FUTURE BIOFUELS AND DRIVING CONCEPTS FOR AGRICULTURAL TRACTORS

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ABSTRACT: Based on an expert workshop and experimental results of studies with pure plant oil fuelled tractors, this work shows the state of the art of renewable energy sources for agricultural machinery, such as pure plant oil fuel, biodiesel, bio-methane, hydrogenated vegetable oil (HVO), hydrogen for fuel cells and plug in electrical power systems. For gaseous fuels compared to liquid fuels, the energy content of a filled tractor tank is significantly lower and additionally the number of filling stations is small. Pure electric or hydrogen based powered tractor concepts have not reached any considerable level of development yet. In short or medium term especially pure plant oil fuel and biodiesel are rated to substitute fossil diesel in tractors, reduce greenhouse gases and increase regional added value significantly. Field tests prove that plant oil fuel and biodiesel have reached the highest technical level of development, regarding renewable fuels with an existing infrastructure. Long-term studies on plant oil fuelled tractors confirm high operational reliability, low engine wear, advanced emission behavior and good compatibility to exhaust gas after-treatment technology. Plant oil fuel is particularly suitable for regional production on a smaller scale with high added value.
Keywords: rapeseed oil, vegetable oil, liquid biofuel, alternative fuel vehicle, emissions, operation and maintenance

1 INTRODUCTION

Due to the greenhouse gas emission (GHG) reduction potential, rising energy prices and shrinking fossil resources, gaseous and liquid biofuels are becoming increasingly important. Despite negative environmental impacts, fossil diesel fuel is still dominant for agriculture tractors, because of high economic efficiency. This is mainly due to tax incentives for diesel fuel used in agriculture and forestry. In Germany the agriculture and forestry is consuming 1.6 million tons of fossil diesel every year. However, there are important challenges for sustainable agriculture that need to be considered:

- Reducing the consumption of fossil resources and increasing energy efficiency
- Reduction of greenhouse gas emissions (GHG) and carbon footprint of agriculture products
- Increase self-sufficiency in food and energy supply for higher independency

Future biofuels and alternative driving concepts used for agricultural tractors can feature additional benefits such as regional added value, synergy effects with feed production and protection of soil and water. There are many differences in the state of the art, for external effects and the process chains of alternative biofuels which have to be evaluated entirely.

Biofuels are subject to various international and national regulations, for example the Renewable Energy Directive (RED), which defines legal thresholds for GHG emissions of biofuels and GHG emission savings compared to fossil fuels [10].

According to the RED [10] currently biofuels have to have a greenhouse gas reduction potential of at least 35 percent. It is required to prove a minimum GHG reduction of 50 percent from the year 2017 and 60 percent from the year 2018 to get energy tax benefits and the eligibility for crediting to the biofuel quota.

Further, gaseous and particulate emissions from the guidelines 1997/68/EG and 2004/26/EG (Non-Road Directive) are also limited. In the 2014 valid U.S. Tier 4 / EU Stage IV regulations in comparison to 1999, a reduction of particulate emissions by 96.5 percent and the nitrogen oxides NO_X of 95.7 percent is required.

Studies and monitoring of biofuels and driving concepts for tractors are necessary to determine the state of the art and to deduce favorable future technologies.

There are specific technical and logistical conditions for driving concepts in agricultural machinery compared to on-road vehicles:

- The scale of the production is much lower and hence the development budget.
- There is little space for attachments on the tractor (e.g. fuel tank or battery).
- The fuel must be provided on the farm, if not a public filling station is nearby.
- Agricultural machines have a high energy demand and require a high range of operation modes for efficient work.
- The work will often be carried out in environmentally sensitive areas.

Based on a workshop with 24 experts from industry, associations and sciences in co-operation with the Association for Technology and Structures in Agriculture (KTBL) the current technical state of development and future options for alternative agricultural driving concepts have been discussed [9].

Furthermore, experimental results of studies at the Technology and Support Centre (TFZ) demonstrate operation reliability, performance and emissions behavior of plant oil fuelled tractors in practice.

