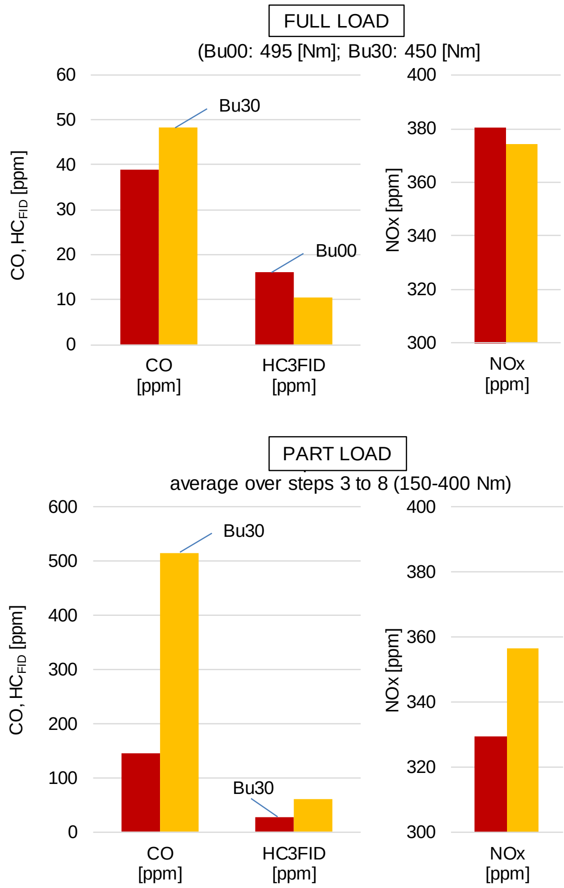


Fig. 7: Comparison of emissions Bu00 & Bu30 at full load and at part load (w DPF DiSiC), E1, 2000 rpm

Fig. 7 summarizes the relationships: at part load and at full load (FL). With the same engine power at part load, there are with Bu30 higher gaseous emissions CO, HC and NO_x. At FL there is a lower engine power (with Bu30) and the relationships for HC and NO_x are inversed.

Fig. 8 gives some examples of the SMPS particle size distributions (PSD) with both investigated fuels.

Since the operation was always with FBC (Fe 20 ppm), there is increased PN-concentration in nuclei mode, in the size range below 20nm.

The comparison at full load with the same injected fuel quantity reveals almost no differences between both fuels, with only slight tendency of lower PN in the accumulation mode with Bu30.

The comparison at part load with the same torque shows clearly lower PN-emissions with Bu30 in the accumulation mode, even if there is a higher injected quantity with Bu30.

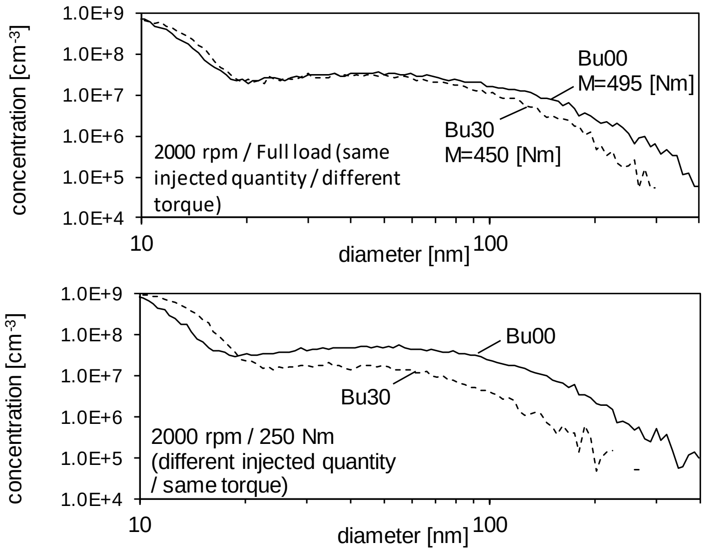


Fig. 8: SMPS – size spectra, without DPF, E1, 2000 rpm

The soot loading and regenerations with DPF weighing before and after regeneration were very well repetitive. With the procedure of soot loading (perpetual load jumps and accelerations), which was established for Diesel fuel, the average soot loading rate was in the range of 0.35 to 0.48 [g/min]. For Bu30, this procedure yielded only a rate of 0.07 [g/min] and it was decided to intensify the procedure by admitting more fuel quantity during accelerations.

The most important result is that Bu30 produces generally less PM and slower soot loading of the DPF.

The FBC-promoted regenerations for both fuels progressed nearly identically with balance point in the 6^{th} step and with the balance point temperature 371-374°C.

The particle count filtration efficiencies obtained with both fuels at 2000 rpm/FL were the same (99.99% for Bu00 and 99.97% for Bu30).

2.4.2 DOC, [4]

This working package concerned the question of functionality of the Diesel oxidation catalyst (DOC) with Bu00 (neat Diesel fuel) and with Bu30 (30% vol n-Butanol in fuel). The used DOC was coated with Platinum and Palladium (3:1). For this research several load ramps with increasing and decreasing engine load and with measurement of the standard gaseous emission components before and after DOC were performed. The engine torque was varied from 0 to 300 Nm and back, at constant air mass flow. This enabled a possibly little variation of space velocity over the DOC.

Fig. 9 compares the average courses of emissions CO and HC with both fuels (Bu00 & Bu30), before/after DOC.

This representation of emission results (CO and HC) in function of exhaust gas temperature after DOC (in the bottom part of the figure) reveals the hysteresis loops, which result from the thermal inertia of DOC. In the traces representing the emissions "downstream DOC" in function of temperature, a reduction of CO nearly to zero and the start of increasing NO_2 (next figure) are observed above approx. 190°C to 200°C. The higher production of CO & HC with Bu30 at lower engine loads is confirmed.

Fig. 10 shows the resulting average conversion rates of CO & HC. With Bu30, the light-off temperature (for K_x = 50%) is approx. 20°C higher than for Bu00. The production of NO_2 starts with Bu00 earlier (at lower t_{exh}) and is in the temperature range of 200-270°C more intense.

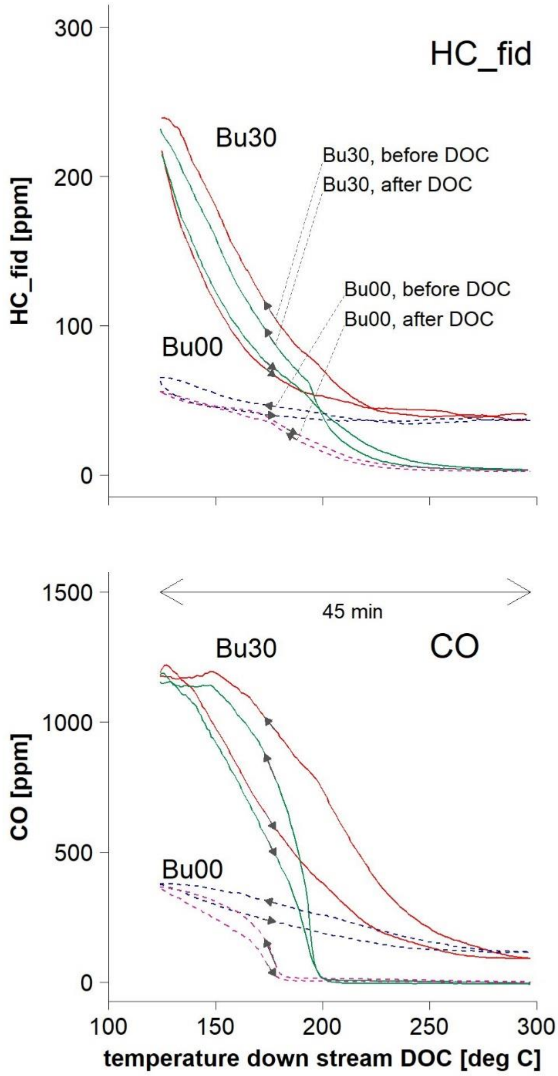


Fig. 9: CO- an HC-emissions before/after DOC during the up-/down-load ramps 0-300 Nm. Bu00/Bu30, average ramps at constant air mass flow, engine E1.

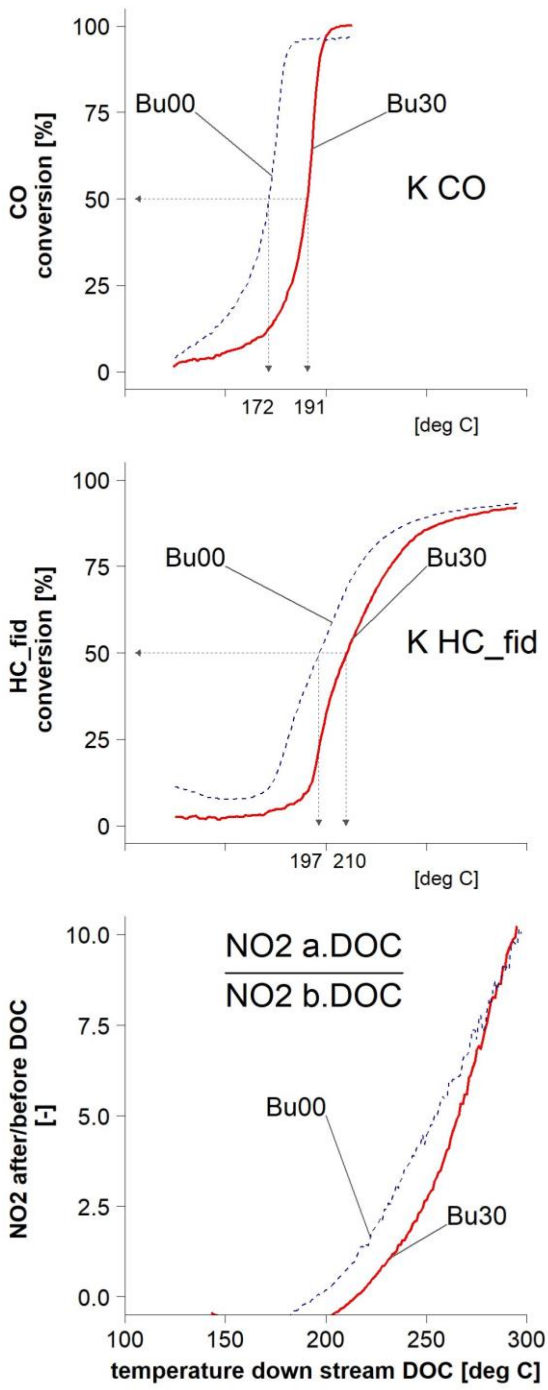


Fig. 10: DOC average catalytic conversion rates of CO & HC and increase of NO_2, in the load ramps with Bu00/Bu30, engine E1

Several dynamic cycles (NRTC) were performed with both fuels (full load line defined for Bu30).

Fig. 11 summarizes the conversion rates of CO & HC in NRTC, which are calculated from the average emission values. With Bu30, there is lower K_{CO} (by 3.5%-points) and lower K_{HC} (by 11%-points). The production of NO_2 in NRTC with Bu30 is by 28% lower than with Bu00.

It can be summarized that with higher Butanol content in fuel (Bu30) there are higher light-off temperatures of DOC and there are lower conversion efficiencies of CO & HC. The production of NO_2 at higher engine loads is with Bu30 slightly reduced.

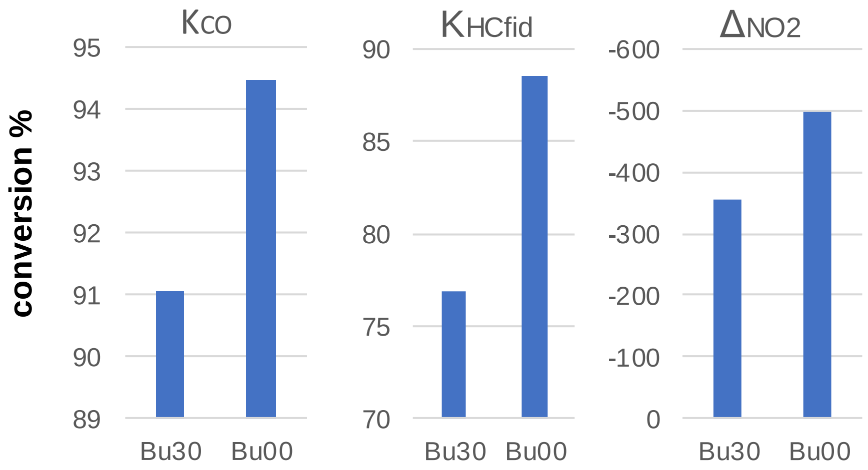


Fig. 11: Comparison of DOC-conversion rates KCO & KHC and of NO_2-increase in NRTC with Bu00/Bu30, engine E1.

2.4.3 Increasing BuXX, [2, 3]

At the beginning of the tests on engine E2 the lowest Butanol content in fuel (Bu05) was used and it was successively increased in further test series. Initially the emissions were tested without ATS at several steady state operating points (OP's) and in transient cycles WHTC and ETC, (see Fig. 4). For all tests on this engine it was decided to keep the EGR closed.

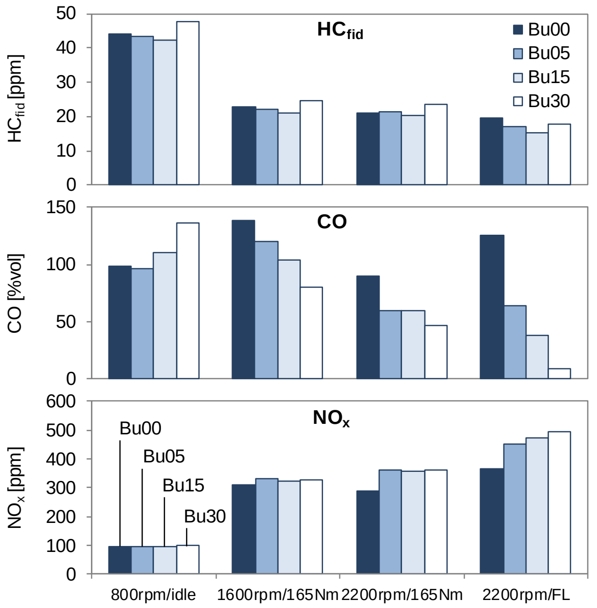


Fig. 12: Emissions with Bu00 / 15 / 30 at some steady state OP's, w/o ATS, EGR closed, engine (E2)

Fig. 12 represents comparison of results from the test series with Bu00/Bu05/Bu15/Bu30 at 4 stationary OP's. It can be stated, that with increasing Bu-content there are:

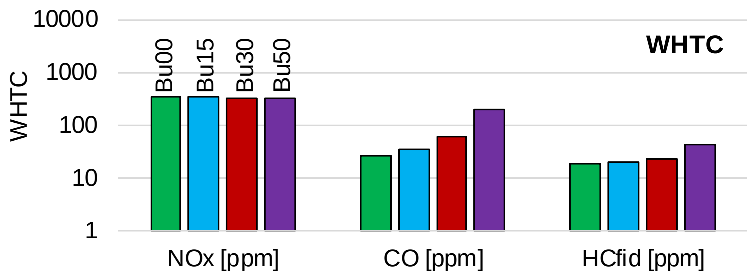
- a clear reduction of CO (except for idling),
- an increase of NO_x (except for idling),
- with Bu30, there is an increase of HC while for the other fuel variants there are no clear tendencies visible.

The precondition of testing was, that with the exchange of fuel no further inputs would be given to the electronic control system of the engine. This is the same way, like in the hand of user, who only feeds fuel to the engine.

It was discovered, that the electronic control system of the engine (FMO) compensates the varying properties of fuel and no differences of heat release can be noticed (up to Bu30). For this reason, it was decided to perform a supplementary research with an increased Bu-rate (Bu50).

This was possible because the engine was started with the dynamic brake (asynchron machine), it could be easily warmed up and no problems were caused by low CN at cold-, or low-load operation.

Fig. 13 compares the average emission values in WHTC for the four investigated fuel qualities (Bu00/15/30/50; FL set for Bu50). With higher Bu-content, there is a clear increase of CO and HC. The NO_x-values are constant, independently on BuXX. In this transient operation the tendency of CO is contrary to the tendency at most steady state OP's (except for idling).



WHTC				
Bu xx	0	15	30	50
NOx [ppm]	339	343	333	330
CO [ppm]	27	36	63	200
HCfid [ppm]	18	20	23	44

Fig. 13: Emissions with different Butanol rate in transient operation WHTC, w/o ATS, EGR closed, engine (E2)

2.4.4 Combustion diagnostics, [2, 3]

Combustion diagnosis was performed by means of combustion pressure indication in the 1st cylinder. The KISTLER KiBox system enabled the dynamic pressure indication (from cycle to cycle) during the transient operation of the engine.

Fig. 14 shows the comparisons of parameters from the dynamic high-pressure indication during a load jump from 40% to 90% at 1500 rpm. This indication statistics is represented in function of time for 13 working cycles of the engine, for all investigated fuels (Bu00/15/30/50).

