

Hydrotreated Vegetable Oils, Biomass to Liquid and Fatty Acid Methyl Ester as Biogen Admixtures for Diesel Engines in Passenger Cars

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ABSTRACT

The increasingly stringent emission legislation worldwide and the demand for independence from fossil energy carriers represent major challenges for the future development of diesel engines, particularly for maintaining the diesel engine's positive characteristics, such as its dynamic driving performance and fuel economy, while drastically reducing emissions. This survey investigates alternative fuel blends used in a state-of-the-art EURO 6 diesel engine with different shares of biomass to liquid, hydrotreated vegetable oils and fatty acid methyl ester, which present a possibility to meet these requirements. In particular, the reduction of particulate matter and, as a result, the possibility to reduce nitrogen oxides emissions holds remarkable potential for the application of synthetic fuels in diesel engines. The investigated fuel blends generally demonstrate good applicability when used in the test engine with standard settings. Adaptions to engine parameters (e.g., injection timing or exhaust gas recirculation) hold further potential. With respect to the EU's targeted 10% bio-quota by 2020 two ternary fuel blends containing conventional diesel fuel, fatty acid methyl ester and biomass to liquid or hydrotreated vegetable oils were also tested and featured excellent performance in terms of emissions and efficiency.

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INTRODUCTION

Diesel engines combined with modern turbocharging and diesel injection systems feature constant high torque over a broad speed range and therefore produce excellent driving performance while maintaining moderate fuel consumption. The reliability and durability of diesel engines make them attractive for deployment in commercial vehicles as well as in passenger cars. Nevertheless, increasingly stringent emission legislation and the growing demand for independence from fossil energy sources will continue to be major challenges. With the globally rising energy demand and the need for energy security, several kinds of energy sources need to be considered. With respect to automotive applications based on diesel fuel, many alternative fuels are being discussed and explored as possible solutions. Among them, fuels derived from biological sources are the center of attention because they are able to reduce carbon dioxide (CO₂) emissions significantly and contribute to global environmental conservation. In fact, activities for expanding the production and utilization of biofuels are already proceeding throughout the world [1,2].

Focusing on the environmental considerations and price risk of traditional fossil fuels, the European Union (EU) has issued a 10% minimum target for renewable energy consumption in the transportation sector by 2020. A new EU directive regarding the utilization of biofuels only promotes biofuels that are not produced from edible feedstock. In this context, the EU has issued a guideline to

limit the share of first-generation biodiesel, almost exclusively fatty acid methyl ester (FAME), to a maximum of 7 vol-%. The commission has proposed meeting the existing bio-quota target of 10% by the year 2020 through biofuel production from waste biomass sources, algae and other non-edible cellulosic materials [2,3,4].

The US is planning to increase the total amount of renewable fuels sold from 53 billion liters per year in 2011 to 136 billion liters in 2022. In relation to total US transportation energy consumption in 2009, this directive is comparable to a renewable share of 15% in the year 2022 [5,6,7].

Figure 1 illustrates the chronological sequence of the realized and targeted shares of renewable energy sources (gasoline and diesel substitutes) for transportation in the US and Europe.

The use of alternative diesel fuels or diesel-biodiesel blends offers further advantages beyond reducing CO₂-emissions and the dependency on oil imports. In particular, fuel blends consisting of hydrotreated vegetable oils (HVO) and/or biomass to liquid (BtL) have the advantageous potential to produce less of regulated emissions, including carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) [8,9,10].

The aim of this study is to demonstrate the already mentioned potential of fuel blends consisting of HVO, BtL and FAME in different shares with respect to combustion, emissions and fuel efficiency.

