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Effect of Biodiesel Addition to Diesel Fuel on Engine Performance and Emissions

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In this paper, exhaust emission measurements are presented, using three conventional diesel-engine vehicles and one stationary Petter diesel engine. The engines were operated with typical automotive diesel fuel, containing 0.2 or 0.05 wt% sulphur, and blends of the fuels and 10 vol% biodiesel. The starting material for biodiesel preparation was sunflower oil, which is an abundant plant oil in many Mediterranean areas. The addition of biodiesel in the traditional diesel fuel resulted in significant reduction of black smoke emissions, and the combination of low-sulphur diesel fuel and biodiesel comprises the best fuel blend tested. The combination of low-sulphur diesel fuel and biodiesel resulted in reducing the particulate matter emissions at higher loads. With regard to fuel consumption, the fuels that contained biodiesel resulted in slightly increased fuel consumption. Wear metal measurements indicated that while the detected metals Ag, Cu, Pb, and Cr were not significantly affected by biodiesel addition, the fuel blend that contained biodiesel led to a slight increase of Fe into the used lubricant.

Nomenclature

Ag = silver, ppmm
CO = carbon monoxide, vol%
CO_2 = carbon dioxide, vol%
Cr = chromium, ppmm
Cu = copper, ppmm
Fe = iron, ppmm
HC = unburned hydrocarbons, ppmv
NO = nitric oxide, ppmv
NO_x = total nitrogen oxides, ppmv
Pb = lead, ppmm
S = sulfur, wt%

Introduction

THE anticipated changes in petroleum distillate demand, the new requirements for modern diesel engines, and the necessity to face the environmental pollution problems lead to the need to improve diesel-fuel quality. The reduction of sulphur content and the detailed investigation of diesel-fuel renewable substitutes are among the measures taken to meet automotive diesel-fuel problems.

The most recent European road diesel-fuel specification has limited the sulphur content up to 0.05 wt%, and the future trend is restricting the diesel-fuel sulfur content even more.[1] A serious problem that has arisen is the insufficient lubrication ability of low-sulfur diesel fuel, caused by the reduction of polar aromatic compounds through the refinery hydrotreatment process.[2]

The substitution of diesel fuel with renewable materials is of particular interest, and biodiesel is an easily prepared substitute for diesel fuel that does not contain sulfur[3] and does not demand significant modifications of the conventional diesel engine.[4,5] Fatty acid methyl esters, commonly known as biodiesel because of their polar nature and increased viscosity,[2,6] seem to alleviate lubricity problems of low-sulphur modern automotive diesel fuels.

As a biomass-derived product, biodiesel has specific advantages[5,7]; the addition of biodiesel into the diesel fuel pool not only reduces reliance on imported crude oil, but also helps to alleviate CO_2 emissions (greenhouse effect) and helps achieve energy storage by replacing fossil diesel fuel. Although the substitution of conventional diesel fuel with rape-seed oil methylesters already comprises a commercial action in many countries of Central Europe, until now, in Greece and other Southern Europe countries, the use of biodiesel was not developed because of the lack of sufficient rape-seed cultivation. However, there are some other types of vegetable oils, such as sunflower oil, which are abundant in many Southern Europe areas and seem to be attractive candidates for biodiesel applications.

Biodiesel is easily prepared from vegetable-oil triglycerides through the transesterification reaction with methanol. Compared with fossil diesel fuel, engine emissions from biodiesel are reduced with respect to particulates, carbon monoxide, and hydrocarbons.[8,9] Biodiesel is nontoxic, contains no aromatics, has higher biodegradability than fossil diesel, and is less polluting to water and soil.[9–11] Emissions from biodiesel engines show reduced values of carcinogenic and mutagenic substances.[10,11] Because biodiesel does not contain sulfur, the use of an oxidation catalyst with the engine has a high potential of reducing exhaust gas-emission components, which might be hazardous for humans.[8]

In an effort to investigate the perspectives of biodiesel production from raw materials that are abundant in Southern Europe, the work described in this paper includes experiments by consuming blends of typical automotive diesel containing ~0.2 or 0.05%, by mass, sulphur, with 10%, by volume, sunflower-oil biodiesel. In some European countries, e.g., Germany, Austria, diesel-engine vehicles are fueled with 100%

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biodiesel. However, in such cases it is best to change the vehicle parts that are affected by the biodiesel, e.g., the elastomers parts. Because it was the first time that biodiesel was introduced in vehicles in Greece, it was decided to follow a more cautious approach and add it in the road diesel fuel in small quantities, following the French example.

Three diesel-powered vehicles and a stationary, single-cylinder, diesel engine were employed for the purposes of this work. The vehicles included one taxicab, one pickup truck, and one minibus. During the test period, all of the vehicles were circulating in the greater Athens area, performing their normal tasks. They were fueled either with typical diesel fuels containing 0.2 or 0.05%, by mass, sulphur, or with blends of diesel fuels with 10%, by volume, sunflower-oil biodiesel. The tests included emission and fuel-consumption measurements. The pickup truck was also employed for investigating the effect of the fuel blends on engine wear, by measuring the levels of wear metals in the lubricating oil.

From the results obtained, it was concluded that the blend of biodiesel and low-sulfur conventional diesel fuel was the best combination for reducing black smoke emissions. However, in some cases, the addition of biodiesel resulted in small increases of nitrogen oxide emissions and volumetric fuel consumption. This behavior is attributed to the oxygen content of the biofuel.