2 APPROACH

2.1 Expert workshop

On an expert workshop in co-operation with the Association for Technology and Structures in Agriculture (KTBL) [9] a questionnaire were worked out and used to evaluate the following six future fuel and driving concepts.

- **Biodiesel** or FAME (fatty acid methyl ester) in conventional combustion engines
- Pure **rapeseed oil** fuel in compatible combustion engines

- **HVO** (hydogenated vegetable oil) for conventional combustion engines
- **Bio-methane** from biogas for combustion engines
- **Hydrogen** in in fuel cells for electrical power drives
- Fully **electric** powered tractors with energy storage in batteries

The 14 following evaluation criteria were queried, and graded from 0 to 4:

- **Potential** and availability of **feedstocks** for energy and fuel production
- **Progress of development** in research and application in tractors
- State of development of **energy carrier allocation** technologies
- **Energy efficiency** throughout the value chain
- **Infrastructure** for distributing the fuel or energy (e.g. gas or service stations)
- **Greenhouse gas emissions (GHG)** generated by using the fuel or energy
- **Quality management and standardization** for fuel production and storage
- **Costs** of purchase and application of the technology
- General **acceptance** by the consumer and population
- **Participation** of the **agriculture** in the added value of the alternative energy carrier production
- **Timeline and** expected **market introduction**
- **Protection** of **water and soil**, if the fuel is released into the environment
- **Level of self-sufficiency** in food and energy supply
- **Control** of **air pollution** generated by using engines

A value of 0 means a negative and a value of 4 a positive valuation of the criterion. The experts were also able to assess the importance of each evaluation criteria. A value of 1 means a low, 2 a middle and 3 a high importance. The result is a common weighted average value for each fuel or driving concept.

2.2 Studies with pure plant oil and bio-methane fuelled tractors

Objects of investigation are 13 plant oil compatible tractors (Table I), 12 of them are being operated at test farms of the Bavarian State Research Center for Agriculture (LfL). Most tractors are fully adapted to pure rapeseed oil usage (single-tank system) without using a secondary fuel system for cold starts or idle/low load operation. Four tractors, however, are equipped with a two-tank solution and featuring a fuel management system, which provides fuel from either, the plant oil or diesel tank depending on the operation mode. During test stand measurement the fuel management system is deactivated for better comparison. This means that during each test cycle, solely one type of test fuel was used. Most tractors fulfill exhaust stage IIIA, two even meet the latest exhaust stage IIIB (corresponding to Tier 4i).

Table I: Data of monitored tractors

Tractor type	Year of manu-facture	Ex-haust stage	Engine/ injection	Engine power in kW	Fuel tanks no.
John Deere 6210R	2012	IIIB	6 cyl. CR[1)]	154	1
Fendt 718 Vario	2012	IIIB	6 cyl. CR[1)]	133	2
John Deere 6630	2012	IIIA	6 cyl. CR[1)]	103	1
John Deere 7830	2010	IIIA	6 cyl. CR[1)]	147	1
New Holland T6080	2010	IIIA	6 cyl. CR[1)]	135	1
Deutz-Fahr M 650	2010	IIIA	6 cyl. CR[1)]	134	2
John Deere 6630	2010	IIIA	6 cyl. CR[1)]	103	1
Fendt 820 Vario greentec	2009	IIIA	6 cyl. CR[1)]	152	2
Fendt 820 Vario greentec	2009	IIIA	6 cyl. CR[1)]	152	2
John Deere 6930	2008	IIIA	6 cyl. CR[1)]	114	1
John Deere 6930	2008	IIIA	6 cyl. CR[1)]	114	1
Deutz-Fahr 1160 Agrotron TTV	2005	II	6 cyl. PLN[2)]	119	1
Fendt 412 Vario	2003	I	4 cyl. PLN[2)]	94	1

[1)] CR = Common-rail injection
[2)] PLN = Pump-line-nozzle

Emission testing is based on the standard procedure of ISO 8178-1 [8]. Differing from type approvals, where engine test stands are used, here the measurement is done at the tractors with mounted engines (Figure 1). The power is measured at the power take-off (PTO) with a dynamometer (EGGERS PT 301 MES). As testing cycle the stationary 8-mode-test, which is also known as Non-Road-Steady-Cycle (NRSC) is applied.

