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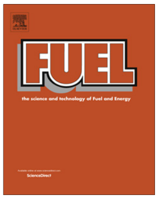

Effects of different biofuels blends on performance and emissions of an automotive diesel engine

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HIGHLIGHTS

- RME and HVO 30% blends with ULSD were evaluated in an automotive diesel engine.
- Full load performance decreases of 5% for RME and of 1% for HVO observed with nominal ECU calibration.
- CO and HC emissions were markedly reduced with both blends at low and medium loads.
- NO_x emissions with both blends were generally comparable with those of diesel fuel.
- Smoke levels with both blends were markedly reduced at medium and high loads.

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ABSTRACT

The impact of blending Ultra Low Sulfur Diesel (ULSD) with different biofuels, obtained from Rapeseed Methyl Ester (RME) and Hydrotreated Vegetable Oil (HVO) respectively, on the performance and emissions of a European passenger car diesel engine was assessed in this paper.

First, the hydraulic behavior of the common rail fuel injection system was analyzed in terms of injected volume, injection rate, spray global shape, single jet tip penetration and cone angle with both RME and HVO blends in comparison with neat ULSD.

Afterwards, the impact of biofuel blends on engine full load performance was analyzed, both for the standard calibration and for a calibration which was specifically adapted to biofuels characteristics. The effects of biofuel blends on brake specific fuel consumption and on regulated exhaust emissions were then evaluated at different part load operating conditions, representative of the New European Driving Cycle.

Finally, the sensitivity of the different fuels to different calibration settings, such as Exhaust Gas Recirculation (EGR) and injection timing, was studied in order to investigate which further emission benefits could be achieved by means of a more extensive engine re-calibration.

Abbreviations: A/F, air to fuel ratio; ASTM, American Society for Testing and Materials; BMEP, Brake Mean Effective Pressure; BSCO, brake specific CO; BSFC, brake specific fuel consumption; BSHC, brake specific HC; $BSNO_x$, brake specific NO_x; BTDC, Before Top Dead Center; CA, crank angle; EC, European Commission; ECU, Electronic Control Unit; EGR, Exhaust Gas Recirculation; EISA, Energy Independence and Security Act; ET, energizing time; EU, European Union; FAME, Fatty Acid Methyl Ester ; FSN, Filter Smoke Number; GHG, Greenhouse Gases; HC, unburned hydrocarbons; HRR, heat release rate; HVO, Hydrotreated Vegetable Oil; ISO, International Organization for Standardization; LHV, Lower (Net) Heating Value; MFB50, 50% of Mass Fraction Burned; Nd-Yag, Neodymium-doped Yttrium aluminum garnet; NEDC, New European Driving Cycle; NO_x, Nitrogen Oxides; PM, Particulate Matter; RFS, Renewable Fuel Standard; RME, Rapeseed Methyl Ester; SOF, Soluble Organic Fraction; SoI, Start of Injection; TDC, Top Dead Center ; ULSD, Ultra Low Sulfur Diesel; US EPA, United States Environmental Protection Agency; VGT, Variable Geometry Turbine; w%, percentage by weight; λ, relative air/fuel ratio.

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1. Introduction

Biofuels have attracted the attention of policy makers, researchers and industry as a renewable, biodegradable, and non-toxic means of increasing energy source diversification and of reducing carbon dioxide emissions from internal combustion engines [1]. At an international level, the United States Environmental Protection Agency's (US EPA) Energy Independence and Security Act (EISA) of 2007 [2] established annual renewable fuel volume objectives, setting an overall target level of 36 billion gallons in 2022. To achieve these volumes, every year, US EPA within the Renewable Fuel Standard program (RFS), issues percentage-based renewable fuel standards for the following year. In Europe, European Directive 2009/28/EC [3] introduced a target for the European Union (EU) Member States concerning the share of energy from renewable sources for all forms of transport. A target of at least 10% of the final energy consumption in transport has to be achieved by 2020.

However, first-generation biofuels had to face challenges regarding the competition with food crops, the high water demand for cultivation and the low power density of fuel crops. The environmental benefits of first generation biofuels have often been overestimated, and a full lifecycle analysis has often been neglected [4–6].

Therefore, international regulations are currently under review by legislators with the purpose of increasing the share of second generation biofuels, e.g. sourced from cellulosic material and food industry waste. In 2013, US EPA proposed 2014 standards for cellulosic biofuel, biomass-based diesel, advanced biofuel, and total renewable fuel. Compared to the 2013 quotas, the volumes of cellulosic would be doubled, while the volume of biomass-based diesel would remain unchanged [7]. The European Parliament is also introducing changes to biofuel legislation. The use of biofuels sourced from agricultural feedstock would be limited to 6%, compared to the 10% target that is currently required by 2020, and the difference would be filled by second-generation biofuels [8].