For the fuels with lower Bu-content (up to Bu30), it can be remarked that there are principally small differences between the fuels. The values of p_{max}, $(dq/d\alpha)_{max}$ and IMEP are identical. With higher Bu-rates the combustion duration is slightly shorter (approximately: Δ1 deg CA with Bu15 and Δ2 deg CA with Bu30). With both fuels (Bu15/30), the 5% of heat release is by the lower OP 1 deg CA and by the higher OP 0.5 deg CA earlier. The reason for the small differences is given by the higher amount of more volatile fuel component (Butanol), which enables a shorter inflammation phase (up to 5% MFB).

For the highest applied Butanol rate (Bu50), the indication statistics of the load jump (40-90% at 1500 rpm) shows clear differences:

Due to the lower energy content, the engine response is slower, and the end value of torque is lower. The combustion duration (5-90%) is with Bu50 up to 6 deg CA shorter than for Bu00.

At the lower OP (before the load jump), the inflammation duration (up to 5% MFB) with Bu50 became slightly longer than for Bu00. This is due to the influence of lower CN, which overcompensated the higher portion of premixed fuel formed during the inflammation lag.

The analysis of injection timing revealed that the timing of the main injection quantity is identical for all fuels. The timing of the pilot injection is connected with a fix interval to the timing of the main quantity and so can be followed that the electronic control of the engine does not influence the injection timing for the investigated fuels with different Bu-content.

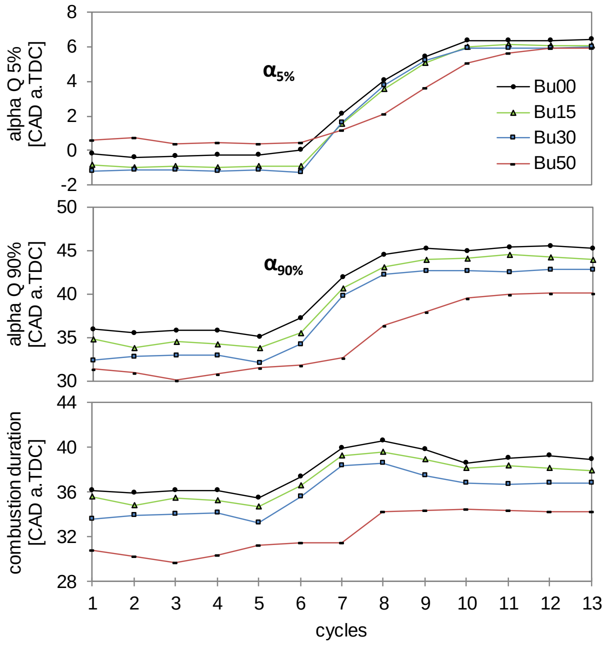


Fig. 14: Indication statistics of load jump 40-90% at 1500 rpm w/o ATS, w/o EGR, engine (E2)

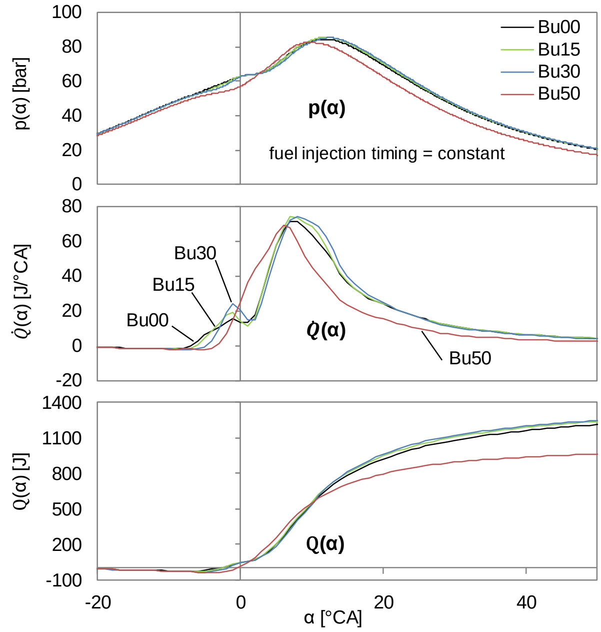


Fig. 15: Indicated pressure and heat release before load jump (cycle nbr.2) w/o ATS, w/o EGR, engine (E2)

Fig. 15 gives an example of the heat release (MFB) and the rate of heat release (ROHR) for the lower OP (with one pre-injection pulse) of the load jump. It is possible to recognize that there is an influence of higher Bu-content on the start of combustion. With the higher Bu-content the start of heat release is slightly retarded (0.5-2 deg CA, lower CN), but due to the higher portion of premixed fuel, the premixed phase of combustion is much quicker which overcompensates the later start for Bu15 and Bu30. For Bu50, the longer inflammation lag preponderates and finally, the 5% MFB follows slightly later (approximately 1 deg CA comparing to Bu00). Similar influences of Butanol blending on the premixed phase of Diesel combustion were remarked in [7] and [8].

For the fuels Bu 0/15/30, the dynamic answer of the engine – performance of the load increase during 4 working cycles – is equal for all three fuels. The electronic control system of the engine compensates very well the varying properties of fuel. There is a regulation algorithm, a “fuel mass observer” FMO, which controls Lambda, air- and fuel mass flow, boost pressure and EGR settings, detects and compensates the deviations of injection quantities from nominal values.

For Bu50, it can be stated that the engine electronic control came to the limit of supervising the combustion with the highest Bu-content. The deviations of the parameters such as heat value, density and Cetane Number (CN) are too big. An independent cold start with Bu50 would not be possible.

2.4.5 SCR, [6]

In this working part the engine E2 (Euro VI) was equipped and investigated with its original aftertreatment system (DPF+SCR); EGR stayed closed. Beside the functionality of SCR-system, attention was paid to some non-legislated gaseous emission components, which are in the public attention. These components are: Acetaldehyde (MeCHO), Isocyanic Acid (HNCO), Formic Acid (HCOOH), Formaldehyde (HCHO); Ammonia (NH_3) and Nitrous Oxide (N_2O).

Fig. 16 shows the time plots of emissions and of some parameters from engine ECU in the sequence of constant OP’s at 2000 rpm. All traces are averages of 3 measurements. This choice of OP’s provokes a variation (in steps) of exhaust temperature and allows to prove the RAI on/off of the SCR-system. It can be observed, that at the lowest operating points OP1 and OP2 there are higher CO and HC values with Bu30 due to lower Cetane Number of this blend fuel.

With Bu30, there are higher PN_{CPC}-values at TP than with Bu00. This difference is produced especially at low-load operation (beginning of a cycle, or the lowest OP1 and OP2) and it is due to the higher particle number concentrations with Bu30 in the lowest particle size spectrum (in the nuclei mode) and to the slightly higher penetration (or reproduction) of this particle sizes through the exhaust and ATS (see also in Fig. 18).

The results from NO_X sensors up-/ downstream SCR show no differences of NO_X-reduction behaviour with both investigated fuels.

An important and repetitive result is a lower soot mass emission (model from the engine ECU) with Bu30.

For non-legislated gaseous emission components there were no significant differences between Bu30 and Bu00 in this test and in the dynamic cycles. An example of that at ETC is given in Fig. 17. An excellent and equal NO_x-reduction potential with both fuels (Bu00/Bu30) is also confirmed in this transient, warm operation (results of sensors upstream/downstream [Us/Ds]).

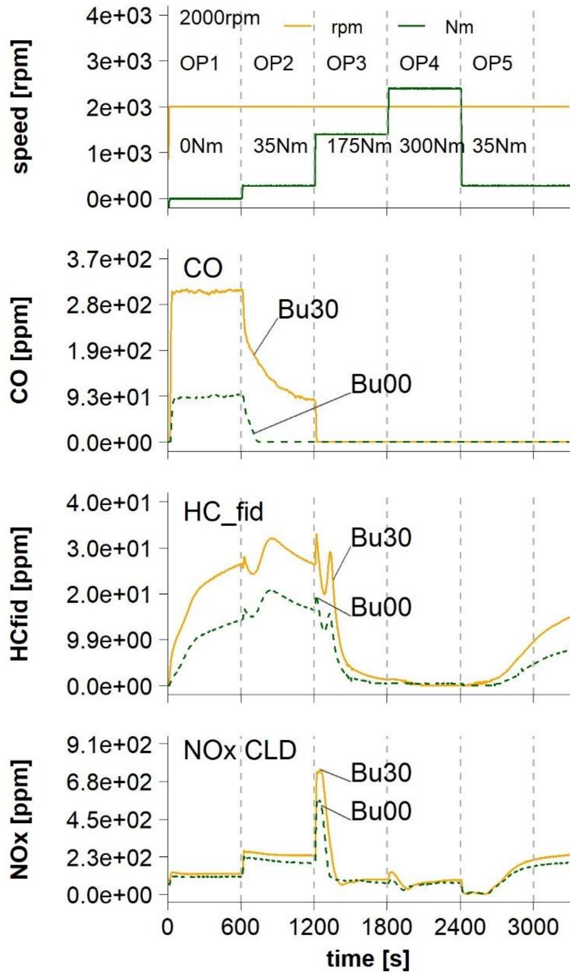


Fig. 16a: Comparison of gaseous emissions in stationary operating points with Bu00/Bu30; engine E2, EGR closed, tailpipe, average of 3 measurements.

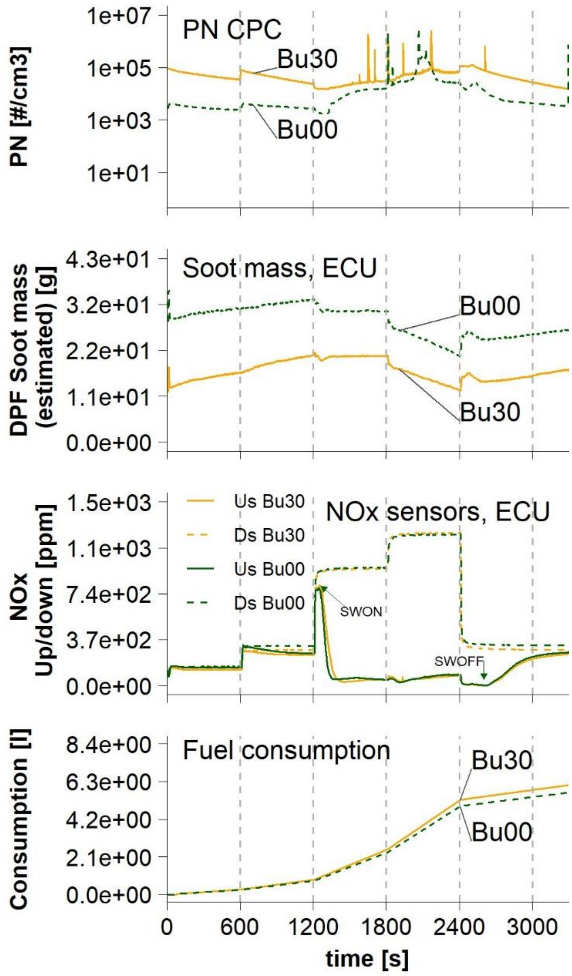


Fig. 16b: Comparison of PN and some ECU-parameters in stationary operating points with Bu00/Bu30; engine E2, EGR closed, tailpipe, average of 3 measurements.

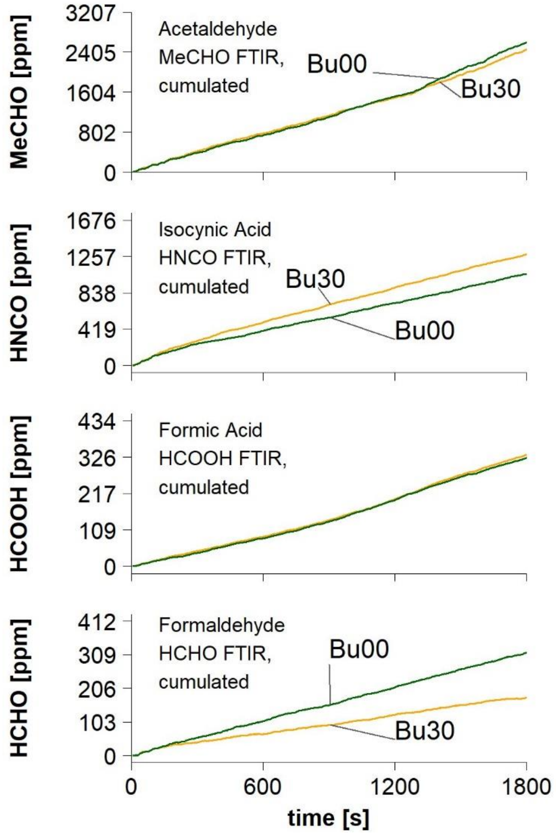


Fig. 17a: Comparison of non-legislated gaseous emissions in ETC with Bu00/Bu30; engine E2 Euro VI, EGR closed, tailpipe, average of 3 measurements

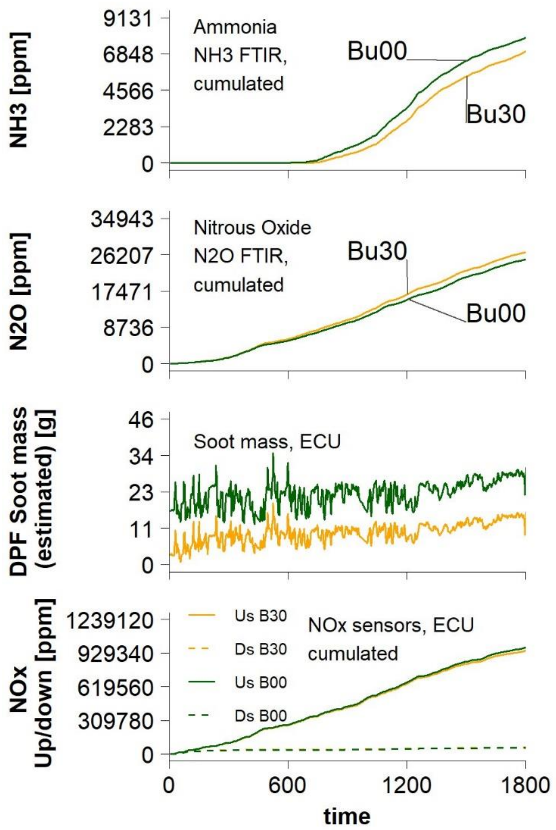


Fig. 17b: Comparison of non-legislated gaseous emissions and some ECU-parameters in ETC with Bu00/Bu30; engine E2 Euro VI, EGR closed, tailpipe, average of 3 measurements

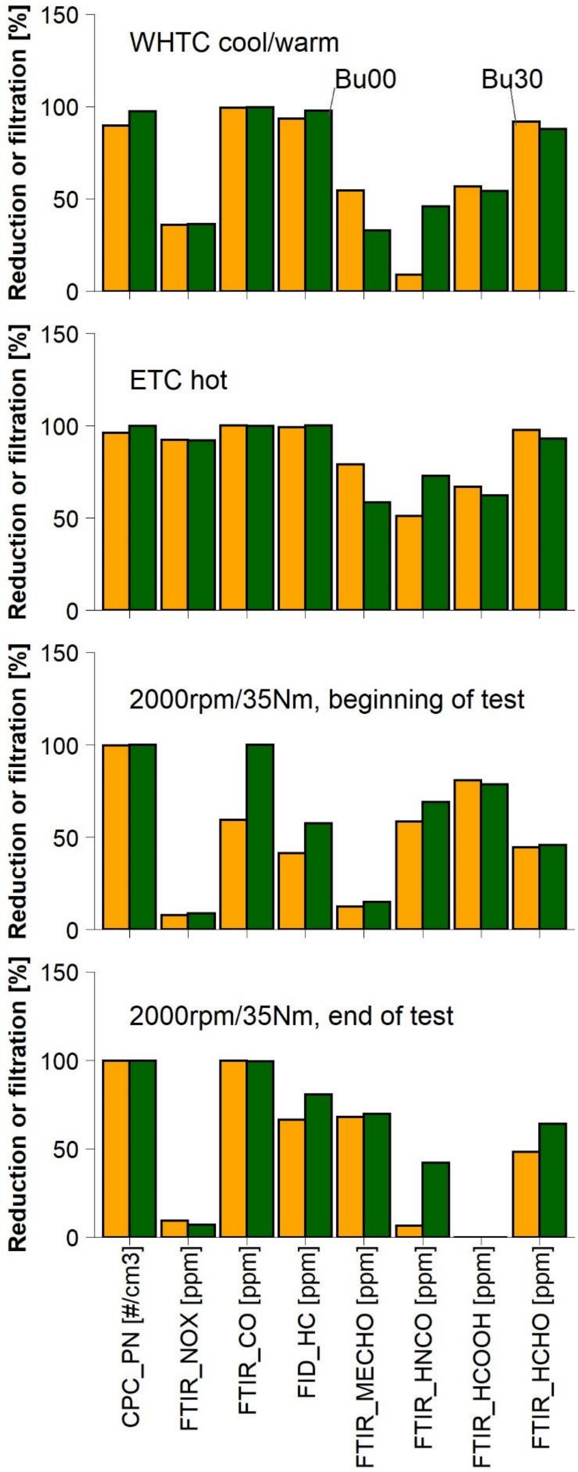


Fig. 18: Reduction rates (RR) of emissions in different operating collectives, with Bu00/Bu30 and with different cool and warm exhaust aftertreatment system (DPF + SCR).