The field experiments for the impact on the wear metals in the lubricant lead to the conclusion that most wear metals remain practically unaffected by the addition of biodiesel. However, for Fe, a small increase was observed in both cases of biodiesel addition, but the changes were small, and, in general, they should be recorded only as a possible trend that must be investigated further.

Experimental Procedure

Three diesel-fueled vehicles and a stationary, single-cylinder, diesel engine (Petter AV1-LAB) were employed for the tests. The engine characteristics are cited in Table 1.

During the test period, the vehicles were running in the greater Athens area, performing their normal tasks. They were fueled either with typical conventional diesel fuel containing ~0.2%, by mass, sulfur, or with typical conventional diesel fuel containing ~0.05% sulfur, or with blends of the preceding types of conventional diesel fuel with 10%, by volume, sunflower-oil biodiesel.

The fleet tests included NO_x and NO emission measurements at idling and a higher speed (~2500 rpm), smoke-opacity measurements, whereas the volumetric fuel consumption and the possible impact on engine wear (via wear metal determinations) were also checked.

Two exhaust emission analysers were used for the emission measurements: a NO_x analyzer (42C $NO-NO_2-NO_x$ Analyzer High Level, Thermo Environmental Instruments, Inc.), and a Tecneco-MSA Mark III opacimeter (that measures black smoke opacity according to the Italian exhaust emission law). The NO_x analyzer was supported by Exhaust Gases Transportation Heated Lines (Signal Instruments Co, model 530/540) and a Prefilter (Signal Instruments Co., Prefilter Unit 333), which restrains the emitted particulates from entering the Horiba and Thermo Environmental analyzers.

For every type of fuel and vehicle, four sets of emission measurements were conducted. The exhaust emission data of every set were in good agreement with the corresponding data of the other measurement sets (same fuel and vehicle). In the tables that follow, the mean values of the emission measurements and their standard deviations at the 95% confidence level are given.

The pickup truck participated in the lubricant tests. It was initially supplied with lubricating oil (Shell, Rimula Oil X, SAE 30) and fueled with typical diesel fuel containing 0.2% sulphur until it covered a distance of 3000 km. After every 750 km of distance, a sample of the used lubricant was drawn and analyzed. When the vehicle covered the required distance of 3000 km, the engine was filled with fresh lubricant of the same type, and the pickup truck completed the same distance, this time being fueled with a blend of 0.2% S diesel fuel with 10%, by volume, sunflower oil biodiesel. Again, after every 750 km, samples of the lubricating oil were drawn and analyzed.

Upon completion of this test, the same vehicle was supplied with a lubricant of different specification (Shell, Myrina Oil D, SAE 20W-50) and fueled with low-sulfur typical diesel fuel (0.05% sulphur), until it covered a distance of 5000 km. Every 1000 km, a sample of the used lubricant was drawn and analyzed. When the truck covered the required distance of 5000 km, it was filled with fresh lubricant of the same type, and repeated the same distance, this time being fueled with a blend of the low-sulfur automotive diesel with 10%, by volume, sunflower-oil biodiesel. Again, every 1000 km, samples of the lubricating oil were drawn and analyzed.

For every lubricating oil cycle, the most important wear metals (Fe, Ag, Cu, Cr, and Pb) in the lubricant were monitored using a Perkin–Elmer atomic absorption spectrometer.[12]

The study also included emission and volumetric fuel-consumption measurements by employing a stationary, diesel, sin-

Table 1 Engine characteristics

Vehicle type	Engine type	Capacity	Speed	Compression ratio	Maximum output	Maximum torque
Taxi cab Opel Vectra (1994)	Turbocharger Air/air intercooler Indirect injection (swirl chamber) In line Five main bearings[a]	1688 cc	——	22/1	60/82 kW/hp CEE at 4400/min	168 Nm at 2400/min
Pickup truck Mercedes (1982)	Indirect injection Prechamber 4 cylinder	2404 cc	——	21/4	48 kW at 4200/min (DIN)	137 Nm at 2400/min
Minibus Ford Transit (1986)	Combi 130 Direct injection 4 cylinder	2496 cc	——	19/1	50 kW at 4000/min (DIN)	143 Nm (DIN)
Stationary, Petter AV1-LAB engine	Single cylinder Indirect injection	553 cc	1500 rpm	19/1	5 hp (3.8 kW)	——

[a]Equipped with two-way catalytic converter.

gle-cylinder, Petter engine, model AV1-LAB, that is basically used for research activities. Fuel was supplied to the Petter engine by an outside tank of about 3-l capacity, which could easily be drained for fuel changes; a glass burette of known volume was also attached parallel to this tank and used for fuel-consumption measurements.

The Petter engine was fueled with the four different fuels and operated under different loads, up to 5 hp; exhaust emissions (NO_x and NO particulates) and fuel consumption were monitored in each case. The particulate matter emitted from the engine was measured using the equipment recommended by the Western Precipitation Division Joy Manufacturing Company.[13] According to this method, exhaust gases pass through a fibber glass filter, while the flue gas volume is recorded by using a gas meter. Particulate matter weight results were obtained by subtracting the weight of the clear fibber glass filter from its weight at the end of the experiment.

Test Fuels and Lubricants

The vehicles were fueled with a conventional diesel fuel containing ~0.2% sulfur (Table 2), a typical road diesel fuel containing ~0.05% sulphur (Table 3), or blends of the preceding fuels with 10%, by volume, sunflower-oil biodiesel (Table 4).

