Research Needs Resulting from Experiences of Fueling of Diesel Engines With Biodiesel

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ABSTRACT

Several universities, government, and private sector research laboratories have actively investigated the use of biodiesel as a fuel for diesel engines during the last decade. The engines have ranged from single cylinder research engines to modern real-world engines. For example, the University of Missouri and University of Idaho have monitored the fueling of four Dodge pickups equipped with the 5.9L Cummins engine and two Ford pickups equipped with the 7.3L Navistar engine. The University of Illinois, Iowa State University, and the Colorado School of Mines have also researched the effects of biodiesel and mixtures of biodiesel and low sulfur petroleum diesel fuel. Both indirect injected (IDI) and direct injected (DI) diesel engines have been fueled with blends that ranged from zero to 100% biodiesel. The experience derived from operating these engines over a wide variety of conditions has generated a number of research issues that must be addressed before biodiesel can be successfully commercialized.

Keywords: diesel engines, diesel fuel, methyl esters, diesel.

INTRODUCTION

Since the 1970s, biodiesel fueled engines have been monitored by researchers under both real-world operating conditions and under controlled conditions in the laboratory. The time that each vehicle has been monitored has ranged from one week to 14 years. Some of the engines were operated as little as 10 hours on a given blend while other engines have logged more than 5000 hours.

Biodiesel, as used in this paper, refers to the alkyl monoester of vegetable oils or animal fats. It is produced by reacting the oil or fat with an alcohol. Most of the research described in the paper refers to biodiesel produced from soybean oil and methanol, also known as *methyl soyate.*

Nearly all research since the mid eighties has focused on blends of biodiesel and low sulfur petroleum diesel fuel that have ranged from 10 to 50 percent biodiesel. Engine operating expenses such as fuel consumption and maintenance costs have been recorded for several of the engines. Some of the diesel engines operating under real-world conditions were power tested while fueled with these blends. In some instances, Environmental Protection Agency (EPA) regulated emissions were recorded using exhaust analyzers and opacity meters.

A number of issues concerning material compatibility and fuel quality remain unresolved. The objective of this paper is to identify these issues to start the process of resolving them.

PURPOSE AND OBJECTIVES

The purpose of this paper will be to review the real world data collected during the years 1991 - 1995 concerning the fueling of diesel powered vehicles with 100% biodiesel and blends of biodiesel with diesel fuel. The scope of the paper is primarily focused on projects when these fuels were used in vehicles that were operated under real-world, non-laboratory conditions. Although conducted under controlled laboratory conditions, the results of two 1000 hour durability tests will also be discussed.

Specifically this paper is designed to:

1. Present an overview of biodiesel fuel research that has been conducted since 1991.

2. Identify the recurring issues arising from this research that must be resolved before biodiesel can be commercialized on a large scale.

BACKGROUND

Each of the in-use projects will be described and the major problems that were encountered will be discussed. Experiences will be drawn from data reported by the University of Idaho, Fosseen Manufacturing and

Urban Bus Data Collection

A total of ten buses have been monitored at Bi-State Development Agency in St. Louis, Missouri since April 14, 1994 (Schumacher, et. al., 1994c). All of the buses are powered by 1988 6V92TA Detroit Diesel engines. Five of the buses have been fueled with a 20% blend of biodiesel in 80% # 2 diesel fuel, and five of the buses are controls fueled with # 2 diesel fuel. Approximately 88,000 miles have been logged on each bus while fueling with a 20% biodiesel blend. The accumulation of wear metals in the engine lubricating oil, engine fuel system material compatibility, and engine durability have been monitored. Data related to fuel consumption, power, and exhaust emissions have been monitored and recorded (Schumacher, et. al, 1995c) (Schumacher & Madzura, 1996). New diesel fuel injectors were installed in each engine at the start of the project.