Figure 18 summarizes the filtration-, or reduction rates (PCFE and RR) in the performed transient tests and two constant OP's. The NO_X concentrations are less reduced in the WHTC, with not entirely warm ATS (result of the conditioning procedure) than in ETC with warmed-up ATS. The influence of operating conditions on RAI is also visible in the stationary OP's (Fig. 16): OP1/2/5 (with SWOFF) – low NO_X-conversion and OP3 and OP4 (with SWON) high NO_X-conversion.

The nanoparticle filtration efficiency of the ATS is generally very high. Nevertheless, with Bu30 there are effects of a slight reduction of PCFE due to the modified size-structure (nuclei mode) and modified diffusion losses or renucleation in the exhaust- and analysis systems.

The absolute values of non-legislated gaseous components are rather quite low (< 100 ppm) and the RR-values scatter considerably.

Interesting is the look on the results from OP2 (beginning of test) and OP5 (end of test): OP5 is in fact a repetition of the OP2, but with a little bit changed prehistory. At OP5, we generally observe higher conversions (RR's) of CO and HC, as a result of higher average temperature of the DOC-substrate. We also observe a changed profile of reduction rates (RR's) of the non-legislated gases (MeCHO, HNCO, HCOOH and HCHO), as a result of a modified state of substances stored in the washcoats and catalytic coatings. It can be stated that the prehistory of the ATS determines the thermo-chemical state and this in turn influence the reduction rates of certain components, especially the non-legislated ones (above-mentioned).

Finally, it can be stated that the investigated blend fuel Bu30 has no significant impact on emissions and on the functionality of the aftertreatment system of this modern investigated engine.

2.4.6 DPF-regeneration, [6]

As a part of conditioning and purifying the exhaust ATS, forced DPF-regeneration procedures were trigged and performed by the engine ECU.

For heating-up the exhaust system and forcing the DPF-regeneration following measures are usually applied: retarding the injection timing, using post injections, controlling EGR, VTG and engine throttling. The exact injection strategy of the present forced regenerations is not known to the authors.

The regenerations were performed at increased engine speed and zero load (high idling) with a warm exhaust and ATS.

Fig. 19 compares the average traces of results with Bu30 and Bu00 during the regeneration procedure. There are higher HC-values with Bu30 (at insignificant absolute level of 2-5 ppm) and there is lower soot mass with Bu30 (from ECU model). Except of that, there are no significant differences of other parameters between the investigated fuels.

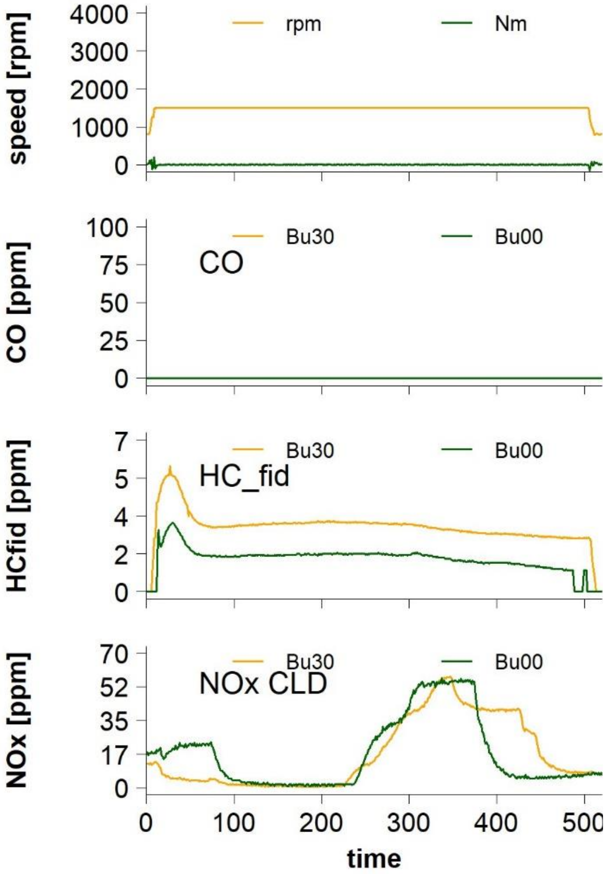


Fig 19a Comparison of emissions in forced regeneration with Bu00/Bu30; engine E2 Euro VI, EGR closed, average of 3 measurements at tailpipe.

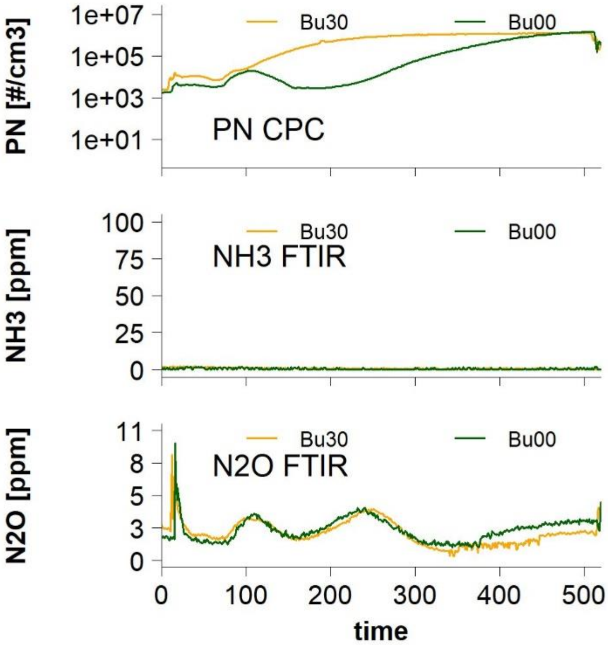


Fig 19b Comparison of emissions in forced regeneration with Bu00/Bu30; engine E2 Euro VI, EGR closed, average of 3 measurements at tailpipe.

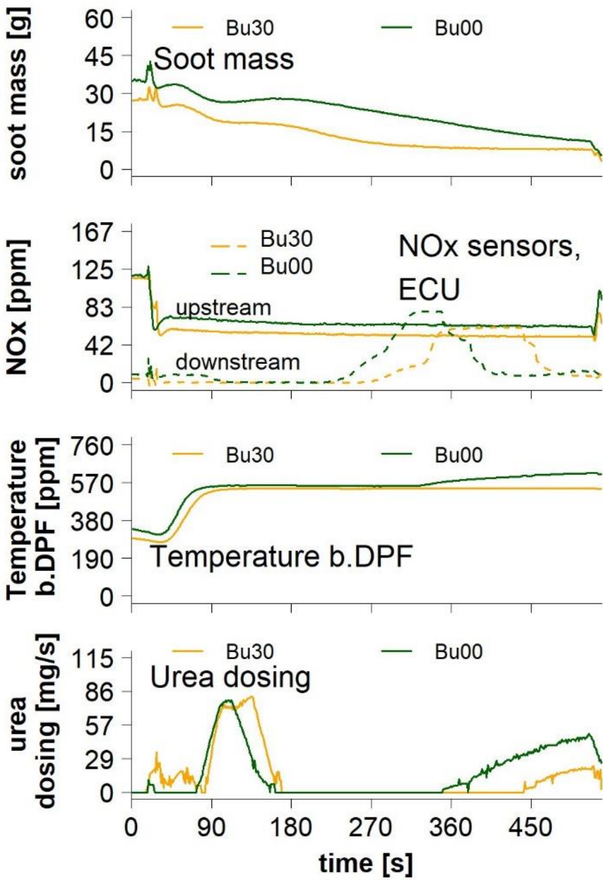


Fig 19c Comparison of some ECU-parameters in forced regeneration with Bu00/Bu30; engine E2 Euro VI, EGR closed, average of 3 measurements at tailpipe.

It can be stated that: CO is entirely converted (zero value). The HC-peak at the beginning (in the range of 6 ppm) indicates the start of the regeneration procedure. Approximately 2 minutes later, the PN_{CPC} increases by nearly 2 orders of magnitude as an effect of heating-up the ATS. After approximately 5 minutes, there is a repetitive and temporary increase (approximately for 3 minutes) of the $NO_{X\ TP}$ up to the level of $NO_{X\ EO}$. This is confirmed by all three NO_X-measuring devices: CLD, FTIR and NO_X-sensors. This temporary increase of $NO_{X\ TP}$ is connected with the temporary interruption of reduction agent injection (RAI). The temperature before DPF attains for both fuels (Bu00 and Bu30) peak values over 530°C. During this regeneration there is a full throttling and EGR is closed.

The non-legislated gaseous emissions (FTIR) are at insignificant, mostly near to zero level. The repeatability of the regeneration procedures is very good.

3 Research on chassis dynamometer

3.1 Test vehicles, fuels and lubricants

The tests were performed with two Diesel passenger cars: Opel Astra (Euro 2) and VW Passat (Euro 6c).

The vehicles are presented in Figure 20 and their most important data are given in the Table 7.

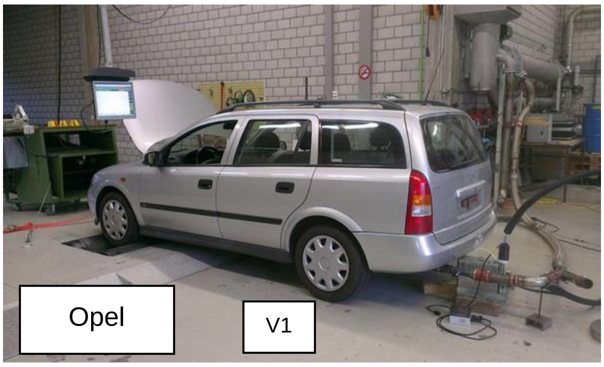


Fig. 20: Test vehicles Opel Astra (Euro 2) and VW Passat (Euro 6c) on chassis dynamometer

Vehicle	**Opel Astra DI16V** **V1**	**VW Passat Variant V 2.0TDI** **V2**
Cylinder	4	4
Overall displacement [cm^3]	1994	1968
Power [kW]	60	110
Injection type	DI	CR
Fuel	Diesel	Diesel
Weight empty [kg]	1390	1621
Transmission	m5 / Front	m7a / Front
Matriculation	20.01.1998	09.02.18
Turbocharging	yes	yes
Exhaust aftertreatment	DOC	DOC, DPF, SCR
Emission level	Euro 2	Euro 6c

Table 7: Data of test vehicles

3.1.1 Fuels

The Diesel fuel used was from the Swiss market, according to SN EN590.

The used blend fuels were: Bu15 (15% v Butanol in Diesel fuel) and Bu30 (30% v Butanol in Diesel fuel).

Some data of Diesel-Butanol blend fuels are given in the Table 4 (chap. 2.1.2).

3.1.2 Lubricants

The lubricants were used according to the recommendations of the manufacturers, they were not specially changed or analyzed.

3.2 Test methods and instrumentation

3.2.1 Chassis dynamometer and standard test equipment

- roller dynamometer: Schenk 500 G5 60
- driver conductor system: Tornado, version 3.3.

- CVS dilution system: Horiba CVS-9500T with Roots blower
- air conditioning in the hall automatic
  (intake- and dilution air)
  temperature: 20 ÷ 30 °C
  humidity: 5.5 – 12.2. g/kg

The driving resistances of the test bench were set according to the legal prescription.

3.2.2 Test equipment for regulated exhaust gas emissions

This equipment fulfils the requirements of the Swiss and European exhaust gas legislation.

- gaseous components:
  exhaust gas measuring system Horiba MEXA-9400H
  CO, CO_2 – infrared analysers (IR)
  HC_{IR}... only for idling
  HC_{FID}... flame ionisation detector for total hydrocarbons
  NO/NO_X... chemoluminescence analyser (CLA) – not heated, only for diluted gas
  O_2... Magnos
  The dilution ratio DF in the CVS-dilution tunnel is variable and can be controlled by means of the CO_2-analysis.

3.2.3 FTIR

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

3.2.4 Nanoparticle analysis

The measurements of NP size distributions were conducted with different SMPS-systems, which enabled different ranges of size analysis:

SMPS: DMA TSI 3081 and CPC TSI 3772 (9.8 - 429 nm)

nSMPS: nDMA TSI 3085 and CPC TSI 3776 (2 - 66 nm).

For the dilution and sample preparation an ASET system from Matter Aerosol was used, Fig. 21 (ASET … aerosol sampling and evaporation tube). This system contains:

- Primary dilution air - MD19 tunable minidiluter (Matter Eng. MD19-2E)
- Secondary dilution air – dilution of the primary diluted and thermally conditioned measuring gas on the outlet of evaporative tube.
- Thermoconditioner (TC) - sample heating at 300°C

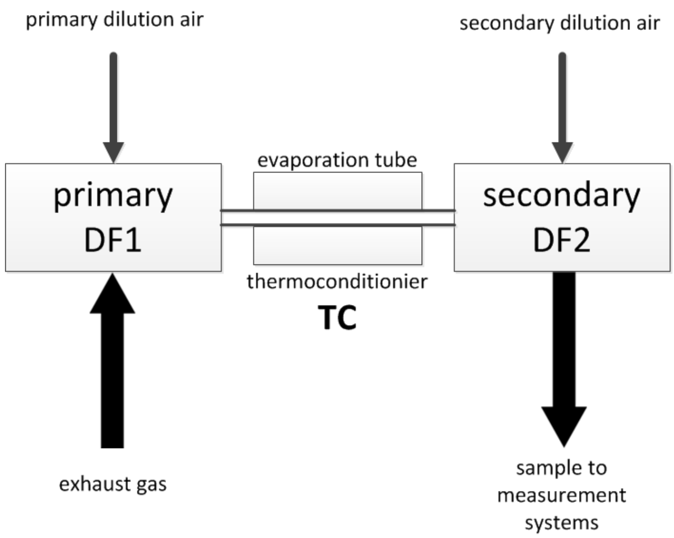


Fig. 21: Set-up of dilution stages and sample preparation for nanoparticle measurements

The measuring set-up on chassis dynamometer and the sampling positions for particle analytics are represented in Fig. 22.

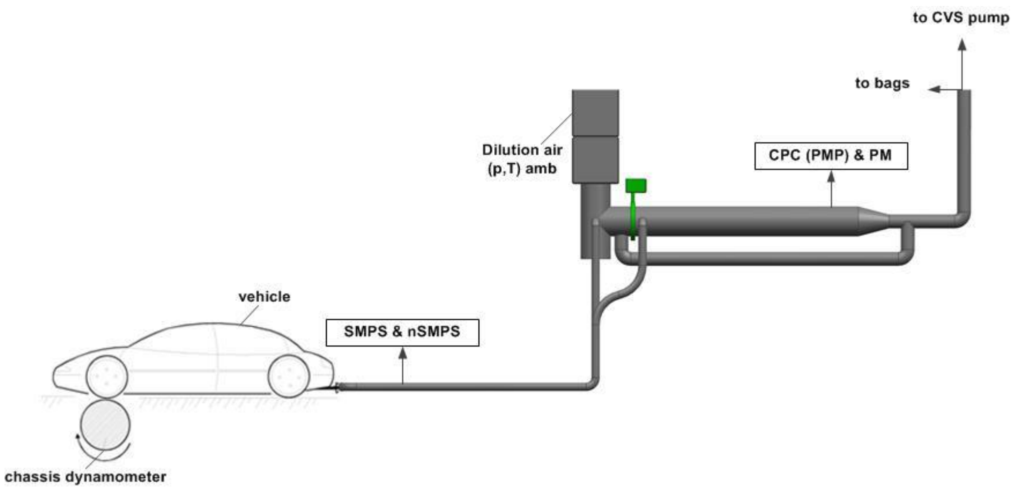


Fig. 22: Sampling of exhaust gas for analysis of particles.

3.3 Test procedures on chassis dynamometer and cold start

The vehicles were tested on a chassis dynamometer in the dynamic driving cycles WLTC and at constant speeds in the steady state cycle SSC.

SSC consists of 20 min steps at constant vehicle speeds 95, 45 km/h and idling, which are driven from the highest to the lowest speed. These vehicle speeds respond to the average speeds in parts of the WLTC.

The test sequences with all fuels were identical: WLTC with cold start (20-25°C), 10 min idling for bag evaluation, acceleration to 95 km/h and continuation of the SSC.

Driving cycle

In terms of the driving cycles an approach to find a homogenized world-wide driving cycle was finished with the development of the homogenized WLTP world-wide light duty test procedure. The WLTC (world-wide light duty test cycle) represents typical driving conditions around the world and is developed based on combination of collected in-use data and suitable weighting factors. This cycle has been used also in this study, Fig. 23. It represents different driving situation, like city, over-land and speed-way.

