2nd VegOil

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1 Summary

From January until November 2009, several engine performance and emission tests were carried out on an engine test bench with a John Deere six cylinder engine (type 6068HL481, serial number CD6068L066866) at the test bench at the TU Kaiserslautern. The engine was operated with diesel fuel in series-production status to gain reference values for further measurements. Those were carried out with the engine adapted for vegetable oil fuel and powered by rapeseed (*Brassica napus* L.) oil fuel. For additional tests, the engine was equipped with a retrofit diesel particulate filter (DPF) to evaluate the influence of different fuels on the filter.

The same tests also were carried out with sunflower oil (*Helianthus annuus* L.), false flax (*Camelina sativa* L.) and Jatropha (*Jatropha curcas* L.) oil. The goal was to keep within the EU stage 3A emission limits and to reach the power level specified for series produced diesel engines with the vegetable oil fuels. These goals were achieved.

2 Test stand setup

2.1 Serial Engine

The tested engine is a John Deere 6068 PowerTech Plus Stage 3A engine (serial number S/N CD6068L066866).

Table 1 shows the basic engine data. It is equipped with:

- A common rail injection system
- An exhaust gas turbo charger with a variable turbocharger geometry
- A charge air cooler
- An exhaust gas recirculation system with exhaust gas cooling

Table 1 Engine data of a John 6068HL481 PowerTech Plus engine.

Parameter		Engine data
cylinder	-	6
engine displacement	liter	6,8
stroke	mm	127
bore	mm	106,5
valves/cylinder	-	4
compression	-	17
rated speed	min^{-1}	2100
low idle speed	min^{-1}	850
high idle speed	min^{-1}	2250
max. injection pressure	bar	1450
engine weight	kg	678
length	mm	1120
width	mm	611
height	mm	1058

2.2 Converted engine

The test bench engine is adapted for vegetable oil fuels with the same technology and components as the tractors of the demonstration fleet. The following engine components were adapted for vegetable oil fuel:

- Fuel cycle
    - Fuel lines
    - Fuel filters
    - Fuel pump
    - Fuel regulating valves
- Fuel preheating equipment
- Electronic control unit (ECU)

2.3 Diesel particulate filter (DPF)

For some tests, the engine is provided with a retrofit diesel particle filter (DPF) from AIRMEEX. This module consists of a silicon carbide (SiC) filter with a diesel oxidation catalyst (DOC) upstream the filter. It is regenerated passively, supported by a fuel born additive. The additive is dosed in the suction side of the fuel line before the fuel pump. Figure 1 shows the design and function of the exhaust aftertreatment system.

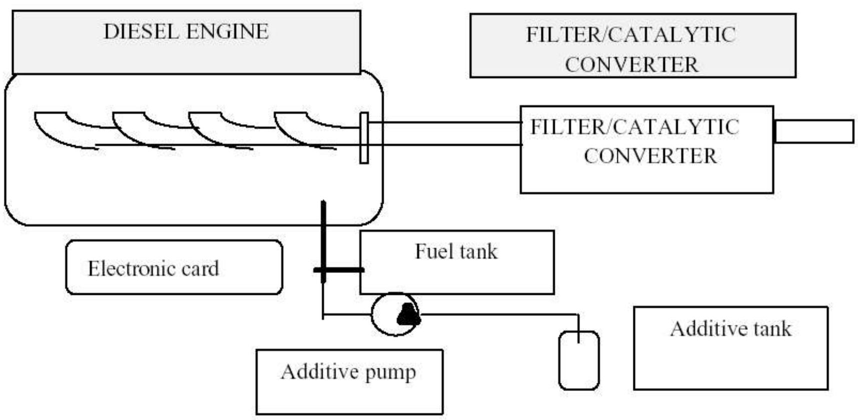


Figure 1: Design and function of the AIRMEEX Carmex-SC DPF

In Figure 2, the exhaust aftertreatment system of Airmeex is displayed as assembled at the test stand.

