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Biodiesel Blend Detection Using a Fuel Composition Sensor

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Abstract. *Biodiesel is an alternative diesel fuel consisting of the alkyl monoesters of fatty acids from vegetable oils and animal fats. Biodiesel can be used in diesel engines as a pure fuel or in blends with petroleum-based diesel fuel. To maintain optimum performance and meet emission regulations, it may be necessary to measure the composition of blended fuels and adjust the fuel injection timing and other injection parameters during operation. The objective of this study was to investigate the suitability of using a commercial Flexible Fuel Composition Sensor for the detection of biodiesel composition in biodiesel/diesel fuel blends. Twelve different biodiesel fuel samples were tested including pure esters and esters from soybean oil, tallow, lard, canola oil, and yellow grease. The sensor produced a frequency output between 58.75 and 60.23 Hz for all of the biodiesel samples. Six different diesel fuel samples were also tested including commercial No.1 diesel fuel and EPA emission certification fuel. All of the diesel fuel samples gave frequencies between 51.84 and 52.62 Hz. The frequency output of the sensor was observed to be linearly proportional to the percentage of biodiesel in blend. The 7.14 Hz average difference from diesel fuel to biodiesel is sufficient to use this fuel composition sensor for blend detection of biodiesel blended fuels.*

Keywords. Esters, Biodiesel, Diesel Fuel, Blend Detection, Fuel Composition Sensor, Dielectric Constant.

Introduction

Limited energy resources and increasingly strict emission regulations have motivated an intense search for alternative transportation fuels over the last three decades. A major obstacle to commercialization of these alternative fuels is the lack of widespread fuel availability. Alternatif fuels that can be blended with existing petroleum-based fuels have a distinct advantage because they can be used when available but the vehicle can also be fueled with conventional fuels when the alternative is unavailable.

Vehicles with the capability to operate on blends of methanol and gasoline from 0 to 85% (percentage of methanol) have been produced on a large scale basis and have demonstrated that the technology is effective and reliable (Kopera, et al. 1992). Ethanol-fueled vehicles are also available. Alcohol fuels do not require major engine modifications to be used in spark ignited engines. However, methanol has about half of the heating value of gasoline and must operate at a different air-fuel ratio. Therefore, the ignition timing and fuel flow rate must be adjusted based on the composition of the fuel. The engine must know the blend ratio of the fuels at all times while the engine is running and for cold starting. In order to determine the blend level, optical fuel composition sensors and dielectric-effect fuel composition sensors were developed.

Biodiesel is an environmentally friendly alternative diesel fuel consisting of the alkyl monoesters of fatty acids from vegetable oils and animal fats. Recent developments in the relative prices of vegetable oils and petroleum have produced conditions where biodiesel is close to being cost competitive. Depending on the trade-off between cost and its environmental benefits, biodiesel will probably be used blended with No. 2 or No. 1 diesel fuels. Similar to alcohol fuels, biodiesel has a lower energy content and different physical properties than diesel fuels (Tat and Van Gerpen, 1999; Tat and Van Gerpen, 2000a; and Tat et al., 2000b) and this may require engine setting adjustments to improve engine performance and emissions. This will require blend detection.

Ford Motor Co. currently uses a Flexible Fuel Composition Sensor to detect the methanol composition in methanol-gasoline blends. The objective of this project was to investigate whether this sensor could be used for measuring the composition of biodiesel-diesel fuel blends.

Background

In order to develop a blend sensor, a specific physical or chemical property must be monitored. Sometimes this measurement must be supported by temperature or some other property measurement in order to compensate for its effect. For alcohol-gasoline blends, two types of fuel composition sensors are most commonly used. The first type is an optical sensor that measures the refractive index and the second type is a dielectric effect sensor that measures the dielectric constant of the fuel blend.

Optical fuel composition sensors measure the refractive index of the fuel using one of two methods. The first method uses detection of the changes in the amount of light that is received by a receiving element and the second method uses measurement of the change in the position of an incident light beam onto a receiving element based on Snell’s law (Suzuki et al., 1991). The first method has not found wide acceptance because it is generally too sensitive to contamination of the optical system. The second method of optical fuel composition sensing is shown in the schematic given in Figure 1. An infrared LED emits light that passes through an optical glass rod prism, then through the fuel sample, and then strikes the reflection mirror. It is reflected by the mirror and goes back through the fuel sample where it hits the rod prism again, However, this time, due to the angle of the rod prism surface and the refractive index ratio between the rod prism and the fuel, the return path for the light varies according to Snell's law. After the light leaves the rod prism it is focused by a condenser lens onto a sensitive detector whose resistance will change based on the incident light location on the detector. This type of optical fuel sensor was developed for two proposes, to measure the blend concentration in blended fuel and to measure gasoline quality (Suzuki and Ogawa,1991). It has been found that the method is effective for both purposes. It gives a linear voltage output, it is resistant to contamination, and it is highly durable. However, they are more sensitive to phase change and the presence of water in the mixture than dielectric effect fuel composition sensors.

