

Potential of Hydrogenated Vegetable Oil (HVO) in Future High Efficiency Combustion System

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ABSTRACT

The limited availability of fossil fuels and the increasing environmental pollution will lead to an increased demand for sustainable biofuels. The production of bio-based diesel fuels from vegetable oils is commonly accomplished using a process known as Trans-esterification. The product of Transesterification is Fatty Acid Methyl Ester (FAME), commonly known as Biodiesel. An alternative process is Hydro-treatment of seed oils or animal waste fats to produce highly paraffinic renewable diesel fuel called Hydrogenated Vegetable Oil (HVO).

Detailed investigations were carried out by the "Department of Advanced Diesel Engine Development" at FEV GmbH Aachen (Germany), to explore the potential of this biofuel compound as a candidate for future compression ignition engines.

Engine results of pure HVO fuel are compared to petroleum based diesel fuel (B0) and rapeseed oil methyl ester (B100) at different part load and full load points with respect to combustion behavior, engine efficiency, combustion sound level (CSL) and emission performance.

To ensure that the findings are relevant for modern automotive business, the testing program was carried out on a EURO 6 compliant High Efficiency Diesel Combustion System (HECS) designed for future passenger car applications.

The results indicate that at lower part loads, the higher cetane number of HVO fuel leads to lower ignition delay periods, resulting in decreased soot reduction potential and improved CSL behavior. On the other hand, at medium and high part load operations, soot emissions with HVO reduced approximately 50% - 60% due to almost aromatic free fuel composition. Furthermore un-burnt HC and CO emissions for HVO were observed to be lowest amongst all investigated fuels.

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INTRODUCTION

With the globally increasing energy demand and the need for energy security, several kinds of energy sources need to be considered. With regard to diesel fuel based automotive applications; many alternative fuels are being discussed and explored as viable solutions. Among them, fuels derived from biological sources have received increasing attention.

The availability of biofuels for transportation throughout the world depends significantly on the socio-economic and political circumstances. For example United States and Europe have already stipulated defined targets for use of biofuels in transportation sector. In the European Union, 10% of the energy content consumed by passenger vehicles in 2020 shall be gained from renewable sources. The US is

planning an increase in the total amount of renewable fuels to be sold from 14 billion of gallons per year in 2011 to 36 billion of gallons in 2022. In relation to the total US transportation energy consumption in 2009, this directive equals a consumed energy fraction of 15 % in 2022 [1, 2, 3, 4]. Figure 1 shows target energy market share of biomass derived fuels according to US and EU legislation.

As per new EU directive on use of biofuels, the EU commission wants to promote only those biofuel candidates that are not produced from edible feedstock. In this context, EU has issued a guideline to limit the share of first generation biodiesel to a maximum of 5 % v/v. The commission has proposed to meet the existing bio-quota target of 10 % by the

year 2020 using biofuel production from waste biomass sources, algae and other non-food cellulosic materials [5].

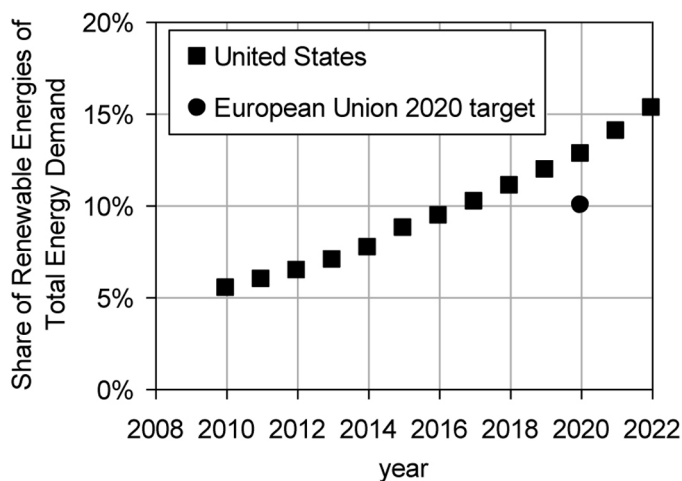


Figure 1. Target energy market share of energy from biomass according to US and EU legislation [1, 2, 4]

Biofuels like Straight Vegetable Oils (SVO) and Fatty Acid Methyl Esters (FAME) derived from vegetable oils or animal fats are commercially available for use. A biofuel candidate which shows good future potential and is already commercialized is Hydrogenated Vegetable Oil (HVO). To date, Synthetic bio based liquid fuels developed from Fischer Tropsch process are produced only on the pilot scale. In FT synthesis, highly complex structures of the plant material are decomposed to form a mixture of CO and H₂ (synthesis gas) involving high temperature processes. These fuels can be produced using waste biomass, as well as other non-food cellulosic raw materials. The physicochemical properties of Fischer-Tropsch fuels (GtL / BtL) are similar to HVO.