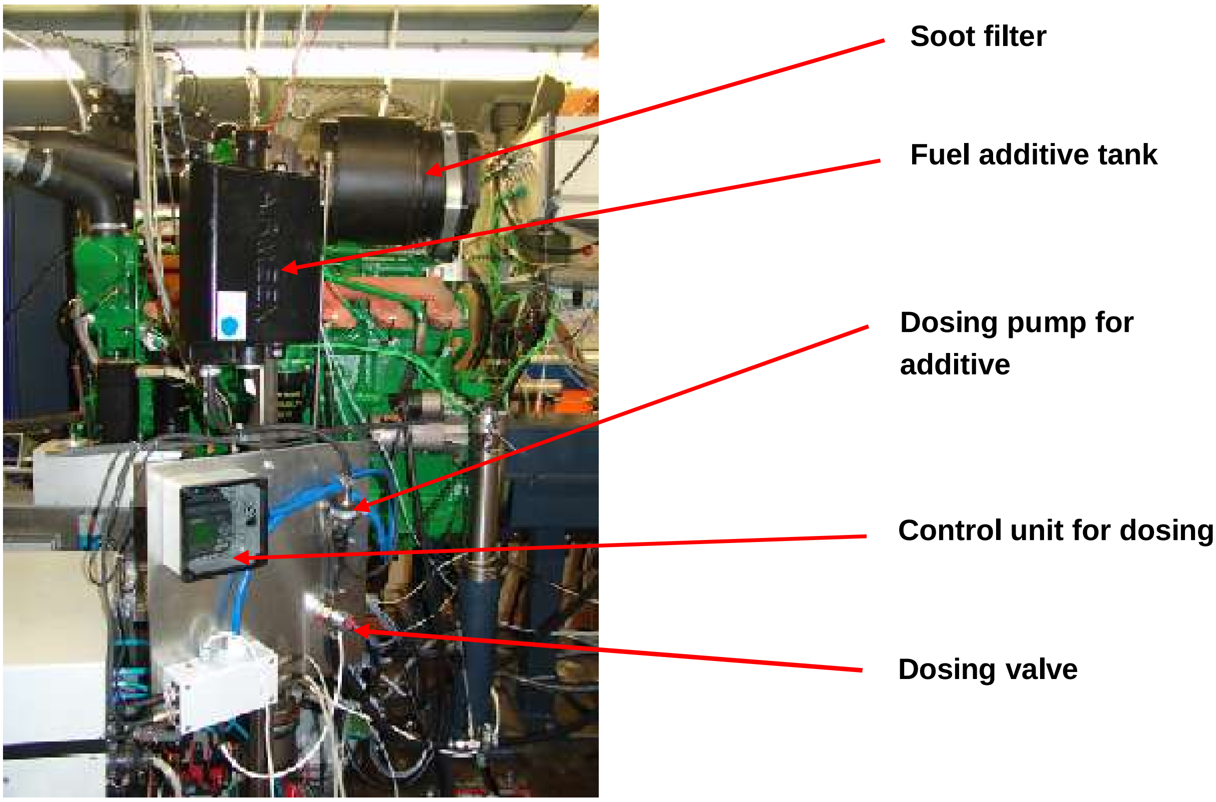


Figure 2: DPF system from Airmeex

In order to decrease the HC and CO emissions as well as the smell of burned vegetable oil it also has a DOC (diesel oxidation catalyst) included upstream of the filter.

2.4 Test bench

For operating the engine on the test rig and to meet the engine application requirements of the manufacturer, several adaptations were necessary:

- The original radiator of the engine cooling was replaced by a water-to-water heat exchanger. The cooling water for this exchanger is delivered by the test bench cooling system. The coolant flow is adjustable to control the engine temperature in the specified rank.
- The charge air cooler is directly cooled by the cooling water of the test bench.
- To guarantee a proper fuel temperature, two heat exchangers were included in the fuel system, one in the inlet and one in the outlet.

In order to identify the engine characteristics at operation with different fuels as well as to ensure a save engine run several engine data are measured (Table 2).

Table 2 Measured values and position of the sensor

	Measured variable and location	Short name
Engine	Engine speed	N_ENG
	Torque	TORQUE
	Throttle	THROTTLE
	Fuel to air ratio	Lambda
	Cylinder pressure 1.Cyl. to 6.Cyl.	P_CYL_1/…/6
Engine oil	Engine oil pressure in the engine block	P_OIL
	Engine oil temperature in the engine block	T_OIL
Exhaust gas	Exhaust gas temperature of the first cylinder	T_EG_DUCT_1
	Exhaust gas temperature of the second cylinder	T_EG_DUCT_2
	Exhaust gas temperature of the third cylinder	T_EG_DUCT_3
	Exhaust gas temperature of the fourth cylinder	T_EG_DUCT_4
	Exhaust gas temperature of the fifth cylinder	T_EG_DUCT_5
	Exhaust gas temperature ot the sixth cylinder	T_EG_DUCT_6
	Exhaust gas temperature in the exhaust manifold	T_EG_MANIF
	Exhaust gas temperature of the recirculating exhaust (EGR)	T_EGR
	Exhaust gas temperature after the turbo charger	T_P_TC
	Exhaust gas temperature after the muffler	T_P_MUFF
	Exhaust gas temperature at exhaust gas measurement equipment	T_AMA
	Exhaust gas pressure in the exhaust manifold	P_EG_MAN
	Exhaust gas pressure after the turbo charger	P_P_TC
	Exhaust gas pressure after the muffler	P_P_MUFF
Intake air	intake air mass flow	MAF
	Intake air temperature before the charge air cooler	T_A_CAC
	Intake air temperature after the charge air cooler	T_P_CAC
	Intake air temperature in the intake manifold	T_INTAKE_MANIF
	Intake air pressure before the air filter	P_A_FILTER_00
	Intake air pressure before the turbo charger	P_A_TURBO
	Intake air pressure before the charge air cooler	P_A_CAC
	Intake air pressure after the charge air cooler	P_P_CAC

	Intake air pressure in the intake manifold	P_INTAKE_MANIF
	Intake air temperature before the turbo charger	T_A_TURBO
Coolant water	Coolant water temperature inlet	T_COOL_IN
	Coolant water temperature outlet	T_COOL_OUT
	Coolant water of the heat exchanger inlet	T_HE_IN
	Coolant water of the heat exchanger outlet	T_HE_OUT
fuel	Fuel temperature inlet	T_FUEL_IN
	fuel temperature outlet	T_FUEL_RETURN
	fuel mass flow	M_FUEL
Ambient	Ambient air temperature	T_TB
	Ambient air pressure	P_TB
	Ambient humidity	HUMIDITY

The exhaust gas is analyzed for

- Hydro carbons (HC)
- Carbon monoxide (CO)
- Nitrogen oxides (NO_X)
- Mass of the particulate matter (PM)
- Size distribution of the PM
- Concentration of the PM

To load the engine, a tandem dynamometer is used. This system consists of a dynamometer for breaking and driving the engine as well as of a hydraulic break.
Additionally, an engine oil sensor is mounted to control the quality of the lubricant. This sensor is from Lubrizol (Lubrizol IQ MFI sensor). It measures the impedance of the lubricant at three different frequencies. As the impedance depends on the temperature, the lubricant temperature as well as the circuit temperature is also measured.

2.5 Fuels

The fuels are specified in Table 3. The reference fuel was diesel according to DIN EN 590 resp. DIN 51628.

