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ABSTRACT

The "Truck in the Park" project was a jointly funded research project which demonstrated the benefits of the use of biodiesel in a tourism related industry. The National Park Service (NPS) operated a truck in Yellowstone National Park (YNP) for 149,408 km (92,838 miles) on 100% biodiesel fuel produced by the University of Idaho. Participants in this project included Montana Department of Environmental Quality, Wyoming Department of Commerce, NPS, Department of Energy's Regional Biomass Energy Program, Koch Agri-Services, Dodge Truck, Cummins Engine Company, J.R. Simplot, Western States Caterpillar, University of California at Davis, and the University of Idaho.

This summary report details the fuel production, engine performance, durability, and engine emissions tests performed on the test vehicle.

The test vehicle was a 1995 Dodge 2500 four-wheel-drive pickup with a Cummins B 5.9 liter turbocharged, direct injected, diesel engine. Chassis dynamometer tests showed that the vehicle did not experience a reduction in power over time. Oil analyses, compression, injector tests, and engine and fuel pump teardown inspections also indicate that the engine did not experience excessive wear or deterioration as a result of using biodiesel as a fuel. The durability was considered equivalent or better than diesel fuel. Emissions tests were performed at the beginning (1995) and end (1998) of the project. Results from these tests indicated HC and CO decreased and PM increased as the percentage of rapeseed ethyl ester (REE) was increased. NO_x generally decreased as the percentage of REE was increased. Fuel use increased by 14% from 1995 to 1998. Cold start emissions data was limited, but it shows that HC, CO, and PM seemed to increase more for diesel cold starts than biodiesel cold starts compared to hot starts with the same fuel. 149,408 km (92,838 miles) of use with 100% biodiesel did not affect the efficiency of the catalytic converter.

INTRODUCTION

Each year, about 3 million people visit Yellowstone National Park (YNP). Over 900,000 automobiles burn thousands of gallons of fuel and produce tons of air pollutants inside the park. With visitation increasing steadily over the last several decades, the National Park Service (NPS) is concerned about the increased vehicular congestion and the threat of increased pollution. NPS is exploring ways to protect the pristine environment of YNP from the increase in vehicle pollution while not detracting from the visitor's experience. As a result, NPS is exploring the use of high occupancy vehicles such as busses, and reducing the amount of pollution produced by each vehicle. Biodiesel has been proposed as the fuel for these high capacity vehicles because it reduces harmful air emissions, has a less noxious smell than diesel, and is readily biodegradable in the event of a spill. In addition, biodiesel is safer to handle, having a higher flash point than diesel and lower toxicity.

The Truck in the Park project is a jointly funded research project which demonstrates the benefits of the use of biodiesel in tourism related industries. Participants include

- Montana Department of Environmental Quality;
- National Park Service;
- United States Department of Energy, Regional Biomass Energy Program;
- Wyoming Department of Commerce;
- Dodge Truck, a division of the Chrysler Corporation;
- Cummins Engine Company
- J.R. Simplot
- Koch Agri-Services of Great Falls, Montana;
- Western States Caterpillar;
- University of California, Davis;
- and the University of Idaho.

fuel injector spray patterns, and flow problems due to the very high viscosity. However, the use of raw vegetable oil may be feasible in blends of 20% or less with pre-combustion chamber engines (9).

TRANSESTERIFIED OILS – After it was found that raw oils were not suitable for use in unmodified diesel engines, the process of transesterification was examined to bring the raw oil's physical properties closer to those of diesel fuel. Transesterification is the process of displacing the glycerol from fats, usually with an alkaline catalyst in the presence of an alcohol such as ethanol or methanol. The resulting product of this process is called an ester (10). The generally accepted name for a vegetable oil ester used as a diesel fuel replacement is "biodiesel."

Biodiesel has some advantages over raw vegetable oils for use as a diesel fuel substitute. Biodiesel's viscosity is about a factor of ten less than that of raw oil, which makes it about twice the viscosity of diesel fuel. Because it has a viscosity much closer to diesel fuel, biodiesel tends to behave more like diesel fuel when sprayed from a diesel injector nozzle. Biodiesel still has to overcome some mild operational issues, which can cause undesirable operation in some engines or environments. Pour points and cloud points are much higher than diesel fuels, which can cause filter plugging and operational difficulties in colder climates. Biodiesel also tends to have lower gross heating values, about 11% less than diesel, but a greater density than diesel, which tends to counteract the effects of the lower energy content. On the positive side, it also has a higher cetane rating than diesel and has a much higher flash point making it safer to handle (11).

ENGINE DURABILITY AND LONG TERM TESTING – Engine manufacturers are naturally concerned with how vegetable oil based fuels will affect their engine's operational lifetime and subsequent emissions. Shäfer (12) of Mercedes-Benz reported problems with certain engine components and fluids subjected to long term exposure or use of vegetable oil methyl esters. These problems included engine oil breakdown, oil dilution, and rubber degradation. Problems such as inlet valve and injector nozzle coking appeared when esters of insufficient quality were used. Goyal (13) echoed these concerns as they relate to John Deere engines and warranty coverage when using biodiesel fuels.

As a result of these concerns, most diesel engine manufacturers either will not warranty engines fueled with biodiesel or specify very strict parameters on the fuel properties to ensure biodiesel fuel of the highest quality is used. A recent joint statement from the Diesel Fuel Injection Equipment (FIE) manufacturers details their concern. They cite the need for quality biodiesel fuel and the importance of a uniform standard and testing protocol in their statement. They concluded by issuing a position statement that states that the use of biodiesel in blends in excess of 5% (vol.) would result in the nullification of the warranty on their fuel system components (14).

EMA tests – The Engine Manufacturers Association (EMA) has devised a 200-hour testing protocol for screening diesel engines fueled with alternative fuels. The test is designed to show engine durability problems in a relatively short period of time and allows assessment of the potential impacts of these fuels on durability (15).

Perkins, et al. (16) ran a 1000-hour test on three Yanmar engines fueled with 100% Rapeseed Methyl Ester (RME), 50% RME blended with diesel, and 100% diesel control fuel. The 1000-hour test was composed of five back to back 200 hour EMA tests. They found that the RME performed similar to diesel with respect to engine wear and long term performance. However, it was noted that a slight decrease in engine oil viscosity was experienced with the ester fuel.

Peterson, et al. (17) ran a similar 1000-hour test with various blends of Hydrogenated Soybean Ethyl Ester (HySEE) biodiesel. The blends tested were 100% HySEE, 50% HySEE, and 25% HySEE blended with diesel. They performed engine oil analysis for wear metals at each oil change interval and concluded that the indicated wear of the 100% HySEE fueled engine was equivalent or better than that of the 25% and the 50% HySEE fueled engines. In addition, it was noted that the internal components of the 100% HySEE fueled engine appeared cleaner and brighter than the 25% or 50% fueled engines.