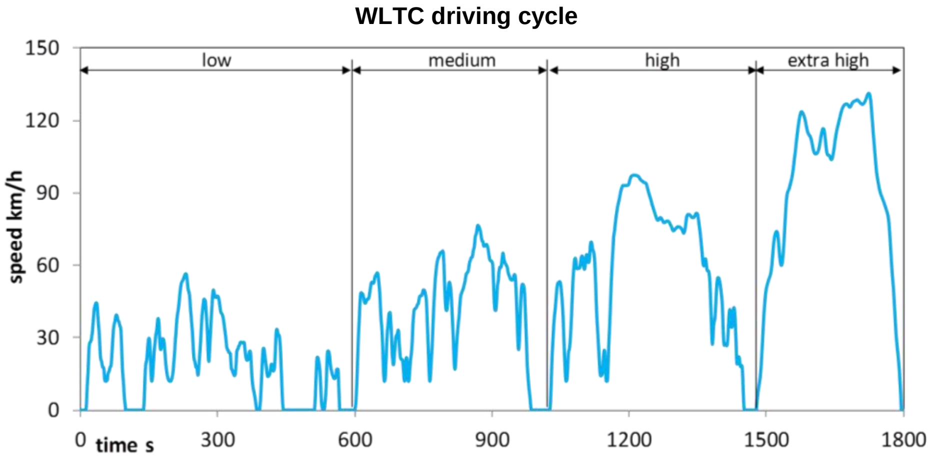


Fig. 23: WLTC driving cycle

3.3.1 Cold start

Repetitive cold start tests were performed with Bu0 / Bu15 / Bu30.

For cold starts (CS), two ranges of start temperature were considered: summer cold start (20 to 25°C, conditioning in the test hall), or mild winter cold start (-2 to 4°C, conditioning outside in the cold weather period).

For simplification of titles and descriptions these temperature ranges will be designed, as 20°C and 0°C.

In the preliminary tests with gasoline vehicles two variants of cold start were investigated:
a. cold start at idling (without chassis dynamometer),
b. cold start with acceleration to 20 km/h and v= const = 20 km on the chassis dynamometer, the braking resistances were set according to legal prescriptions and they responded to the horizontal road.

It was stated after this test period, that the CS on chassis dynamometer (with 20 km/h) does not bring any further information potentials and further research was generally limited to the CS at idling.

Vehicle, which was conditioned outside for the mild winter CS was pushed in the test hall, attached to the measuring systems, started and operated in the conditions of the hall (intake air 20-25°C).

After the test, the vehicle was conditioned by driving a WLTC on the chassis dynamometer.

3.4 Results

3.4.1 Comparisons of emissions of vehicles with older and with newer technology

Fig. 24 shows the cumulated emissions of both vehicles in $WLTC_{cold}$. It can be remarked, that with increasing Butanol content in the fuel (BuXX), the cumulated emissions of CO, HC and NO_x in the $WLTC_{cold}$ increase and PN decrease. Similar tendency, but less pronounced is also given in $WLTC_{warm}$ (not presented here).

Vehicle V2 (with newer technology) has much lower emission level and the differences between Bu00 and Bu30 are less significant.

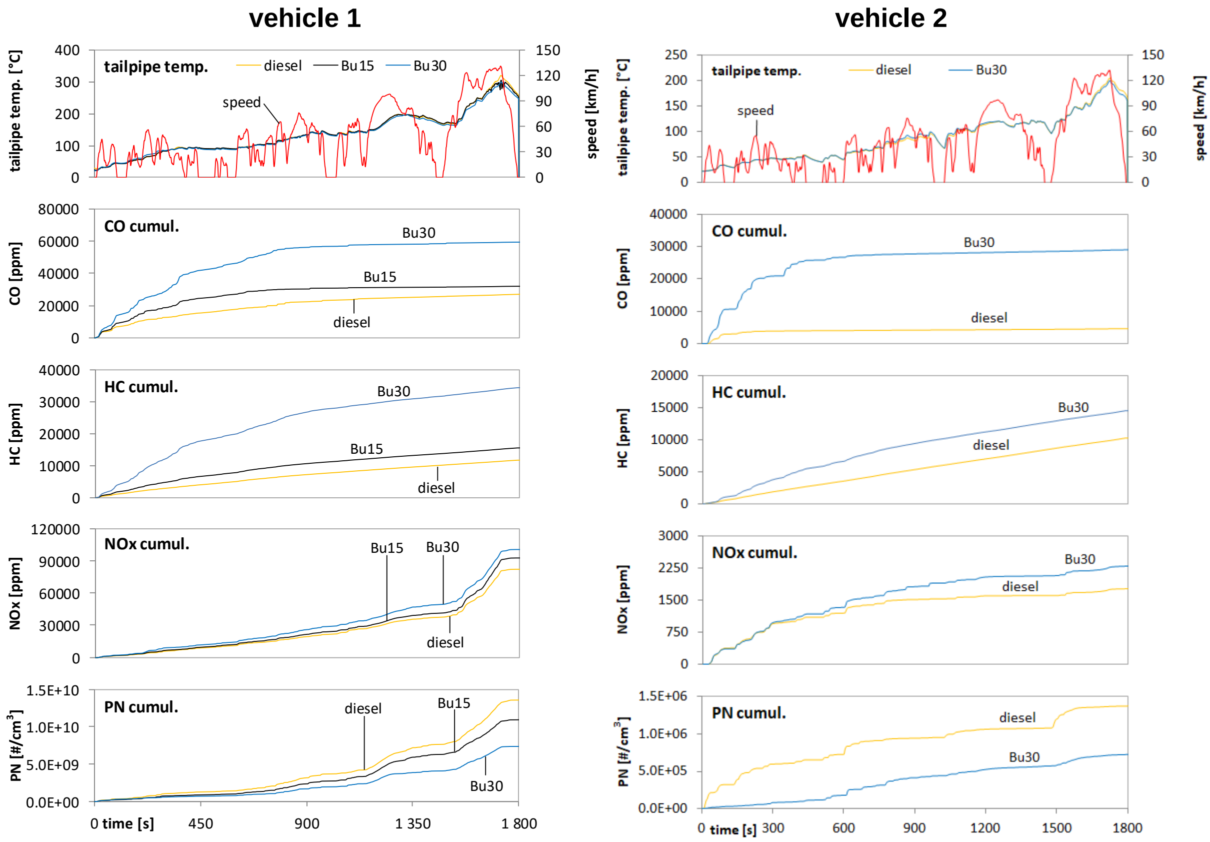


Fig. 24: Cumulated diluted exhaust emissions and tailpipe temperatures in WLTC cold with different fuels, V1 & V2.

Fig. 25 compares the SMPS particle size distributions (PSD) of both vehicles at two constant OP's (idling and 95 km/h). For better representation linear and logarithmic scales are used. In the linear scale, the Eu6c (V2) particle numbers are not visible. In the logarithmic scale single counts (no distributions) are possible to remark for Eu6c.

Without DPF (V1) the same tendency, like in previous research, was found: with increasing BuXX there are: higher PN in nuclei mode and lower PN in accumulation mode. So that the summary PN is lower.

With DFP (V2) the particle count concentrations are strongly reduced (by 2 to 5 orders of magnitude), but they are higher with Bu30, than with Bu00. This also confirms the tendency found previously on engine (E2) and it is explained with another composition of the aerosol (SOF) and consequently modified behavior (nucleation, diffusion loses) in the exhaust and in the sampling systems.

More detailed explanation of this artefact is: the presence of Butanol in the blend fuel causes among others a modified structure of heavy SOF in exhaust. Part of these SOF, which pass the DPF in gaseous state of aggregation produce spontaneous condensates, which become semi-solids in the sampling (analyzing) line and cannot be entirely eliminated by the sample treatment of the PN measuring system. These effects are only visible with a very low PN emission level with DPF. Without DPF (Eu2) the PN emission level is up to 5 ranges of magnitude higher and the effects from engine-out emissions are predominant.

Despite that the DPF reduces or eliminates the nanoparticles down to the ambient level or below it.

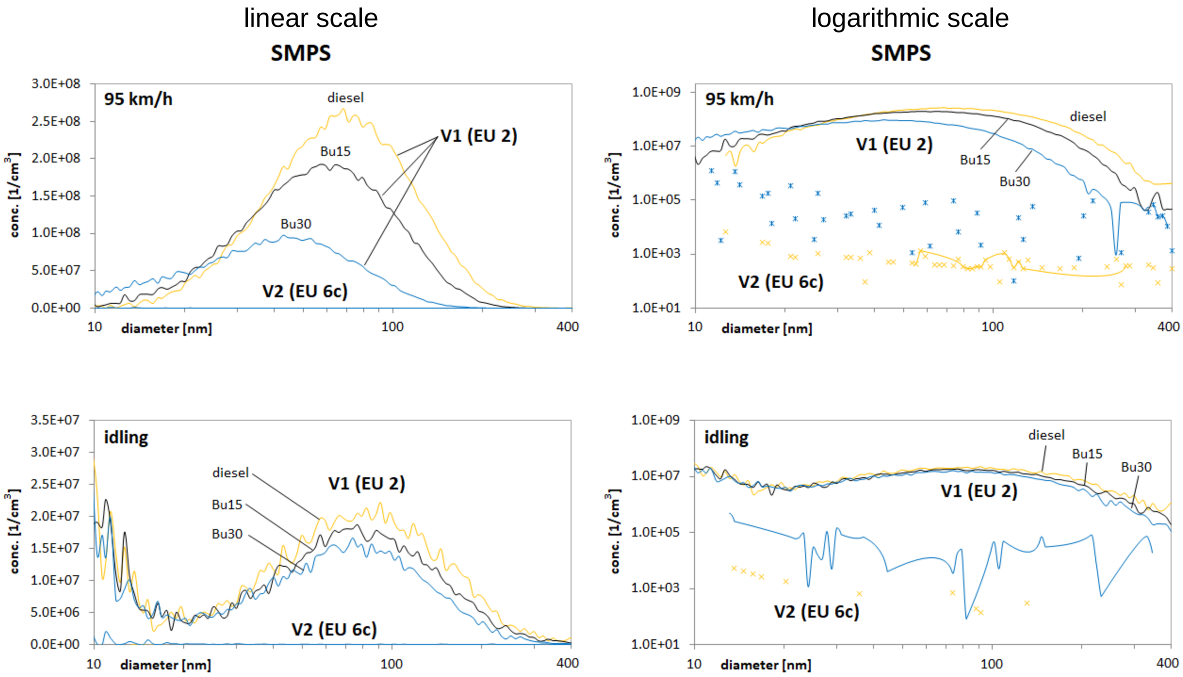


Fig. 25: Comparison of the Particle Size Distribution (PSD) during the driving cycle SSC with different fuels and with vehicle V1 & V2.

Fig. 26 gives a sample of PSD results with SMPS (10-400 nm) and with nSMPS (2-66 nm). The results of both measuring systems correlate very well in the common measured size range (10-66nm). Without DPF (V1) there are sporadic counts down to 5 nm, with DPF (V2) there are no counts below 10 nm. It can be stated that the filtration efficiency of a right-quality DPF is valid or even improved in the sub 23 nm size range. There are no differences of count concentrations with different investigated fuels.

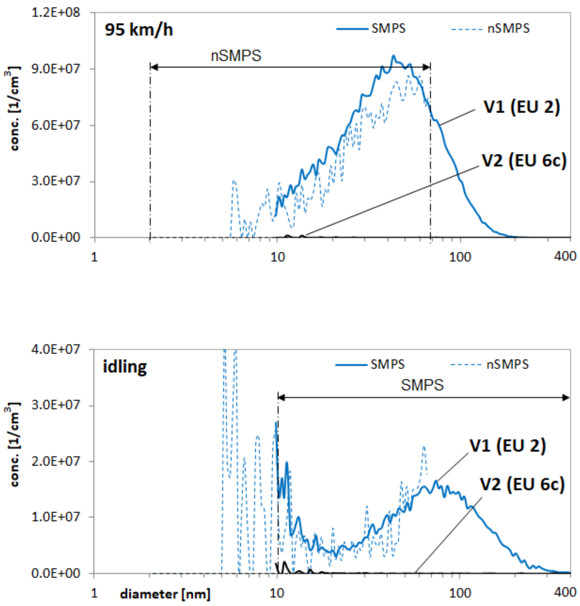


Fig. 26 Particle Size Distribution (PSD) during the SSC cycle in different ranges of size spectrum, Comparisons SMPS – nSMPS, Bu30, V1 & V2.

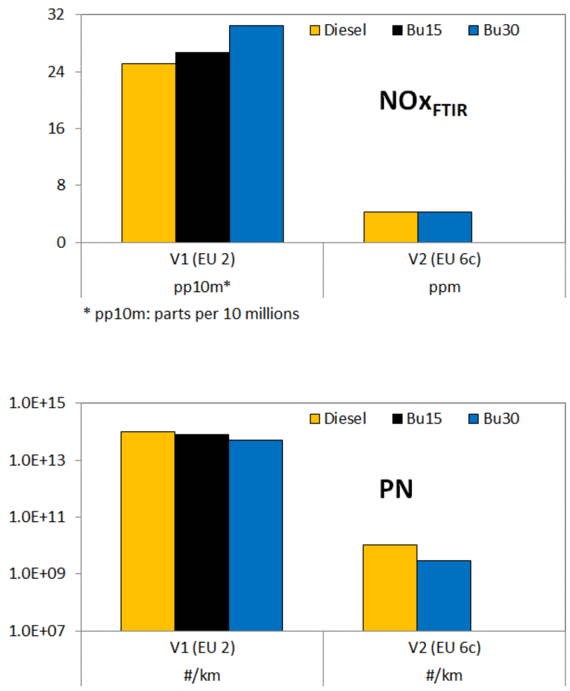


Fig. 27: Comparison of NOx- and PN-emissions in WLTC warm with different fuels and with both vehicles V1 & V2.

Fig. 27 summarizes the comparisons of NO_x and PN with both vehicles and with different fuels in $WLTC_{warm}$. The lower emissions of vehicle V2 (with DOC/DPF/SCR) are clearly visible. With increasing BuXX for vehicle V1 NO_x increases and PN decreases, while for vehicle V2 there is no effect on NO_x and a reduction of PN.

3.4.2 Non-legislated emissions of both vehicles

Comparisons of non-legislated gaseous emissions, as average values in $WLTC_{warm}$ are represented in Fig. 28 for both vehicles and for all investigated fuel variants. With higher Bu-content, especially with Bu30 the emissions of Formaldehyde (HCHO) and of Acetaldehyd (MeCHO) are clearly increased with V1 (older technology) while with V2 (new technology) these emissions are near to zero and there is no influence of Bu-rate.

With the vehicle V2, the emission of NO_2 is nearly eliminated and the emission of N_2O is increased staying nevertheless at a very low absolute level < 4 ppm.

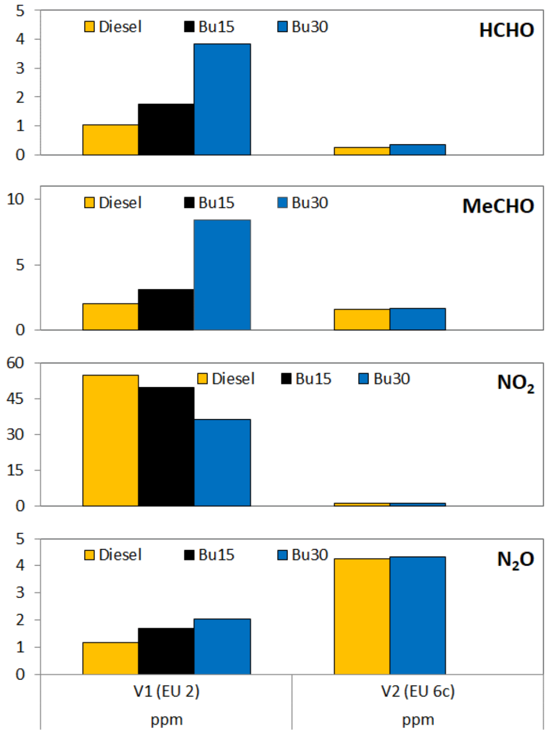


Fig. 28: Comparison of average non-legislated gaseous emissions in WLTC warm with different fuels and with both vehicles V1 & V2.

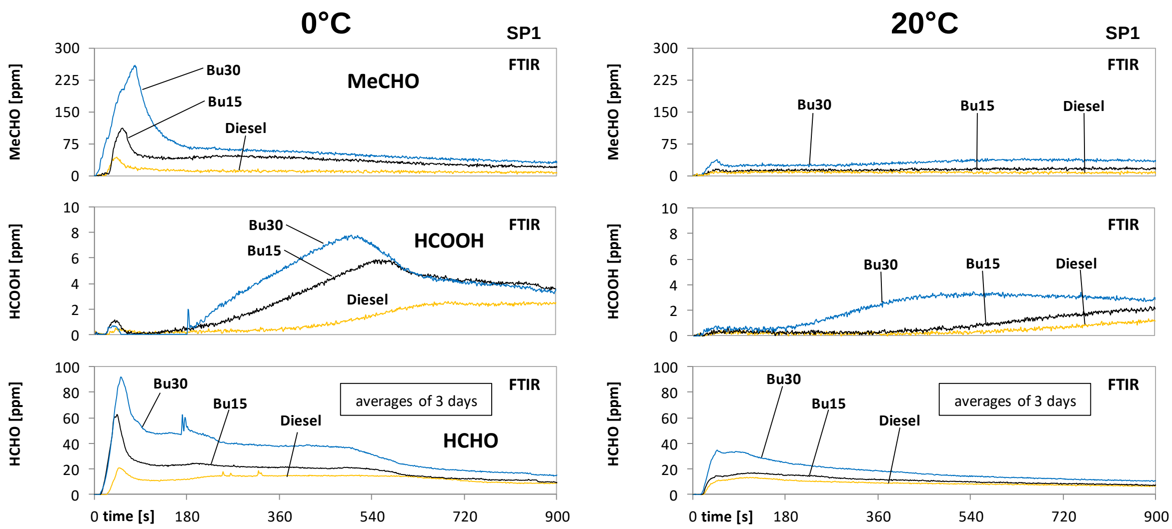


Fig. 29: Comparison of the non-legislated gaseous emissions during cold start (CS) at idling, with Bu 00/15/30, measured with FTIR at tailpipe, vehicle V1

3.4.3 Cold start

Fig. 29 shows some non-legislated gaseous components, emitted by vehicle V1, comparing Bu00/Bu15/Bu30 in two temperature domains of the CS: 0°C and 20°C. All measurements at cold starts (CS) were performed with FTIR at tailpipe i.e. sampling position SP1.

