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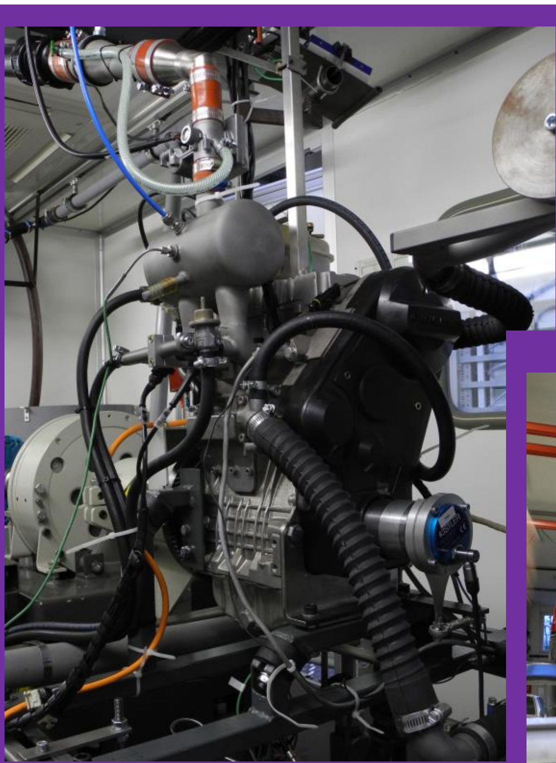
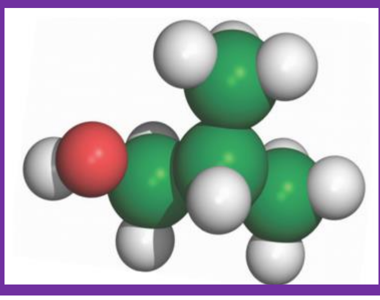
Final report

GasBut

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





B493

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

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

Author:
J. Czerwinski, AFHB, jan.czerwinski@bfh.ch
P. Comte, AFHB, pierre.comte@bfh.ch
M. Güdel, AFHB, martin.guedel@bfh.ch

SFOE head of domain: C. Alles, carina.alles@bfe.admin.ch
SFOE programme manager: S. Renz, renz.btr@swissonline.ch
SFOE contract number: SI/501272-01

Swiss Federal Office of Energy SFOE
Mühlestrasse 4, CH-3063 Ittigen; postal address: CH-3003 Bern
Phone +41 58 462 56 11 · Fax +41 58 463 25 00 · contact@bfe.admin.ch · www.bfe.admin.ch

Zusammenfassung

Die Untersuchungen mit verschiedenen Zumischungsraten von Butanol (BuXX) zum Benzin wurden am Motor- und am Rollenprüfstand durchgeführt.

Beim stationären Betrieb am Motorprüfstand wurde gefunden, dass die Bu-Zumischung generell die Emissionen CO, HC, NO_x im unbehandelten Abgas mindert und sehr geringe Einflüsse auf die Konvertierungsraten des 3-Weg-Katalysators ausübt. Bei tieferer Motorteillast verkürzt "Bu" die Entflammungsphase und mindert die zyklischen Schwankungen der Verbrennung. Dieser Vorteil verschwindet jedoch bei höheren Lasten und höheren Bu-Anteilen.

Beim dynamischen Betrieb am Rollenprüfstand wurde die Einwirkung des veränderten, sauerstoffhaltigen Kraftstoffes auf die Lamda-Regelung speziell beim älteren Fahrzeug sichtbar. Es bestehen Tendenzen zu Erhöhung der nichtlimitierten Komponenten: Ammoniak, Aldehyde und Acetaldehyd mit steigendem Bu-Gehalt. Höhere Zumischungsraten als Bu30 führten zum unbefriedigendem Betrieb des Fahrzeuges, oder verunmöglichten den Kaltstart.

Der vorliegende Bericht zeigt einige Beispiele der wichtigsten Resultate.

Résumé

La recherche avec différentes proportions de Butanol dans l'essence a été exécutée sur le banc moteur et sur le banc à rouleaux.

Pendant l'opération stationaire sur le banc moteur, nous avons découvert que l'addition du « Bu » réduit en général les émissions de CO, HC et NO_x dans les gaz d'échappement non-traités. De plus, les taux de conversion du catalyseur à 3-voies sont très peu influencés. A charge partielle et basse du moteur, le « Bu » racourcit la phase d'inflammation et réduit les fluctuations cycliques de la combustion. Cet avantage disparait avec la charge plus élevée du moteur et avec des proportions de « Bu » supérieures dans le carburant.

Pendant l'opération dynamique sur le banc à rouleaux, l'influence du carburant avec plus de teneur en oxygène a visiblement modifié la régulation Lambda et ce, surtout, sur le plus ancien véhicule.

Avec une teneur en « Bu » supérieure, une tendance plus haute aux émissions non-limitées : ammoniac, aldéhydes et acétaldéhyde est constatée. Quand le taux du « Bu » est plus élevé que celui du B30, cela peut engendrer un mauvais fonctionnement du véhicule et empêcher un démarrage à froid.

Le rapport montre quelques exemples de résultats les plus importants.

Summary

The investigations with different Butanol portions in gasoline (BuXX) were performed on the engine and on chassis dynamometer.

In the steady state operation on engine dynamometer, it was found that Bu-blends generally reduce the emissions of CO, HC, NO_x in untreated exhaust gas and have a very little influence on catalytic conversion rates of the 3-way-catalyst. At lower engine part load, "Bu" shortens the inflammation lag and reduces the cyclic dispersion of combustion. Nevertheless, this advantage disappears at higher engine loads and with higher "Bu" portions.

At the dynamic operation on chassis dynamometer, the effects of the modified, oxygen-containing fuel became visible, this especially for the older vehicle. There are tendencies of increasing the non-legislated components: ammonia, aldehydes and acetaldehyde with growing Bu-content. When the "Bu" rates are higher than the B30, it can cause an unsatisfactory vehicle operation or make the cold start impossible.

The present report shows some examples of the most important results.

Appendix *)

Supplementary information from project partners about GasBut:

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

A2 BioButanol – situation of industry, markets and perspectives

A3 Investigations of Combustions and Emissions of a MPI-SI-Engine with Butanol Blend Fuels – poster Verbrennungstagung BfE/ETHZ, 2015

*) Appendices see at the end of the report

Content

*) Appendices see at the end of the report

List of abbreviations

A/F	air/fuel ratio
AFHB	Abgasprüfstelle FH Biel, CH
ASET	Aerosol Sampling & Evaporation Tube
BAFU	Bundesamt für Umwelt, (see FOEN)
BfE	Bundesamt für Energie (FOE)
BMEP	break mean effective pressure
B/S	bore/stroke
Bu	Butanol
Bu85	Butanol 85% vol
BuXX	Butanol content XX% v
CA	crank angle
CLA	chemiluminescent analyzer
CO	carbon monoxide
CO_2	carbon dioxide
COV	coefficient of variance
CPC	condensation particle counter
CS	cold start
CVS	constant volume sampling
DF	dilution factor
DI	Direct Injection
DMA	differential mobility analyzer
dQ/dα	ROHR, rate of heat release
ECE	Economic Commission for Europe
ECU	electronic control unit
EGR	exhaust gas recirculation
EUDC	Extra Urban Driving Cycle
EV	Erdöl Vereinigung
EXX	Ethanol content XX% v
E85	Ethanol 85% v
FFV	flex fuel vehicle
FL	full load
FID	flame ionization detector
FOE	Federal Office of Energy
FOEN	Federal Office for Environment
FTIR	Fourier Transform Infrared analyzer

GasBut	Gasoline Buthanol project
GDI	gasoline direct injection
HC	unburned hydrocarbons
HCHO	Formaldehyde
H_u	lower heat value
IMAP	intake manifold pressure
IP	inflammation phase α_z until 5% heat release
K_i	[%] of knocking cycles, knock intensity
K_x	conversion (reduction) efficiency of the component “X”
L_{st}	stoichiometric air requirement
LGW	Lombardini Gasoline Watercooling
LHV	lower heat value
M	torque
MD	minidiluter
MeCHO	Acetaldehyde
MFB	mass fraction burned, heat release
MPI	multi point port injection
n	engine speed
N_2	nitrogene
N_2O	nitrous oxide
NEDC	New European Driving Cycle
NH_3	Ammonia
NO	nitrogen monoxide
NO_2	nitrogen dioxide
NO_x	nitric oxides
NP	nanoparticles < 999 nm
nSMPS	nano SMPS
OBD	on-board diagnostics
OP	operating point
PC	particle counts (integrated)
PM	particle mass
p_{max}	maximum cylinder pressure
p_{me}	b.m.e.p (brake mean effective pressure)
p_{mi}	mean indicated pressure
PMP	Particle Measuring Program of the GRPE
PN	particle numbers
PSD	particle size distribution

RON	Research Octane Number
R18	Renault 18
$sdev_{pmi}$	standard deviation of mean indicated pressure
SI	Spark Ignition
SMPS	scanning mobility particle sizer
SSC	steady state cycle
TC	thermoconditioner
Texh	Exhaust gas temperature at tailpipe
t_{Exh}	temperature measured near λ-Sonde
TDC	top dead center
THC	total hydrocarbons
throttle	throttle opening rate
TPN	total particle number
TWC	three way catalyst
V	vehicle
V60	Volvo V60
WLTC	Worldwide Light Duty Test Cycle
WLTP	worldwide harmonized light duty test procedure
WOT	wide open throttle
$\alpha_{50\%}$	crank angle of 50 % heat release
α_{fkp}	α first knocking peak (on the pi-signal)
α_{pmax}	crank angle of p_{max}
α_z	spark angle
Δ_{pmax}	max. rate of pressure raise
σ_{pmi}	standard deviation of mean indicated pressure
α_{zopt}	optimum spark timing [deg. CA b. TDC] for the best torque
λ	air excess factor (m_{air} / m_{air} stoichiometric)
3WC	three way catalyst

1. Introduction & objectives of GasBut

Using Bioalcohols as renewable energy source to substitute a part of fossil energy 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 GasBut focused on the application of butanol-blends in SI-engines only. The project consisted of two parts.

Part 1: investigations of combustion on engine dynamometer, with the objectives:

- full load (FL) characteristics.
- variations of spark timing (αz).
- research of lean operation limit at part load (λ-variations).
- research of EGR limit at part load (EGR-variations).
- influences on light-off and on catalytic conversion rates of 3-way-catalyst (3WC).
- research of knock limit at FL.

With this research, it was possible to investigate the influences of fuel quality on engine internal processes as well as on the standard exhaust aftertreatment (3WC).
The research was performed with Bu0, Bu30, Bu60 and Bu100.

Part 2: investigations of emissions in legal driving cycle on chassis dynamometer.

This research was performed on two cars:
an older one, with MPI & λ=1 concept and a newer one (Euro 5), with GDI, λ=1 concept and flex fuel aptitude.

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

Special attempts of cold starts were conducted and compared with the equivalent results with Bu0 & Exx. The tests were performed with Bu0, B15 and Bu30.

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

2. Research on engine dynamometer

2.1 Test engine, fuels and lubricant

2.1.1 Test engine

Fig. 1 shows the engine on the engine dynamometer and Tab. 1 summarizes the most important engine data.

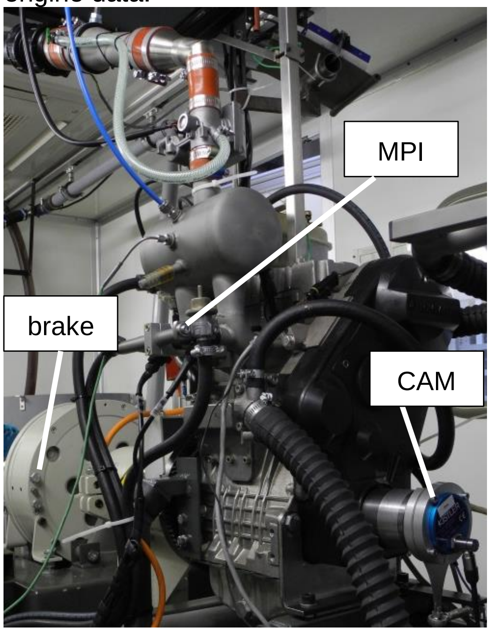

Fig. 1: Test engine on the engine dynamometer

Engine specification		
Manufacturer		Lombardini
Type		LGW 523
Cylinder		2 in-line
Displacement	[dm^3]	0.505
Compression ratio		8.7 : 1
Rated speed	[rpm]	5000
Rated power	[kW]@ 5000 rpm	15
Combustion process		multipoint fuel injection
Catalyst		no at this stage

Table 1: Engine specification Lombardini LGW523

The research was conducted on a Lombardini 2-cylinder SI-engine 0.5L. This engine is equipped with a programmable control unit, which allows a flexible parametrisation of spark timing and equivalence ratio. There is a combustion chamber pressure indication with data acquisition and processing, which allows an accurate combustion diagnostics. The test bench with eddy-current dynamometer is equipped with analysis of limited exhaust gas components.

2.1.2 Fuels

Following base fuels were used for the research:

- gasoline (RON 95) from the Swiss market
- n-Butanol or i-Butanol from Thommen-Furler AG.

