2nd VegOil

Demonstration of 2nd Generation Vegetable Oil Fuels in Advanced Engines

Workpackage 2

Engine development

Deliverable N° 2.4:

Functional stage 3B pure vegetable oil engine

Publishable summary

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List of Acronyms

ASTM	American Society for Testing and Materials
CLD	Chemiluminescence detector
CO	Carbon monoxide emissions
DB	Durability built
DK	Diesel fuel
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
ECU	Engine control unit
FID	Flame ionization detector
FLRS	Full load rated speed
JD	John Deere
FB	Feasibility built
HC	Hydrocarbon emissions
HCI	Hydro Carbon Injection
KL	Kaiserslautern
MFDA	Multi Functional Diesel Additivs
NDIR	Non-dispersive infrared
NO_x	Nitrogen oxide emissions
NRSC	Non road stationary cycle
NRTC	Non road transient cycle
PIN	Product identification number
PM	Particulate matter
PPO	Pure Plant Oil
2G-PVO-RS	2nd Generation Pure Vegetable Oil based on Rape seed oil
RS	2nd Generation Pure Vegetable Oil based on Rape seed oil
WIPO	World Intellectual Property Organization

1 Summary

The new JD PowerTech PVX engine complying with EU stage 3B was installed on a test rig at the TU Kaiserslautern. Basic testing with diesel and vegetable oil was carried out and showed similar behaviour of the engine like the preceding stage 3A PowerTech Plus engine. Therefore the engine hardware was adapted according to the experiences from stage 3A engine development. The ECU software was already modified such that the primary full load curve with diesel fuel and series software was achieved also with rapeseed oil and a modified software version. The next step will be to further optimize the software calibration with regard to the stage 3B emission compliance, where NO_x again proved to be the most critical exhaust gas component.
On the PowerTech PVX engine there is for the first time at JD a DOC/DPF unit integrated. This device is reducing the PM emissions which have to be 90% lower than in stage 3A. To maintain the functionality of the DOC and the DPF, the use of 2nd generation vegetable oil fuels is essential. Furthermore the active regeneration system, which includes a system dosing fuel into the exhaust pipe, has to be modified to generate a proper fuel spray when vegetable oil is used for the regeneration. So far the regeneration was done with diesel fuel, the regeneration with vegetable oil fuels will be discussed in deliverable 2.5. The regeneration unit is analyzed within this document.

2 Testing environment

In the following sections the new stage 3B engine as well as the testing environment will be explained.

2.1 Engine specification

For stage 3B engine testing, a completely new engine generation of JD will be used, the PowerTech PVX 6.8L. This stage 3B (interim Tier 4) compliant engine will be the first of its kind to be used with 100% biofuels on a test bench.
The major difference compared to the stage 3A engine is the integrated exhaust aftertreatment system, which consists of a combination of diesel oxidation catalyst (DOC) and a diesel particulate filter (DPF). With this system, 90% of the engine out particulate emissions can be reduced. Additionally, the EGR flow and EGR cooler performance are increased, which results in a 50% NO_x reduction compared to the stage 3A engine of the same power range. An additional feature is also the air intake throttle, which is used during regeneration to increase the combustion and thus the exhaust gas temperature. More details are listed in Table 1.

Table 1 **Engine data of the JD**

Parameter		Engine data
cylinder	-	6
engine displacement	liter	6,8
valves/cylinder	-	4
FLRS power	kW	125

To increase the exhaust gas temperature before and during DPF regenerations, some new features are integrated. The exhaust assembly also includes a post injection unit, where fuel is injected during the active regeneration of the DPF. It is oxidized in the DOC to CO_2 and water. This exothermic reaction is increasing the temperature in the DPF to enable active soot regeneration. The temperature management by catalytic HC oxidation in a DOC is easier to control than an open flame burner, for example. One of the great challenges will be to make this regeneration injection unit capable for 2G-PVO.

2.2 Test rig layout

The engine test rig is displayed in Figure 1. To load the engine a Schenck W 400 eddy-current brake is installed. It is capable to load engines up to 400 kW, with a maximum torque of 2000 Nm and speed of 5500 rpm. The test rig is controlled by a Schenck automation system and the LabView PCI MIO 16 data logging system. All installed sensors are listed in Table 2.

