Environmental Pollution 158 (2010) 1451–1460

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Effects of low concentration biodiesel blend application on modern passenger cars. Part 1: Feedstock impact on regulated pollutants, fuel consumption and particle emissions

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Fleet-wide biodiesel application on passenger cars may affect pollutant emissions and the impact can vary depending on biodiesel feedstock.

ARTICLE INFO

Article history:
Received 22 July 2009
Received in revised form
9 December 2009
Accepted 16 December 2009

Keywords:
Exhaust emissions
Biodiesel
Regulated pollutants
Particle emissions

ABSTRACT

Five biodiesels from different feedstocks (rapeseed, soy, sunflower, palm, and used fried oils) blended with diesel at 10% vol. ratio (B10), were tested on a Euro 3 common-rail passenger car. Limited effects (−2% to +4%) were observed on CO_2 emissions. CO and HC emissions increased between 10% and 25% on average, except at high speed – high power where emissions were too low to draw conclusions. NOx emissions increased by up to 20% for two out of the five blends, decreased by up to 15% for two other blends, and remained unchanged for one blend. Particulate matter (PM) was reduced for all blends by up to 25% and the reductions were positively correlated with the extent of biodiesel saturation. PM reductions are associated with consistent reductions in non-volatile particle number. A variable behaviour in particle number is observed when volatile particles are also accounted.

1. Introduction

Biofuel use in transportation is promoted in the European Union in an effort to tackle climate change, diversify energy sources, and secure energy supply. Directive 2003/30/EC stipulated that 5.75% of total petrol and diesel consumption in transport should be replaced by biofuels by 2010. In 2009 the new Directive 2009/28/EC introduced new targets stating that each member state shall ensure that the share of energy from renewable sources in all forms of transport in 2020 is at least 10% of the final consumption of energy in transport in that Member State. Since the use of other renewable energy sources in the transport sector is rather difficult to achieve, it is expected that the goal set by the new regulation will be mainly met through biofuels application. For various reasons, biodiesel has been the biofuel of choice in Europe, with its share reaching 75% of total biofuel consumption in transport in 2007 (Eurobserver, 2008).

Biodiesel differs from petroleum derived diesel (petro-diesel) as the former consists mainly of mono-alkyl esters (fatty-acid methylesters – FAME), which contain two oxygen atoms per molecule. As a result, biodiesel contains 10–12% wt. oxygen, which leads to proportionally lower energy density (Graboski and McCormick, 1998). In addition, due to the ester content, biodiesel differs from petro-diesel in that it has a zero or ultralow natural sulphur content, it contains no aromatic or polyaromatic hydrocarbons, it has a higher cetane value, a lower heating value, better lubricity, higher viscosity, and a higher flash point.

Previous evidence has shown (Graboski and McCormick, 1998; Lapuerta et al., 2008a; Kousoulidou et al., 2009) that petro-diesel blending with biodiesel rather decreases all regulated pollutants but NOx. The increase in NOx is not yet clear, but several mechanisms have been proposed, including the different fuel chemistry and fuel spray characteristics (Marshall et al., 1995; EPA, 2002; Tat, 2003; Knothe and Steidley, 2005; Sze, 2007). Such NOx increases may particularly aggravate air quality conditions in European cities.

In addition, more information is required with respect to biodiesel effects on the concentration and characteristics of exhaust particulate matter (PM). PM is the pollutant responsible for most premature deaths in Europe and significant concentration exceedances still occur in several urban environments (WHO, 2005). In particular, ultrafine particles (<0.1 μm diameter), such as

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doi:10.1016/j.envpol.2009.12.033

the ones produced by mobile combustion, are deposited with much higher efficiency in the pulmonary alveoli than fine particles (Kawanaka et al., 2004) because of their small size. Biodiesel may alter particle characteristics, as the different fuel chemistry, the higher viscosity, and the different surface tension may change the in-cylinder fuel spray characteristics. This has been shown to lead to higher particle number emissions in some studies, although the extent of this phenomenon is not yet clear (Mathis et al., 2005b; Lapuerta et al., 2008b).