Table 3 Fuels for EU stage 3A engine development

	Limit DIN V 51605 (rapeseed oil)	Rapeseed oil	Sunflower oil	False flax oil	Jatropha oil
		Brassica napus L.	*Helianthus annuus* L.	*Camelina sativa* L.	*Jatropha curcas* L.
Density (kg/m³)	900…930	919	922.7	926.4	918
Calorific value (MJ/kg)	36.0	37.6	37.2	37.2	37.2
Cinematic viscosity @40°C (mm²/s)	max. 36	35.0	31.7	29.8	34.2
Ignitability	min. 39	47.6	49.4	47.3	55.9
Flashpoint (°C)	min. 220	280	234.5	254	229
Carbon residues (% m/m)	max. 0.40	0.29	0.27	0.28	0.24
Iodine number (g Iodine/100 mg)	95…125	110	128	148	99
Sulfur content (mg/kg)	max. 10	4.0	2	3.2	<1
Total contamination (mg/kg)	max. 24	3	16	-	15
Acid number (mg KOH/g)	max. 2.0	0.99	1.41	3.46	11.20
Oxidation stability (h)	min. 6	7.4	3.7	1.3	37.6
Phosphorous content (mg/kg)	max. 12	0.8	<0.5	<0.5	<0.5
Calcium +magnesium content (mg/kg)	max. 20	1.2	<0.5	<0.5	<0.5
Oxide ash (% m/m)	max. 0.01	<0.001	0.002	<0.001	0.001
Water content (mg/kg)	750	586	594	823	668

The diesel fuel for the tests with diesel was Shell V-Power Diesel. In comparison with normal diesel Shell V-Power Diesel has a share of synthetic fuel (GTL) and additives which avoid deposits of the fuel in the fuel system and support the cutback of existing deposits.
The four vegetable oils were chosen because of their relevance for transport (rapeseed oil, sunflower), their agricultural potential (camelina sativa) and their social and environmental aspects (Jatropha oil). All four vegetable oils have a good potential for being used as fuels for diesel engines.

Rapeseed (*Brassica napus* L.) belongs to the family of crucifers. The flower forms 5 cm to 10 cm long pods with multiple spherical, blue-black to blue-brown seeds. The one thousand grain weight is 3.5 to 6.5 g. The oil content of seeds of winter rapeseed is 39 to 43 mass%. Summer rapeseed has an oil content of 38 to 40 mass%. There is a negative correlation between the oil and the protein content. Its yield is about 1300 l/ha.

The sunflower (*Helianthus annuus* L.) belongs to the daisy family. The oil content of sunflower seeds is 35 to 52 mass% (with seed coat) or 55 to 60 mass% (without seed coat).

Camelina, or false flax, (*Camelina sativa* L.) belongs to the family of crucifers. It has a height of 30 cm to 120 cm. It forms pods with pear-shaped oblong, yellow-to red-brown seeds, which have a thousand grain weight of approximately 1 g. The oil content is about 40%. Camelina sativa oil contains more than 50% polyunsaturated fatty acids (linoleic and linolenic acids), while erucic acid is less than 4%. The use of the press residue as fodder is permitted in the EU since July 2008 [2]. *Camelina sativa* is a co-crop in mixed-cropping with cereals and/ or fodder peas. Mixed cropping, the cultivation of two or more plant species at the same time on the same field, allows switching from conventional to organic agriculture without yield losses. The broadleaves of camelina sativa prevent weeds to sprout. The corn and peas are higher up and less exposed to humidity, therefore less threatened by fungi. This allows avoiding chemical plant protection almost entirely. The oil from camelina sativa is an additional yield and 100-300 liters can be obtained per hectare in addition to the yield of the main crop. The potential of camelina sativa oil from mixed-cropping in the EU is about 60 PJ.

Jatropha curcas L. is often referred to as ‘jatropha’. It is a plant that produces seeds with a high oil content. The seeds are toxic and in principle non-edible. Jatropha grows under (sub)tropical conditions and can withstand conditions of severe drought and low soil fertility. Because of its capability to grow on marginal soil, it can also help to reclaim wasteland and restore eroded areas. As it is not a food or forage crop, it plays an important role in deterring cattle, and thereby protects other valuable food or cash crops. Jatropha seeds can be pressed into bio-oil that has good characteristics for direct combustion in compressed ignition engines or for the production of biodiesel. The bio-oil can also be the basis for soap-making. The pressed residue of the seeds (press cake) is a good fertilizer and can also be used for biogas production. *Jatropha curcas* L. is a tall bush or small tree that can grow up to six meters tall, belonging to the Euphorbiaceae family. Its lifespan is in the range of 50 years. The fruits have a shape resembling an “American football” and are about 40 mm long. Each fruit contains three seeds, though occasionally one may have 4 or 5 seeds. Jatropha seeds look like black beans and are on average 18 mm long and 12 mm wide and 10 mm thick. It contains various toxic components (phorbol esters, curcin, trypsin inhibitors, lectins and phytates) and is therefore non-edible. Seeds consist of a hard shell and a soft white kernel. The dry seeds contain between 32 and 40% of oil, with an average of 34%. The average yield of Jatropha is about 1.5 tons per hectare.

2.6 Emission tests

The emission test cycle is based on the ISO 8178- C1 non-road stationary cycle (NRSC) [4]. This cycle is also the basis for homologation of EU stage 3A engines. It consists of eight load points (steps) with different loads at three different engine speeds. The minimum duration for each step is 10 minutes. Figure 3 shows the measuring points for the engine CD6068L066866 according to its full load curve.

