ENGINE PERFORMANCE AND EXHAUST EMISSIONS FROM A DIESEL ENGINE USING COTTONSEED OIL BIODIESEL

A Thesis

by

JACOB JOSEPH POWELL

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2007

Major Subject: Biological and Agricultural Engineering

ENGINE PERFORMANCE AND EXHAUST EMISSIONS FROM A DIESEL ENGINE USING COTTONSEED OIL BIODIESEL

A Thesis

by

JACOB JOSEPH POWELL

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Co-Chairs of Committee,	Sergio C. Capareda
	Calvin B. Parnell, Jr.
Committee Members,	David E. Claridge
	Bryan W. Shaw
Head of Department,	Gerald L. Riskowski

December 2007

Major Subject: Biological and Agricultural Engineering

ABSTRACT

Engine Performance and Exhaust Emissions from a Diesel Engine Using
Cottonseed Oil Biodiesel. (December 2007)
Jacob Joseph Powell, B.S., Texas A&M University
Co-Chairs of Advisory Committee: Dr. Sergio Capareda
Dr. Calvin Parnell, Jr

Non-road diesel engines are significant contributors to air pollution in the United States. Recent regulations put forth by EPA and other environmental agencies have laid out stringent guidelines for engine manufacturers and fuel producers. Recent increases in oil prices and foreign energy dependency has led to a push to produce renewable fuels, which will supplement current reserves. Biodiesel is a clean-burning renewable fuel, that can be blended with petroleum diesel. It is important to understand the effect on engine performance and exhaust emissions when using biodiesel from different feedstocks. The objective of this research was to determine the relationship between engine performance and emissions and cottonseed oil biodiesel used in a diesel engine rated for 14.2 kW.

When using cottonseed oil biodiesel blends, CO, hydrocarbon, NO_x, and SO_2 emissions decreased as compared to petroleum diesel. Carbon dioxide emissions had no definitive trend in relation to cottonseed oil biodiesel blends. Carbon monoxide emissions increased by an average 15% using B5 and by an average of 19% using B100.

Hydrocarbon emissions decreased by 14% using B5 and by 26% using B100. Nitrogen oxide emissions decreased by four percent with B5, five percent with B20, and 14% with B100. Sulfur dioxide emissions decreased by an average of 86% using B100, and by 94% using B50 blended with ultra-low sulfur diesel. The difference between peak output power when using biodiesel and diesel was insignificant in blends less that B40. Peak measured power using B100 was about five percent lower than for diesel fuel. Pure cottonseed oil biodiesel achieved and maintained a peak corrected measured power of 13.1 kW at speeds of 2990, 2875, and 2800 rpm at loads of 41.3, 42.7, and 43.8 N-m. Using B5 produced a peak power of 13.6 kW at 2990 rpm and 43.9 N-m and at 2800 rpm and 46.7 N-m, while using B20 produced a peak power of 13.4 kW at 2990 rpm and 43.7 N-m. Brake-specific fuel consumption at peak measured load and torque using B100 was 1238 g/kW-h. Brake-specific fuel consumption at peak measured power and loads using B5 and B20 were 1276 and 1155 g/kW-h.

DEDICATION

This thesis is dedicated to Sandy.

ACKNOWLEDGEMENTS

I would, most importantly, like to thank God for the opportunities he has given me. I would like to thank my wife, Sandy, for her love and support, and I would like to thank my family who laid the foundation that has allowed me to get to where I am today. I would like to thank my professors, especially Dr. Capareda and Dr. Parnell, who gave me a chance and supported my work, and Dr. Shaw and Dr. Claridge, for their guidance. I would also like to thank Cotton, Inc., Texas Agricultural Experiment Station, Texas Engineering Experiment Station, and the Cotton Foundation for their financial support, as well as the Food & Protein Research & Development Center for providing fuels for testing. My thanks also go out to The Crew for all of their help and hard work. I would especially like to thank Barry, Ordway, Cale, Jared, Bert, and Greg for the extra hours put into getting the engine lab ready. And to all my friends along the way, thank you.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

With the increased emphasis on the need for clean, renewable fuels, it is imperative to fully understand the operational characteristics of biodiesel. The idea of using vegetable oil as fuel has been in existence since Rudolph Diesel demonstrated his compression engine, the diesel engine, in the late 1800s. However, for many years, petroleum has been the primary source for diesel fuels (Schumacher et al., 2001). For most of the twentieth century, an abundant supply for petroleum allowed for affordable petroleum diesel. However, in recent years the supply of petroleum has slowed, while the need for petroleum fuels has substantially increased. Petroleum diesel consumption has nearly doubled over the last twenty years. In the transportation sector alone, diesel fuel usage has increased from about 1.5 million barrels per day in 1986 to more than 2.9 million barrels per day in 2006. In 2006, almost 14 million barrels of petroleum fuels as a whole were consumed. (EIA, 2007) With the increasing need for energy, the decreasing rate of oil production, and the increased awareness in environmental protection, there has been a desire for alternative, clean-burning, renewable fuels. This has been sent to the forefront by the recent increase in oil prices and stringent regulatory actions. The Ag Energy Working Group, with support from the Energy Future Coalition, has developed a plan of action with the goal that "agriculture will provide 25 percent of the total energy consumed in the United States by 2025, while continuing to produce abundant, safe and

---

This thesis follows the style of *Transactions of the ASAE.*

affordable food and fiber" (AEWG, 2004). The United States consumes more than 20 million barrels of petroleum each day, with over half of that being imported. In 2005, the United States consumed about 100 quads (quadrillion BTU) of energy. Only about six percent of that consumed is from renewable energy sources (EIA, 2006).

According to the Environmental Protection Agency, or EPA, (2004), non-road diesel engines are significant contributors of air pollution in the United States. Non-road diesel engines are found primarily in construction, agricultural, and industrial applications. According to Kean et al. (2000), 10 percent of NO_x and PM_{10} emissions come from off-road diesel engines, while the EPA (2004) claims that these sources are responsible for about 25 percent. These engines are projected to continue to contribute large quantities of pollutants that may be part of the cause of serious public health problems. The primary pollutants of interest include carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NO_x), and sulfur oxides (SO_x). The Clean Air Act directs the EPA to study emissions from non-road engines to determine whether the associated emissions "cause, or significantly contribute to, air pollution which may reasonably be anticipated to endanger public health or welfare" (CAA, 1990) If it is determined that emissions from all non-road engines contribute significantly to ozone or CO non-attainment areas, then the EPA is required to establish emissions standards for classes of new non-road engines and vehicles that contribute to such pollution. The EPA is also allowed to set emission standards regulating any other emissions from non-road engines that may reasonably be anticipated to endanger public health or welfare (EPA, 2007) Health problems associated with these pollutants include premature mortality, aggravation of respiratory and cardiovascular disease and various other respiratory-related ailments. The EPA (2004) also believes that diesel exhaust may be carcinogenic to humans. "Ozone, NO_x, and PM also cause significant public welfare harm such as damage to crops, eutrophication, regional haze, and soiling of building materials." (EPA, 2004). The EPA has adopted new emissions standards for non-road diesel engines and sulfur reductions in non-road diesel fuel, effective August 30, 2004. These changes should reduce harmful emissions, as well as help states and local areas designated as 8-hour ozone non-attainment areas to improve their air quality. According to the Texas Commission on Environmental Quality, or TCEQ, (2005), ozone is not directly emitted into the air; it is formed during a series of atmospheric chemical reactions involving sunlight, NO_x, and reactive volatile organic compounds (RVOCs). Table 1 below shows a summary of the current EPA emission standards for engines smaller than 130 kW (EPA, 2002).

Table 1. Non-road diesel engine emission standards (g/kW-h).

Rated Power (kW)	Tier	Model Year	NOx	HC	NMHC + Nox	CO	PM
kW < 8	1	2000	-	-	10.5	8.0	1.0
	2	2005	-	-	7.5	8.0	0.80
8 ≤ kW < 19	1	2000	-	-	9.5	6.6	0.80
	2	2005	-	-	7.5	6.6	0.80
19 ≤ kW < 37	1	1999	-	-	9.5	5.5	0.80
	2	2004	-	-	7.5	5.5	0.60
37 ≤ kW < 75	1	1998	9.2	-	-	-	-
	2	2004	-	-	7.5	5.0	0.40
	3	2008	-	-	4.7	5.0	0.40
75 ≤ kW < 130	1	1997	9.2	-	-	-	-
	2	2003	-	-	6.6	5.0	0.30
	3	2007	-	-	4	5.0	0.30

The model years listed indicate the model years for which the specified tier of standards take effect.

The EPA finalized a two-step sulfur standard for non-road, locomotive, and marine (NRLM) diesel fuel. The sulfur requirements under this standard are similar to those established for highway diesel fuel. “Beginning June 1, 2007, refiners will be required to produce NRLM diesel fuel with a maximum sulfur content of 500 ppm. Then, beginning June 1, 2010, the sulfur content will be reduced for non-road diesel fuel to 15 ppm" (EPA, 2004). This standard will achieve considerable, cost-effective reductions of sulfate PM and SO_2 emissions, which will provide substantial public health and environmental benefits, which outweigh the cost of meeting the standards necessary to achieve them. The final sulfur standards will also allow high efficiency control technology to be applied to non-road engines, since sulfur can inhibit or impair the function of diesel exhaust emission control devices that will be necessary for non-road diesel engines to meet the finalized emission standards (EPA, 2004).

Sulfur in diesel fuel also acts as an engine lubricant. This is important because reducing sulfur content reduces fuel lubricity. While newer engines may be designed to handle low sulfur fuel, older engines may not. For example, fueling an older model engine with low sulfur diesel for an extended period of time may result in injectors sticking.

Biodiesel is a cleaner-burning, renewable fuel that is compatible with petroleum diesel and can be produced domestically (NBB, 2006a). Biodiesel contains essentially zero sulfur compared to petroleum diesel, as well as producing less soot and polycyclic aromatic hydrocarbon (PAH) emissions. Biodiesel also has a higher cetane number than petroleum diesel, as well as having a positive carbon dioxide (CO_2) balance. Since biodiesel is a renewable, bio-based product, it can be supplementary for a portion of the petroleum diesel consumed. The production of biodiesel will also provide another market for agricultural commodities (Schumacher, et al., 2001). Biodiesel can be produced from essentially any plant oil or animal fat, from sunflower, canola, or cottonseed oil, to chicken fat, beef tallow, or spent restaurant grease (yellow grease). Further research is needed to understand regulated and unregulated emission impacts of biodiesel for non-road applications (Gratton and Hansen, 2003).

Biodiesel can serve several purposes: lubrication, which is seen with blends of two to five percent biodiesel (B2-B5); fuel supplementation, which is seen with blends of twenty percent biodiesel (B20); and as a stand-alone fuel, when pure biodiesel (B100) is used. Blends such as B2 or B5 can be utilized as a lubricating fuel in place of high sulfur fuel. According to the NBB (2006b), “there is a marked improvement in lubricity when biodiesel is added to conventional diesel fuel”. Most engine manufacturers warrant engines for use with these small percentage blends, and many manufacturers require that new vehicles leave the lot with these types of blends. Some manufacturers warrant the use of biodiesel blends up to B20 in diesel engines. Very few manufacturers warrant the use of B100 in diesel engines. It is important to note that federal law prohibits voiding an original equipment manufacturer, or OEM, warranty just because of the use of biodiesel in an engine; the biodiesel has to be the cause of the failure in order for the warranty to be voided (DOE, 2004).

While there is a wealth of available data regarding some types of biodiesel (Munoz et al., 2004), there is little data regarding the effect of cottonseed oil (CSO) biodiesel on diesel engine performance and exhaust emissions. Soybean oil is the primary source for biodiesel in the United States. However, other biodiesel feedstocks, such as cottonseed oil, can help to meet the increasing desire for alternative fuels by filling a particular niche. This niche is primarily based on the availability of a feedstock in a particular area. Figure 1 illustrates the trend of cotton production in the United States since 1995.

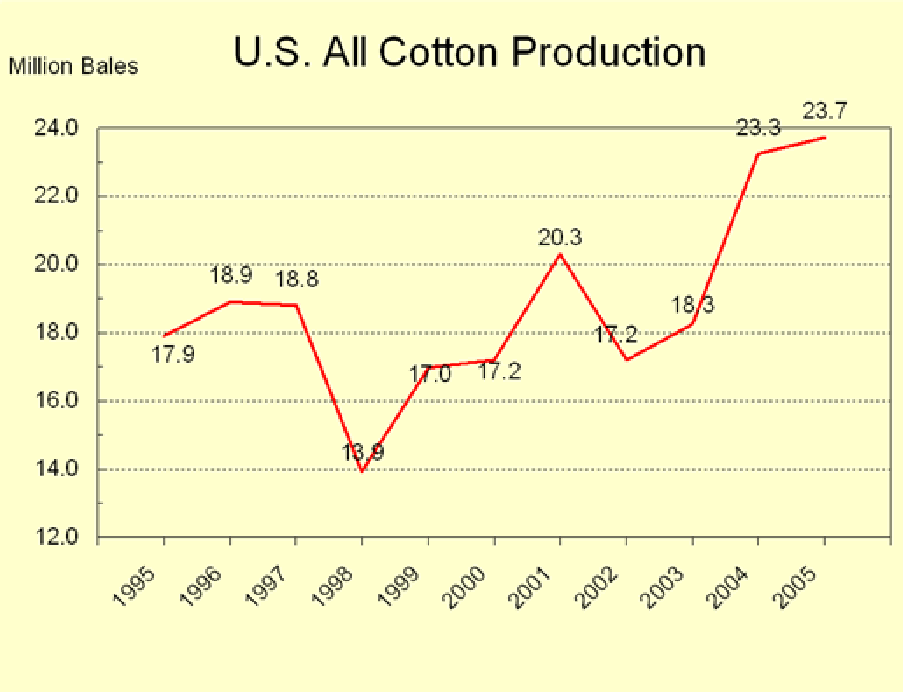


Figure 1. United States cotton production by year (USDA, 2006).

According to the U.S. Census Bureau (DOC, 2005), the United States produced about 880 million pounds, or about 117 million gallons, of cottonseed oil in 2004. According to the National Cottonseed Production Association, or NCPA, (2002) cottonseed oil ranks third in volume of oil produced in the United States behind soybean and corn oil. According to Tickell (2000), 243 lbs of cottonseed oil can be produced per acre of cotton. Recent trends have shown a decrease in desire to use CSO as food oil, since CSO contains trans-fatty acids. This trend has an inverse effect on the desire and availability of CSO to be used in biodiesel production.

With the large amount of cotton produced in the southern United States, and the growing need for utilizing agricultural byproducts, it is important to investigate engine performance using biodiesel from cottonseed oil, as well as analyzing the exhaust emissions produced.

1.1 Objectives

The objective of this research is to gain a better understanding of cottonseed oil biodiesel by:

- Determining the relationship between diesel engine performance and the percentage of cottonseed oil biodiesel in fuel blends;
- Determining the relationship between pollutant concentrations in diesel engine exhaust and the percentage of cottonseed oil biodiesel in fuel blends; and
- Evaluating the implications of the results of this study with current and proposed regulations on the use of biodiesel and biodiesel blends as fuel for diesel engines.

2. LITERATURE REVIEW

Understanding the overall effect of using biodiesel as a fuel is a complex science. This complexity owes to the fact that biodiesel can be produced from almost any plant oil or animal fat. Each of these feedstocks has different characteristics that can affect production cost, engine performance, and exhaust emissions. The objective of this section is to provide a review of previous research associated with biodiesel cost, composition, performance, and emissions. A review of regulations that pertain to non-road engines and alternative fuels is also included.

2.1 Economics

The primary factors affecting the economics of biodiesel include the purchase price and the quality of feedstock (Piazza, 2007). Raw materials for fuel production, such as soybean oil, cottonseed oil, renderings, and waste oil each carry a purchase price based on feedstock quantity and geographic availability, competition with other uses of the feedstock, and product quality (Capareda, 2007). High quality feedstocks tend to require little pre-treatment , but they can have a high purchase price. Low quality oils can be purchased at a lower price, but usually require a greater deal of pre-treatment. Pre-treatment processes include refining, degumming, neutralizing, drying, bleaching, and dewaxing. Low quality oils also tend to be variable in free fatty acid composition; using low quality fuels can have a negative effect on end product cold flow properties (Capareda, 2007). Feedstock quality is dependent upon the amount of phosphatides, free fatty acids, waxes, insoluble impurities, and water present in the feedstock (Piazza, 2007). Figure 2 below illustrates the cost of several biodiesel feedstocks:

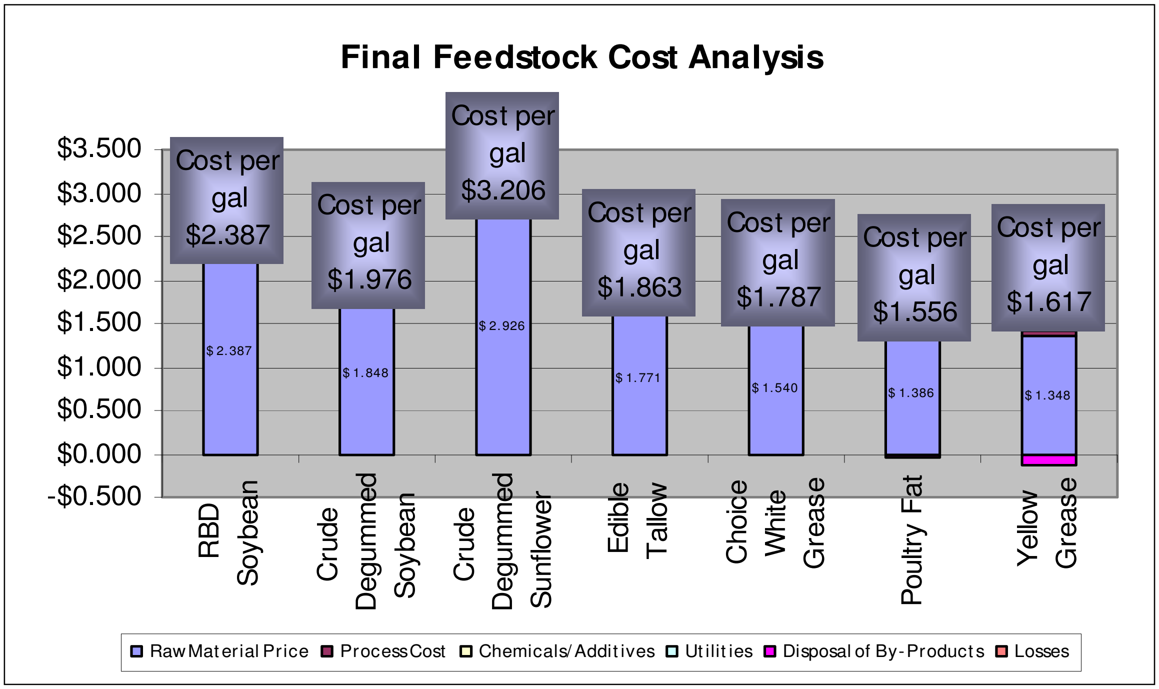


Figure 2. Feedstock cost analysis (Piazza, 2007).

According to Piazza, raw material costs have the largest effect on the cost of biodiesel, and processing costs are significant.

2.2 Engine Performance

Alternative fuel use can only be considered feasible alternatives if engine performance is maintained when using alternative fuels and fuel blends. Three points of interest when determining engine performance are brake effective power (BEP), brake-specific fuel consumption (BSFC), and thermal efficiency.

Since the energy content of biodiesel is approximately eight percent lower than that of petroleum diesel, it is expected that, in certain situations, engines fueled with biodiesel will not produce the same power that is produced when using petroleum diesel. At full-load conditions with a wide-open throttle (WOT), or at intermediate loads with equal fuel consumption or accelerator position, the output power should reduce with respect to energy content (Lapuerta et al., 2007). Wide-open throttle is equivalent to the accelerator being fully pressed. Contrary to the expected, researchers have reported varying results. Some authors have shown a smaller decrease in power than expected when using biodiesel, while some have reported power loss in the same scope as reduced energy content, and others have shown an increase in rated power and torque. Some have also reported no significant difference in output power and torque (Lapuerta et al., 2007).

Cetinkaya et al. (2005) observed that the reduction of torque was only three to five percent when comparing waste oil biodiesel to petroleum diesel in a 75 kW four-cylinder common rail engine. Lin et al. (2006) found that the power at full load when using pure palm oil biodiesel was only 3.5% less than that of petroleum diesel in a 2.84 L naturally aspirated engine.

When using a 70% tall oil biodiesel blend, Altiparmak et al. (2007) measured a 6.1% increase in maximum torque. Usta (2005) observed inceases in torque and power when fueling an indirect injection diesel engine with tobacco seed oil biodiesel blends.

Yucesu and Ilkilic (2006) observed that the heating value for cottonseed oil (CSO) biodiesel was only five percent less than the heating value of petroleum diesel. They observed power and torque reductions of three to eight percent when using pure CSO biodiesel. Murillo et al. (2007) also observed power loss similar to the percent reduction in heating value when using cooking oil biodiesel.