On-RoadTests – Many researchers have tested biodiesel fuels in on-road vehicles to prove the fuel's viability in the real-world. Some of these vehicles were fueled with 100% neat biodiesel, some with blends. Typical problems encountered were rusting of mild steel components in the fuel system and hardening of rubber engine seals and hoses exposed to the fuel. Two such demonstration projects are summarized below.

Schumacher, et al. (18) reported on two Dodge pickup trucks fueled with 100% soybean methyl ester run for about 80,500 km (~50,000 miles) each. The trucks were equipped with the Cummins B 5.9 liter engine. Engine coking did not appear abnormal when inspected with an engine borescope. Engine oil analysis of the biodiesel fueled trucks showed lower engine wear compared to diesel in three key contaminants, Fe, Pb, and Si. Both trucks produced slightly less power, lower CO, HC, PM and smoke, but higher NO_x compared to diesel. The 100% soybean methyl ester fuel rapidly deteriorated OEM rubber fuel lines.

Peterson, et al. (19) reported on a 1992 Dodge pickup with a Cummins B 5.9 liter engine running 20% Rapeseed Methyl Ester (RME) with 80% Diesel for 161,000 km (100,000 miles). They looked at chassis dynamometer tests, engine oil analyses, injector coking, and injector valve opening pressures at regular intervals. Oil analysis reports indicated that no unusual deterioration of the engine took place. The engine was removed from the vehicle, disassembled, and examined by the engine manufacturer after 163,800 km (101,785 miles). The condi-

Air Toxics – Kado, et al. (24) reported on bioassay testing of theTruck in the Park. The emissions from REE biodiesel used neat and in blends compared with diesel control fuel were examined. Of interest were polycyclic aromatic ʼdrocarbons (PAH). Many of these compounds, typiɔally found in diesel exhaust, are known or suspected carcinogens. This team of researchers found that emissions of polycyclic aromatic hydrocarbons (PAHs) were significantly lower for REE and blends of REE as compared to diesel. Also, many toxic species found in diesel exhaust were conspicuously absent from the biodiesel exhaust samples. The exception was the PAH called benzo(a)pyrene which was slightly higher for 100% REE and 50% REE as compared to 100% diesel. Benzo(a)pyrene is commonly found in combustion of biomass.

Kado (25) reported bioassay testing of 50% hydrogenated soybean ethyl ester (HySEE) fuels. The study looked at the particulates and semi-volatile compounds present in the exhaust of 100% HySEE, 50% HySEE blended with diesel, and 100% diesel fuel. The mutagenicity was rated in units of revertants per bhp-hr. The 100% HySEE mutagenicity emission rates were approximately 6 times lower than the diesel emission rates with metabolic enzymes added. The mutagenicity emission rates for the 50% HySEE blend were higher than the 100% HySEE emission rates, but lower than the 100% diesel emission rates

ʼuman Exposure Risks and Health Effects – Some conɔern over the toxicity to humans who have ingested or who have been dermally exposed to biodiesel was raised. Reece and Peterson (26) looked at acute oral and dermal toxicity and acute aquatic toxicity of rapeseed methyl ester (RME) and rapeseed ethyl ester (REE) biodiesel fuels and their blends with diesel. In general, they report that the occurrence of clinical observations increased as the ratio of diesel fuel in the blend being tested increased. 100% RME was the least severe in the acute oral toxicity study and the 100% REE was the least severe in the acute dermal toxicity study. In the aquatic toxicity tests, biodiesel was found to be not as toxic as the reference toxicant, sodium chlorided, but diesel fuel was 2.6 times more toxic.

Greenhouse Gas Emissions and Ecological Effects – On December 10, 1997, one hundred sixty industrialized nations around the world signed an historic agreement in Kyoto, Japan to reduce the future amount of carbon dioxide emissions and other so called "greenhouse" gasses to levels below those in 1990. It is widely believed by scientists that increased CO_2 in the atmosphere can cause global warming by allowing solar radiation to reach the earth, but restricting infrared radiation from escaping ʰack into space. Combustion of fossil fuels, which are ɔmprised of ancient carbon, in a relatively short period of time increases the accumulation of carbon in the atmosphere, eventually leading to global warming. Peterson and Hustrulid (27) conducted a carbon cycle study of rapeseed oil biodiesel fuels as compared to petroleum diesel. The authors propose that any substitution of biodiesel for petroleum diesel will ultimately slow the accumulation of atmospheric carbon. The basis for this proposal is that the carbon released from combustion of the biomass fuel has recently been extracted by the oil producing plant, thus saving a nearly equivalent amount of ancient carbon from accumulating in the atmosphere.

Gibbs (28) recently reported on the need for carbon-reduction technologies to offset carbon emissions from petroleum fuel use. The Kyoto Protocol requires CO_2 reduction of 8% over 1990 levels for participating industrialized nations, but the outlook seems grim given current trends. Gibbs predicted that the doubling time of vehicles worldwide would be reduced from 26 years to 6-10 years due to the emergence of active consumer economies from nations such as China, India, Mexico and the former USSR. This has the potential of increasing the atmospheric carbon levels by nearly 1 gigaton every 15-20 years. Biomass fuels offer considerable promise for reducing or stopping additional carbon release in the atmosphere by recycling atmospheric CO_2.

Franke and Reinhardt (29) looked at the environmental impacts of biodiesel fuels specifically. They performed a life cycle analysis of biodiesel fuel use and interpreted the environmental impacts. They concluded that RME has or can have an "overall" ecological advantage as compared to diesel fuel. This conclusion is based on CO_2 balances, NO_x, SO_2, N_2O, PAH, dioxins, and furans.

Biodegradability – Zhang, et al. (3) examined the biodegradability of biodiesel in the aquatic environment using a CO_2 evolution method. They concluded that biodiesel fuels are readily biodegradable when introduced in neat form and also appeared to co-metabolize petroleum diesel fuels in blends. Diesel degradation rates when in a blend were increased to three times that of diesel alone due to co-metabolism.

COMPUTER COMBUSTION MODELS In general, computer simulations of combustion have not been explored extensively in the area of vegetable oil fuels, but have great potential for insight into the combustion and emissions differences between biodiesel and diesel. The lack of research in this area is mainly due to the enormous computing resources required to run a detailed combustion analysis with the tools available. There is, however, at least one significant paper in this area. Vander Griend, et al. (30) ran a KIVA combustion simulation of raw oils and methyl esters of winter rapeseed at Los Alamos National Laboratory. The KIVA model attempts to predict cylinder pressures over a complete engine cycle given parameters such as combustion chamber dimensions, injector spray geometries, and specific fuel properties. This research serves as a basis for validation of such models used with vegetable oil esters and shows the potential value of tools such as KIVA in the development of alternative fuels for CI engines.

tracted to determine the total glycerol, free glycerine, mono-glycerides, di-glycerides, tri-glycerides, free fatty acids, and ethyl ester content of the fuel.