Some fuel filter plugging was noted during the first weeks of fueling. Midway through the project, one injector was removed from each of the biodiesel buses and sent to Diesel Technology Company (DTC) for analysis. DTC noted that cavitation had occurred on two of the five injectors that were analyzed. The biodiesel buses have experienced a higher level of cooling system maintenance than the diesel control buses. Radiators were removed, rodded, and/or replaced for nearly all of the biodiesel fueled buses. Large variations in fuel economy were noted in the project but these were attributed to fuel blending problems.

5.9L Cummins Engines in Dodge Pickups at the University of Missouri

Starting in 1991, a 1991- 5.9L 6B Cummins engine and in 1992, a 1992- 5.9L 6B Cummins engine have been fueled with 100% neat biodiesel (Schumacher, et al., 1995a,d). The accumulation of wear metals has been noted in the engine lubricating oil, and the engine fuel system material compatibility, fuel economy, power, emissions, and engine durability have been monitored.

Nitrile rubber fuel lines were replaced on the 1991 Dodge because they had deteriorated due to the solvent characteristics of the biodiesel. This was not necessary for the 1992 pickup as Dodge began using an elastomer that was resistant to biodiesel. At approximately 50,000 miles (1991-55,000 miles, 1992- 47,000 miles) a 30% power loss was noted during power testing. The fuel transfer pumps were subsequently replaced. Upon inspection, the diaphragm of each fuel transfer pump had deteriorated. This prevented the fuel transfer pump from delivering a full charge of fuel to the engine. After replacing the pumps, the pickups were retested for power, but were unable to match the performance of earlier power tests. The Bosch VE pump was removed from each pickup and examined by Capitol Diesel, a diesel injection pump repair facility located near Jefferson City, Missouri. They found that the aneroid sensor of each injection pump had failed. The technician found a brown gelatin-like material in the aneroid sensor of each injection pump. The Bosch diesel fuel injectors of both engines were analyzed after approximately 50,000 miles of fueling by Bosch GmbH. Their report stated that no problems were noted and that Bosch approved of the use of 100% biodiesel in their fuel system. Approximately 100,000 miles had been logged on the 1992 pickup when the test was terminated on May 17, 1996. The engine was disassembled and examined by a team of Cummins Engine Company experts during the first week of June 1996. The draft report by Cummins indicated that the engine was wearing at a normal rate.

Fueling a Diesel Locomotive with a Biodiesel Blend

A 1945 GM diesel electric locomotive in St. Joseph, Missouri was fueled with a 20% blend of biodiesel in 80% # 2 diesel fuel for approximately six months. Opacity readings were recorded while the locomotive was moving grain cars for the Bartlett Grain Company.

The engine experienced starting difficulties during cold weather and slightly higher opacity readings were noted when fueling with the biodiesel blend. A light gray colored exhaust smoke was noted when the engine accelerated. No differences were noted by the operators concerning fuel economy, engine oil consumption, engine oil dilution or material compatibility.

5.9L and 7.3L Navistar Engines in Para-transit Vehicles and Refuse Trucks

The city of Columbia, Missouri fueled one 5.9L Navistar and one 7.3L Navistar diesel engine using a 20% blend of biodiesel and # 2 diesel fuel (Schumacher, et. al., 1995b). The Para-transit van (7.3L) logged 10,000 miles while the refuse truck (5.9L) logged 5,000 miles. Data related to fuel consumption, power, and exhaust emissions were monitored and recorded. Some fuel filter plugging was experienced although the engines were fueled during warm weather. The biodiesel powered vehicles occasionally produced a gray-white smoke when fueled with biodiesel and one of the operators complained that the biodiesel fueled engines did not idle smoothly. Fuel economy dropped significantly (>10%) when compared to the buses fueled with # 2 diesel fuel. The maintenance costs were essentially the same as the diesel control vehicle. Researchers tested the power and opacity of the engines before fueling with biodiesel. After six months of biodiesel fueling on a 20% blend, the engine exhaust opacity improved when the 5.9L engine fueled was tested on # 2 diesel fuel.

