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Emissions Testing with Blends of Esters of Rapeseed Oil Fuel With and Without a Catalytic Converter

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ABSTRACT

Two pickup trucks, both with 5.9 L, turbocharged and intercooled, direct injection diesel engines, were tested for regulated emissions at the Los Angeles County Metropolitan Transit Authority Emissions Testing Facility, one in 1994 and the other in 1995. Emissions testing was conducted using the Dynamometer Driving Schedule for Heavy Duty Vehicles (Code of Federal Regulations 40, Part 86, Appendix 1, Cycle D). Emissions data generated included total hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NOx) and particulate matter (PM). All tests were with a chassis dynamometer capable of transient testing.

This paper presents an analysis and comparison of the emissions tests for each year as well as a comparison between years. Differences in emissions found between years are reported. Test methods, procedures and the experimental designs are discussed. The test data presented in this report represents the emissions of three biodiesel fuel blends. In 1995, all fuels were initially tested with the vehicle catalytic converter installed on the vehicle. Subsequent testing was then conducted with the catalytic converter removed from the vehicle. A catalytic converter was not available for the 1994 vehicle.

The 1994 tests included both a double arterial cycle of 768 seconds duration and the EPA heavy duty vehicle cycle of 1,060 seconds duration. Rapeseed methyl (RME) and ethyl esters (REE) and blends were compared with a low sulfur diesel reference fuel (D2). In these tests, 100% REE reduced HC (8.7%), CO (4.3%) and NOx (3.4%) compared to 100% RME. The 1994 tests resulted in reductions of HC (52.4%), CO (47.6%), NOx (10.0%) and increases in CO_2 (0.9%) and PM (9.9%) for the average of REE and RME compared to diesel.

The 1995 tests included only the EPA heavy duty cycle. Fuels used in 1995 were low sulfur diesel reference fuel, 100% REE, and blends of 20% REE-80% diesel and 50%REE-50% diesel. The 1995 tests resulted in reductions in HC (63%), CO (33%), NOx (10%), CO_2 unchanged and increases of PM (30%) for 100% REE compared to D2. The catalytic converter had an affect on only the HC and PM. It reduced HC for diesel 10.5% and for REE 13.6%. It also reduced PM for diesel 45% and for REE 56%.

INTRODUCTION

The Los Angeles County Metropolitan Transportation Authority (LA-MTA) conducts exhaust emissions tests on heavy-duty vehicles at the Emissions Testing Facility (ETF) in an effort to provide data to expand the use of clean air technology and alternate fuels in heavy-duty vehicles. The ETF, located in the greater Los Angeles area, is a state-of-the-art laboratory specifically designed and built for the purpose of collecting exhaust emissions data from heavy-duty vehicles during transient chassis dynamometer operations. In addition to supplying data to the scientific community and private customers, the ETF provides exhaust emissions testing and data to California regulatory agencies in an effort to support the development of new emissions regulations for heavy-duty vehicles.

University of Idaho personnel have been researching the use of vegetable oil as a fuel since 1979. The first tests were with raw vegetable oils of various types and then with methyl and ethyl esters of rapeseed oil. Vegetable oil esters, sometimes called Biodiesel, have been shown to be very good fuels for compression ignition engines. Many tests have shown these fuels to have characteristics as good as, or superior to, common diesel fuel. In spite of these excellent fuel characteristics many hurdles (such as cost, production capacity, engine durability verification and infrastructure) remain before these fuels will be available for general use.

Transesterification is the process of using an alcohol, ethanol or methanol, in the presence of a catalyst, such as sodium hydroxide or potassium hydroxide, to chemically

break the molecule of the oil or fat into an ester and glycerol. Recently, recipes for using ethanol as the reacting agent with the rapeseed oil to form ethyl ester have been successfully carried out. Fuel characterization and short and long term engine tests have shown the ethyl ester of rapeseed oil (REE) to be equivalent, or superior to, the methyl ester of rapeseed oil (RME).

The Clean Air Act (CAA) forms the legislative base for fuel, engine, and emissions standards. The Environmental Protection Agency (EPA) has set emissions standards. This has resulted in engine manufacturers and refinery operations spending billions of dollars each year to meet the stringent requirements. Electronic engine control, advanced fuel systems, engine oil control methods, and combustion chamber design are making engines more sensitive to changes in the physical and chemical properties of the fuel. Biodiesel presents an attractive solution to environmental problems for many circumstances.

Vegetable oil esters have been reported to be cleaner burning than diesel fuel in a typical compression ignition (CI) engine. Feldman (1)* reported smoke opacities reduced as much as 70% with methyl ester of rapeseed oil compared to commercial diesel fuel.

Two limitations of the University of Idaho test program are the lack of suitable facilities for measurement of exhaust emissions (other than through the use of an opacity meter), and a dynamometer capable of transient cycles. Grants from the Pacific Northwest and Alaska Regional Bioenergy Program in 1994 and a contract with the State of Montana Department of Environmental Quality in 1995 provided a unique opportunity to conduct these tests at the LA-MTA, ETF. Several different biodiesel fuel blends were evaluated during the testing program. This paper reports on this cooperative transient dynamometer test of gaseous emissions and particulates using the LA-MTA, ETF with diesel on-road vehicles fueled with vegetable oil esters produced by the Agricultural Engineering Department at the University of Idaho. Certification low-sulfur diesel fuel was also tested to provide a baseline reference point. Two test vehicles were used, both were Dodge 2500, pickup trucks with 5.9 liter, turbocharged and intercooled Cummins diesel engines. One vehicle was a 1994 model and the other a 1995 model. It is the intent of the sponsors to test the 1995 Dodge pickup again when it reaches 100,000 miles.