NGINE PERFORMANCE TESTIN

Engine performance was determined by chassis dynamometer tests, which were conducted by the University of Idaho. Additional parameters were examined at the dynamometer test intervals, including condition of cylinder bore, injector coking, injector pressures, and engine compression. The objective of vehicle performance testing was to monitor engine performance to detect any emerging problems.

The test vehicle was performance tested at Western States Caterpillar in Spokane, WA or Tractor & Equipment in Billings, MT a total of five times. The vehicle was tested at 4,764 km (2,960 miles), 25,465 km (15,823 miles), 42,165 km (26,200 miles), 81,726 km (50,782 miles) and 142,186 km (88,350 miles). The facilities were equipped with a SuperFlow SF-601 chassis dynamometer and Caterpillar PAR software. The SF-601 chassis dynamometer is a water brake dynamometer capable of applying a fixed load to the drive wheels. A lug curve was produced by programming 11 lug points into the computer. These lug points started at 1450 RPM and proceeded to 2950 RPM with 150 RPM intervals. Three replicates of the lug curve were made for each fuel tested.

igure 1 compares the overall average of all the dynamometer tests for REE and diesel. The values are a composite of all REE and Diesel runs for the five dynamometer test events. This figure shows that REE has slightly less power than diesel, which is expected due to the lower energy of the REE fuel per volume.

Figure 2 shows that the vehicle did not experience a sustained reduction in power over time. There was some variability in power over time, but this may be attributed to variables such as different testing locations (Billings and Spokane), environmental effects such as high ambient temperature, humidity, and different dynamometer software on the last test. The SuperFlow dynamometer uses standard SAE correction formulas for power correction, but these corrections are good only for a mild variance from standard conditions (+/-7%) and only take into account the change in air density. There were significant differences in ambient air temperature between test days. Variability in power between replicates on the same day was small.

Engine cylinder compression tests were performed on the engine at each engine performance test interval. Cylinder compression varied from 450 psi to 500 psi, but individual cylinders didn't vary by more than 7% of the verage for that particular test. The results are given in Figure 3.

Injector valve opening pressure tests were performed on the injectors at each engine performance test interval. Injector pressures varied from 3400 psi to 3950 psi, but each injector didn't vary by more than 6% of the average during that particular test. The results are given in Figure 4. Notice that valve opening pressures tended to decrease over time. This agrees with the injector evaluation performed at the engine teardown performed by Intermountain Cummins which reported lower than normal injector valve opening pressures. Bosch reported that valve opening pressures were low, but not abnormal for the mileage of the engine. Both of these reports are summarized in later sections of this report.

A cylinder borescope was used to visually inspect the cylinder walls, tops of the pistons, and combustion chamber for excessive coking or premature wear. The borescope was inserted into the injector holes in the head while the injectors were removed for valve opening pressure tests. Inspections were performed at each dynamometer test interval. The borescope inspections did not show any evidence of excessive coking or premature wear of the engine.

The fuel injectors were removed and examined for excessive coking or build-up after each dynamometer test. The injectors did not appear to accumulate excessive build-up between test runs and was comparable to that of diesel fuel in the same engine.

ENGINE TEARDOWN AND DURABILITY

Overall engine durability was estimated by considering engine oil analysis data, engine teardown inspection, engine component measurements, and a fuel injection pump evaluation from the manufacturer. Engine durability was difficult to determine directly in this test since the engine was only in service for 149,408 km (92,838 miles), considerably shorter than its expected service life. This section summarizes these observations and measurements.

The objective of the teardown and durability analysis is to determine if any abnormal or excessive wear occurred with the engine due to the use of biodiesel fuel.

The truck was moderately to heavily loaded during its operation at the park. This was mainly achieved by the 1,135 liter (300 gallon) auxiliary fuel tank that was installed by the Park Service to extend the truck's useful range. When full, the truck was nearly at it's recommended load capacity. On occasion, the truck was used to haul livestock trailers for the Park Service and was used off-road. The Park Service maintained a detailed fueling and driving log which cataloged the type of driving the truck experienced.

Oil was analyzed at every oil change using Chevron Lube Watch analysis services of Spokane, Washington. A small sample was taken during the oil drain procedure and submitted to the lab for analysis. The LubeWatch service reports a number of wear metals, oil contaminants, other values such as viscosity and total base number.

The ETF is equipped with a single 1.83 m (6 ft) diameter roll chassis dynamometer capable of testing single-axle or dual-axle vehicles from 2,268 kg (5,000 lbs) to 45,360 kg (100,000 lbs) GVW. The facility is controlled by a computerized vehicle emissions testing system (VETS) consisting of an exhaust sampling dilution tunnel, analyzer and computer software to interface the sampling and analysis of the exhaust gas emissions. The facility, emissions sampling hardware and integral software were designed and built to meet the requirements of the Code of Federal Regulations (CFR) Title 40, Part 86, "Control of air pollution from new and in-use motor vehicles and new and in-use motor vehicle engines: Certification and test procedures". The VETS is designed to perform exhaust emissions sampling and analysis to the requirements of the CFR for both compression ignition (CI) (diesel cycle) and spark ignition (SI) (Otto cycle) engines. The system permits the testing of vehicles over a variety of standardized operating conditions called drive cycles and a variety of vehicle load conditions. A complete detailed description of this facility can be found in Dunlap (34).

The vehicle had accumulated 5,955 km (3,700 mi.) at the time of the first test and 139,466 km (86,660 mi.) at the time of the second test. The weight used during the coast down and testing was 3,692 kg (8,140 lb.). The vehicle was driven from Moscow, Idaho to Los Angeles, California on 100% REE fuel for testing. Temperature and pressure sensors were instrumented to the test vehicle engine and exhaust systems so that specified vehicle operating conditions could be monitored during testing.

The engine was not fundamentally modified in any way for use with the vegetable oil fuels. Only the fuel delivery system was modified for convenience of changing fuels between test runs. Fuel delivery and fuel return lines were broken so that quick couplers could be installed. Individual 19-liter (5-gallon) fuel tanks were modified with fuel filter and flexible lines which could be connected to the quick couplers. During normal operation, fuel is delivered and returned to the vehicle tank. During testing the lines were disconnected from the main tank and connected to the external lines to which the correct test fuel was connected. For the tests, the fuel filter assembly mounted on the engine was removed and replaced with an aluminum block with internal connecting ports. This block was necessary to minimize the volume of fuel in the system when a fuel switch was required. Each tank of fuel had an individual fuel filter mounted on the tank.

Timed practice sessions with fuels of different colors showed that a minimum of 20 seconds was required for the return lines to be clear of the previous fuel. During actual testing, the return line was directed to a waste fuel tank while the engine was operated for 40-50 seconds at which time the return line was directed back into the test fuel tank. The low standard deviations in emissions data between tests of the same fuel is indicative of the success of the procedure for changing fuels.