Romig and Spataru (1996) observed no significant difference in rated power when using rapeseed and soybean oil biodiesel blends in a 6-cylinder DDC engine. Shaheed and Swain (1999) also observed no significant differences when using CSO biodiesel at several speeds in a single cylinder 2.75 kW engine.

Brake-specific fuel consumption is the ratio between the mass of fuel consumed and the brake effective power produced by an engine. Brake-specific fuel consumption is inversely proportional to themal efficiency (Lapuerta et al., 2007). Graboski et al. (1996) found a good correlation between fuel oxygen content, which is higher for biodiesel, and BSFC when using soybean oil biodiesel. According to Rakopoulos et al. (2004), the increase in BSFC is attributed to oxygen enrichment from fuel, and not from intake air. Most authors have reported an increase in BSFC when using biodiesel and biodiesel blends. Turrio-Baldassarri et al. (2004), Hansen and Jensen (1997), Last et al. (1995), Alam et al. (2004), Canakci and Van Gerpen (2001), and Senatore et al. (2000) reported increases in BSFC when using biodiesel and biodiesel blends, compared to petroleum diesel fuel. These increases tended to be in line with the loss of heating value in the fuel blends.

According to Lapuerta et al. (2007), “thermal efficiency is the ratio between power output and energy introduced through fuel injection.” Most authors observed no significant change in thermal efficiency when using biodiesel. Some of those authors include Lapuerta et al. (2007b), Canakci (2005), and Monyem et al. (2001).

2.3 Exhaust Emissions

According to the National Biodiesel Board (2006), biodiesel is a clean burning alternative fuel produced from domestic, renewable resources, such as plant oils or animal fats. While bio-diesel contains no petroleum, it can be blended with petroleum diesel to create a fuel suitable for use in diesel engines. It is important to understand the relationship between biodiesel blends and exhaust emissions.

Pure biodiesel is essentially free of sulfur compared to petroleum diesel. Biodiesel blends, consequently, contain less sulfur than petroleum diesel. Since biodiesel blends have less sulfur than petroleum diesel, using biodiesel blends should decrease the emission of SO_2 and sulfate particulate matter.

Munoz et al (2004) found that the concentration of carbon monoxide (CO) in the exhaust decreased, except at high speed and load, while hydrocarbon emissions (THC) reduced at low loads, and NO_x emissions depended on the speed and load of the engine when petroleum diesel was replaced with biodiesel mixtures.

Graboski and McCormick (1998) found that, for biodiesel, NO_x emissions increase when large, two-stroke engines were tested at full load. Schumacher et al. (2001) found that, as the percent mixture of biodiesel increased, emissions of THC, CO, and PM decreased, while emissions of NO_x increased. Neat biodiesel exceeded the 1991-1994 nitrogen oxide emission standards. Using biodiesel blends yielded a positive CO_2 balance. According to Schumacher et al. (2001b), as the percentage of biodiesel in the blend increased, with no timing changes and no addition of alkylates, THC, CO, and PM exhaust emissions decreased, while NO_x increased.

Canakci and Van Gerpen (2001) found that CO, THC, and NO_x emissions significantly increased with pure biodiesel made from yellow grease and soybean oil in comparison to DF. When using B20, there was not a significant change in the emission of HC and NO_x; the decrease in the levels of CO was borderline significant. No significant changes were observed for CO_2 emissions when using biodiesel. In 2003, Canakci and Van Gerpen found statistically significant reductions in CO and hydrocarbon emissions when using biodiesel from sunflower oil and yellow grease.

Nitrogen oxide emissions are of specific importance due to the fact that NO_x is a contributor to ozone. Since it has been found that NO_x emissions tend to increase with bioiesel blends, measures have been taken in an attempt to decrease NO_x emissions when using biodiesel blends. Sometimes these efforts result in increased emissions of other pollutants. According to Schumacher et al. (2001b), NO_x emissions can be reduced by retarding injection timing or by substituting 20 percent of the petroleum diesel in the B20 blend with heavy alkylate. Replacing DF with heavy alkylate also reduced CO and PM concentrations, while THC concentrations were not affected. Retarding injection timing increased CO concentrations.

Munoz et al. (2004) found that, when injection timing was moved up by 3°, THC emissions generally increased, while NO_x emissions were observed to decline slightly at medium engine speeds at certain loads. Jha et al. (2006) blended ethanol with bioiesel blends in an effort to reduce NO_x emissions. Jha et al. observed an increase in NO_x emissions when using a diesel, biodiesel, ethanol (DBE) mixture in an old engine, while using DBE in new engines reduced NO_x emissions. Carbon monoxide emissions increased with an increase in ethanol in the fuel blends.

Kass et al. (2006) observed a decrease in NO_x and PM emissions when using a biodiesel emulsified with 10% water, by mass. Using the emulsified blend along with exhaust gas recirculation (EGR), lowered both NO_x and PM emissions. Last et al. (1995)

incorporated retarding injection timing with EGR and observed a 30% decrease in NO_x emissions.

2.4 Rules and Regulations

Federal standards for new non-road diesel engines were originally adopted in 1994 for engines rated for greater than 37 kW, to be phased in from 1996 to 2000. In 1996, a Statement of Principles was signed between engine makers, EPA, and the California ARB, and in 1998, the EPA finalized the rule reflecting the SOP. Tier 1 standards for engines less than 37 kW and more stringent Tier 2 and 3 standards for all non-road equipment were scheduled to be phased in from 2000 to 2008. In 2004, the EPA finalized Tier 4 emission standards, which are to be phased in through 2015 (DieselNet, 2007). EPA regulations for mobile non-road diesel engines may apply to those who manufacture and import diesel engines intended to be used in non-road vehicles or movable equipment. Producers and importers of vehicles and machinery that use these engines may also be affected. Those who convert non-road vehicles and equipment to use alternative fuels, and those that produce and distribute non-road diesel fuel also fall under the umbrella of these regulations (EPA, 2004).

According to the final rule for the control of emissions of air pollution from non-road diesel engines and fuel (EPA, 2004), vehicles and fuels are generally treated as a system, so standards shall be promulgated in tandem. This will achieve the greatest emission reductions while maintaining cost-effectiveness. Standards for non-road diesel engines and fuels have been constructed using on-highway diesel engine standards as a model. In an effort to extend advanced emission controls, engine standards and emission test procedures have been set out, along with sulfur control requirements for diesel. Included in the engine standards will be not-to-exceed, or NTE, requirements. Diesel engine manufacturers will have to ensure that their non-road engines meet the standards and specifications laid forth by the EPA, and the engines must not surpass the NTE standards, which are typically 1.25 or 1.5 times the NSPS. In an effort to lower SO_2 emissions, new standards for sulfur content in non-road diesel fuel were established. Starting in 2007, non-road diesel fuel shall have a maximum sulfur concentration of 500 ppm; starting in 2010, the maximum sulfur concentration will be lowered to 15 ppm. Federal engine and fuel standards affect the emissions of NO_x, VOC_s, SO_2, $PM_{2.5}$, CO, HC, and air toxins (EPA, 2004; DieselNet, 2007).

Tables 2 and 3 below list the federal emission standards for mobile non-road diesel engines (DieselNet, 2007).

Table 2. Tier 1-3 emission standards.

EPA Tier 1-3 Nonroad Diesel Engine Emission Standards, g/kWh (g/bhp·hr)

Engine Power	**Tier**	**Year**	**CO**	**HC**	**NMHC+NOx**	**NOx**	**PM**
kW < 8 (hp < 11)	Tier 1	2000	8.0 (6.0)	-	10.5 (7.8)	-	1.0 (0.75)
	Tier 2	2005	8.0 (6.0)	-	7.5 (5.6)	-	0.8 (0.6)
8 ≤ kW < 19 (11 ≤ hp < 25)	Tier 1	2000	6.6 (4.9)	-	9.5 (7.1)	-	0.8 (0.6)
	Tier 2	2005	6.6 (4.9)	-	7.5 (5.6)	-	0.8 (0.6)
19≤ kW < 37 (25 ≤ hp < 50)	Tier 1	1999	5.5 (4.1)	-	9.5 (7.1)	-	0.8 (0.6)
	Tier 2	2004	5.5 (4.1)	-	7.5 (5.6)	-	0.6 (0.45)
37 ≤ kW < 75 (50 ≤ hp < 100)	Tier 1	1998	-	-	-	9.2 (6.9)	-
	Tier 2	2004	5.0 (3.7)	-	7.5 (5.6)	-	0.4 (0.3)
	Tier 3	2008	5.0 (3.7)	-	4.7 (3.5)	-	-†
75 ≤ kW < 130 (100 ≤ hp < 175)	Tier 1	1997	-	-	-	9.2 (6.9)	-
	Tier 2	2003	5.0 (3.7)	-	6.6 (4.9)	-	0.3 (0.22)
	Tier 3	2007	5.0 (3.7)	-	4.0 (3.0)	-	-†
130 ≤ kW < 225 (175 ≤ hp < 300)	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2003	3.5 (2.6)	-	6.6 (4.9)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
225 ≤ kW < 450 (300 ≤ hp < 600)	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2001	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
450 ≤ kW < 560 (600 ≤ hp < 750)	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2002	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
kW ≥ 560 (hp ≥ 750)	Tier 1	2000	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2006	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)

† Not adopted, engines must meet Tier 2 PM standard.

Table 3. Tier 4 emission standards.

Tier 4 Emission Standards—Engines Up To 560 kW, g/kWh (g/bhp-hr)

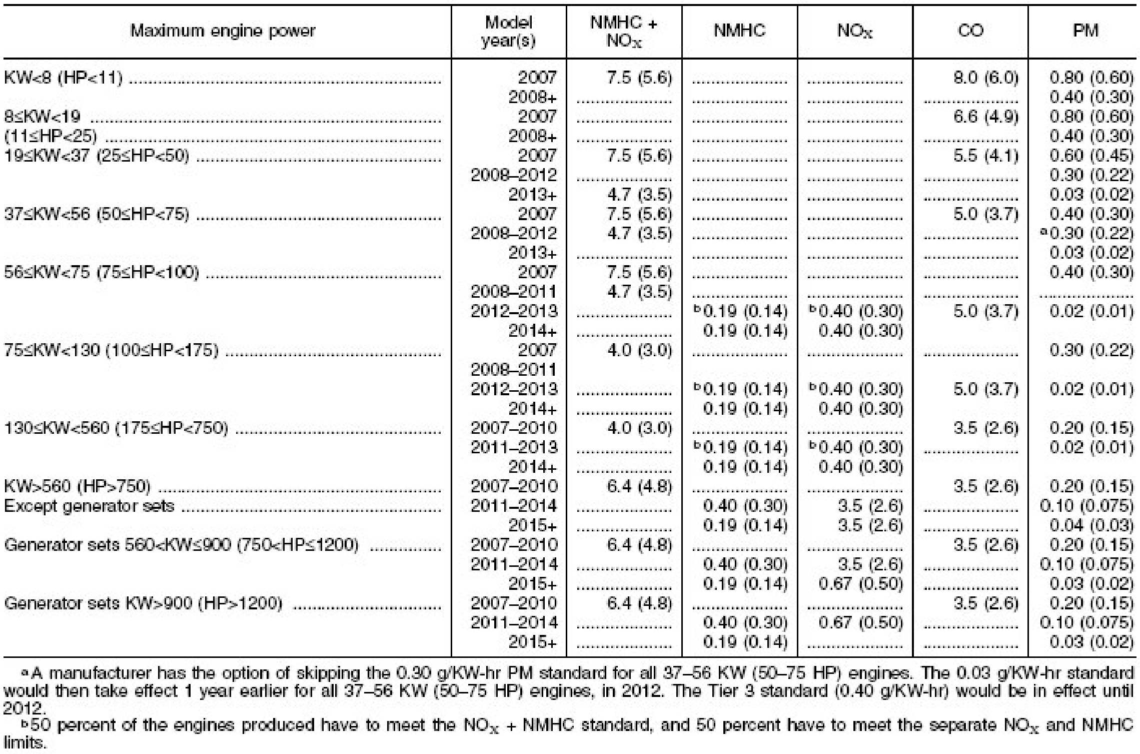
Engine Power	**Year**	**CO**	**NMHC**	**NMHC+NO_x**	**NO_x**	**PM**
Kw < 8 (hp < 11)	2008	8.0 (6.0)	-	7.5 (5.6)	-	0.4[a] (0.3)
8 ≤ kW < 19 (11 ≤ hp < 25)	2008	6.6 (4.9)	-	7.5 (5.6)	-	0.4 (0.3)
19 ≤ kW < 37 (25 ≤ hp < 50)	2008	5.5 (4.1)	-	7.5 (5.6)	-	0.3 (0.22)
	2013	5.5 (4.1)	-	4.7 (3.5)	-	0.03 (0.022)
37 ≤ kW < 56 (50 ≤ hp < 75)	2008	5.0 (3.7)	-	4.7 (3.5)	-	0.3[b] (0.22)
	2013	5.0 (3.7)	-	4.7 (3.5)	-	0.03 (0.022)
56 ≤ kW < 130 (75 ≤ hp < 175)	2012-2014[c]	5.0 (3.7)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)
130 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)	2011-2014[d]	3.5 (2.6)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)

a - hand-startable, air-cooled, DI engines may be certified to Tier 2 standards through 2009 and to an optional PM standard of 0.6 g/kWh starting in 2010
b - 0.4 g/kWh (Tier 2) if manufacturer complies with the 0.03 g/kWh standard from 2012
c - PM/CO: full compliance from 2012; NOx/HC: Option 1 (if banked Tier 2 credits used)—50% engines must comply in 2012-2013; Option 2 (if no Tier 2 credits claimed)—25% engines must comply in 2012-2014, with full compliance from 2014.12.31
d - PM/CO: full compliance from 2011; NOx/HC: 50% engines must comply in 2011-2013

In 2006, the EPA adopted the Compression Ignition Internal Combustion Engine performance standards for stationary diesel engines (EPA, 2006). The pollutants regulated by this rule include NO_x, PM, CO, and NMHC. Sulfur oxides shall be reduced with the use of low sulfur non-road fuel, and smoke emissions will be reduced. Sources affected by the NSPS (New Source Performance Standard) include stationary, non-road diesel engines manufactured or reconstructed after 2005. Engines are considered stationary if they are not mobile and remain at one location for a year (EPA, 2006; DieselNet, 2007).

Tables 4 and 5 below show the emission standards for stationary non-road diesel engines (EPA, 2006).

Table 4. Emission standards for 2007 model year and later engines.

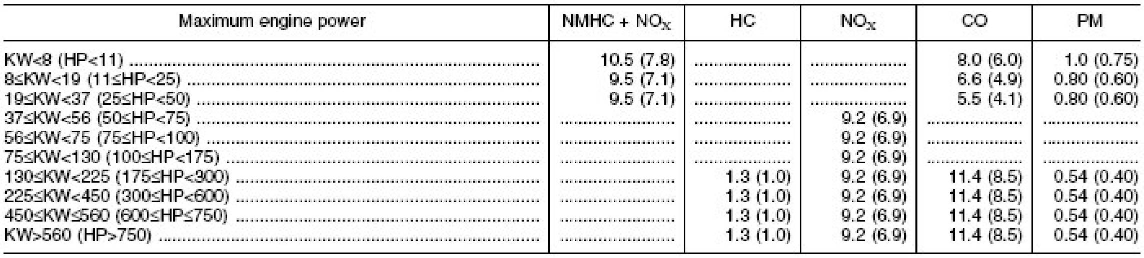


Maximum engine power	Model year(s)	NMHC + NO_X	NMHC	NO_X	CO	PM
KW<8 (HP<11)	2007	7.5 (5.6)	......	......	8.0 (6.0)	0.80 (0.60)
	2008+	......	......	......	......	0.40 (0.30)
8≤KW<19	2007	......	......	......	6.6 (4.9)	0.80 (0.60)
(11≤HP<25)	2008+	......	......	......	......	0.40 (0.30)
19≤KW<37 (25≤HP<50)	2007	7.5 (5.6)	......	......	5.5 (4.1)	0.60 (0.45)
	2008–2012	......	......	......	......	0.30 (0.22)
	2013+	4.7 (3.5)	......	......	......	0.03 (0.02)
37≤KW<56 (50≤HP<75)	2007	7.5 (5.6)	......	......	5.0 (3.7)	0.40 (0.30)
	2008–2012	4.7 (3.5)	......	......	......	[a]0.30 (0.22)
	2013+	......	......	......	......	0.03 (0.02)
56≤KW<75 (75≤HP<100)	2007	7.5 (5.6)	......	......	......	0.40 (0.30)
	2008–2011	4.7 (3.5)	......	......	......	......
	2012–2013	......	[b]0.19 (0.14)	[b]0.40 (0.30)	5.0 (3.7)	0.02 (0.01)
	2014+	......	0.19 (0.14)	0.40 (0.30)		
75≤KW<130 (100≤HP<175)	2007	4.0 (3.0)	......	......	......	0.30 (0.22)
	2008–2011					
	2012–2013	......	[b]0.19 (0.14)	[b]0.40 (0.30)	5.0 (3.7)	0.02 (0.01)
	2014+	......	0.19 (0.14)	0.40 (0.30)		
130≤KW<560 (175≤HP<750)	2007–2010	4.0 (3.0)	......	......	3.5 (2.6)	0.20 (0.15)
	2011–2013	......	[b]0.19 (0.14)	[b]0.40 (0.30)	......	0.02 (0.01)
	2014+	......	0.19 (0.14)	0.40 (0.30)		
KW>560 (HP>750)	2007–2010	6.4 (4.8)	......	......	3.5 (2.6)	0.20 (0.15)
Except generator sets	2011–2014	......	0.40 (0.30)	3.5 (2.6)	......	0.10 (0.075)
	2015+	......	0.19 (0.14)	3.5 (2.6)	......	0.04 (0.03)
Generator sets 560<KW≤900 (750<HP≤1200)	2007–2010	6.4 (4.8)	......	......	3.5 (2.6)	0.20 (0.15)
	2011–2014	......	0.40 (0.30)	3.5 (2.6)	......	0.10 (0.075)
	2015+	......	0.19 (0.14)	0.67 (0.50)	......	0.03 (0.02)
Generator sets KW>900 (HP>1200)	2007–2010	6.4 (4.8)	......	......	3.5 (2.6)	0.20 (0.15)
	2011–2014	......	0.40 (0.30)	0.67 (0.50)	......	0.10 (0.075)
	2015+	......	0.19 (0.14)	......	......	0.03 (0.02)

[a] A manufacturer has the option of skipping the 0.30 g/KW-hr PM standard for all 37–56 KW (50–75 HP) engines. The 0.03 g/KW-hr standard would then take effect 1 year earlier for all 37–56 KW (50–75 HP) engines, in 2012. The Tier 3 standard (0.40 g/KW-hr) would be in effect until 2012.

[b] 50 percent of the engines produced have to meet the NO_X + NMHC standard, and 50 percent have to meet the separate NO_X and NMHC limits.

Table 5. Emission standards for engines manufactured before 2007.



Maximum engine power	NMHC + NO_x	HC	NO_x	CO	PM
$KW<8$ ($HP<11$)	10.5 (7.8)	....	....	8.0 (6.0)	1.0 (0.75)
$8 \le KW<19$ ($11 \le HP<25$)	9.5 (7.1)	....	....	6.6 (4.9)	0.80 (0.60)
$19 \le KW<37$ ($25 \le HP<50$)	9.5 (7.1)	....	....	5.5 (4.1)	0.80 (0.60)
$37 \le KW<56$ ($50 \le HP<75$)	....	....	9.2 (6.9)	....	....
$56 \le KW<75$ ($75 \le HP<100$)	....	....	9.2 (6.9)	....	....
$75 \le KW<130$ ($100 \le HP<175$)	....	....	9.2 (6.9)	....	....
$130 \le KW<225$ ($175 \le HP<300$)	....	1.3 (1.0)	9.2 (6.9)	11.4 (8.5)	0.54 (0.40)
$225 \le KW<450$ ($300 \le HP<600$)	....	1.3 (1.0)	9.2 (6.9)	11.4 (8.5)	0.54 (0.40)
$450 \le KW \le 560$ ($600 \le HP \le 750$)	....	1.3 (1.0)	9.2 (6.9)	11.4 (8.5)	0.54 (0.40)
$KW>560$ ($HP>750$)	....	1.3 (1.0)	9.2 (6.9)	11.4 (8.5)	0.54 (0.40)

The Texas Commission for Environmental Quality has attempted to ban sales of B20 in Texas in order to prevent the increase of NO_x levels in several parts of the state. As of December 2006, the ban has been delayed (Lacey, 2007). TCEQ began a program called the Texas Low Emission Diesel (TxLED) program in order to help control NO_x emissions. Currently, no biodiesel is TxLED certified, which signifies that the fuel has been formulated to decrease NO_x emissions. The EPA is now developing a report regarding NO_x emissions when using biodiesel. The goal is that this research presented in this report will clarify previously conflicting results dealing with NO_x emissions. Despite some research claiming that NO_x increases are neglible, an EPA study in 2002 found that using a 20% biodiesel blend increased NO_x emissions above the levels allowed by TxLED (Lacey, 2007). If TCEQ decides to uphold the ban on sales of biodiesel blends throughout Texas or in the 110 Texas counties surrounding the critical air quality areas, Texas biodiesel producers will likely have to ship their product out of state or begin building biodiesel plants out of state (Lacey, 2007; Stillman, 2006).