Figure 1: Plant oil compatible tractor at test stand of the Technology and Support Centre (TFZ)

Within the NRSC the emission results of every single test stage are added up with consideration of specified weighting factors. At the end of a measurement the emission results over the whole test cycle are calculated in g/kWh$_{PTO}$. A detailed description of the exhaust gas test stand is given in Thuneke et al. (2009) [5].

Measured exhaust gas emissions are nitrogen oxides (NO_X), carbon monoxide (CO), hydrocarbons (HC) and particulate mass (PM), which are limited by law and thus referred to as "limited components". Besides the emission concentrations, the power at the rear power take-off (PTO), torque and fuel consumption are logged continuously.

As reference fuel specified diesel test fuel (CEC RF-06-03) was used. Tested plant oil fuel was cold-pressed rapeseed oil, complying with the national German standard DIN 51605 [1] for rapeseed oil or plant oils according to the standard DIN SPEC 51623 [2].

3 RESUTLS AND DISCUSSION

3.1 Expert workshop

As result of the questioning of 24 experts, pure rapeseed oil (2.75) and biodiesel (2.56) are rated in sum with highest values as best options for alternative driving concepts in agriculture and forestry machinery. Figure 2 shows the average consent to each discussed fuel or driving concept over all criteria. Electrical power (2.09) and bio-methane (2.04) concepts have a significantly lower level of approval. Future concepts with HVO (1.59) and hydrogen (1.48) received the lowest mean value.

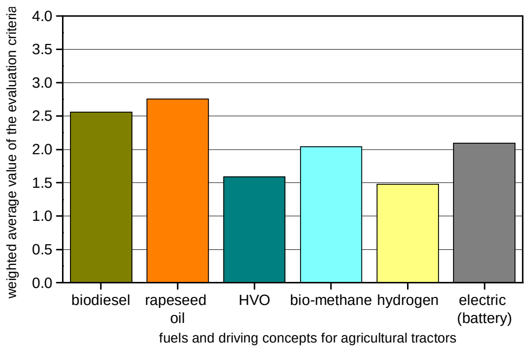

Figure 2: Results of the evaluation for different driving concepts and fuels for agricultural tractors

The results of the different evaluation criteria vary considerably according to the fuel, which can be seen in Figure 3. The high weighting of all evaluation criteria showed that all criteria must be considered.

Due to the same raw material base, pure rapeseed oil and biodiesel have close corresponding reviews. For these two options the timeline, progress of development, infrastructure and energy efficiency were much better evaluated than for all other options. A possible reason is that pure rapeseed oil and biodiesel fuelled machines have been available on the market for years, whereas HVO, bio-methane, hydrogen and electric powered tractors are still in the research stadium. The quality of pure rapeseed oil and biodiesel is also standardized.

These so-called first generation fuels are also evaluated as the most economical and energy efficient alternatives to diesel. However, there are slightly higher advantages for pure rapeseed oil in the level of self-sufficiency, participation of the agriculture as well as water and soil protection. Pure rapeseed oil is often produced regionally in oil mills and the fuel is classified as harmless to water and soil. In contrast biodiesel is produced in larger scale plants and is classified in water hazard class 1 (slightly water hazardous). According to the experts, biodiesel and rapeseed oil have the best feedstock potential and infrastructure.