OBJECTIVES

The objectives of this experiment were:
1) to compare regulated emissions data including total hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter (PM), for ethyl

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*Numbers in parentheses designate references at the end of paper.

ester of rapeseed oil, methyl ester of rapeseed oil, and diesel control fuel;
2) to obtain emissions data for 100% REE, 100% RME, and 20% and 50% blends of both REE and RME with diesel control fuel.
3) to compare emission levels for the 1994 and 1995 vehicles using Biodiesel fuels.
4) to determine baseline emissions data on the 1995 vehicle with and without the OEM catalytic converter.

A REVIEW OF LITERATURE

One of the critical issues to be resolved for vegetable oil fuels as they seek status as replacements for petroleum diesel fuel is how they affect emissions from a standard diesel engine. A comprehensive literature review of emissions from Biodiesel fuels was published in an earlier paper by Peterson and Reece (2), thus this review will give only a brief overview of emissions tests with Biodiesel fuels. Test procedures, engines, and instrumentation vary widely from one report to another. Standard EPA procedures are rarely followed. Emissions testing on the official level requires more human, capital, and equipment resources than most engine test facilities have available.

Emissions testing is a case where the protocol is so restrictive as to limit testing to only a very few laboratories. To counteract the official level, many scientists use techniques of their own to give "relative" data. As the data is examined, it is easy to see that these many different local procedures give a wide range of results. Acceptable research protocols should be suggested within the reach of the average engine test cell that would bring uniformity to the tests.

Power and performance tests have shown esters of vegetable oil to be good replacements for diesel, Zhang et al. (3) for example. Many labs have only an opacity or smoke meter available and report this as emissions testing. Some have maintenance shop type instruments for the regulated emissions of total hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NOx), and particulate matter (PM). These instruments are usually operated with little or no calibration and offer, in many cases, too little precision and/or sensitivity to give real "relative" data. These tests report smoke opacities reduced from 33% to 83% when biodiesel replaces diesel fuel (1,4,5,6,7,8,9). The literature clearly shows that smoke meter or opacity data indicate only visible smoke and are not necessarily related to the regulated quantity called particulate matter (PM).

The next level is from tests which have good quality analyzers with heated lines and, hopefully, calibration procedures for HC, CO, CO_2, and NOx (10,11,12,13,14,15,9,16,17,). In every case, these test cells did not have access to a dilution tunnel for measuring PM. In most cases they still use opacity or smoke for PM. These test cells also do not have capability for transient cycles and instead report steady state data. In some cases, they use the 13 mode test, while in most cases they use a protocol of their

own, generally a constant speed, variable load test. These data are generally reported as being "relative" to the transient cycle required by EPA.

The third level of sophistication is a testing lab with a transient capable dynamometer, a dilution tunnel, calibration and all the required instrumentation to be called "EPA Certified" for emissions testing (18,19,29,21,22). Even in these labs, however, there is not uniformity of data because cycles differ, reference fuels differ, engines differ, methods of changing fuels differ and there is a wide selection of vegetable oil ester fuels from different origins. Another problem is the need for "cold start" and "hot start" tests. These requirements are probably reasonable for certifying an engine if the lab is available. However, when one does a comparison of many different fuels, additives, engine adjustments, or blends it becomes an impossible task to create a reasonably scientific experiment given a normal budget and time to use the dynamometer facility.

Some laboratories also measure the unregulated aldehydes, ketones, and polycyclic aromatic hydrocarbons (PAH) that are potential health problems. Only a few reports relate to these constituents; however, most show that vegetable oil esters produce PAH's lower than those from diesel fuel (17,23,24,25).

In general the emissions tests show that ethyl and methyl esters of vegetable oils are essentially similar to diesel fuel in their emissions characteristics. HC is reduced in some studies as much as 50%; CO is reduced by as much as 10%; NOx and PM are related and tend to change inversely with each other, differing from diesel by at most 10-15%. Generally, NOx was found to be slightly higher than diesel and PM slightly lower than diesel, although this differs with particular conditions. Even in the worst case, NOx was about 0.56 gm/mile for Biodiesel and 0.48 gm/mile for diesel. Barenescu (27) and Holmberg and Peeples (28) reports "There is an inverse correlation between emissions of NOx and PM. If an engine is optimized to reduce NOx emissions, each unit of NOx reduction will routinely result in a unit increase of PM. Similarly, a reduction in PM will result in an increase in NOx. Although the inverse correlation holds true for biodiesel as well, the severity of the trade-off is not as significant as in petrodiesel."

Sales of diesel fuel in the U. S. are nearly 190 billion liters (50 billion gallons) per year, 53.4% goes to transportation according to the Energy Information Administration (26). Diesel engines were designed over many years to operate on petroleum diesel. It is surprizing that they perform as well as they do on methyl and ethyl esters of vegetable oils and that the emissions are so low.

The U.S. regulations that take effect in 1994 and 1998 will push the design limitations of heavy-duty diesel engines. The Federal heavy-duty diesel engine emission regulations for 1991 and 1994 have prompted a comprehensive re-examination of the diesel combustion process. These regulations require major reductions in the NOx and particulate emissions of diesel engines used in trucks over 3,864 kg (8500 lb) gross vehicle weight (GVW).

According to EPA 86.094-11, exhaust emissions from new 1994 and later model year diesel heavy-duty engines shall not exceed the following: HC 1.3 gm/bhp-hr; CO 15.5 gm/bhp-hr; Oxides of Nitrogen 5.0 gm/bhp-hr; PM for diesel engines to be used in urban buses 0.07 gm/bhp-hr; PM for all other diesel engines 0.10 gm/bhp-hr. The opacity of smoke emissions shall not exceed the following: 20% during the acceleration mode; 15 percent during the lugging mode; 50% during the peaks in either mode.