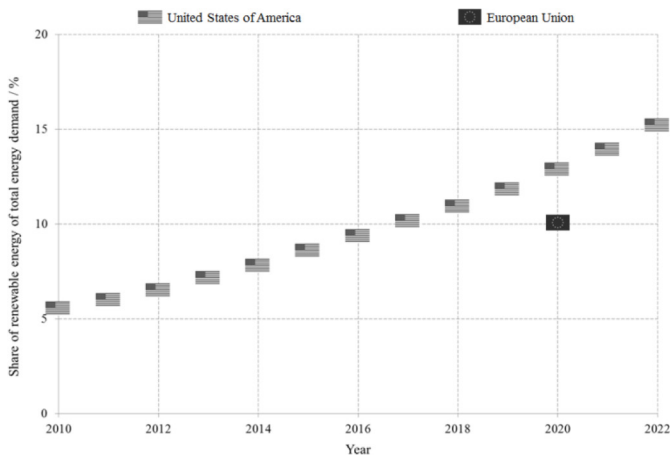


Figure 1. Chronological sequence of realized and targeted renewable substitution [2]

Alternative Fuels for Diesel Engines

For diesel vehicles, FAME made from vegetable oils is generally used as biodiesel and has dominated the market for many years. In recent years, hydrotreated vegetable oil has also become increasingly popular. In addition, biomass-to-liquid fuel, which can theoretically be made from any kind of biomass by gasification and Fischer-Tropsch synthesis, is expected to be commercialized in the future. This section's goal is to give an overview of the production, including feedstocks, as well as fuel properties, characteristics during combustion and impacts to emissions of FAME, HVO and BtL [11].

Fatty Acid Methyl Ester

FAME is produced from vegetable oils, animal fats or waste cooking oils by transesterification. In this process, a triglyceride reacts with an alcohol in the presence of a catalyst, forming a mixture of single fatty acid esters and glycerol. Rapeseed, sunflower, palm oil, soybean and animal fat are the most common raw materials used to produce FAME. Disadvantages come into existence if the transport distances of raw materials increase or if the methanol, which is needed for transesterification, is mostly based on fossil resources, which downgrade the overall CO₂ savings [11].

The applicability of FAME in diesel engines is well-known, but as an oxygenated fuel, it features disadvantages particularly regarding nitrogen oxides (NO_x) emissions. The so-called "biodiesel NO_x effect" describes the sum of single effects on ignition timing, ignition delay, adiabatic flame temperature, radiative heat loss and other combustion phenomena, which all might influence NO_x formation [12,13]. Nevertheless, FAME has proven potential to decrease emissions of CO, HC and PM, either as B100 or as a biogenous substituent to conventional diesel [11,14,15,16,17].

The technical limitations of FAME include its low oxidation stability (during storage), deposit formation, dilution of engine oil and partly insufficient properties at low temperatures [18,19].

Hydrotreated Vegetable Oil

HVO is a renewable diesel fuel with properties comparable to those of BtL diesel fuels. HVO can be produced from a broad range of feedstocks, such as vegetable oils, animal fats and waste oils, without having significant impacts on the properties of the final fuel. The HVO process consists of feedstock pretreatment, hydrotreatment (hydro-cracking) and isomerization. HVO only consists of straight-chain paraffinic compounds without any aromatics, olefins or naphthenes and is free of sulfur. Consequently, its cetane number is very high, its calorific value is slightly higher and its density is lower compared to conventional fossil diesel [20,21,22,23].

HVO does not have the inherent disadvantages of ester-type fuels, like increased NO_x - emissions, the formation of deposits, oxidation stability problems, more rapid aging of engine oil or poor low-temperature properties [18,19,24].

It has been reported that HVO fuels produce cleaner exhaust gas emissions, notably with regard to soot emission and improved engine performance, particularly with adapted engine controlling [25,26].

Biomass to Liquid

BtL also exclusively consists of straight-chain paraffins without any aromatic compounds. It is obtained by the Fischer-Tropsch process, in which hydrocarbons are synthesized out of CO and hydrogen (H₂) using cobalt-containing catalysts. The required CO and H₂ (synthesis gas) are generated by gasification of (waste) biomass or other nonfood cellulosic raw materials [11,27,28].