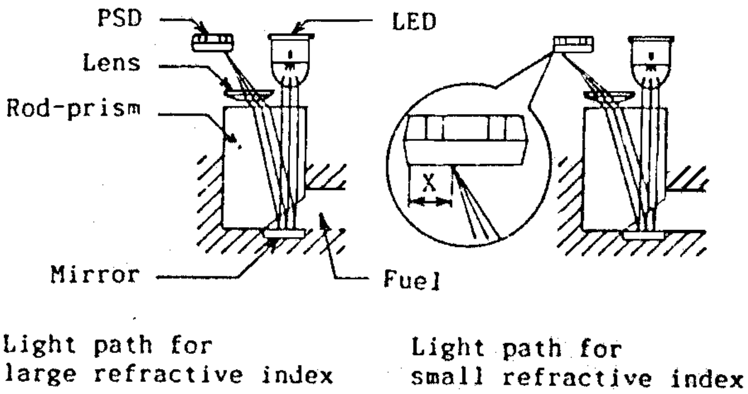

Figure 1. Schematic Shown of Optical Fuel Sensor (Suzuki et al., 1991).

The early design of dielectric fuel composition sensors followed the equivalent circuit given in Figure 2. The circuit includes two resistances and a capacitor. The capacitor was made using a concentric cylinder with the inner and outer cylinders being electrodes (Schmitz et al., 1990). Fuel was the dielectric medium flowing between the concentric cylinders. The voltage transfer function from Vin to Vout in this circuit depends on the input voltage frequency and the capacitance change which varies as a function of the dielectric constant of the fuel. The conductivity and temperature of the sample were measured by a signal conditioning unit and the data evaluated by a controller unit.

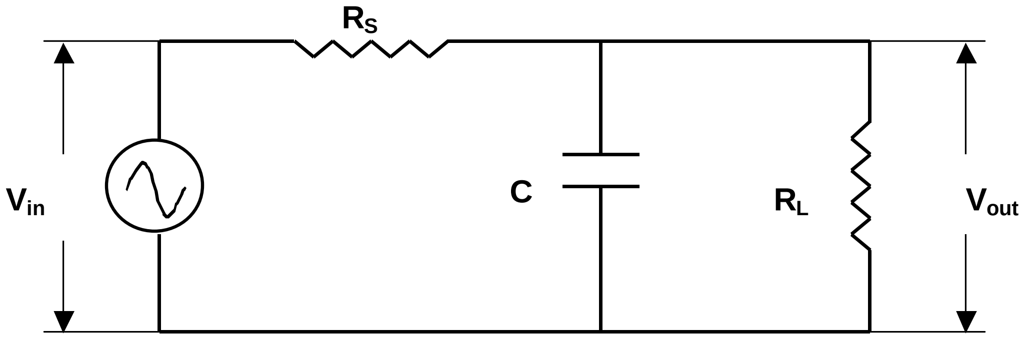

Figure 2. Equivalent circuit for basic dielectric fuel composition sensor (Meitzler et al. 1992).

Ford Motor Co. has described two alternative dielectric fuel composition sensors, the Pi-Filter Network sensor and the Resonant Cavity sensor (Meitzler et al., 1992 and Meitzler et al.,1994). The basic principle is the same as the simple circuit described above except that instead of one capacitor they used three capacitors and two coils in parallel with two of the capacitors creating a pi network. When they tried to simplify the pi-network, they put three capacitors in-line as a coaxial structure and they produced the Resonant Cavity Sensor. The idea of the Resonant Cavity Sensor comes from the electromagnetic theory of resonant cavities. These designs increased the sensitivity of the sensor and they are more dependable.

Another type of dielectric fuel composition sensor that has been developed consists of a wound coil which is was immersed into the fuel blend. The fuel is the dielectric medium to be measured and the turns of the coil act as the equivalent electrodes of a capacitor (Kopera et al., 1993, Kopera, 1992, and Depa et al., 1992).

Materials and Method

Ford Motor Co. donated one dielectric fuel composition sensor originally designed for detection of the methanol concentration in methanol-gasoline blends. Although the operating principle has not been confirmed, it is believed to be a resonant cavity dielectric sensor. The sensor is shown in Figure 3. The sensor gives a square wave output with a frequency that is proportional to the blend composition and the duration of the high portion of the wave is proportional to the temperature of the blend. A HP 5335 A Universal Counter was used to measure the frequency output of the sensor. A 12 Volt power supply provided power to the sensor, and a pull-up resistor was connected from the output of the sensor to 12V. A schematic diagram of the connections is given in Figure 4.