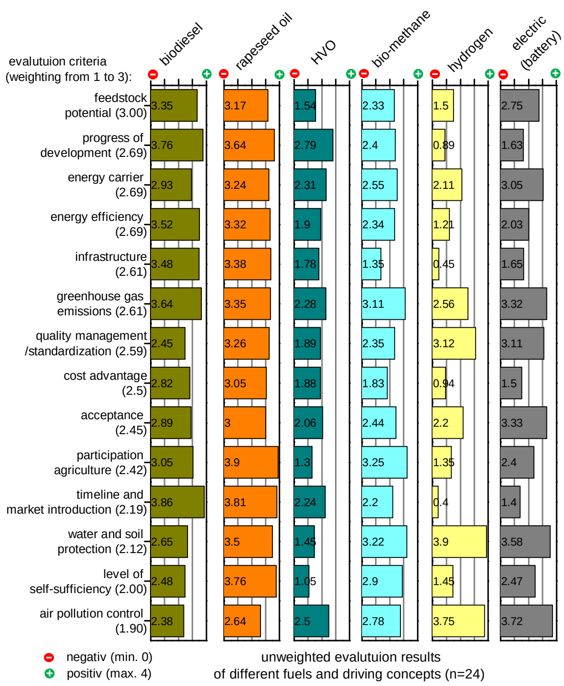

Figure 3: Results of the evaluation for various criteria for different driving concepts and fuels for agricultural tractors

The gaseous fuels bio-methane and hydrogen provide, in addition to liquid biofuels, another way to use renewable energies in the mobility sector. There are already prototype gaseous fuelled tractors from different manufactures. It becomes apparent that in the survey, the gaseous fuels achieved positive consent in the evaluation criteria air pollution control, water and soil protection, quality management and greenhouse gas emission reduction.

In Germany about 900 bio-methane filling stations exist, which are primarily used by cars and buses. Hydrogen filling stations are not common in Germany. The lack of infrastructure is a significant barrier for the use of gaseous fuels in agriculture and forestry. Similar to decentralized liquid fuels the experts think that bio-methane produced by upgrading biogas increases the value added in the agricultural sector. The costs of bio-methane were considered critical because of the complex after-treatment of biogas, which is only economically efficient in large-scale plants. First results of actual in-field and test stand studies with a bio-methane tractor are validating a good technical standard.

First results regarding the operation behavior of HVO fuelled on-road vehicles are available, which is reflected positively in the valuation of the progress of development. Due to similar physical properties like diesel, HVO can be used in diesel engines without adaptation, but practical experiences in tractors are not available yet. Similar to hydrogen the experts see problems in feedstock availability, participation of the agriculture and level of self-supply.

According to the survey, electric drive concepts have a high level of acceptance. The use of electricity as a mobile energy source indicates advantages in energy carrier allocation, quality management as well as water and soil protection. In terms of avoiding greenhouse gas emissions the use of renewable electricity, rapeseed oil and biodiesel in mobile machines offers the greatest advantages. Additionally there is a potential to use temporary surplus electricity from renewable sources, such as wind or solar power. On the other hand there are many hurdles, regarding on-board storage technology of electric energy in terms of energy efficiency, weight, costs etc. of accumulators.

3.2 Field studies with pure plant oil

Operating behavior

Two plant oil operated tractors (exhaust stages I and II) proved their full suitability in everyday use, performing more than 10,000 operating hours altogether. Investigation of eight further tractors (exhaust stage IIIA) overall with a runtime of more than 15,000 hours and two tractors with exhaust stage IIIB showed no considerable failures or damages.

Even exhaust gas after-treatment systems enabled a reliable operation with high emission reduction efficiency.

Exemplary for the long-term durability of rapeseed oil powered tractors the engine of the Deutz-Fahr Agrotron TTV 1160 was inspected after 1,171 and 4,600 h. The inspection confirmed the good condition of tractor in terms of wear and deposits. Figure 4 shows the injection holes of the six-hole nozzle. The injectors were examined by light microscopy and basically every injection hole was visible. Despite visible deposits on injectors, injection quality was not affected seriously, which could be confirmed by the positive results of the spray pattern test.