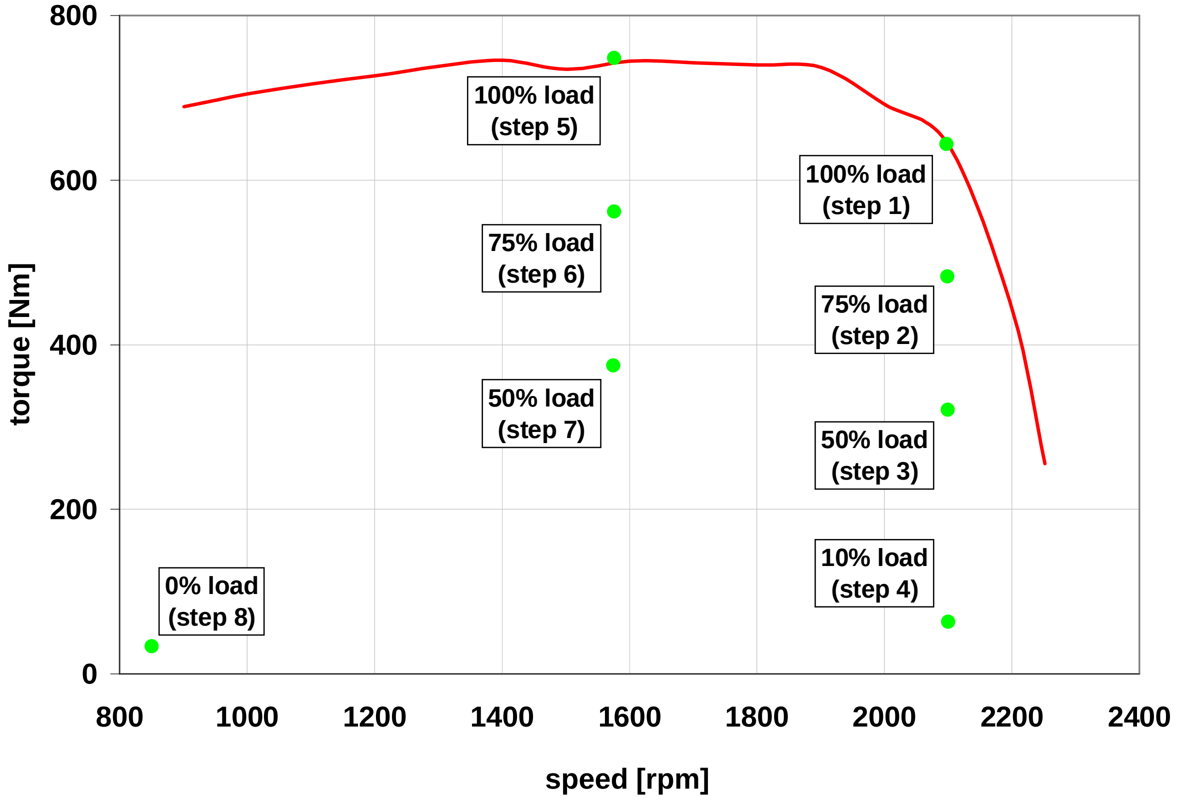


Figure 3 Applied stationary emission cycle based on NRSC

The full load curve of series software and diesel fuel serves as the basic reference for those eight load points. It is also the basis for the vegetable oil fuels. Therefore the fuel amount was increased to compensate the lower calorific value of the biofuels.

For the engine variants where a DPF was used in combination with rapeseed oil, the non-road transient cycle (NRTC) [4] was carried out. For the NRTC, load and speed is changed every second, see Figure 4. The cycle is applied directly after a cold start (weighing factor 0.1) and after a warm-up phase (weighing factor 0.9) (see [4]).

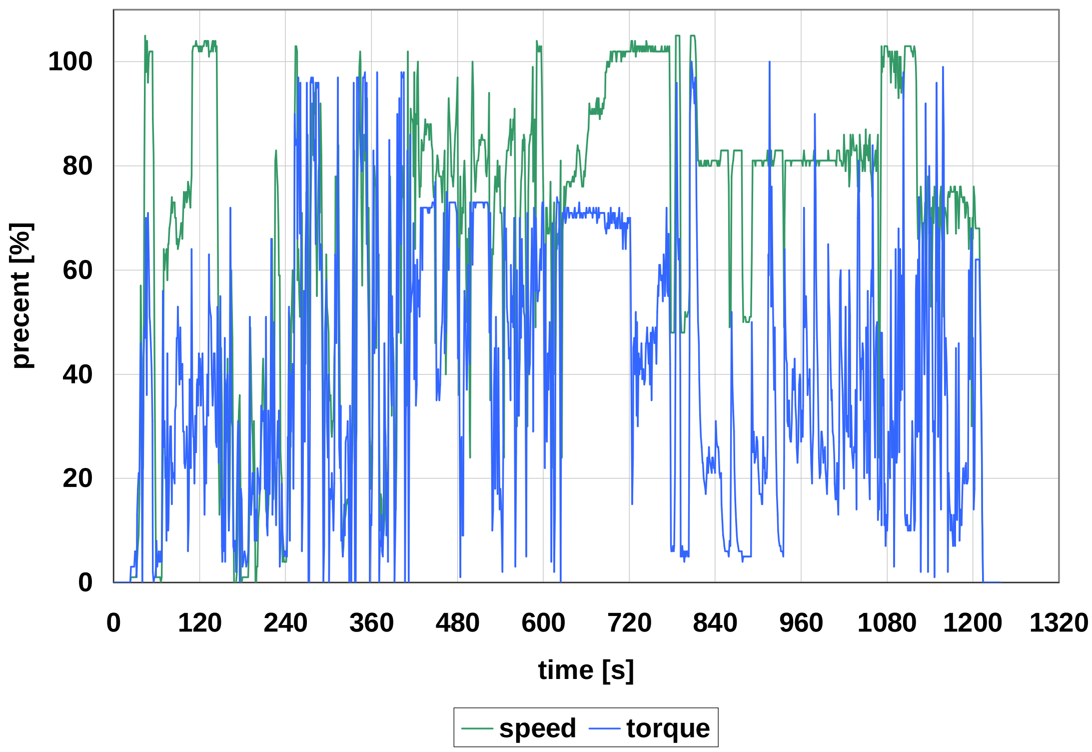


Figure 4 Applied transient emission cycle based on NRTC

The NRTC is the obligatory test cycle for PM from EU stage 3B onwards. It is carried out to get a first tendency of how the engine will react with rapeseed oil fuel to this highly transient cycle. Thus the compliance of the engine with the emission limits 3A or 3B are neither expected nor required when this cycle is applied.