The previous evidence shows that biodiesel effects on engine emissions may be quite significant. However, most studies have been conducted on heavy-duty and, generally, older technology engines. Only few studies are available on modern diesel engines and passenger cars, employing common-rail engine systems and aftertreatment technologies. Most of these studies show that biodiesel application on modern engines and particularly on vehicles equipped with some form of exhaust aftertreatment system can lead to results not consistent with what is generally reported (Durbin et al., 2007; Martini et al., 2007; Mazzoleni et al., 2007; Ropkins et al., 2007; Fontaras et al., 2009; Karavalakis et al., 2009; Lujαn et al., 2009). Therefore, a recent technology diesel passenger car has been employed in the current study to investigate the effects of five different biodiesel blends on exhaust emissions. The blends have been produced by mixing 10% vol. biodiesel (B10) of different feedstock in petro-diesel. The study aims at providing a representative picture of biodiesel effects on gaseous and particulate emissions of passenger cars, shedding some light on the influence of biodiesel feedstock and properties on emissions.

2. Methods

2.1. Fuels and test vehicle

Five biodiesel blends were prepared by mixing neat biodiesel, originating from five different feedstocks, with a base petro-diesel at a 10% vol. ratio (B10). The most commonly used feedstocks in Europe were selected, i.e. rapeseed oil, sunflower oil, soybean oil, palm oil and used frying oils, and their methyl ester blends are referred to as RME, SUME, SME, PME, and UFOME, respectively. Each biodiesel was from a single batch and prior to the measurements all necessary handling and storage actions were taken in order to avoid degradation. The base fuel was a typical automotive, low sulphur diesel (<50 ppm S) complying with EN590:2004 (Directive 2003/17/EC). This base fuel may already contain a minimal biodiesel content (<2%), blended at the refinery. Hence, the total biodiesel content in the test fuels is estimated in the range between 11% and 12%.

The main properties of the test (blended) fuels are shown in Table 1. All fuels comply with EN590:2004. In addition, all neat biodiesels were tested according to the EN14214 standard, and their properties are presented in Table 2. Iodine number and CFPP, were slightly above the EN14214 limits. These deviations are rather expected as the EN14214 standard was originally introduced for RME and the standard's limits were adjusted to the properties of that particular fuel.

The blends were tested on a Renault Laguna 1.9 dCi passenger car, complying with Euro 3 emission standard. The vehicle was equipped with a high-pressure common-rail diesel engine, exhaust gas recirculation (EGR) for NOx control, a closed-coupled pre-catalyst and an underfloor main oxidation catalyst also used for PM control. This combustion and emission control technology is the most widespread one in diesel cars today. The main engine and vehicle characteristics are provided in Table 3.

2.2. Testing facility – particle sampling

Emission measurements were conducted following the European regulations (Directive 70/220/EEC and amendments). The exhaust gas was primarily diluted and conditioned by means of Constant Volume Sampling (CVS). A 6 m long corrugated stainless steel tube transferred the exhaust from the tailpipe to the CVS tunnel inlet. The tube was insulated to minimize heat losses and particle thermophoresis and was clamped onto the vehicle exhaust pipe with a metal-to-metal connection to avoid exposing the hot exhaust gas to any synthetic material connectors. A flowrate of 500 Nm^3/h was maintained in the CVS tunnel by a positive displacement pump. The dilution air was filtered through a HEPA class H13/EN1822 filter at the inlet of the dilution tunnel. Proportional diluted exhaust samples were collected in bags for gaseous pollutants measurements. Gaseous pollutants were measured with laboratory analyzers (chemiluminescence for NOx, flame ionization detector for HC and non dispersive infrared for CO and CO_2).