With higher Bu-content the peaks of Formaldehyde HCHO and of Acetaldehyde MeCHO after CS increase. Starting with a lower temperature, these peak-values are higher and can attain for MeCHO 250 ppm.

During the warm-up of the exhaust system, between 180s and 900s idling time, there is a clear influence of BuXX on the production of Formic Acid HCOOH. Nevertheless, it appears in insignificant concentrations (up to 7ppm at 0°C). The Ammonia NH_3 concentrations in all CS-attempts were zero and are not further represented.

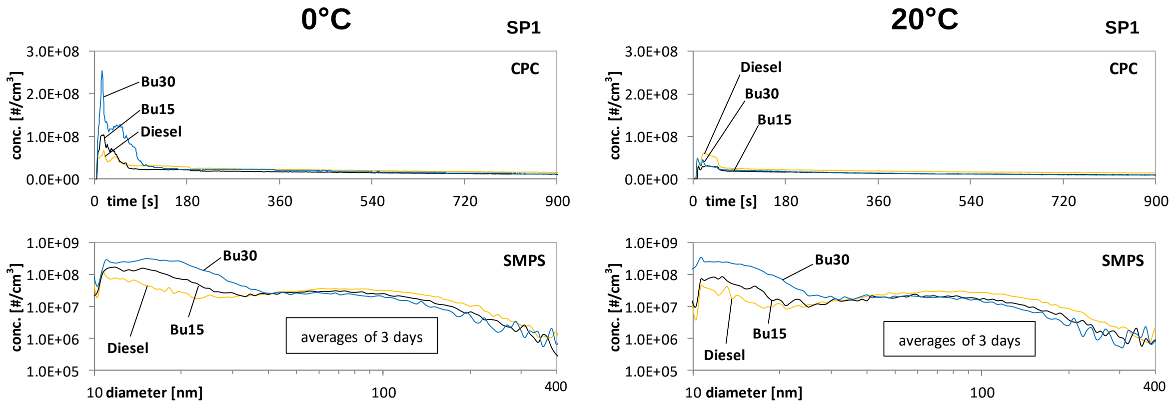


Fig. 30: Comparison of the particle counts during cold start (CS) at idling, with Bu 00/15/30, measured with CPC and with SMPS at tailpipe, vehicle V1

Fig. 30 compares the nanoparticle emissions with the fuels Bu0 / Bu15 / Bu30 at CS in both temperature ranges 0°C & 20°C. CPC (condensation particle counter) measures the particle numbers of all particle sizes according to the PMP-guidelines. SMPS (scanning mobility particle sizer) measures the particle numbers in function of their size.

The SMPS-particle size distributions were taken in the successive parts of the warm-up period: (1) 0-120s; (2) 120-300s and (3) 300-600s.

The successive SMPS-scans of each CS-attempt (not represented here) showed clearly the lowest PC-level of the latest sample. The 1st sample was well repeatable and the PSD's in Fig. 30 are averages from three cold starts of the 1st scan (in the period 0-120s).

The most important information of Fig. 30 is, that during the CS Bu15 emits similar or slightly higher level of particle counts concentration, like Bu0, while B30 increases clearly the PN emissions. This increase is produced in the first 1.5 min after CS and originates mainly from the higher nuclei mode (with higher BuXX).

The PN concentrations in accumulation mode nevertheless are lower with higher BuXX – this is similar finding like observed on engines.

Similar representations of emissions during the cold start tests in both temperature ranges (0°C and 20°C) are given for vehicle V2 in the Figures 31 and 32. The most important observations are:

- with cold start (WLTC cold), the concentrations of Formaldehyde HCHO and Acetaldehyde MeCHO are with Bu30 higher than with Bu00; the absolute average values of those components are, nevertheless, insignificant (0.5 – 8 ppm),
- the particle counts (PC) concentrations (after DPF) are very low, there are no particle size distributions, but occasional, scattered counts; in sub 23 nm size range, there are no counts at all; the PC's with Bu30 are higher than with Bu00 – this is the effect of modified chemistry of the fuel and consequently modified interaction of fuel and of combustion with the lube oil,
- at cold start, there are higher values of CO, HC (not represented in these figures), HCHO and MeCHO with Bu30.

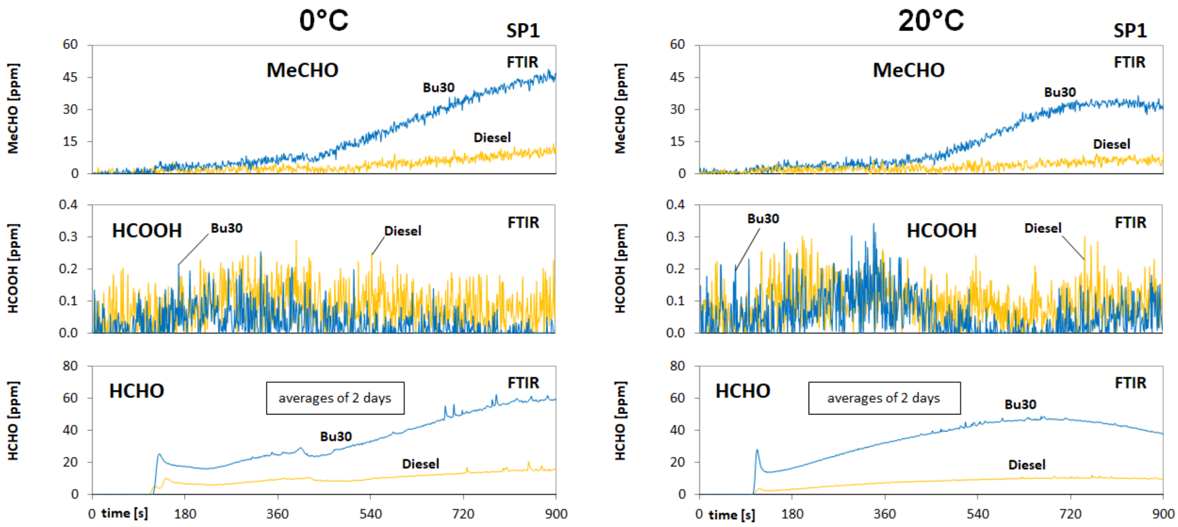


Fig. 31: Comparison of the non-legislated gaseous emissions during cold start (CS) at idling, with Bu00 / Bu30, measured with FTIR at tailpipe, vehicle V2.

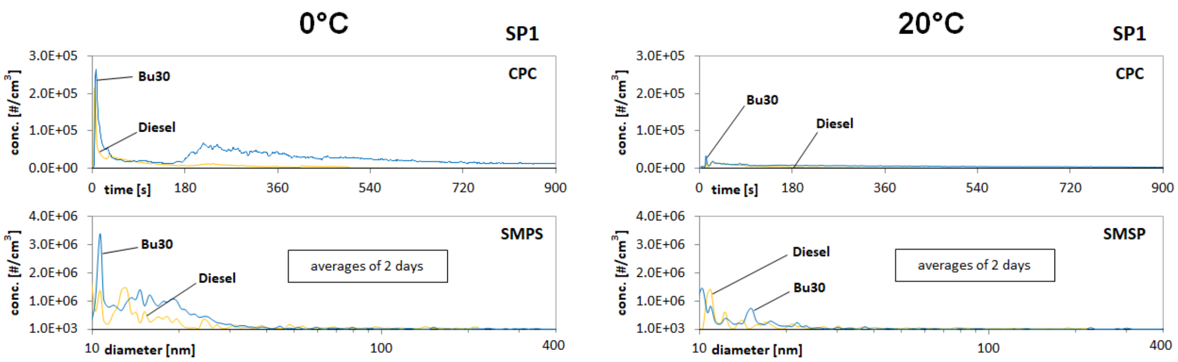


Fig. 32: Comparison of the particle counts during cold start (CS) at idling, with Bu00 / Bu30, measured with CPC and with SMPS at tailpipe, vehicle V2.

Direct comparisons of emissions of both investigated vehicles at 0°C cold start are given in the following figures:

Fig. 33 shows the plots of the most prominent non-legislated components at cold start 0°C. With an older technology, the higher Bu-content in fuel increases significantly the emission peaks of Acetaldehyde (MeCHO) and Formaldehyde (HCHO) at cold start. With a newer technology, this tendency is also present but at a very low and insignificant absolute emission level.

[Fig. 34](#) shows PN-emissions during and after the cold start at 0°C with both vehicles. The significantly lower PN-emission with DPF is confirmed.

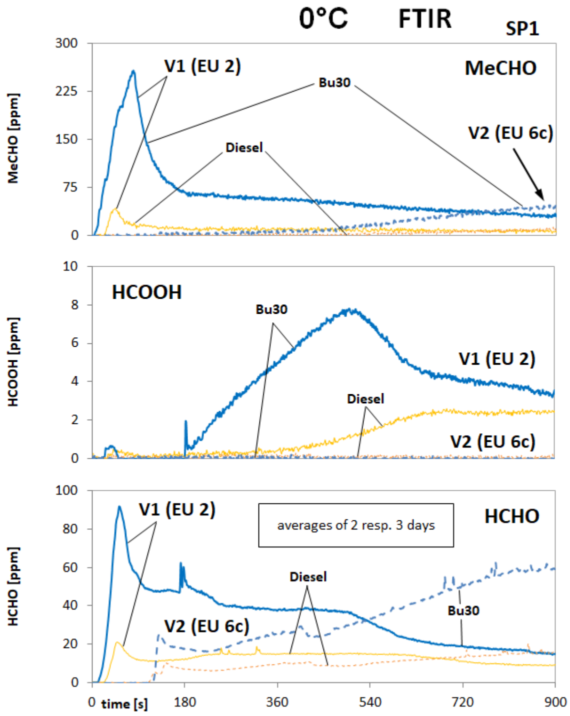


Fig. 33: Comparison of non-legislated gaseous exhaust emissions during cold start at 0°C and idling with different fuels, V1 & V2.

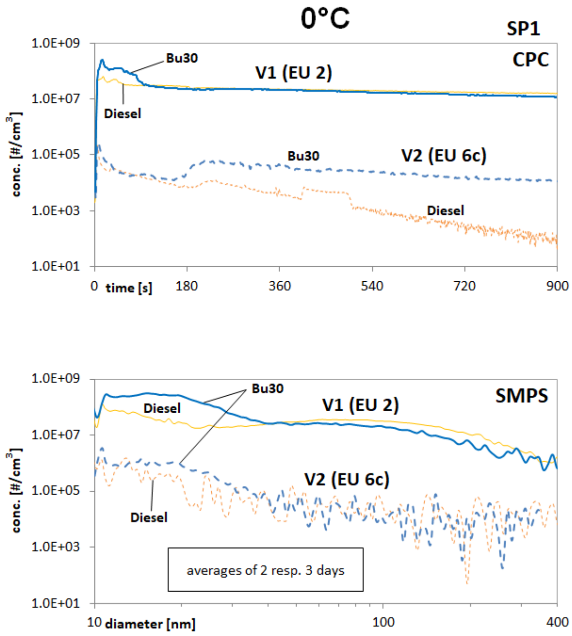


Fig. 34: Comparisons of the particles counts during cold start at 0°C and idling with different fuels, V1 & V2.

4 Conclusions

4.1 Findings on engine dynamometers

The most important experiences gained on engines are:

For engine (E1), production of the year 2005:

- The operation of this engine with Bu30 is instable at lower part load due to the lower Cetane Number of the blend fuel. Bu30 is considered as a limit of the blending ratio for this engine.
- The PM-emissions with Bu30 are lower, so the soot loading of DPF takes a longer time.
- The regeneration step test (according to SN277206) shows for both fuels similar results: the balance point is attained in the 6th step (at 60% engine load) with the balance point temperature 371-374°C.
- The emissions of CO and HC with Bu 30 at engine part load are higher and the emissions of PN at full load with Bu30 are lower than with Bu0.
- The lower overall heat value of Bu30-blend leads to a respectively lower full load torque without corrections of the injected fuel quantity.
- The emissions of CO and HC with Bu 30 at engine part load are higher than with Bu00.

- In the investigated load ramps, the light-off temperature (K_x 50%) of DOC with Bu30 is higher (in the range of Δt = 20°C) than with Bu00.
- In NRTC, the conversion rate of DOC with Bu30 is lower: for CO by 4%-points, for HC by 10%-points.
- With Bu30, there is in the DOC a lower production of NO_2 in the higher temperature range above 200°C.

For engine (E2), production of the year 2017:

- With higher Butanol content, there is a lower heat value of the fuel and there is lower torque at FL.
- The repeatability of results at constant operating points (FL), and in dynamic operation (WHTC) is very good.
- At transient operation (WHTC), CO and HC increase with higher BuXX and NO_x stays constant.
- At steady state operation (constant OP's), CO decreases with higher BuXX (except of idling), HC and NO_x slightly increase.
- The dynamic answer of the engine – performance of the load increase during 4 working cycles – is equal for all three fuels: Bu00/15/30.
- The electronic control system of the engine, (FMO), compensates very well the varying properties of the fuels Bu00/15/30, so that in the combustion diagnostics no differences of heat release can be noticed.
- With Bu50, the engine electronic control cannot entirely compensate the deviating fuel parameters, the dynamic answer of the engine is slower and weaker.
- There are influences of Bu-rate on the inflammation phase and on the combustion duration; there are partly controversial effects of lower self-ignition aptitude (lower CN) and of quicker mixing and higher portion of premixed combustion.
- At stationary part load operating condition with higher Bu-content the start of heat release is slightly retarded (0.5-2 deg CA due to lower CN), but due to the higher portion of premixed fuel, the premixed phase of combustion is much quicker which may overcompensate the later start for BuXX < 30%.
- The operation with Bu50 was only possible for research purposes thanks to the external strong starting system (dynamic brake). A field application of this high Bu-rate is not recommendable.
- There are no differences of NO_X-reduction behaviour of the SCR-system with both investigated fuels, Bu30 and Bu00.
- An important and repetitive result is a lower soot mass emission (model from the engine ECU) with Bu30.
- In transient cycles (WHTC and ETC) for legislated and non-legislated gaseous emission components there are no significant differences between Bu30 and Bu00.
- The procedure and emissions of the forced DPF-regenerations are well repeatable and independent on the fuel quality.

4.2 Findings on chassis dynamometers

The most important statements for the Diesel cars are:

- The emissions of CO, HC and NO_x with Bu 30 in WLTC and at engine part load are higher than with Bu00. With the modern exhaust aftertreatment technology (DOC / DPF / SCR / EGR), with a significantly lower emission level, these differences are smaller or not existing.
- Higher Bu-content lowers the PN-emissions. With DPF nevertheless, the influence of fuel on PN is insignificant.
- In the SMPS size range (10-400 nm) at constant speed operation, there is a clear tendency of increasing the particle counts (PC) concentrations in nuclei mode (< 25 nm) and reducing PC in accumulation mode (> 25 nm) with higher BuXX. With DPF, these tendencies are not visible.
- In the sub 23 nm range, there are almost no differences of PC-concentrations with different fuels, but smaller particles (down to 6nm) are detected with Bu30 and Bu15.

- Higher Butanol content interferes more with the lube oil and tendentiously increases the nanoparticles counts in nuclei mode (without DPF).
- Without DPF (Eu 2), the results of both measuring systems SMPS and nSMPS correlate very well in the common part of the size spectrum; at lower engine load (idling), there are generally higher PC-concentrations in the size range 5-10 nm than at higher load (95 km/h).
- With the newest technology (Eu6c), the particle counts (PC) concentrations (after DPF) are very low. There are no particle size distributions, but occasional, scattered counts. In sub 23 nm size range, there are no counts at all.
- At cold start and warm-up all three investigated fuels produce increased CO-, HC- and NP-values in similar way.
- With an older technology (Eu 2), the higher Bu-content in fuel increases significantly the emission peaks of Acetaldehyde (MeCHO) and Formaldehyde (HCHO) at cold start. With a newer technology (Eu 6c), this tendency is also present but at a very low and insignificant absolute emission level.