The last note on the literature review is that of the approximately 20 papers reviewed, no two used the same protocol so as to be directly comparable.

MATERIALS AND METHODS

The emissions tests were conducted at the Los Angeles Metropolitan Transit Authority (MTA) Emissions Testing Facility (ETF) located in Los Angeles, California. This facility has instrumentation to measure all regulated emissions: total hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter (PM). The ETF provides quality assurance test results and calibrations in accordance with California Air Resources Board (CARB) quality assurance recommendations (29).

FACILITIES - The ETF is equipped with a single roll, 1.8 m (6 ft) diameter, chassis dynamometer capable of testing single-axle or dual-axle vehicles from 2,200 kg to 45,000 kg (5,000 lbs to 100,000 lbs) gross vehicle weight, and a computerized vehicle emissions testing system (VETS) consisting of an exhaust sampling dilution tunnel, analyzer and computer software to interface with the sampling and analysis of the exhaust gas emissions. The facility, emissions sampling hardware and integral software were designed and built to meet the requirement of the Code of Federal Regulations 40 (CFR40), 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. This system permits the testing of vehicles over a variety of standardized operating conditions called drive cycles and a variety of vehicle load conditions.

EMISSIONS ANALYZER - For a complete description of the emissions analyzer refer to Dunlap (30).

TEST VEHICLE INSTALLATION - In 1995, the vehicle tested was a 1995 Dodge 2500, 4x4 WD pickup truck rated at 3,900 kg (8,600 GVW.) The vehicle was powered by a 5.9 liter, turbocharged and intercooled Cummins diesel engine. The vehicle had accumulated 5,950 km (3,700 miles) at the

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time of the test. The weight used during the coast down and testing was 3,700 kg (8,140 pounds). 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.

In 1994, the vehicle tested was a two wheel drive 1994 Dodge pickup with a direct injected, turbocharged and intercooled, 5.9 liter Cummins diesel engine. The vehicle had accumulated 2,414 km (1,500 miles) on diesel and 3,860 km (2,400 miles) on rape ethyl ester at the time of this test. The vehicle was driven from Moscow, Idaho to Los Angeles, California on 100% REE fuel for testing. Weight used during the test and for coast down was 3,590kg (7,900 pounds).

The engines were not modified in any way for use with the vegetable oil fuels. The fuel delivery system was modified for convenience of changing fuels between test runs. Fuel delivery and fuel return lines were broken and 3-way, manually operated valves were installed so that stub lines with quick couplers could be installed on one part of the 3-way valves. Individual 19 liter (5 gallon) fuel tanks were modified with fuel filter and flexible lines which could be connected to the 3-way valves. During normal operation, fuel is delivered and returned to the vehicle tank. During testing the valves were switched 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 change was necessary to minimize the amount of fuel in the system when a fuel switch was required. Timed practice sessions with fuels of different colors showed that a minimum of 20 seconds was required for the return lines to be cleared of the previous fuel. During actual testing, the return line was directed to a waste fuel tank while the engine was operated for 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.

ETF QUALITY ASSURANCE - Standard operational quality assurance (QA) is conducted in accordance with the California Air Resources Board (CARB) 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 backflush, 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.

TEST DATA ANALYSIS - Emissions test data in units of grams per mile (gm/mile) are generated through the VETS for HC, CO, NOx, CO_2, and PM. Fuel economy (FE) estimated 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.

TEST CYCLES - Two test cycles were utilized for the 1994 test program, Figure 1. The first was a modified arterial cycle (arterial). The standard form event cycle was doubled, creating a 758 second, 8 event cycle. The arterial cycle, as used, has eight repetitions of accelerating to 64 km/h (40 mph) and decelerating to 0 km/h (0 mph.) The second was the EPA Dynamometer Driving Schedule for Heavy-Duty Vehicles (Code of Federal Regulations 40, Part 86, Appendix 1, Cycle D)(EPA). The EPA cycle has a total time of 1060 seconds. Only the EPA cycle was used for the 1995 tests.
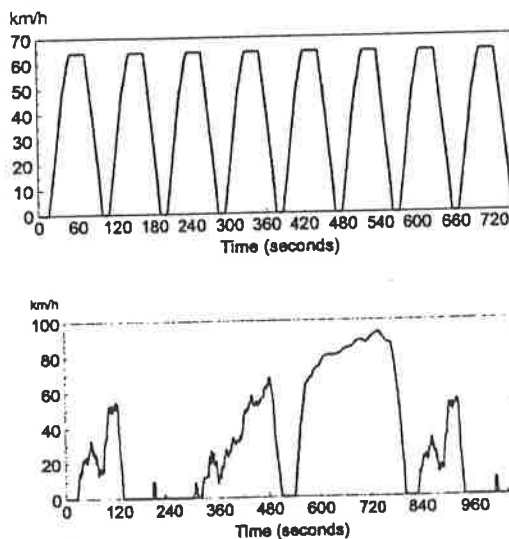

Figure 1. Test cycles used for the emissions tests; modified arterial cycle upper and EPA cycle lower

ROAD LOAD SIMULATION - In order to measure the emissions of a vehicle during operation, the actual driving conditions of the vehicle on the road must be simulated on the dynamometer. The dynamometer control system must simulate the force that would act on the vehicle if the vehicle were travelling on the road. This force, or Road Load (RL), is defined by the equation below. (29)

$$RL = F_0 + F_1 V + F_2 V^n + I^{dv}/_{dt} + mg \sin (grad)$$

where:

RL = Road Load (force at roller surface)
F_0 = Coefficient of friction force - independent of velocity
F_1 = Coefficient of friction force - dependent on velocity