Measurements were conducted at room temperature, 23 °C. The sensor was filled with a fuel sample through the inlet or outlet port, and the square waves were counted for three minutes. The counter was started and stopped manually with the elapsed time measured using a stopwatch. This measurement was repeated four times for each sample in random order. The sensor was cleaned between measurements by rinsing with ethanol and dried using compressed air.

Twelve different types of biodiesel including pure esters as well as esters from soybean oil, tallow, lard, canola oil and yellow grease were tested. A complete list of the esters is shown along the abscissa of Figure 5 and in Table 1. Biodiesel is generally prepared by chemically reacting a fat or oil with an alcohol in the presence of a catalyst. When methanol is used as the alcohol, the resulting esters are methyl esters. When ethanol is used, the esters are ethyl esters. The samples studied for this project included both types so the effect of the alcohol type could be determined. Some of the samples were derived from animal fats with high saturation levels, and some came from vegetable oils with low saturation level so that the effect of saturation level on the dielectric constant could be determined. Also, some of the fuel samples were oxidized so that effect could be characterized also. The biodiesel samples were collected from a variety of sources including a previous collaborative project with the Colorado School of Mines. Although complete property information is not available for some of the fuels, fatty acid composition and some property data are provided in Tables A.3, A.4, and A.5 of the Appendix.

Six different kinds of diesel fuel were tested. These diesel fuel samples included two low sulfur (<500ppm) No. 2 diesel fuels which contained no additives. These two fuels came from different refineries and were identified as F5 and F6. Another fuel, designated as F4, was a low sulfur No. 2 diesel fuel and contained a commercial additive package. The last three fuels were an EPA emissions certification fuel and locally obtained commercial No. 1 and No. 2 diesel fuels. Distillation curves, specific gravity, and some other properties of these fuels are shown in Tables A.1 and A.2 of the Appendix.

Blends of 20%, 50%, and 75% Methyl Soy Ester with the commercial No. 2 and No. 1 diesel fuels were prepared by weight at 23 °C, and measured with the other samples in order to characterize the blend behavior between the diesel and biodiesel fuels.

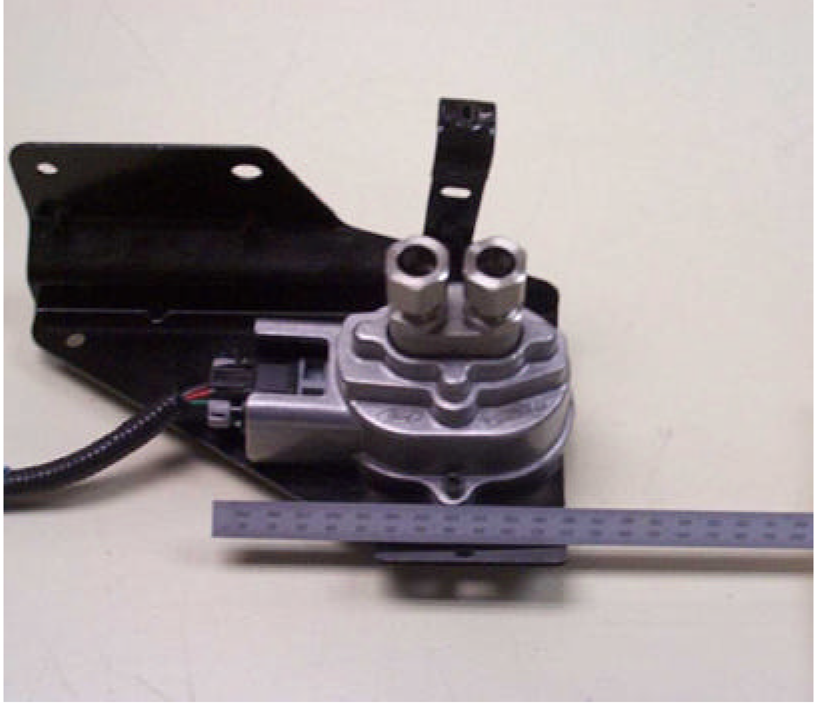

Figure 3. Flexible Fuel Composition Sensor (Ford Part No. 9C044).