5 Outlook and next steps

For practical implementation of the Butanol blend fuels in Diesel engines it is important to mention that the questions of durability of the injection system due to lower lubricity of Butanol blend fuels and durability of the lube oil were not investigated in the present project. These research and development activities would require very extensive durability tests and significantly higher time & cost efforts.

The application of PtX (Power to X) fuels is viewed today as one of the most important options for carbon-free transportation.

With combination of different research methods and different test objects, the present project elucidated the effects of new fuels on engine operation and on emissions. The methodology is appropriate to be used for other new fuels or fuel blends, which are considered as potential products for the future market.

Reflexions GasBut – DiBut

Research of engine operation and emissions with Gasoline-Butanol blend fuels (GasBut) was performed in 2015-2017 in a similar way as DiBut, [5, 6].

Butanol also creates with gasoline durable mixtures and can be used as a blend-component in spark ignition (SI) engines. It has nevertheless low volatility (higher boiling point, than Ethanol) and with higher Butanol portion in fuel there are problems of cold start and irregular operation at part load, due to insufficient mixture preparation. Blending ratio of 30% Butanol was found to be a limit, like for DiBut.

Thanks to the use of research vehicles with older and newer technology, it was possible to observe certain limits and differences. First of all, the cold start and cold operation with higher Butanol rates produce higher emissions with older technology and especially emissions of Formaldehyde and Acetaldehyde, which are insignificant with the newer technology both with gasoline and with Diesel.

Older date Lambda regulation is more sensitive to the higher Oxygen content of the fuel, it produces more Lambda-excursions and finally lower NO_x-conversion.

A modern Diesel exhaust aftertreatment system (DOC/DPF/SCR) was insensitive to the Butanol rate and reduced very well PN- and NO_x- emissions for some blended fuels, showing a big difference and progress in comparison with the older technology (DOC only).

The use of 12.5% vol. Butanol blends in SI application in the fleet is accepted in the USA (see annex A1-1). For Diesel application, it would be necessary to define the "no-problem" blending level for the long-time fleet operation without precautions for fuel lubricity and for lube oil durability.

6 Publications

[1] Engelmann, D.; Czerwinski, J.; Comte, P.; Nauroy, H.; Hüssy, A.: Influences of Butanol Blend Fuels on Combustion and Emissions of Diesel Engines. Technische Akademie Esslingen (TAE), June 2019.

[2] Engelmann, D.; Czerwinski, J.; Nauroy, H.; Comte, P.; Hüssy, A.; Renz, S.; Bonsack, P.: Use of Butanol Blend Fuels on Diesel Engines – Effects on Combustion and Emissions. SAE Techn. Paper 2020-01-0333, Detroit, April 2020

[3] Czerwinski, J.; Comte, P.; Engelmann, D.; Renz, S.; Bonsack, P.: Non-Legislated Emissions and PN of Two Passenger Cars with Diesel-Butanol Blends. (In print).

[4] Poster: see annex A6

[5] Czerwinski, J.; Güdel, M.; Engelmann, D.: Influences of Butanol Blends on Combustion and Emissions of a Small SI Engine., SAE Techn. Paper 2018-32-0058/20189058, Dusseldorf, Germany

[6] Czerwinski, J.; Comte, P.; Engelmann, D.; Bonsack, P.: Non-Legislated Emissions and PN of Two Passenger Cars with Gasoline-Butanol Blends. PTNSS, Journal Combustion Engines, 2018, 172(1), 64-72. DOI:10.19206/CE-2018-108.

7 References

[1] Czerwinski, J.; Nauroy, H.; Hüssy, A.; Zimmerli, Y.; Clénin, M.: Influences of Butanol Blend Fuels on Emissions and on DPF-Regeneration on Liebherr Engine D 934 S. Laboratory for IC-Engines and Exhaust Emission Control of the University of Applied Sciences, Biel-Bienne, B509, 1st report DiBut, June 2018.

[2] Czerwinski, J.; Nauroy, H.; Hüssy, A.; Clénin, M.: Influences of Butanol Blend Fuels on Combustion and Emissions of an Iveco Engine F1C Euro VI. Laboratory for IC-Engines and Exhaust Emission Control of the University of Applied Sciences, Biel-Bienne, B514, 2nd report DiBut, August 2018.

[3] Czerwinski, J.; Nauroy, H.; Hüssy, A.; Clénin, M.: Influences of Butanol Blend Fuels on Combustion and Emissions of an Iveco Engine F1C Euro VI; Transient Operation. Laboratory for IC-Engines and Exhaust Emission Control of the University of Applied Sciences, Biel-Bienne, B522, 3rd report DiBut, December 2018.

[4] Czerwinski, J.; Nauroy, H.; Zimmerli, Y.; Clénin, M.: Influences of Butanol Blend Fuel Bu30 on Emissions and DOC Functionality on Liebherr Engine D 934 S. Laboratory for IC-Engines and Exhaust Emission Control of the University of Applied Sciences, Biel-Bienne, B527, 4th report DiBut, March 2019.

[5] Czerwinski, J.; Comte, P.; Wili, Ph.; Clénin, M.: Influences of Butanol Blend Fuels on Emissions of two Diesel Passenger Cars Euro 2 and Euro 6c. Laboratory for IC-Engines and Exhaust Emission Control of the University of Applied Sciences, Biel-Bienne, B528, 5th report DiBut, April 2019.

[6] Czerwinski, J.; Nauroy, H.; Clénin, M.: Influences of Butanol Blend Fuels on Emissions of an Iveco Engine F1C Euro VI; Transient Operation; DPF + SCR. Laboratory for IC-Engines and Exhaust Emission Control of the University of Applied Sciences, Biel-Bienne, B530, 6th report DiBut, June-September 2019.

[7] Lennox, S.; Lukács, K.; Torok, A.; Akos, B.; Makame, M.; Penninger A.; Kolesnikov, A.: Combustion and emission characteristics of n-butanol/diesel fuel blend in a turbo-charged compression ignition engine. Elsevier Fuel Journal homepage: www.elsevier.com/locate/fuel. Fuel 107 (2013) 409-418.

[8] Srivastava, D. K.; Agarwal, A. k.; Datta, A.; Maurya, R. K.: Advances in Internal Combustion Engine Research. Energy, Environment, and Sustainability. Springer ISSN 2522-8366, ISBN 978-981-10-7574-2. https://doi.org/10.1007/978-981-10-7575-9.

8 Appendices

Supplementary information about DiBut:

A1 Butanol Blend Fuels – Application in IC-Engines, literature survey

A2 BioButanol – situation of industry, markets and perspectives

A3 Engine dynamometer and test equipment, engine E1

A4 Engine dynamometer and test equipment, engine E2

A5 FTIR measured parameters

A6 Influences of Butanol blend fuels on combustion and emissions of Diesel engines – poster Verbrennungstagung BfE/ETHZ, 2019

PRELIMINARY INFORMATION & LITERATURE SURVEY

Butanol

It is generally accepted, that the fossil energy sources have to be gradually replaced by renewable and CO_2-neural energy carriers. The liquid biofuels, like ethanol, or biodiesel are most valuable and versatile alternatives in this context. In recent years; however, biobutanol has emerged as a potential biofuel, or blend-component to other fuels.

Butanol, a four-carbon alcohol, is another candidate alternative fuel, with properties closer to gasoline than Ethanol. Two of its isomers, n-Butanol (1-butanol) and iso-Butanol can be considered for use in spark ignition (SI) engines and as a blending component in Diesel engines.

Like Ethanol, Butanol is a biomas-based renewable fuel that can be produced by alcoholic fermentation of sugar beet, sugar can, corn, wheat (bio-Butanol), although petro-Butanol also exists, i.e., Butanol produced from fossil fuels. Moreover, in order to increase the production scale and avoid the use of food crops, there is an ongoing research effort aimed at developing the technology to process lignocellulosic biomass (wood, grasses, agricultural wastes, etc) into Butanol too.

The biorefineries producing cellulosic ethanol from wood or agricultural residues can be retrofitted to enable the production of butanol, which is actually practiced in US, [1, 2]. There are several further developments and progressive activities of biorefineries, which according to the demand can produce biobutanol, [3, 4].

Butanol ($CH_3(CH_2)_3OH$) has a four-carbon structure and is a higher-chain alcohol than Ethanol, as the carbon atoms can either form a straight chain (*n*-Butanol) or a branched structure (iso-Butanol), thus resulting in different properties. Consequently, it exists as different isomers depending on the location of the hydroxyl group (-OH) and carbon chain structure, with Butanol production from biomass tending to yield mainly straight chain molecules. 1-Butanol, better known as *n*-Butanol (normal Butanol), has a straight-chain structure with the hydroxyl group (-OH) at the terminal carbon.

n-Butanol is of particular interest as a renewable biofuel as it is less hydrophilic, and possesses higher energy content, higher cetane number, higher viscosity, lower vapour pressure, higher flash point and higher miscibility than Ethanol, making it more preferable than Ethanol for blending with Diesel fuel. It is also easily miscible with gasoline and it has no corrosive, or destructing activity on plastics, or metals, like Ethanol or Methanol.

Several research works were performed with different Butanol blends BuXX, [5-19].

Generally, there are advantages of higher heat value (than Ethanol). The oxygen content of Butanol has similar advantages, like with other alcohols: tendency of less CO & HC, but possibility of increasing NO_x (depending on engine parameters setting).

The good miscibility, lower hygroscopicity and lower corrosivity make Butanol to an interesting alternative.

Now, ASTM D7862-13, “Specification for Butanol for Blending with Gasoline for Use as Automotive Spark-Ignition Engine Fuel”, covers butanol, which is intended in US to be blended with gasoline at 1 to 12.5 volume percent for use as an automotive spark-ignition engine fuel.

ASTM D7862 establishes performance requirements and test methods for butanol content, water content, acidity, inorganic chloride, solvent-washed gum, sulfur content and total sulfate.

Research works & some results

The trend of downsizing the SI-engines in the last years implies much higher specific torques and with it an aptitude of knocking and mega-knocking at high- and full load. The alcohols have a higher Octane Numbers (RON), are more resistant to knocking and are a welcomed solution for this new technology of engines, [5].

The most important data of gasoline, ethanol and butanol are given according to [5]:

	Gasoline RON 95	Ethanol	n-Butanol	iso-Butanol
Oxygen content m [%]	2.26	34.73	21.58	21.58
density kg/m³	737	786	806	803
viscosity [mPa*s]	~0.42	1.08	2.53	3.00
boiling temp. [°C]	41.5-173.5	78	118	99
stoich. air requirement [kg/kg]	14.14	8.98	11.16	11.16
lower heat value [MJ/kg]	42.13	26.84	33.12	32.92
Research Octane Number RON [-]	96.3	108.6	99.2	105

Table 1: Data of alcohols compared with gasoline, [5].

Blending of different heavier alcohols can result in improved blend fuel characteristics. A method of predicting the fuel properties of multi-component alcohol blends was established in [6] and an optimal composition consisting of iso-propanol, iso-butanol and iso-pentanol was identified and experimentally evaluated. The objective of optimisation was to combine a possibly high energy content of the fuel with high RON and a high petroleum replacement equivalent.

A basic research of butanol blends Bu20 & Bu100 was performed on mono-cylinder engines with optical access to the combustion chamber, [7, 8]. One of the engines was with GDI configuration. It was demonstrated, that the alcohol blend improved the internal mixture preparation and reduced the carbonaceous compounds formation and soot.

Concerning the characteristics of combustion Bu100 was similar to gasoline. This research considered only little number of constant operating points.

Using n-Butanol in a optical port fuel injection (PFI) SI engine slightly higher combustion rates and lower formation of particulates was found compared to gasoline, [9, 10]. Similarly [11] reported that the duration of the early combustion stage and length of combustion in an SI engine were, compared to gasoline, shortened with increased n-Butanol share, and slightly lower variability of indicated mean pressure (IMEP) was observed when running on neat n-butanol. Shorter early combustion stage, faster combustion and better combustion stability were also observed by other researchers [12, 13].

The alcohol blend fuels E85 & Bu85 were tested on a vehicle with 3WC in road application and with on-board measuring system for exhaust emissions, [14]. It was stated for butanol, that it has no significant influence on CO & HC, but it increases strongly NO_x. Nevertheless, this is due to the limits of Lambda regulation and, as effect of it, due to the production of too many lean Lambda excursions during the transients.

The warm operation with Bu85 was with no problems the cold startability and emissions were not investigated.

Butanol is easy miscible with diesel fuel and can contribute to the advantages similarly to other oxygenated compounds. In an extensive study of published results, [15], it was confirmed that butanol lowers the PM- and CO-production, has tendencies of increasing HC and no clear tendency concerning NO_x. These are statistical statements concerning different diesel engines with different technical state of the art. The influences on nanoparticle emissions were mentioned as an open field for further investigations.

Other studies, on single-cylinder diesel engines with older technology and Bu10, remark no substantial differences between the results with neat Diesel fuel and with Bu10, [16, 17].

In [18], n-Butanol was injected in the intake port of a DI-Diesel engine operated with biodiesel. This partial premixed charge compression ignition (PCCI) created a great reduction of soot- and NOx-emissions at part load operation of the engine.

Interesting combustion research on a single cylinder engine was performed by [19]. A partially premixed Diesel combustion (split combustion) was found to yield particular advantages with high Butanol shares in fuel. With rising Butanol shares of fuel blends their characteristics are changing towards a fuel showing better evaporation, but worse self-ignition properties. Butanol lowers significantly the Cetane Number.

Another problem is the lower lubricity of Butanol, which can be addressed with special lubricating additives. Nevertheless, this problem needs further research and solutions.

Some data of Diesel-Butanol blend fuels, according to [19], are given in the following Table 2:

	Ref. Diesel	**Bu15**	**Bu30**	**Bu50**
Density at 15°C in kg/m³	833-837	832	828	822
Net calorific value in MJ/l	35.3	34.0	32.8	31.4
Stoichiometric air/fuel ratio	14.6	14.0	13.5	12.9
Oxygen content in wt.-%	<0.03	3.1	6.4	10.7
H:C ratio (molar)	0.157	0.165	0.170	0.179
Cetane number	52-54	≈ 48	≈ 43	≈ 35

Table 2: Data of Diesel fuel, Butanol and their blends (according to [19]).

Information about the Butanol market and production capacities in the last years is given in annex A1.

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Introduction of Biobutanol as supplementary fuel-estimate of actual situation of industry, markets and perspectives

Biobutanol in US, [1]:

Butanol is commonly produced using fossil fuels, but it can also be produced from biomass, in which case it is called biobutanol. Biobutanol is produced from the same feedstocks as ethanol—corn, sugar beets, and other types of biomass. Biobutanol is considered a renewable fuel and qualifies under the Renewable Fuel Standard; the category it falls under depends on the feedstock used to produce it.
There are two Clean Air Act provisions that allow blending of up to 12.5% biobutanol with gasoline, and under the Octamix waiver, with human health effects testing; a 16% biobutanol blend is a legal fuel equivalent to E10. Biobutanol has an ASTM D7862 fuel quality standard for blends up to 12.5% with gasoline. It is important to ensure that biobutanol blended with ethanol/gasoline combinations do not result in an oxygen content exceeding the U.S. Environmental Protection Agency (EPA) limit of 3.7%.
Oak Ridge National Laboratory has researched the compatibility of fueling equipment materials with biobutanol and found that equipment compatible with ethanol blends is compatible with biobutanol. Underwriters Laboratories announced in 2013 that equipment certified under testing subject 87A (for blends above E10) could also retain certification if used with biobutanol. It is anticipated that biobutanol would be distributed by tanker truck and rail, with the potential for transportation in pipelines upon research demonstrating its safety.

Production

Producing biobutanol via fermentation has been possible since the early 1900s, but it is currently more expensive than producing petrochemicals. Modern butanol is produced almost entirely from petroleum. Renewed interest in biobutanol as a sustainable vehicle fuel has spurred technological advances to ferment it. The first biobutanol plants are retrofits of existing corn ethanol plants. Biobutanol companies produce a range of products—solvents/coatings, plastics, fibers, and transportation fuel—to enhance economic performance through diversification. There are intense R&D activities to make the large scale production of biobutanol more efficient and competitive.

Research and Development

The U.S. Department of Agriculture's Agricultural Research Service is studying various aspects of biobutanol production:

- Advanced Conversion Technologies for Sugars and Biofuels
- Improving Biochemical Processes for the Production of Sustainable Fuels and Chemicals
- Mixed Community Bioreactors to Convert Lignocellulosic Feedstocks into the Liquid Biofuel Butanol

The U.S. Department of Energy (DOE) and the EPA are funding biobutanol research and development as part of their Small Business Technology Transfer and Small Business Innovation Research programs.

Companies involved in biobutanol production include DuPont and BP (Butamax) and Gevo.

Gevo & Butamax, [2]:

The two leading technology developers in this area in US are: Gevo and Butamax

Gevo

On 24 May 2012, Gevo commenced production at the world's first commercial-scale 18 MGPY biobutanol plant, developed by conversion of the former Agri-Energy corn ethanol plant in Luverne.