Standard operational quality assurance (QA) is conducted in accordance with the California Air Resources Board (ARB) recommended practices. This includes gas analyzer six-point calibration, NOx converter efficiency test, CVS injection, CO_2 interference, and HC hang-up checks. Additional equipment checks and QA, such as analyzer zero/span and analyzer purge and back-flush, are performed at the beginning and the conclusion of each emissions test. Due to the extended length of the tailpipe system to the dilution tunnel connection, a set-up test drive cycle was conducted as part of the QA for this program. This was conducted to verify the analyzer system operations and time delay and corrections were made as necessary.

Emissions test data in units of grams per mile (gm/mile) are generated through the VETS for HC, CO, NO_x, CO_2, and PM. Fuel economy (FE) estimates were calculated and reported as described below. Three tests were completed for each fuel blend during both phases of vehicle configuration testing. The exhaust emission data are recorded and reported through the VETS. It is noteworthy that no anomalies were observed and no driver error occurred during any phase of this test program.

The EPA Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles was used as the test cycle for both the 1995 and 1998 tests. The EPA cycle has a total time of 1,060 seconds. The same driver and emissions analysis team were used for both tests.

A coast down test was performed by the University of Idaho personnel to provide a basis for inertial compensation calculations. Based on the coast down data,LA-MTA personnel developed a set of coefficients as a starting point for a road load model. Once the vehicle was installed on the dynamometer, coast downs were conducted and the model was refined to match the average on-road data. This refinement process was necessary to "factor out" the internal dynamometer resistance.

Fuels tested during the course of the two years tests included:

1. Phillips D2 low-sulfur diesel control fuel (DIESEL or D2)
2. 100% rapeseed ethyl ester (100REE)
3. 50% REE - 50% diesel (50REE)
4. 20% REE - 80% diesel (20REE)

The REE was produced in the Biological and Agricultural Engineering Laboratory using Dwarf Essex variety of industrial rapeseed at the University of Idaho.

The test vehicle was installed on the chassis dynamometer in accordance with typical ETF practice. A total of six sensors were installed. The test sensor locations were at the oil filter adapter housing, boost pressure at manifold, exhaust temperature at tailpipe adapter, fuel temperature at pump inlet, coolant temperature, and inlet air temperature.

HC emissions generally decreased as the percentage of REE was increased in the fuel blend. The mean average emissions for HC for both the 1995 and 1998 tests both with and without the catalytic converter are shown graphically in Figure 9.

CO emissions decreased as the percentage of REE was increased regardless of the vehicle test configuration. In 1995, the decrease was less dramatic when increasing from 50REE to 100REE. CO emissions for both 1995 and 1998 tests with and without the catalytic converter are shown graphically in Figure 10.

NOx emissions decreased as the percentage of REE was increased with the catalytic converter installed on the vehicle. However, in 1995, NO_x emissions increased from the 20REE to 50REE when the vehicle was tested without the catalyst installed. NO_x emissions for both 1995 and 1998 with and without the catalytic converter are shown in Figure 11.

The percentage of REE had no significant effect on CO_2 emissions. CO_2 emissions for both 1995 and 1998 with and without the catalytic converter are shown graphically in Figure 12.

PM emissions generally increased as the REE percent concentration was increased regardless of the vehicle test configuration. However, PM emissions were higher with the exhaust catalyst removed from the test vehicle, indicating the effect of the catalytic converter. PM emissions for both 1995 and 1998 without the catalytic converter are shown graphically in Figure 13.

Figure 14 shows the fuel use data obtained by direct weighing. Fuel use increased as the REE percent concentration was increased regardless of the vehicle test configuration. This was expected due to the lower energy content of the ester fuels. Fuel use in the 1998 tests was significantly higher than the 1995 tests. There was no obvious reason for the increase in fuel use, but because the power was measured at the wheels, several factors, including increased drive train resistance, could have caused this difference.

In both tests, comparisons were made between blends of rapeseed oil ethyl ester and diesel reference fuel with and without the catalytic converter. Rapid relative comparisons are provided in the following tables and any desired absolute value can be found through multiplication. For clarity Figures 9 through 14 were provided to give an overview of the data trends.

<u>Analysis of 1995 Emissions Dat</u> – The data collected in 1995 for each of the regulated emission compounds are shown in tables 3 through 6. The results shown in the tables are for diesel reference fuel, 20% REE, 50% REE and 100% REE. Tables 3 and 5 are in grams/mile and Tables 4 and 6 are normalized by dividing by the diesel level of emissions. For example, diesel/diesel is show as 1.0 and the other fuels are relative to diesel. Thus, HC for 100% REE/diesel is 0.364 or 100% REE is about 36% of diesel.

Table 3. 1995 Emissions Data, EPA Cycle, with catalytic converter (gm/mile)

	HC	CO	NO_x	CO_2	PM
Diesel	0.763a*	3.600a	6.697a	663.503a	0.101b
20REE	0.637b	2.960b	6.457b	668.147a	0.129a
50REE	0.480c	2.490c	6.243c	666.547a	0.142a
100REE	0.278d	2.405c	6.153c	677.483a	0.127a
Average	0.540	2.864	6.387	668.920	0.125

*Numbers in the same column followed by the same letter of the alphabet are not significantly different according to Fischer's protected LSD comparison ($p < 0.05$).

Table 4. 1995 Emissions Data, EPA Cycle, with catalytic converter, ratios (blend value/diesel)

	HC	CO	NO_x	CO_2	PM
Diesel	1.000a*	1.000a	1.000a	1.000a	1.000b
20REE	0.834b	0.822b	0.964b	1.007a	1.278a
50REE	0.628c	0.692c	0.932c	1.005a	1.403a
100REE	0.364d	0.668c	0.919c	1.021a	1.255a

*Numbers in the same column followed by the same letter of the alphabet are not significantly different according to Fischer's protected LSD comparison ($p < 0.05$).

Table 5. 1995 Emissions Data, EPA Cycle, no catalytic converter (gm/mile)

	HC	CO	NOx	CO2	PM
Diesel	0.854a*	3.683a	6.747a	669.540ab	0.184b
20REE	0.712b	3.033b	6.240b	646.550b	0.195b
50REE	0.483c	2.400c	6.550a	687.050a	0.249a
100REE	0.324d	2.403c	5.913c	654.813b	0.261a
Average	0.593	2.880	6.363	664.488	0.222

*Numbers in the same column followed by the same letter of the alphabet are not significantly different according to Fischer's protected LSD comparison ($p < 0.05$).