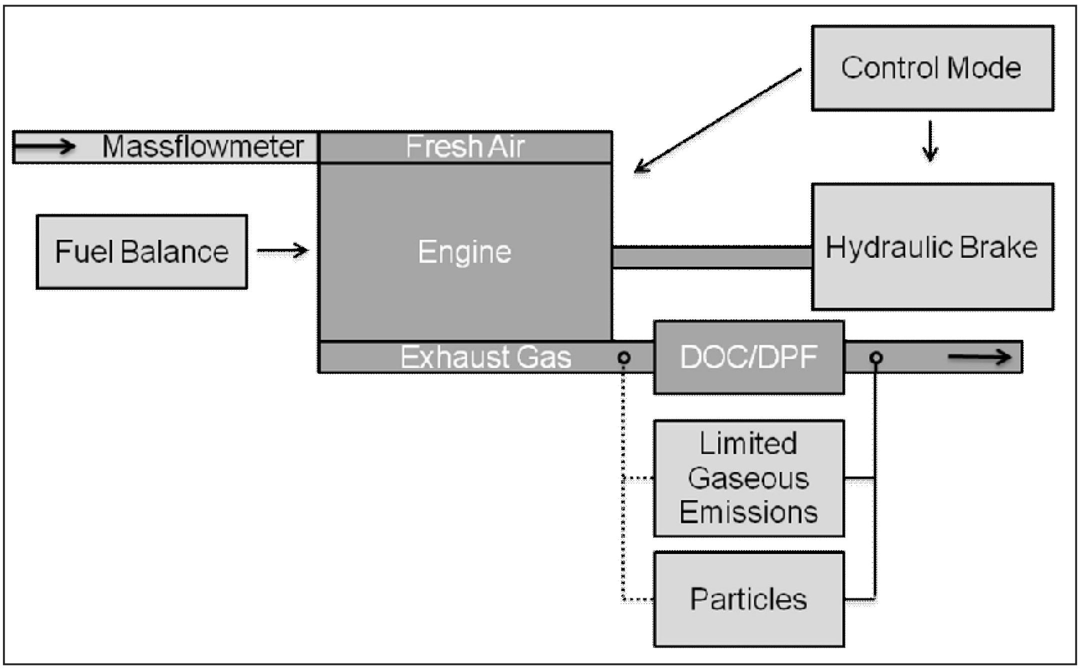

Figure 1 **Test rig layout**

Table 2 **Measurement equipment of the test rig**

Measured parameter	Engine parameter	Sensor type	Sensor properties
Static low pressure		Endress+Hauser Cerabar T	0...1.6 bar; …4 bar; …10 bar
Low pressure	Intake, exhaust pressure	Kistler 4075A10	0…10 bar
High pressure	Cylinder pressure	Kistler 6052C	0… 250 bar
Crank angle recording	Crank angle recording	Heidenhein	3600 increments
Air flow	Mass air flow	Sensycon Sensyflow P	
Fuel consumption	Fuel consumption (combustion and regeneration)	Mettler Toledo XS32001L	
Temperature	Exhaust temperature	NiCrNi thermocouples	
	Air temperature	Pt100	
	Fuel temperature	Pt100	
Exhaust gas components	**Equipment type**	**Measurement principle**	**Measurement range**
HC	Tesla FID 123	Flame ionisation detector	0…100 ppm
NOx	Ecophysics CLD 700	Chemiluminescence detector	0…1000 ppm

CO	Rosemount Binos NDIR	Non dispersive infra-red detector	0…1500 ppm
CO_2	Leybold Heraeus BINOS NDIR	Non dispersive infra-red detector	0…16%
Smoke number	AVL 415S Smoke Meter	Optical	0…10
Particle size, number	TSI EEPS 3090	Electrical mobility spectroscopy	5.6…560 nm
Particle mass	AVL SmartSampler SPC 472	Gravimetric	Not applicable

2.3 Test plan

The testing proceedings are based on those applied at the EU stage 3A engine (see 2nd VegOil deliverable 2.2 [5] and 2.3 [3]). The scheduled test plan for the development of a functional stage 3B vegetable oil engine is listed below. Within this document, tasks I to XI will be discussed.