The chemical characteristics of the mentioned biofuels (hydrocarbon chain length and distribution, bonded oxygen content & its functionality, sulphur content, ash etc.) are considerably different from the petroleum based diesel fuels.

Hydrogenated Vegetable Oils are paraffinic based liquid fuels produced from vegetable oils, recycled oils or animal fats. HVO fuel does not contain poly aromatic hydrocarbons and sulphur, which aids in particulate matter formation and faster deterioration of sophisticated exhaust after treatment catalysts respectively.

The increased amount of paraffinic components in HVO fuel and the absence of aromatics lead to a high cetane number (CN). High CN can help in reducing the ignition delay time, improving the cold start ability, as well as diesel knock. Several studies have been conducted for the evaluation of HVO fuels in diesel engines [6,7,8,9,10,11,12,13].

In modern passenger car diesel engines the amount of fuel injected into the combustion chamber is controlled by the energizing time of the fuel injector and the fuel pressure. Thus, the maximum power output of the engine is related to both, the engine parameters (such as efficiency, injector energizing time, fuel pressure) and fuel properties (such as, energy content of the fuel, density and viscosity). HVO fuel, due to its paraffinic nature, has lower density compared to petroleum based diesel fuel. Consequently the volumetric energy content of HVO is lower than petroleum based diesel fuel. In common rail injection systems it has been seen that with the same indicated injection duration, larger volume of paraffinic fuel is actually injected in the cylinder, which compensates the difference in volumetric energy content. With this type of injection system HVO produces the same engine power and torque as EN 590 diesel [7].

The emission performance of HVO fuel is better than EN590 diesel fuel in a Euro 5 passenger car. Typical CO and HC emissions are reduced by more than 50 % while particulates and smoke emissions are reduced by over 30 % with essentially the same NO_x emission. [7, 14, 15]. The previous studies on first generation biodiesel (i.e. FAME) show that the impact of use of biodiesel on exhaust gas emissions largely depends on the engine technology and duty cycle. Concerning particulate matter emissions, a decreasing trend is observed with neat biodiesel, whereas NO_x emissions showed a slightly increased trend. Previous works have shown that increased oxygen content in the fuel results in significant reduction of particulate emissions [16,17,18]. On the other hand, there are several research issues associated with the use of oxygenated fuels and FAME in modern combustion engines. For example, problems concerning material compatibility and oxidation stability can occur as a result of the oxygen in the fuel [19]. The problems concerning injector coking and plugging of fuel filters have been reported in several previous studies. With regard to fuel quality, a wide variation is observed in the quality of FAME available in the US and EU [20]. Keppeler et. al. have reported increase of emissions due to aging of biodiesel [21]. Due to these issues associated with FAME, the use of FAME is limited to 7% by all the Fuel Injection Equipment (FIE) manufacturers [22, 23].

The lower volumetric energy content of 100 % HVO means about 3% - 5 % higher volumetric fuel consumption than with EN590 diesel fuel but still lower consumption than with 100 % FAME [6]. Investment costs of HVO production are higher than for FAME production. This makes the entry to the already existing biofuels market very challenging despite the advantage in product quality and properties. Currently there are over two million tons per year of production capacity of HVO made available by two companies in Europe, Asia and USA. More capacities are being planned by additional companies and are scheduled to come into production in 2013 and 2014. In comparison to HVO volumes, there is approximately 50 million tons per

year production capacity already available for FAME [6, 31, 32]

The goal of the investigations described in this paper is to make statements regarding the behavior of hydrogenated vegetable oil (HVO) on a Euro 6 compliant high efficiency diesel combustion system. Engine results of pure HVO fuel are compared to petroleum based diesel fuel (B0), used as a reference fuel, and a commercially available first generation biofuel, rapeseed oil methyl ester (RME-B100). The test conditions were optimized by means of a Design of Experiment (DOE) approach at four engine part-load conditions and full-load, which represents a wide range of engine operation including NEDC load points.