Today, trans-esterified vegetable oil (often referred to as biodiesel, or FAME, Fatty Acid Methyl Ester) is the second largest category of global biofuel, accounting for 6.9 billion gallons globally in 2013, i.e. 22.6% of total biofuel production and still the most commonly used biofuel in Europe, covering approximately 80% of the biofuel market [9].

The usage of biodiesel for fuelling diesel engines, generally in blend with fossil fuels, has been increasingly spreading, thanks to its chemical and physical properties, which are quite similar to those of fossil diesel fuels [10]. However, unsaturated FAMEs such as Rapeseed Methyl Ester (RME) or Soy Methyl Ester (SME), are known to adversely impact on fuel oxidation stability [11–13]. Hence, FAME percentages that can be blended into automotive diesel fuel is currently limited in Europe to 7% on a volume basis, although higher percentages, up to 30% are currently being considered.

Recently, Hydrotreated Vegetable Oil (HVO), obtained by means of a refinery-based process that converts vegetable oils into paraffinic hydrocarbons, has been gaining increasing attention. Its combustion characteristics are particularly attractive, being sulfur and aromatics free and having a high cetane number [14–17]. Moreover, its oxidation stability has been demonstrated to be better than that of FAME, thanks to the lack of unsaturated compounds [14]. Finally, additional advantages in terms of environmental impact of the HVO production process have been highlighted showing good performance in terms of Greenhouse Gases (GHG) emissions. Moreover, HVO could be produced in existing oil refineries without the need for additional chemicals, such as methanol which is requested for FAME production, or for the disposal of by-products such as glycerol [5,14].

Although the effects of HVO on engine emissions have already been investigated by several researchers (see [18] for a recent review), as well as a plethora of studies concerning the effects of FAME can be found in literature (see for instance [19–22]), only few studies concerning last generation automotive engines are available [23–26].

Experimental activities reported in literature are usually carried out running the engine with the original, diesel oriented, Electronic Control Unit (ECU) calibration. A specifically adjusted ECU calibration optimized for alternative fuels is rarely used [27–29] and the possible decrease in engine torque output is often recovered by increasing the torque demand through an increase of the accelerator pedal position, thus simulating a switch of the supplied fuel.

An extension of the investigations to modern engines, which may include advanced combustion technologies and closed-loop combustion controls [28,29] seems therefore to be necessary in order to fully understand the effects of both FAME and HVO usage.

The aim of the present work is therefore the analysis of the effects of blending Ultra Low Sulfur Diesel (ULSD) with different biofuels, obtained from Rapeseed Methyl Ester (RME) and Hydrotreated Vegetable Oil (HVO) respectively, on the performance and emissions of a European passenger car diesel engine, featuring advanced combustion technologies and a closed-loop combustion control. To this end, not only the engine performance and emissions were carefully investigated, but also the injection system behavior was thoroughly analyzed in order to better understand the impact of the biofuel blends on fuel injection and combustion and to support a proper engine tuning for the full exploitation of the biofuel blends characteristics.

2. Experimental set-up

2.1. Test fuels

Tests were performed by using the three following fuels:

- Ultra Low Sulfur Diesel (ULSD), compliant with EN590 (sulfur < 10 mg/kg) and hereafter referred to as "Diesel";
- 30% by volume blend of Rapeseed Methyl Ester (RME) biodiesel with 70% diesel, hereafter referred to as "RME-B30";
- 30% by volume blend of Hydrotreated Vegetable Oil (HVO) with 70% diesel, hereafter referred to as "HVO-B30".

The main properties of the test fuels are listed in Table 1 while distillation curves and viscosity versus temperature trends are shown in Fig. 1a and b, respectively. It can be immediately noticed that HVO-B30 shows distillation and viscosity characteristics which are closer to those of diesel fuel in comparison with the RME-B30 blend. On the contrary, RME-B30 shows a distillation curve with a significant shift toward fractions with higher boiling temperatures, as well as higher viscosity levels which could potentially worsen fuel spray and evaporation characteristics of the fuel blend [30].

As far as the energy content of the fuels is concerned, the oxygen content of the RME blend reduces its Lower Heating Value (LHV) of about 4% with respect to diesel fuel LHV, while RME-B30 density is about 2% higher than diesel fuel density. Considering, on first approximation, the injection rate independent from fuel viscosity and bulk modulus, the amount of fuel injected should scale as the square root of the pressure drop across the injector nozzle multiplied by the fuel density. Therefore, injected quantities with RME-B30 should be about 1% higher than diesel for the same injection pressure and duration while the energy content introduced into the cylinder should be about 3% lower in

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