The conventional diesel fuel was supplied by the Hellenic Aspropyrgos Refinery. The sunflower-oil biodiesel was prepared in Italy by the Florys SPA company, and its properties were in accordance with the Italian specifications for biodiesel (CUNA standards), except for the glycerine content that was about 1400 ppm. However, there was no danger for engine problems as a result of the glycerine content, as the biodiesel concentration in the fuel blend was just 10%.

Tables 5 and 6 present the specifications of the lubricating oils used for engine-wear experiments (wear metals determinations).

Results and Discussion

Fleet Test: Impact on Exhaust Emissions and Fuel Consumption

The exhaust emission measurements included NO_x and NO measurements at idling (Tables 7 and 8) and a higher speed (~2500 rpm). In addition, opacity measurements were conducted and the volumetric fuel consumption was checked. The vehicles circulated in Athens consuming, in turn, the four types of fuel described earlier.

Owing to the oxygen content of fatty acid esters,[14] it is generally accepted that particulate emissions are reduced by the addition of biodiesel into conventional diesel fuel.[15,16] The emitted black smoke measured with an opacimeter, according to the Italian emission law,[17] has a legal limit for buses of 65%, and for all the other vehicles the limit is 70%. Our fleet tests pointed out that the use of conventional diesel fuel of lower sulfur content results in lowering black smoke opacity, whereas in almost all cases, black smoke is reduced when biodiesel is added into the diesel fuel (Tables 7 and 8). Among the fuels tested, the blend of low-sulfur diesel fuel and bio-

Table 2 Diesel fuel properties[a]

Property	Unit	Value range	Test method
Density at 15°C	kg/l	0.8444–0.8582	ASTM D 1298
Distillation curve	vol%	——	ASTM D 86
Recovered at 250°C	——	5–10	——
Recovered at 350°C	——	86–88	——
Recovered at 370°C	——	95	——
Sulfur	wt%	0.18–0.19	ASTM D 4294
Copper strip corrosion	——	1A	ASTM D 130
Flash point	°C	90–99	ASTM D 93
Kinematic viscosity at 40°C	cSt	4.0–4..5	ASTM D 445
Water	mg/kg	118–188	ASTM D 1744
Cetane index	——	54.0–57.5	ASTM D 4737
Ash	wt%	0.005	ASTM D 482
Conradson carbon residue	wt%	0.02	ISO 10370
Cold filter plugging point	°C	4–5	IP 309
Suspended matter	mg/kg	<24	DIN 51419
Oxidation stability	g/m^3	<25	ASTM D 2274

[a] Higher sulfur content.

Table 3 Diesel fuel properties[a]

Property	Unit	Value range	Test method
Density at 15 °C	kg/l	0.8396–0.8538	ASTM D 1298
Distillation curve	vol%		ASTM D 86
Recovered at 250°C	——	13–22	——
Recovered at 350°C	——	89–92	——
Recovered at 370°C	——	95–97	——
Sulfur	wt%	0.039–0.046	ASTM D 4294
Copper strip corrosion	——	1A	ASTM D 130
Flash point	°C	67–74	ASTM D 93
Kinematic viscosity at 40°C	cSt	3.1–4.2	ASTM D 445
Water	mg/kg	50–113	ASTM D 1744
Cetane index	——	52.1–55.5	ASTM D 4737
Ash	wt%	0.005	ASTM D 482
Conradson carbon residue	wt%	0.02	ISO 10370
Cold filter plugging point	°C	(−5)–(−11)	IP 309
Suspended matter	mg/kg	<24	DIN 51419
Oxidation stability	g/m^3	<25	ASTM D 2274

[a] Lower sulfur content.

Table 4 CUNA specifications for biodiesel

Property	Unit	Minimum value	Maximum value	Test method
Acidity	mg KOH/g	——	0.5	ASTM D 664
Water content	ppm	——	700	ASTM D 1744
Ash	wt%	——	0.01	ASTM D 482
Distillation	——	——	——	ASTM D 86
Initial boiling point	°C	300	——	——
95% recovery	°C	——	360	——
Density at 15°C	kg/mc	860	900	ASTM D 1298 ISO 3675
Phosphorous	ppm	——	10	DFG C III 16A-89
Bounded glycerine	wt%	——	——	GLC 1(#)
Monoglyceride		——	0.8	——
Diglyceride		——	0.2	——
Triglyceride		——	0.1	——
Free glycerine	wt%	——	0.05	GLC 2(#)
Methanol	wt%	——	0.2	GLC 3(#)
Methylester	wt%	98.0	——	GLC 1 (#)
Saponification number	mg KOH/g	170	——	NGD H 14
Flash point	°C	100	——	ASTM D 93
Pour point	°C	——	0	ASTM D 97
Conradson carbon	wt%	——	0.5	ASTM D 189
Residue (10% distillation residue)	——	——	——	ISO 10370
Viscosity at 40°C	cSt	3.5	5.0	ASTM D 445 ISO 3104
Sulfur	wt%	——	0.01	ASTM D 1552 ISO 8754

Table 5 Typical characteristics of the lubricant used[a]

Property	Unit	Value	Test method
Kinematic viscosity at 40°C	cSt	93.9	IP 71
Kinematic viscosity at 100°C	cSt	10.9	IP 71
Viscosity index	——	100	IP 226
Density	kg/l	0.886	IP 365
Flash point	°C	210	IP 34
Pour point	°C	−18	IP 15
Total base number	mg KOH/g	8.5	IP 276
Sulfated ash	wt%	1.0	IP 163

[a]Shell, Rimula X, SAE 30.