The results are compared with regard to combustion behavior, engine efficiency, combustion sound level (CSL) and emission performance. To maintain identical engine operating conditions and assure valid comparability conditions, all measurements were carried out at constant Indicated Specific NO_x levels. Furthermore the centre of combustion (CA_{50}) was also maintained constant irrespective of the fuel properties.

EXPERIMENTAL APPARATUS AND TEST CONDITIONS

Single Cylinder Research Engine

The single-cylinder diesel research engine used for the present work is optimized for improved combustion characteristics with regard to low emission levels and at the same time high fuel efficiency [24,25,26]. The hardware enhancements include high fuel injection pressures and stronger charge air and exhaust gas recirculation cooling, to achieve low intake charge temperatures even at the highest EGR rates.

To optimize the flow characteristics, one intake port is designed as a filling port and the other as a classic tangential port. Creating the charge movement is supported by seat swirl chamfers on both intake valves. The layout of the combustion chamber geometry shows a conventional recess shape, which was further optimized together with the nozzle geometry (8-hole, $\text{ks}=1.5$) in order to achieve the best possible air utilization. The recessed valves make it possible to eliminate valve pockets in the piston and thus further improve the flow quality near the recess. A compression ratio of 15:1 was selected to represent acceptable peak pressures in spite of the increased charge density. The combustion system reaches a specific output of 80 kW/l at maximum peak firing pressures under 190 bar. An advanced common rail system is used as injection system; the injector can quickly open and close the nozzle needle at a maximum injection pressure of 2000 bar. Reducing the compression ratio, using a higher maximum cylinder and rail pressure, as well as improved EGR cooling makes lowest particulate emissions possible. As a result the research engine meets the Euro 6 standard (Engine out raw NO_x emissions Euro 6 level and an use of DPF is necessary

for meeting PM emission limit). The performance of the single-cylinder diesel engine thus exceeds that of currently available production engines. These technical enhancements will also be implemented in future diesel engines. Table 1 shows a summary of the details of the test engine used. Additional information on the single-cylinder research engine can be found in [24,25,26].

Table 1. Hardware specifications for the research engine

Parameters	Units	Specifications
Emission Status	-	Euro 6
Displacement	cm^3	390
Stroke	mm	88.3
Bore diameter	mm	75
Compression ratio	-	15
Valves per cylinder	-	4
Maximum peak pressure	bar	220
Maximum injection	bar	2000
Hydraulic Flow Rate (HFR)	$\text{cm}^3/30\text{s}$	310
Nozzle hole diameter	μm	109
Number of spray holes	-	8
Spray Cone Angle	$^\circ$	153
Charging level	bar	Max. 3.5 bar (Absolute)

Engine load points

Engine tests for the fuel investigations were carried out in four part load points, as shown in Figure 2.

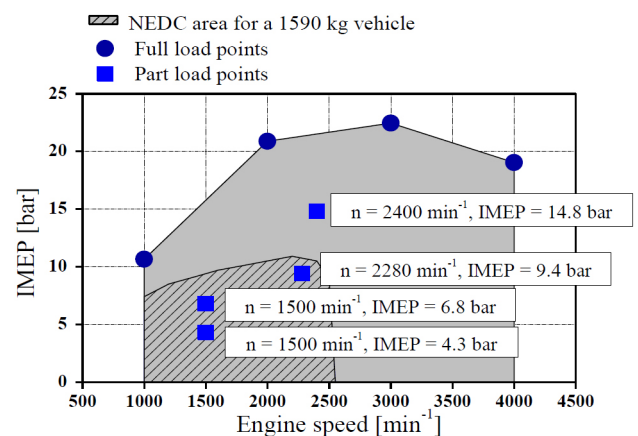


Figure 2. Engine operating points representative to NEDC driving profiles

Three of the four part-load points are located within the reference area of the New European Driving Cycle (NEDC) while the highest load point at 2400 rpm and 14.8 bar Indicated Mean Effective Pressure (IMEP) is either within NEDC range or outside this range depending upon vehicle inertia class. Full load behavior was also tested at three different engine speeds (i.e. 2000 rpm, 3000 rpm and 4000 rpm). The full load points were evaluated to ensure acceptable engine operation and ensure that the engine could

meet the required performance levels. Full load operation was limited by either the smoke emissions or the exhaust gas temperature. Based on the NEDC, the maximum Indicated Specific NO_x (ISNO $_x$) and Indicated Specific PM (ISPM) emissions were estimated for each part-load point. The estimation of target emission level for different Euro norms are based on a quasi-stationary approximation of operation modes in NEDC cycle with reduced number of operation points considering the appropriate weighing factors. These targets take into account the expected impact of transient operation and cold start and include an appropriate engineering margin. The estimated NO_x and PM target levels are summarized in [Tables 2](#) and [Table 3](#). Investigations on a chassis dynamometer confirmed these estimated targets [25].