3. ENGINE PERFORMANCE

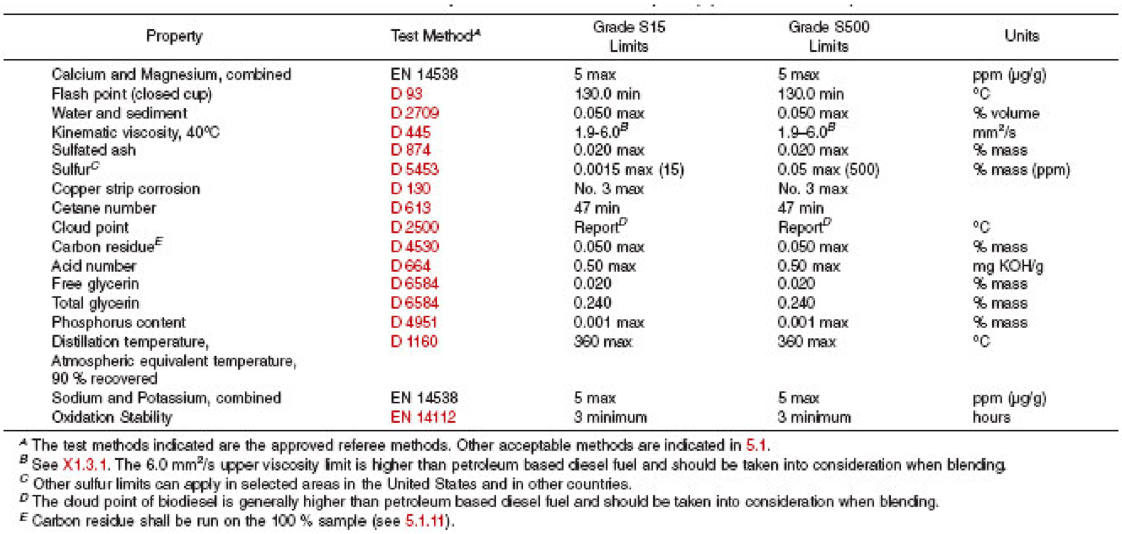
The idea of using vegetable oils as fuel originated alongside the invention and advancement of the diesel engine. Rudolph Diesel originally fueled his engine with peanut oil, and he thought that utilizing biomass fuel was the principal future of the diesel engine. Diesel wanted his engine to be a means for farmers, smaller industries, and “common” people to compete with large, monopolizing industries controlling energy production (Yokayo, 2003). This early biofuel eventually gave way to petroleum diesel as the primary fuel used in diesel engines. The availability of economical middle-distillate petroleum fuels left little reason to search for alternative, renewable fuel sources. However, the oil crisis of the 1970s rekindled interest in utilizing alternative sources for fueling engines (Canakci and Van Gerpen, 2001). Again, the current energy crisis and the rise in fuel costs, as well as the increased desire for clean-burning fuels, has thrust forward the importance of finding and utilizing alternative, renewable energy sources. The desire for alternative energy has been placed in prominence, as illustrated by the campaign that calls for 25 percent of the energy consumed in the United States to be produced from biofuels by the year 2025 (AEWG, 2006).

Interest in using vegetable oils as fuels arose again within the agricultural community as a fuel for tractors and equipment (ASAE, 1982). Around the world, vegetable oils were being studied for their viability as a legitimate fuel (Korbitz, 1995). Extensive testing showed that diesel engines could be operated acceptably using minimally processed vegetable oils. However, using straight vegetable oil as fuel resulted in issues with fuel injectors, piston rings, and oil stability (Bechtold, 1997). Additional research showed that further processing of vegetable oils produces methyl esters, fuels suitable for diesel engines and compatible for mixing with diesel. Methyl esters came to be known as biodiesel,

Biodiesel can be used as a stand-alone fuel, as well as being blended with petroleum diesel. Biodiesel blends are generally referred to according to the percent of biodiesel in a fuel mixture. A fuel mixture with two percent biodiesel and 98 percent petroleum diesel is designated B2, a fuel mixture with five percent biodiesel is designated B5, and so on. Unmixed, or neat, biodiesel is referred to as B100. For the purpose of this manuscript, this designation will be used, followed by the type of diesel used in the mixture. The diesel will be differentiated based on sulfur content. Diesel with 500 ppm sulfur is designated DF500, while DF15 refers to diesel with 15 ppm sulfur. So, a blend that contains 20 percent biodiesel and 80 percent 500 ppm sulfur diesel is given the short form of B20/DF500. Biodiesel mixed in small blends, such as B2 and B5, serves as a lubricant. This is especially important given the mandated decrease in the concentration of sulfur, which acts as a lubricant, in diesel. Biodiesel also serves as a supplemental fuel when used in blends such as B20.

In order for biodiesel to be sold for use in vehicles, it must meet ASTM D6751. Adhering to ASTM D6751 ensures that biodiesel meets the same standards set forth for petroleum diesel. ASTM D6751 encompasses a wealth of standards that provide guidelines for determining characteristics such as cetane number, kinematic viscosity, distillation temperatures, sulfur content, and more. A summary of the test methods laid out by ASTM D6751 can be seen in the table 6 below:

Table 6. Summary of biodiesel testing standard ASTM D 6751 (ASTM, 2007).



Property	Test Method[A]	Grade S15 Limits	Grade S500 Limits	Units
Calcium and Magnesium, combined	EN 14538	5 max	5 max	ppm (µg/g)
Flash point (closed cup)	D 93	130.0 min	130.0 min	°C
Water and sediment	D 2709	0.050 max	0.050 max	% volume
Kinematic viscosity, 40°C	D 445	1.9-6.0[B]	1.9–6.0[B]	mm^2/s
Sulfated ash	D 874	0.020 max	0.020 max	% mass
Sulfur[C]	D 5453	0.0015 max (15)	0.05 max (500)	% mass (ppm)
Copper strip corrosion	D 130	No. 3 max	No. 3 max	
Cetane number	D 613	47 min	47 min	
Cloud point	D 2500	Report[D]	Report[D]	°C
Carbon residue[E]	D 4530	0.050 max	0.050 max	% mass
Acid number	D 664	0.50 max	0.50 max	mg KOH/g
Free glycerin	D 6584	0.020	0.020	% mass
Total glycerin	D 6584	0.240	0.240	% mass
Phosphorus content	D 4951	0.001 max	0.001 max	% mass
Distillation temperature, Atmospheric equivalent temperature, 90 % recovered	D 1160	360 max	360 max	°C
Sodium and Potassium, combined	EN 14538	5 max	5 max	ppm (µg/g)
Oxidation Stability	EN 14112	3 minimum	3 minimum	hours

[A] The test methods indicated are the approved referee methods. Other acceptable methods are indicated in 5.1.
[B] See X1.3.1. The 6.0 mm^2/s upper viscosity limit is higher than petroleum based diesel fuel and should be taken into consideration when blending.
[C] Other sulfur limits can apply in selected areas in the United States and in other countries.
[D] The cloud point of biodiesel is generally higher than petroleum based diesel fuel and should be taken into consideration when blending.
[E] Carbon residue shall be run on the 100 % sample (see 5.1.11).

Neat biodiesel has a lower energy content than diesel (Peterson et al., 2002; Canakci and Van Gerpen, 2003), which can be attributed to the oxygen content of biodiesel of about 10 percent (Bechtold, 1997). Biodiesel has a higher specific gravity than diesel (Canakci and Van Gerpen, 2003; Bechtold, 1997). Overall, biodiesel has approximately seven percent less energy per unit volume than diesel (Bechtold, 1997). It is thus expected that biodiesel blends have lower energy content than petroleum diesel. Biodiesel has a higher viscosity, cloud point, and pour point than biodiesel, which can be problematic in cold temperatures (Canakci and Van Gerpen, 2003; Peterson et al., 2002; Bechtold, 1997). Biodiesel is also prone to deteriorating certain types of seals, hoses, and gaskets, particularly those comprised of natural rubbers. Biodiesel resistant hoses and seals are available.

Biodiesel can be produced from most vegetable oils and animal fats using a process called transesterification. Transesterification uses methanol or ethanol in the presence of an alkaline catalyst, such as sodium hydroxide or potassium hydroxide, to produce methyl or ethyl esters (Dorado et al., 2002; Peterson et al, 2002). Most biodiesel production plants use methanol in order to yield methyl esters (Peterson et al., 2002). Common vegetable oils used in biodiesel production include soybean oil, waste vegetable oil, sunflower seed oil, rapeseed oil, peanut oil, Chinese tallow oil, and cottonseed oil (Capareda, 2007; Munoz et al, 2004; Bechtold, 1997). Table 7 below shows the amount of oil produced by certain plants.

Table 7. Plant oil production per unit area (Tickell, 2000).

Oil Producing Crops

	Plant	kg oil/ha		Plant	kg oil/ha
1	Corn	145	25	Tung Oil Tree	790
2	Cashew Nut	148	26	Sunflower	800
3	Oat	183	27	Cocoa	863
4	Palm	189	28	Peanut	890
5	Lupine	195	29	Opium Poppy	978
6	Rubber Seed	217	30	Rapeseed	1000
7	Kenaf	230	31	Olive Tree	1019
8	Calendula	256	32	Piassava	1112
9	Cotton	273	33	Gopher Plant	1119
10	Hemp	305	34	Castor Bean	1188
11	Soybean	375	35	Bacuri	1197
12	Coffee	386	36	Pecan	1505
13	Linseed	402	37	Jojoba	1528
14	Hazelnut	405	38	Babassu Palm	1541
15	Euphorbia	440	39	Jatropha	1590
16	Pumpkin Seed	449	40	Macadamia Nut	1887
17	Coriander	450	41	Brazil Nut	2010
18	Mustard	481	42	Avocado	2217
19	Camelina	490	43	Coconut	2260
20	Sesame	585	44	Oiticia	2520
21	Crambe	589	45	Buriti Palm	2743
22	Safflower	655	46	Pequi	3142
23	Buffalo Gourd	665	47	Macauba Palm	3775
24	Rice	696	48	Oil Palm	5000

One of the key issues facing the matter of streamlining biodiesel as a fuel is economics. Nearly 80 percent of the cost to produce biodiesel lies with feedstock costs (Capareda, 2007). Some of the more common feedstocks used to produce biodiesel are also used as food oils; the high price of these oils drives up the price of producing biodiesel. Currently, the federal government provides a subsidy of about one dollar per gallon, which helps make producing and using biodiesel economical. This subsidy is given to the mixer of the biodiesel. The potential markets for biodiesel are as a fuel supplement, in mixtures of about 20 percent, and as a lubricant in the place of sulfur. Neat biodiesel makes up a very small protion of the market (Lacey, 2007). In 2005, only 75 million gallons of biodiesel were produced commercially. This leaves a large market for production (Capareda, 2007.) Most engine manufacturers warrant the use of biodiesel in their engines in blends of up to 20 percent, while some warrant the use of B100. Many automobile manufacturers now require that new diesel vehicles leave the plant with B2 or B5 in the fuel tank. Biodiesel also has a specific potential for non-road vehicles. Farmers can produce biodiesel for use in farm trucks and tractors, while cooperatives can provide biodiesel or biodiesel blends as a fuel option to cooperative members.

3.1 Objective

The overall objective of the research discussed in this section is to gain a better understanding of engine performance when using cottonseed oil biodiesel. Specific objectives for this research are as follows:

- To evaluate torque, brake power, and fuel consumption of biodiesel and biodiesel blends;
- To compare the evaluated torque, brake power, and fuel consumption of biodiesel to pure diesel; and
- To evaluate advantages and/or disadvantages of using biodiesel blends.

3.2 Experimental Method

Engine power tests were conducted using a 14.2 kW (19 hp) diesel engine fueled with several blends of petroleum diesel and cottonseed oil biodiesel. The CSO biodiesel used for all performance tests was purchased from Safe Renewable Fuels, Inc. The blends included in these tests are listed below:

- B5/DF500;
- B20/DF500;
- B40/DF500;
- B60/DF500;
- B80/DF500;
- B100; and
- DF500.

Engine power tests were conducted using the SAE Standard Engine Power Test Code for diesel engines (SAE, 1983) as a guideline. The Engine Power Test Code can be found in Appendix A. According to this standard, "engine power is defined as the product of engine dynamometer speed and torque obtained at wide-open-throttle." Using the determined engine power and observed fuel consumption, brake-specific fuel consumption, or BSFC, can be calculated. Brake-specific fuel consumption is a useful indicator of the performance of fuels in engines, since it describes fuel consumption in relation to power produced. Engine efficiency, or the efficiency of an engine converting potential energy in fuel to kinetic energy, is generally the same when using diesel or biodiesel (Schumacher et al, 2001). Engine efficiency is different than fuel efficiency, since fuel efficiency describes fuel consumption in an engine. Brake-specific fuel consumption is a key indicator of fuel efficiency, and is dependent upon the energy content of a fuel. Determining the relationship between biodiesel blends and engine performance provides an understanding of the expected fuel consumption when using cottonseed oil biodiesel as fuel in a non-road diesel engine. Using this data, consumers can determine the cost effectiveness of using CSO biodiesel blends.

Performance curves were developed for a three-cylinder 14.2 kW (19 hp) Yanmar 3009D diesel engine, manufactured by John Deere Power Systems, Waterloo, IA. The diesel engine tested was fueled by several blends of CSO biodiesel. These performance curves were developed according to the Engine Power Test Code for diesel engines (SAE, 1983). As laid out in the Engine Power Test Code, the following parameters were measured:

- Torque;
- Engine speed;
- Engine, water, oil, and ambient temperatures; and
- Inlet air pressure.

To define the power curve, data was recorded for five operating speeds, approximately evenly spaced, between the lowest stable speed and the maximum speed recommended by the manufacturer. The following data were recorded during engine testing (SAE, 1983):

- Engine speed;
- Beam load;
- Ambient air temperature, pressure, humidity;
- Inlet air pressure, temperature;
- Exhaust system pressure;
- Fuel supply temperature;
- Oil and coolant temperature;
- Oil pressure;
- Intake manifold temperature, pressure;
- Exhaust manifold temperature, pressure;
- Air cleaner and piping restriction;
- Ignition/injection timing; and
- Fuel supply pressure.

The engine was loaded for testing with a water-cooled eddy current absorption dynamometer rated at 22.4 kW (30 hp), manufactured by Pohl Associates, Inc., Hatfield, PA. Dynamometer load was controlled using a Dynamatic® EC 2000 controller (Drive Source International, Inc., Sturtevant, WI.). Torque and engine speed data were collected using LabView 8.0. Fuel flow was measured using a Model 214 Piston Flow Meter and transmitted using a Model 294 High Resolution, Linearized Frequency Transmitter (Max Machinery, Inc., Healdsburg, CA) Figure 3 shows the dynamometer test system.

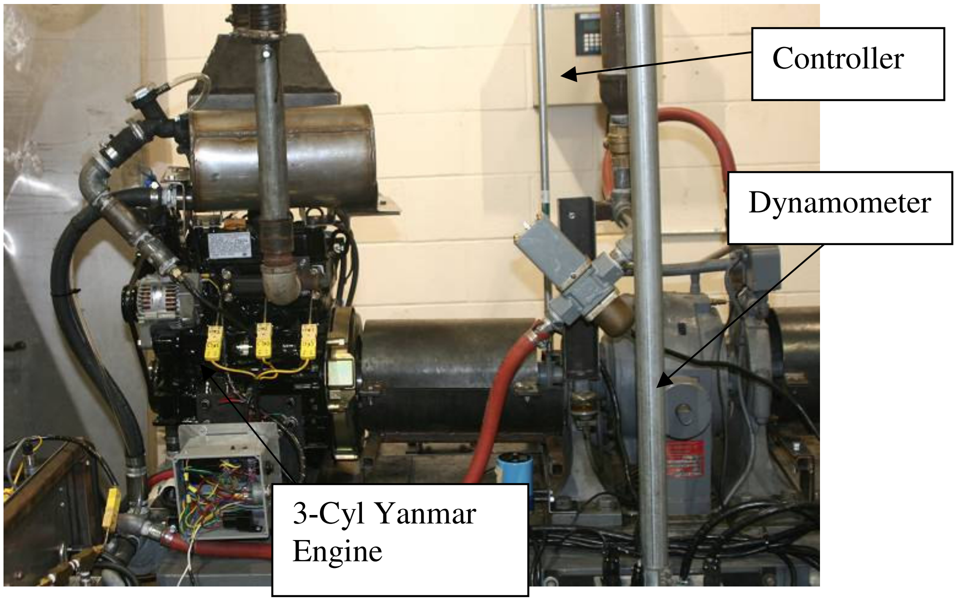


Figure 3. Dynamometer test system.

For each fuel blend, the engine was started and allowed to warm up for several minutes at half throttle and a load of approximately 10.8 N-m (eight ft-lb). The throttle was then increased until the engine reached wide-open throttle (WOT). Once WOT was obtained, the engine load was increased to the highest possible load at which the engine speed was maintained. Preliminary tests were conducted in order to determine the stable speed range of the engine. Speed intervals that provided stabilized speed and torque measurements were chosen. The maximum loaded engine speed for the purpose of these tests was approximately 3150 revolutions per minute (rpm). The engine was allowed to run at this setting until speed and torque measurements were stable for at least two minutes. Once the measurements were stabilized, data collection was initiated. See Appendix B for the step-by-step procedure of data collection that was used. Upon completion of data collection, the load on the engine was then increased, while maintaining WOT, until the engine speed decreased to the next desired engine speed The measurements were, again, allowed to stabilize, and data collection was repeated. The testing process was repeated for each desired engine speed. The five engine speeds targeted were 3150, 3065, 2975, 2885, and 2800 rpm. These five speeds were chosen because they are fairly evenly spaced, and they provided a speed-load combination that was stable enough for testing purposes.

This range of operating speeds is representative of most stationary non-road diesel engines, which generally operated at consistent, intermediate loads. However, this range does not completely represent mobile non-road engines, which may be operated at maximum engine speed. An example of this is a tractor pulling a PTO powered implement. Further tests should be conducted to analyze engine performance, as well as exhaust emissions, at maximum rated engine speed, which is 3200 rpm for this engine.

Engine speed and torque were used to determine horsepower of the engine at each targeted speed. Engine power was found using equation 1:

$$P = \frac{T \times N}{9{,}549} \qquad (1)$$

Where,

P = power, kW

N = engine speed, rpm

T = torque, N•m

Diesel engine performance is affected by inlet air pressure, temperature, and humidity. In order to provide a standard basis of comparison, it is necessary to apply a correction factor to account for the difference between standard inlet air conditions and inlet air conditions observed during testing (SAE, 1983). Inlet air conditions were assumed to be the same as ambient weather conditions; weather data was obtained from Easterwood Airport hourly weather data. According to the Power Test Code, observed brake power was corrected using equation 2, assuming a constant fuel rate during testing.

$$P_c = P_o \left(fa \right)^{fm} \qquad (2)$$

Where,

P_c = corrected brake power, kW

P_o = observed brake power, kW

fa = atmospheric factor

fm = engine factor

The atmospheric factor for naturally aspirated engines, like the one used during testing, was found using equation 3.

$$fa = \left(\frac{99}{B_{do}}\right)^{1.1} \left(\frac{t+273}{298}\right)^{1.2} \qquad (3)$$

Where,

B_{do} = observed inlet dry air pressure, kPa

t = observed inlet air temperature, °C

The engine factor, fm, has a value of 1.2 when q/r is greater than 65. The variable q was found using equation 4 for four stroke engines. The engine pressure ratio, r, is the ratio of the observed inlet manifold pressure to the observed inlet air pressure. For naturally aspirated engines, the pressure ratio has a value of one.

$$q = 120{,}000 \times \frac{F}{DN} \qquad (4)$$

Where,

q = the ratio of the rate of fuel consumed to the engine displacement multiplied by the engine speed, mg/L-cycle

F = fuel rate, g/s

D = engine displacement, L

N = engine speed, rpm.

Engine displacement for the Yanmar engine used during testing is 0.879 L. The value of q/r was greater than 65 for all tests.