In December 2013, Gevo announced that the U.S. Army successful trials of a 50/50 blend of Gevo's ATJ-8 fuel in a Sikorsky UH-60 helicopter. The use of 16% isobutanol in UL 87A pumps has also been approved by Underwriter Laboratories, with no need for any equipment modification.

Butamax

In October 2013, Butamax™ Advanced Biofuels LLC, and Highwater Ethanol LLC, a leading producer of first generation ethanol, commenced a retrofit of Highwater's ethanol plant in Lamberton, Minnesota for the production of biobutanol. In August 2014, phase one of the retrofit was completed, with the implementation of a proprietary Butamax technology
In April 2012, Butamax entered into collaboration with leading biofuels engineering and construction company Fagen Inc. for commercial-scale biobutanol production (via retrofit of ethanol plants) using Butamax technology.
In December 2011 Butamax™ Advanced Biofuels announced agreement on commercialization principles with Highwater Ethanol, the first entrant to the Butamax Group.

In June 2006, DuPont and BP formed a partnership to develop new biobutanol production technology using lignocellulosic feedstocks. In July 2009 the partnership was cleared to take over the US company Biobutanol LLC. In 2009, BP and DuPont formed Butamax™ Advanced Biofuels, Wilmington.

Further important players

Green Biologics (UK), [3]

In the UK, Green Biologics has developed butanol-producing GM microbial strains and will integrate these into a novel fermentation process. This technology advance should result in a step change in the economic viability of the fermentation and enable the large scale production of Green Biologics' Butafuel™ product.
In January 2015, Green Biologics announced it has raised $76m towards acquisition and conversion of a 21 MMgy plant (Central MN Ethanol Co-op) based in Little Falls, Minnesota. Initially the facility will continue to produce ethanol, but aims to start production of n-butanol and acetone in 2016.

Cobalt Technologies (US Cal), [4]

In April 2013, it was announced that Cobalt Technologies, Naval Air Warfare China Lake Weapons Division, Show Me Energy Cooperative and NREL will cooperate in a $2.5m pilot plant for conversion of 'switchgrass butanol' to military-grade jet fuel. In March 2012 it was announced that Albermale would manufacture biojet fuel from butanol, provided by Cobalt, using NAWCWD's alcohol to jet technology. Cobalt and Rhodia have formed a partnership to develop a demonstration plant in Brazil to convert sugarcane bagasse and other non-food feedstocks into biobutanol.

Other developments and demonstrations in butanol production:

Other companies developing butanol technology include Tetravitae Bioscience, **[5],** (Eastman Chemical Company US Cal), and METabolic EXplorer, **[6],** (France).
Butalco GmBH, Switzerland, **[7]**, is developing new production processes for biobutanol based on genetically optimised yeasts together with partners in downstream processing technologies.
Optinol (US Cal), **[8]**, has developed a "patented non-GMO clostridium strain that naturally and prolifically favors the production of butanol, without acetone or ethanol". The technique has been developed by researchers at Louisiana State University, US. Optinol says the method can produce butanol at cost parity with bioethanol.

Ceresana market study, [9], - Biobutanol Market Growth;

Given their specific solvent properties, butanol (also known as n-butanol) and its derivatives are important ingredients of many paints and varnishes.
Global demand for butanol rose by, on average, 2.7% p.a. between 2005 and 2013
(Ceresana study).

Besides the commercial use of butanol in chemical applications, this alcohol is also deemed to offer significant potential for the biofuel industry. Already existing and progressing technologies to produce biobutanol by the fermentation of biomass are increasingly becoming the center of attention. Butanol offers a range of advantages when compared to conventional biofuel made from ethanol: Butanol has higher energy content and is easily miscible with diesel and gasoline. In addition, it can be combusted in conventional Otto-cycle engines without modifying the engine. **Bioethanol**, however, already is an established biofuel in Europe and North America, and a changeover of production facilities to manufacture **biobutanol** is expensive. Another possibility is converting the bioethanol that is being produced into butanol. Adequate and competitive technologies, however, are still in development.

China Dominating Market
In 2013, Chinese processors consumed about the same amount of butanol as Western Europe and North America taken together. Ceresana forecasts demand for butanol on the saturated markets of Western Europe and North America to increase by only 0.4% and 0.5% p.a. respectively until 2021. As development in industrialized Asian countries such as Japan will falter as well, China will expand its dominating role on the market for butanol even further. The main motor of this growth is the construction sector, followed by the growth markets wood processing and the automotive industry. Demand for butanol on the part of Chinese processors is projected to amount to almost 1.64 million tonnes in 2021.

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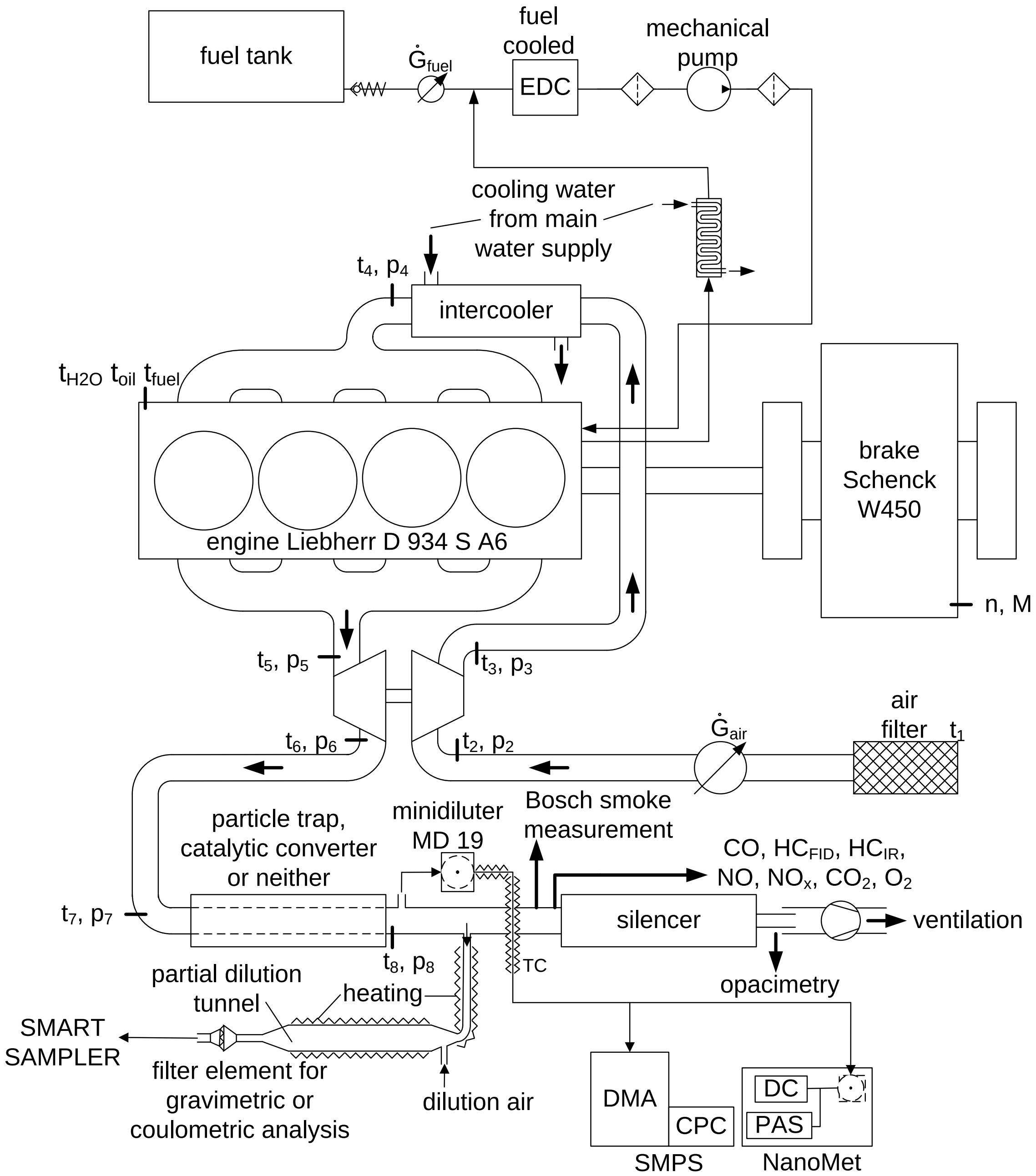
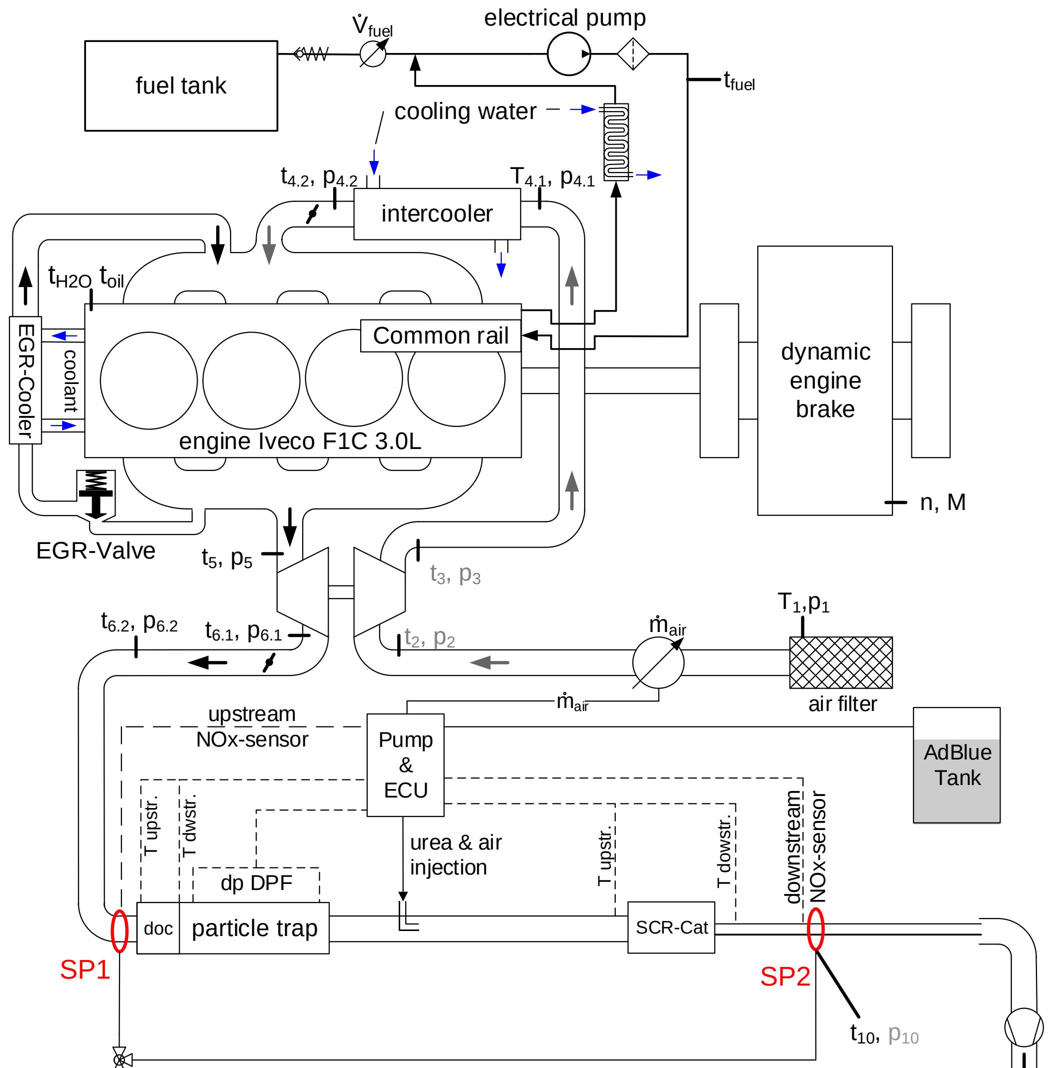
Engine dynamometer and test equipment, engine E1



Engine dynamometer and test equipment with ATS, engine E2



SP1: Sample Point 1, engine out

SP2: Sample Point 3, tailpipe

heated line: - HC_{FID}, NO_x
dry exhaust gases: -NO, NO_x, CO, CO_2, O_2

AVL SESAM-FTIR

minidiluter MD 19

TC → CPC

AVL SESAM-FTIR : measured values

AFHB

				Range [ppm]
Conventional Components :				
✓	CO	Carbon monoxide		0 - 8000
✓	CO2	Carbon dioxide		0 - 200'000
✓	NO	Nitrogen monoxide		0 - 10'000
✓	NO2	Nitrogen dioxide		0 - 1'000
✓	NOx	Total Nitrogen oxides	calulated	0 - 10'000
	HC	Hydrocarbons		
Non Regulated Components :				
✓	H2O	Water		0 - 250'000
✓	CH4	Methane		0 - 1'000
✓	SO2	Sulphur dioxide		0 - 1'000
✓	N2O	Nitrous oxide		0 - 1'000
✓	NH3	Ammonia		0 - 1000
✓	COS	Carbonoxidsulfid		0 - 200
Differentiated Hydrocarbons :				
✓	C2H2	Acetylene		0 - 1'000
✓	C2H4	Ethene		0 - 1'000
✓	C2H6	Ethane		0 - 1'000
✓	C3H6	Propene		0 - 1'000
✓	C4H6	1,3 butadiene		0 - 1'000
	NC5	n-Pentane		
	IC5	iso-Pentane		
✓	NC8	n-Octane		0 - 1'000
	AHC	Aromatic hydrocarbons		
Optional Components :				
✓	C3H8	Propane		
✓	HCHO	Formaldehyde		0 - 1'000
	CH3OH	Methanol		
✓	CH3CHO	Acetaldehyde		
	C2H5OH	Ethanol		0 - 1'000
✓	HCOOH	Formic Acid		0 - 1'000
✓	HCN	Hydrocyanic Acid		0 - 1'000
✓	HNCO	Isocyanic Acid		
✓	HCD	Total Hydrocarbon Diesel	calculated	0 - 30'000
✓	NMHC	Non Methanic Hydrocarbons	calculated	

sources: AVL, technical data sheet

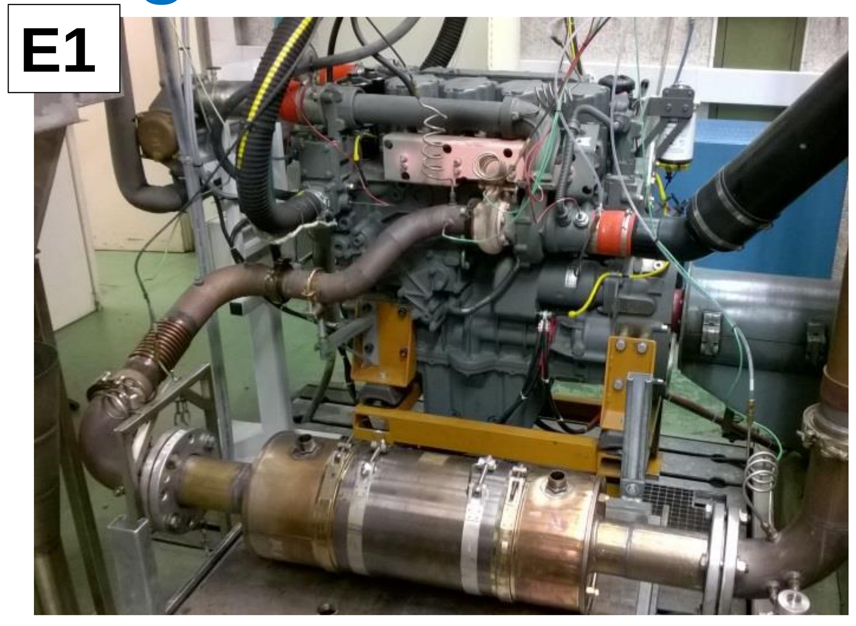
Influences of Butanol Blend Fuels on Combustion and Emissions of Diesel Engines

D. Engelmann, H. Nauroy and J. Czerwinski, AFHB, University of Applied Sciences, Biel-Bienne, CH

Abstract

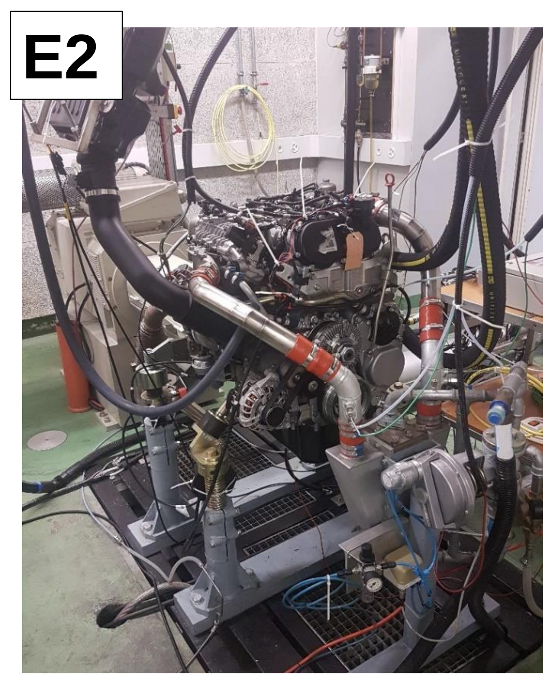
Butanol, a four-carbon alcohol, is considered in the last years as an interesting alternative fuel, both for Diesel and for Gasoline application. Like Ethanol, Butanol can be produced as a biomass-based renewable fuel or from fossil sources.
In the research project, DiBut (Diesel and Butanol) addition of Butanol to Diesel fuel was investigated from the points of view of engine combustion and of influences on exhaust aftertreatment systems and emissions. One investigated engine (E1) was with emission class “EU Stage 3A” for construction machines, another one, engine (E2) was HD Euro VI. The operation of engine (E1) with Bu30 was instable at lower part load due to the lower Cetane Number of the blend fuel. The electronic control system of the engine (E2) compensated very well the varying properties of fuels.