BtL does not contain oxygen or sulfur and has narrow distillation temperatures, compared to conventional diesel fuel from fossil resources. Moreover, it shows a similarly high cetane number as HVO, which positively influences the internal combustion, particularly during the early phases. In general, the physicochemical properties of Fischer-Tropsch fuels such as BtL are similar to those of HVO [2,29].

Considering engine performance, both BtL and HVO can provide improved engine performance, in particular by means of fine-tuning several engine parameters (e.g., compression ratio, fuel injection timing and fuel injection pressure) [30,31,32].

To date, biomass-to-liquid fuels processed by Fischer-Tropsch synthesis are produced only on pilot scale [2].

METHODOLOGY

Engine and Test Bench

Over the course of this survey, the engine characteristics were investigated on an engine test bench consisting of a typical EURO 5/6 engine for passenger cars and a water-cooled eddy current brake. To understand the effects of diesel fuel properties on engine performance, the engine was instrumented with thermocouples and pressure transducers, and the data were recorded using National Instruments LabView. Furthermore, a measurement system was implemented to analyze thermodynamic combustion, which consists of an AVL

INDICOM with an AVL GU13G-14 piezoelectric pressure sensor and a Kistler Type 5011 amplifier. In addition, ETAS INCA ES 590.1 was utilized for CAN communication to the engine control unit (ECU) to measure proprietary data and adjust parameters. The data output delivered by the ECU and additionally a thermal mass flow meter were used to maintain accurate measurement of the intake air flow rate. Moreover, the fuel consumption calculated by the ECU was further confirmed by a measuring system based on the Coriolis principle.

The raw exhaust gas was sampled 0.3 m downstream from the exit of the exhaust gas turbine and was transported to the gas analyzers and the AVL smokemeter inside heating pipes. To improve the explanatory power of the investigations focusing on the internal combustion, the test engine was not fitted with any components of the exhaust gas after treatment system (e.g., diesel particulate filter or catalysts). The measurement methods to evaluate the emission data included non-dispersive infrared spectroscopy (NDIR) for CO and CO₂, a heated flame ionization detector (HFID) for total hydrocarbons (THC) and a chemiluminescence detector (CLD) for NO_x.

The backpressure in the exhaust gas system was generated by an adjustable flap. Figure 2 reveals a pictorial description of the experimental setup. The tested engine was equipped with a variable nozzle turbine (VNT)-turbocharger, an intercooler and an exhaust gas recirculation (EGR) cooler.

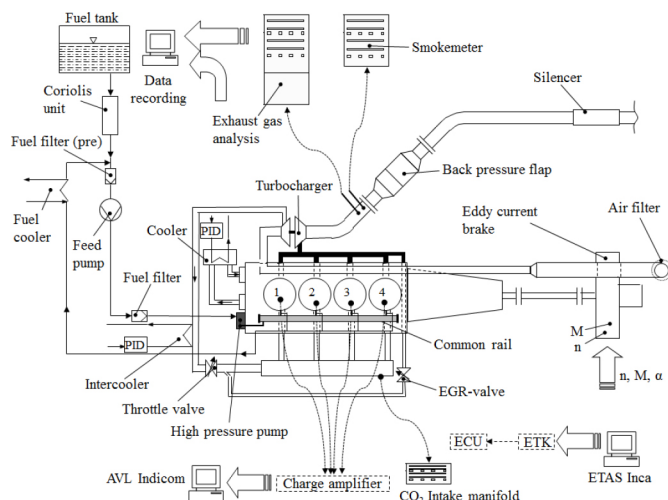


Figure 2. Setup of the engine test bench measurement systems and the gas analytics

Table 1 shows the most relevant technical data of the engine.