Fueling Farm Tractors with Biodiesel Blends

Quantitative data related to fuel consumption, power, and exhaust emissions were monitored and recorded while fueling Case-International 5120, 5130, & 5250 and Ford 4600 & 7740 tractors with blends ranging from 0 to 100% biodiesel.

Material compatibility problems were noted when fueling with an experimental biodiesel fueling station. The 100% biodiesel dissolved the rubber fill hose after one month of use so that fuel leaked from the hose when refueling.

John Deere tractors, models 6300, 7200, 7800 ran hotter when fueled with biodiesel (Schumacher, et al., 1994a). The tractors were tested for power while changing between blends of 0, 10, 20, 30, 40, 50, and 100% biodiesel / # 2 diesel fuel. Testing occurred on the same day, under similar temperature and humidity conditions, and within minutes of the previous test. When each engine fueled with 100% diesel fuel, the viscous fan that is designed to engage when cooling needs are the greatest, seldom engaged. The viscous fan almost always engaged when fueled with a biodiesel blend. The power that each engine was able to produce declined as the concentration of biodiesel increased. However, the decline in power seldom exceeded 1-3% except when the engine was converted to 100% biodiesel.

1000 Hour Durability testing

Two 1000 hour durability tests have been conducted by ORTECH International (Mississauga, Ontario, Canada) for the National Biodiesel Board (ORTECH, 1995 and Fosseen, 1995b). Both two-stroke (6V92-TA Detroit Diesel) and four-stroke (N14 Cummins) diesel engines were tested for power and long term durability. In both situations, the OEM selected the durability cycle that would be used when fueling the engine. Power and emissions were documented prior to initiating each 1000 hour durability test. The emissions produced by the engines paralleled data previously reported in the literature: NOx increased while CO, HC, and PM declined. Injector cavitation problems were noted for the 6V92-TA at the end of the 1000 hour test. No injector problems were noted for the N14. Both engines experienced a loss in power during the testing. The power loss noted for the 6V92-TA was attributed to injector cavitation. The power loss for the N14 was the result of fuel filter plugging and the formation of a varnish-like residue in the fuel system. This varnish-like residue reduced the ability of the PT injection pump system to deliver a full charge of fuel to the engine.

Tractor and Pickup testing at the University of Idaho

The Mitsubishi Satoh Tractor operated the first 650 hours on a fuel blend of 50% rapeseed methyl ester (RME) and 50% D2 fuel (Peterson, 1996). Rubber fuel lines were replaced with "viton" fuel lines. No other changes were needed to convert the tractor to be fueled with methyl ester. Routine maintenance has included collecting engine oil analysis samples and changing of the oil and filters for oil, fuel, and air every 100 hours. No problems attributable to the fuel have been noted. Specifically, no fuel filter plugging or power loss was noted when fueling with methyl esters.

A John Deere 3150 tractor was broken in for 50 hours with 100% D2. Fueling with a 50% blend of rapeseed methylester began at the 50-hour mark. Rubber fuel lines were changed for "viton" fuel lines. Routine maintenance included engine oil analysis of the lubricating oil and replacement of fuel, air and oil filters every 100 hours. No detectable power loss has been observed. Smoke emissions (opacity) appear reduced when performing heavy tillage loads.

The University of Idaho has monitored three 5.9L 6B Cummins powered diesel pickups that are powered with 100% rapeseed methyl ester (RME), 100% rapeseed ethyl ester (REE), and a 20% RME blend in # 2 diesel fuel. The Cummins engines were unmodified, but the rubber fuel lines were replaced with viton lines.

Rust was noted in the fuel system of the 1992 Dodge pickup that was fueled with 20 percent RME. Rust accumulated in the mild steel RME tank and the mild steel small mixing chamber. This vehicle also experienced the need for frequent fuel filter replacements. The mild steel tanks were changed to stainless steel and a different fuel supplier selected. These two changes have almost eliminated the excessive filter plugging. The fuel injectors were cleaned at 79,340 km (49,300 miles) due to rust. Otherwise, the vehicle has been driven normally; engine oil analysis did not indicate any abnormal engine problems.