Engines



Manufacturer / type	Liebherr Machines Bulle S.A./ D 934 S
Emission level	97/68/EG step 3A; EPA/CARB Tier 3
Cylinder number and configuration	4 cylinders in-line
Rated power / Rated speed (present EDC setting)	105 [kW] @ 2000 [min^{-1}]
Low idle speed / high idle speed	800 [min^{-1}]; 2170 [min^{-1}]
Overall displacement	6.36 [dm^3]
Compression ratio	17 [-]
Year of manufacture	2005
Cooling medium	water
Combustion process	direct injection
Fuel system type	unit pump Bosch
Speed governor	EDC
Method of air aspiration	turbo charging
Charge air cooling system	Intercooler

Test engine (E1) Liebherr D934S on the engine dynamometer



Manufacturer	IVECO, Torino Italy
Type, emission level	F1C Euro VI
Displacement	3.0 liters
Cylinder number and configuration	4 cylinders in-line
Engine speed	Max. 4200 rpm
Rated power	107kW@3500 rpm
Combustion process	direct injection
Fuel system type	Common Rail Bosch LWR-20
Method of air aspiration	turbo charging
Charge air cooling system	Intercooler

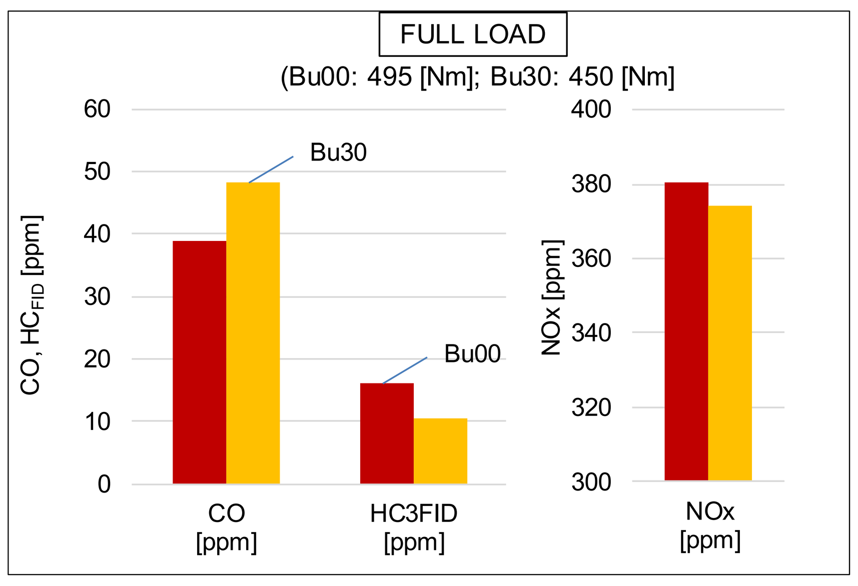
Iveco F1C engine (E2) on the engine dynamometer

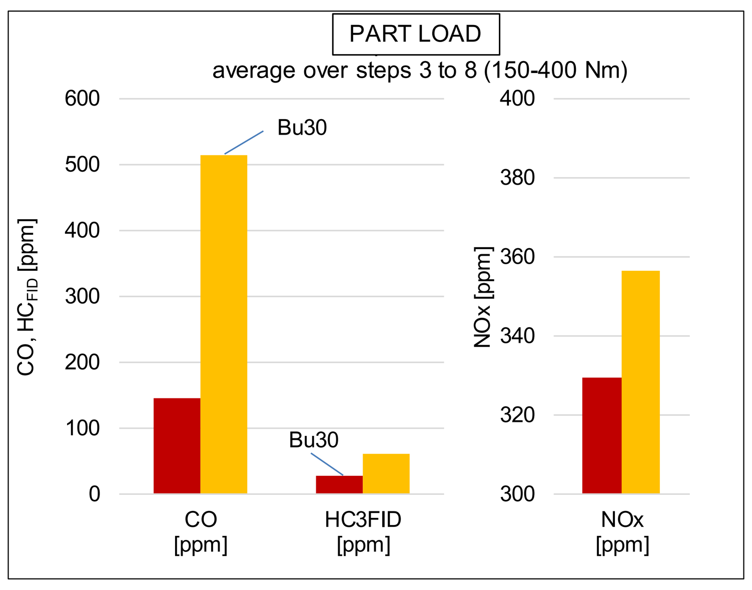
Fuels

	Ref. Diesel	Bu05	Bu15	Bu30	Bu50
Density at 15°C in kg/m³	833-837	833	832	828	822
Net calorific value in MJ/l	35.3	34.9	34.0	32.8	31.4
Stoichiometric air/fuel ratio	14.6	14.4	14.0	13.5	12.9
Oxygen content in wt.-%	<0.03	1.1	3.1	6.4	10.7
H:C ratio (molar)	0.157	0.160	0.165	0.170	0.179
Cetane number	52-54	≈ 51	≈ 48	≈ 43	≈ 35

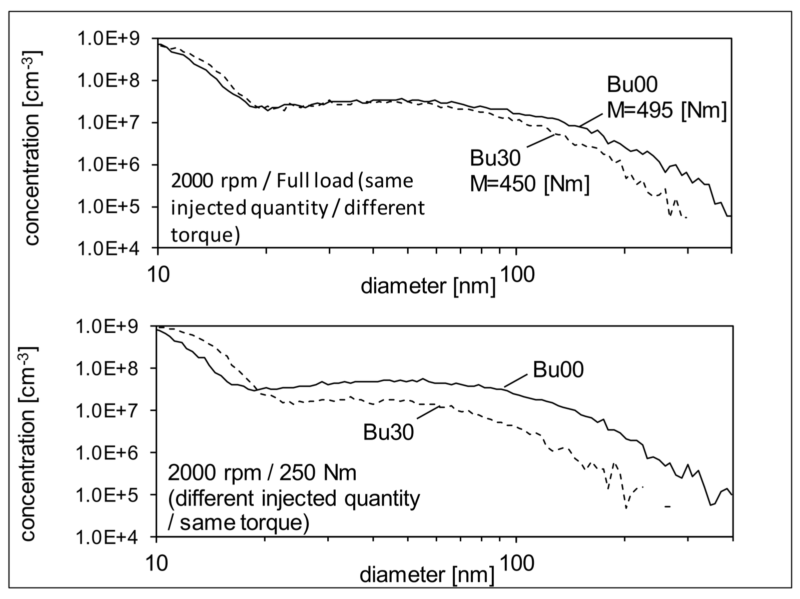
Data of Diesel fuel, Butanol and their blends

Emissions Engine E1



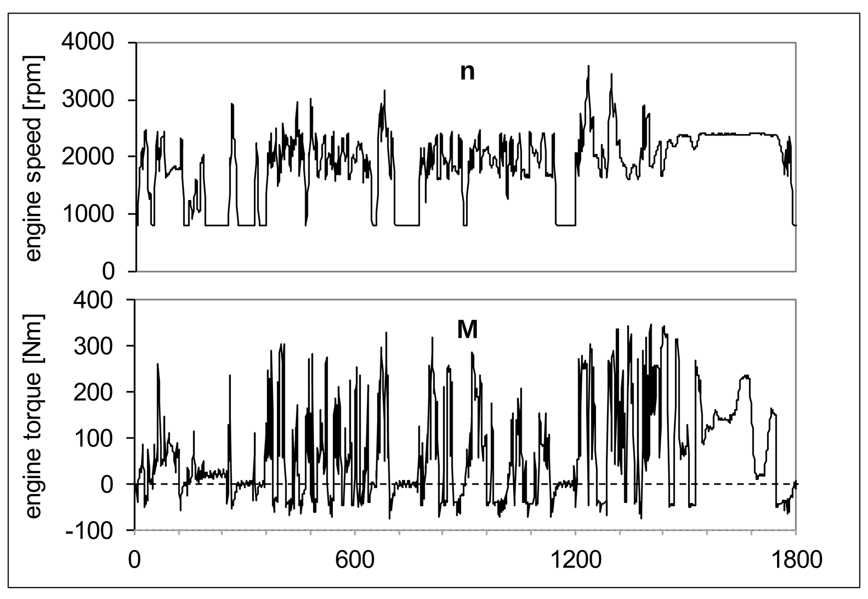


Comparison of Emissions Bu00 & Bu30 at full load and at part load (w DPF DiSiC), E1

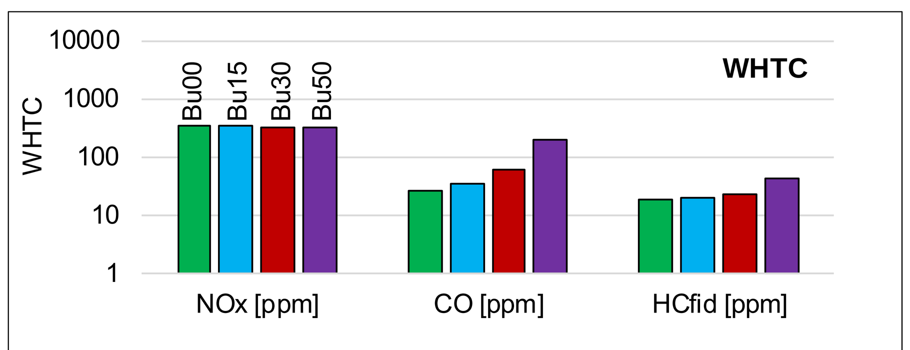


SMPS – size spectra, without DPF, E1

Emissions Engine E2



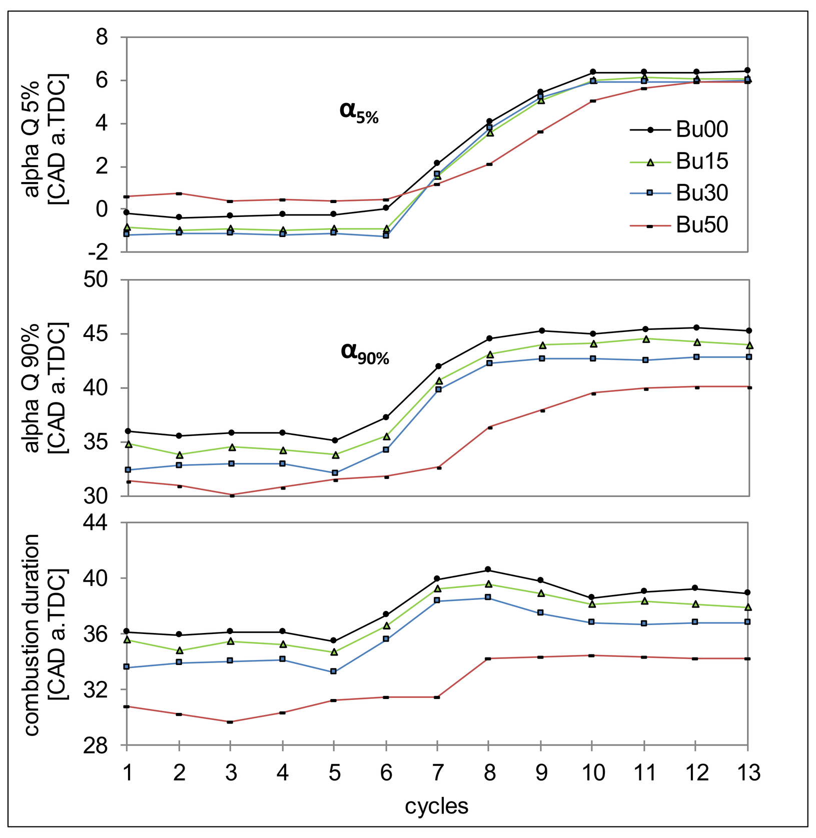
Torque & engine speed (E2) in WHTC



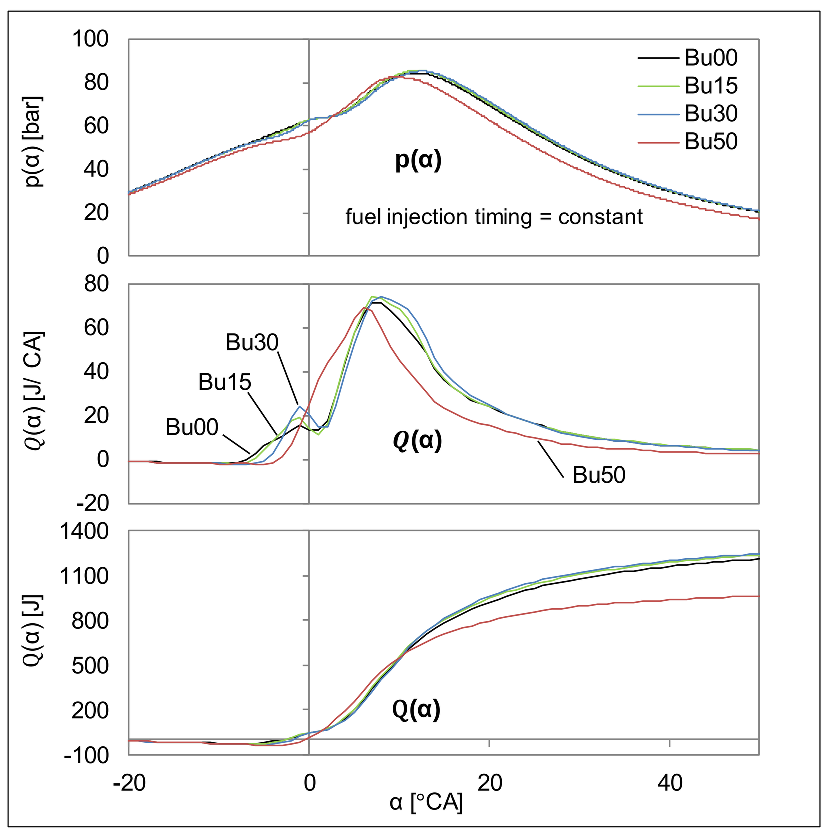
WHTC				
Bu xx	0	15	30	50
NOx [ppm]	339	343	333	330
CO [ppm]	27	36	63	200
HCfid [ppm]	18	20	23	44

Emissions with different Butanol rate in transient operation WHTC, engine (E2)

Combustion Engine E2



Indication statistics of load jump 40-90% at 1500 rpm w/o ATS, w/o EGR, engine (E2)



Indicated pressure and heat release before load jump (cycle nbr.2) w/o ATS, w/o EGR, engine (E2))

Conclusions

For engine (E1), production of the year 2005:

- The operation of this engine with Bu30 is instable at lower part load due to the lower Cetane Number of the blend fuel. Bu30 is considered as a limit of the blending ratio for this engine.
- The PM-emissions with Bu30 are lower, so the soot loading of DPF takes a longer time.
- The regeneration step test (according to SN277206) shows for both fuels similar results: the balance point is attained in the 6th step (at 60% engine load) with the balance point temperature 371-374°C.
- The emissions of CO and HC with Bu 30 at engine part load are higher and the emissions of PN at full load with Bu30 are lower than with Bu0.
- The lower overall heat value of Bu30-blend leads to a respectively lower full load torque without corrections of the injected fuel quantity.

For engine (E2), production of the year 2017:

- With higher Butanol content, there is a lower heat value of the fuel and there is lower torque at FL.
- The repeatability of results at constant operating points (FL), and in dynamic operation (WHTC) is very good.
- At transient operation (WHTC), CO and HC increase with higher BuXX and NO_x stays constant.
- At steady state operation (constant OP’s), CO decreases with higher BuXX, HC and NO_x slightly increase.
- The dynamic answer of the engine – performance of the load increase during 4 working cycles – is equal for all three fuels: Bu0/15/30.
- The electronic control system of the engine, (FMO), compensates very well the varying properties of the fuels Bu0/15/30, so that in the combustion diagnostics no differences of heat release can be noticed.
- With Bu50, the engine electronic control cannot entirely compensate the deviating fuel parameters, the dynamic answer of the engine is slower and weaker.
- There are influences of Bu-rate on the inflammation phase and on the combustion duration; there are partly controversial effects of lower self-ignition aptitude (lower CN) and of quicker mixing and higher portion of premixed combustion.
- At stationary part load operating condition with higher Bu-content the start of heat release is slightly retarded (0.5-2 deg CA due to lower CN), but due to the higher portion of premixed fuel, the premixed phase of combustion is much quicker which may overcompensate the later start for BuXX < 30%.
- The operation with Bu50 was only possible for research purposes thanks to the external strong starting system (dynamic brake). A field application of this high Bu-rate is not recommendable.