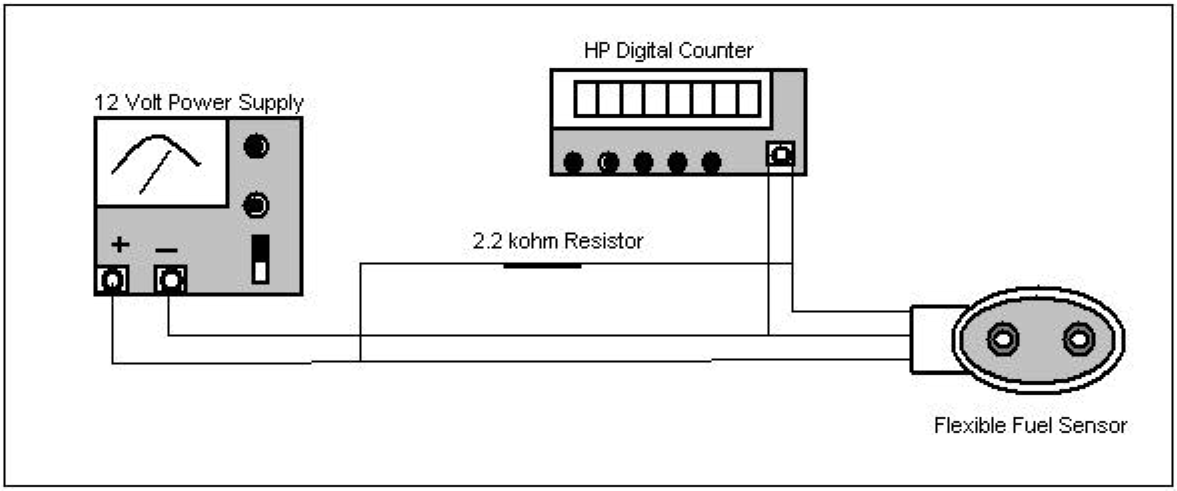

Figure 4. Schematic of the Instrumentation Set Up.

Results

The measurement results are given in Table 1 for a total of 24 samples. The values reported are the average and standard deviation of four measurements. Figure 5 presents the measured results for the 12 biodiesel fuel samples. Even though many types of biodiesel fuels were tested, the range of frequencies produced by the sensor is quite narrow. The biodiesel frequencies varied from 58.75 Hz to 60.23 Hz. There does not appear to be a consistent trend for the sensor response corresponding to the different esters. While both of the highly unsaturated esters (methyl linoleate and ethyl linoleate) gave frequencies that were on the high end of the range, the highest frequency came from the brown grease methyl ester which was highly saturated. There also appeared to be no consistent trend with methyl and ethyl esters. The ethyl soy ester frequency was higher than the methyl soy ester, but the oxidized methyl and ethyl soy esters were about the same. The methyl linoleate and ethyl linoleate also gave about the same sensor response. The slight variations in frequency between the biodiesel samples are apparently due to differences that were not controlled for this experiment but they are not large enough to interfere with the sensor's ability to distinguish between biodiesel and diesel fuel. Future work is planned to investigate the effect of polar contaminants on the sensor response. Glycerin was found to give a frequency output of 162.2 Hz.

In Figure 6, it can be seen that the diesel fuels show even less variation than the biodiesel samples. The minimum frequency was found for the No. 1 diesel fuel at 51.84 Hz and the highest was 52.63 Hz from the commercial No. 2 diesel fuel. The average values of the biodiesel and diesel fuel samples are given in Table 2. The difference between the averages was 7.15 Hz and this corresponds to a 0.07 Hz increase in frequency per percent of the blend.

Figure 7 shows the variations in the sensor frequency output as the blend level of biodiesel and diesel fuel was varied. It is clear that the change in sensor output from diesel fuel to biodiesel is linear.

The biodiesel and diesel fuel variations from their maximum value to their minimum value were about 20% and 11% of the 7.15 Hz difference between the averages for the two types of fuel. The greatest deviation occurred for the methyl ester of yellow grease #1 with the lowest frequency output of 58.75 Hz. The difference between the lowest frequency output and the average value for biodiesel was 0.7141 Hz. If we divide this number with frequency change for per percentage (0.0714) the error was about 10.5 percent. This result showed that the total variation is large enough and maximum error small enough to use this sensor for biodiesel blend detection. Because the maximum timing change due to biodiesel use in diesel engine is likely to be only 2 - 3 crank angle degrees (Tat et al. 2000b) an error of 10% in blend concentration should only produce an error of 0.2° - 0.3° in injection timing, which is close to current manufacturing tolerances.

Table 1. Average Frequency Output and Standard Deviations for All Fuel Samples.