3 Calculations

3.1 Emissions

The calculation of the emissions was done in conformity with 97/68/EC. For the calculation of the gaseous emissions (CO, HC, NO_X) during NRSC the average concentration of the last minute of each load point was used. These concentrations are standardized according to temperature and humidity. Then the emission mass flow was computed:

$$\dot{m}_{Gas} = conc_{Gas} \cdot u \cdot \dot{m}_{Exh}$$

With: m_{Gas}: Mass flow of the single limited emission component (e.g. HC or NO_x)
$conc_{Gas}$: concentration of the limited emission component
u: specific coefficient
m_{Exh}: Exhaust gas mass flow

The values for u are shown in Table 4.

Table 4 Values for u

Gas	u	Unit
CO	0.000966	ppm
HC	0.000479	ppm
NO_X	0.001587	ppm

To get the specific emissions in g/kWh following equation is used

$$spec.emission_{Gas} = \frac{\sum \dot{m}_{Gas} \cdot WF}{\sum P_i \cdot WF}$$

P_i is the average power during the last minute of the load point. WF means weighting factor (Table 5).

Table 5 Weighting factor according to 97/68 EG

Load points	1	2	3	4	5	6	7	8
WF	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

For the calculation of the specific emissions during NRTC the following equations are used. The mass of each emission gas is:

$$m_{Gas} = \sum conc_{Gas} \cdot u \cdot \dot{m}_{Exh} \cdot \frac{1}{f}$$

With: f: Frequency of measurement (in Hz)

The specific emission of an emission gas is:

$$spec.\,emission_{Gas} = \frac{m_{Gas}}{W_{act}}$$

W_{act} means the actual work measuring point.

$$W_{act} = \overline{P}_{n-(n-1)} \cdot \Delta t_{n-(n-1)}$$

With: $P_{n-(n-1)}$: Mean power during one measuring step
$\Delta t_{n-(n-1)}$: Duration of one measuring step

3.2 Brake specific fuel consumption and efficiency

The equation for the brake specific fuel consumption (BSFC) during NRSC is:

$$BSFC = \frac{\sum \dot{m}_{fuel} \cdot WF}{\sum P_i \cdot WF}$$

The equation for the efficiency during NRSC is:

$$efficiency = \frac{\sum \dot{m}_{fuel} \cdot calorific\ value \cdot WF}{\sum P_i \cdot WF}$$

4 Results

Below the results for performance and emission measurements with diesel, rapeseed oil, false flax, sunflower and jatropha oil are detailed. Further, the influences on the DPF are evaluated.

4.1 Full load curves

Figure 5 shows the torque curve of the

- serial engine,
- converted engine with diesel, serial ECU, without (variant 1) and with DPF (variant 2)
- converted engine with rapeseed oil (Roil), with the ECU converted for Roil without (variant 3) and with DPF (variant 4)

In Table 6, the maximum torque and the corresponding engine speed of these engine parameters are listed. One of the targets of the ECU software conversion was to adapt the ECU software for rapeseed oil in order to have the best possible analogy with the torque characteristics with diesel and serial ECU software. The maximum difference between the torque curves in a speed range of 900 rpm and 2100 rpm of the variants 1 and 3 in comparison with the serial engine is about 1.5% respectively 2.5%. The maximum difference in torque in the same speed range between variant 2 and 4 is about 4%. The maximum torque difference of the variant 1 and 2 and between variant 3 and 4 is about 2.1% respectively 5%. The reason for this power reduction is the increased exhaust back pressure caused by the DPF (Figure 6). Higher exhaust gas back pressure produces higher pumping work for the engine. Thus, the output power is decreasing and the specific fuel consumption is increasing.