A 1994 Dodge pickup has been driven under normal highway driving conditions. No engine modifications have been made to this engine except that the rubber fuel lines of this pickup were replaced. Engine dynamometer tests and oil analysis do not indicate any unusual problems.

A 1995 Dodge pickup has been operated by National Park Service personnel at Yellowstone National Park. The vehicle has been operated year round as a service vehicle during extremely cold weather. It has experienced slightly more fuel dilution of the lubricating oil than has the other RME fueled pickups. This may be due to the extended idling time during cold weather operation. A fuel line failed, but the engine has generally performed in a normal manner.

Mercedes-Benz - Novamount Experience

In 1992, Mercedes-Benz conducted a fleet test with 20 Taxis that were fueled with RME (Schaefer, 1988 and 1993). The fleet was monitored for a total of 1.8 million kilometers of operation. After approximately 30,000 km of RME fueling, the engine exhaust emissions exceeded what was typical for a diesel engine. It was discovered that the glycerine levels of the biodiesel did not meet European standards. The test was replicated approximately one year later with biodiesel that met European standards. The emissions did not deteriorate as was noted when fueling with the biodiesel did not meet specifications.

Boone, Iowa Biodiesel Demonstration Project

The Iowa Department of Transportation (IDOT) Maintenance Facility in Boone, Iowa operated its vehicle fleet on a 20% blend of biodiesel in 80% diesel fuel for 12 months during 1995 (Fosseen, 1996). Both # 1 and # 2 diesel fuels were used for blending depending on the time of the year. The fleet included nine snow removal trucks, four tractors, a motor grader and a wheel loader. During the one year demonstration, the entire fleet consumed 15,650 gallons of biodiesel.

The IDOT had problems with fuel gelling, loss of power, poor fuel economy, material compatibility, and higher particulate emissions. In anticipation of fuel gelling problems, in-tank fuel heaters were installed on most of the equipment and a pour-point depressant was added to the fuel. The single instance of fuel gelling occurred on a truck that only had an in-line fuel heater, not an in-tank heater. The loss of power complaints were associated with blends of # 1 diesel fuel and biodiesel. No loss of power complaints were observed when the biodiesel was blended with # 2 diesel fuel. The nine snow removal trucks experienced a 7% reduction in fuel economy when compared to the previous year when they had been fueled with diesel fuel. The IDOT experienced problems with gasket deterioration in two places: one was for the fuel tank heater and the other was a spacer gasket associated with the fuel tank mount. The spacer had come into contact with biodiesel due to spills and overfills. The particulate emissions from the vehicles were observed to be particularly high during start-up when using the biodiesel blend. The equipment operator complained that soot was accumulating on the equipment and could actually be swept off the floor. The IDOT concluded that in spite of the problems they observed, there did not seem to be any major operational problem with using biodiesel. They have since discontinued the project due to the high cost of the biodiesel.

Waterloo, Iowa Biodiesel Demonstration Project

A biodiesel demonstration project was conducted with the Metropolitan Transit Authority (MET) of Blackhawk County in Waterloo, Iowa (Fosseen, 1995a). A 20% blend of biodiesel was used in a variety of city buses which accumulated more than 230,800 miles during a five month period. More than 10,819 gallons of biodiesel were consumed. The MET observed little or no change in fuel economy, and no significant changes in the lubricating oil analysis data. They ran a 20% blend in February and March and had no problems with fuel gelling. The only complaint with the test was the high cost of the fuel and this was cited as the reason for not continuing to use the fuel after the demonstration had ended.

RESEARCH ISSUES

The major research issues that have surfaced during biodiesel research conducted in the public and private sectors are described below.

Blending of Biodiesel and Low Sulfur Diesel Fuel

To achieve consistent results with biodiesel requires that the fuel be thoroughly mixed. Initially, the biodiesel industry advocated a "splash" blending approach when mixing biodiesel and petroleum diesel fuel. A 20/80 blend of biodiesel and low sulfur diesel fuel (BD20) was prepared for Bi-State Development Agency in St. Louis, MO under these guidelines. Fuel sampling by MU researchers followed by fuel sample analysis indicated that "splash" blending was ineffective when blending in large storage tanks and that splash blending may have been responsible for the vast differences noted in fuel economy.