Diesel Fuel Samples	**Sensor Output Frequency, Hz**	**Standard Deviations (4 Measurements)**
Diesel Fuel Samples		
F6 No. 2 Diesel Fuel	52.34	0.06
F5 No. 2 Diesel Fuel	52.56	0.02
F4 No. 2 Diesel Fuel	52.54	0.04
EPA Emission Certification Fuel	52.17	0.12
Commercial No. 2 Diesel Fuel	52.63	0.13
Commercial No. 1 Diesel Fuel	51.84	0.08
Biodiesel Fuel Samples		
Methyl Soy Ester	58.96	0.14
Ethyl Soy Ester	59.94	0.06
Methyl Tallow	59.01	0.21
Methyl Lard	59.02	0.08
Methyl Canola	59.29	0.06
Methyl Oxidized Soy	59.61	0.09
Ethyl Oxidized Soy	59.69	0.17
Yellow Grease Methyl Ester (#1)	58.75	0.04
Methyl Linoleate	60.02	0.03
Ethyl Linoleate	60.05	0.10
Yellow Grease Methyl Ester (#2)	59.27	0.15
Brown Grease Methyl Ester	60.23	0.16
Biodiesel Blends with No. 2 and No. 1 Diesel Fuels		
75% Methyl Soy Ester with 25% Commercial No. 2 Diesel Fuel	57.19	0.23
50% Methyl Soy Ester with 50% Commercial No. 2 Diesel Fuel	55.67	0.20
20% Methyl Soy Ester with 80% Commercial No. 2 Diesel Fuel	53.91	0.14
75% Methyl Soy Ester with 25% Commercial No. 1 Diesel Fuel	57.02	0.09
50% Methyl Soy Ester with 50% Commercial No. 1 Diesel Fuel	55.34	0.09
20% Methyl Soy Ester with 80% Commercial No. 1 Diesel Fuel	53.56	0.03

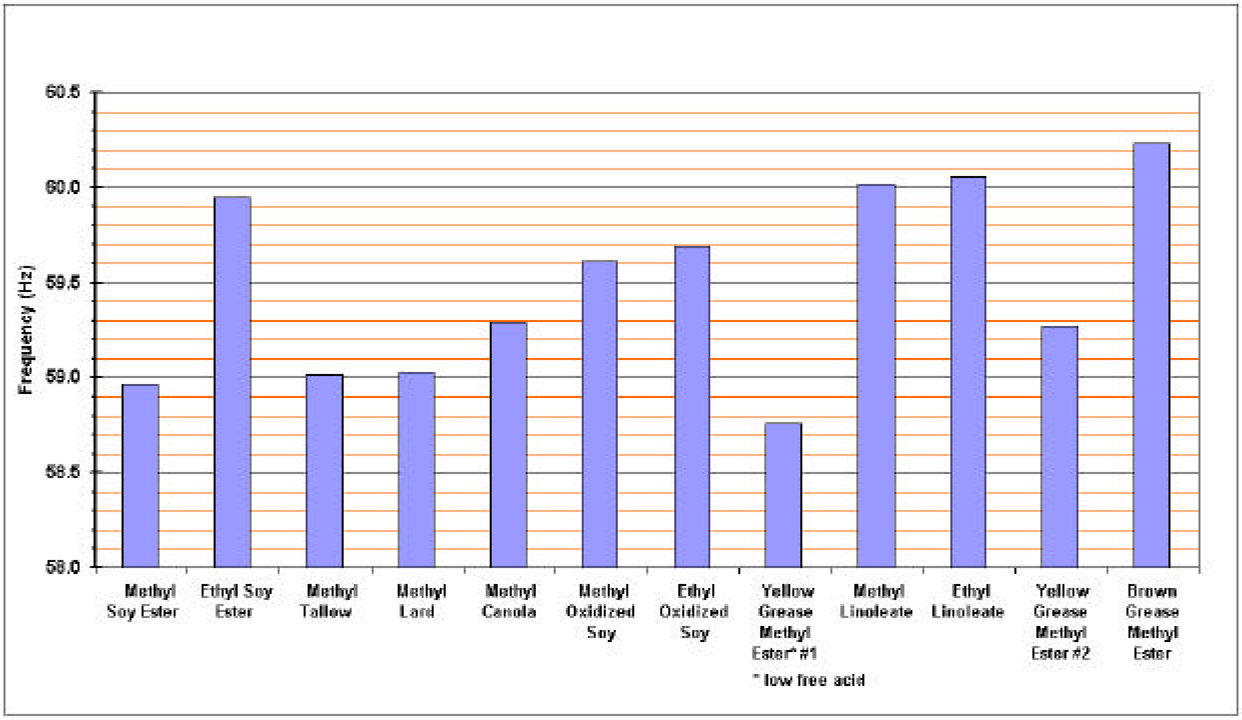

Figure 5. Biodiesel Fuel Samples.