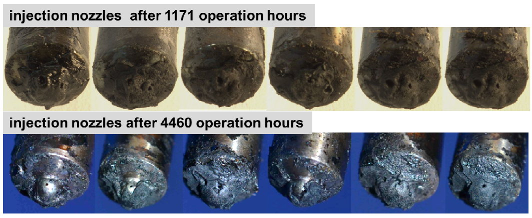

Figure 4: Injection nozzels (no. 1 to no. 6 from left to right) of Deutz-Fahr Agrotron TTV 1160 (exhaust gas stage II) at engine inspection after 1171 and 4460 h.

As seen in Figure 5 the analyses of the engine oil demonstrate the necessity of a more frequent engine oil exchange for the vegetable oil compatible tractors with pump-line-nozzle injection, due to the typical accumulation of vegetable oil fuel. However, for all tractors of stage IIIA and beyond with common-rail injection the amount of fuel, accumulating in the engine oil is very low. This indicates a proper combustion and results in reduced maintenance, which is comparable with diesel operation. For example fuel accumulation in engine oil for the John Deere tractors was less than 4 % after 500 operating hours.

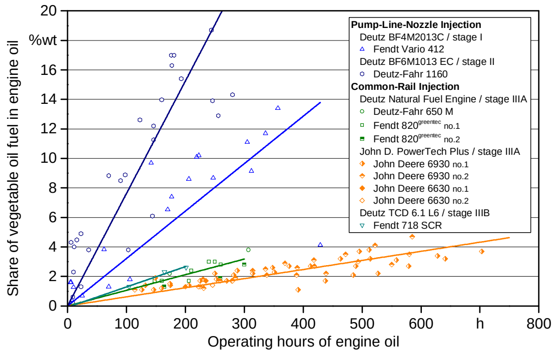

Figure 5: Share of vegetable oil fuel in engine oil over operating hours of engine oil of various tractors (analysed values and trend lines)

Emissions

The exhaust gas components nitrogen oxides (NO_X), carbon monoxide (CO), hydrocarbons (HC) and particulate mass (PM) are determined at a tractor test stand. Figure 6 gives an overview of the results of emission measurements for a tractor with exhaust gas stage IIIB with rapeseed oil and diesel fuel after 10, 50 and 250 operation hours. The tractor is equipped with a two-tank fuel-system, engine settings were left unchanged. The height of the columns in figure 6 corresponds to the arithmetic average of three repetitions.

The 8 percent higher NO_X emissions in the untreated exhaust emissions result from fuel born oxygen in rapeseed oil and higher combustion temperatures, both factors that stimulate NO_X-formation. However, the oxygen in the fuel causes 30 percent lower HC emission of the engine. Over 200 h operation on the test farm, the untreated engine emissions were nearly constant with rapeseed oil.

There is a significant reduction of the NO_X and HC emission level through the selective catalytic reduction (SCR-System) and oxidation catalyst after-treatment. Measurements after 10 and 50 h with rapeseed oil and diesel fuel show a high efficiency of 89 percent in the NO_X reduction and 94 percent in the HC reduction over the test cycle. As a result of 200 h field test operation, there is a slightly decreased NO_X reduction efficiency. It is not clear whether the efficiency decrease was caused by the use of rapeseed oil, or if these are normal running-in effects of the SCR-System, which can occur with permanent diesel usage as well. Further testing will validate if it is a permanent trend.

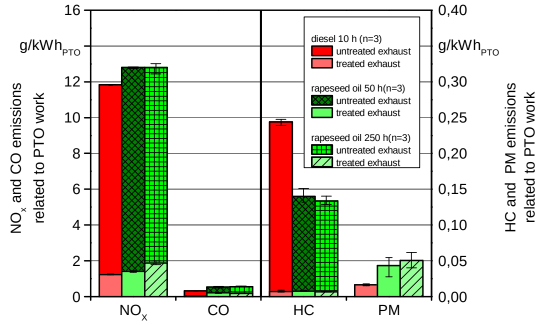

Figure 6: Emissions of a stage IIIB Fendt Vario 718 tractor after 10 hours (diesel), 50 and 250 hours (rapeseed oil) with and without exhaust gas after-treatment system

The marginal higher PM emissions with rapeseed oil are mainly an effect of the idle operation phase in the test cycle. In practice idle operation with rapeseed oil is avoided by switching to diesel supply (two-tank fuel-system. Optimization of injection parameters can also result in improvements.