As blend fuels were used: Bu30, Bu60 and Bu100 (30% vol, 60% vol Butanol and respectively neat Butanol 100% vol).

Tab. 2 represents the most important data of the fuels (according to the literature sources).

specification		RON 95	n-Butanol	Bu30	Bu60	i-Butanol
Other name		Gasoline, Bu0	1-Butanol			2-Butanol
Formula		-	$C_4H_{10}O$			$C_4H_{10}O$
Density	[kg/dm³]	0.737	0.806	0.759	0.781	0.803
Stoichiometric AF-ratio	[kg air]	14.70	11.10	13.55	12.46	11.10
Lower heating value	[MJ/kg]	42.70	33.12	39.60	36.60	32.92
O_2 fraction	[$\%_m$]	1.70	21.62	8.08	14.10	21.62
Boiling range	[°C]	38-175	118			99
Blending RON		95	99			105
Blending MON		87	84			91
Self-ignition temperature	[°C]	300	343			
Flash point	[°C]	<-40	34			30
Viscosity @ 40°C	[mPa*s]	0.83	2.90			3.00

Table 2: Fuel properties of the test fuels

It can be remarked that with increasing share of Butanol the Oxygen content of blend fuel increases and the heat value and stoichiometric air requirement decrease.

2.1.3 Lubricant

For all tests a special lubeoil MOTUL 300V Le Mans 20W-60 was used.

Table 3 shows the available data of this lubricant.

Property		MOTUL 300V
Viscosity grade		SAE 20W-60
Density	@ 20°C [kg/dm³]	0.867
Viscosity	@ 40°C [mm²/s]	168.3
Viscosity	@ 100°C [mm²/s]	23.8
HTHS viscosity	@ 150°C [mPa*s]	6.3
Pour point	[°C]	-39
Flash point	[°C]	238

[source: data of manufacturer]

Table 3: Data of the utilized engine lubricant.

2.2 Test methods and instrumentation

2.2.1 Engine dynamometer and standard test equipment

Fig. 2 represents the special systems installed on the engine, or in its periphery for analysis of emissions and for combustion diagnostics.

In the present work, an EGR-system (EGR-line, valve and cooler) was installed on the engine. The EGR-rate is estimated by means of CO_2-measurement in exhaust and intake of the engine.

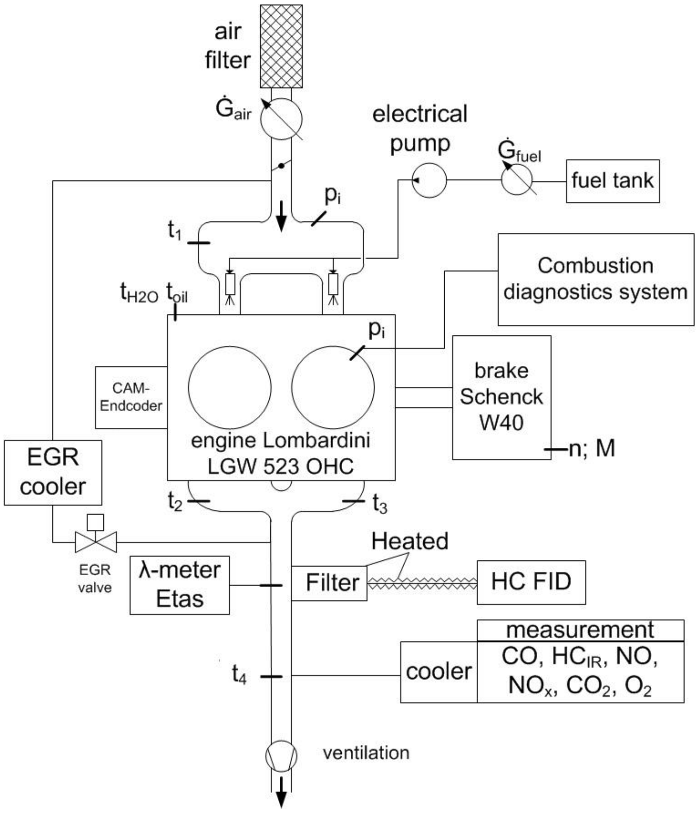

Fig. 2: Measuring set-up on engine dynamometer

Table 4 shows the used laboratory equipment of the engine dynamometer.

Different parameters are registered on-line via PC. The continuous registration of all parameters is possible.

Equipment	Type
Eddy current brake	Schenk W40
Air-flow sensor	Bosch HFM 5
Lambda sonde	ETAS LA3
Data acquisition	Dspace 1103
Temperature measurement	Thermo-couples Type K
Pressure measurement	Saurer pressure measurement 82

Table 4: Laboratory equipment used for tests.

2.2.2 Test equipment for regulated exhaust gas emissions

Table 5 shows the equipment used for measurements of exhaust gas emissions.

Components	Measuring instruments	Measured components
Volatile components	Horiba VIA-510	CO_2, CO, HC_{IR}, NO_x, O_2
	Testa FID 123	HC_{FID} (heated line)

Table 5: Equipment for exhaust gas emissions

2.2.3 Combustion diagnostics – pressure indication

During all tests, cylinder pressure was indicated, so that the combustion characteristics could be valued in each case. Therefore, following devices were used.

Equipment	Type
Spark Plug / Pressure Sensor	Kistler 6117BFD16
Charge Amplifier	Kistler 5011B
Signal Conditioner	Kistler 5219A
Crank Angle Adapter	Kistler 2612C
Combustion Analysis	Datac compact

Table 6: Equipment used for the combustion diagnostics

Fig. 3 gives an example of indicated pressure and of heat release, which are analyzed at all operating conditions of the engine.

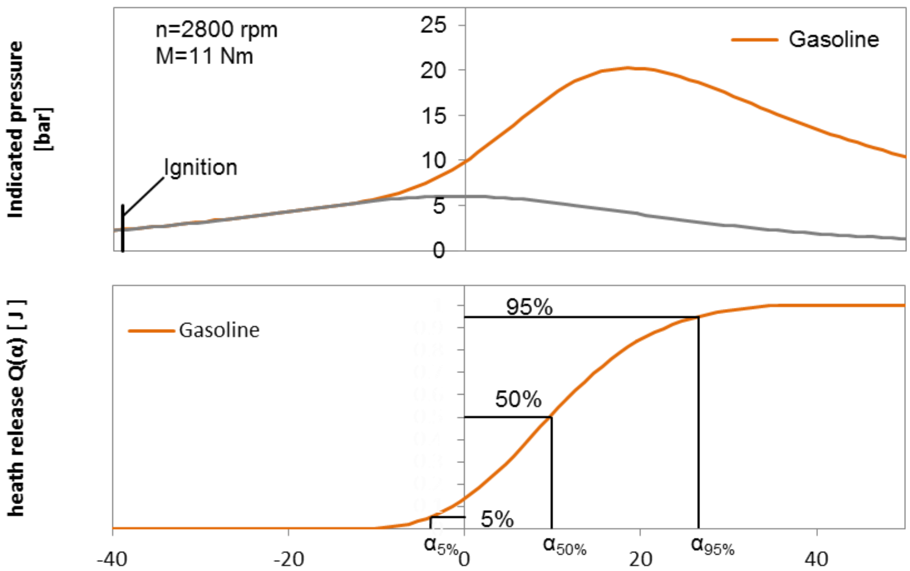

Fig. 3: Indicated pressure and heat release

2.3 Test procedures on engine dynamometer

The stationary testing was performed at different constant operating points (OP's) of the engine. These OP's were chosen at different speeds and at different loads. One part shows the full load characteristics and the other part represents partial load. The operating points in the engine map for entire test program show Fig. 4 and Table 7.

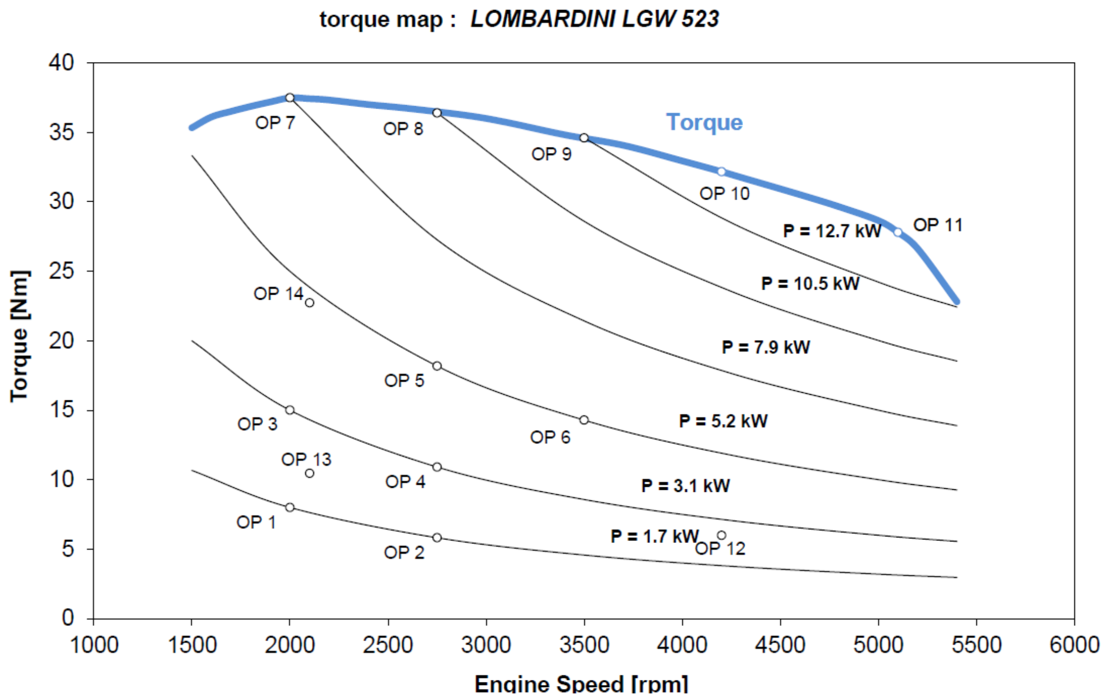

Fig.4: Engine map of the Lombardini LGW523 engine and tested OP's

OP	n [rpm]	M [Nm]	p_{me} [bar]	
1	2000	8	2.0	Part load
2	2800	6	1.4	
3	2000	15	3.7	
4	2800	11	2.7	
5	2800	18	4.5	
6	3500	14	3.6	
12	4200	6	1.4	
13	2100	10	2.6	
14	2100	22	5.0	
7	2000	38	9.3	Full load
8	2800	32	7.1	
9	3500	35	8.6	
10	4200	32	7.1	
11	5100	28	6.0	

Table 7: description of OP's

2.4 Results

2.4.1 Variations of spark timing αz

Variation of spark advance at engine part load can be performed in two ways: at constant OP (n/M), or at constant throttle position. Both variants of tests have been performed with all investigated fuels at different OP's

Fig. 5 shows the gaseous emissions at higher part load and Fig. 6 represents some combustion characteristics at lower and at higher part load. These pictures represent mostly the advantages of Butanol blends. Nevertheless, the complete picture, which results from all tests (4 OP's not represented here) shows some limited or some neutral results.

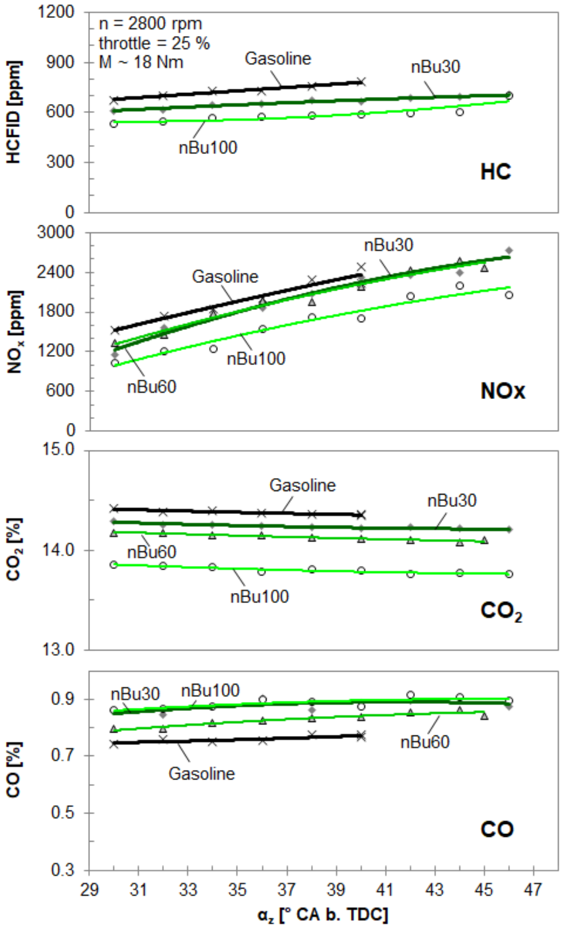

Fig.5: Comparison of emissions with different fuels during spark angle variation @ partial load

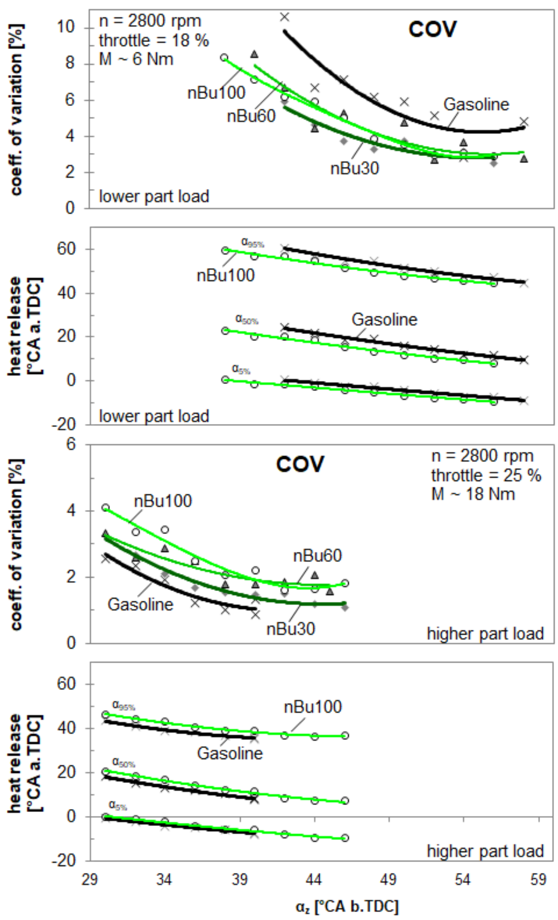

Fig.6: Comparison of coefficient of variation & heat release during spark angle variation @ lower & higher part load

Following tendencies can generally be remarked with increasing share of nButanol in the blend fuel:

- no effect on CO at low load, increased CO at higher load,
- lowering of HCFID,
- no effect on NOx at low load, clear reduction of NO_x at higher load especially with nBu100,
- lowering of CO_2,
- αz for α50%@9°CA a.TDC generally later for BuXX,
- lower cyclic irregularities, quicker combustion and higher pmax at low load, inversely at high load.