Table 2. Biodiesel and Diesel Fuels Analytical Averages and Standard Deviations

Fuel Samples	Fuel Type Average	Fuel Type Standard Deviation
Biodiesel Fuel Samples	59.49	0.50
Diesel Fuels Samples	52.35	0.30

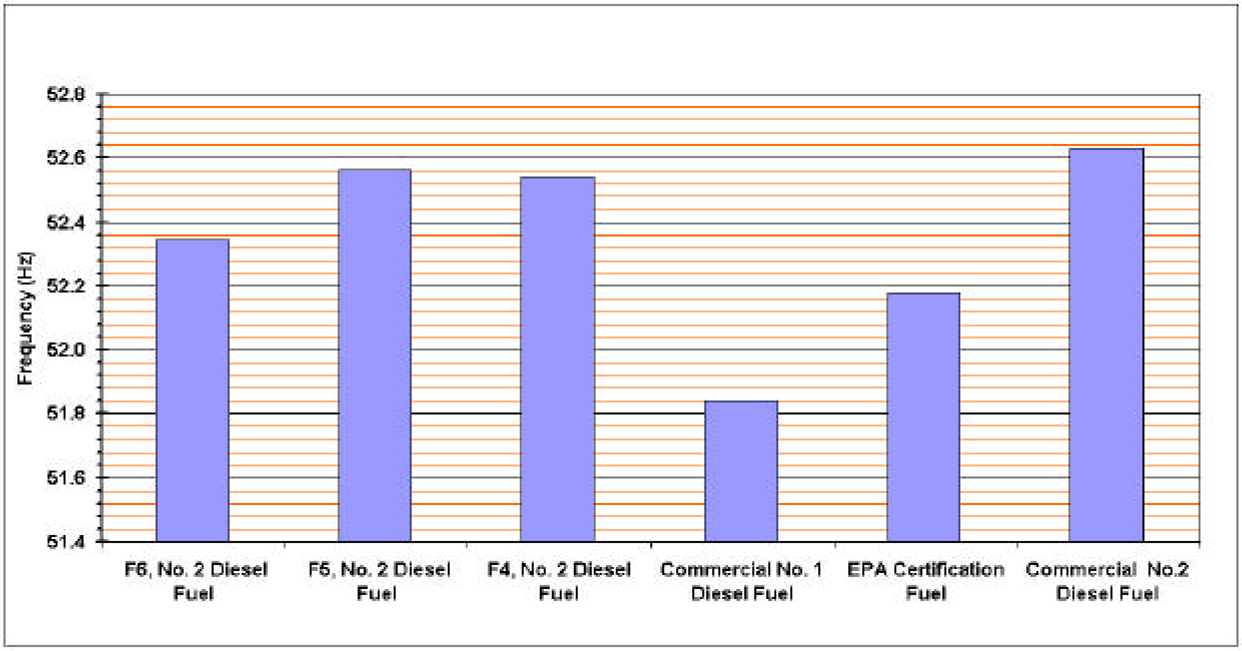

Figure 6. Diesel Fuel's Frequency Distribution.