Overall, despite the non-adapted motor settings, there are very low concentrations of NO_X, CO and HC in the after-treated exhaust gas, which were under the limiting values of exhaust stage IIIB. The PM emissions are on a very low level, too and close to the limiting value. With convenient optimization of engine parameters a significant reduction seems to be possible.

Considering the higher values determined at a tractor test stand (by referring them to the work at the power take-off) in comparison to crankshaft related values at engine test stands for type approvals, the relevant limiting values can be met by all tractors with diesel and rapeseed oil fuel.

The results demonstrate an equal good operation and emission behavior as investigated in studies from Hassel et al. (2005) [3], Rathbauer et al. (2008) [4], Dieringer et al. (2011) [7], Thuneke et al. (2009) [5] [11] and Emberger et al. (2013) [6] up to exhaust emission stage IIIA.

A sample calculation in Figure 7 displays the positive external effects in consequence of the use of rapeseed oil fuel for 28,000 operation hours on the test farms. It becomes apparent that due to the coupled production of protein press cake and rapeseed oil some 460,000 kg soy protein feed imports, 260,000 liters of fossil diesel and 513,000 kg of CO_2 equivalent greenhouse gases were avoided. The straw, roots and stubbles are an organic fertilizer for the next crop.

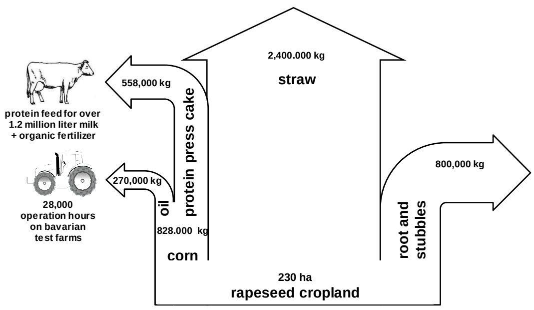

Figure 7: Material flows and external effects due to the demand of 270,000 liters of rapeseed oil fuel through field test (sample calculation)

4 CONCLUSIONS AND OUTLOOK

In the next decades combustion engines will continue to be the key drive technology for agricultural tractors and machinery. The expert survey shows that rapeseed oil according to current knowledge is the best way to drive tractors sustainably. Biodiesel have reached nearly the same level of consent. The lack of infrastructure is a significant barrier for the use of gaseous fuels like bio-methane in agriculture and forestry. A soon market launch of HVO, hydrogen and electric powered tractors is currently not expected. Due to heterogenic advantages all options have to be pursued and not be excluded prematurely.

The monitored field-test tractors (exhaust gas stage I, II, IIIA and IIIB) have proved full suitability with over 28,000 operating hours in everydays use. The inspection of engines from tractors with up to almost 5,000 operating hours confirmed the very good condition of the tractors. Performance and fuel consumption showed no changes during the investigated period. Even exhaust gas after-treatment systems enabled a reliable operation with significantly lower emissions. Differences between plant oil and diesel fuel are not evident at low emission levels such as exhaust stage IIIB.

Plant oil fuel is particularly suitable for regional production at a smaller scale and is ideally linked to the provision of protein feed, mainly for cattle and dairy farming.

For a higher share of plant oil fuel used in agricultural machinery public relation work has to be enhanced and framework conditions have to be improved for market stimulation. Measures can be for example:

- European harmonisation of taxation of fossil diesel fuel used in agriculture and forestry
- Tax incentives for biofuels, used in the agriculture and forestry sector
- Investment grants for plant oil fuel compatible agriculture and forestry machinery
- Consulting of farmers
- Encouragement of industry, farmers and politicians regarding promotion of future fuels and driving concepts in agriculture and forestry
- Increase of fuel efficiency and saving of fossil fuels as basic requirement for the transition to sustainable fuels and driving concepts in agriculture and forestry.

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