Table 6 Typical characteristics of the lubricant used[a]

Property	Unit	Value	Test method
Kinematic viscosity at 40°C	cSt	160	IP 71
Kinematic viscosity at 100°C	cSt	18.20	IP 71
Viscosity index	——	126	IP 226
Density	kg/l	0.904	IP 365
Flash point	°C	203	IP 34
Pour point	°C	−18	IP 15
Total base number	mg KOH/g	10	IP 276
Total acid number	mg KOH/g	3.3	ASTM D 664

[a]Shell, Myrina Oil D, 20W-50.

diesel comprised the best combination for reducing black smoke opacity. Depending on the type of the engine, the presence of an oxidation catalyst and the maintenance condition, the measured reduction of the emitted black smoke, in the case of adding biodiesel in 0.2% sulfur conventional diesel fuel, lies between −29 to −2%, whereas in the case of biodiesel addition into the low-sulfur diesel fuel, it is in the range of −33 to −26% (Fig. 1).

In some cases, the addition of biodiesel caused a small increase of NO and NO_x emissions, whereas in other cases, a small decrease was also observed (Tables 7 and 8). This verifies previous research work, where the addition of oxygen compounds to diesel fuel caused either an increase[18,19] or a decrease to the emitted nitrogen oxides.[14] It must be mentioned that engine technology plays an important role in these emissions,[20,21] and the maintenance condition of the engine must be taken into consideration. Considering conventional diesel fuels, the tradeoff between particulate and nitrogen oxide emissions means that lowering particulate emissions usually results in increased NO_x emissions,[22] depending on the engine technology as well. According to the course of our experiments, in most cases, when the smoke opacity was significantly reduced, the addition of biodiesel in the conventional diesel fuel did not lead to a clear increase of NO_x emissions. Similar tendencies have been recorded in other studies as well.[14,23]

When adding sunflower-oil biodiesel in 0.2% sulfur automotive diesel fuel, at idling speed, the observed changes of NO emissions lie between −3 to +8%, whereas at 2500 rpm, the changes fluctuate between −5 and +15%. When adding sunflower-oil biodiesel in 0.05% sulfur automotive diesel fuel, the changes of NO emissions are between −6 and +12% at the idling speed, and −6 to +14% at 2500 rpm.

Total nitrogen oxide emissions appear to have similar tendencies. In the case of adding sunflower-oil biodiesel in 0.2% sulfur diesel fuel, the observed changes of NO_x emissions lie between −1 and +9%, whereas at 2500 rpm, the changes fluctuate between −6 and +17%. For the addition of biodiesel in low-sulfur diesel fuel, the changes of NO_x emissions are between −8 and +11% at the idling speed, and −7 to +13% at 2500 rpm.

With respect to hydrocarbons and carbon-monoxide emissions, it has been reported that the use of biodiesel fuel results in the reduction of both of these pollutants.[24,25] However, in the course of our experiments, both of these pollutants were practically unaffected by the type of fuel used. The specific diesel engines employed in this study emitted very low amounts of hydrocarbons and carbon monoxide, even when fueled with conventional diesel fuels. Moreover, these emission levels were much lower than the measuring accuracy of the Horiba analyzer used for these types of emissions.[26]

As illustrated in Fig. 2, under the same driving conditions (circulation in the Athens area), the addition of biodiesel to both types of conventional diesel fuel resulted in slightly increased volumetric fuel consumption. Compared with conventional diesel fuel, biodiesel has a lower calorific value, owing to the oxygen contained in the ester fuel. Consequently, a small increase in volumetric fuel consumption was expected.[27,28]

Table 7 Mean values and standard deviations of NO/NOx emission measurements and black smoke opacity[a]

Fuel	NO, ppmv[b]		NO_x, ppmv[b]		Smoke opacity, %	Vehicle
Diesel fuel	82 ± 3.51	66 ± 3.05	85 ± 2.31	70 ± 1.52	60 ± 5.12	Taxicab
+10% biodiesel	80 ± 0.71	76 ± 0.73	84 ± 0.71	82 ± 0.72	59 ± 4.60	(Idling speed: 900 rpm)
Diesel fuel	62 ± 3.19	57 ± 2.82	89 ± 6.00	75 ± 3.60	82 ± 7.94	Pickup truck
+10% biodiesel	60 ± 3.09	56 ± 2.79	92 ± 4.04	84 ± 4.66	55 ± 6.64	(Idling speed: 550 rpm)
Diesel fuel	172 ± 7.51	148 ± 5.00	178 ± 6.50	160 ± 5.78	47 ± 4.12	Minibus
+10% biodiesel	185 ± 6.88	141 ± 4.46	194 ± 7.32	151 ± 5.27	45 ± 4.71	(Idling speed: 700 rpm)

[a]Diesel fuel with higher sulfur content.
[b]Idling speed 2500 rpm.

Table 8 Mean values and standard deviations of NO/NO_x emission measurements and black smoke opacity[a]

Fuel	NO, ppmv[b]		NO_x, ppmv[b]		Smoke opacity, %	Vehicle
Diesel fuel	78 ± 3.06	75 ± 2.00	90 ± 4.00	87 ± 1.15	65 ± 5.60	Taxicab
+10% biodiesel	83 ± 4.43	81 ± 4.26	94 ± 4.74	93 ± 4.40	48 ± 4.11	(Idling speed: 900 rpm)
Diesel fuel	63 ± 3.37	62 ± 3.32	91 ± 6.89	88 ± 6.11	76 ± 8.45	Pickup truck
+10% biodiesel	59 ± 2.88	58 ± 2.90	84 ± 4.09	82 ± 3.89	53 ± 6.20	(Idling speed: 700 rpm)
Diesel fuel	147 ± 4.82	128 ± 4.41	169 ± 6.55	150 ± 5.06	54 ± 5.35	Minibus
+10% biodiesel	164 ± 6.00	146 ± 5.27	188 ± 7.21	170 ± 7.62	36 ± 1.83	(Idling speed: 700 rpm)

[a]Low sulfur diesel fuel.
[b]Idling speed 2500 rpm.