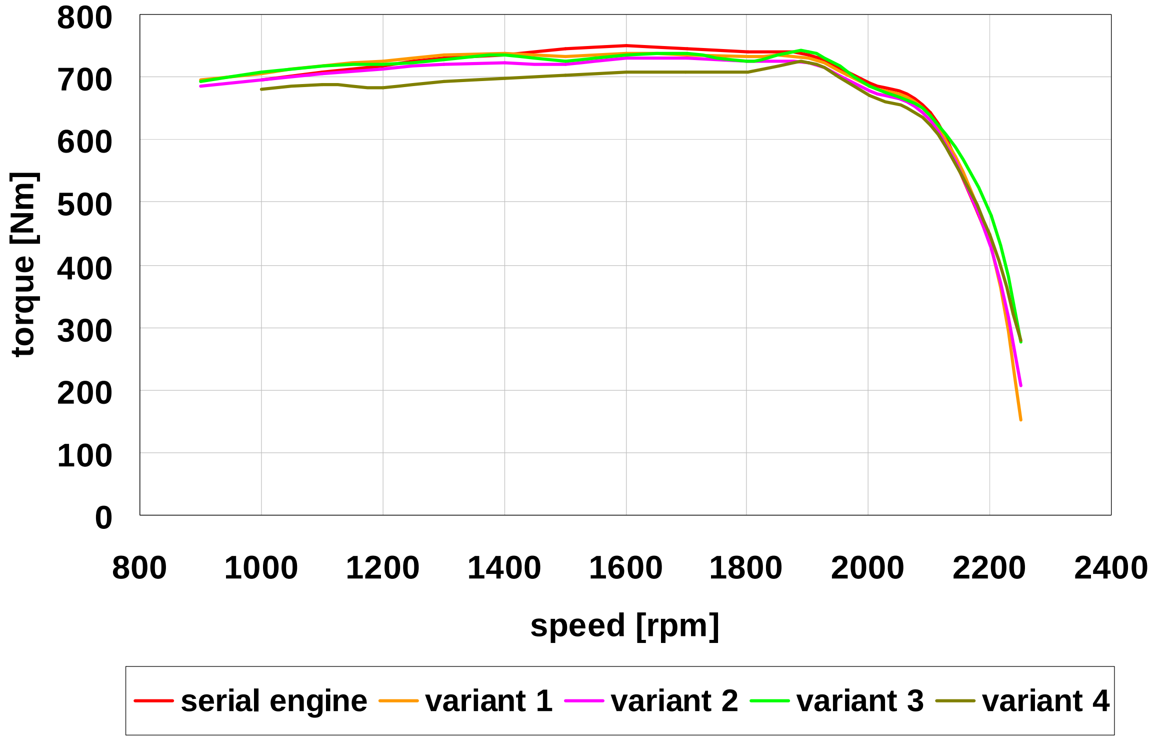


Figure 5: **Torque curve of different engine configurations, diesel and rapeseed oil fuel**

Table 6: **Maximum torque of the different variants**

Serial engine	750 Nm	1600 rpm
Variant 1 (hardware converted, software serial, diesel fuel)	739 Nm	1600 rpm
Variant 2 (hardware converted, software serial, diesel fuel, DPF)	729 Nm	1700 rpm
Variant 3 (hardware and software converted, rapeseed oil)	740 Nm	1900 rpm
Variant 4 (hardware and software converted, rapeseed oil, DPF)	723 Nm	1900 rpm

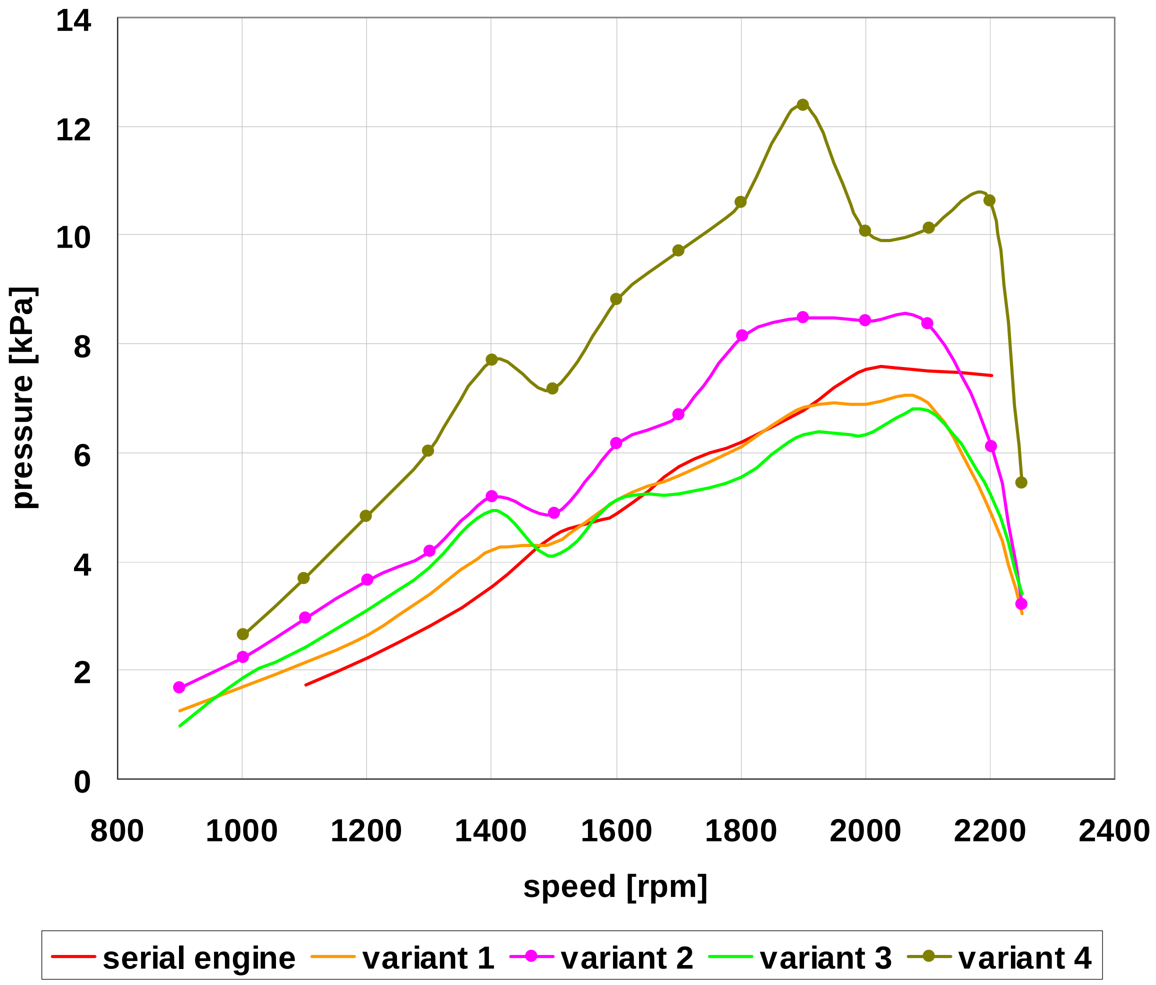


Figure 6 **Exhaust gas back pressure of the four engine variants**

4.2 Efficiency and specific fuel consumption

The weighted BSFC and the efficiency during NRSC are shown in Table 7. The BSFC of the engine operating with diesel is not comparable to the BSFC operating with rapeseed oil due to the lower calorific value of rapeseed oil.