For comparisons: nBu100 → iBu100 it can be remarked that iBu100 causes:

- higher HCFID at low load and no clear differences (against nBu100) at higher load,
- generally lower CO- and higher CO_2 values,
- generally lower NO_x values,
- no differences of inflammation phase, combustion duration, COV and pmax.

Generally, the findings at part load could be confirmed: with increased share of Butanol there is lowering of NO_x, HC and CO. The necessary spark timing ($\alpha_{z\ opt}$) is nearer to the TDC, the maximum pressure rise is higher and the cyclic irregularities of combustion are lower. All these are signs of accelerated and improved inflammation phase. These effects of improved combustion are more pronounced at OP1 (lowest engine speed & torque) than at higher OP4 and OP6

2.4.2 Variations of Lambda λ

These variations were also performed with all fuels at different engine operating points. Figures 7 & 8 represent an example from the lowest part load OP.

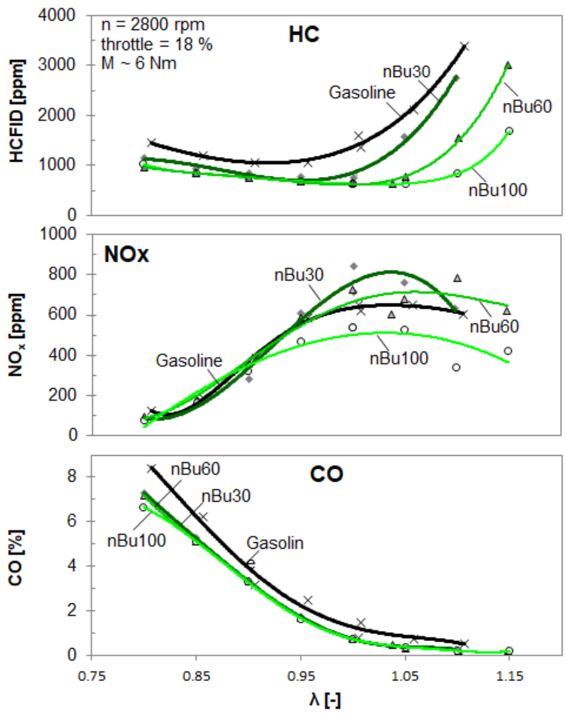

Fig.7: Emissions during Lambda variation @ low partial low

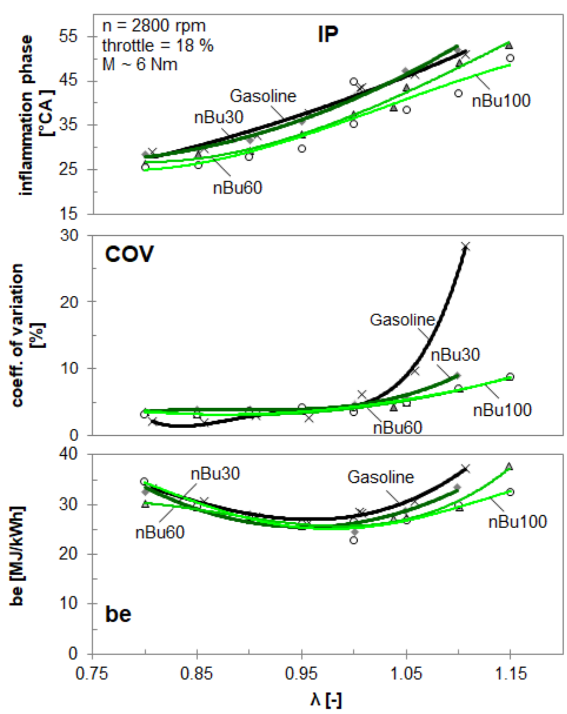

Fig.8: Combustion & specific energy consumption during Lambda variation @ low partial load

Increasing of Lambda was performed up to the lean operation limit, which was attained at strong increasing of cyclic irregularities (high values of COV) and increasing of HC.

The lean limit for this engine was:

at OP2: λ = 1.10 – 1.15

at OP4: λ = 1.15 – 1.20

at OP5: λ = 1.25

The reason for this tendency is the lowering of the internal residual gas content with the increasing engine load.

The diagrams of results in function of λ show the comparisons between the fuels. With increasing of Butanol content following tendencies can be remarked:

- lower HC-values and lower HC-increase at lean limit,
- lower maximum values of NO_x,
- shorter inflammation phase (IP = $\alpha_{5\%}$ - α_z), especially with Bu60 & Bu100,
- lower cyclic dispersion (COV) at lean limit.

Comparisons of fuels at $\lambda \cong 1.10$ and α_{zopt} confirm these statements. With increasing BuXX there are:

- reduction of HC
- shortening of IP (except OP2) and reduction of COV.

There are also tendencies of reducing NO_x and lowering T_{exh} with the higher Butanol content.

Summarizing: the present results of Lambda variations confirm the statements from previous tests.

Butanol blended to gasoline slightly shortens the inflammation phase and lowers the cyclic irregularities of combustion at part load operation of the engine. It moves the lean operation limit to higher λ-values and it has positive influences on lowering NO_x and HC.

2.4.3 Variations of EGR

The variations of EGR at part load were initially performed at OP4 with all fuels (Bu 0/30/60/100).

General tendency was found, that the higher Bu-content enables higher EGR-rate at the same COV (cyclic dispersion). This is a result of improved inflammation with Butanol.

At OP12 there was only a limited possibility of realizing EGR (gasoline up to 1%, Bu 100 up to 6%), but the effects of increasing Bu-content were well visible.

Figures 9 & 10 give examples of emissions and combustion parameters at OP5.

The findings are confirmed: with increasing Butanol share at part load there is an improved inflammation, the IP-duration is shortened and higher EGR-rates can be attained (at COV = idem). The combustion duration is only slightly shortened with higher Bu60 and Bu100. The gaseous emission components CO, HC, NO_x are generally reduced with higher BuXX.

Summarizing: there are positive effects of Butanol on inflammation at part load, which enable application of higher EGR-rates. There are also positive influences of Butanol on emissions and on the specific energy consumption.

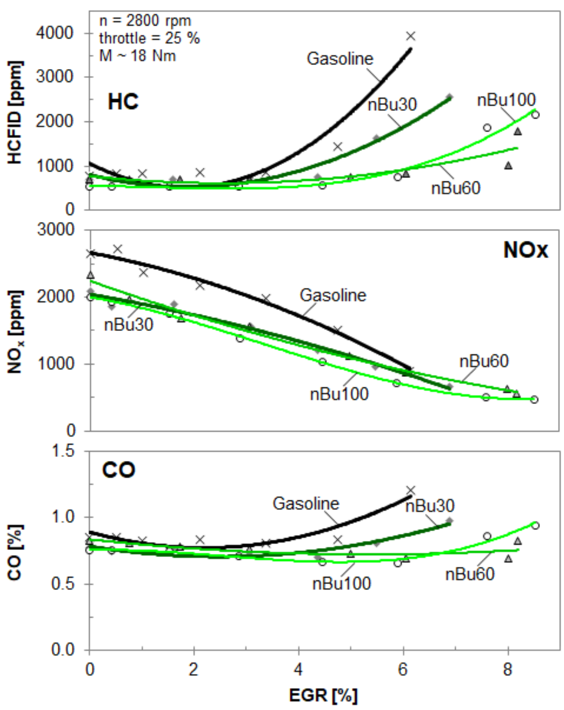

Fig.9: Emissions during EGR Variation @ partial load

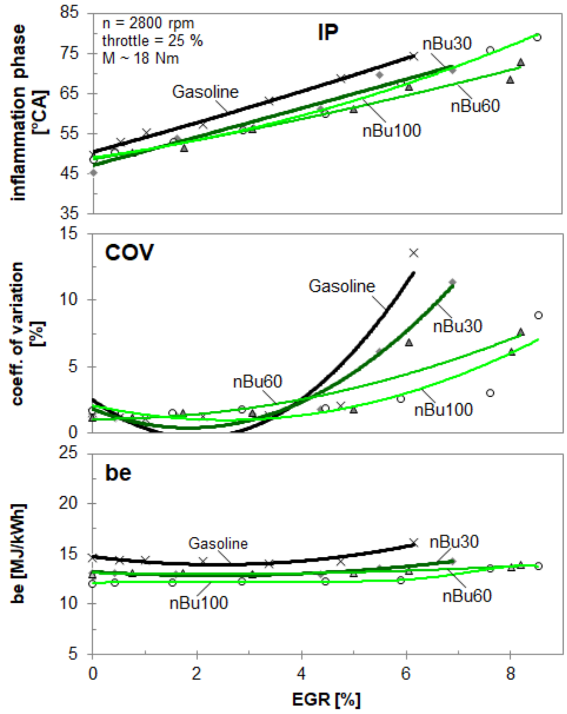

Fig.10: Combustion & specific energy consumption during EGR variation @ partial load

2.4.4 Light-off and conversion efficiencies of the 3WC

For the investigations, a TWC with metal support, EMITEC 400 cpsi, Pd/Rh = 14:1 was used.

The catalyst was fixed in the exhaust system of the engine by means of quick-assembling flanges.

To eliminate the dispersion of results originating from different cold starts the engine was warmed up without catalyst, then the cold catalyst (ambient temperature) was mounted and a new engine start was performed. The engine stop time was always 6 min and so the procedure of engine warm start, but with a cold catalyst was strictly repetitive.

In order to express the conversion rates of emission components over time, the same test was performed without catalyst mounted.

An exemplary comparison of diagrams with catalyst and without catalyst (both not represented here) allows the remarks about the principal effects of the mounted TWC: with catalyst, after approximately 3 min from the engine start, the light-off is visible as a sudden reduction of CO, HC & NO_x. After around 6 min the T_{after} TWC increases over the level of T_{before} TWC as a result of the catalytic activity and exothermic heating.

Without catalyst, all those effects are not present.

Fig. 11 shows the plots of conversion rates K_x over time. It is not possible to find a clear and unified trend, but there is a tendency of shorter light-off time for HC and longer light-off time for CO with higher BuXX. For K_{NOX} there is no clear tendency concerning light-off time, but the fact, that for Bu60 and Bu100 only lower K_{NOX}-values are reached, confirms the interference with λ-regulation at this OP.

At OP4 (2800 rpm/11Nm) the frequency and amplitude of Lambda tension was varied by means of the ECU.

Fig. 12 summarizes the average conversion efficiencies with the six most probable variants of λ-tension signal.

It can be remarked, that with increasing Bu-content in fuel there is a slight increase of conversion efficiencies for CO and for HC, but no influence on K_{NOX}.

The use of isoButanol makes, in this respect, no differences comparing with nButanol.