Table 6. 1995 Emissions Data, EPA Cycle, no catalytic converter (gm/mile)

	HC	CO	NO_x	CO_2	PM
Diesel	1.000a*	1.000a	1.000a	1.000ab	1.000b
20REE	0.834b	0.824b	0.925b	0.966b	1.059b
50REE	0.565c	0.652c	0.971a	1.026a	1.352a
100REE	0.380d	0.652c	0.876c	0.978b	1.420a

*Numbers in the same column followed by the same letter of the alphabet are not significantly different according to Fischer's protected LSD comparison ($p < 0.05$).

other tests. In general, the catalytic converter reduced HC and PM emissions, with PM emissions being most heavily affected.

ble 13. Comparison of 1995 EPA cycle with and without catalytic converter (ratio With Converter/Without Converter; a number of 1 indicates no change)

	HC	CO	NO_x	CO_2	PM
Diesel	0.894*	0.977	0.993	0.991	0.549*
20REE	0.895*	0.976	1.035*	1.033*	0.663*
50REE	0.994	1.038	0.953*	0.970*	0.570*
100REE	0.857*	1.001	1.040*	1.035*	0.485*

*Numbers followed by an asterisk imply a significant difference between with the catalytic converter and without the catalytic converter for that comparison according to Fischer's protected LSD ($p < 0.05$).

Table 14. Comparison of 1998 EPA cycle with and without the catalytic converter (ratio With Converter/Without Converter; a number of 1 indicates no change)

	HC	CO	NO_x	CO_2	PM
Diesel	0.878*	1.053	1.022	1.024	0.565*
20REE	1.035	1.225*	0.999	1.030*	0.720*
50REE	0.947	1.064	1.007	1.003	0.531*
100REE	0.917	1.017	1.008	1.018	0.465*

*Numbers followed by an asterisk imply a significant difference between with the catalytic converter and without the catalytic converter for that comparison according to Fischer's protected LSD ($p < 0.05$).

Comparison of Cold Start vs. Hot StartTests – In 1995 and 1998, one cold start test was conducted each test day. Two cold start tests were conducted with the catalytic converter and two without the catalytic converter. Tables 15 and 16 are relative comparisons between the cold start data and the hot start data for each of the fuels tested.

Table 15. Comparison of 1995 EPA cycle cold and hot starts. (Average of with and without catalytic converter; ratio 1995 Cold Start/1995 Hot Start; a number of 1 indicates no change)

	HC	CO	NO_x	CO_2	PM
Diesel	1.326	2.042	0.951	1.139	2.074
REE	1.961	1.947	1.359	1.147	1.665
verage	1.643	1.994	1.155	1.143	1.870

(Insufficient data for statistical comparisons)

Table 16. Comparison of 1998 EPA Cycle cold and hot starts. (Average of with and without catalytic converter; ratio 1998 Cold Start/1998 Hot Start; a number of 1 indicates no change)

	HC	CO	NO_x	CO_2	PM
Diesel	2.386	2.336	1.084	1.122	2.815
REE	2.114	1.622	1.054	0.803	1.749
Average	2.250	1.979	1.069	0.963	2.282

(Insufficient data for statistical comparisons)

General Observations for Emissions Data – These data show a significant reduction in HC, CO, and NO_x as percent of vegetable oil is increased and a non-significant increase in PM. The PM data had the most variability of the data and an examination of the raw data shows that there is scatter sufficient to neutralize differences.

These data show that HC levels for 100REE were reduced by more than 60% compared to the D2 levels and CO levels for 100REE were reduced by more than 50% compared to the D2 levels. The CO_2 showed no significant differences between fuels tested in the same year. NO_x was generally decreased with increasing ester. PM generally increased with increasing ester in the fuel blend.

It has generally been found that the fatty acid esters increase NO_x and decrease PM, however in these tests, generally speaking, the reverse was true. One might speculate that this trend is due to the fatty acid constituents of rapeseed esters tested or that it is a characteristic of this particular engine. Also, most other emissions tests involving esters used a PTO engine test cycle instead of a chassis test. Cycle differences and test condition differences between the driving cycle and the PTO cycle could possibly influence NO_x formation. In either case, the results were consistent for both years of testing.

The catalytic converter had a consistently significant effect on the PM and HC emissions, reducing PM by approximately 50% for 100REE. It is interesting to note that the efficiency of the OEM catalytic converter was not affected by the long-term use of ethyl esters in this engine.

Specific conclusions of the emissions study are:

1. HC and CO decreased as the percentage of REE was increased. PM generally increased with increased REE and there was no statistically significant change in CO_2 for any of the fuels. HC decreased nearly linearly with blend of Biodiesel, while CO had most of its decrease in the 0 - 50% blend range.
2. NOx decreased as the percentage of REE was increased in the fuel with the exception of the 50% REE data point in 1995 without a catalytic converter.

PM seemed to increase more for diesel cold starts than REE cold starts compared to hot starts with the same fuel. There was no deterioration of the catalytic converter's efficiency with the use of biodiesel over long periods of time. Biodiesel actually appears to increase the efficiency of the catalytic converter.

In this test, NO_x was lower and PM was higher with biodiesel when compared to 100% diesel. This contradicts many previous engine tests with biodiesel which typically show NO_x emissions from biodiesel higher with a corresponding decrease in PM. This critical difference may be due to the type of dynamometer tests performed. This test was a chassis driving test where the vehicle is rarely driven at or near 100% of its maximum power or torque. This is due to the high power to weight ratio on a pickup truck as compared to a heavy duty truck. The FTP for engine or PTO dynamometer testing outlines the procedure to "map" the engine's maximum torque and power. The specified dynamometer target points on the cycle are then derived from these maximum values. As a result, the engine dynamometer test loads the engine near its maximum load more often resulting in a different emissions profile. The higher NO_x and reduced PM reported in other studies from biodiesel tested with an engine dynamometer is due to this higher loading.