Table 7 BSFC und efficiency during NRSC

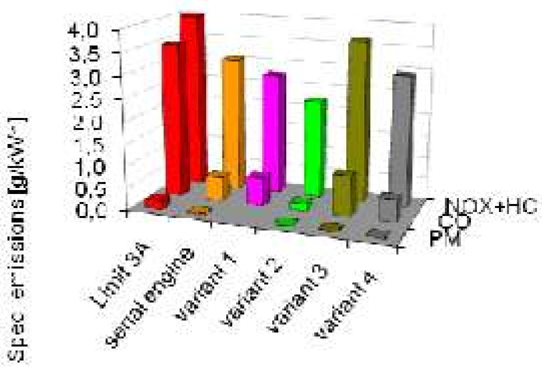
		Serial engine	Variant 1 (hardware converted, software serial, diesel fuel)	Variant 2 (hardware converted, software serial, diesel fuel, DPF)	Variant 3 (hardware and software converted, rapeseed oil)	Variant 4 (hardware and software converted, rapeseed oil, DPF)
BSFC	**g/kWh**	221	231	233	261	263
Efficiency	**%**	37.7	36.2	35.8	36.9	36.7

4.3 Emissions

The emissions were measured with the serial engine as well as with all engine software and hardware modifications described above (chapter 4.1, p.17).

4.3.1 Emissions during the NRSC with diesel and rapeseed oil

In Figure 7, the emissions of all evaluated engine and fuel combinations are displayed. The emissions are below the limits of EU stage 3A for all combinations. The adaptation of the engine hardware for rapeseed oil improves the NO_x+HC emissions with diesel fuel. With rapeseed oil and the same hardware, but adapted software, the NO_x emissions are rising significantly, but are still below the 3A limit.



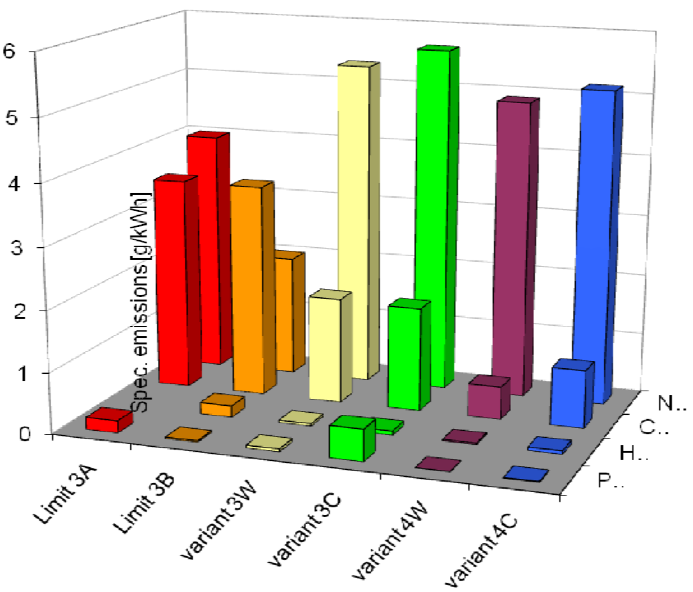
	Limit 3A	serial engine	variant 1	variant 2	variant 3	variant 4
PM	0,20	0,03		0,00	0,05	0,03
CO	3,50	0,64	0,84	0,16	0,92	0,60
NOX+HC	4,00	3,04	2,78	2,23	3,84	2,97

Figure 7 Emissions of all evaluated engine/fuel configurations during the NRSC

The influence of the oxidation catalyst, which is installed after the DPF to reduce the typical smell of biofuel combustion, can be seen in the CO emissions. The alternatives (variant 2 and 4) for which a DPF/DOC was installed produced less than 50% of the CO emissions compared to the same configuration without DPF/DOC (variant 1 and 3). The PM emissions are for all combinations very low and approximately ten times lower than the limit of stage 3A.

4.3.2 Emissions during NRTC with diesel and rapeseed oil

The NRTC test is obligatory for PM emissions from stage 3B onwards. Therefore also the emissions of the 3A engine were measured in the NRTC test to get a first impression of the engine's behaviour in the transient cycle. The NRTC was performed with a cold engine ("C" in Figure 8) as well as with a warm engine ("W") according to 2004/26/EC [4].



	Limit 3A	Limit 3B	variant 3W	variant 3C	variant 4W	variant 4C
PM	0,20	0,03	0,05	0,52	0,00	0,01
HC		0,19	0,04	0,07	0,02	0,06
CO	3,50	3,50	1,74	1,71	0,54	0,95
NOx	4,00	2,00	5,34	5,66	4,90	5,16

Figure 8 Emissions of all evaluated engine/fuel configurations during the NRTC

The PM emissions are still significantly below the 3A limit, as well as they are below stage 3B limits in the NRTC tests with a DPF. The NO_x emissions are significantly higher than both the limit of stage 3A and 3B. This is acceptable, as on the one hand the NO_x emissions are and will be certified with the NRSC test, in which the engine complies with the limits with all combinations of engine modifications and fuel. On the other hand, the applied engine (stage 3A) was calibrated for the NRSC test only. The next engine on the test rig (3B level) will be calibrated for the transient cycle and is therefore expected to show a better performance for NO_x emissions also.

4.3.3 Emissions during NRSC with sunflower, false flax and jatropha

According to the preceding tests with rapeseed oil, the limited emissions were also measured with sunflower, false flax and jatropha oil fuel. The engine hardware modification was the same for all tested fuels. The software for diesel fuel was the series software while for the vegetable oil fuels the same adapted software was used. The results are presented in Figure 9 and Figure 10. In Figure 9 the engine out emissions are displayed, which were measured before the DPF/DOC.