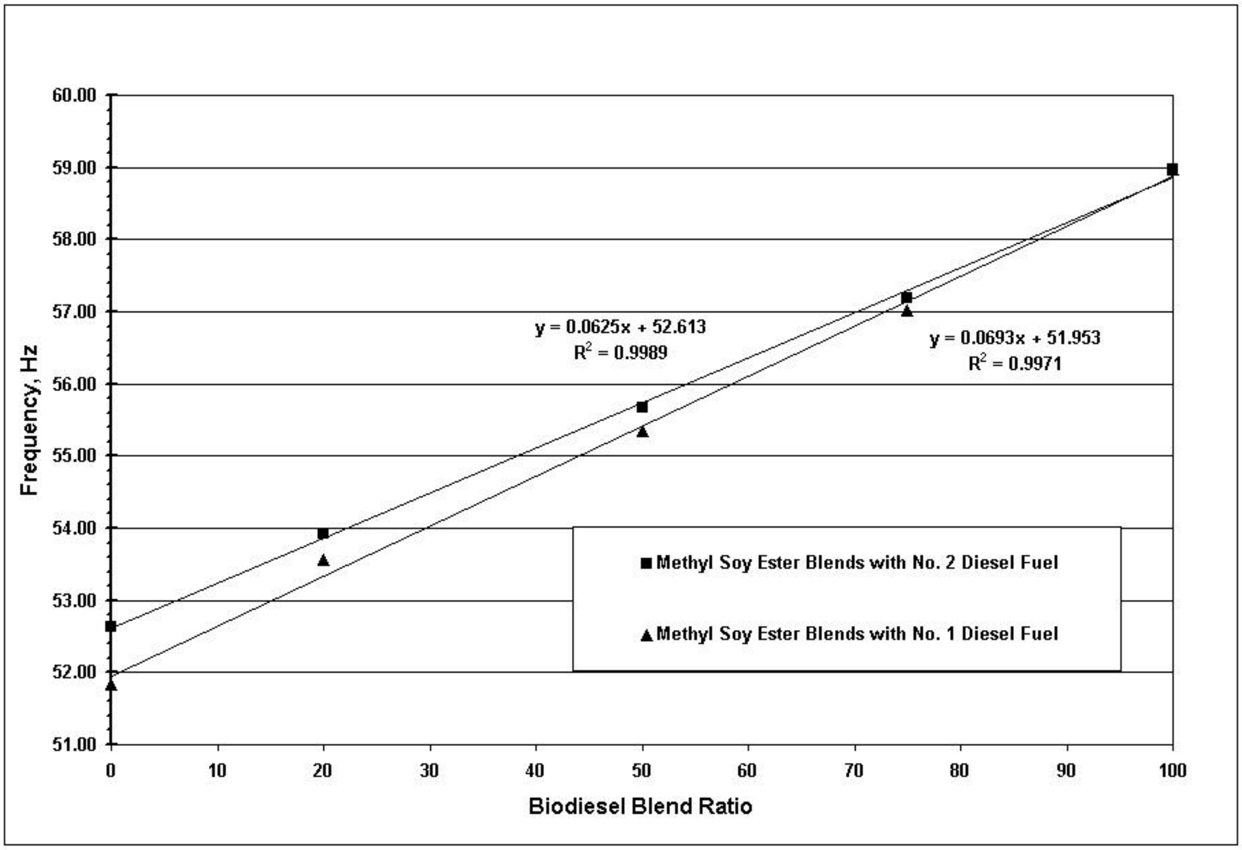

Figure 7. Methyl Soy Ester Blends with No. 2 and No. 1 Diesel Fuel.

Conclusions

Biodiesel is currently being promoted as an environmentally friendly alternative diesel fuel. Its use will depend on the trade-off between cost and its environmental benefits. It will most likely be used in blends with diesel fuel. Because of its different physical and chemical properties, biodiesel can produce higher NOx and lower power. This problem can be solved by using a fuel composition sensor that will detect the biodiesel-diesel fuel blend during engine operation. Based on the detected blend ratio, the engine control unit can adjust the injection timing and duration to improve the engine emissions and performance.

A commercially available Fuel Composition Sensor was tested with twelve biodiesel and six diesel fuels. It was found that the difference between the biodiesel and diesel fuels was 7.14 Hz and the intermediate blends followed a linear relationship. While the variability in response between the different fuels tested may cause 10% error in the blend level estimate, the sensor appears to be usable for development of a biodiesel flexible fuel vehicle.

Acknowledgments

The Colorado School of Mines provided several of the biodiesel fuel samples used for this study.

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Appendix

Table A.1 The Physical and Chemical Properties of Commercial No.2 and No. 1 Diesel Fuels.

Test Property	**Commercial No. 2 Diesel Fuel**	**Commercial No.1 Diesel Fuel**
Carbon (% mass)	86.70[a]	86.83[a]
Hydrogen (% mass)	12.71[a]	12.72[a]
Oxygen (% mass)	-	-
C/H Ratio	6.82	6.826
Sulfur (% mass)	0.041[a]	0.045[a]
Cetane Number (ASTM D613)	42.6[a]	45.3[a]
Gross Heat of Combustion (kJ/kg)	45,339[a]	45,991[a]
Net Heat of Combustion (kJ/kg)	42,640[a]	43281[a]
Specific Gravity (@21 °C)	0.8537[c]	0.8162[c]
Kinematic Viscosity (cSt, @40 C)	2.8271[c]	1.759[c]
Total Glycerin (%)	-	-
Free Glycerin (%)	-	-
Distillation (ASTM D86, °F)[a]		
Initial Boiling Point	*352*	348
5%	392	373
10%	413	384
20%	440	394
30%	462	406
40%	482	416
50%	502	426
60%	522	440
70%	543	454
80%	569	474
90%	602	503
95%	630	535
End Point	653	580
Recovery (%)	98.0	98.0
Residue (%)	1.9	1.9
Loss (%)	0.1	0.1

[a] Measured by Phoenix Chemical Laboratory Inc., Chicago IL.

[b] Measured by Williams Laboratory Services, Kansas City, KS.

[c] Measured in the Department of Mechanical Engineering, Iowa State University, Ames, IA.

[d] Calculated using Universal Oil Products Method 375-86, Des Plaines IL.

[e] Calculated from Fatty Acid Distribution.

Table A.2 The Physical and Chemical properties of F4, F5, and F6 Diesel Fuels.