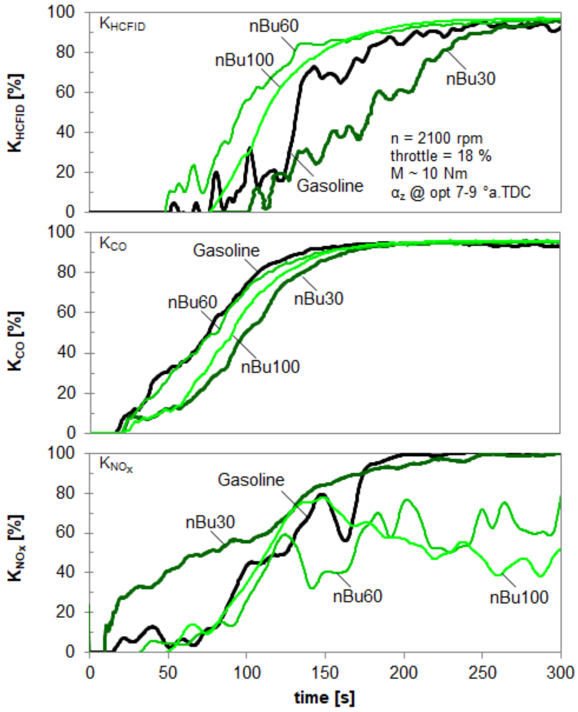

Fig.11: Light-off of a cold TWC with different BuXX

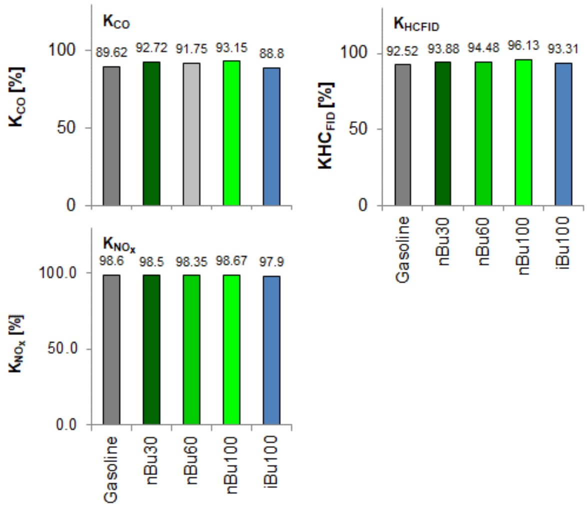

Fig.12: Average conversion efficiencies with different blend fuels

2.4.5 Knocking

The objective of this part of tests was to confirm the potentials of iButanol (with higher RON) concerning knocking. It was necessary to approach slightly the knock limit and indicate the knocking with a very low intensity to avoid damaging the engine. The chosen OP was WOT at 2100 rpm with variation of spark timing and the compared fuels were: gasoline and iBu100.

Fig. 13 represents cyclic dispersion of indicated pressure traces and samples of cycles without and with weak knocking.

To recognize weak knocking (weak oscillations, or irregularities on the indicated pressure signal) methods with differentiation of pressure (dp/dα) or with ROHR (dQ/dα) are applied. The second one, according to [2], was applied in the present tests.

Fig. 14 confirms the advantages of iBu concerning knocking: advancing spark timing (α_z) the very weak knocking starts to be recognized with iBu at α_z, which is more than 10°CA b.TDC earlier than with gasoline. Until the end of α_z-variation range (70°CA b.TDC) the knocking with iBu stays very weak (K_i = 0.4%), while with gasoline the knock probability increases (up to K_i = 3.6%). In other words: the use of iBu moves the knock limit at FL to the higher values of spark advance. This can offer clear advantages of power and of fuel consumption in modern engines with higher compression ratio and with electronic knock control system.

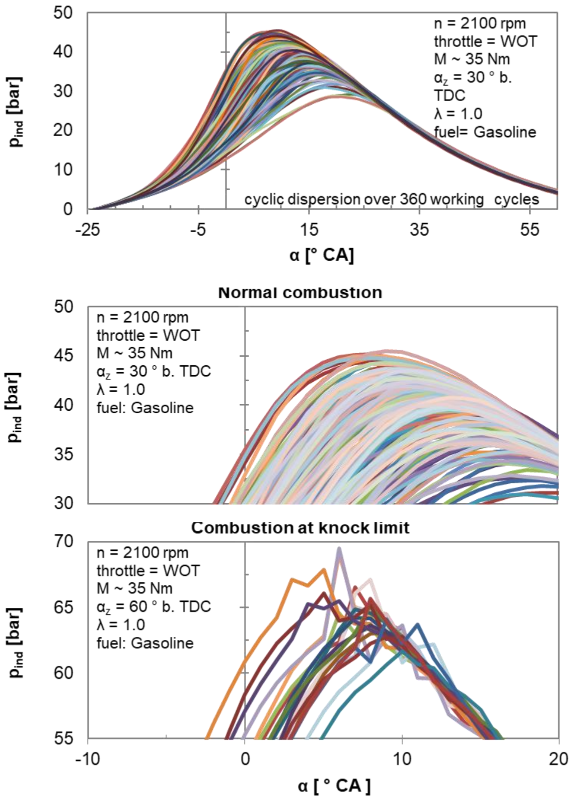

Fig.13: Examples of knocking cycles

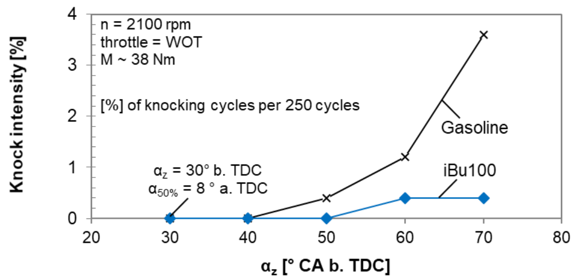

Fig.14: Comparison of knock behavior with different fuels

3. Research on chassis dynamometer

3.1 Test vehicles, fuels and lubricants

The tests on gasoline vehicles were performed: with a Renault 18 Break (SI, MPI, 3WC), which represents an older technology in this project and with a flex fuel vehicle (FFV) Volvo V60 (GDI, Euro 5), which represents a newer technology. These vehicles were operated with gasoline, in original condition (3WC) and with two Butanol blend fuels Bu15 and Bu30

The vehicles are presented in Fig. 15 and Tab. 8.

Fig. 15: Gasoline vehicles for research of emissions

Vehicle	Renault 18 Break	Volvo V60 T4F
Engine code	J7T-718	B4164T2
Number and arrangement of cylinders	4 / in line	4 / in line
Displacement cm^3	2164	1596
Power kW	74 @ 5000 rpm	132 @ 5700 rpm
Torque Nm	162 @ 2000 rpm	240 @ 1600 rpm
Injection type	MPI	DI
Curb weight kg	1110	1554
Gross vehicle weight kg	1585	2110
Drive wheel	Front-wheel drive	Front-wheel drive
Gearbox	m5	a6
First registration	01.04.1985	27.01.2012
Exhaust	EURO 0	EURO 5a
VIN	VF1135B00F0000505	YV1FW075BC1043598

Table 8: Data of tested vehicles

Fuels

The gasoline used was from the Swiss market, RON 95, according to SN EN228; n-Butanol was purchased from Thommen-Furler AG.

As blend fuels were used: Bu15 and Bu30 (15% vol and 30% vol Butanol).

Table 9 represents the most important data of the fuels (according to the literature sources).

specification		RON 95	n-Butanol	Bu15	Bu30
Other name		Gasoline, Bu0	1-Butanol		
Formula		-	$C_4H_{10}O$		
Density	[kg/dm³]	0.737	0.810	0.748	0.759
Stoichiometric AF-ratio	[kg air]	14.70	11.10	14.12	13.55
Lower heating value	[MJ/kg]	42.7	33.0	41.1	39.6
O_2 fraction	[$\%_m$]	1.70	21.62	3.50	8.08
Boiling range	[°C]	38-175	115-119		
Blending RON		95	99		
Blending MON		87	84		
Self-ignition temperature	[°C]	300	343		
Flash point	[°C]	<-40	34		
Viscosity @ 40°C	[mPa*s]	0.83	2.9		

Table 9: Fuel properties of the test fuels

It can be remarked that with increasing share of Butanol the Oxygen content of blend fuel increases and the heat value and stoichiometric air requirement decrease.

Lubricants

In the present tests the lube oil was not changed and analyzed – the same oil was used for all tests.

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 3025 (3 - 64 nm).

For the dilution and sample preparation an ASET system from Matter Aerosol was used, Fig. 16 (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

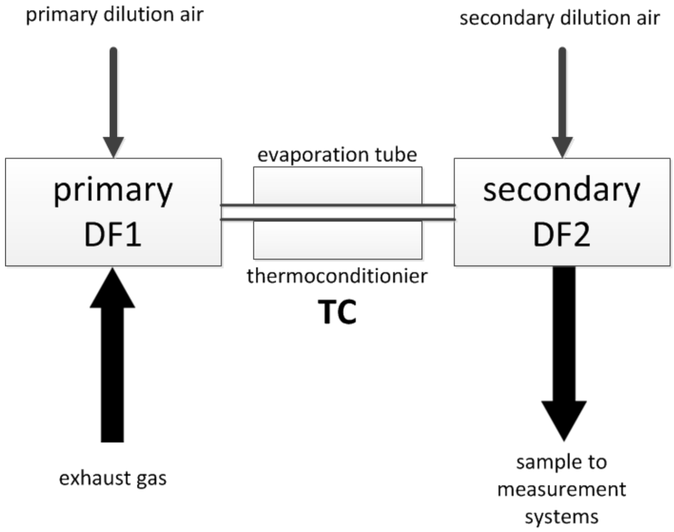

Fig. 16: Set-up of dilution stages and sample preparation for nanoparticle measurements

The measuring set-up on chassis dynamometer and the sampling positions for particle analytics are represented in Fig. 17.

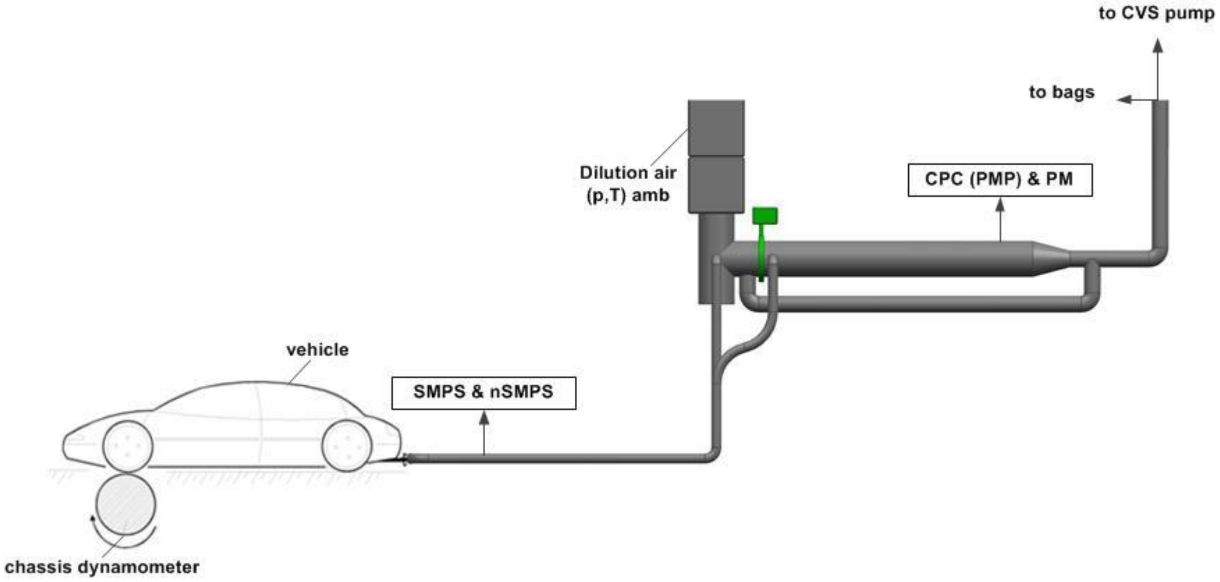

Fig. 17: Sampling of exhaust gas for analysis of particles.

3.3 Test procedures on chassis dynamometer

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. 18. It represents different driving situation, like city, over-land and speed-way.

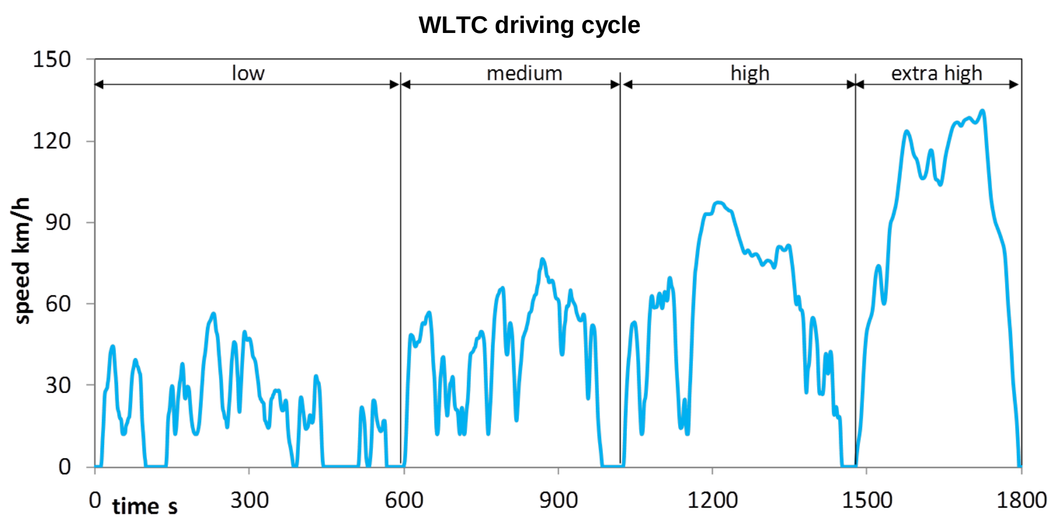

Fig. 18: WLTC driving cycle

3.4 Results

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

Regarding the comparison of emissions time-plots in WLTC (not represented here), it can be generally remarked for all three fuels (Bu0, Bu15 and Bu30):

- with the older vehicle (R18) there are considerably higher emissions of CO and HC at cold start and there are higher and more frequent peaks of all components (CO, HC and NO_x) during the driving cycle,
- all non-legislated emissions: NH_3, HCHO, MeCHO and N_2O are for R18 significantly higher.