I. Integration of the engine into the test rig environment.
II. Start up and basic functional testing with diesel fuel.
III. Reference measurements with diesel fuel: full load performance, emission testing, part load map characteristics.
IV. Adaptation of hardware based on experiences from stage 3A engine development.
V. Evaluation of functionality of hardware adaptation (leakage, compliance with engine application requirements, performance).
VI. Switch to vegetable oil by blending diesel fuel step by step with 2G-PVO-RS during engine operation.
VII. Evaluation of functionality of hardware measures with 2G-PVO-RS.
VIII. Reference measurements with 2G-PVO-RS according to III.
IX. Evaluation of differences between diesel and 2G-PVO-RS regarding power, emissions and general performance.
X. Determination of required software modifications for 2G-PVO-RS to achieve the power and emission levels of diesel fuel. (No I vegetable oil software)
XI. Emission testing according to 97/68/EC [8] and 2004/26/EC [9] with No I vegetable oil software.
XII. Further improvement of basic software for transient cycles, regeneration, cold starting.

All testing with 2G-PVO-RS described in this document refers to the use as "in cylinder" fuel only, which means that the DPF regeneration by fuel injection into the exhaust assembly is done with diesel fuel. The dosing unit will be adapted for the injection of 2G-PVO-RS within task XII, which will be documented in deliverable No 2.5. A first analysis of this system will although be discussed in the following sections.

2.4 Test fuels

The same fuels as used on the 3A engine will be used on the 3B engine: diesel according to DIN 51628 and 2G-PVO-RS according to DIN V 51605 with a higher quality regarding the element content. The fuel analysis is displayed in Table 3.

Table 3 Analysis results of the used rapeseed oil fuel

	Limit DIN V 51605 (rapeseed oil)	Rapeseed oil
Density @15°C (kg/m³) DIN EN ISO 12185	900…930	919
Calorific value (MJ/kg) DIN 51900-2	36.0	37.6
Cinematic viscosity @40°C (mm²/s) DIN EN ISO 3104	max. 36	35.0
Ignitability IP 498	min. 39	47.6
Flashpoint (°C) DIN EN ISO 2719	min. 220	280
Carbon residues (% m/m) DIN EN ISO 10370	max. 0.40	0.29
Iodine number (g Iodine/100 mg) DIN EN 14111	95…125	110
Sulfur content (mg/kg) DIN EN ISO 20884	max. 10	4.0
Total contamination (mg/kg) DIN EN 12662	max. 24	3

Acid number (mg KOH/g) DIN EN 14104	max. 2.0	0.99
Oxidation stability (h)	min. 6	7.4
Phosphorous content (mg/kg) DIN EN 14107	max. 12	0.8
Calcium +magnesium content (mg/kg) DIN EN 14538	max. 20	1.2
Oxide ash (% m/m) DIN EN ISO 6245	max. 0.01	<0.001
Water content (mg/kg) DIN EN ISO 12937	750	586

3 Engine conversion

3.1 Analysis of the the DPF regeneration unit

The main difference between the stage 3A and 3B engine is the exhaust gas aftertreatment system. The 3B engine is additionally equipped with a DPF system which includes an active regeneration unit. This unit is completely new on JD engines and therefore needs to be investigated thoroughly.

The delivered injection nozzle is fitted into the exhaust gas system. When the fuel pressure is rising the needle will open to inject the fuel.

3.1.1 DK injection

First the nozzle was tested with diesel fuel (DK). The nozzle test stand showed a very low opening pressure. The exact opening pressure could not be measured due to using a standard nozzle test stand with a large scale. The fuel is well dispersed as can be seen in Figure 2.

Figure 2 DK injection on the nozzle test stand

3.1.2 2G-PVO injection

The second test was done with rapeseed oil (2G-PVO-RS). Unlike DK the RS fuel was not well dispersed as can be seen in Figure 3.