For NO_x emissions, the objective is to meet the different Euro emission limits using engine internal measures (i.e. through the use of EGR) without NO_x exhaust after treatment. However the use of a particulate filter is necessary to meet the PM emission limits. It should be noted from the [Table 3](#) that Euro 5 and Euro 6 engine out ISPM emission targets were maintained same considering implementation of diesel particulate filters (DPF) in most of the present day and future passenger cars.

Table 2. Estimated Indicated Specific NO_x (ISNO $_x$) targets required to meet different Euro Emission limits at the four part-load operating points used in the present study [25]

ISNO $_x$ [g/kWh]	1500 rpm, 4.3 bar IMEP	1500 rpm, 6.8 bar IMEP	2280 rpm, 9.4 bar IMEP	2400 rpm, 14.8 bar IMEP
Euro 4	0.6	0.6	1.8	2.25
Euro 5	0.4	0.4	1.2	1.50
Euro 6	0.2	0.2	0.6	0.75

Table 3. Estimated Indicated Specific PM (ISPM) targets required to meet different Euro Emission limits at the four part-load operating points used in present study [25]

ISPM [g/kWh]	1500 rpm, 4.3 bar IMEP	1500 rpm, 6.8 bar IMEP	2280 rpm, 9.4 bar IMEP	2400 rpm, 14.8 bar IMEP
Euro 4	0.0030	0.0279	0.0706	0.2129
Euro 5	0.0006	0.0056	0.0141	0.0426
Euro 6	0.0006	0.0056	0.0141	0.0426

The engine operating parameters and calibration of different part load points have been summarized in [Table 4](#).

Table 4. Engine Calibration of different load points

	Center of Combustion (CA $_{50}$)	Rail Press- ure	Boost Press- ure	Exhaust Back Press- ure	Charge Air Temper- ature
	°CA ATDC	bar	bar (abs)	bar (abs)	°C
n=1500 min $^{-1}$; IMEP=4.3 bar	6.6	720	1.07	1.13	25
n=1500 min $^{-1}$; IMEP=6.8 bar	5.8	904	1.5	1.60	30
n=2280 min $^{-1}$; IMEP=9.4 bar	9.2	1399	2.29	2.39	35
n=2400 min $^{-1}$; IMEP=14.8 bar	10.8	1800	2.6	2.80	45

Test Fuels

Three different diesel fuels were used for the present investigations. Petroleum based diesel fuel was used as reference for baseline tests and other two fuels are derived from biogenic sources, out of which one fuel has oxygen content in the fuel molecular structure.

Petroleum based diesel fuel consists of approximately 200 different types of hydrocarbons. EN 590 Diesel available in Germany at fuelling stations contains approximately 5%-7% FAME. For the present studies we used a Diesel fuel (without FAME) as baseline reference fuel instead of EN 590 diesel fuel to avoid any influence of FAME content (in particular oxygen content) on combustion and emission characteristics.

One of today's commercially available 1st Gen. biofuel candidate investigated is a FAME known as Biodiesel (B100). The FAME used in this study was a Rapeseed Oil Methyl Ester (RME) that conforms with EN 14214 specifications. It consists of saturated as well as unsaturated fatty acids with 12 to 22 carbon atoms. Rapeseed methyl ester is a first generation biodiesel fuel which is already admixed today to fossil Diesel. Although B100 consists of approximately 10 w-% of oxygen, several properties like the cetane number or the upper boiling range are comparable to conventional Diesel fuel. [16,17,18,19,20,21].

Another biomass derived fuel candidate selected for this study is a Hydrogenated Vegetable Oil. In the HVO production process, hydrogen is used to remove oxygen from the triglyceride vegetable oil molecules and to split the triglyceride into three separate chains thus creating paraffinic hydrocarbons which are similar to existing diesel fuel components. The paraffins are further isomerized to improve