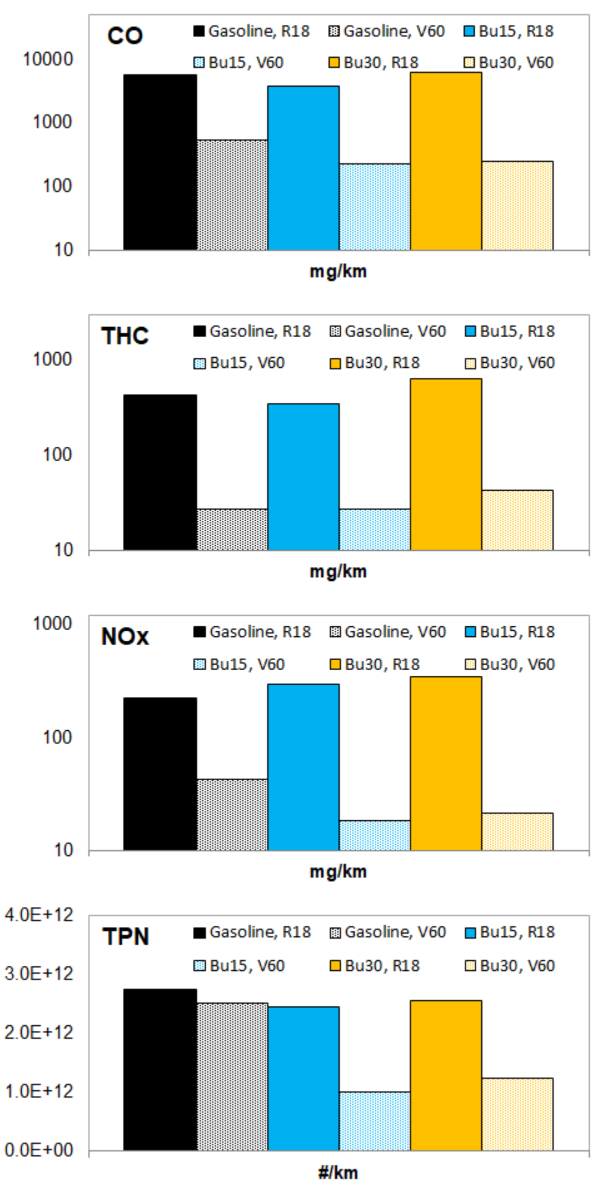

Fig.19: Comparisons of emissions R18 vs V60 in WLTC cold with Bu0, Bu15 & Bu30

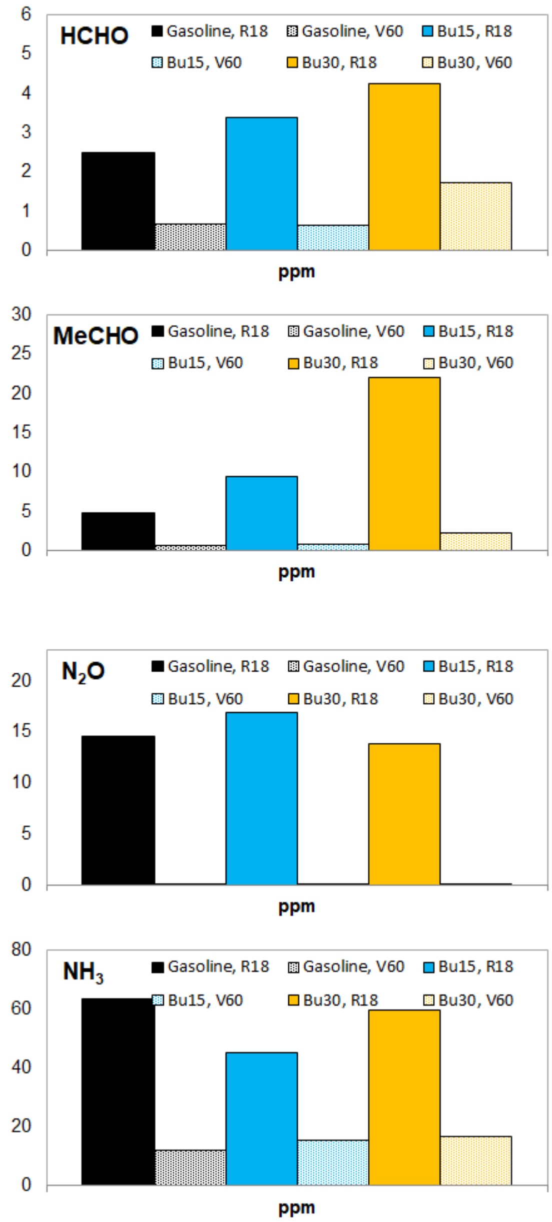

Fig.20: Comparisons of non-legislated emissions in WLTC cold

Considering the integral average emissions in WLTC (whole cycle), Figures 19 and 20, these statements can be confirmed:

- higher CO- and HC-values with R18,
- with Bu15 CO is reduced more for V60, than for R18,
- with Bu30 CO for V60 stays at the level of Bu15, while for R18 it increased again to the original level of Bu0,
- HC for both vehicles is unchanged, or slightly reduced with Bu15, but it generally increases with Bu30,

- NO_x is strongly increased by both BuXX fuels for the older vehicle (R18) and it is reduced for the newer vehicle (V60) – this is a sensitive indication of better functioning of the Lambda regulation of V60, with less "lean-excursions",
- the nanoparticle emission of V60 is significantly reduced with both BuXX-fuels; the PN emission of R18 is not influenced by the fuel,
- all non-legislated emissions: NH_3, HCHO, MeCHO and N_2O are for R18 significantly higher,
- there is a tendency of increasing HCHO and MeCHO with increasing BuXX for both vehicles,
- with increasing BuXX there is an increase of NH_3 for V60 and approximately no influence for R18.

One example of time-plots of non-legislated gaseous components, with both vehicles and with gasoline (Bu0), is given in Fig. 21. It clearly demonstrates the advantages of the newer car (V60).

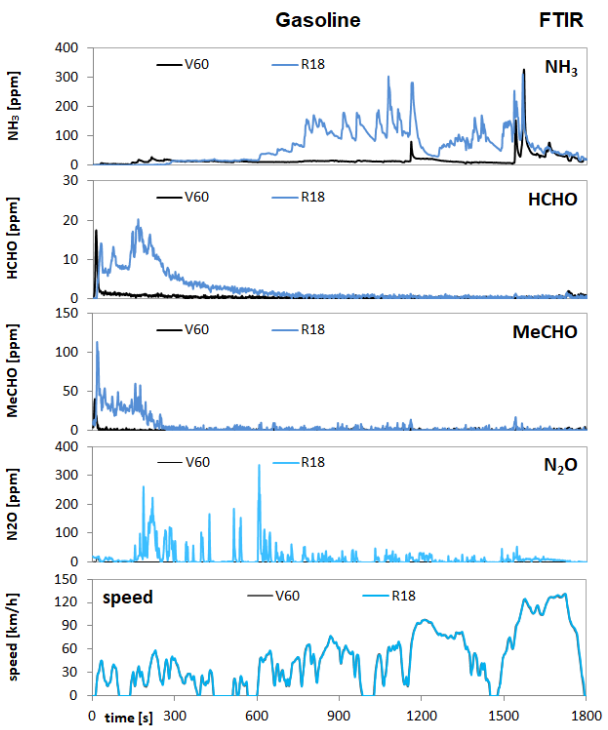

Fig.21: Comparison of NH_3-, HCHO-, MeCHO and N_2O-emissions of two vehicles during the driving cycle WLTC cold.

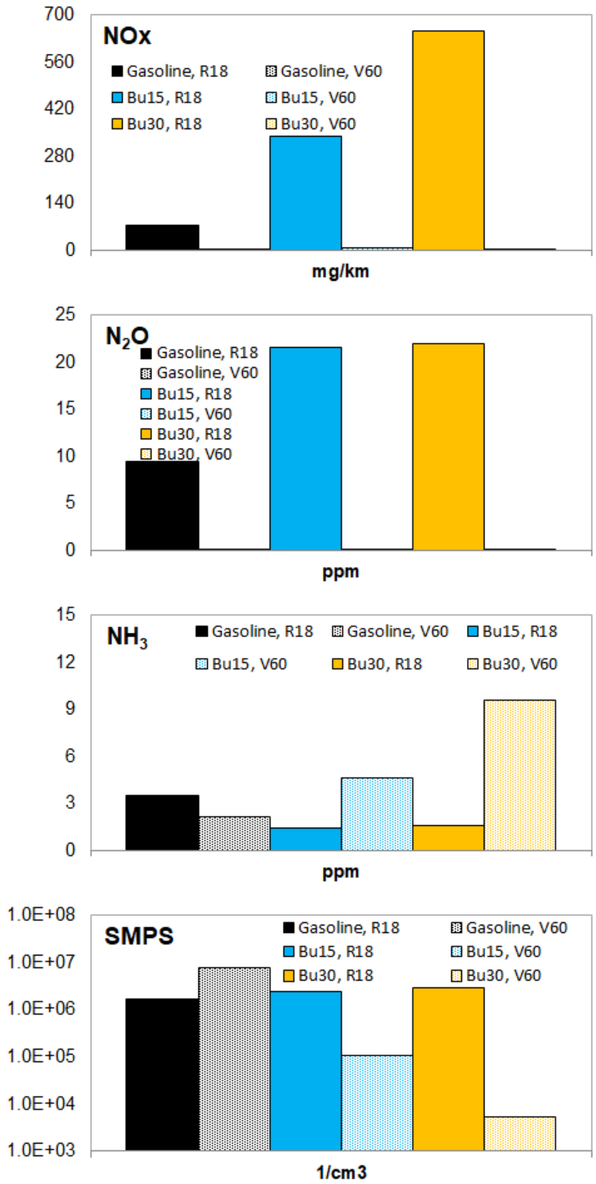

Fig.22: Comparison of exhaust emissions of two vehicles at 95 km/h with different fuels.

Fig. 22 illustrates the relationships of emissions at 95 km/h (in the 1st step of SSC).

A look on the average emission values in SSC allows the general statements:

- in most cases there are higher CO-and HC-values for R18,
- with increasing Bu-content at 95km/h there is a strong increase of NO_x for R18 and no influence on NO_x for V60,
- the nanoparticle emission of V60 is significantly reduced with both BuXX-fuels; the PN emission of R18 is not influenced by the fuel,
- in most cases the higher values of NH_3, N_2O and MeCHO are confirmed for R18.

In the first step (95 km/h) Volvo (V60) has with gasoline higher nanoparticle emissions (CPC), than Renault (R18). With Bu15 and Bu30 this is no more the case, since the NP are for V60 considerable reduced with BuXX.

After switching the operation to idling there is for R18 an increase of NP (CPC), because there are the highest PN-emissions at idling for this vehicle. These NP consist in a large portion of unburned lube oil and it is not surprising that their number increases gradually with the cooling down the exhaust system and the catalyst (not represented here).

The highest NP-emissions at idling of R18, as well as their appearance mainly in the nuclei mode are documented in Fig. 23. The nanoSMPS offers at certain operating points, especially at 45 km/h, valuable supplementary information.

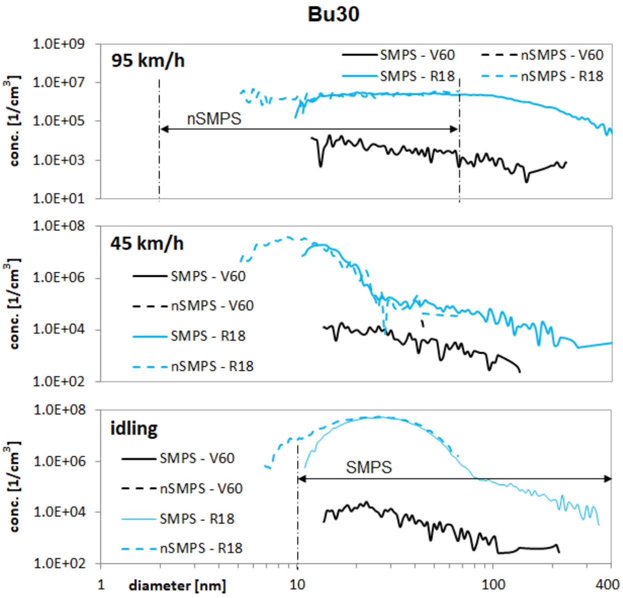

Fig.23: Particle Size Distribution (PSD) during the SSC cycle. Comparison SMPS - nSMPS of two vehicles.

3.4.2 Non-legislated emissions of both vehicles

Figures 24 & 25 represent for both cars some non-legislated components in the first part of the cycle with cold start and warm-up. The sequence of increased emission peaks with higher Bu-content is clearly repetitive. There are considerable peak values with Bu30. For R18: HCHO up to 30 ppm and MeCHO up to 950 ppm and for V60: HCHO up to 60 ppm and MeCHO up to 220 ppm. N_2O emission peaks depend only few from the fuel variant. NH_3-values are generally low after the cold start and they become higher in the hot last part of the cycle.