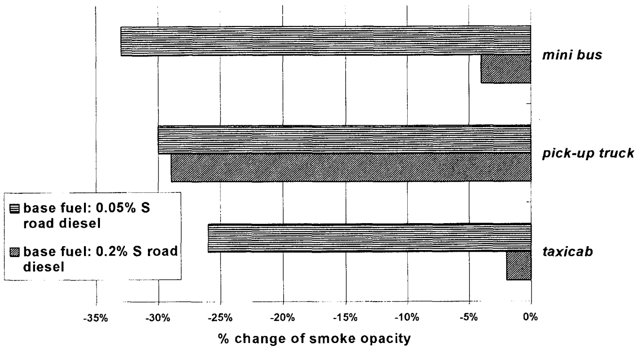

Fig. 1 Impact of biodiesel addition on smoke opacity.

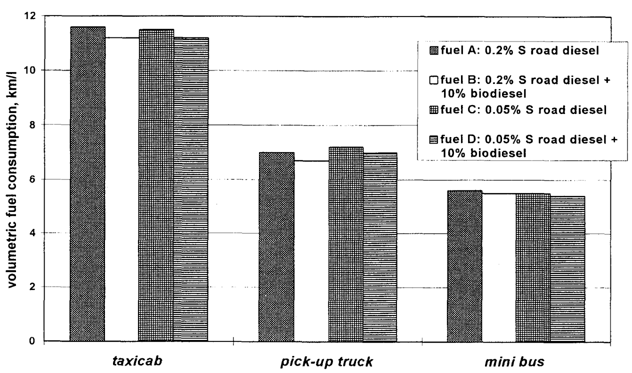

Fig. 2 Impact of biodiesel addition on the volumetric fuel consumption.

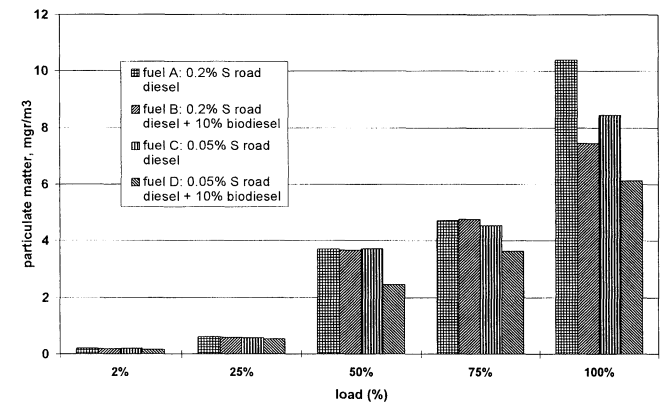

Fig. 3 Particulate matter emissions under different loads (Petter AV1-LAB engine).

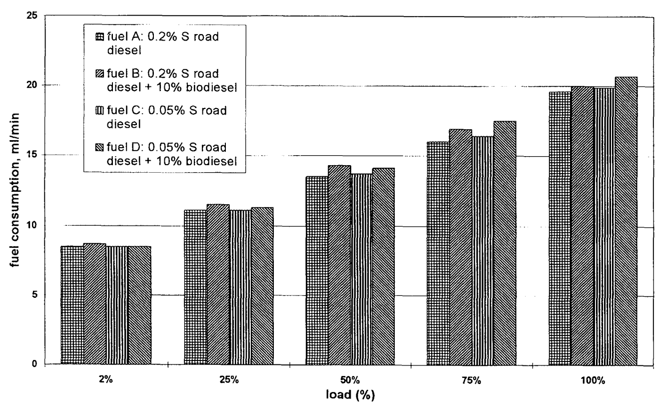

Fig. 4 Volumetric fuel consumption under different loads (Petter AV1-LAB engine).

Petter Engine: Emission and Fuel-Consumption Measurements

The Petter engine experiments included exhaust emission (NO_x and particulates) and volumetric fuel-consumption measurements, under different loads up to 5 hp, using the same four fuels.

Figure 3 shows the impact of the four different fuels used, on particulate matter emissions. Biodiesel appears to reduce particulate emissions, whereas the combination of 0.05% S typical diesel fuel with biodiesel resulted in the largest reduction, particularly at higher loads.

Figure 4 shows the impact of the four different fuels on volumetric fuel consumption. The two mixtures that contained biodiesel resulted in a slight increase of fuel consumption. Again, owing to the oxygen content of biodiesel, this behavior was expected.

Figures 5 and 6 show how the four fuels examined affect nitrogen oxide emissions. The addition of 10%, by volume, of sunflower-oil biodiesel to both types of traditional diesel fuel does not have a significant impact on NO_x and NO emissions. In general, low engine loads reduce NO_x emissions, whereas at high engine loads, a slight increase is observed in the presence of biodiesel. However, the differences monitored are very small, and may be considered as casual fluctuations.