Table 1. Hardware specification of the test engine

Cylinders	Inline-Four
Capacity	1995 cm ³
Compression Ratio	16:1
Rated Power at Speed	120 kW at 4000 min ⁻¹
Rated Torque at Speed	360 Nm at 2000 min ⁻¹
Engine Control Unit	Bosch EDC 17
Emission Standard	EURO 5/6

Operation Points and Varied Parameters

The experiments on the engine test bench took place by investigating different fuel blends at four stationary operation points out of the engine's overall operating map. The selected operation points cover typical low and medium load conditions with and without EGR as well as full-load operation points. Figure 3 outlines the investigated operation points, as indicated by the engine's speed and torque.

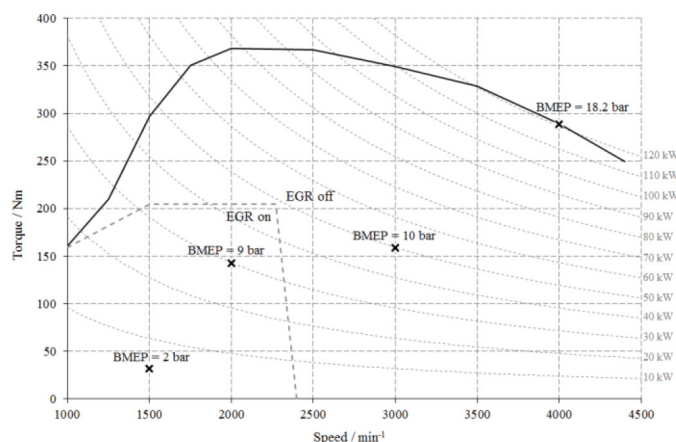


Figure 3. Map of empirically investigated operation points of the test engine

For the low and medium load operation points with EGR, the investigations were conducted by varying the EGR rate. Because the ECU deactivates the EGR at operation points with higher loads, other variation parameters included the injection timing and the start of the main injection (SOI), respectively. Table 2 gives an overview of the in this paper discussed operation points, the varied parameters and their range.

Table 2. Operation points, varied parameters and ranges

Speed / BMEP	Varied Parameter	Range
1500 min ⁻¹ / 2 bar	EGR	0.7 – 47%
2000 min ⁻¹ / 9 bar	EGR	0.7 – 13%
3000 min ⁻¹ / 10 bar	SOI	16.5 – 0.5° BTDC
4000 min ⁻¹ / 18.2 bar	-	-

The EGR variation was performed by modifying the flow rate of fresh intake air while holding the total amount of combustion air constant. Furthermore, the torque had to remain constant, which implicates that the injected fuel quantity was adjusted. Due to these procedures, the ECU adjusted the boost pressure and thus the position of the EGR valve.

For the variation of the SOI at the operation points with comparable higher loads, all other injection parameters were held constant (e.g., pilot injection, timing and quantity). Reappearing fluctuations in torque were compensated for by readjusting the fuel quantity of the main injection.

The two full-load operation points were investigated by using constant default values for the fuel injection without any variations to identify the maximum power output and fuel consumption for all of the tested fuel blends.

Fuel Blends and Preliminary Fuel Analysis

The investigated fuel blends were chosen on the one hand with respect to EU's targeted 10% bio-quota and on the other hand to prove the potential of higher shares of BtL and HVO admixed to regular ultra-low-sulfur diesel (ULSD). Ternary fuel blends consisting of ULSD, FAME and BtL or HVO were selected to diminish inherent disadvantages of binary blends containing only ULSD and FAME (e.g., rise in NO_x -emissions). The tested fuel blends, which consisted of the basic fuel ULSD, BtL, HVO and FAME, as well as their volumetric compositions are presented in the itemization below:

50 vol-% ULSD: 50 vol-% BtL

80 vol-% ULSD: 20 vol-% BtL

90 vol-% ULSD: 7 vol-% FAME: 3 vol-% HVO

90 vol-% ULSD: 7 vol-% FAME: 3 vol-% BtL

100 vol-% ULSD (reference fuel)

To enable a coherent interpretation of the results, physical and chemical properties of the basic fuels were determined in a preliminary step. These studies included:

Composition of the fuels (C/H/O)

Content of aromatic compounds

Calorific value

Density

Viscosity number

Cetane number

Distillation curve

Table 3 presents the physical and chemical properties of the basic fuels and the applied test methods. Mass fractions of C, H and O were determined by an elementary analysis, total aromatics by gas chromatography and the calorific value with a bomb calorimeter.