Fuel consumption was derived by means of the exhaust-to-fuel carbon balance, taking into account the oxygen content of fuels. Although regulations foresee correction values for other fuels, in addition to diesel and gasoline, there is no methodology proposed for biodiesel hence the following formula was used:

$$FC = \left(\frac{E_{CO_2}}{44.011} + \frac{E_{CO}}{28.011}\right)(12.011 + 1.008 r_{H:C} + 16.000 r_{O:C})(g/km)$$

Where: E: stands for the emissions of CO_2 and CO as calculated from the bag samples in (g/km); $r_{H:C}$ is the hydrogen to carbon ratio in the fuel molecule. This was 1.85 for the base fuel and 1.865 for the biodiesel blends; $r_{O:C}$ is the oxygen to carbon ratio which was zero for the base fuel and 0.011 for the biodiesel blend.

PM samples were collected on 47 mm PTFE-coated fibre filters (Pallflex TX40HI20-WW) which were conditioned for 24 h in a constant temperature (22 °C) and humidity (40%) room before and after the particulate collection and prior to weighing.

Fig. 1 presents the setup used for airborne particle sampling. Aerosol samples were taken from the CVS through an FPS-4000 dilutor (Dekati Ltd, Finland), operating at a nominal dilution ratio of 12:1. This was followed by two calibrated ejector-type diluters (Giechaskiel et al., 2004) used in series, in order to reduce the particle number concentration within the measuring range of the instruments. A Condensation Particle Counter (CPC, Model 3010, TSI Inc, Shoreview, MN) was employed during the transient driving cycles to monitor the total particle number concentration. The CPC was replaced by a scanning mobility particle sizer (SMPS, Model 3936L, TSI Inc, Shoreview, MN) during the steady-state tests (50–90–120 km/h), to monitor the mobility size distribution. It is obvious that once the mobility size distributions are obtained, the total particle number can also be calculated. On a different sampling branch, an Electrical Low Pressure Impactor (ELPI) (Dekati Ltd, 2001) provided the aerodynamic size distribution in real time. The ELPI was connected downstream of a Dekati thermodenuder, operating at 250 °C, which removed volatile and semi-volatile exhaust components to sample non-volatile particles only. The ELPI operated with oil-soaked sintered plates and a filter stage that extended the lower cutpoint to ∼7 nm (Marjamaki et al., 2002).

In the following sections, particle number emissions measured by the CPC, the ELPI and the SMPS are expressed per unit of distance driven (km^{-1}). The conversion from cm^{-3} to km^{-1} is done by multiplying the total number of particles measured with the diluted exhaust volume through the CVS, and dividing with the corresponding distance driven by the car during the measurement. The particle

Table 1
Properties of the base diesel fuel and the biodiesel blends.

Properties	Diesel	B10 PME	B10 RME	B10 SUME	B10 UFOME	B10 SME	EN 590 limits	Test methods
Viscosity (40 °C, $mm^2 s^{-1}$)	3.61	3.81	4.0	3.89	4.21	3.97	2.00–4.50	EN ISO 3104
Density, (15 °C, g cm^{-3})	0.834	0.838	0.841	0.839	0.839	0.838	0.820–0.845	EN ISO 3675
Flash point, (°C)	71	67	65	67	64	66	55 min	EN 22719
Sulphur content, (μg g^{-1})	24	22	19	20	18	21	50 max	EN ISO 20846
Water content, (μg g^{-1})	52	65	78	62	97	118	200 max	EN ISO 12937
CFPP, (°C)	−9	−7	−8	−9	−6	−8	+5 max	EN 116
Cetane number	55.5	55.5 ± 0.5 (within the accuracy limits of the measurement)					51 min	EN ISO 5165
Distillation								EN ISO 3405
IBP	179	182	185	183	178	180		
10	220	225	228	231	219	226		
50	281	290	298	297	276	289		
90	344	346	349	348	342	342		
FBP	367	355	360	359	358	361		
Gross heating value, (kJ kg^{-1})	45 605	44 923	44 635	44 748	44 814	44 777		IP 12