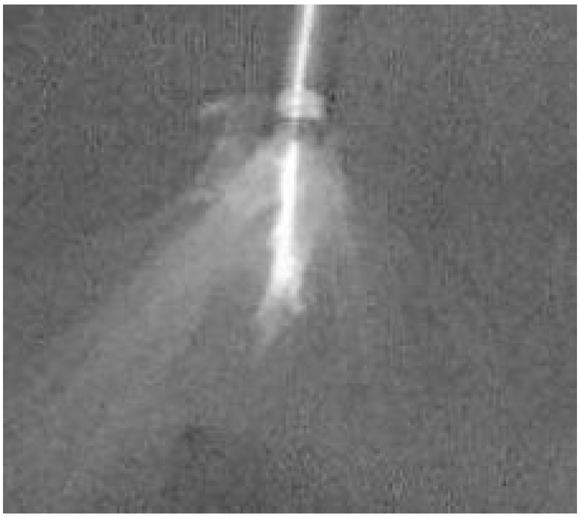

Figure 3 RS injection on the nozzle test stand

4 Results

4.1 Stage 3B baseline testing with diesel fuel

For the first part of the 3B engine testing, diesel fuel was used to understand the series engine control strategy as well as to generate reference values which serve as a basis for all following tests.

4.1.1 Full load performance

The reference full load curves measured with diesel fuel are presented in Figure 4. Though the first measurement was carried out on a totally different test bench at JDPS in Saran, France, the curves fit each other very well. Small differences around 1100 rpm may be caused by an older ECU software version, which was further developed until the beginning of 2nd VegOil testing with this engine.

The goal of the following engine adaptation, especially of the software calibration, is to hit this curve (as a reference the full load curve with diesel fuel on the 1 June 2010 was selected) with 2G-PVO fuels within a margin of +/- 3%, which is die acceptable end of line variance of JD engines.

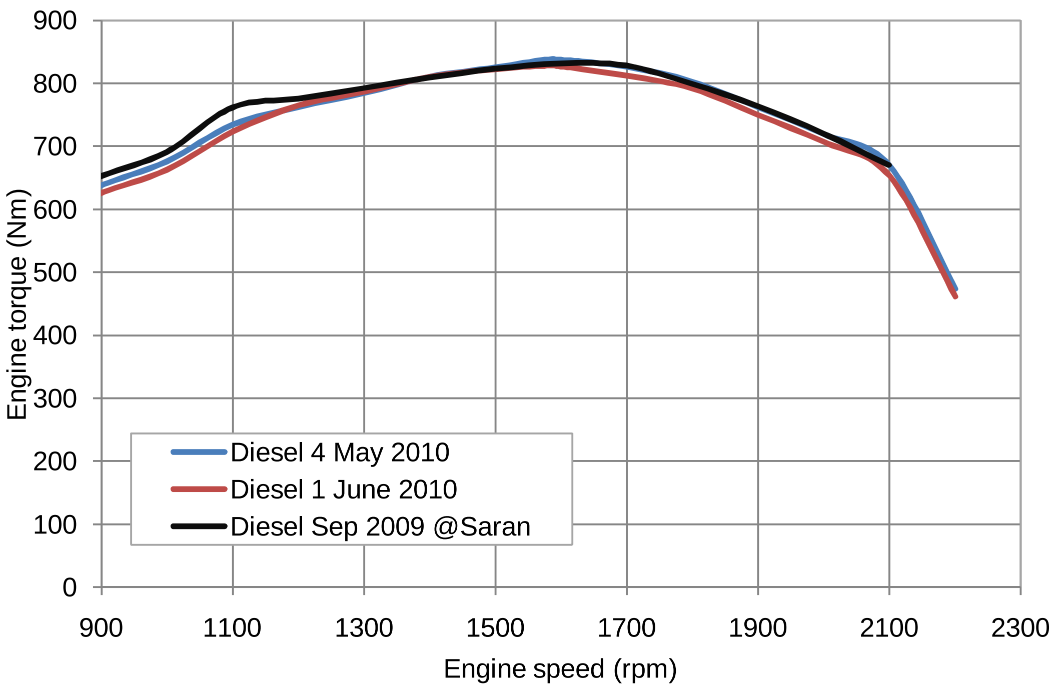

Figure 4 Reference full load curves with diesel fuel (engine CD6068R000040)

4.1.2 Emission testing

At the moment only the NRSC according to 97/68/EC [8] can be performed on the 3B engine test rig. The NRTC [9] will be performed during the following months, after the engine is shifted to another test cell. The results for the gaseous emissions as well as for the PM emissions are listed in the following chapters, though the PM should correctly be measured in the NRTC.