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F_2 = Coefficient of windage force (Drag coefficient)
n = Velocity exponent
V = Velocity at the roller surface
I = Vehicle Inertia (Dyno inertia plus appropriate amount of inertia as simulated by the control system)
dv/dt = Acceleration
m = Vehicle Mass
g = Acceleration due to gravity
grad = Gradient in percent (%)

The EPA and Arterial test cycles do not include any gradients (uphill or downhill) therefore, the Road Load equation becomes:

$$RL = F_0 + F_1V + F_2V^n + I\,dv/dt$$

To aid in the development of a set of coefficients, University of Idaho personnel conducted coast down evaluations of the test vehicles in Idaho prior to the scheduled ETF test date, Figure 2.
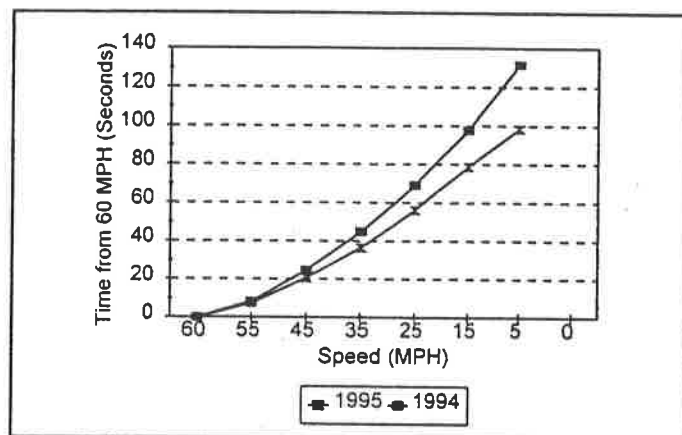

Figure 2. Coast down data for both the 1994 and 1995 vehicles used in the emissions tests.

Based on the coast down data, LA-MTA personnel developed a set of coefficients as a starting point for road load model development. 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. The coefficients developed for this program for 1994 were F_0 = 50 lbs., F_1 = 0.84 lbs/mph, F_2 = 0.00009 lbs/mph^2 and I = 7,900 lbs and for 1995 were F_0 = 120 lbs., F_1 = 0.75 lbs/mph, F_2 = -0.0075 lbs/mph^2 and I = 8,140 lbs. Road gradient was 0 degrees throughout the tests.

FUELS TESTED - Fuels tested during the course of the two years tests included:
(1) Phillips D2 low-sulfur diesel control fuel (DIESEL or D2);
(2) 100% rape methyl ester (100RME);
(3) 100% rape ethyl ester (100REE);
(4) 50% RME - 50% diesel (50RME);
(5) 50% REE - 50% diesel (50REE);
(6) 20% RME - 80% diesel (20RME);
(7) 20% REE - 80% diesel (20REE);

The RME and REE were produced in the Agricultural Engineering Laboratory at the University of Idaho. Complete fuel characterization data according to ASAE EP X552 (31) are provided in Table 1.

VEHICLE INSTALLATION - The test vehicle was installed on the chassis dynamometer in accordance with typical ETF practice. A total of seven sensors were installed but the fuel pressure sensor was not utilized due to a problem which occurred with the sensor fitting. The test sensor locations were at the oil filter adapter housing, boost pressure at manifold, exhaust temperature at tailpipe adapter, fuel pressure at pump inlet, coolant temperature, and inlet air temperature.

FUEL MASS FLOW RATE - Fuel consumption was determined by direct weighing. The weight of fuel was read at the start and end of each test. In practice, this method had considerable error due to vibrations set up by running the truck because of the direct connection between the fuel tank on the scales, the fuel delivery and return lines and engine connections.

Table 1.
Fuel Characterization Data

	RME	REE	50REE	20REE	D2
Fuel Specific Properties					
Specific Gravity, 60/60	0.8802	0.876	0.862	0.8535	0.8495
Viscosity, cSt @ 40°C	5.65	6.17	4.06	3.2	2.96
Cloud Point, °C	0	-2	-9	-12	-12
Pour Point, °C	-15	-10	-13	-15	-22
Flash Point, PMCC, °C	179	171	79	79	74
Boiling Point, °C	347	273	204	213	191
Water and Sediment, % Vol.	<0.005	<0.005	<0.005	<0.005	<0.005
Carbon Residue, % wt	0.08	0.06	0.07	0.12	0.16
Ash, % wt	0.002	0	0	0	0.002
Sulfur, %wt	0.012	0.012	0.024	0.033	0.036
Cetane Number	61.8	59.7	54.2	50.7	49.2
Heat of Combustion, MJ/kg					
Gross	40.54	40.51	42.94	44.64	45.42
Net	37.77	37.82	40.08	41.94	42.90
Copper Corrosion	1A	1A	1A	1A	1A
Karl Fischer Water, ppm	757	761	308	200	38
Particulate Matter, mg/L					
Total	1.1	1.4	1.4	1.1	0.9
Non-Combustible	<0.1	<0.1	<0.1	<0.1	<0.1
Elemental Analysis					
Nitrogen, ppm	10	11			
Carbon, %	78.7	76.83	82.07	84.73	86.87
Hydrogen, %	12.66	11.8	13.49	12.73	12.98
Oxygen, % (by difference)	9.22	11.36	4.42	2.51	0.33
Iodine Number	91.9	96.7	52.6	24.3	8.6
Ester Specific Properties					
Percent Esterified	98.02	94.75			
Acid Value	0.128	0.097			
Free Glycerine, %wt	0.4	0.72			
Total Glycerine, %wt	0.86	0.93			
Free Fatty Acids, %wt	0.57	0.58			
Monoglycerides, %wt	0	0.58			
Diglycerides, %wt	1.35	1.33			
Triglycerides, %wt	0.45	2.17			
Alcohol Content, % mass	<1	<1			
Catalyst, ppm	11	12			
Fatty Acid Composition					
Palmitic (16:0)	2.8	2.6			
Stearic (18:0)	0.9	0.9			
Oleic (18:1)	12.6	12.8			
Linoleic (18:2)	12.1	11.9			
Linolenic (18:3)	8	7.7			
Arachidic (20:0)	0.8	0.7			
Eicosenoic (20:1)	7.4	7.4			
Behenic (22:0)	0.7	0.7			
Erucic (22:1)	49.8	49.7			
Nervonic (24:1)	0.9	0.9			