Brake specific fuel consumption (BSFC), which is a good comparator of fuel blends, is a measure of the fuel efficiency of an engine. BSFC is the ratio of the rate of fuel consumption to the rate of power production using that fuel, and has units of grams per kilowatt-hour (g/kW-hr). BSFC is, essentially, a function of the energy content of a fuel. Diesel has an energy content of about 36,200 kilojoules per liter (kJ/L), while cottonseed oil biodiesel has an energy content of about 33,500 kJ/L. The difference in energy content of CSO biodiesel and petroleum diesel is about eight percent. Equation 5 was used to find BSFC.

$$BSFC = \frac{f}{0.10472 \times N \times 0.001 \times T} \qquad (5)$$

Where,

BSFC = brake specific fuel consumption, g/kW-h

f = fuel consumption, g/h

N = engine speed, rpm

T = torque, N•m

Performance tests were completed using three randomized blocks, with each block containing one set of tests for each fuel blend. Brake specific fuel consumption for each fuel blend at each speed interval was compared BSFC for DF500 using a t-test with a confidence interval of 0.95. These tests were used to determine whether or not there is significant difference between the BSFC of CSO biodiesel blends and DF500. Emissions tests were conducted concurrently with performance tests. Emissions test results will be presented in Section 4.

3.3 Results

Figure 4 shows brake power and torque for diesel and B100.

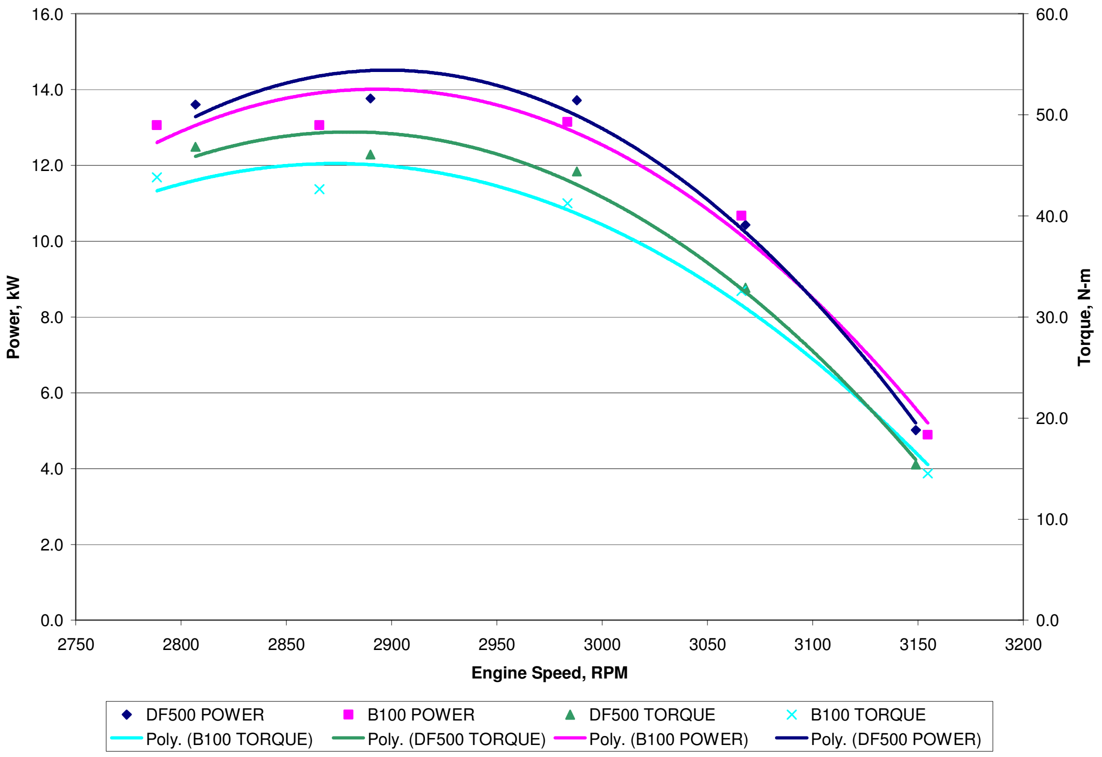


Figure 4. Brake power and torque using B100 and diesel.

The engine achieved a peak corrected brake power of 13.8 kW (18.5 hp) using farm diesel at an engine speed of approximately 2875 rpm. The peak power achieved when using B100, 13.1 kW (17.6 hp) was about five percent lower than when using diesel fuel. At high speeds (3065 rpm and greater), CSO biodiesel achieved approximately the same torque and brake power as diesel.

Figure 5 below compares brake power and torque for B5 and diesel.

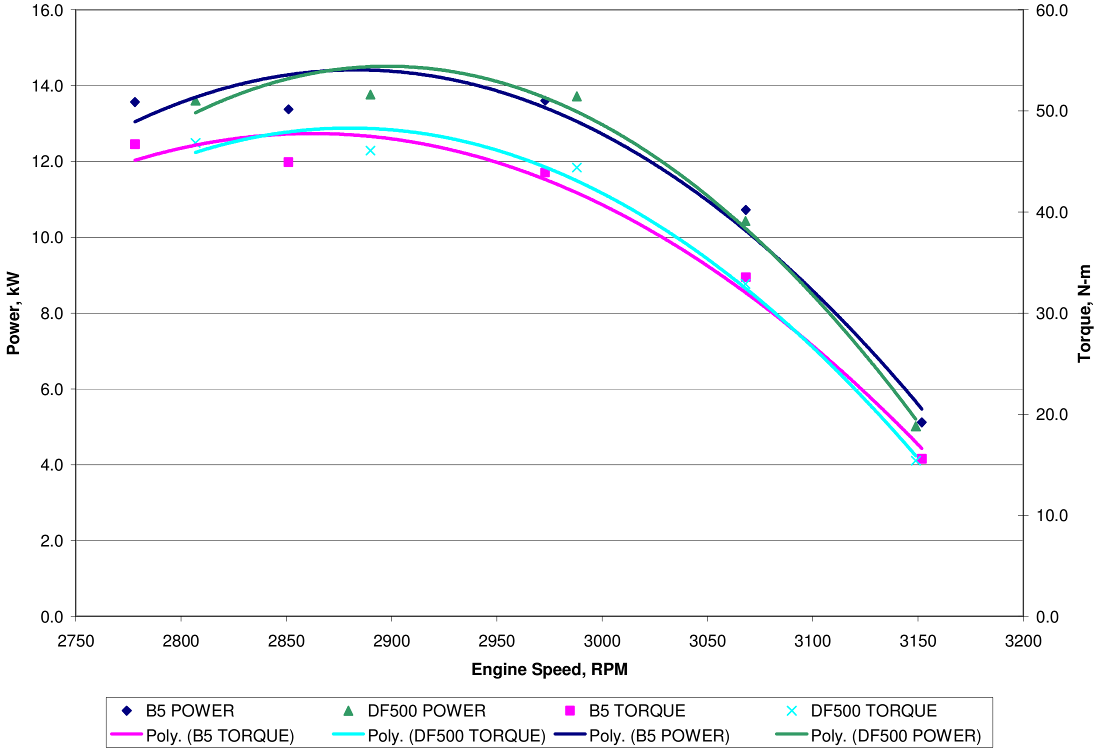


Figure 5. Brake power and torque using B5 and diesel.

Peak brake power when using B5 was about one percent lower than when using pure diesel, and about four percent higher than when using B100. When using B5, the engine produced as much or more power than when using DF500 at speeds of 3150, 3065, and 2800 rpm. As seen in the figures above, as well as table 8 below, none of the CSO biodiesel blends produced the peak brake power produced when using petroleum diesel.

Table 8. Corrected brake power.

	Corrected Brake Power, kW				
	3150 rpm	3065 rpm	2990 rpm	2875 rpm	2800 rpm
DF500	5.0	10.4	13.7	13.8	13.6
B5	5.1	10.7	13.6	13.4	13.6**
B20	5.3	10.3	13.4	13.2*	13.2
B40	5.1	10.3	13.4	13.3	13.3
B60	4.9	10.4	13.0	12.9	12.9
B80	4.7	10.3	12.9	13.0	12.9
B100	4.9	10.7	13.1*	13.1	13.1

*Significantly different from the corrected brake power achieved by using DF500 at the same engine speed

**Insufficient data to determine statistical difference

Power achieved by each CSO biodiesel blend at a specific engine speed was compared to the power achieved by DF500 at the same engine speed. Only two scenarios produced significantly less power at a particular load: B100 at 2990 rpm and B20 at 2875 rpm. The significance in the difference in power produced when using B20 at 2875 rpm may be attributed to engine speed and load becoming unstable. The peak corrected brake power produced tended to decrease as the percent of CSO biodiesel in the fuel blend increased, but the decrease was usually insignificant. This is reasonable, since the energy content of biodiesel is lower than the energy content of farm diesel.

Figure 6 illustrates the brake-specific fuel consumption for diesel, B5, abd B100.

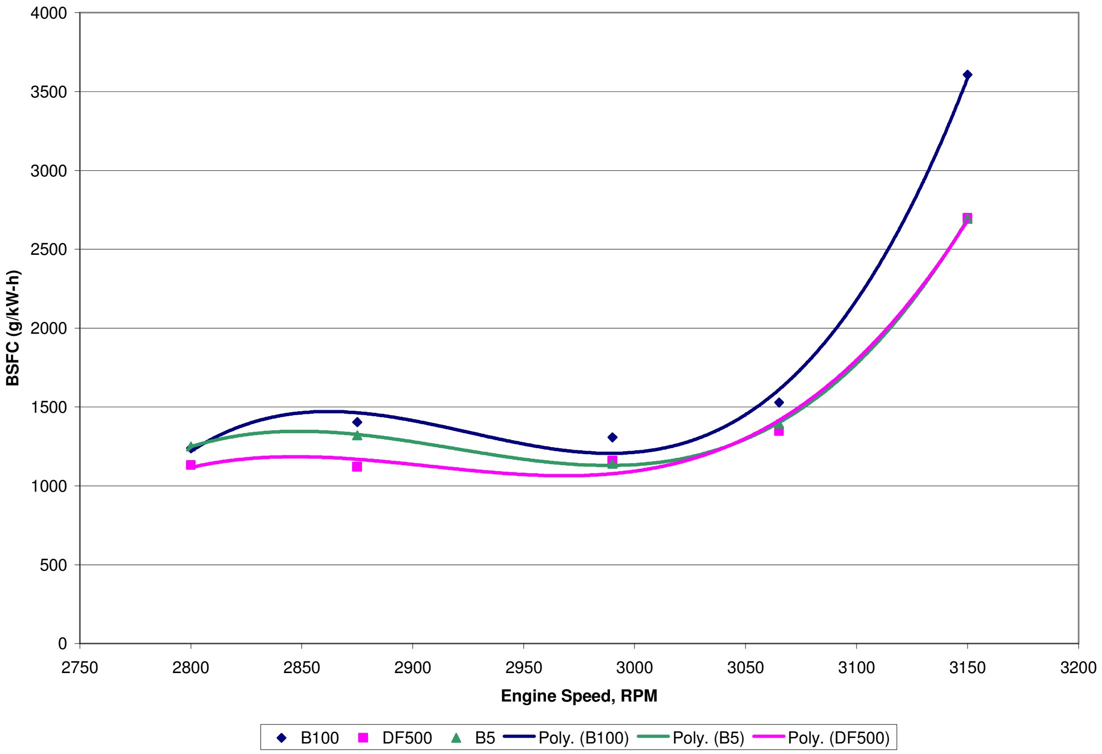


Figure 6. Corrected BSFC using B5, B100, and diesel.

At each speed interval, BSFC tended to increase as the percentage of biodiesel in the blend increased. The corrected BSFC values for each fuel can be found in table 9. The corrected BSFC for B100 was, on average, 19% higher than the corrected BSFC for DF500. When using B5, the corrected BSFC was eight percent higher than when using DF500, on average. The average corrected BSFC when using B20 was four percent lower than when using diesel fuel. This was the only blend that produced an average decrease in corrected BSFC when compared to diesel.

Table 9. Corrected brake-specific fuel consumption.

	BSFC, g/kW-h (Corrected)				
DF	2699	1348	1159	1120	1133
B5	2665	1421	1168	1357	1276
B20	2522	1421	1155	1114	946
B40	2945	1443	1147	1224	1195
B60	2833	1364	1142	1180	1313
B80	3601	1567	1305	1329*	1270
B100	3606	1527	1307*	1405	1238

*Significantly higher than DF500

Corrected values for BSFC were found to be significantly different from that of DF500 when using B100 at 2990 rpm and when using B80 at 2875 rpm. .

3.4 Summary

Peak power produced when using cottonseed oil biodiesel blends failed to match the peak power produced when using farm diesel. The peak power produced when using B100 was about five percent less than when using DF500. This difference is less than the difference in heating value between CSO biodiesel and diesel fuel (seven percent). The difference in peak power was not usually significant, especially when using biodiesel blends of less than B40. Likewise, the brake-specific fuel consumption tended to increase when using biodiesel blends, especially in blends with a high percentage of biodiesel, such as B80 and B100. The increase in corrected BSFC when using B100 ranged from nine percent at 2800 rpm to 34% at 3150 rpm. These results agree with Lin et al. (2006) and Cetinkaya et al. (2005), who observed a moderate decrease in output power when using biodiesel blends, and with Canakci and Van Gerpen (2001) who observed an increase in BSFC when using biodiesel blends.

The data presented in this section provides support for using biodiesel as a supplemental fuel for non-road diesel engines. When using small percentage fuel blends, such as B5 and B20, peak power and BSFC are not significantly different from that of straight farm diesel. This is in general agreement with Shaheed and Swain (1999), who observed no significant differences when using CSO biodiesel in a single cylinder 2.75 kW engine. Consumers that elect to use these blends can also take advantage of the lubricity of biodiesel. By producing and using cottonseed oil biodiesel as a fuel supplement, the agricultural industry is provided an opportunity to utilize an agricultural byproduct, as well as acting as an agent in the push toward becoming less dependent on non-renewable energy sources

4. EXHAUST EMISSIONS

It is important to have a thorough understanding of the emissions associated with alternative fuels, such as biodiesel. The difference in the composition of diesel and biodiesel, and of different types of biodiesel, has an effect on the composition of exhaust emissions. Understanding the exhaust emissions will help in determining the feasibility of using biodiesel as a diesel fuel supplement. According to Lapuerta et al. (2007), the effect of biodiesel is specific for each type of pollutant and depends on engine type, operating conditions, and the origin and quality of biodiesel. Pollutants of interest include $NO_{x,}$, SO_2, THC, CO, and PM. Understanding the relationship between biodiesel blends and the emission of these pollutants will aid engine manufacturers in adapting engines for use with biodiesel blends (Lapuerta et al., 2007).

The EPA finalized a two-step sulfur standard for non-road, locomotive, and marine (NRLM) diesel fuel. The sulfur requirements under this standard are similar to those established for highway diesel fuel. "Beginning June 1, 2007, refiners will be required to produce NRLM diesel fuel with a maximum sulfur content of 500 ppm. Then, beginning June 1, 2010, the sulfur content will be reduced for non-road diesel fuel to 15 ppm" (EPA, 2004). Currently, farm diesel is only available in blends up to 15 ppm sulfur; marine vessels are allowed to use diesel with up to 500 ppm sulfur. This standard will achieve considerable, cost-effective reductions of sulfate PM and SO_2 emissions, which will provide substantial public health and environmental benefits which outweigh the cost of meeting the standards necessary to achieve them. The final sulfur standards will also allow high efficiency control technology to be applied to non-road engines, since sulfur can inhibit or impair the function of diesel exhaust emission control devices that will be necessary for non-road diesel engines to meet the finalized emission standards (EPA, 2004).

According to the National Biodiesel Board (2006), biodiesel is a clean burning alternative fuel produced from domestic, renewable resources, such as plant oils or animal fats. While bio-diesel contains no petroleum, it can be blended with petroleum diesel to create a fuel suitable for use in diesel engines. Pure biodiesel is essentially free of sulfur compared to petroleum diesel. Biodiesel blends, consequently, contain less sulfur than petroleum diesel. Since biodiesel is renewable and can be domestically produced, it is capable of strengthening United States energy security by reducing dependence on imported oil (Morris, 1993).

A large amount of research has been carried out dealing with engines fueled by biodiesel, including biodiesel produced from soybean, sunflower, and rapeseed oil. However, there is limited data regarding biodiesel produced from cottonseed oil. With the large amount of cotton produced in the United States, and the growing need for utilizing agricultural byproducts, it is important to investigate the effects on exhaust emissions when using biodiesel from cottonseed oil.

4.1 Objective

The overall objective of the research discussed in this section was to gain a better understanding of cottonseed oil biodiesel by determining the relationship between pollutant concentrations in diesel engine exhaust and the percentage of cottonseed oil biodiesel in fuel blends. Specific objectives of this research are as follows:

- To evaluate the effect of using cottonseed oil biodiesel and biodiesel blends on the emissions of CO, CO_2. THC, NO_x, and SO_2;
- To compare emissions from diesel and cottonseed oil biodiesel and biodiesel blends; and
- To compare results with published standards and regulations.

4.2 Experimental Method

Exhaust emissions were measured for a three-cylinder 14.2 kW (19 hp) Yanmar 3009D diesel engine (John Deere Power Systems, Waterloo, IA) fueled using various blends of CSO biodiesel. These measurements were conducted in two manners: concurrent with performance tests and exclusive of performance tests. For both manners of testing, emissions were measured with an ENERAC 3000E (Enerac, Inc., Westbury, NY), which measures CO_2, and THC concentrations using nondispersive infrared (+/- 5% accuracy) sensors. High sensitivity, wide range electrochemical SEM sensors (+/- 2% accuracy) were used by the ENERAC 3000E to measure CO, NO_x, and SO_2.

The first emissions tests were run concurrently with performance tests. The CSO biodiesel used during these tests was purchased from Safe Renewable Fuels, Inc. The blends analyzed during these tests are listed below:

- DF500;
- B5/DF500;
- B20/DF500;
- B40/DF500;
- B60/DF500;
- B80/DF500; and
- B100.

Emissions tests were also conducted exclusive of performance tests. The CSO biodiesel used during these tests came from two sources: Safe Renewable Fuels, Inc. and the Food & Protein Research & Development Center at Texas A&M University. For the purpose of this paper, biodiesel blends comprised of CSO biodiesel from the Food & Protein Research & Development Center will be referred to with “FP” placed before the blend name. The blends analyzed during these tests are listed below:

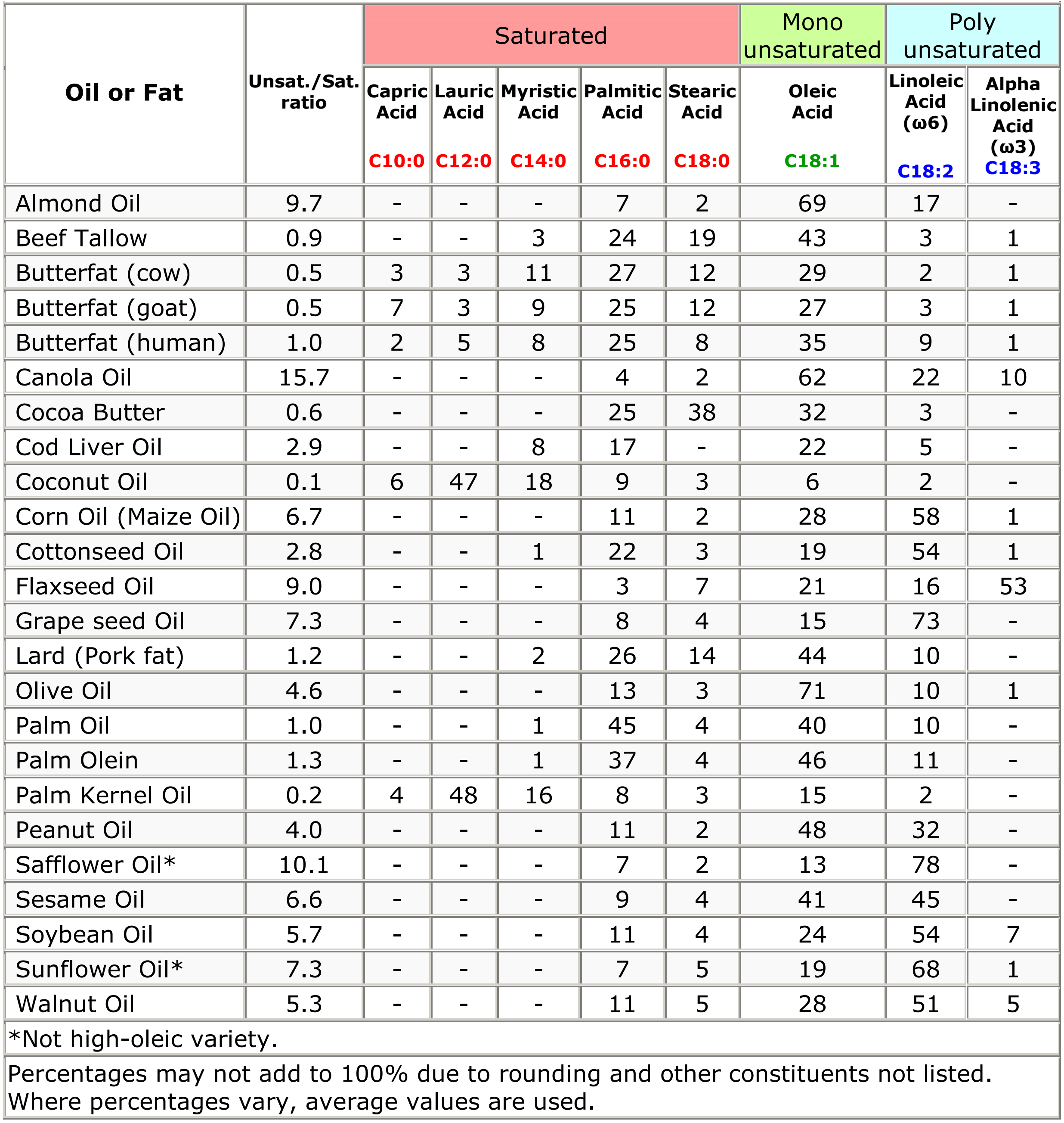
- FPB10/DF500;
- FPB20/DF500;
- B5/DF15;
- B20/DF15; and
- B50/DF15.