Table 3. Physical and chemical properties of the basic fuels

Quantity	EN-method	Unit	ULSD	BtL	HVO	FAME
C	-	wt-%	86.2	84.9	84.9	76.7
H	-	wt-%	13.3	15.1	15.1	12.5
O	-	wt-%	0.0	0.0	0.0	10.6
Total Aromatics	-	wt-%	16.2	< 0.1	< 0.1	< 0.1
Calorific Value	-	MJ·kg ⁻¹	42.6	43.9	44.1	37.3
Density at 298 K	EN 3675	kg·m ⁻³	835.6	778.6	776.6	882.5
Viscosity at 313 K	EN 3104	mm ² ·s ⁻¹	3.15	3.11	3.11	2.81
Cetane Number	EN 5165	-	55.0	78.0	79.0	56.0

Because the quality of the mixture preparation depends greatly on the evaporation properties of the basic fuels, their distillation curves were determined by an atmospheric distillation in accordance to EN 3405, and the results are displayed in figure 4.

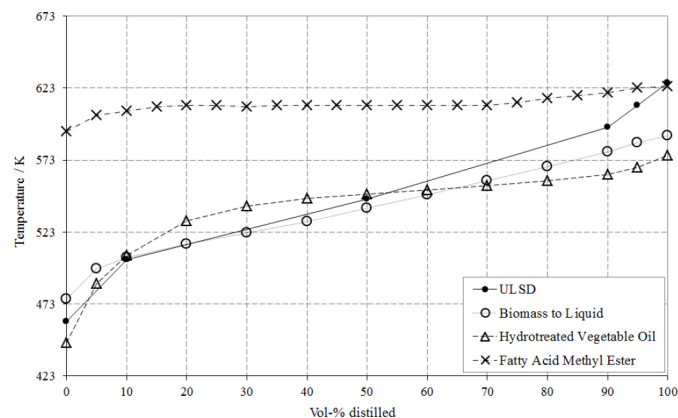


Figure 4. Distillation curves of the basic fuels before blending

The results of this preliminary physical and chemical analysis are in accordance with previous studies from Erkkilä et al. [14], Hartikka et al. [22] and Jaroonsathian et al. [30].

DISCUSSION OF THE RESULTS

With respect to the extent of this paper, the discussion of the results is limited to one operation point for each load case (low load with EGR, medium load with/without EGR and full load).

Low-Load Conditions with EGR

This load scenario is represented by the operation point with an engine speed of 1500 min⁻¹ and a torque of 32 Nm, which equates to 2 bar brake mean effective pressure (BMEP).

NO_x- and PM- Emissions

Figure 5 reveals the specific NO_x- and PM- emissions for the investigated fuel blends and for the regular ULSD at different EGR rates.

A comparison of the graphs shows that blending considerable portions of BtL with ULSD significantly reduces PM- emissions and confirms previous surveys [33, 34]. In the case of ULSD, PM is formed in the presence of unburnt aromatic hydrocarbons, which promote particulate matter formation between 1500 K and 2000 K. In this range, new soot particles are formed by partial oxidation and/or by thermal and oxidative pyrolysis of aromatics under rich conditions [34]. Formation of PM also occurs for fuel blends with lower aromatics content caused by insufficient mixture preparation after injection and diffusion-limited combustion.

Both FAME blends showed significant reductions in PM- emissions in this low load operation point, which is caused by the bonded oxygen in the FAME and the lowered content of total aromatics. One possible explanation for the observable difference between the two ternary FAME blends could be the limited oxidation stability of the FAME share. Due to the fact that the test runs of the ternary blends could not be conducted simultaneously, oxidation reactions could have occurred and potentially degraded the FAME resulting in increased PM emissions [35].