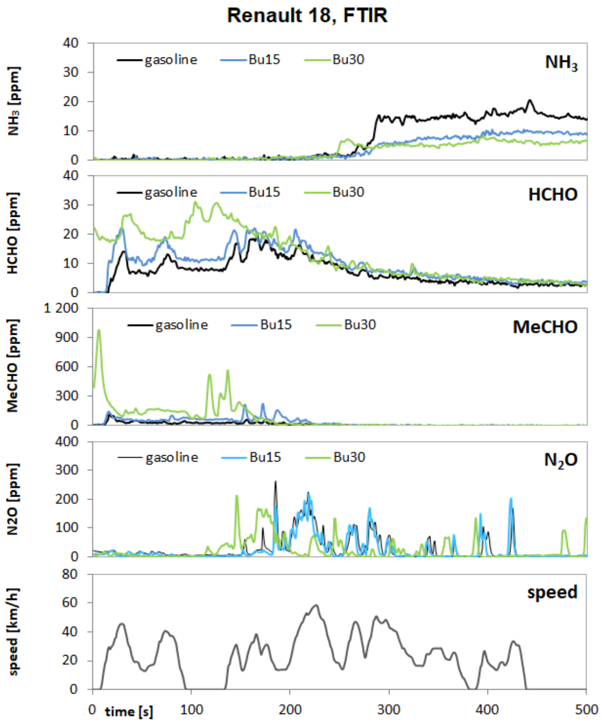

Fig.24: Comparison of NH_3-, HCHO-, MeCHO- & N_2O-emissions in the first part of WLTC cold with different fuels.

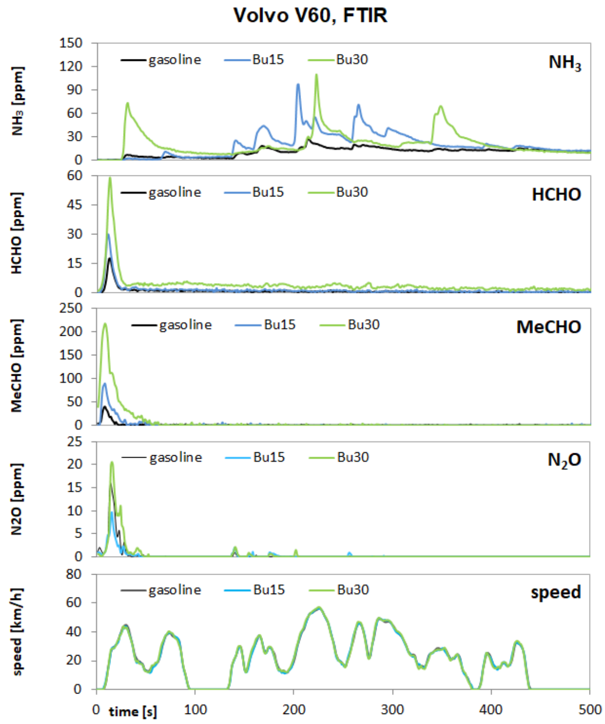

Fig.25: Comparison of NH_3-, HCHO-, MeCHO- & N_2O-emissions in the first part of WLTC cold with different fuels.

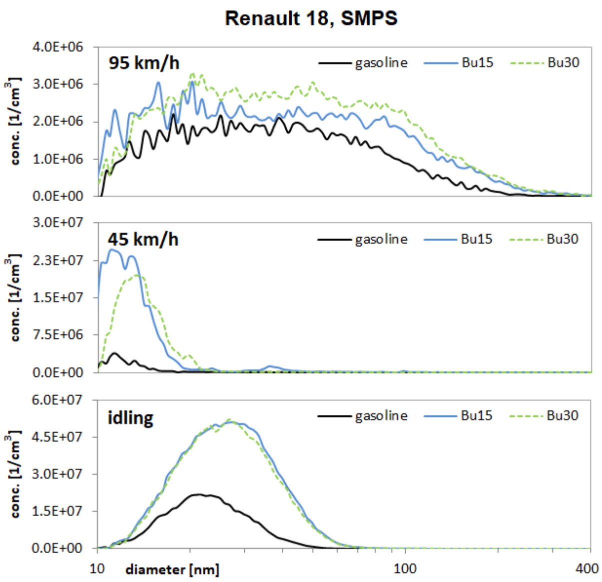

Fig.26 Comparison of the Particle Size Distribution (PSD) during the driving cycle SSC with different fuels.

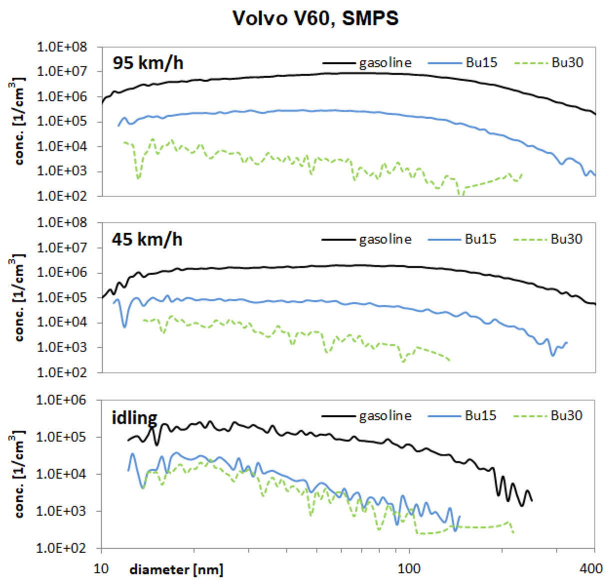

Fig.27: Comparison of the Particle Size Distribution (PSD) during the driving cycle SSC with different fuels.

Figures 26 & 27 offer a consideration of SMPS particle size distributions for both vehicles, with three fuels and in all steps of the SSC.

For R18, the particle size distributions with SMPS (and with nSMPS) show principally higher PN-values with higher Butanol content. At 45 km/h there is a major part of nanoparticles in the smallest sizes, below the measuring range of SMPS. The highest PN-concentration are reached at idling. This vehicle is known to produce excessive NP-emissions in nuclei mode, which originate from the higher lube oil consumption.

For V60, there is an inverse influence of Bu-blends: there is a clear lowering of particle number (PN) with increasing BuXX. At idling, generally the lowest PN counts concentrations are resulting.

From the comparisons in this section, it can be concluded that the different engines' ages and technology (different mixtures' preparations MPI/DI, combustion, lube oil consumption and exhaust aftertreatment) have a significant impact on the emissions and especially on the emissions at cold start.

3.4.3 Cold start

Repetitive cold start tests were performed with Volvo V60 and 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 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 NEDC on the chassis dynamometer.

Fig. 28 shows some non-legislated gaseous components, comparing Bu0 / Bu15 / Bu30 in two temperature domains of the CS: 0°C and 20°C. With higher Bu-content the peaks of Formaldehyde HCHO and of Acetaldehyde MeCHO increase. Starting with a lower temperature, these peak-values are higher and can attain for MeCHO 250 ppm. The Ammonia NH_3 concentrations are at cold start (CS) near to zero and they increase slightly after engine warms up. Nevertheless, there is for NH_3 no correlation with fuel quality.

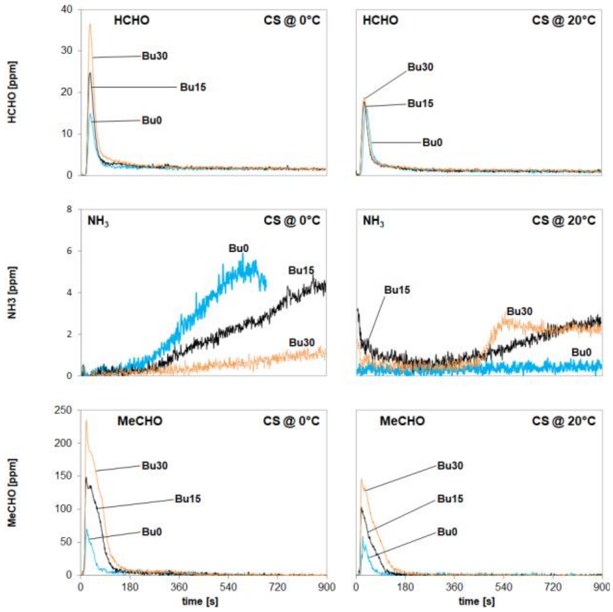

Fig.28: Comparison of the non-legislated gaseous emissions during cold start at idling with different fuels, measured with FTIR at tailpipe.

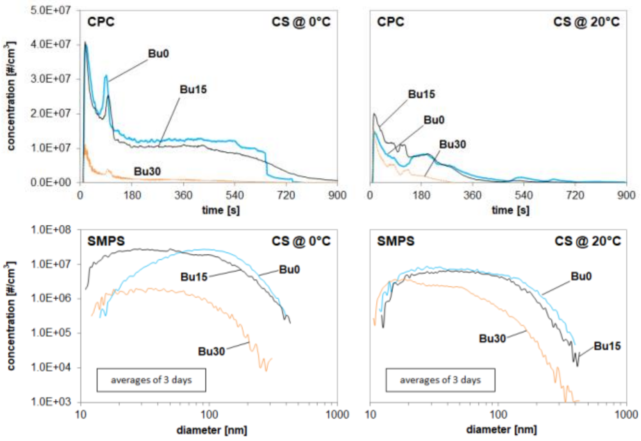

Fig.29: Comparison of the particles counts during cold start at idling with different fuels, measured with both systems at tailpipe.

Fig. 29 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. 4 are averages from three cold starts of the 1st scan (in the period 0-120s).

The CPC-signals at 0°C have a second peak after approximately 2 min. This is visible particularly with gasoline (E0). This peak is a repeatable event, it can also be found in other emission courses (like N_2O) and it is attributed to the changes introduced by the engine ECU in function of temperature, like possibly catalyst heating, switching of internal EGR by vario cams, or heat management.

The most important information of Fig. 29 is that Bu15 emits similar level of particle counts concentration, like Bu0, while B30 reduces clearly the PN emissions.

Bu15 has similar oxygen content like E10. Nevertheless, it was found that Bu15 produces significantly higher peaks of MeCHO and HCHO at cold start than E10, [3].

4. Conclusions

4.1 Findings on engine dynamometer

The most important statements can be summarized as follows:

- The operation with Butanol blended to gasoline is possible without any problem. With neat Butanol (Bu100) nevertheless the cold start is problematic (with engine motoring).
- The lower overall heat value of BuXX-blends leads to a respectively lower full load torque without corrections of fuel dosing.
- The α_z-variations at part load of the engine show lowering of HC, NO_x & σpmi with increasing Butanol rate.
- The improvements of combustion at part load are not observed at full load and with higher Bu-content there is even longer inflammation phase and longer combustion duration.
- IsoButanol causes lower CO-, higher CO_2- and lower NO_x values than nButanol, the development of combustion is affected by isoButanol, in the same way as by nButanol.
- The λ-variations at part load of the engine show lowering of HC, NO_x & COV with increasing Butanol rate.
- Butanol blended to gasoline slightly shortens the inflammation phase and lowers the cyclic irregularities of combustion at part load operation of the engine.
- With higher Bu-content the lean operation limit at part load is moved to higher λ-values.
- Higher Bu-content enables higher EGR-rate at the same COV (cyclic dispersion).
- There are positive influences of Butanol on emissions and on the specific energy consumption.
- Concerning TWC light-off it is not possible to find a clear and unified trend, but there are mostly signs of retarded light-off with the highest Butanol content.
- In the operation with 3WC and λ-regulation there is a little influence on conversion efficiencies (K_x) with increasing Bu-content in fuel.
- Concerning knocking: the use of iBu moves the knock limit at FL to the higher values of spark advance.

4.2 Findings on chassis dynamometer

The elaborated results allow following observations for R18:

- At cold start and warm-up all three investigated fuels produce increased CO-, HC- and NP-values in similar way.
- The emissions of HCHO and MeCHO at cold start increase in the sequence of increasing Butanol content.
- In the “high” and “extra high” parts of WLTC there are the highest NH_3 peaks, which coincide with the strongest acceleration events in the cycle.
- Regarding the average emission values in WLTC cold: with increasing Butanol content (BuXX) there is a clear tendency of increasing the emissions of: NO_x, HCHO, MeCHO and ETOH. The average emissions of N_2O and NH_3 are independent on the BuXX.

- At steady state operation (in SSC) with increasing Butanol content there are:
  - higher NO_x-values at the highest speed (95 km/h).
  - higher PN-values at all operating conditions.
- ➢ With higher Butanol content, the Lambda regulation of this vehicle has difficulty to compensate the higher Oxygen content of the fuel. As a result, there is a leaner operation and lower NO_x-conversion in the TWC.
- ➢ Higher Butanol content interferes more with the lube oil and tendentiously increases the nanoparticles counts.
- ➢ Higher Butanol content also creates favourable conditions to produce more Formaldehyde (HCHO) and Acetaldehyde (MeCHO) at cold start.

With B30 the excessive leaning was remarkable as a less powerful load responses and worse driveability. B30 is regarded as a maximum of Butanol content to be recommended for this vehicle.