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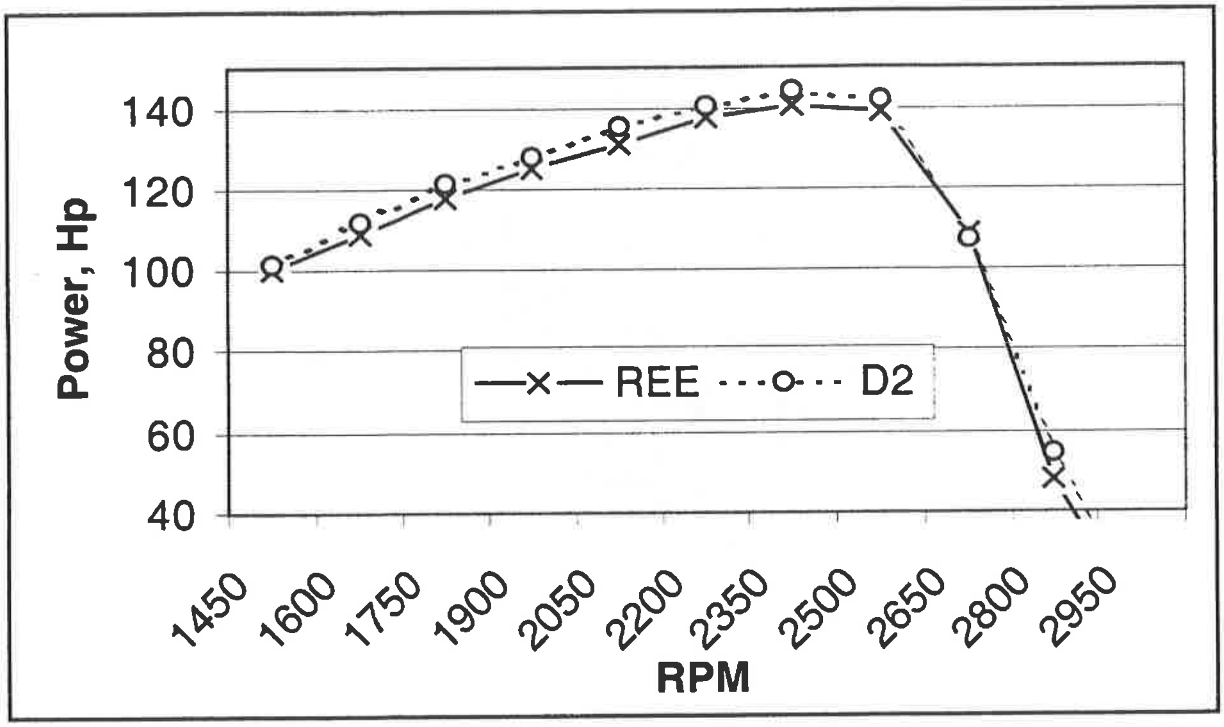

Figure 1. Overall Average of REE and Diesel Runs

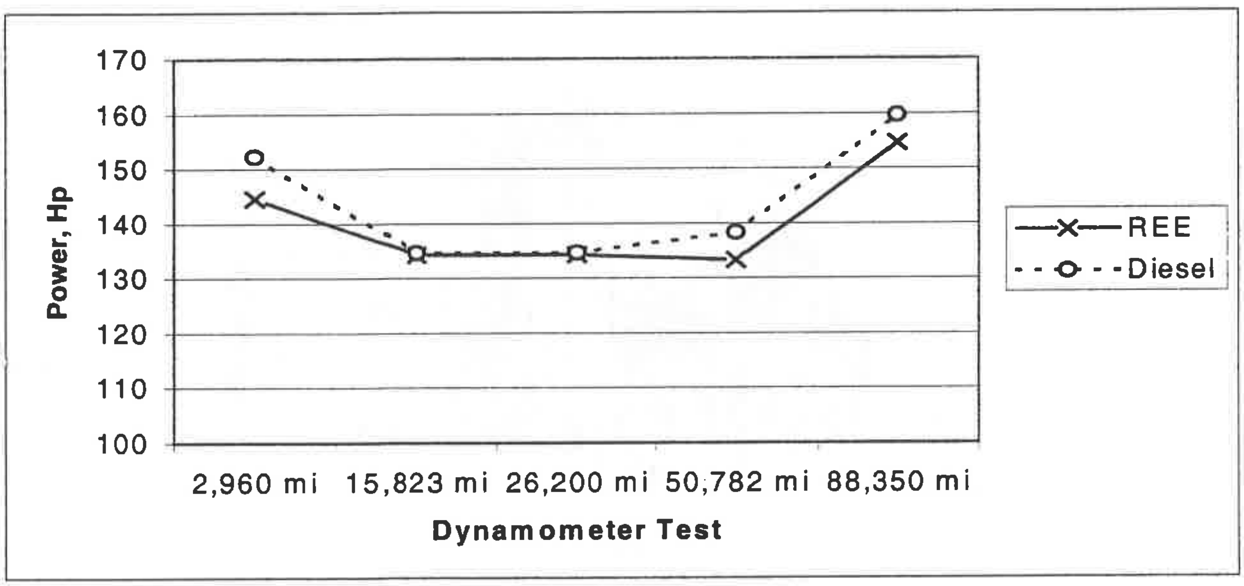

Figure 2. Comparison of average power at 2350 RPM over time for diesel and REE.

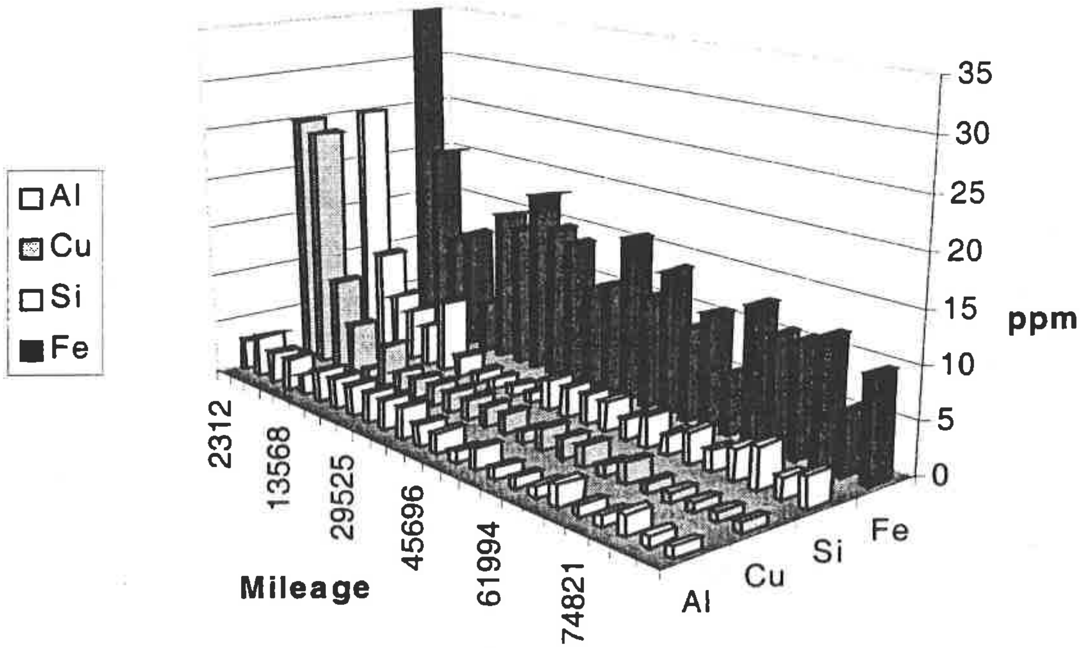

Figure 5. Wear metals in the engine oil at each oil change interval. (Acceptable limits of each one: Al<30 ppm, Cu<40 ppm, Si<20 ppm, Fe<100 ppm.)