During the emissions tests concurrent with performance tests, engine exhaust emission measurements were collected at three even increments during each performance test for each fuel blend at each load. These three measurements for each pollutant were averaged using a simple arithmetic mean to represent the pollutant exhaust concentration for that specific fuel blend at that specific load during a specific test. The load intervals for each test were based on targeted engine speeds. Details on the performance testing method can be found in Section 3.

Exhaust concentrations for NO_x, SO_2, CO, and THC were measured in units of ppm, while CO_2 was measured in percentage. Carbon dioxide concentrations were converted to ppm by multiplying the concentration of CO_2 (%) by 10^4. In order to compare these emissions to the non-road diesel engine emission standards set forth by EPA, the measurements were converted to grams per kilowatt-hour, or g/kW-h. In order to convert from ppm to g/kW-h, the ratio between exhaust and fuel was required; the exhaust-to-fuel ratio, or EFR, is defined as the mass of exhaust produced per unit mass of fuel combusted. The EFR for CSO biodiesel and petroleum diesel were calculated based on assumed combustion equations. Ten percent excess air was assumed to be available during combustion.

During transesterification, oils are mixed with a methanol and sodium hydroxide and heated in order to produce methyl esters, or biodiesel. Emissions produced when using biodiesel are dependent upon the composition of biodiesel feedstock. Table 10 below lists common edible fats and oils and their associated fatty acid compositions:

Table 10. Percent weight of total fatty acids in common fats and oils (Stauffer, 1996).



Oil or Fat	**Unsat./Sat. ratio**	Saturated					Mono unsaturated	Poly unsaturated	
		Capric Acid C10:0	**Lauric Acid** C12:0	**Myristic Acid** C14:0	**Palmitic Acid** C16:0	**Stearic Acid** C18:0	**Oleic Acid** C18:1	**Linoleic Acid (ω6)** C18:2	**Alpha Linolenic Acid (ω3)** C18:3
Almond Oil	9.7	-	-	-	7	2	69	17	-
Beef Tallow	0.9	-	-	3	24	19	43	3	1
Butterfat (cow)	0.5	3	3	11	27	12	29	2	1
Butterfat (goat)	0.5	7	3	9	25	12	27	3	1
Butterfat (human)	1.0	2	5	8	25	8	35	9	1
Canola Oil	15.7	-	-	-	4	2	62	22	10
Cocoa Butter	0.6	-	-	-	25	38	32	3	-
Cod Liver Oil	2.9	-	-	8	17	-	22	5	-
Coconut Oil	0.1	6	47	18	9	3	6	2	-
Corn Oil (Maize Oil)	6.7	-	-	-	11	2	28	58	1
Cottonseed Oil	2.8	-	-	1	22	3	19	54	1
Flaxseed Oil	9.0	-	-	-	3	7	21	16	53
Grape seed Oil	7.3	-	-	-	8	4	15	73	-
Lard (Pork fat)	1.2	-	-	2	26	14	44	10	-
Olive Oil	4.6	-	-	-	13	3	71	10	1
Palm Oil	1.0	-	-	1	45	4	40	10	-
Palm Olein	1.3	-	-	1	37	4	46	11	-
Palm Kernel Oil	0.2	4	48	16	8	3	15	2	-
Peanut Oil	4.0	-	-	-	11	2	48	32	-
Safflower Oil*	10.1	-	-	-	7	2	13	78	-
Sesame Oil	6.6	-	-	-	9	4	41	45	-
Soybean Oil	5.7	-	-	-	11	4	24	54	7
Sunflower Oil*	7.3	-	-	-	7	5	19	68	1
Walnut Oil	5.3	-	-	-	11	5	28	51	5

*Not high-oleic variety.

Percentages may not add to 100% due to rounding and other constituents not listed. Where percentages vary, average values are used.

According to the National Cottonseed Products Association (2002), cottonseed oil is composed, primarily, of palmitic acid ($C_{18}H_{36}O_2$), oleic acid ($C_{20}H_{38}O_2$), and linoleic acid ($C_{20}H_{36}O_2$). The primary methyl esters found in CSO biodiesel, therefore, are $C_{18}H_{36}O_2(OCH_3)$, $C_{20}H_{38}O_2(OCH_3)$, and $C_{20}H_{36}O_2(OCH_3)$. The equation below was used for stoichiometric combustion of CSO biodiesel: Palmitic acid, and fatty acids with similar molecular weights, make up about 25.6% of the fatty acids of cottonseed oil. Oleic and linoleic acids, and fatty acids with similar molecular weights, make up about 19.4% and 55% of cottonseed oil biodiesel.

$$0.256C_{18}H_{36}O_2(OCH_3)+0.194C_{20}H_{38}O_2(OCH_3)+0.55C_{20}H_{36}O_2(OCH_3)+28.84[O_2+3.76N_2]$$
$$\rightarrow 20.49CO_2+19.70H_2O+108.44N_2$$

From this equation, the stoichiometric air-to-fuel ratio (AFR) was determined as follows:

$$AFR=\frac{m_{air}}{m_{fuel}} \qquad (6)$$

Where,

AFR = air-to-fuel ratio, g air/g fuel

m_{air} = mass of air present during combustion, g

m_{fuel} = mass of fuel combusted, g.

EFR was calculated using equation 8:

$$EFR=\frac{1.1\times m_{air}+m_{fuel}}{m_{fuel}} \qquad (7)$$

Where,

EFR = exhaust-to-fuel ratio, g exhaust/g fuel.

For calculating EFR, it is assumed that 10% excess air is present during combustion, and that the mass of fuel and air present during combustion equals the mass of exhaust leaving the engine. According to Weathers (1981), diesel engines intake as much as 25% excess air at full throttle. The EFR for CSO biodiesel was found to be 15.94 g exhaust/g fuel. The assumed stoichiometric equation for combustion of petroleum diesel is shown below; sulfur content was not taken into account when determining EFR for petroleum diesel.

$$C_{12}H_{26} + 18.5[O_2 + 3.76N_2] \rightarrow 12CO_2 + 13H_2O + 69.56N_2$$

The EFR for diesel was found to be 17.43 g exhaust/ g fuel. EFR for biodiesel blends can be determined using a weighted average of the EFR for CSO biodiesel and diesel, based on the percentage of biodiesel in each blend. Table 11 below lists the EFR for each fuel blend used for converting concentration units from ppm to g/kW-h:

Table 11. Exhaust-to-fuel ratios.

Blend	EFR [g exhaust/ g fuel]
DF500	17.43
B5	17.36
B20	17.13
B40	16.83
B60	16.54
B80	16.24
B100	15.94

Equation 8 was used to convert pollutant concentrations from ppm to g/kW-h, assuming 100% fuel combustion.

$$C' = C_{ppm} \times \frac{\rho_{pollu\tan t}}{\rho_{exhaust}} \times EFR \times BSFC \qquad (8)$$

Where,

C’ = concentration, g pollutant/kW-h

C_{ppm} = concentration, ppm

$\rho_{pollutant}$ = density of pollutant (g/L)

$\rho_{exhaust}$ = density of exhaust (g/L)

EFR = exhuast-to-fuel ratio, g air/ g fuel

BSFC = brake-specific fuel consumption, corrected for dry air, g fuel/kW-h.

Table 12 below lists the densities for the compounds measured. The density of exhaust was assumed to be 1.18 g/L.

Table 12. Exhaust pollutant densities.

Compound	Density (g/L)
CO	1.14
CO2	1.8
THC (as propane)	1.8
NOx (as NO2)	1.88
SO2	2.62

Exhaust pollutant concentrations were compared using a t-test with a confidence interval of 0.95. These tests were used to determine whether or not there was a significant difference between exhaust pollutant concentrations measured when using biodiesel blends and when using DF500.

During the second set of tests, exclusive from performance tests, exhaust emissions were measured for each fuel blend at three pre-determined engine loads. For each fuel blend, the engine was started and allowed to warm up at half-throttle and an engine load of approximately 10.8 N-m (eight ft-lb). After a few minutes, throttle was increased until the engine reached WOT. Engine load was then increased to about 16.3 N-m (12 ft-lb), and the engine was allowed to run until engine speed and torque measurements were stabilized for two minutes. Once the measurements had stabilized, exhaust emissions measurements were collected. Once measurements were taken, the engine load was increased to approximately 32.5 N-m (24 ft-lb), and then to about 40.7 N-m (30 ft-lb) for exhaust emissions measurements. The concentrations measured were averaged using a simple arithmetic mean in order to provide a representative set of measurements for each blend at each load. Similarly to the performance tests, the engine was loaded for testing with a water-cooled eddy current absorption dynamometer rated at 30 hp, manufactured by Pohl Associates, Inc., Hatfield, PA. Dynamometer load was controlled using a Dynamatic® EC 2000 controller (Drive Source International, Inc., Sturtevant, WI.). Engine speed and torque data were collected using LabView 8.0. This second method of testing compared CSO biodiesel from two sources, as mentioned previously.

4.3 Results

Figure 7 below shows the corrected emissions for carbon monoxide resulting from the emission tests conducted concurrent with performance tests when using B5, B20, B100, and diesel.

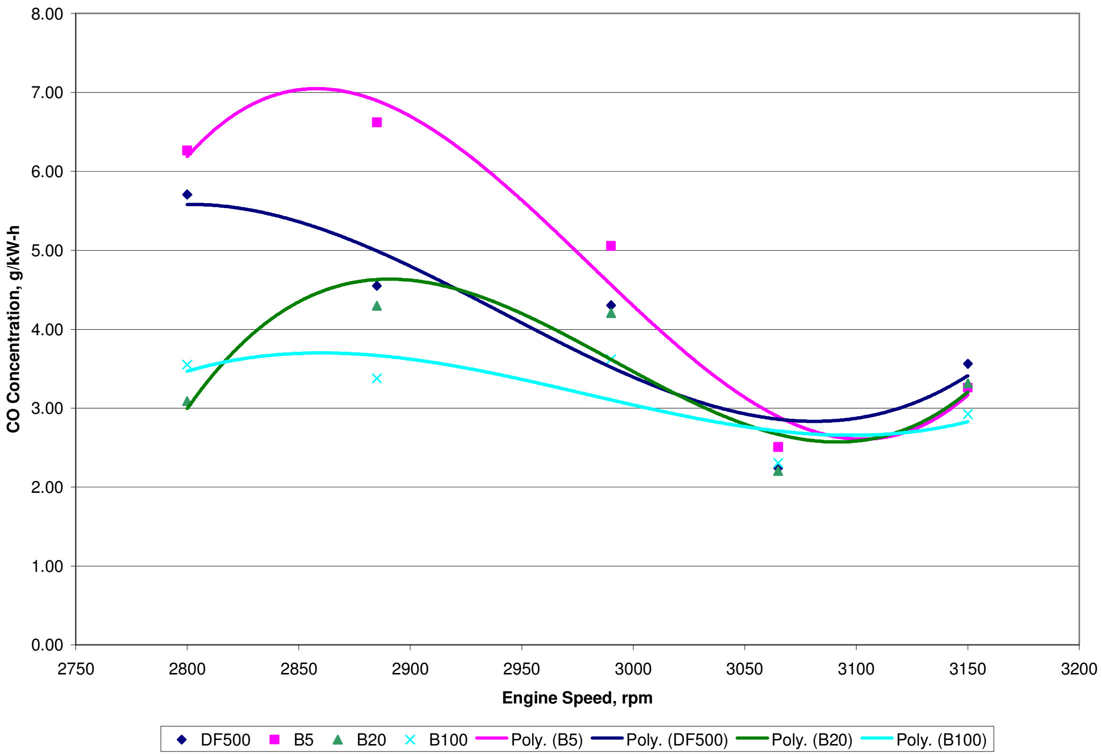


Figure 7. CO emissions using DF, B5, B20, B100.

Carbon monoxide concentrations decreased by 12 and 19% when using B20 and B100, respectively, when compared to diesel fuel. However, CO concentrations increased by an average of 15% when using B5. In general, CO concentrations tended to decrease as the percentage of CSO biodiesel in the fuel blend increases. The decrease is generally significant in blends of B60 and greater. These results are in agreement with Schumacher et al. (2001), who found that CO emissions decreased as biodiesel percentage in fuel blends increased.

Exhaust concentrations of CO_2 found during the first set of tests can be found below in figure 8.

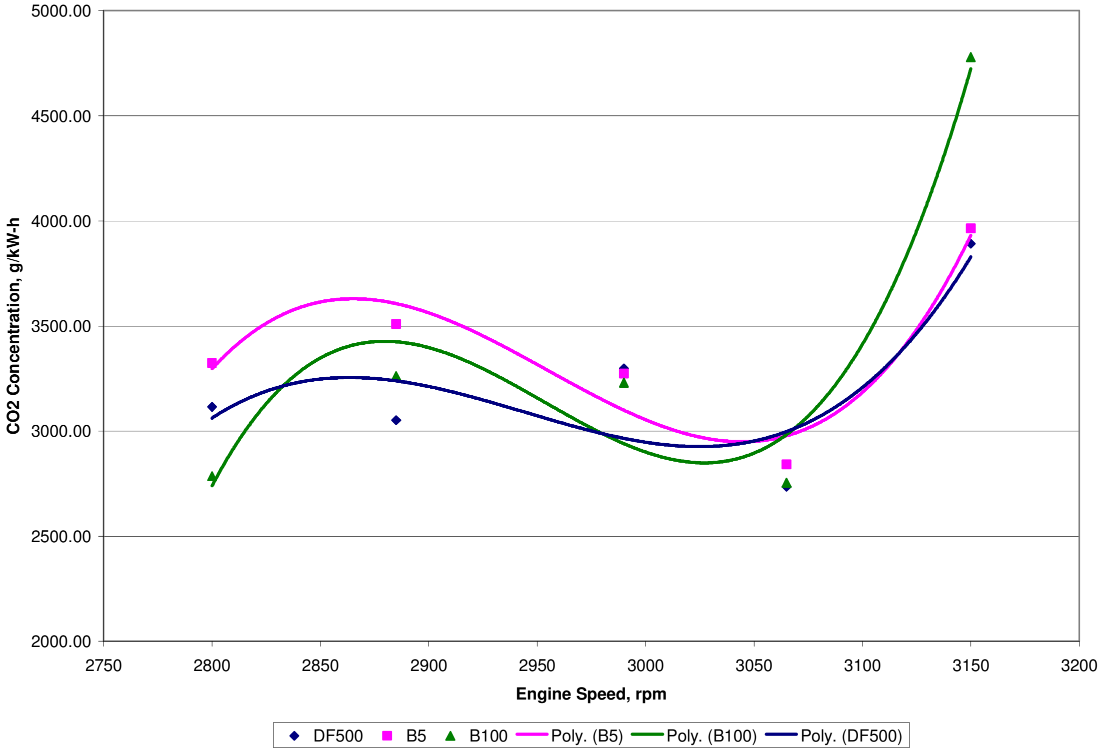


Figure 8. CO_2 emissions using DF, B5, B20, B100.

The results for the first set of tests show that, at 3150 rpm, CO_2 emissions increased as the percentage of CSO biodiesel increased; no definitive trend was found at other speeds.

Figure 9 below illustrates THC emissions found using diesel, B20, and B100 during the first set of tests.

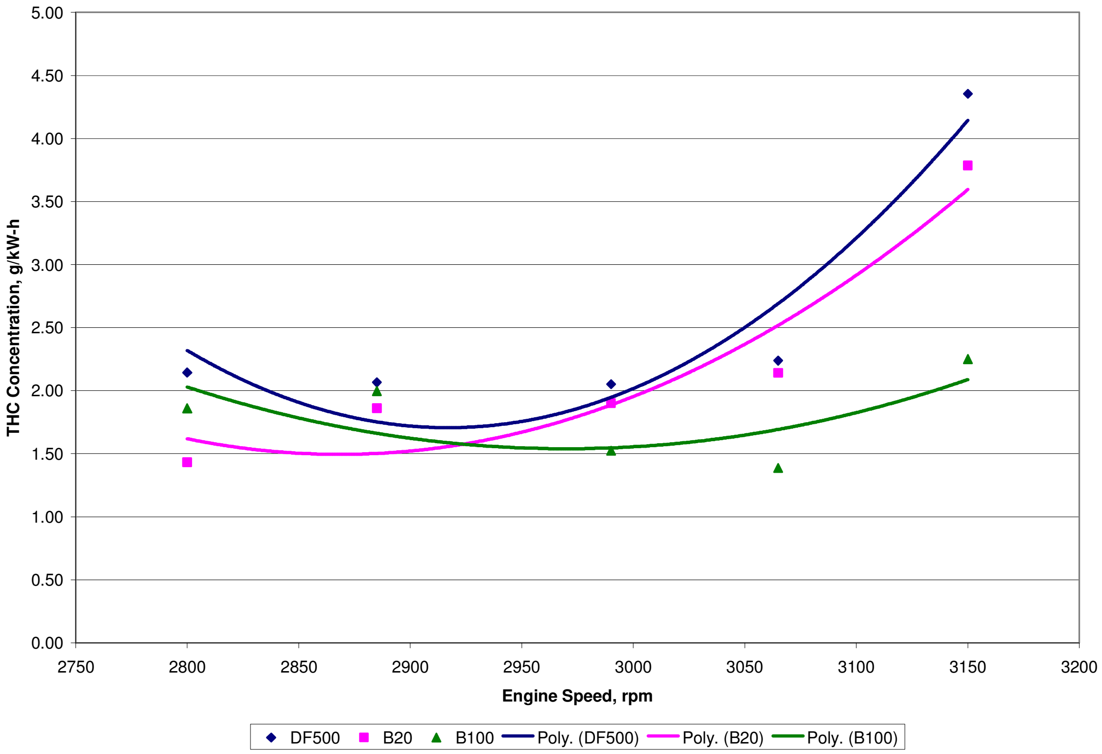


Figure 9. THC emissions using DF, B20, B100.

As expected, hydrocarbon emissions tended to decrease as the percentage of CSO biodiesel in the fuel blends increased. This decrease was significant in blends 80 percent or greater at speeds of 3065 rpm and 3150 rpm. When using B20, THC concentrations decreased by 14% when compared to DF500, while using B100 resulted in a 26% decrease. These results were similar to those observed by Krahl et al. (2005), who found that THC was significantly decreased when using biodiesel.

Figure 10 below displays NO_x emissions obtained during the first set of tests.

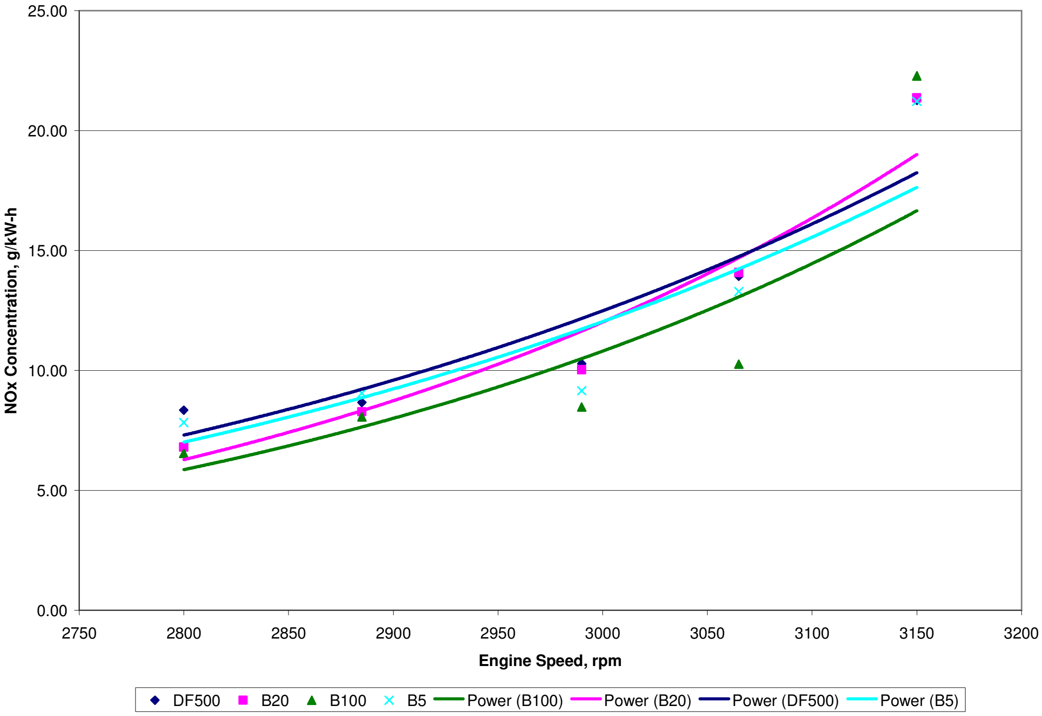


Figure 10. NO_x emissions using diesel, B5, B20, and B100.