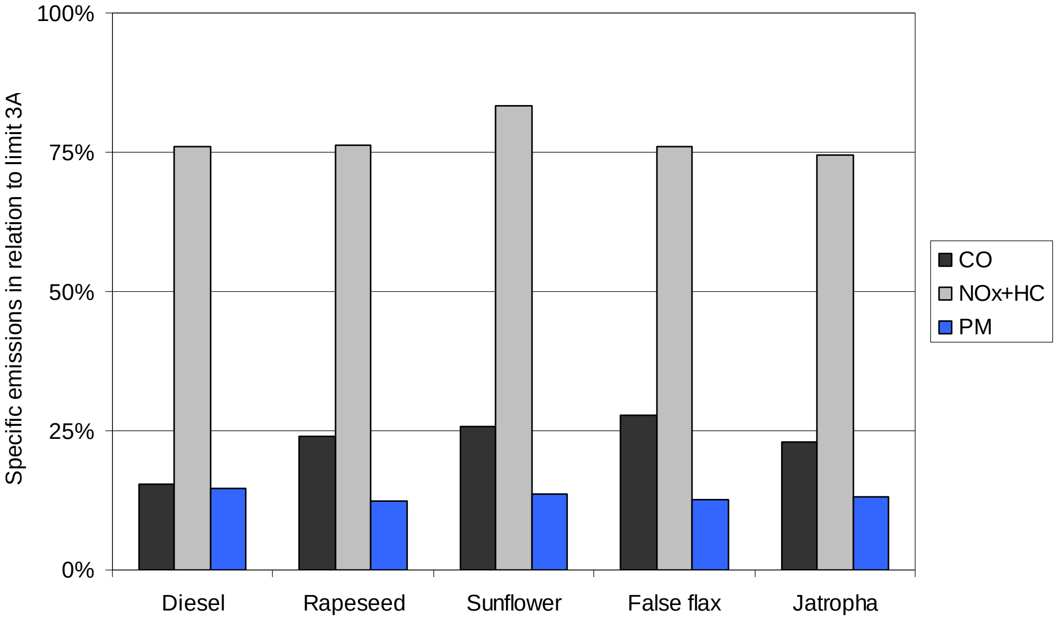


Figure 9 **Limited engine out emissions of stage 3A engine (ante DPF/DOC) with different fuels**

In Figure 10, the emissions after the DPF/DOC are presented, which show lower PM emissions due to the DPF and lower CO emissions due to the DOC. The average efficiency of the DPF is 83% and was stable during the testing period.

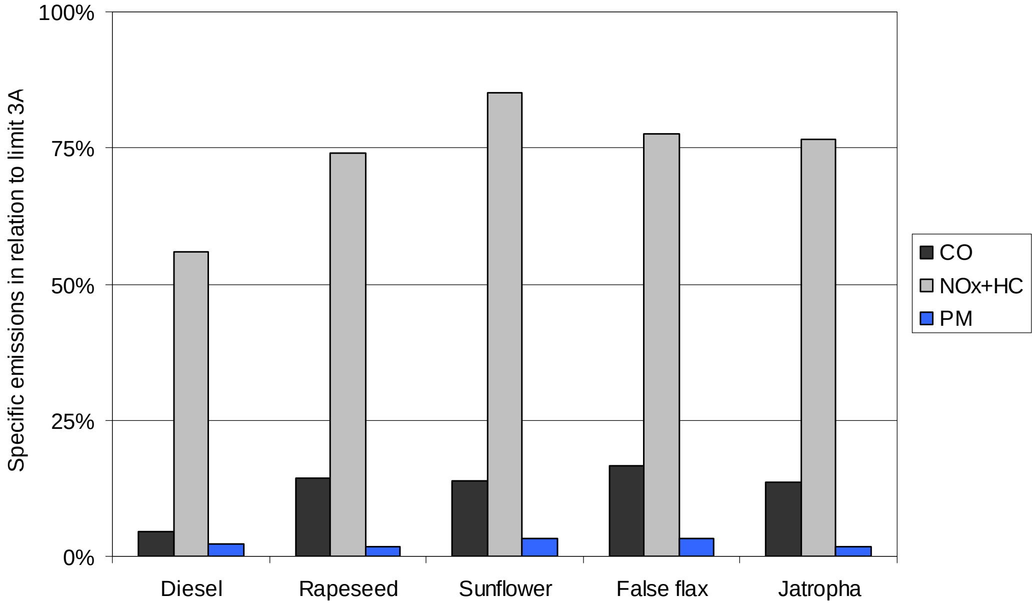


Figure 10 **Limited emissions of stage 3A engine (post DPF/DOC) with different fuels**

4.4 DPF/DOC operation

The DPF/DOC operation was stable during the whole testing period. It shows a moderate increase of the backpressure over time (order of fuels is chronological) which can be correlated with the soot loading of the DPF.

5 Literature

[1] Fachagentur für nachwachsende Rohstoffe e.V. (FNR) (Hrsg.): Biokraftstoffe Basisdaten Deutschland, Gülzow 2008.

[2] Directive 2008/76/EC of the European Commission of 25 July 2008, changing Appendix I of Directive 2002/32/EC of the European Parliament and the European Council about undesired substances in animal fodder, Official Journal L 198/37 of 26.7.2008.

[3] Jatropha handbook http://www.fact-foundation.com/en/Publications/Handbooks?session=rgsji47tqncht6l57s73rt3vr1

[4] Directive 2004/26/EC amending Directive 97/68/EC on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery. Official Journal of the European Union, L225. Brussels, 25.6.2004.