For Volvo V60 and for transient operation in WLTC can be remarked:

- With increasing portion of Butanol in fuel (BuXX) there are increasing peak values of HC, HCHO, MeCHO, ETOH and N_2O at cold start.
- During and after the acceleration events in the highest part of the cycle there are emission peaks of some components, but they cannot be attributed to a specific Bu-content (BuXX).
- The comparison of average emission values in WLTC, confirms the lower CO- and lower PN-values with BuXX, while it is difficult to notice the difference between Bu15 and Bu30.
- The average of FTIR-values confirms the higher values of: HCHO, MeCHO and NH_3 with BuXX.
- There is a clear lowering of particle number (PN) with increasing BuXX.

Comparison R18-V60 in WLTC

- Higher CO- and HC-values with R18 and no clear influence of fuel on these emissions.
- HC for both vehicles is unchanged, or slightly reduced with Bu15, but it generally increases with Bu30.
- NO_x is strongly increased by both BuXX fuels for the older vehicle (R18) and it is reduced for the newer vehicle (V60) – this is a sensitive indication of better functioning of the Lambda regulation of V60, with less “lean-excursions”.
- The nanoparticle emission of V60 is significantly reduced with both BuXX-fuels; the PN emission of R18 is not influenced by the fuel.
- All non-legislated emissions: NH_3, HCHO, MeCHO and N_2O are for R18 significantly higher.
- There is a tendency of increasing HCHO and MeCHO with increasing BuXX for both vehicles.
- With increasing BuXX there is an increase of NH_3 for V60 and approximately no influence for R18.

For cold start tests with Volvo V60 can be concluded:

- With increasing Butanol content (Bu0/Bu15/Bu30) the emissions at cold start are influenced in following way:
  - Higher peaks of Acetaldehyde (MeCHO) at start.
  - Higher peaks of Formaldehyde (HCHO) at start.
  - The nanoparticles with Bu15 have similar level as with Bu0 (both CPC and SMPS), with Bu30 they are approximately 1 order of magnitude lower.
- The higher temperature of the cold start generally lowers the emission peaks.

It is important to mention that the original plans of this project part were to test the cold start with Bu85. This was also tried in both temperature domains (0°C & 20°C) but without success. The start and the operation were not possible with this FFV.

Butanol has a higher boiling point, than Ethanol and therefore the quality of mixture preparation (part of evaporated fuel) with Butanol is worse. The investigated vehicle (FFV) is developed for Ethanol and cannot work adequately with higher butanol contents.

5. Literature

[1] Pechout, M.; Czerwinski, J.; Güdel, M.; Vojtisek-Lom, M.: Experimental Investigation of Fuel Injection and Spark Timing for the Combustion of n-Butanol and iso-Butanol and their Blends with Gasoline in a Two-Cylinder SI Engine. SAE Technical Paper 2017-21-0115, doi:10.4271/2017-24-0115

[2] Ohler, S.: Entwicklung und Vergleich von Kriterien zur Erkennung der Klopfenden Verbrennung in Ottomotoren. Dissertation, Fakultät für Maschinenbau, Universität der Bundeswehr, Hamburg, 2014

[3] Czerwinski, J.; Comte, P.; Güdel, M.: Non-Legislated Emissions of a GDI Flex Fuel Passenger Car at Cold Start with Ethanol and Butanol Blend Fuels. TAE Paper. 11th International Colloquium Fuels, 27 to 29 June 2017, Stuttgart / Ostfildern.

Remark: more references are mentioned at the end of annexes 1 & 2.

BFH | AFHB | Gwerdtstrasse 5 | CH-2560 Nidau

Bern University of Applied Sciences
Engineering and Information Technology

Automotive Engineering

Laboratory for IC-Engines and
Exhaust Emission Control (AFHB)
Gwerdtstrasse 5
CH-2560 Nidau
T +41 (0)32 321 66 80
F +41 (0)32 321 66 81
www.afhb.bfh.ch

Annex 1

Butanol Blend Fuels – Application in IC-Engines

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.
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, [5-12].
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.

Information from the literature

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**	**1-Butanol**	**2-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 Octan Number RON [-]	96.3	108.6	99.2	105

Table 1: Data of alcohols compared with gasoline

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.

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, [9]. 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 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, [10], 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.

Another 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, [11, 12].

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BFH | AFHB | Gwerdtstrasse 5 | CH-2560 Nidau

Bern University of Applied Sciences
Engineering and Information Technology

Automotive Engineering

Laboratory for IC-Engines and
Exhaust Emission Control (AFHB)
Gwerdtstrasse 5
CH-2560 Nidau
T +41 (0)32 321 66 80
F +41 (0)32 321 66 81
www.afhb.bfh.ch

Annex 2

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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Bern University of Applied Sciences
Biel-Bienne Switzerland
AFHB | IC-Engines and Exhaust Gas Control

Investigations of Combustion and Emissions of a MPI-SI-Engine with Butanol Blend Fuels

M. Güdel, Y. Zimmerli, J. Czerwinski AFHB, University of Applied Sciences, Biel-Bienne, CH

Abstract

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.

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.

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.

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 NOx (depending on engine parameters setting).
The good miscibility, lower hygroscopicity and lower corrosivity make Butanol to an interesting alternative.

In a research project GasBut (with support of BfE, BAFU & EV) addition of Butanol to gasoline is investigated from the points of view of engine combustion and of non-legislated emissions of cars in transient operation.
In the present poster some examples from the preliminary engine research are given.

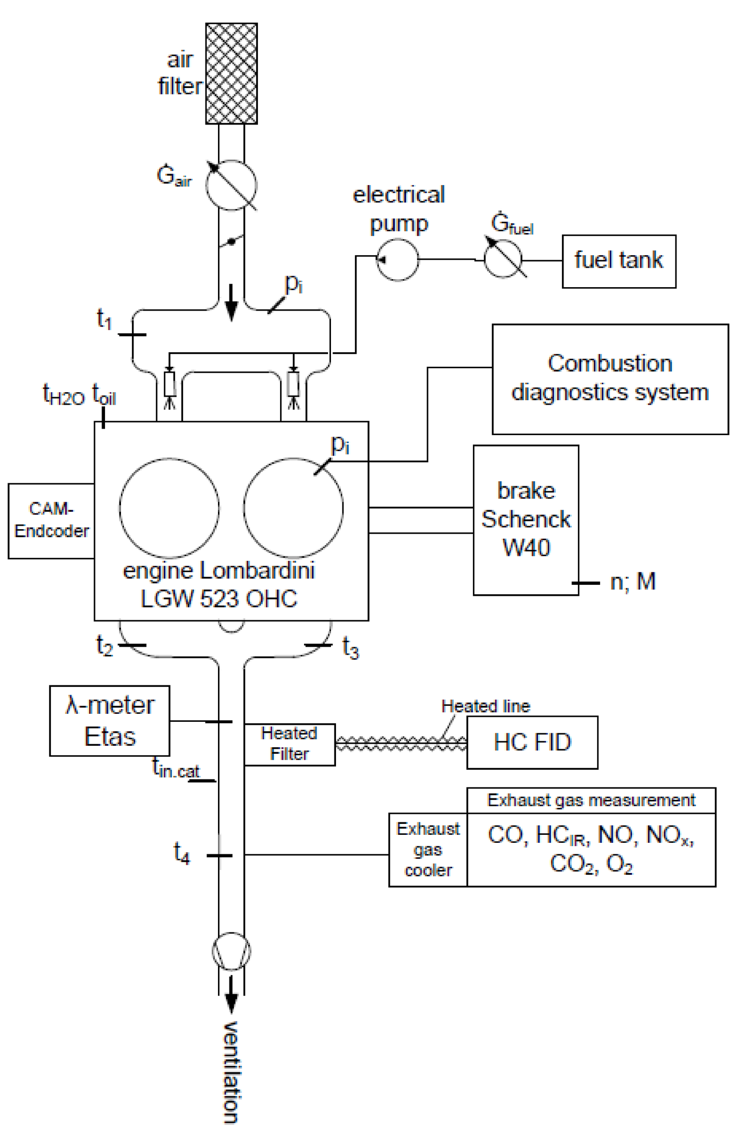

Figure 3: Schematic of the engine dynamometer

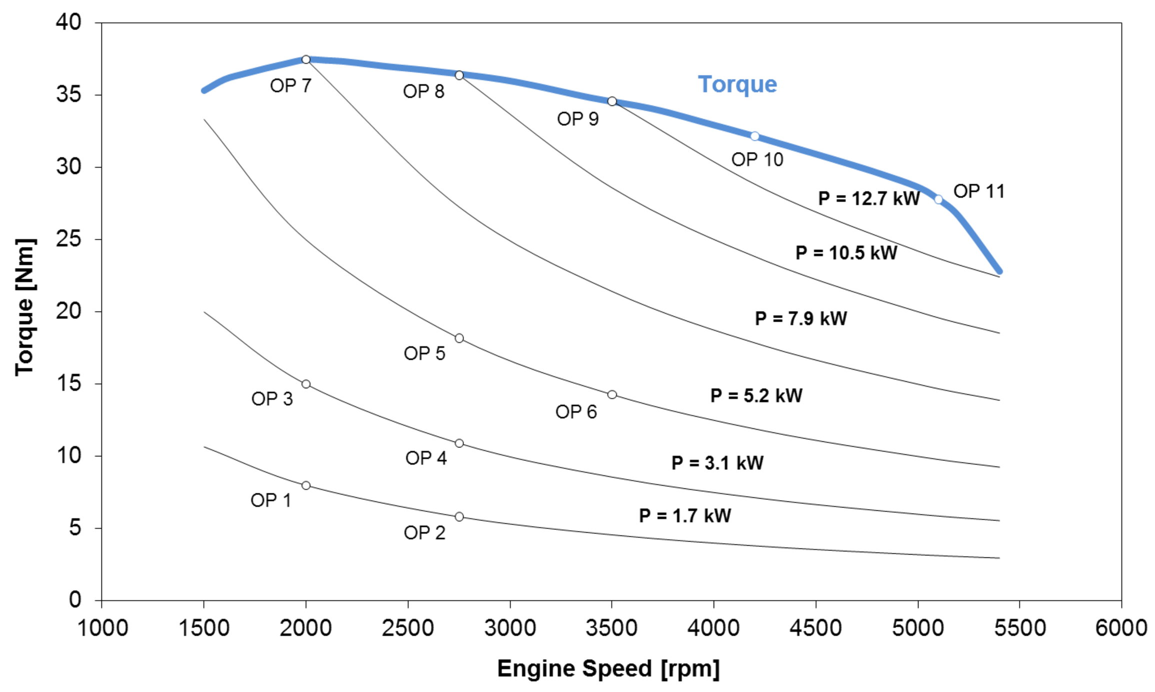

Figure 4: Torque map LOMBARDINI LGW 523 and the tested operating points (OP's)

specification	n-Butanol	Iso-Butanol	RON 95
	1-Butanol	2-Methyl-1-propanol	
Formula	$C_4H_{10}O$	$C_4H_{10}O$	-
Moleculare weight [g/mol]	74.1	74.1	60-150
Density [kg/gm^3]	0.809-0.813	0.802	0.737
Boiling range [°C]	115-119	108	38-175
Blending RON	94	113	95
Blending MOM	78	94	87
Lower heating value [MJ/kg]	33	33	41
Self-ignition temperature	343	430	300
Stoichiometric AF-ratio	11.2	11.2	14.7
Flash point [°C]	34	28	<-40
Viscosity [mPa*s]	2.9	3.95	0.83

Figure 6: Differences between fuels (in present tests n-Butanol)

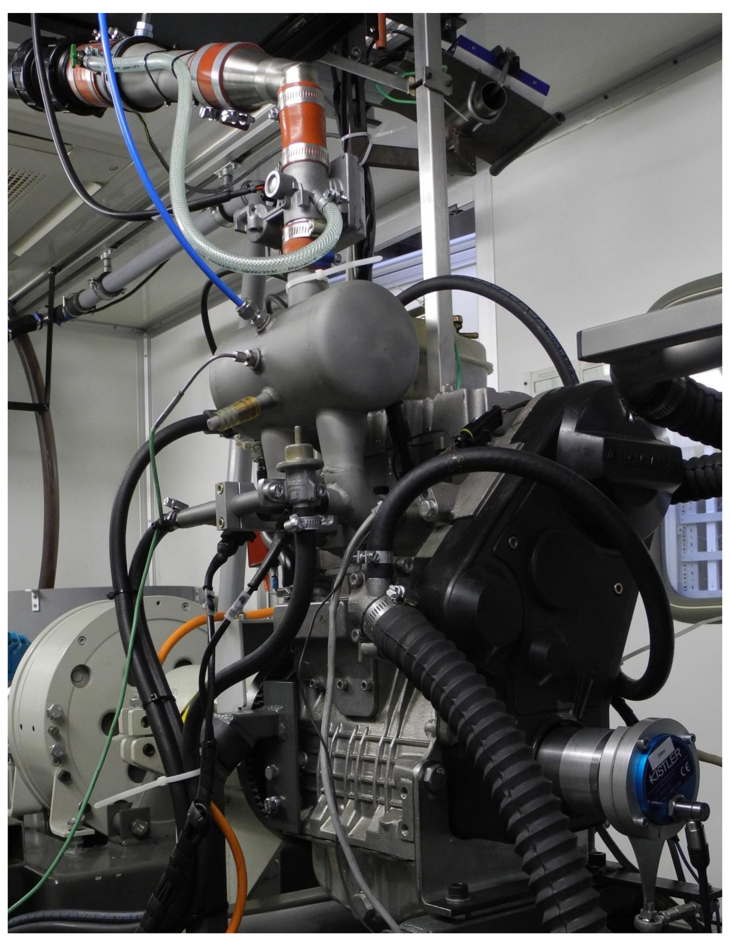

Figure 5: shows the test engine on the engine dynamometer

Conclusions

- The operation with Butanol blended to gasoline is possible without any problem. With neat Butanol (Bu100) nevertheless the cold start is problematic.
- The α_z-variations at part load of the engine show lowering of HC, NO_x & σ_{pmi} and a slight increase of CO with increasing Butanol rate.
- The aptitude of lean operation at part load is with Bu30 similar, as with Bu0 (further tests follow).
- With Bu30 the inflammation phase is shortened and the cyclic irregularity of combustion is slightly reduced.
- The lower overall heat value of BuXX-blends leads to a respectively lower full load torque without corrections of fuel dosing.