On average, NO_x emissions decreased by four percent when using B5, and by five percent when using B20 as compared to diesel. When using B100, NO_x emissions decreased by 14%. Graboski and McCormick (1998) found that NO_x emissions increased when using biodiesel at full loads. According to Capareda (Personal communication, 2007) recent studies have shown a relationship between unsaturation of biodiesel feedstock oils and NO_xemissions. Many of the previous emissions tests, such as those conducted by Graboski and McCormick (1998), were performed using soybean oil, which has an unsaturated to saturated fatty acid ratio of 5.7. Cottonseed oil has an unsaturated to saturated fatty acid ratio of 2.8. This difference in unsaturated fatty acid composition could factor into the decrease in NO_x emissions when using CSO B100.

Figure 11 below displays sulfur dioxide emissions obtained during the first set of tests when using diesel, B5. B20, and B100.

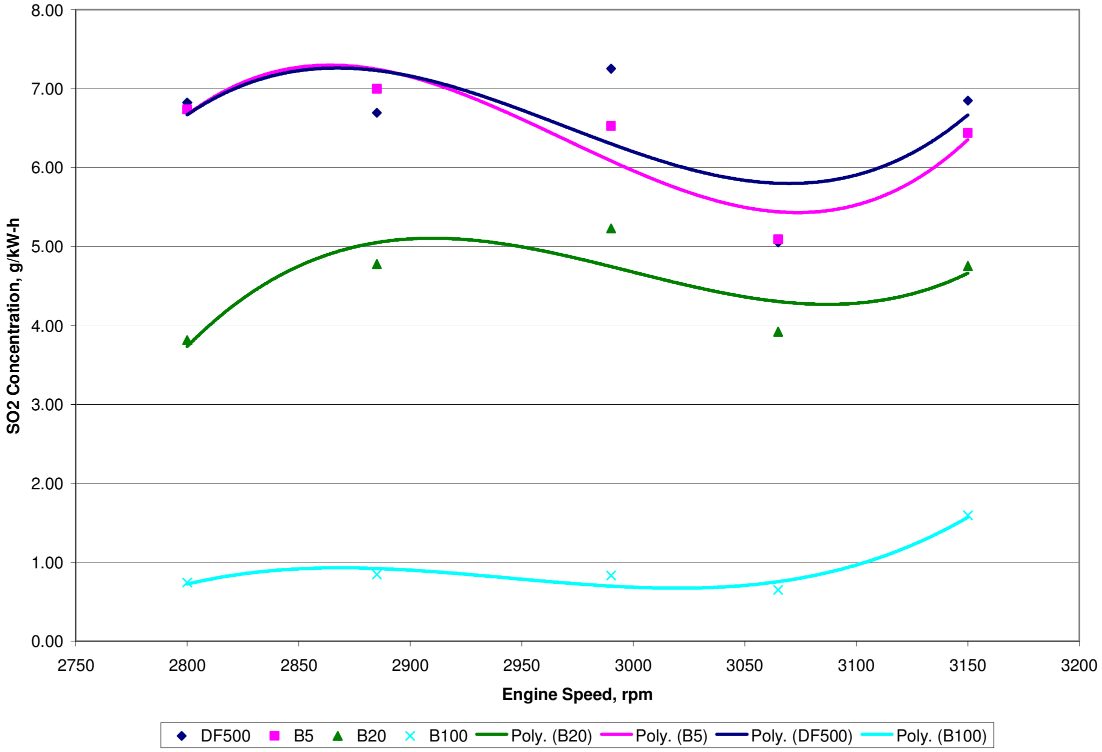


Figure 11. SO_2 emissions using diesel, B5, B20, and B100.

Sulfur dioxide emissions decreased as the percentage of CSO biodiesel in the fuel blends increased. The decrease in SO_2 emissions was consistently significant in CSO biodiesel blends of B20 and greater. The decrease in SO_2 concentrations ranged from two percent when using B5 to 86% when using B100. Given the decrease in fuel sulfur concentration, the decrease in SO_2 emissions was expected.

Exhaust emissions for CO, THC, NO_x, and SO_2 were also converted to units of grams per mile (g/mi), which are the standard units for on-road vehicles. Tables 13 through 16 below list emissions for DF500, B5, and B100.

Table 13. Carbon monoxide emissions (g/mi).

CO (g/mi)	3150	3065	2990	2885	2800
DF500	158	99	191	202	253
B5	144	111	223	293	277
B100	120	94	148	138	145

Table 14. Hydrocarbon emissions (g/mi).

THC (g/mi)	3150	3065	2990	2885	2800
DF500	193	99	91	92	95
B5	1027	312	182	175	61
B100	92	57	62	82	76

Table 15. NO_x emissions (g/mi).

NOx (g/mi)	3150	3065	2990	2885	2800
DF500	944	618	456	385	370
B5	938	587	405	400	346
B100	912	420	347	330	268

Table 16. SO_2 emissions (g/mi).

SO2 (g/mi)	**3150**	**3065**	**2990**	**2885**	**2800**
DF500	304	224	322	297	303
B5	284	225	288	309	298
B100	65	27	34	35	31

Emissions of CO, THC, NO_x, and SO_2 per mile tended to decrease when using CSO biodiesel blends.

The second set of tests was conducted exclusive of performance tests. As in the first tests, CO, THC, NO_x, and SO_2 were measured in ppm, while CO_2 was measured in percent. During these tests, fuel consumption was not monitored. In order to convert the measured units to g/kW-h, BSFC had to be assumed. Corrected BSFC for B100 and DF500, which was determined during the first set of tests, was used to approximate the BSFC for each fuel blend using a weighted average. Emissions for each blend were compared to emissions when using DF500 during the first set of tests.

Tables 17 through 19 show the emissions for each fuel blend at each targeted load.

Table 17. Exhaust emissions at 16.3 N-m (12 ft-lb).

16.3 N-m		FPB10***	FPB20***	B5/DF15	B20/DF15	B50/DF15	DF500**
CO	g/kW-h	3.0	3.1	2.9	2.8	3.0	3.6
CO_2	g/kW-h	3653.7	3789.7	3488.7	3664.2	4013.1	3892.5
THC	g/kW-h	3.9	3.9	3.8	3.9	4.2	4.4
NO_x	g/kW-h	18.0	18.5	16.2	16.8	18.5	21.3
SO_2	g/kW-h	2.5	2.8	1.4	0.8	0.9	6.8

*Significantly different from DF500.

**DF500 results were obtained from results during the first set of tests.

***CSO biodiesel from Food & Protein Research Department blended with DF500.

Table 18. Exhaust emissions at 32.5 N-m (24 ft-lb).

32.5 N-m		FPB10***	FPB20***	B5/DF15	B20/DF15	B50/DF15	DF500**
CO	g/kW-h	1.6	1.5	1.7	1.6	1.8	2.2
CO_2	g/kW-h	2424.4	2434.7	2406.9	2410.6	2402.5	2735.8
THC	g/kW-h	1.9	1.9	1.9	1.9	2.0	2.2
NO_x	g/kW-h	11.3	11.2	10.2	10.1	10.2	13.9
SO_2	g/kW-h	2.1	1.8	0.4	0.3	0.2	5.1

*Significantly different from DF500.

**DF500 results were obtained from results during the first set of tests.

***CSO biodiesel from Food & Protein Research Department blended with DF500.

Table 19. Exhaust emissions at 40.7 N-m (30 ft-lb).

40.7 N-m		FPB10***	FPB20***	B5/DF15	B20/DF15	B50/DF15	DF500**
CO	g/kW-h	2.2	1.8	1.7	1.8	2.2	4.3
CO_2	g/kW-h	2547.6	2536.5	2408.6	2608.9	2604.7	3297.3
THC	g/kW-h	1.7	1.7	1.6	1.7	1.9	2.1
NO_x	g/kW-h	9.4	9.5	8.7	8.8	8.7	10.3
SO_2	g/kW-h	2.6	1.9	0.2	0.3	0.3	7.3

*Significantly different from DF500.

**DF500 results were obtained from results during the first set of tests.

***CSO biodiesel from Food & Protein Research Department blended with DF500.

At each load, emissions for CO, CO_2, THC, NO_x, and SO_2 tended to be lower with CSO biodiesel blends than with DF500. Sulfur dioxide concentrations were lowest when CSO biodiesel was blended with DF15; using B50/DF15 resulted in a 94% decrease in SO_2 concentrations when compared to DF500 at medium and high loads. Nitrogen oxide emissions were lower for biodiesel blends than for DF500 throughout. On average, using a 20% CSO biodiesel blend with ultra-low sulfur diesel (DF15) resulted in a 21% decrease in NO_x emissions when compared to DF500.

4.4 Summary

Carbon monoxide emissions tended to decrease as the percentage of CSO biodiesel increased. The EPA standards for CO emissions from a stationary and mobile non-road diesel engine were exceeded when using a CSO biodiesel blend of B5 at an engine speed of approximately 2875 rpm. The CO emissions standards were not exceeded with any other fuel blend at any other speed.

Total hydrocarbon emissions decreased as the percentage of CSO biodiesel increased. The decrease in THC concentrations was generally significant in blends of B60 and greater. Hydrocarbon concentrations decreased by 26% when using B100 as compared to DF500.

On average, NOx emissions decreased when using blends of B5, B20, B60, B80, and B100 when compared to DF500. On average, NO_x emissions were equal when using

B40. EPA standards for NO_x emissions alone are not applicable for diesel engines rated between eight and 19 kW. However, the standard for NMHC +NO_x was consistently exceeded when using biodiesel blends, pure biodiesel, and farm diesel.

Sulfur dioxide concentrations decreased as the percentage of CSO biodiesel increased. This decrease tended to be significant in blends greater than five percent. The decrease in SO_s emissions was especially noticeable with ultra-low sulfur diesel (DF15). During the first tests, SO_2 emissions were decreased by an average of 86% when using B100; when using B50/DF15 during the second tests, SO_2 emissions were decreased by 96% at medium and high loads. These results are reasonable, considering the decrease in fuel sulfur content when blending diesel fuel with CSO biodiesel.

5. SUMMARY

The objective of this section is to provide an overview of the results presented in this manuscript. The observations made when dealing with engine performance, exhaust emissions, and the effect on regulations support the utilization of cottonseed oil biodiesel as a fuel supplement.

Carbon monoxide emissions decreased as the percentage of CSO biodiesel in fuel blends increased, with the exception of using B5. Carbon monoxide emissions increased by an average of 15% when using B5, with the largest increases observed at speeds of 2990 rpm and lower. When using pure CSO biodiesel, CO concentrations decreased by 19%, on average. This decrease in CO emissions is beneficial to areas in Texas and around the nation that are non-attainment for CO. Carbon monoxide emissions also decreased when using CSO biodiesel blended with DF15. The CO emissions measured were lower than the Tier 1 EPA emissions standard for both mobile and stationary diesel engines. This data supports those who wish to convert diesel engines to become compatible with alternative fuels. Manufacturers can also be confident that non-road diesel engines will maintain low CO emissions if alternative fuels are used.

Carbon dioxide emissions did not maintain any specific trend. It is important to note that CO_2 levels did not significantly increase throughout the tests. Cottonseed oil biodiesel, as well as other types of biodiesel, can be consumed without significantly increasing CO_2 emissions. Carbon dioxide, a greenhouse gas, is currently not considered a pollutant, and is therefore not regulated. However, it is possible that in the future, regulations will be placed upon greenhouse gases.

As the percentage of CSO biodiesel in fuel blends increased, the concentration of THC in the exhaust decreased. Hydrocarbon emissions decreased by 14% using B5 and by 26% using B100, as compared to farm diesel. Emissions of THC also decreased when using CSO biodiesel blended with ultra-low sulfur. This decrease is important to public health and welfare since hydrocarbons are considered by some to possibly be carcinogenic. The decrease in hydrocarbons will be a factor in determining whether or not the standard for NMHC + NO_x is exceeded when using biodiesel blends. During these tests, the Tier 1 standard for NMHC + NO_x was exceeded.

Sulfur dioxide emissions were significantly reduced when CSO biodiesel blends were used. Cottonseed oil biodiesel, which is essentially sulfur-free, can be used as a fuel additive for lubrication purposes, while maintaining low sulfur concentrations in fuels. Secondary effects of reducing SO_2 emissions include a decrease in the production of sulfate particles. Sulfate particles are believed by the EPA to contribute to particulate matter in the air, specifically $PM_{2.5.}$ Emissions of SO_2 were reduced by 14% using B5 and by 86% using B100, when being compared to DF500. A blend on B50/DF15 produced 94% less SO_2 than DF500.

Nitrogen oxide emissions usually decreased when using cottonseed oil biodiesel blends as compared to farm diesel. With B5, NO_x emissions decreased by four percent, while B20 and B100 resulted in five and 20% decreases in NO_x, as compared to DF500. This decrease in NO_x emissions may be attributed to the relatively low unsaturated-to-saturated fatty acid ratio of cottonseed oil biodiesel. More tests should be conducted in order to better gauge the effects of CSO biodiesel, as well as other types of biodiesel, on NO_x emissions. Tests should be conducted with the same engine as has been tested, as well as with other diesel engines. Methods of reducing NO_x emissions, such as retarding injection timing, utilizing exhaust gas recirculation (EGR), and water emulsification, should be further researched. If it can be shown that a certain type of biodiesel does not significantly increase NO_x emissions when blended with diesel fuel, then there will be an opportunity to produce B20 that meets TxLED fuel specifications.

Cottonseed oil biodiesel, while being environmentally friendly, may also be a sensible alternative to petroleum diesel. Although cottonseed oil biodiesel blends failed to match the peak power produced when using farm diesel, the difference in peak power was insignificant with blends of less than 40 percent. Peak brake power produced decreased by about one percent using B5, three percent using B20, and five percent using B100 as compared to petroleum diesel. The difference in peak power produced can be explained by the lower energy content of CSO biodiesel than petroleum diesel, however the percent difference in peak power was less than the percent difference in fuel energy content (eight percent). Generally, intermediate power levels were met when using CSO biodiesel blends. At a blend of B5, brake-specific fuel consumption decreased by an average of four percent when compared to DF500. All other CSO biodiesel blends resulted in an increase of BSFC, with a 19% increase in BSFC being observed when using B100. These results demonstrate the feasibility of using cottonseed oil biodiesel, as well as other types of biodiesel, as a fuel additive or supplement in non-road diesel engines.

REFERENCES

AEWG. 2004. 25 by 25: Agriculture's Role in Ensuring U.S. Energy Independence- A Blueprint for Action. St. John, Washington: Ag Energy Working Group. Available at: www.bio.org. Accessed May 4, 2007.

Alam, M., Song, J., Acharya, R., Boehman, A., Miller, K. 2004. Combustion and emissions performance of low sulfur, ultra low sulfur and biodiesel blends in a DI diesel engine. *SAE* 2004-01-3024.

Altiparmak, D., Deskin, A., Koca, A., Guru, M. 2007. Alternative fuel properties of tall oil fatty acid methyl ester-diesel fuel blends. *Bioresource Technology* 98:241–6.

ASAE. 1982. Vegetable Oil Fuels, In *Proc. of the International Conference on Plant and Vegetable Oils as Fuels*, August 2-4, 1982, St. Joseph, MI. ASAE.

Bechtold, R.L. 1997. *Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications.* Warrendale, PA: Society of Automotive Engineers, Inc.

Canakci, M. 2005. Performance and emissions characteristics of biodiesel from soybean oil. *Proc I MECH E Part D J Automobile Engineering.* D7:915–22.

Canakci M. and Van Gerpen, J.H. 2001. Comparison of engine performance and emissions for petroleum diesel fuel, yellow grease biodiesel, and soybean oil biodiesel. *ASAE Annual International Meeting.* Paper No. 016050.

Canakci, M. and J.H. Van Gerpen, 2003. Comparison of engine performance and emissions for petroleum diesel fuel, yellow grease, and soybean oil. *Transactions of the ASAE* 46(4):937-944.

Capareda, S. 2007. *Biodiesel and Industrial Products from Oils.* 4th Short Course. Texas A&M University. College Station, TX.

Cetinkaya M, Ulusay Y, Tekı`n Y, Karaosmanoglu F. 2005. Engine and winter road test performances of used cooking oil originated biodiesel. *Energy Conversion Management* 46:1279–91.

DieselNet. 2007. Nonroad Diesel Engines. Available at: www.dieselnet.com/standards/us/offroad.htm. Accessed 17 June 2007.

DOC. 2005. Fats and Oils: Oilseed Crushings: 2004. United States Census Bureau. Washington, D.C.: United States Department of Commerce. Available at: www.census.gov. Accessed 13 April 2006.

DOE. 2004. 2004 Biodiesel Handling and Use Guidelines. Washington, D.C.: US Department of Energy. DOE/GO-102004-1999 Revised. 2004. Available at: www.greenlineindustries.com. Accessed December 12, 2006.

Dorado, M.P. et al. 2002. The effect of a waste vegetable oil blend with diesel fuel on engine performance. *Transactions of the ASAE* 45(3):519-523.

EIA. 2006. Annual Energy Review 2005. Washington, D.C.: Energy Information Administration.

EIA. 2007. Annual Energy Review 2006. Washington, D.C.: Energy Information Administration.

EPA. 1990. The Clean Air Act of 1990. Washington, D.C.: GPO.

EPA. 2004. Control of Emissions of Air Pollution from Nonroad Diesel Engines and Fuel; Final Rule. 40 CFR Parts 9, 69, et al. Washington, D.C.: United States Environmental Protection Agency.

EPA. 2006. Standards of Performance for Stationary Compression Ignition Internal Combustion Engines; Final Rule. 40 CFR Parts 60, 85, et al. Vol. 71, No. 132. Washington, D.C.: Environmental Protection Agency.

EPA. 2007. Control of Emissions from Nonroad Spark-Ignition Enginges and Equipment; Proposed Rule. 40 CFR Parts 60, 63, et al. Vol. 72, No. 96. Washington, D.C.: Environmental Protection Agency.

Graboski, M.S. and R.L. McCormick. 1998. Combustion of fat and vegetable oil derived fuels in diesel engines. *Prog. Energy Combust. Science* 24: 125-164.

Graboski, M.S., Ross, J.D., McCormick, R.L. 1996. Transient emissions from no. 2 diesel and biodiesel blends in a DDC series 60 engine. Paper No. 961166, Warrendale, PA: SAE.

Gratton, M.R. and A.C. Hansen. 2003. Diesel engine emissions characteristics and measurement requirements of biofuels. *ASAE Annual International Meeting*. Las Vegas, Nevada, USA.

Hansen K.F. and M.G. Jensen. 1997. Chemical and biological characteristics of exhaust emissions from a DI diesel engine fuelled with rapeseed oil methyl ester (RME). Paper No. 971689, Warrendale, PA: SAE.

Jha, S.K., Fernando, S., Columbus, E., Wilcutt, H. 2006. A comparative study of exhaust emissions using diesel-biodiesel ethanol blends in new and used compression ignition engines. *ASABE Annual International Meeting* Paper No. 066138. Portland, OR.

Kass, M. D., Swartz, M. M., Lewis, S. A., Huff, S. P., Lee, D., et al. 2006. Lowering NO_x and PM Emissions in a Light-Duty Diesel Engine with Biodiesel-Water Emulsions. *ASABE Annual International Meeting* Paper No: 066137. Portland, OR.

Kean, A.J., Sawyer, R.F., Hartley, R.A. 2000. A fuel-based assessment of off-road diesel engine emissions. *J. of Air & Waste Management Association* 50:1929-1939.

Korbitz, Werner, 1995. Status and Development of Biodiesel Production and Projects in Europe and North America. SAE Paper No. 952768, Warrendale, PA: SAE.

Krahl J., et al. 2005. Fuel design as constructional element with the example of biogenic and fossil diesel fuels. *Agric Eng Int: CIGR J Sci Res Dev* VII: manuscript EE 04 008.