Table 4 **Results of the baseline emission tests with diesel fuel (97/68/EC)**

	Limit of stage 3B	Ante DOC/DPF	Post DOC/DPF
CO (g/kWh)	3.5	0.86	0.07
HC (g/kWh)	0.19	0.11	0.01
NO_x (g/kWh)	2.0	1.65	1.65
PM (g/kWh)	0.025	0.04	0.003

For the certification of stage 3B engines, the emissions after the exhaust aftertreatment system are considered. The emissions upstream the DOC/DPF are although listed, which serve as an indicator of the proper functionality of the DOC/DPF system. The DOC's performance can be evaluated on the one hand by the temperature rise during regeneration (post injected fuel is oxygenated to CO_2 and H_2O in an exothermic reaction). On the other hand especially its long term functionality during non-regeneration modes can be evaluated by the reduction factor of CO and HC emissions, which is decreasing when the catalytic coating is damaged, for example.
The results for HC and CO are far below the stage 3B limits as well as the PM which are reduced by the DPF. Therefore the NO_x emissions are the crucial emission component for further software calibration for vegetable oil fuel, especially as former surveys proved an increase of NO_x emissions with biofuels [1]-[5], [7].

4.2 Stage 3B baseline test with 2G-PVO-RS

The baseline testing with 2G-PVO-RS serves as a reference as well as a functionality test for the engine hardware modifications. The same tests carried out with diesel (full load performance, NRSC) were repeated with rapeseed oil.

4.2.1 Full load performance

For baseline testing with 2G-PVO-RS, the engine hardware was modified. These hardware adaptations were successfully approved during engine operation with diesel fuel. For the first operation with 2G-PVO-RS the engine was operated with diesel, and the biofuel was added to the fuel scales container step by step. This way, the engine could be operated in a load point which is beneficial for vegetable oil fuel, and critical incidents could be anticipated during this initial testing.
The functionality of the engine was approved first with a fuel blend of 50% diesel and 50% 2G-PVO-RS, then with 100% rapeseed oil. For both fuels a full load curve was measured with the series ECU software, see Figure 5. The power decrease is proportional with the biofuel content. This gap has to be closed by software modifications.
The ECU software was adjusted to achieve the series power with vegetable oil, see Figure 6. The difference between the full load curve with vegetable oil and the “version 0” biofuel software is less than 1% compared to the diesel full load curve with series software.

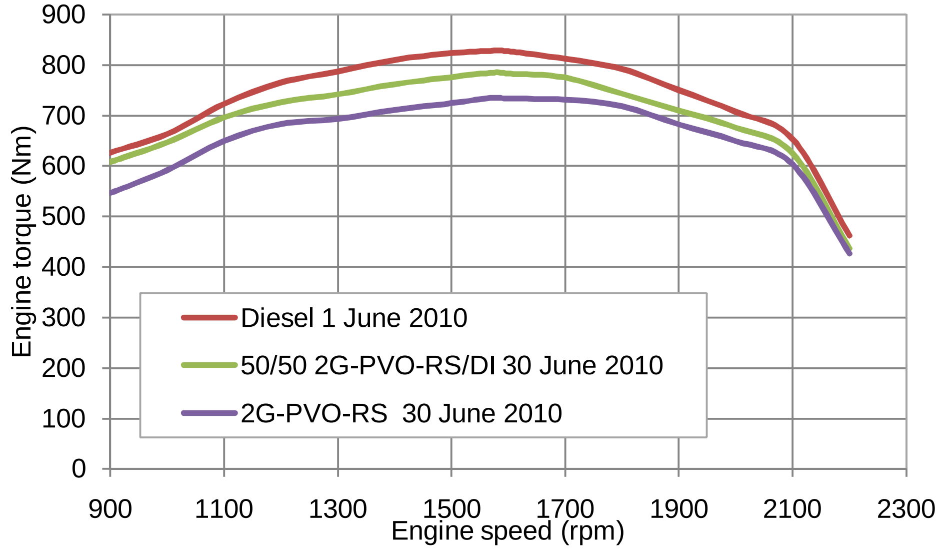

Figure 5 **Full load curves of the CD6068R000040 engine with diesel, 50% rapeseed iol in diesel and 100% rapeseed oil, series software**