α_z –Variation 3500 rpm / 14Nm

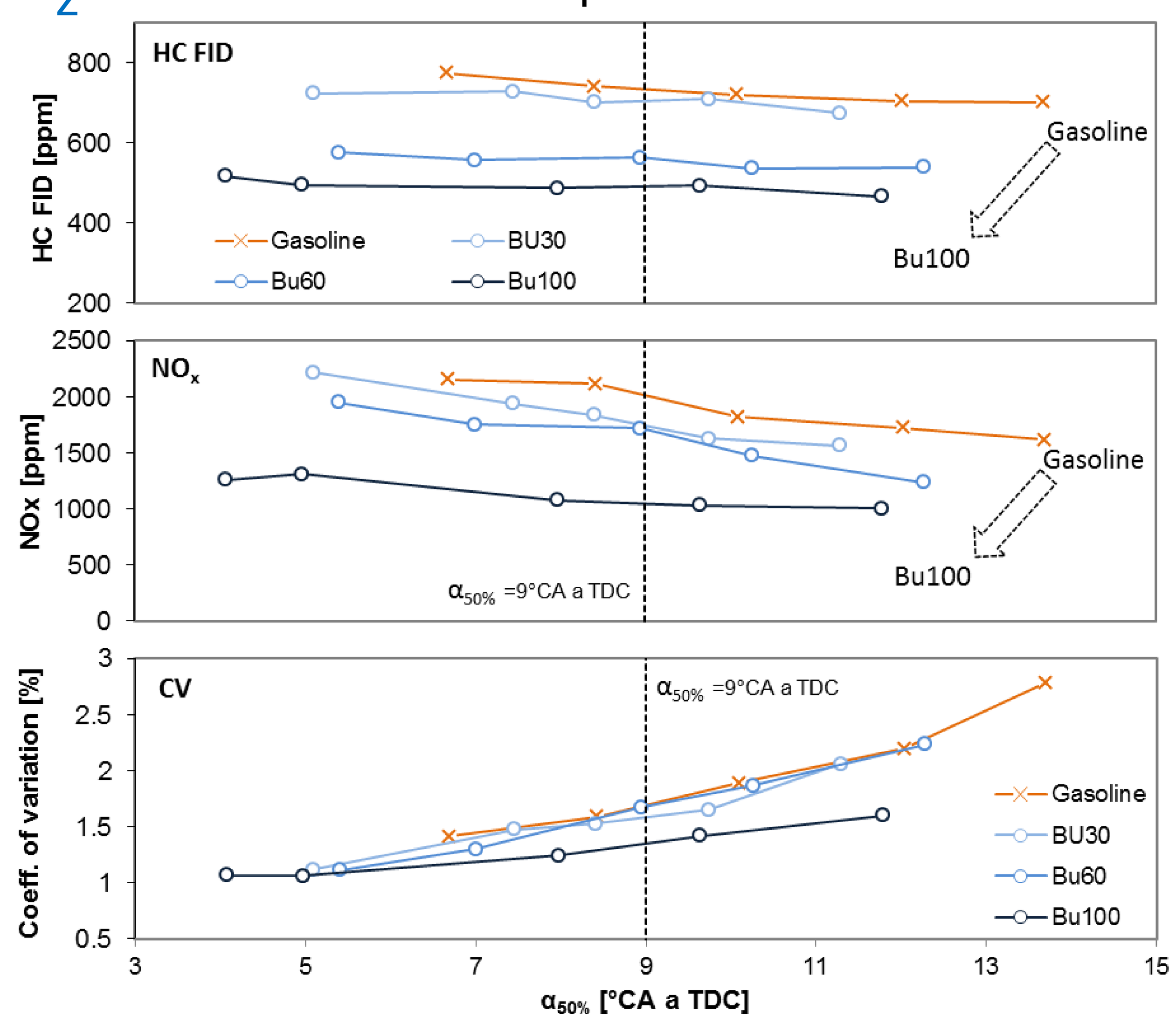

Figure 1: Comparison of fuels at variation of spark angle
Gasoline; Bu30; Bu60; Bu100; w/o catalyst; λ = 1.0

λ –Variation 2800 rpm / 11Nm

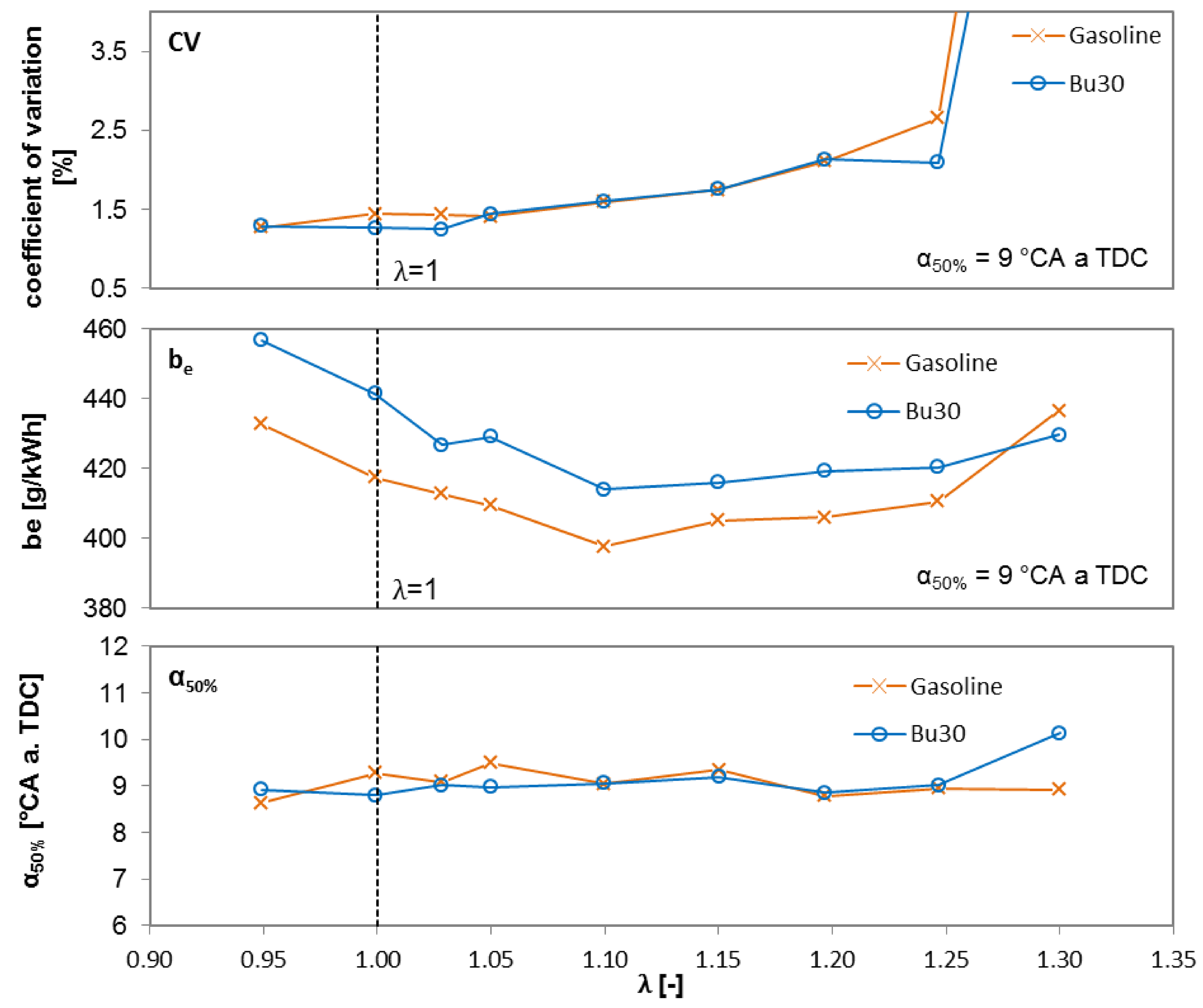

Figure 2: Comparison of fuels at variation of Lambda
Gasoline; Bu30; w/o catalyst; λ = 0.95 - 1.30

Heat Release 2800 rpm / 11Nm

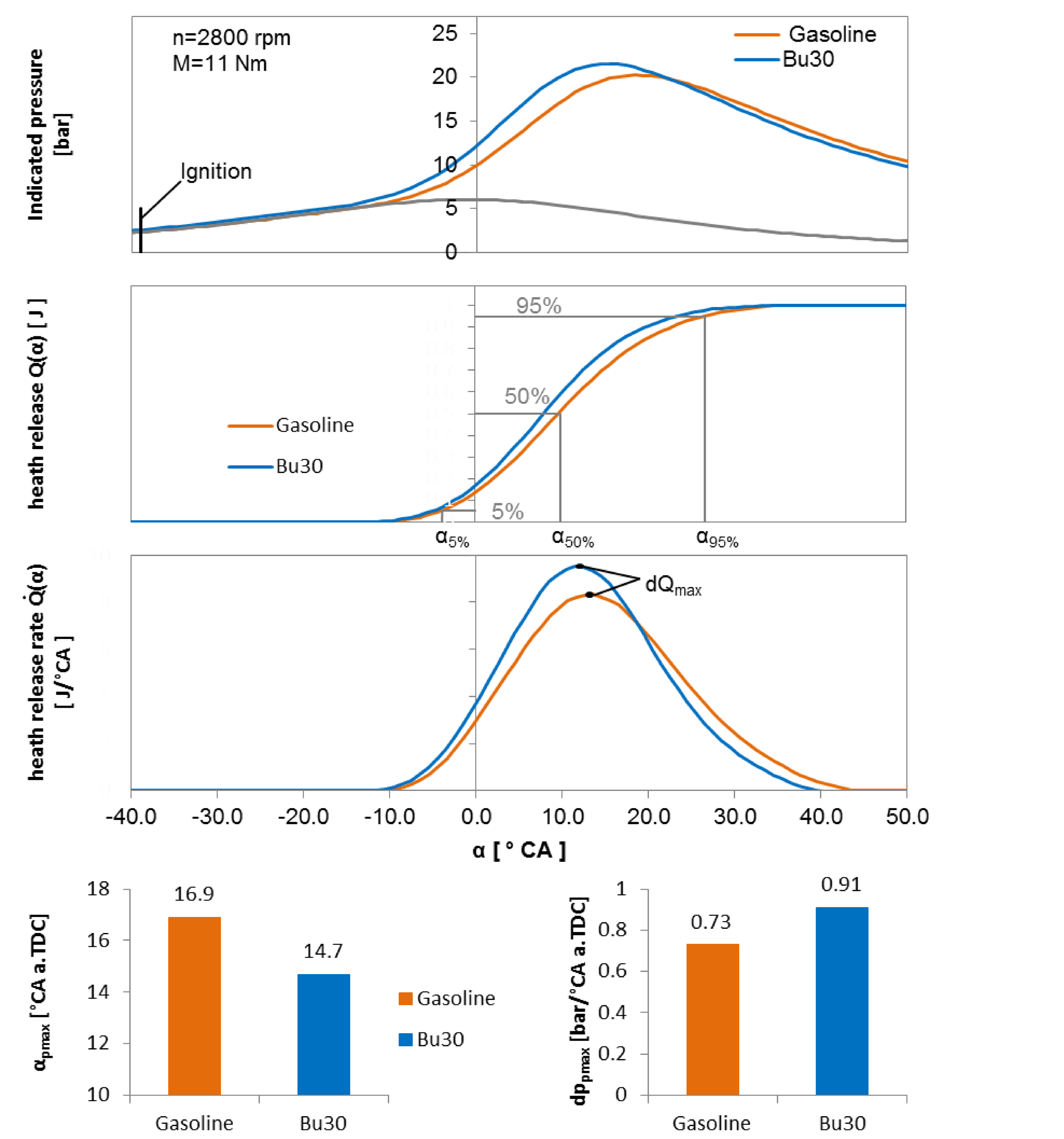

Figure 6: Comparisonn of cynder pressure and heat release with different fuels
Gasoline; Bu30; w/o catalyst; λ = 1.0

Further information; martin.guedel@bfh.ch, jan.czerwinski@bfh.ch