TEST DESIGN - Two problems had to be overcome in developing a test design. The first was that the number of potential test runs was unpredictable. The test facility was scheduled for one week during which time all testing had to be completed. The second hurdle was a tendency for emissions to vary with ambient conditions. A randomized block design with unequal sample numbers was developed. In this design the main fuels were randomized and tested first and tests of fuel blends were included in later tests in each block. The fuel test procedure is shown in Table 2. As it turned out, sufficient time was available to test each fuel and desired blend. A Fisher's Protected LSD analysis using SAS (Statistical Analysis System) was carried out on the data.

TEST PROCEDURES - Although no standardized test procedures for heavy-duty vehicle chassis dynamometer emissions testing currently exist, the ETF has integrated the applicable requirements and guidelines of CFR 40, Part 86, Subpart B, "Emission Regulations for 1977 and Later Model Year New Light-Duty Vehicles and New Light-Duty Trucks; Test Procedures" and Subpart N, "Emissions Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines: Gaseous and Particulate Exhaust Test Procedures". Specific test programs may vary from these guidelines as dictated and noted by the customer contract.

Table 2
Test Plan for Emissions Tests

1994 Arterial Cycle

Block 1:	100% REE	100% Diesel	100% RME
Block 2:	100% Diesel	100% REE	100% RME
Block 3:	20% REE	20% RME	50% RME
	50% REE	100% Diesel	
Block 4:	100% Diesel	100% RME	100% RME
	100% REE	100% REE	
Block 5:	20% REE	100% Diesel	20% RME
	50% REE	50% RME	100% Diesel

1994 EPA Cycle

Block 1:	100% REE	100% Diesel	100% RME
	100% REE	100% RME	100% Diesel
	100% RME		
Block 2:	20% RME	20% REE	100% REE
	100% Diesel	50% REE	

1995 EPA Cycle (Tests are Hot Start unless indicated)

Block 1: With the Catalytic Converter:
Cold Start - 100% REE, 100% REE, 100% REE, 100% REE, Diesel
Diesel, Diesel, Cold Start - Diesel, 20% REE, 20%, REE 20%
REE, 50% REE.50% REE, 50%. REE, 100% REE

Block 2: Without the Catalytic Converter
Cold Start - 100% REE, 100% REE, 100% REE, 100% REE, Diesel
Diesel, Diesel, Cold Start - Diesel, 20% REE, 20% REE 20% REE,
50% REE,50% REE

The Hot Start" test procedure was as follows:
1. The test fuel delivery tube was connected to the input line and the return line was connected to the waste tank. The engine was started and run for 50 seconds.
2. The engine was stopped and the return line was connected to the test fuel tank.

3. The engine was restarted and idled for approximately 10 minutes until the MTA technicians were ready to run the test.
4. The vehicle was operated under load until the operating temperatures stabilized.
5. The test was started and the cycle completed.
6. While the technicians were taking data, weighing particulate filters, etc., the fuel was switched to the next fuel to be tested.

The first test each day was a cold start test using the fuel from the last test of the previous day so the engine could be started and that test run without delay. Tests were conducted on March 14-18, 1994 and March 20-24, 1995. Twenty-six modified arterial cycles and 13 EPA test cycles were completed in 1994 and 28 EPA cycles including 4 cold start tests (one each morning) were completed in 1995.

PRESENTATION AND DISCUSSION OF RESULTS

Since a large amount of data was collected, only data collected during the 1994 and 1995 emissions tests which provide comparisons will be presented in this paper. A more detailed description of the 1994 emissions tests can be found in Peterson and Reece (2). Modal data were archived every 1 second during the test. Average and total values were calculated for cycles, phases and overall. Thus the potential exists for additional analysis of test data. A general overview of the 1994 tests compared to the 1995 tests is shown in Figures 3 - 7. With the exception of PM, exhaust emissions were generally lower when the vehicle was tested using the 100% REE fuel.

HC emissions generally decreased as the percentage of REE was increased in the fuel blend. HC emissions did increase slightly from the 20REE to 50REE fuel blends when the vehicle was tested without the catalytic converter installed. However, emissions continued to decrease when the same vehicle configuration was tested using 100REE. The mean average emissions for HC for both the 1994 and 1995 tests, both without the catalytic converter, are shown graphically in Figure 3.
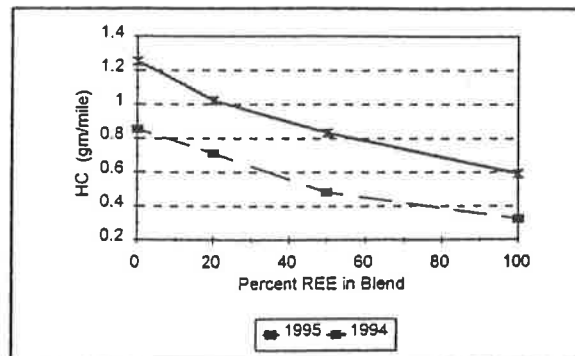

Figure 3. 1994 and 1995 data for HC for the EPA cycle and various blends of diesel and REE without the Catalytic converter.