Test Property	**F4 No. 2 Diesel Fuel**	**F5 No.2 Diesel Fuel**	**F6 No. 2 Diesel Fuel**
Specific Gravity (@21 °C)	0.8563[a]	0.8478[a]	0.8557[a]
Kinematic Viscosity (cSt, @40 C)	2.4914[a]	2.8165[a]	2.5026[a]
Distillation (ASTM D86, °F)[a]			
Initial Boiling Point	360	350	348
5%	400	390	390
10%	416	410	408
20%	442	438	436
30%	462	460	456
40%	582	482	476
50%	500	504	496
60%	518	524	514
70%	536	546	532
80%	556	572	552
90%	582	608	578
95%	602	632	596

[a] Measured in the Department of Mechanical Engineering, Iowa State University, Ames, IA.

Table A.3. Fuel Analysis Results for Some of the Biodiesel Fuel Samples.

Fuel	Acid Number	Iodine Number	Peroxides	Water And Sediment	Glycerol, wt%		Glycerides			Total Glycerin
Ester	mg KOH/g	mg I_2/g	mg/kg	vol%	Free	Bound	Mono-	Di-	Tri-	
1. Methyl Linoleate	0.41	151	148	0	0.001	0.126	0.078	0.153	0.79	0.126
2. Ethyl Linoleate	0.81	140	655	0	0	0.089	0.326	0.03	0	0.089
3. Ethyl Soy Ester	3.02	122	123	0	0.003	0.031	0.083	0.036	0.01	0.031
4. Methyl Oxidized Soy	0.6	131	1861	0	0.001	0.012	0.018	0.036	0.01	0.012
5. Ethyl Oxidized Soy	3.81	118	210	0	0.001					

Table A.4. Fatty Acid Composition of Some Fuels Tested.

	Myristic	Penta-decanoic	Palmitic	Palmitoleic	Margaric	Stearic	Oleic	Linoleic	Linolenic	Arachidic
Ester	C14:0	C15:0	C16:0	C16:1	C17:0	C18:0	C18:1	C18:2	C18:3	C20.0
1. Methyl Linoleate	-	-	1.4	-	-	0.7	5.2	86.5	6.2	-
2. Ethyl Linoleate	-	-	2.7	-	-	2.4	6.4	88.5	-	-
3. Methyl Soy Ester	-	-	10.56	-	0.11	1.74	22.51	52.39	8.2	-
4. Ethyl Soy Ester	-	-	14	-	-	9	52.7	24.3	-	-
5. Methyl Oxidized Soy	-	-	15.2	-	-	5.3	57	22.5	-	-
6. Ethyl Oxidized Soy	-	-	15	-	-	7	55.3	22.6	-	-
7. Yellow Grease Methyl Ester	2.42	0.36	22.77	3.84	0.95	12.03	44.98	7.8	0.79	0.14
8. Brown Grease Methyl Ester	1.63	0.19	22.84	3.06	0.58	12.94	42.51	11.61	0.79	0.21

Amounts reported for individual fatty acids combine methyl and ethyl esters when both were present during measurement.

Table A.5. Chemical Properties of Some Ester Samples.

Test Identification	Description	Methyl Soy Ester	Methyl Lard	Methyl Canola	Methyl Tallow
D93	Flash, Pensky Martens, °F		263	326	344
D97	Pour Point, °F		55	25	60
D130	Corrosion		1A	1A	1A
D240	Heat of Combustion/Gross Calorific Value, BTU/lb	17145	17165	17241	17144
D445	Kinematic Viscosity, cSt @ 40 °C				4.908
D524	Carbon Residue, Ramsbottom, 100% as 10%		0.04	0.04	
D613	Cetane Number		xxxxxx	53.9	64.8
D664	Acid Number by Potentiometric Titration, mg		0.76	0.13	0.32
D1298	Specific Gravity @ 74 °F, g/ml		0.8762	0.8811	0.8708
D2500	Cloud Point, °F		56	26	66
D2622	Sulfur, wt%		0.0000	0.0000	0.000
D3242	Neutralization Number, mg KOH/g		0.760	0.120	0.350
D5291	CH				
D5291	Carbon, wt%	77.10	77.36	77.68	77.07
D5291	Hydrogen, wt%	11.81	12.5	12.25	12.05
IP309	Cold Filter Plugging Point, °F		52	24	
C. Plank	Impurities in Biodiesel Methyl Esters				
C. Plank	Free glycerin, wt%	0.000	0.000	0.001	0.000
C. Plank	Monoglycerides, wt%	0.107	0.563	0.738	0.320
C. Plank	Diglycerides, wt%	0.00	0.093	0.020	0.120
C. Plank	Triglycerides, wt%	0.00	0.005	0.010	0.014
C. Plank	Total glycerides, wt%	0.028	0.160	0.196	0.102