Impact on Engine Wear

The pickup truck participated in the lubricant tests as described in the Experiment Procedure section of this paper. Tables 9 and 10 present the results of wear metal analyses. In general, the precision of this type of analysis is better than 10–15% by mass.[29]

When 0.2% sulphur diesel fuel plus 10% sunflower oil was used, a clear increase of Fe into the used lubricant was monitored, because the vehicle had reached 1500 km (it is recommended the SAE 30 lubricant to be changed every 3000 km) (Fig. 7). Taking into consideration that the metal parts of the engine contain significant quantities of Fe, while the other metals exist in much lower concentrations, the higher values for Fe, in either fuel, are explained. The metals Ag, Cu, Pb, and Cr were not significantly affected by biodiesel addition because the recorded changes were just a few ppm (Table 9).

Similar behavior was observed by the addition of 10%, by volume, sunflower oil biodiesel in the low-sulfur diesel fuel, using a lubricant of higher viscosity and better viscosity index (SAE 20W-50) (Fig. 8, Table 10).

Conclusively, owing to the large quantities of Fe that the metal parts of the engine contain, it could be said that, in the case of biodiesel addition, a very small tendency in increasing engine wear exists. However, as the increase in detected Fe was just a few parts per million (ppm), we cannot conclude that biodiesel blends affect the engine life negatively. A possible explanation for this small increase in Fe concentration inside the lubricant could be the fact that both lubricants employed were mainly designed for conventional diesel-fuel applications.

The slight increase of Fe concentration in the lubricant, because of the use of biodiesel, has been reported in other studies, mainly regarding experiments with rape-seed oil esters.[30] Another study[31] mentions that the presence of rape-seed methyl

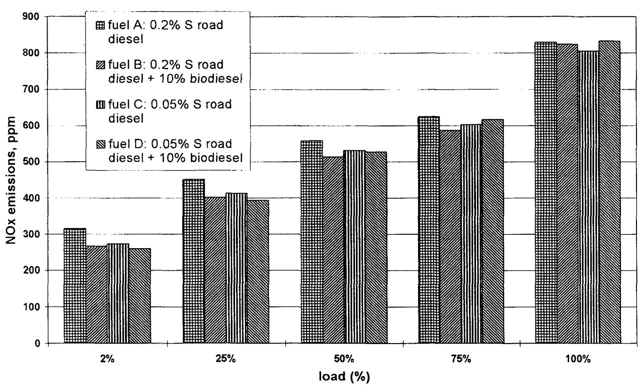

Fig. 5 NO_x emissions under different loads (Petter AV1-LAB engine).

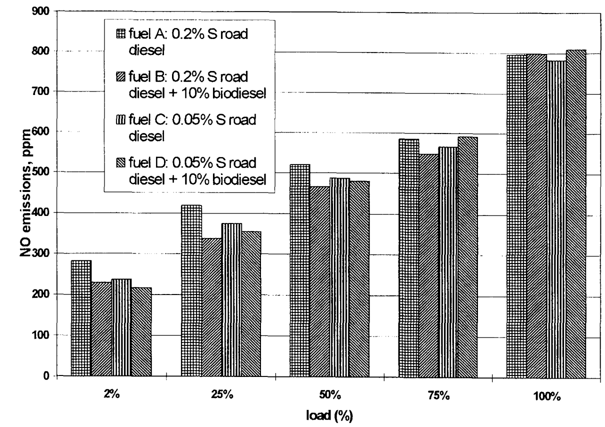

Fig. 6 NO emissions under different loads (Petter AV1-LAB engine).

Table 9 Wear metals analyses[a]

Fuel	Sample no.	Fe, ppmm	Ag, ppmm	Cu, ppmm	Pb, ppmm	Cr, ppmm
Diesel fuel	1 (0 km)	6.9	0.7	0.5	4.1	1.0
(DF)	2 (750 km)	63.3	0.7	3.8	8.2	3.4
	3 (1500 km)	87.2	0.7	4.2	9.9	3.7
	4 (2250 km)	101.5	0.8	5.5	11.4	5.3
	5 (3000 km)	139.5	0.9	7.5	12.9	7.9
10% biodiesel in diesel fuel	1 (0 km)	6.9	0.7	0.5	4.1	1.0
(DFS)	2 (750 km)	62.2	0.6	4.1	9.3	3.8
	3 (1500 km)	130.8	0.6	5.8	9.8	5.0
	4 (2250 km)	175.8	0.7	8.2	11.2	7.3
	5 (3000 km)	200.2	0.8	9.7	12.8	10.1

[a]Pickup truck, 0.2% S diesel fuel, 10% sunflower-oil biodiesel.

Table 10 Wear metal analyses[a]

Fuel	Sample no.	Fe, ppmm	Ag, ppmm	Cu, ppmm	Pb, ppmm	Cr, ppmm
Diesel fuel	1 (0 km)	5	0.0	0.0	3.4	0.5
(DF)	2 (1000 km)	67	0.1	4.0	3.6	3.0
	3 (2000 km)	100	0.2	5.5	3.7	3.9
	4 (3000 km)	139	0.3	7.7	5.7	5.2
	5 (4000 km)	144	0.6	8.5	6.0	7.1
	6 (5000 km)	164	0.6	8.8	7.0	7.3
10% biodiesel in diesel fuel	1 (0 km)	5	0.0	0.0	3.4	0.5
(DFS)	2 (1000 km)	94	0.2	2.0	2.6	4.0
	3 (2000 km)	122	0.4	2.8	4.9	4.4
	4 (3000 km)	151	0.5	3.9	7.0	5.0
	5 (4000 km)	179	0.6	9.4	7.0	7.1
	6 (5000 km)	193	0.6	10.1	9.0	7.7

[a]Pickup truck, 0.05% S diesel fuel, 10% sunflower-oil biodiesel.