A demonstration project conducted by Fosseen Manufacturing and Development (Fosseen, 1995) also observed that splash mixing was inadequate, particularly when mixing was attempted when the two fuels were at different temperatures. In their project, 8000 gallons of very cold # 1 diesel fuel were added to a 10,000 gallon underground tank containing 2000 gallons of methyl soyate. They immediately encountered fuel filter plugging and later analysis showed that the fuels were inadequately mixed.

Research is needed to determine the amount of agitation required to ensure adequate mixing of biodiesel and diesel fuel. Research is also needed to determine whether conditions exist under which biodiesel could separate from petroleum diesel fuel.

Cold Starting Tendencies

Cold start issues have not been resolved, raising concerns for engine operators when fueling under adverse weather conditions. Researchers at the University of Missouri and the University of Idaho installed fuel tank heaters in their Dodge pickups to minimize these tendencies. The fueling of a diesel locomotive in St. Joseph, MO with a 20% biodiesel blend was discontinued after the engine experienced starting difficulties during cold weather.

Condition of Engine Lube Oil

Blackburn, et al (1983) noted unacceptable levels of ester contamination in the crankcase lubricant. Peterson, (1996) reported increases in engine oil dilution with the Yellowstone National Park "Truck in the Park" Dodge pickup that was fueled with 100% ethyl ester of rapeseed oil. However, a review of the engine oil analysis for five BD20 buses that have been fueled at Bi-State Development Agency in St. Louis, MO suggests that fuel dilution is negligible. The engine oil analysis of a 1991- 5.9L Cummins engine and a 1992- 5.9L Cummins engine that was fueled with 100% biodiesel by Schumacher (1995a, d) also suggests that fuel dilution is not a problem. Schumacher (1996) did not find any lubrication oil deposits on the head or in the oil pan when examining the 1992 engine after 100,000 miles of operation.

The OEMs have taken a conservative stand on this issue. It is their recommendation that the normal oil change interval should be cut by half to minimize problems associated with engine lubricating oil (Engine Manufacturers Association, 1995).

Cooling System Issues

A total of ten buses have been monitored at Bi-State Development Agency in St. Louis, MO. Of these buses, the five BD20 fueled buses required significantly more cooling system maintenance. Schumacher (1994a) also noted when testing tractors equipped with viscus clutch-type cooling fans, that the fan would engage more frequently when operating on blends as low as 10% biodiesel. Additional research is needed to confirm that this effect exists, but both of these situations suggest that the engine cooling system may need additional maintenance and that in some instances the capacity of the cooling system may need to be increased.

Engine Exhaust Emissions

Several research laboratories that have measured engine exhaust emissions produced by in-use engines have found that the data paralleled that previously reported in the literature: NOx increased while CO, HC, and PM usually declined. Peterson (1996), however, found very little if any increase in oxides of nitrogen emissions. Peterson used methyl and ethyl esters of rapeseed oil when testing biodiesel power and emissions. West Virginia University (Schumacher, 1995c), ORTECH International (ORTECH, 1995), and Cummins Engine Company researchers (Schumacher, 1995a) all used methyl ester of soybean oil.

Fuel Economy

The nine snow removal trucks operated by the IDOT experienced a 7% decrease in fuel economy. This is well beyond the decrease that would be expected due to the lower energy content of the fuel. Similarly, the buses at Bi-State Development Agency have also experienced excessive fuel economy decreases.

Fuel Filter Plugging

Some fuel filter plugging was noted during the start-up of biodiesel fueling at Bi-State Development Agency in St. Louis, Missouri. Periodic fuel filter plugging was also noted by the University of Missouri when fueling a 5.9L a 7.3L Navistar engine with a 20% blend of biodiesel for the city of Columbia. Peterson (1996) has also noted an increase in fuel filter plugging when fueling a pickup with a 20% biodiesel blend at the University of

Idaho.