CO emissions decreased as the percentage of REE was increased regardless of the vehicle test configuration. CO emissions for both 1994 and 1995 without the catalytic converter are shown graphically in Figure 4.
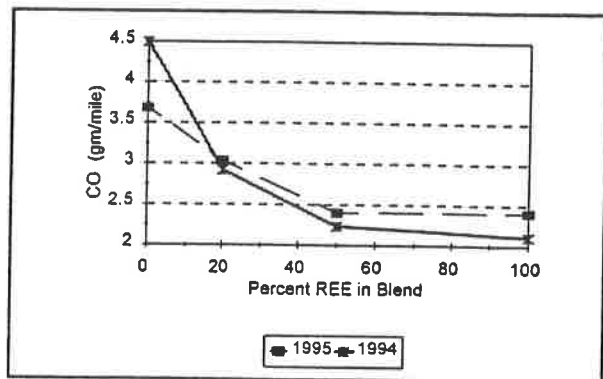

Figure 4. 1994 and 1995 data for CO for the EPA cycle and various blends of diesel and REE without the catalytic converter.

NO_x 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 1994 and 1995 without the catalytic converter are shown in Figure 5.
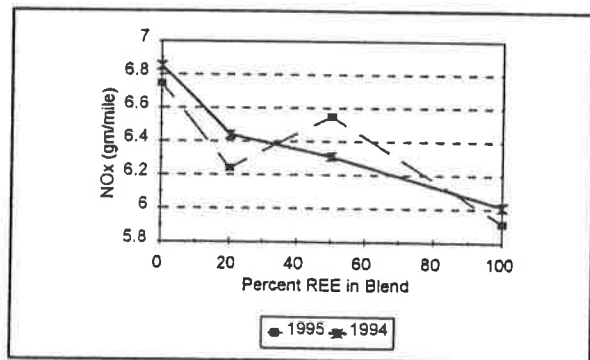

Figure 5. 1994 and 1995 data for NO_x for the EPA cycle and various blends of diesel and REE without the catalytic converter.

CO_2 emissions increased as the percentage of REE increased with the catalyst installed on the vehicle. CO_2 emissions for both 1994 and 1995 without the catalytic converter are shown graphically in Figure 6.

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. PM emissions for both 1994 and 1995 without the catalytic converter are shown graphically in Figure 7.

In 1994, comparisons were made between blends of rapeseed oil ethyl ester, rapeseed oil methyl ester and diesel reference fuel. Also in 1994, two cycles were used as
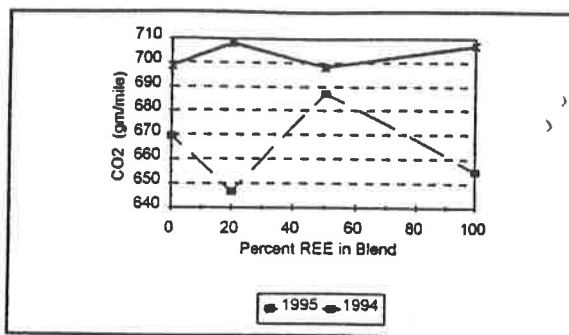

Figure 6. 1994 and 1995 data for CO_2 for the EPA cycle and various blends of diesel and REE without the catalytic converter.
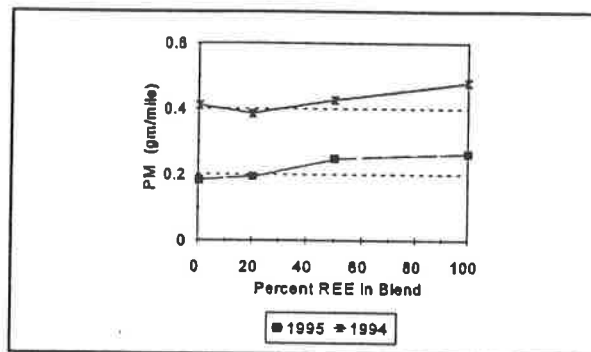

Figure 7. 1994 and 1995 data for PM for the EPA cycle and various blends of diesel and REE.

previously described, the arterial cycle and the EPA cycle. In 1995, only the EPA cycle was used. Fuels compared in 1995 were blends of rapeseed ethyl ester and diesel reference fuel. Also in 1995, the vehicle was tested with and without the catalytic converter. The data will be presented first by showing the absolute values for the 1994 and 1995 tests with blends of REE and diesel using the EPA cycle. The comparisons will then be shown as ratios of either the 1994 or 1995 data sets. Thus, rapid relative comparisons are provided in the tables and any desired absolute value can be found through multiplication. For clarity Figures 3-7 were provided to give an overview of the data trends.

1994 RESULTS - The data collected in 1994 (with no catalytic converter) for each of the regulated emission compounds for diesel reference fuel, 20% REE, 50% REE and 100% REE are shown in Table 3 in grams/mile and in Table 4 with values normalized by dividing by the diesel level. Diesel/diesel is shown as 1.0 and the other fuels relative to diesel, HC for 100% REE/diesel = 0.472 or 100% REE is 47% of diesel, for example.