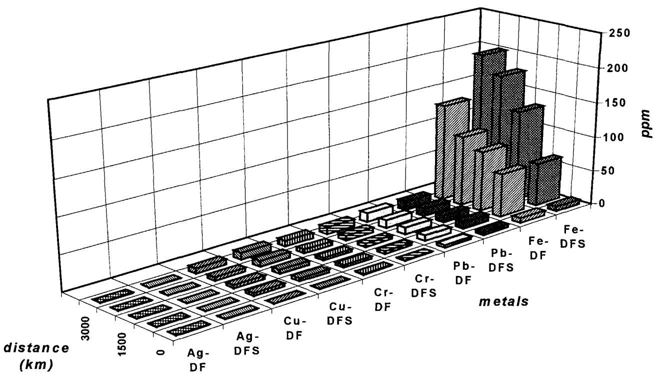

Fig. 7 Blend with 0.2% sulfur diesel fuel–wear metal analysis.

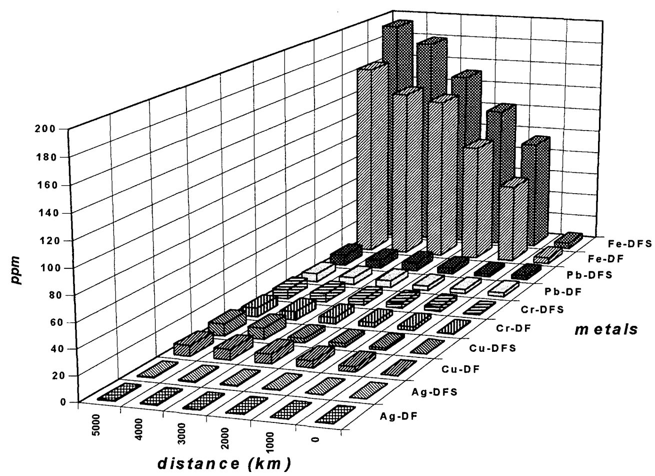

Fig. 8 Blend with 0.05% sulfur diesel fuel–wear metal analysis.

esters in the engine oil, although it decreases frictional wear and increases corrosive wear because of the acidity of the biodiesel detected in the lubricant.

Conclusions

This paper examines the impact of the addition of 10% v/v of sunflower-oil biodiesel to typical diesel fuels containing about 0.2 or 0.05% S, with regard to exhaust emissions, fuel consumption, and engine wear. For this purpose, three diesel engine vehicles, representative of the Athens diesel vehicle fleet, were employed and circulated in Athens, whereas a stationary, single-cylinder engine was also used for emission and fuel-consumption measurements.

The interpretation of the results leads to the following conclusions:

1) The addition of biodiesel in the traditional diesel fuel results in significant reduction of black smoke emissions, and the combination of low-sulfur diesel fuel and biodiesel comprises the best fuel blend tested. Even more, the combination of low-sulfur diesel fuel and biodiesel resulted in significantly improving the particulate matter emissions at higher loads.

2) With regard to fuel consumption, as expected, under the same circulation conditions, the fuels that contained biodiesel resulted in slightly increased fuel consumption. The experiments at the stationary engine gave similar results.

3) Wear metal measurements indicated that while the detected metals Ag, Cu, Pb, and Cr were not significantly affected by biodiesel addition, the fuel blend that contained biodiesel led to a slight increase of Fe into the used lubricant.

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References

[1]"European Fuel Specification Year 2000 and 2005 Proposals," Common Position (European Commission) No. 39/97, Oct. 7, 1997, and European Parliament 2nd reading, Brussels, Belgium, Feb. 1998.

[2]Hales, B. C., and Russell, M. F., "The Use of Fatty Acid Methyl Esters as Fuel for Diesel Engines," Lucas Diesel Systems, Lucas Varity, London, 1997.

[3]"Draft, Proposal for a Standardisation of Vegetable Oil Methylester (Biodiesel)," European Commission, Directorate General XVII, Brussels, Belgium, April 1992.

[4]Francese, D., Gamba, G., Aroldi, C., and Rocchietta, C., "Environmental Effects and Economic Viability of Alternative Diesel Fuels from Vegetable Oils," *Proceedings of the 9th International Symposium on Alcohol Fuels*, Firenze, Milano, Italy, 1991, pp. 984–987.

[5]"Biodiesel for Vehicles—Future Applications of Technology," TÜV Bayern Holding AG, Transportation and Vehicle Technology Div., Munich, Germany, 1996.

[6]Wills, J. G., *Lubrication Fundamentals*, Marcel Dekker, New York, 1980, pp. 29–31, 75–87.

[7]Koerbitz, W., "Recent Developments in Biodiesel," Symposium LIPIDEX '97, Antwerp, Belgium, March 1997.

[8]Scharmer, K., Gosse, G., Gabrielle, B., Golbs, G., Lambert, L., Poschmann, T., Rodenbrock, A., and Zimalla, K., "Energy Balance, Ecological Impact and Economics of Biodiesel Production in Europe," Altener Programme 4.1030/E/94-002-1, Pt. II, Dec. 1996.

[9]Syassen O., "The Development Potential of Diesel Engines with Biodiesel as Fuel," *Proceedings of the 2nd European Motor Biofuels Forum*, European Commission and Joanneum Research, Graz, Austria, 1996, pp. 191–202.