Lacey, S. 2007. *Texas Biodiesel Ban Delayed.* Peterborough, NH: Renewable Energy Access. Available at: www.renewableenergyaccess.com. Accessed 6 October 2007.

Lapuerta, M., Armas, O., Rodriguez-Fernandez, J. 2007. Effect of biodiesel fuels on diesel engine emissions. *Progress in Energy and Combustion Science* 10.1016.

Lapuerta, M., Rodrıguez-Fernandez, J., Agudelo, J.R. 2007. Diesel particulate emissions from used cooking oil biodiesel. *Bioresource Technology* 88:1, 47-54.

Last, R.J., Kruger, M., Durnholz, M. 1995. Emissions and performance characteristics of a 4-stroke, direct injected diesel engine fueled with blends of biodiesel and low sulfur diesel fuel. SAE Paper No. 950054, Warrendale, PA: SAE.

Lin Y.C., Lee W.J., Wu T.S., Wang, C.T. 2006. Comparison of PAH and regulated harmful matter emissions from biodiesel blends and paraffinic fuel blends on engine accumulated mileage test. *Fuel* 85:2516–23.

Monyem, A. and J.H. Van Gerpen. 2001. The effect of biodiesel oxidation on engine performance and emissions. *Biomass Energy* 20:317-325.

Morris, D. 1993. *How much energy does it take to make a gallon of soydiesel?* Washington, D.C.: The Institute for Local Self-Reliance.

Murillo, S., Mıguez, J.L., Porteiro, J., Granada, E., Moran, J.C. 2007. Performance and exhaust emissions in the use of biodiesel in outboard diesel engines. *Fuel.* 86:1765–71.

Munoz, M., Moreno, F., Morea, J. 2004. Emissions of an automobile diesel engine fueled with sunflower methyl ester. *Transactions of the ASAE* 47(1): 5-11.

NCPA. 2002. Cottonseed Oil. Cordova, TN: National Cottonseed Products Association. Avilable at: www.cottonseed.com/publications/csobro.asp. Accessed 10 June 2007.

NBB. 2006a. Biodiesel Basics. Jefferson City, MO: National Biodiesel Board. Available at: www.biodiesel.org. Accessed 9 March 2006.

NBB. 2006b. Performance. Jefferson City, MO: National Biodiesel Board. Available at: www.biodiesel.org. Accessed 12 December 2006.

Peterson, C.L., Taberski, J.S., Thompson, J.C., Chase, C.L. 2002. The effect of biodiesel feedstock on regulated emissions in chassis dynamometer tests of a pickup truck. *Transaction of the ASAE.* 43(6):1371–81.

Piazza, J. 2007. Feedstock economics: A comparison of feed stocks. *Biodiesel and Industrial Products from Oils.* 4th Short Course. Texas A&M University. College Station, TX.

Rakopoulos C.D., Hountalas, D.T., Zannis, T.C., Levendis, Y.A. 2004. Operational and environmental evaluation of diesel engines burning oxygen-enriched intake air or oxygen-enriched fuels: a review. *SAE* 2004-01-2924.

Romig, C. and A. Spataru. 1996. Emissions and engine performance from blends of soya and canola methyl esters with ARB#2 diesel in a DDC 6V92TA MUI Engine. *Bioresource Technology* 56:25–34.

SAE. 1983. *Engine Power Test Code- Spark Ignition and Compression Ignition- Gross Power Rating*. Troy, MI: Society of Automotive Engineers. SAEJ1349 Revised Jun 1983.

Schumacher, L.G., Clark, N.N., Lyons, D.W., Marshall, W. 2001. Diesel engine exhaust emissions evaluation of biodiesel blends using a Cummins L10E engine. *Transactions of the ASAE* 44(6): 1461-1464.

Schumacher, L.G., Marshall, W., Krahl, J., Wetherell, W.B., Grabowski, M.S.. 2001. Biodiesel emissions data from series 60 DC engines. *Transactions of the ASAE* 44(6): 1465-1468.

Senatore, A., Cardone, M., Rocco, V., Prati, M.V. 2000. A comparative analysis of combustion process in D.I. Diesel engine fueled with biodiesel and diesel fuel. *SAE* 2000-01-0691.

Shaheed, A, and E. Swain. 1999. Combustion analysis of coconut oil and its methyl esters in a diesel engine. *Proc I MECH E Part A J Power Energy* 213(5):417–25.

Stauffer, C. E. 1996. *Fats and Oils: Practical Guides for the Food Industry*. Eagan Handbook Series. St. Paul, MN: Eagan Press.

TCEQ. 2005. *Ozone: The Facts.* Austin, TX: Texas Commission on Environmental Quality. Available at: www.tceq.state.tx.us. Accessed March 9, 2006.

Tickell, J. 2000. From the fryer to the fuel tank: The complete guide to using vegetable oil as an alternative fuel. Ed. Kaia Roman. Tallahassee, FL: Tickell Energy Consulting.

Turrio-Baldassarri, L., Battistelli, C. L., Conti, L., Crebelli, R., De Berardis, B., et al. 2004. Emission comparison of urban bus engine fuelled with diesel oil and biodiesel blend. *Sci Total Environ* 327:147–62.

USDA. 2006. Cotton: Production by Year, US. National Agricultural Statistics Database. Washington, D.C.: USDA National Agricultural Statistics Service. Available at: www.nass.usda.gov. Accessed 13 April 2006.

Usta, N. 2005. An experimental study on performance and exhaust emissions of a diesel engine fuelled with tobacco seed oil methyl ester. *Energy Conversion Management* 46:2373–86.

Weathers, T. 1981. *Diesel Engines for Automobiles and Small Trucks*. Reston, VA: Reston Publishing Company, Inc.

Yokayo. 2003. *A History of the Diesel Engine.* Ukiah, CA: Yokayo Biofuels. Available at: www.ybiofuels.org. Accessed 12 June 2007.

Yucesu, H.S. and C. Ilkilic. 2006. Effect of cotton seed oil methyl ester on the performance and exhaust emission of a diesel engine. *Energy Sources.* Part A 28:389–98.

APPENDIX A

Procedure for Performance Testing, Concurrent with Emissions Testing

1. Start the engine and increase throttle to half throttle. Apply a load of about 8 ft-lb with the Dynamatic controller;
2. Once the engine is warm, increase the throttle to a wide-open position, and allow to run for about 2 minutes;
3. Set the dynamometer to the maximum load that allows the engine to maintain about 3150 rpm;
4. Let the measurements stabilize for at least 2 minutes;
5. Collect speed, torque, and power readings be using the "print screen" key on the computer (do this twice with about 5-10 second between readings);
6. Collect emissions data (at this point, hit "Text" on the Enerac 3000E);
7. Measure fuel flow by observing the Scope Meter hooked up to the fuel flow meter (5 observations);
8. Collect emissions data;
9. Collect speed, torque, and power readings be using the "print screen" key on the computer (do this twice with about 5-10 second between readings);
10. Measure return fuel flow with a graduated cylinder and a stopwatch by measuring the amount of time it takes to collect 50 mL of fuel from the return line;
11. Collect emissions data;
12. Collect speed, torque, and power readings be using the "print screen" key on the computer (do this twice with about 5-10 second between readings);
13. Increase the load so that the next speed interval is maintained;
14. Speed intervals measured are 3150, 3065, 2990, 2875, and 2800 rpm.

This set of tests was performed 3 times for each fuel blend, in 3 randomized blocks.

Emissions Testing Procedure, Exclusive from Performance Testing

15. Start the engine and increase throttle to half throttle. Apply a load of about 8 ft-lb with the Dynamatic controller;
16. Once the engine is warm, increase the throttle to a wide-open position, and allow to run for about 2 minutes;
17. Set the dynamometer to a load of 12 ft-lb;
18. Let the engine run for 2 minutes so that the engine can stabilize and the measurement/output time lag can pass;
19. Print screen 3 times with 5-10 seconds between each;
20. Collect emissions data (at this point, hit "Text" on the Enerac 3000E);
21. Repeat these tests for loads of 24 and 30 ft-lb.

This set of tests was performed 3 times for each fuel blend, in 3 randomized blocks.

APPENDIX B

Appendix B contains the complete set of emissions observed during tests concurrent with performance tests.

Table C-1. Carbon Monoxide Concentrations.

CO (g/kW-h)	3150	3065	2990	2885	2800
DF500	3.56	2.24	4.30	4.55	5.71
B5	3.26	2.51	5.05	6.62	6.26
B20	3.32	2.20	4.21	4.30	3.09
B40	2.95	2.31	4.02	4.21	4.59
B60	5.07	2.65	3.32	3.53	4.03
B80	3.01	2.17	3.47	3.02	3.24
B100	2.93	2.30	3.62	3.38	3.55

Table C-2. Carbon Dioxide Concentrations.

CO2 (g/kW-h)	3150	3065	2990	2885	2800
DF500	3891.71	2735.70	3297.91	3051.78	3114.91
B5	3964.30	2840.63	3273.07	3508.65	3323.61
B20	3756.42	2827.06	3198.61	2933.76	2405.87
B40	3931.47	2700.98	3092.35	3188.74	3060.11
B60	4347.64	2816.68	3064.55	2991.44	3367.57
B80	4905.74	2917.33	3350.51	3205.60	2999.37
B100	4779.25	2754.36	3230.53	3261.47	2785.38

Table C-3. Total Hydrocarbon Concentrations.

THC (g/kW-h)	3150	3065	2990	2885	2800
DF500	4.35	2.24	2.05	2.07	2.14
B5	23.24	7.07	4.13	3.97	1.39
B20	3.79	2.14	1.90	1.86	1.43
B40	4.17	2.34	2.16	2.50	2.55
B60	3.42	1.63	1.48	1.51	1.77
B80	2.33	1.46	1.48	1.73	1.71
B100	2.25	1.39	1.53	2.00	1.86

Table C-4. Nitrogen Oxide Concentrations.

NOx (g/kW-h)	3150	3065	2990	2885	2800
DF500	21.27	13.92	10.28	8.67	8.35
B5	21.22	13.29	9.16	9.05	7.83
B20	21.36	14.09	10.04	8.28	6.81
B40	22.12	13.14	9.67	9.19	8.28
B60	21.90	11.50	8.82	7.81	8.24
B80	24.96	12.01	9.58	8.66	7.58
B100	22.28	10.26	8.48	8.07	6.55

Table C-5. Sulfur Dioxide Concentrations.

SO2 (g/kW-h)	**3150**	**3065**	**2990**	**2885**	**2800**
DF500	6.85	5.05	7.25	6.70	6.82
B5	6.44	5.09	6.53	7.00	6.74
B20	4.75	3.92	5.23	4.78	3.81
B40	3.80	2.86	3.86	3.91	3.90
B60	3.62	2.40	2.91	2.90	3.31
B80	2.42	1.50	1.98	1.89	1.72
B100	1.60	0.65	0.83	0.85	0.75

APPENDIX C

COPYRIGHT NOTICE

This document is copyrighted by the American Society for Testing and Materials (ASTM), 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA. All rights reserved.

ASTM grants you a license as follows: The right to download an electronic file of this ASTM standard for temporary storage on one computer for purposes of viewing, and/or printing one copy of the ASTM standard for individual use. Neither the electronic file nor the hard copy print may be reproduced in any way. In addition the electronic file may not be redistributed elsewhere over computer networks or otherwise. The hardcopy print may only be distributed to other employees for their internal use within your organization.

ILI makes no guarantees or warranties as to the correctness of the document or as to the results arising from the purchase and use of the document and is not responsible for problems in the delivery of the document. Any difficulties or queries should be addressed to ILI below.

ILI

In USA and Canada Contact:-

ILI INFODISK INC, 610 Winters Avenue, Paramus, NJ 07652
☎ **Toll Free 1-888-454-2688 or 201-986-1131** Fax: 201-986-7886 E-mail: sales@ili-info.com
Web: www.ili-info.com

In Rest of World Contact:-

ILI, Index House, Ascot, Berks, SL5 7EU, UK
☎: +44 (0)1344 636400 Fax: +44 (0)1344 291194 E-mail: standards@ili.co.uk
Web: www.ili.co.uk

Designation: D 6751 – 07

An American National Standard

Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels[1]

This standard is issued under the fixed designation D 6751; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This specification covers biodiesel (B100) Grades S15 and S500 for use as a blend component with middle distillate fuels.

1.2 This specification, unless otherwise provided by agreement between the purchaser and the supplier, prescribes the required properties of biodiesel fuel at the time and place of delivery.

1.3 Nothing in this specification shall preclude observance of federal, state, or local regulations which may be more restrictive.

NOTE 1—The generation and dissipation of static electricity can create problems in the handling of distillate fuel oils with which biodiesel may be blended. For more information on the subject, see Guide D 4865.

1.4 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

2. Referenced Documents

2.1 *ASTM Standards:* [2]

D 93 Test Methods for Flash Point by Pensky-Martens Closed Cup Tester
D 130 Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test
D 189 Test Method for Conradson Carbon Residue of Petroleum Products
D 445 Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)
D 524 Test Method for Ramsbottom Carbon Residue of Petroleum Products
D 613 Test Method for Cetane Number of Diesel Fuel Oil
D 664 Test Method for Acid Number of Petroleum Products by Potentiometric Titration
D 874 Test Method for Sulfated Ash from Lubricating Oils and Additives
D 974 Test Method for Acid and Base Number by Color-Indicator Titration
D 975 Specification for Diesel Fuel Oils
D 976 Test Method for Calculated Cetane Index of Distillate Fuels
D 1160 Test Method for Distillation of Petroleum Products at Reduced Pressure
D 1266 Test Method for Sulfur in Petroleum Products (Lamp Method)
D 1796 Test Method for Water and Sediment in Fuel Oils by the Centrifuge Method (Laboratory Procedure)
D 2274 Test Method for Oxidation Stability of Distillate Fuel Oil (Accelerated Method)
D 2500 Test Method for Cloud Point of Petroleum Products
D 2622 Test Method for Sulfur in Petroleum Products by Wavelength Dispersive X-ray Fluorescence Spectrometry
D 2709 Test Method for Water and Sediment in Middle Distillate Fuels by Centrifuge
D 2880 Specification for Gas Turbine Fuel Oils
D 3117 Test Method for Wax Appearance Point of Distillate Fuels
D 3120 Test Method for Trace Quantities of Sulfur in Light Liquid Petroleum Hydrocarbons by Oxidative Microcoulometry
D 3242 Test Method for Acidity in Aviation Turbine Fuel
D 3828 Test Methods for Flash Point by Small Scale Closed Cup Tester
D 4057 Practice for Manual Sampling of Petroleum and Petroleum Products
D 4177 Practice for Automatic Sampling of Petroleum and Petroleum Products
D 4294 Test Method for Sulfur in Petroleum and Petroleum Products by Energy-Dispersive X-ray Fluorescence Spectrometry
D 4530 Test Method for Determination of Carbon Residue (Micro Method)
D 4737 Test Method for Calculated Cetane Index by Four Variable Equation

---

[1] This specification is under the jurisdiction of ASTM Committee D02 on Petroleum Products and Lubricants and is the direct responsibility of Subcommittee D02.E0 on Burner, Diesel, Non-Aviation Gas Turbine, and Marine Fuels.

Current edition approved Feb. 1, 2007. Published February 2007. Originally approved in 1999 as PS 121–99. Adopted as a standard in 2002 as D 6751–02. Last previous edition approved in 2006 as D 6751–06b.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard's Document Summary page on the ASTM website.

*A Summary of Changes section appears at the end of this standard.

D 4865 Guide for Generation and Dissipation of Static Electricity in Petroleum Fuel Systems

D 4951 Test Method for Determination of Additive Elements in Lubricating Oils by Inductively Coupled Plasma Atomic Emission Spectrometry

D 5453 Test Method for Determination of Total Sulfur in Light Hydrocarbons, Spark Ignition Engine Fuel, Diesel Engine Fuel, and Engine Oil by Ultraviolet Fluorescence

D 5773 Test Method for Cloud Point of Petroleum Products (Constant Cooling Rate Method)

D 6217 Test Method for Particulate Contamination in Middle Distillate Fuels by Laboratory Filtration

D 6450 Test Method for Flash Point by Continuously Closed Cup (CCCFP) Tester

D 6469 Guide for Microbial Contamination in Fuels and Fuel Systems

D 6584 Test Method for Determination of Free and Total Glycerin in B-100 Biodiesel Methyl Esters By Gas Chromatography

2.2 *Government Standard*:

40 CFR Part 79 Registration of Fuels and Fuel Additives Section 211(b) Clean Air Act[3]

2.3 *Other Documents*:[4]

UOP 389 Trace Metals in Oils by Wet Ashing and ICP-OES

UOP 391–91 Trace Metals in Petroleum Products or Organics by AAS

EN 14112 Fat and oil derivatives—Fatty acid methyl esters (FAME)—Determination of oxidation stability (Accelerated oxidation test)[5]

EN14538 Fat and oil derivatives—Fatty acid methyl esters (FAME)—Determination of Ca, K, Mg and Na content by optical emission spectral analysis with inductively coupled plasma (ICP OES)[5]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard*:

3.1.1 *biodiesel, n*—a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, designated B100.

3.1.1.1 *Discussion*—*Biodiesel*, as defined above, is registered with the U.S. EPA as a fuel and a fuel additive under Section 211(b) of the Clean Air Act. There is, however, other usage of the term biodiesel in the marketplace. Due to its EPA registration and the widespread commercial use of the term biodiesel in the U.S. marketplace, the term biodiesel will be maintained for this specification.

3.1.1.2 *Discussion*—Biodiesel is typically produced by a reaction of a vegetable oil or animal fat with an alcohol such as methanol or ethanol in the presence of a catalyst to yield mono-alkyl esters and glycerin, which is removed. The finished biodiesel derives approximately 10 % of its mass from the reacted alcohol. The alcohol used in the reaction may or may not come from renewable resources.

3.1.2 *biodiesel blend, BXX*, *n*—a blend of biodiesel fuel with petroleum-based diesel fuel.

3.1.2.1 *Discussion*—In the abbreviation BXX, the XX represents the volume percentage of biodiesel fuel in the blend.

3.1.3 *biodiesel fuel, n*—synonym for *biodiesel*.

3.1.4 *diesel fuel*, *n*—middle petroleum distillate fuel.

3.1.5 *free glycerin, n*—a measure of the amount of glycerin remaining in the fuel.

3.1.6 *Grade S15 B100, n*—a grade of biodiesel meeting ASTM Specification D 6751 and having a sulfur specification of 15 ppm maximum.

3.1.7 *Grade S500 B100, n*—a grade of biodiesel meeting ASTM Specification D 6751 and having a sulfur specification of 500 ppm maximum.

3.1.8 *middle distillate fuel*, *n*—kerosines and gas oils boiling between approximately 150°C and 400°C at normal atmospheric pressure and having a closed-cup flash point above 38°C.

3.1.9 *total glycerin*, *n*—the sum of the free glycerin and the glycerin portion of any unreacted or partially reacted oil or fat.

4. Requirements

4.1 The biodiesel specified shall be mono-alkyl esters of long chain fatty acids derived from vegetable oils and animal fats.

4.2 Unless otherwise specified, samples for analysis shall be taken by the procedure described in Practices D 4057 or D 4177.

4.3 The biodiesel specified shall conform to the detailed requirements shown in Table 1.

NOTE 2—A considerable amount of experience exists in the U.S. with a 20 % blend of biodiesel, primarily produced from soybean oil, with 80 % diesel fuel (B20). Experience with biodiesel produced from animal fat and other oils is similar. Experience with B20 and lower blends in other applications is not as prevalent. Although biodiesel (B100) can be used, blends of over 20 % biodiesel with diesel fuel (B20) should be evaluated on a case by case basis until further experience is available.

NOTE 3—The user should consult the equipment manufacturer or owner's manual regarding the suitability of using biodiesel or biodiesel blends in a particular engine or application.

5. Test Methods

5.1 The requirements enumerated in this specification shall be determined in accordance with the following methods.

5.1.1 *Flash Point*—Test Methods D 93, except where other methods are prescribed by law. Test Methods D 3828 or D 6450 can also be used. The precision and bias of Test Methods D 3828 and D 6450 with biodiesel is not known and is currently under investigation. Test Methods D 93 shall be the referee method.

5.1.2 *Water and Sediment*—Test Method D 2709. Test Method D 1796 may also be used. Test Method D 2709 shall be the referee method. The precision and bias of these test methods with biodiesel is not known and is currently under investigation.

5.1.3 *Viscosity*—Test Method D 445.

5.1.4 *Sulfated Ash*—Test Method D 874.

5.1.5 *Oxidation Stability*—Test Method EN 14112.

---

[3] Available from Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

[4] Available from ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA. Visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org.

[5] This European Standard is available from the National CEN Members listed on the CEN website (www.cenorm.be) or via the liaised CEN/TC19 secretariat.