Table 3
1994 Emissions Data, EPA Cycle
(no catalytic converter)
(gm/mile)

	HC	CO	NOx	CO_2	PM
Diesel	1.254a*	4.497a	6.850a	698.58a	0.411a
20REE	1.021b	2.920b	6.440b	708.18a	0.386a
50REE	.834c	2.230c	6.310bc	698.32a	.428a
100REE	.592d	2.107c	6.013c	707.04a	.480a

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

Table 4
1994 Emissions Data, EPA Cycle
(no catalytic converter)
(blend value/diesel)

	HC	CO	NOx	CO_2	PM
Diesel	1.000a*	1.000a	1.000a	1.000a	1.000a
20REE	0.814b	0.649b	0.940b	1.014a	0.938a
50REE	0.665c	0.496c	0.921bc	1.000a	1.040a
100REE	0.472d	0.468c	0.878c	1.012a	1.169a

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

Table 5, shows how the arterial cycle compares with the EPA cycle in the 1994 tests. The relative consistency of the values down the columns for each compound indicates that the trends for the various fuels were essentially the same for both cycles but the absolute values in grams/mile were lower in the arterial cycle than for the EPA cycle.

Table 5
1994 Emissions Data for Rapeseed Ethyl Ester
Comparing the Arterial and EPA Cycles
(no catalytic converter)
(Arterial cycle/EPA cycle)

	HC	CO	NOx	CO_2	PM
Diesel	0.664*	0.729*	0.909*	0.933*	0.732*
20REE	0.655	0.813	0.928	0.923*	0.741
50REE	0.649*	0.827	0.906*	0.941	0.789*
100REE	0.562*	0.824*	0.919*	0.931*	0.635
Average	0.633	0.798	0.915	0.932	0.724

*Numbers followed by an asterisk imply a significant difference between the arterial cycle and the EPA cycle for that comparison according to Fischer's protected LSD (p <0.05).

1995 EMISSIONS DATA - The data collected using the EPA cycle in 1995, without the catalytic converter, for each of the regulated compounds for diesel, 20% REE, 50% REE

and 100% REE are shown in Table 6 in grams/ mile and in Table 7 with values normalized by dividing by the diesel level. Diesel is then shown as 1.0 and the other fuels as a percent of diesel, HC for 100% REE is 38% of diesel, for example.

Table 6
1995 Emissions Data for Rapeseed Ethyl Ester, EPA Cycle
(no catalytic converter)
(gm/mile)

	HC	CO	NOx	CO_2	PM
Diesel	0.854a	3.683a	6.747a	669.54a	0.184a
20REE	0.712b	3.033b	6.240b	646.55a	0.195b
50REE	0.483c	2.400c	6.550b	687.05a	0.249c
100REE	0.324d	2.403c	5.913c	654.81a	0.264d

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

Table 7
1995 Emissions Data, EPA Cycle
(no catalytic converter)
(blend value/diesel)

	HC	CO	NOx	CO_2	PM
Diesel	1.000a	1.000a	1.000a	1.000a	1.000a
20REE	0.834b	0.824b	0.925b	0.966a	1.059b
50REE	0.565c	0.652c	0.971b	1.026a	1.352c
100REE	0.380d	0.652c	0.876c	0.978a	1.434d

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

RME - REE COMPARISON - In 1994, rapeseed oil methyl ester and rapeseed oil ethyl esters were both tested as fuels using the EPA and Arterial cycles. Table 8 shows a comparison of the two cycles by showing the ratio (RME/REE) for diesel, 20%Biodiesel, 50%Biodiesel, and 100%Biodiesel. In this chart diesel is always 1 (diesel is the control), the 50%Biodiesel data are not shown for the EPA cycle because no data were taken due to a lack of time. The data show that 100% RME is higher in HC (10.5%), NOx (3.7%) , and PM (5.8%) averaged for both cycles. For the arterial cycle CO was higher for 100RME than for 100REE (9.2%) but was lower (1.1%) for the EPA cycle. CO_2 was lower for RME than for REE, which it would have to be since the other carbon containing compounds were higher.

Table 8
1994 Emissions Data, Arterial Cycle
Data shown is the ratio RME/REE
(no catalytic converter)

Arterial Cycle					
	HC	CO	NOx	CO$_2$	PM
Diesel	1.000	1.000	1.000	1.000	1.000
20RME/20REE	0.995	1.032	1.015	0.997	0.944
50RME/50REE	0.967	1.081	1.032*	0.998	0.961
100RME/100REE	1.112	1.092	1.024*	0.997	1.054
EPA Cycle					
Diesel	1.000	1.000	1.000	1.000	1.000
20RME/20REE	0.981	1.051	1.025	1.001	0.915
50RME/50REE	NA	NA	NA	NA	NA
100RME/100REE	1.098	0.989	1.050	0.996	1.062

*Numbers followed by an asterisk imply a significant difference between RME and REE for that comparison according to Fischer's protected LSD (p <0.05).

1994 VS 1995 WITHOUT THE CATALYTIC CONVERTER

Table 9 shows the comparison of the 1995 and 1994 tests; the numbers shown are the ratio of 1995 divided by 1994) for the EPA cycle with rapeseed oil ethyl ester as a fuel in the blends shown and both years without the catalytic converter. 1995 data tends to be lower for HC (63%), CO$_2$ (94.5%) and PM (52%) compared to 1994 data. CO was 18.1% lower for diesel and 14.1% higher for 100% REE in 1995 compared to 1994.

Table 9
A Comparison of Emission Data for 1994 and 1995, Data, EPA Cycle
(no catalytic converter)
(ratio 1995/1994)

	HC	CO	NOx	CO$_2$	PM
Diesel	0.681*	0.819*	0.985	0.958	0.448*
20REE	0.697*	1.039	0.969	0.913*	0.506*
50REE	0.579*	1.076	1.038	0.984	0.582*
100REE	0.548*	1.141*	0.983	0.926*	0.550*
Average	0.626	1.019	0.994	0.945	0.521

*Numbers followed by an asterisk imply a significant difference between 1994 and 1995 for that comparison according to Fischer's protected LSD (p <0.05).