[10]Graboski, M. S., Ross, J. D., and Mccormick, R. L., "Transient Emissions from No. 2 Diesel and Biodiesel Blends in a DDC Series GO Engine," Society of Automotive Engineers, Paper 961166, New York, 1996.

[11]Tertois, V., "Trials of RME Blends in Home-Based Transport Fleets," *Proceedings of the Conference of the Altener Programme: Renewable Energy Entering the 21st Century*, European Commission, DG XVII, Brussels, Belgium, 1996, pp. 1409–1415.

[12]"Spectrometric Analysis of Lubricants for Aircrafts," U.S. Air Force, TB 55-6650-300-15, 1989.

[13]*Methods for Determination of Velocity, Volume, Dust and Mist Content of Gases*, 7th ed., Western Precipitation Div., JOY Manufactoring Co., Los Angeles, CA, 1988.

[14]Sams, T., "Use of Biofuels Under Real World Engine Operation," *Proceedings of the 2nd European Motor Biofuels Forum*, European Commission and Joanneum Research, Graz, Austria, 1996, pp. 225–231.

[15]Schaefer, A., "Biodiesel as an Alternative Fuel for Commercial Vehicle Engines," *Proceedings of the 2nd European Motor Biofuels Forum*, European Commission and Joanneum Research, Graz, Austria, 1996, pp. 233–244.

[16]Chang, D. Y. Z., Van Gerpen, J. H., Lee, I., Johnson, L. A., Hammond, E. G., and Marley, S. J., "Fuel Properties and Emissions of Soybean Oil Esters as Diesel Fuel," *Journal of the American Oil Chemists' Society*, Vol. 73, No. 11, 1996, pp. 1549–1555.

[17]*Opacimetro, Tecneco MSA, Mark III, by FIAT, LANCIA, VIA PO 13/17-20089 Rozzano (ML)*, Msa Italiana S.P.A., Milano, Italy, 1989.

[18]ADEME, ALTENER Programme, European Commission DG XVII, "The Non-Technical Barriers Liquid Biofuels European Network (Used in Engines and Boilers)," ADEME, Paris, 1995.

[19]Serdari, A., "Novel Methods for the Upgrading of Middle Distillate Petroleum Fractions by Using Substitute Fuel Components and Additives," Ph.D., Dissertation, National Technical Univ., Athens, Greece, 1994, pp. 145–155.

[20]Karonis, D., "Effect of Liquid Fuel Properties on Exhaust Emissions," Ph.D. Dissertation, National Technical Univ., Athens, Greece, 1995, p. 270.

[21]"Pilot Actions Aimed at Introducing Liquid Fuels Derived from Biomass in Place of Petroleum Products in the Transport Sector," Fuels and Lubricants Lab., 2nd Interim Rept., Altener Project XVII/4.1030/AL/103/95/GR, National Technical Univ. of Athens, Athens, Greece, Dec. 1997.

[22]"Diesel Fuel Quality and Its Relationship with Emissions from Diesel Engines," CONCAWE Rept. 10/87, Hague, The Netherlands, 1987.

[23]Starr, M. E., "Influence on Transient Emissions at Various Injection Timings, Using Cetane Improvers, Bio-Diesels, and Low Aromatic Fuels," Society of Automotive Engineers, Paper 972904, 1997.

[24]Marshall, W., Schumacher, L., and Howell S., "Engine Exhaust Emissions Evaluation of a Cummins L10E when Fueled with a Biodiesel Blend," Society of Automotive Engineers, Paper 952363, 1995.

[25]Akasaka, Y., Suzuki, T., and Sakurai, Y., "Exhaust Emissions of a DI Diesel Engine Fueled with Blends of Biodiesel and Low Sulfur Diesel Fuel," Society of Automotive Engineers, Paper 972998, 1997.

[26]*Instruction Manual, Automotive Emission Analysers MEXA 544 GE, MEXA 554 GE MEXA 574 G*, Horiba Ltd., Kyoto, Japan, 1990.

[27]Wiesbauer, H., "Eight Years Experience with Biodiesel in Farm Tractors (Steyr Daimler Puch AG)," *Proceedings of the International Conference on Standardization and Analysis of Biodiesel*, Research Inst. for Chemistry and Technology of Petroleum Products (FICHTE), Vienna Univ. of Technology, Vienna, Austria, 1995, pp. 64–70.

[28]Horstmann, B., and Stumpf, W., "Rape Methyl Ester and Soy Methyl Ester Test Experience," *Proceedings of the International Conference on Standardization and Analysis of Biodiesel*, Research Inst. for Chemistry and Technology of Petroleum Products (FICHTE), Vienna Univ. of Technology, Vienna, Austria, 1995, pp. 103–112.

[29]*Analytical Methods for Atomic Absorption Spectrophotometer*, Perkin Elmer, 1982.

[30]"Development of Rapeseed Biodiesel for Use in High-Speed Diesel Engines," Progress Report for the United States Department of Energy, Bonneville Power Administration, Dept. of Biological and Agricultural Engineering, Contract 93BIO9233, 302, Univ. of Idaho, Sept. 1996, pp. 42–52.

[31]Baumann, W., "Solving Bearing Corrosion in Biodiesel Fuelled Engines," *Proceedings of the International Conference on Standardization and Analysis of Biodiesel*, Research Inst. for Chemistry and Technology of Petroleum Products (FICHTE), Vienna, Austria, 1995, pp. 196–198.