TABLE 1 Detailed Requirements for Biodiesel (B100) (All Sulfur Levels)

Property	Test Method[A]	Grade S15 Limits	Grade S500 Limits	Units
Calcium and Magnesium, combined	EN 14538	5 max	5 max	ppm (μg/g)
Flash point (closed cup)	D 93	130.0 min	130.0 min	°C
Water and sediment	D 2709	0.050 max	0.050 max	% volume
Kinematic viscosity, 40°C	D 445	1.9–6.0[B]	1.9–6.0[B]	mm^2/s
Sulfated ash	D 874	0.020 max	0.020 max	% mass
Sulfur[C]	D 5453	0.0015 max (15)	0.05 max (500)	% mass (ppm)
Copper strip corrosion	D 130	No. 3 max	No. 3 max	
Cetane number	D 613	47 min	47 min	
Cloud point	D 2500	Report[D]	Report[D]	°C
Carbon residue[E]	D 4530	0.050 max	0.050 max	% mass
Acid number	D 664	0.50 max	0.50 max	mg KOH/g
Free glycerin	D 6584	0.020	0.020	% mass
Total glycerin	D 6584	0.240	0.240	% mass
Phosphorus content	D 4951	0.001 max	0.001 max	% mass
Distillation temperature, Atmospheric equivalent temperature, 90 % recovered	D 1160	360 max	360 max	°C
Sodium and Potassium, combined	EN 14538	5 max	5 max	ppm (μg/g)
Oxidation Stability	EN 14112	3 minimum	3 minimum	hours

[A] The test methods indicated are the approved referee methods. Other acceptable methods are indicated in 5.1.

[B] See X1.3.1. The 6.0 mm^2/s upper viscosity limit is higher than petroleum based diesel fuel and should be taken into consideration when blending.

[C] Other sulfur limits can apply in selected areas in the United States and in other countries.

[D] The cloud point of biodiesel is generally higher than petroleum based diesel fuel and should be taken into consideration when blending.

[E] Carbon residue shall be run on the 100 % sample (see 5.1.11).

5.1.6 *Sulfur*—Test Method D 5453. Other test methods may also be suitable for determining up to 0.05 % sulfur in biodiesel fuels such as Test Methods D 1266, D 2622, D 3120 and D 4294 but may provide falsely high results (see X1.5) although their precision and bias with biodiesel is unknown. Test Method D 5453 shall be the referee test method.

5.1.7 *Corrosion*—Test Method D 130, 3 h test at 50°C.

5.1.8 *Cetane Number*—Test Method D 613.

5.1.9 *Cloud Point*—Test Method D 2500. Test Method D 5773 may also be used. Test Method D 3117 may also be used because it is closely related. Test Method D 2500 shall be the referee test method. The precision and bias of Test Method D 3117 for biodiesel is not known and is currently under investigation.

5.1.10 *Acid Number*—Test Method D 664. Test Methods D 3242 or D 974 may also be used. Test Method D 664 shall be the referee test method.

5.1.11 *Carbon Residue*—Test Method D 4530. A 100 % sample shall replace the 10 % residual, with percent residue in the original sample reported using the 10 % residual calculation (see X1.9.1). Test Methods D 189 or D 524 may also be used. Test Method D 4530 shall be the referee method.

5.1.12 *Total Glycerin*—Test Method D 6584.

5.1.13 *Free Glycerin*—Test Method D 6584.

5.1.14 *Phosphorus Content*—Test Method D 4951.

5.1.15 *Distillation Temperature, Reduced Pressure*—Test Method D 1160.

5.1.16 *Calcium and Magnesium, combined*—Test Method EN 14538. Test Method UOP 389 may also be used. Test Method EN 14538 shall be the referee test method.

5.1.17 *Sodium and Potassium, combined*—Test Method EN 14538. Test Method UOP 391 may also be used. Test Method EN 14538 shall be the referee test method.

6. Workmanship

6.1 The biodiesel fuel shall be visually free of undissolved water, sediment, and suspended matter.

7. Keywords

7.1 alternative fuel; biodiesel fuel; diesel fuel oil; fuel oil; renewable resource

APPENDIXES

(Nonmandatory Information)

X1. SIGNIFICANCE OF PROPERTIES SPECIFIED FOR BIODIESEL FUEL

X1.1 Introduction

X1.1.1 The properties of commercial biodiesel fuel depends upon the refining practices employed and the nature of the renewable lipids from which it is produced. Biodiesel, for example, can be produced from a variety of vegetable oils or animal fats which produce similar volatility characteristics and combustion emissions with varying cold flow properties.

X1.1.2 The significance of the properties in this appendix are based primarily on the commercial use of biodiesel in on-road and off-road diesel engine applications. Some of the properties may take on other significance if biodiesel is used as a fuel or blending component in other applications. See the respective finished product specifications for additional information on significance of properties of those applications.

X1.2 Flash Point

X1.2.1 The flash point for biodiesel is used as the mechanism to limit the level of unreacted alcohol remaining in the finished fuel.

X1.2.2 The flash point is also of importance in connection with legal requirements and safety precautions involved in fuel handling and storage, and is normally specified to meet insurance and fire regulations.

X1.2.3 The flash point specification for biodiesel is intended to be 100°C minimum. Typical values are over 160°C. Due to high variability with Test Method D 93 as the flash point approaches 100°C, the flash point specification has been set at 130°C minimum to ensure an actual value of 100°C minimum. Improvements and alternatives to Test Method D 93 are being investigated. Once complete, the specification of 100°C minimum may be reevaluated.

X1.3 Viscosity

X1.3.1 For some engines it may be advantageous to specify a minimum viscosity because of power loss due to injection pump and injector leakage. Maximum allowable viscosity, on the other hand, is limited by considerations involved in engine design and size, and the characteristics of the injection system. The upper limit for the viscosity of biodiesel (6.0 mm^2/s at 40°C) is higher than the maximum allowable viscosity in Specification D 975 Grade 2-D and 2-D low sulfur (4.1 mm/s at 40°C). Blending biodiesel with diesel fuel close to its upper limit could result in a biodiesel blend with viscosity above the upper limits contained in Specification D 975.

X1.4 Sulfated Ash

X1.4.1 Ash-forming materials may be present in biodiesel in three forms: (*1*) abrasive solids, (*2*) soluble metallic soaps, and (*3*) unremoved catalysts. Abrasive solids and unremoved catalysts can contribute to injector, fuel pump, piston and ring wear, and also to engine deposits. Soluble metallic soaps have little effect on wear but may contribute to filter plugging and engine deposits.

X1.5 Sulfur

X1.5.1 The effect of sulfur content on engine wear and deposits appears to vary considerably in importance and depends largely on operating conditions. Fuel sulfur can also affect emissions control systems performance and various limits on sulfur have been imposed for environmental reasons. B100 is essentially sulfur-free.

NOTE X1.1—Test Method D 5453 should be used with biodiesel. Use of other test methods may provide falsely high results when analyzing B100 with extremely low sulfur levels (less than 5 ppm). Biodiesel sulfur analysis from RR: D02-1480[4], *Biodiesel Fuel Cetane Number Testing Program, January-April, 1999*, using Test Method D 2622 yielded falsely high results due to the presence of the oxygen in the biodiesel. Sulfur results using Test Method D 2622 were more accurate with B20 than with B100 due to the lower oxygen content of B20. Potential improvements to Test Method D 2622 may provide more accurate values in the future.

X1.6 Copper Strip Corrosion

X1.6.1 This test serves as a measure of possible difficulties with copper and brass or bronze parts of the fuel system. The presence of acids or sulfur-containing compounds can tarnish the copper strip, thus indicating the possibility for corrosion.

X1.7 Cetane Number

X1.7.1 Cetane number is a measure of the ignition quality of the fuel and influences white smoke and combustion roughness. The cetane number requirements depend on engine design, size, nature of speed and load variations, and on starting and atmospheric conditions.

X1.7.2 The calculated cetane index, Test Methods D 976 or D 4737, may not be used to approximate the cetane number with biodiesel or its blends. There is no substantiating data to support the calculation of cetane index with biodiesel or biodiesel blends.

X1.8 Cloud Point

X1.8.1 Cloud point is of importance in that it defines the temperature at which a cloud or haze of crystals appears in the fuel under prescribed test conditions which generally relates to the temperature at which crystals begin to precipitate from the fuel in use. Biodiesel generally has a higher cloud point than petroleum based diesel fuel. The cloud point of biodiesel and its impact on the cold flow properties of the resulting blend should be monitored by the user to ensure trouble-free operation in cold climates. For further information, consult Appendix X4 of Specification D 975.

X1.9 Carbon Residue

X1.9.1 Carbon residue gives a measure of the carbon depositing tendencies of a fuel oil. While not directly correlating with engine deposits, this property is considered an

---

[4] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR: D02–1480.

approximation. Although biodiesel is in the distillate boiling range, most biodiesels boil at approximately the same temperature and it is difficult to leave a 10 % residual upon distillation. Thus, a 100 % sample is used to replace the 10 % residual sample, with the calculation executed as if it were the 10 % residual. Parameter E (final weight flask charge/original weight flask charge) in 8.1.2 of Test Method D 4530-93 is a constant 20/200.

X1.10 Acid Number

X1.10.1 The acid number is used to determine the level of free fatty acids or processing acids that may be present in biodiesel. Biodiesel with a high acid number has been shown to increase fueling system deposits and may increase the likelihood for corrosion.

NOTE X1.2—Acid number measures a different phenomenon for biodiesel than petroleum based diesel fuel. The acid number for biodiesel measures free fatty acids or degradation by-products not found in petroleum based diesel fuel. Increased recycle temperatures in new fuel system designs may accelerate fuel degradation which could result in high acid values and increased filter plugging potential.

X1.11 Free Glycerin

X1.11.1 The free glycerin method is used to determine the level of glycerin in the fuel. High levels of free glycerin can cause injector deposits, as well as clogged fueling systems, and result in a buildup of free glycerin in the bottom of storage and fueling systems.

X1.12 Total Glycerin

X1.12.1 The total glycerin method is used to determine the level of glycerin in the fuel and includes the free glycerin and the glycerine portion of any unreacted or partially reacted oil or fat. Low levels of total glycerin ensure that high conversion of the oil or fat into its mono-alkyl esters has taken place. High levels of mono-, di-, and triglycerides can cause injector deposits and may adversely affect cold weather operation and filter plugging.

X1.13 Phosphorus Content

X1.13.1 Phosphorus can damage catalytic converters used in emissions control systems and its level must be kept low. Catalytic converters are becoming more common on diesel-powered equipment as emissions standards are tightened, so low phosphorus levels will be of increasing importance. Biodiesel produced from U.S. sources has been shown to have low phosphorus content (below 1 ppm) and the specification value of 10 ppm maximum is not problematic. Biodiesel from other sources may or may not contain higher levels of phosphorus and this specification was added to ensure that all biodiesel, regardless of the source, has low phosphorus content.

X1.14 Reduced Pressure Distillation

X1.14.1 Biodiesel exhibits a boiling point rather than a distillation curve. The fatty acids chains in the raw oils and fats from which biodiesel is produced are mainly comprised of straight chain hydrocarbons with 16 to 18 carbons that have similar boiling temperatures. The atmospheric boiling point of biodiesel generally ranges from 330 to 357°C, thus the specification value of 360°C is not problematic. This specification was incorporated as an added precaution to ensure the fuel has not been adulterated with high boiling contaminants.

NOTE X1.3—The density of biodiesel meeting the specifications in Table 1 falls between 0.86 and 0.90, with typical values falling between 0.88 and 0.89. Since biodiesel density falls between 0.86 and 0.90, a separate specification is not needed. The density of raw oils and fats is similar to biodiesel, therefore use of density as an expedient check of fuel quality may not be as useful for biodiesel as it is for petroleum based diesel fuel. This section has been added to provide users and engine interests with this information.

NOTE X1.4—In certain items of fuel injection equipment in compression ignition engines, such as rotary/distributor fuel pumps and injectors, the fuel functions as a lubricant as well as a source for combustion. Blending biodiesel fuel with petroleum based compression-ignition fuel typically improves fuel lubricity.

X1.15 Calcium and Magnesium

X1.15.1 Calcium and magnesium may be present in biodiesel as abrasive solids or soluble metallic soaps. Abrasive solids can contribute to injector, fuel pump, piston, and ring wear, as well as to engine deposits. Soluble metallic soaps have little effect on wear, but they may contribute to filter plugging and engine deposits. High levels of calcium and magnesium compounds may also be collected in exhaust particulate removal devices, are not typically removed during passive or active regeneration, and can create increased back pressure and reduced time to service maintenance.

X1.16 Sodium and Potassium

X1.16.1 Sodium and potassium may be present in biodiesel as abrasive solids or soluble metallic soaps. Abrasive solids can contribute to injector, fuel pump, piston and ring wear, and also to engine deposits. Soluble metallic soaps have little effect on wear, but they may contribute to filter plugging and engine deposits. High levels of sodium or potassium compounds may also be collected in exhaust particulate removal devices, are not typically removed during passive or active regeneration, and they can create increased back pressure and reduced period to service maintenance.

X1.17 Oxidation Stability

X1.17.1 Products of oxidation in biodiesel can take the form of various acids or polymers, which, if in high enough concentration, can cause fuel system deposits and lead to filter clogging and fuel system malfunctions. Additives designed to retard the formation of acids and polymers can significantly improve the oxidation stability performance of biodiesel. See Appendix X2 for additional information on long-term storage.

X2. LONG-TERM STORAGE OF BIODIESEL

X2.1 *Scope*

X2.1.1 This appendix provides guidance for consumers of biodiesel (B100) who may wish to store quantities of fuels for extended periods. Consistently successful long-term fuel storage requires attention to fuel selection, storage conditions, and monitoring of properties prior to and during storage. This appendix is directed toward biodiesel (B100) and may be more or less applicable to blends of biodiesel with petroleum based diesel fuel.

X2.1.2 Normally produced biodiesel has adequate stability properties to withstand normal storage without the formation of troublesome amounts of insoluble degradation products, although data suggests some biodiesel may degrade faster than petroleum based diesel fuel. Biodiesel that is to be stored for prolonged periods should be selected to avoid formation of sediments, high acid numbers, and high viscosities that can clog filters, affect fuel pump operation or plug combustor nozzles or injectors. The selection of biodiesel should result from supplier-user discussions.

X2.1.3 These suggested practices are general in nature and should not be considered substitutes for any requirement imposed by the warranty of the distillate fuel equipment manufacturers or by federal, state, or local government regulations. Although they cannot replace knowledge of local conditions or good engineering and scientific judgment, these suggested practices do provide guidance in developing an individual fuel management system for the biodiesel fuel user. They include suggestions in the operation and maintenance of existing fuel storage and handling facilities and for identifying where, when, and how fuel quality should be monitored.

X2.2 Terminology

X2.2.1 *bulk fuel*—fuel in the storage facility in quantities over 50 gallons.

X2.2.2 *combustor fuel*—fuel entering the combustion zone of the burner or engine after filtration or other treatment of bulk fuel.

X2.2.3 *fuel contaminants*—foreign materials that make fuel less suitable or unsuitable for the intended use. Fuel contaminants include materials introduced subsequent to the manufacture of fuel and fuel degradation products.

X2.2.4 *fuel-degradation products*—those materials formed in fuel after it is produced. Insoluble degradation products may combine with other fuel contaminants to reinforce deleterious effects. Soluble degradation products (acids and gums) may be more or less volatile than the fuel and may cause an increase in injector and nozzle deposits. The formation of degradation products may be catalyzed by contact with metals, especially those containing copper and, to a lesser extent, iron.

X2.2.5 *long-term storage*—storage of fuel for longer than 6 months after it is received by the user.

X2.3 Fuel Selection

X2.3.1 The stability properties of biodiesel are not fully understood and appear to depend on the vegetable oil and animal fat sources, severity of processing, and whether additional production plant treatment has been carried out or stability additives are present.

X2.3.2 The composition and stability properties of biodiesel produced at specific production plants may be different. Any special requirements of the user, such as long-term storage, should be discussed with the supplier.

X2.4 Fuel Additives

X2.4.1 Available fuel additives appear to improve the long term storage of biodiesel. Most additives should be added as close to the production site as possible to obtain maximum benefits.

X2.4.2 Biocides or biostats destroy or inhibit the growth of fungi and bacteria which can grow at fuel-water interfaces to give high particulate concentrations in the fuel. Available biocides are soluble in the fuel phase or the water phase, or both. Refer to Guide D 6469 for a more complete discussion.

X2.5 Tests for Fuel Quality

X2.5.1 Test methods for estimating the storage stability of biodiesel (B100) are being developed. Modifications of Test Method D 2274 to use glass fiber filters, varying times and temperatures, and the measurement of pre-test and post-test acid number and viscosity appear promising. However, correlation of this test with actual storage stability is unknown, and may depend upon field conditions and fuel composition.

X2.5.2 Performance criteria for accelerated stability tests that ensure satisfactory long-term storage of biodiesel (B100) have not been established.

X2.6 Fuel Monitoring

X2.6.1 A plan for monitoring the quality of bulk fuel during prolonged storage is an integral part of a successful monitoring program. A plan to replace aged fuel with fresh product at established intervals is also desirable.

X2.6.2 Stored fuel should be periodically sampled and its quality assessed. Practice D 4057 provides guidance for sampling. Fuel contaminants and degradation products may settle to the bottom of a quiescent tank although detrimental changes to biodiesel can occur (rising acid value) without causing sediment formation. A *Bottom* or *Clearance* sample, as defined in Practice D 4057, should be included in the evaluation along with an *All Level* sample.

X2.6.3 The quantity of insoluble fuel contaminants present in biodiesel can be determined using Test Method D 6217 with glass fiber filters and abundant washing although no precision or bias testing has been performed with biodiesel using Test Method D 6217.

X2.6.4 The acid value of biodiesel appears to exceed its specified maximum before other deleterious fuel property changes occur. A conscientious program of measuring the acid value of biodiesel may be sufficient for monitoring biodiesel stability.

X2.7 Fuel Storage Conditions

X2.7.1 Contamination levels in fuel can be reduced by storage in tanks kept free of water, and tankage should have provisions for water draining on a scheduled basis. Water promotes corrosion, and microbiological growth may occur at a fuel-water interface. Refer to Guide D 6469 for a more complete discussion. Underground or isothermal storage is preferred to avoid temperature extremes; above-ground storage tanks should be sheltered or painted with reflective paint. High storage temperatures accelerate fuel degradation. Fixed roof tanks should be kept full to limit oxygen supply and tank breathing. The use of airtight sealed containers, such as drums or totes, can enhance the storage life of biodiesel.

X2.7.2 Copper and copper-containing alloys should be avoided with biodiesel due to increased sediment and deposit formation. Contact with lead, tin, and zinc can also cause increased sediment levels that can rapidly plug filters and should be avoided.

X2.7.3 Appendix X3 of Specification D 2880 discusses fuel contaminants as a general topic. The discussion in Specification D 2880 pertains to gas turbine combustion which may or may not be applicable to diesel engine combustion.

SUMMARY OF CHANGES

Subcommittee D02.E0 has identified the location of selected changes to this standard since the last issue (D 6751–06b) that may impact the use of this standard. (Approved Feb. 1, 2007.)

(*1*) Removed the open end agreement in Footnote A of Table 1.
(2) Included Test Method D 5773 as an alternative to Test Method D 2500.
(3) Removed references to blending with Specification D 975 and made Specification D 6751 a generic blend stock specification.
(*4*) Added a sentence to Note 2.
(*5*) Added X1.1.2.

Subcommittee D02.E0 has identified the location of selected changes to this standard since the last issue (D 6751–06a) that may impact the use of this standard. (Approved Dec. 1, 2006.)

(*1*) Added Test Method EN 14112 to the Referenced Documents, Table 1, and 5.1.5.
(2) Added X1.17.
(3) Added Test Method EN 14538 to the Referenced Documents and Table 1.
(*4*) Added 5.1.16.
(*5*) Added 5.1.17.

Subcommittee D02.E0 has identified the location of selected changes to this standard since the last issue (D 6751–06$^{\epsilon1}$) that may impact the use of this standard. (Approved Aug. 1, 2006.)

(*1*) Revised the Scope.
(2) Added UOP 389 to the Referenced Documents.
(3) Added calcium and magnesium information to Table 1 and X1.15.

Subcommittee D02.E0 has identified the location of selected changes to this standard since the last issue (D 6751–03a) that may impact the use of this standard. (Approved May 3, 2006.)

(*1*) Revised acid value in Table 1 from 0.80 to 0.50 maximum mg KOH/g.
(2) Total combined sodium plus potassium content of 5 ppm maximum was added to Table 1.
(3) Added X1.16.
(4) Added UOP 391 to Table 1 and Section 2.

VITA

Name:	Jacob Joseph Powell
Address:	14865 Watson Road # 1 Von Ormy, TX 78073
Email Address:	JPowell@pape-dawson.com
Education:	B.S., Agricultural Engineering, Texas A&M University, 2005
Employment:	Engineer I Pape-Dawson Engineers, Inc. San Antonio, TX