CATALYTIC CONVERTER VS. NO CATALYTIC CONVERTER

Table 10 shows the comparison of the 1995 test data with and without the OEM catalytic converter for the same fuels as reported in the other tests. The catalytic converter reduced HC (9%) and PM (43.4%) but had little effect on the other compounds.

Table 10
A Comparison of Emission Data With and Without the Catalytic Converter
EPA Cycle
(ratio With Converter/Without Converter)

	HC	CO	NOx	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	1.037	0.953*	0.970	0.570*
100REE	0.857*	1.001	1.040*	1.035	0.481*
Average	0.910*	0.998	1.005	1.007	0.566*

*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).

COLD START TESTS

In 1995, each day, one cold start test was conducted resulting in two tests with the catalytic converter and two without the catalytic converter. Table 11 is a relative comparison between the cold start data and the hot start data for each of the fuels tested.

Table 11
Cold Start Emissions Data
With and Without the Catalytic Converter, EPA Cycle
(ratio 1995 Cold Start/Hot Start)

	HC	CO	NOx	CO$_2$	PM
Without the Catalytic Converter					
Diesel	1.529	2.203	0.771	1.134	2.332
100REE	1.914	1.946	1.585	1.134	1.365
Average	1.721	2.074	1.178	1.134	1.849
With the Catalytic Converter					
Diesel	1.144	1.884	1.131	1.144	1.932
100REE	2.001	1.947	1.125	1.160	1.793
Average	1.573	1.916	1.128	1.152	1.863

*Insufficient data for statistical comparison's

Table 11 is indicative of the change between the cold start and hot start emissions for both the vehicle with and without the catalytic converter installed for all compounds. The absolute cold start PM values (gm/mile) were as follows:

	gm/mile
Diesel - No Catalytic Converter	0.3557
Diesel - With Catalytic Converter	0.2358
100% REE - No Catalytic Converter	0.4734
100% REE - With Catalytic Converter	0.1733

These data show a larger increase in PM when the catalytic converter is installed and the fuel is diesel than for when it is not on the vehicle and a smaller increase in PM with the catalytic converter installed when 100% REE is the fuel. It should be remembered that only one run of the cold start test was used to generate the data.

GENERAL OBSERVATIONS - These data show similar trends for all fuels with a slight reduction in CO and NOx for ethyl ester compared to methyl ester. They also show a significant reduction in HC, CO, and NOx as the 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 and CO were reduced approximately 50% by using rapeseed esters. CO_2 increased by an amount indicative of the reduction in CO while no statistically significant change in PM was detected although the trend was lower PM at the 20% vegetable oil ester and increased PM at the 100% fuel mixture. Other researchers have indicated that NOx and PM are inversely related, and that may explain the apparent difference in results from these tests. It has more generally been found that the esters increase NOx 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. In either case, the result was consistent for both methyl and ethyl ester and for both cycles tested. Ethyl ester at the 100% and 50% level were lower in NOx than methyl ester.

Repeatability for HC, CO, CO_2 and NOx was very good. When one experiments with a number of fuels on a limited budget, setting up a test procedure is extremely critical. It would have been more desirable to have replicated each fuel two or three times in succession and to have replicated each fuel in time in random fashion as well. However, time did not allow this luxury. As a compromise, each fuel was tested in random fashion in time and then during one block, fuels were tested in succession. The 1994 data show that the test procedure was successful in preventing mixing of fuels and that the previous fuel did not effect the outcome of the succeeding fuel.

CONCLUSIONS

Specific conclusions of this study are:
1. HC and CO decreased and CO_2 and PM emissions increased as the percentage of REE was increased in the fuel blend. HC decreased nearly linearly with blend of

Biodiesel, while CO had over 90% of it's decrease in the 0 - 50% blend range.

2. NOx decreased as the percentage of REE was increased in the fuel blend with the catalytic converter installed. Without the catalytic converter NOx increased between 20% and 50% REE and then declined for 100% REE.

3. HC emissions for 100% REE fuel was only 47% that of diesel in 1994 and 38% in 1995. CO emissions for 100% REE fuel were 47% that of diesel in 1994 and 65% in 1995. CO emissions for 20% REE fuel were 65% that of diesel in 1994 and 82% in 1995.

4. NOx emissions were reduced to 88% that of diesel in both 1994 and 1995.

5. CO_2 emissions for 100% REE were increased 1.2% compared to diesel in 1994 and were decreased 2% in 1995.

6. PM emissions for 100% REE was increased 17% in 1994 and 43% in 1995 compared to diesel.

7. The modified arterial cycle generally resulted in lower absolute emissions (gm/mile) than the EPA cycle, however, the trend of comparisons between biodiesel and diesel were similar.

8. The data shows that 100% RME is higher in HC (10.5%), NOx (3.7%), and PM (5.8%) than 100% REE. But for CO, 100% RME was higher than 100% REE (9.2%) for the arterial cycle but lower (1.1%) for the EPA cycle. CO_2 was lower for RME than for REE, which it would have to be since the other carbon compounds were higher.

9. 1995 data tends to be lower for HC (37%), CO_2 (5.5%) and PM (48%) compared to the 1994 data. CO was 18.1% lower for diesel and 14.1% higher for 100% REE in 1995 compared to 1994.

10. The catalytic converter reduced HC (9%) and PM (43.4%) but had little effect on the other compounds.

11. Cold start tests resulted in higher regulated emissions for all compounds than hot start tests. Biodiesel increases were HC (95.7%), CO (94.7%), NOx (35.5%), CO_2 (14.7%) and PM (57.9%).

ACKNOWLEDGEMENTS

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