In some situations, a brown gelatin-like deposit has accumulated at the bottom of the OEM fuel tank. This material was subsequently found in fuel filters thus preventing the high pressure injection fuel pump from delivering the fuel needed by the engine. The origin of the materials plugging the fuel filters is unclear, however, elements such as iron, zinc, and others have been noted in the samples that have been analyzed. At the present time, the fuel properties that contribute to these problems are not known.

Fuel Quality

The University of Missouri researchers have noted an opaque cream-colored material suspended in some samples of biodiesel (Schumacher, 1996). A rust colored substance has settled to the bottom of OEM fuel tanks and the fuel storage tank. An analysis of this material by researchers at Iowa State University revealed that the rust colored materials contained iron. The cream-colored material was found to be high in mono-glycerides (6%).

University of Missouri researchers, when fueling the 1991- 5.9L 6B Cummins engine and the 1992- 5.9L 6B Cummins engine with 100% biodiesel, noted that the aneroid sensor of each high pressure fuel injection pump failed at approximately 50,000 miles. An analysis of the fuel indicated that the glycerin level of the fuel exceeded the draft biodiesel specification that has been established by the National Biodiesel Board.

Power losses were noted after 200 hours of fueling an N14 Cummins engine with a 20% blend (ORTECH, 1995). The power losses for the N14 were believed to be a result of fuel filter plugging brought on by the formation of a varnish-like residue in the fuel system. An analysis of the biodiesel indicated that the acid value exceeded the draft biodiesel specification.

Injector Failure

Nearly all of the buses that have been fueled with BD20 at Bi-State Development Agency in St. Louis, MO have experienced injector problems. Similar injector cavitation problems were noted at the end of a 1000 hour 6V92-TA durability test conducted at ORTECH with a 20% blend (Fosseen, 1995b). Tests conducted on the injectors of two 5.9L 6B Cummins engines at the University of Missouri and one N14 at ORTECH International have shown no injector problems (Schumacher, 1996 and ORTECH, 1995).

Questions concerning why injector cavitation was found when fueling a Detroit Diesel Corporation 6V92TA but not when fueling Cummins engines remain unresolved.

Material Compatibility

According to Schumacher (1995a), nitrile rubber fuel lines were replaced on the 1991 Dodge equipped with the 5.9L Cummins engine. This was not necessary for the 1992 pickup as Dodge began using a plastic type of fuel line in 1992. The fuel transfer pumps were replaced on both engines after 50,000 miles. Upon inspection, the diaphragm of each fuel transfer pump had deteriorated. This prevented the fuel transfer pump from delivering a full charge of fuel to the engine.

Material compatibility problems resulted in the replacement of four fuel valves, five electric fuel pumps, two mechanical transfer fuel pumps, and several fuel lines. The biodiesel industry recognizes the solvent capabilities of biodiesel and that problems will surface when fueling with 100% neat biodiesel. However, no hard data are currently available concerning material compatibility problems associated with biodiesel blends.

A related issue is whether biodiesel with its excellent solvency characteristics, will dissolve existing gums and sediments in fuel storage tanks. This could cause fuel filter plugging.

Smoke Increases

Some vehicles have exhibited a light gray exhaust smoke when idling. For example, a diesel locomotive in St. Joseph, Missouri was fueled with a 20% blend of biodiesel and petroleum diesel fuel for approximately six months. Slightly higher opacity readings were noted when fueling with the biodiesel blend as compared to petroleum diesel fuel.

A 5.9L Navistar engine that powered a para-transit vehicle and a 7.3L Navistar engine that powered a refuse truck in the city of Columbia, Missouri were fueled using a 20% blend of biodiesel and # 2 diesel fuel. The vehicles were quite new and very few miles had been logged prior to biodiesel blend fueling. Some filter plugging was experienced when fueling with the biodiesel blend. The biodiesel powered vehicles occasionally produced a gray-white smoke when fueled with biodiesel and the operators complained that the biodiesel fueled engines did not idle smoothly.