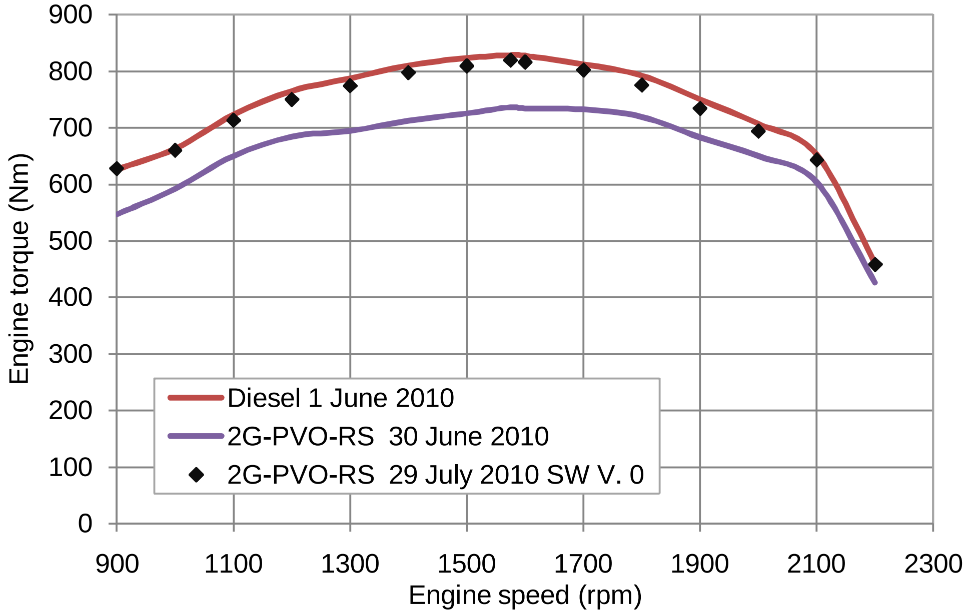

Figure 6 **Full load curves of the CD6068R000040 engine with diesel and rapeseed oil with series software and with rapeseed oil and modified software (vegetable oil SW version No 0)**

4.2.2 Emission testing

Another NRSC was performed with the series SW and rapeseed oil fuel to determine the initial situation with the new fuel. The results are listed in Table 5. As can be seen, the NO_x are increasing with vegetable oil fuel. This effect has to be eliminated by a modified ECU software calibration.

Table 5 Results of the baseline emission tests with 2G-PVO-RS and series software (97/68/EC)

	Limit of stage 3B	Ante DOC/DPF	Post DOC/DPF
CO (g/kWh)	3.5	0.66	0.09
HC (g/kWh)	0.19	0.04	0.01
NO_x (g/kWh)	2.0	2.14	2.17
PM (g/kWh)	0.025	0.04	0.008

Engine out (ante DOC/DPF) HC and CO emissions are below the values of diesel fuel, which was also observed in former surveys [1]-[5], [7]. This phenomenon is explained by the 11% oxygen content of vegetable oil (diesel 0%), which leads to a higher oxygen excess and thus lower CO, HC and PM emissions and higher NO_x emissions.

5 Conclusions from the baseline 3B engine testing

The principle functionality and response of the base JD PowerTech PVX engine (stage 3B) is comparable to its predecessors, the stage 3A JD common rail engines PowerTech Plus., though the aftertreatment system needs to be further investigated.
The next steps will be to modify the HC injection system (pump, doser, injector) to generate a good spray behaviour of the vegetable oil in the exhaust pipe. At the moment, there is no proper spray formation, as the vegetable oil's viscosity is too high at the existing temperatures and pressures. A solution has to be found to increase the fuel temperature as well as the pressure in this post injection system.
An additional approach will be to evaluate potential software adjustments to improve the post injection spray formation. Looking at the ECU control software, there are more tasks which will be discussed in Deliverable 2.5. Besides the DPF regeneration, the software has to be adjusted to comply with stage 3B emission limits with vegetable oil.

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