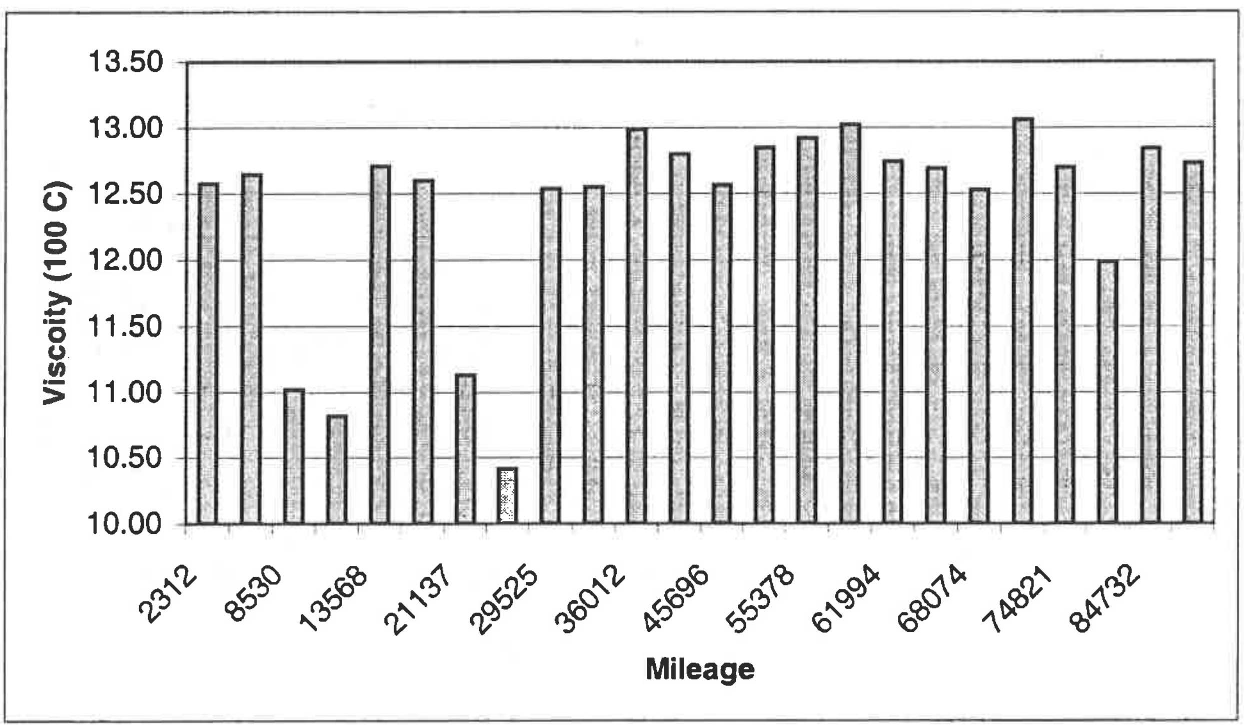

Figure 6. Viscosity of the engine lube oil at each oil change interval. (New Delo 15W-40 has a viscosity of 15.0 CSt @ 100 C)

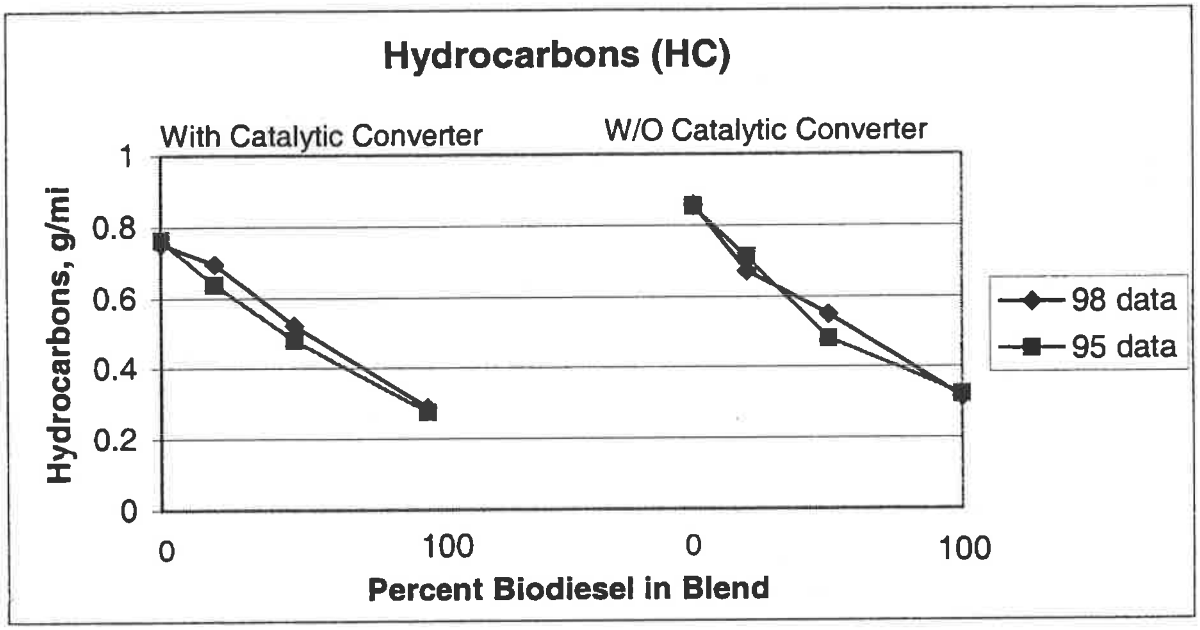

Figure 9. 1995 and 1998 data for HC for the EPA cycle and various blends of diesel and REE.