Questions such as "what conditions facilitated the formation of light gray smoke in the exhaust and will this condition inhibit the commercialization of biodiesel?" must be addressed..

Power Test Results

Some operators have complained that they have noted a reduction in power when fueling with a biodiesel blend. Chassis dynamometer testing conducted by the University of Idaho (Peterson, 1996) and the University of Missouri (Schumacher, 1995b, d)as well as laboratory testing by Southwest Research Institute (Sharp, 1994) and ORTECH Corporation (ORTECH, 1994) substantiates the concerns expressed by operators. Schumacher (1994a) however, reported that very small differences in power were detected until the concentration of biodiesel exceeded 50% by volume. The question remains, why has real world testing of biodiesel blends left operators with the perception that vast differences in power can be expected? Fuel filter plugging, the gum-like accumulation in injection pumps, and injector cavitation have been blamed for these differences. The quality of the fuel may, in fact, have contributed to each of the causes mentioned.

POTENTIAL IMPLICATIONS

A matrix reported in Table 1 summarizes the problems noted when fueling with biodiesel and biodiesel blends. An "x" indicates that problems were noted when that engine was fueled with biodiesel. Problems that surfaced regularly could be interpreted as requiring more attention by biodiesel researchers during the coming year. For example, fuel quality issues and loss of power were consistently reported by the operators (73%). Fuel filter plugging was a close second as 64% of the operators reported this problem. Approximately 45% of the operators experienced cold start problems and material compatibility problems while operating these engines.

Some problems were infrequently noted when reviewing this matrix. One must interpret these findings with care as although only one demonstration experienced rusting tendencies with their fuel tank, the composition of the material found in some the fuel filters contained iron. On the positive side, problems such as algae growths in biodiesel were almost nonexistent. Other problems associated with storage and handling were minimal. These problems are to be expected and they should be solvable once they are understood.

Recurring issues arising from this review of research that must be resolved before biodiesel can be commercialized on a large scale include: blending procedures needed to insure a homogenous blend with diesel, cold start tendencies, engine lube oil dilution, increased cooling system needs, variances noted in engine exhaust emissions, decline in fuel economy, increased fuel filter plugging tendencies, fuel quality, injector failure, material compatibility, light gray smoke, power loss, paint damage, variances noted in opacity test results, rusting of storage tanks, and storage/handling procedures and/or guidelines.

Based on our evaluation of this matrix, the following problem areas are presented in rank order by the authors:

1)Fuel Quality,

2) Fuel Filter Plugging,

3) Injector Failure,

4) Material Compatibility, and

5) Fuel Economy.

This list was developed based on the frequency of occurrence of these problems and the severity of the potential damage to the engine associated with these problems. These problem areas need to be resolved before biodiesel can reach full commercialization.

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Table 1. Research issues identified when fueling diesel engines with biodiesel and biodiesel/low sulfur diesel fuel blends.

Problem Noted	MU 5.9L Pickups	St. Louis 6V92 Urban Buses	MU 5.9L & 7.3L Navistar	MU Tractor Testing	MSMC Ford Pickup	St. Joe Diesel Locomotive	NBB 1000 hr Testing	Mercedes Taxis	Cedar Falls Demo
Algae Growth	x								
Blending with Diesel		x							
Cold Start Tendencies	x				x	x			
Condition of lube oil								x	x
Cooling System Issues		x		x					
Exhaust Emissions	x	x						x	
Fuel Economy	x	x	x						x
Fuel Filter Plugging	x	x	x		x		x	x	
Fuel Quality	x		x	x	x	x	x	x	
Injector(s) Failure	x	x					x		
Material Compatibility	x			x	x				
Smoke Increases	x		x	x	x	x			
Power	x	x	x	x	x		x		
Paint Problems	x				x				
Rusting of Tanks					x				
Storage/Handling		x							