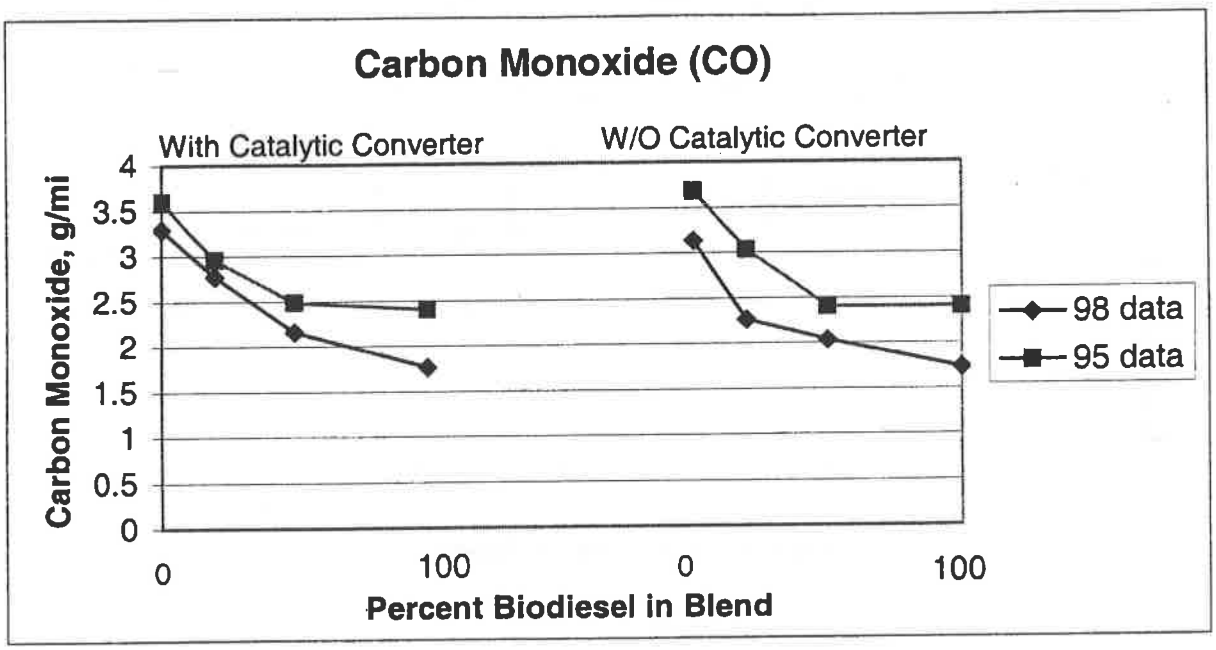

Figure 10. 1995 and 1998 data for CO for the EPA cycle and various blends of diesel and REE.

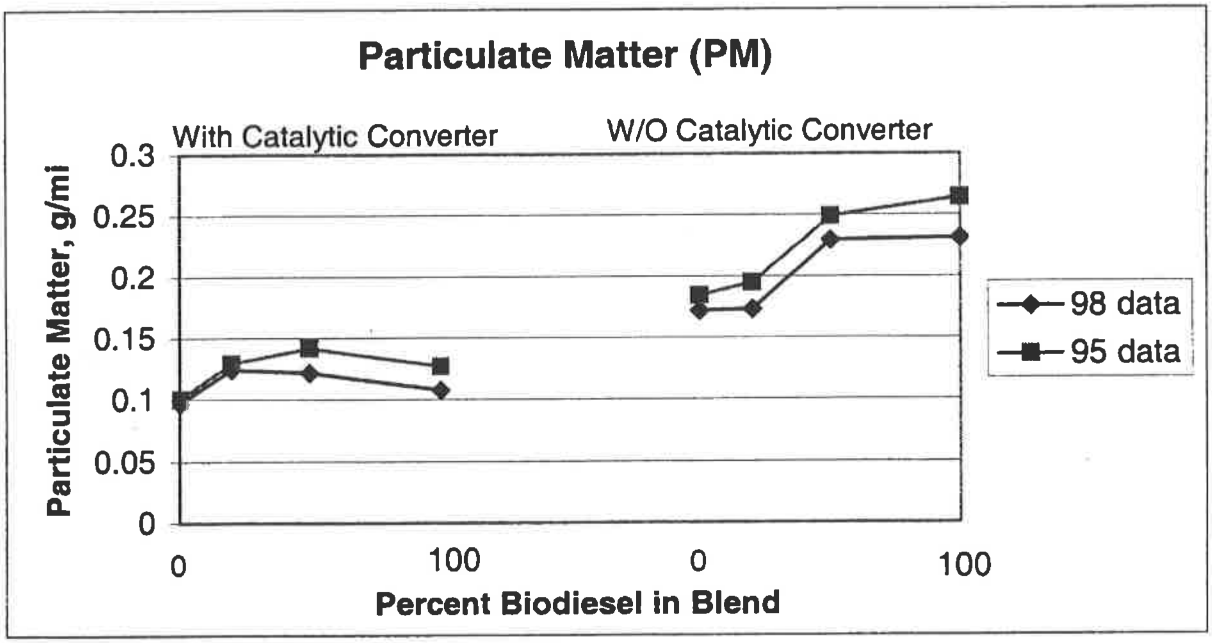

Figure 13. 1995 and 1998 data for PM for the EPA cycle and various blends of diesel and REE.

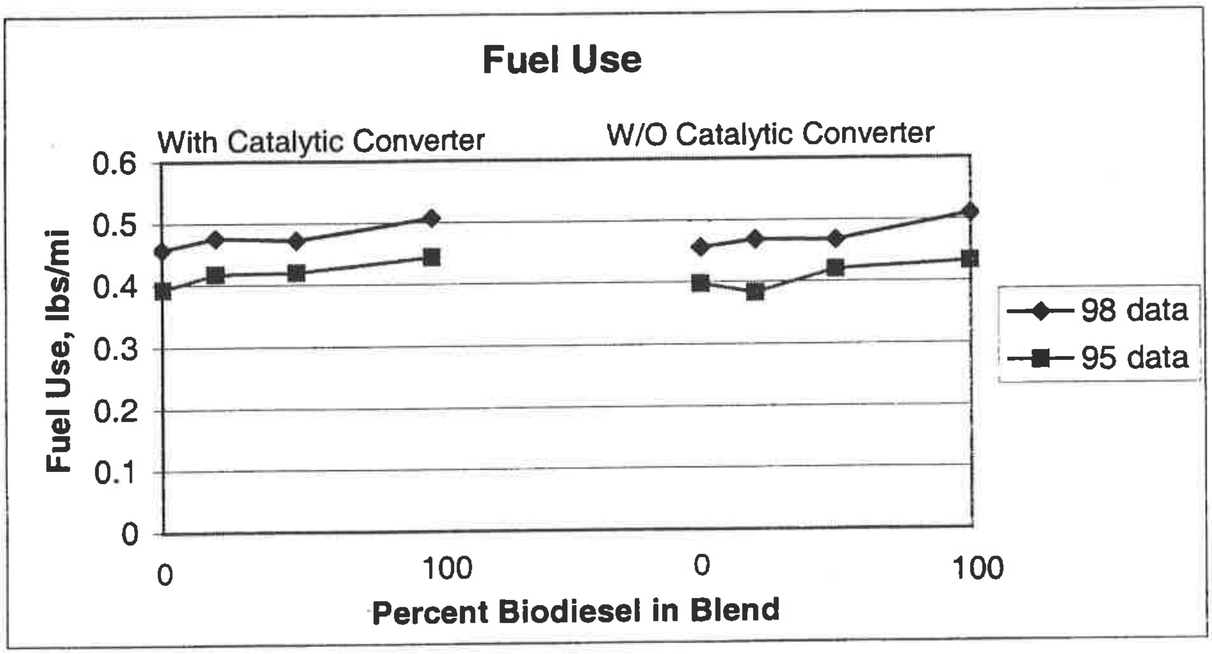

Figure 14. 1995 and 1998 fuel consumption data for the EPA cycle with various blends of diesel and REE.