Exhaust Emissions and Engine Performance from the Use of Soya Methyl Ester Blended with ARB #2 Diesel in a 6V92TA MUI Engine

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ABSTRACT

This project's objective was to examine the viability of a soya bean oil derivative, soya methyl ester (methyl ester) and ARB diesel fuel blends as an interim emissions-reduction solution for California's transit properties as they progressively convert to cleaner technologies and fuels. A Detroit Diesel 6V92TA MUI engine was operated on a blend of two fuels: #2 diesel, subject to October 1, 1993 California Air Resources Board standards (ARB diesel) and methyl ester. Fuel characterization was conducted on ARB diesel, methyl esters from various suppliers and methyl ester/ARB diesel blends. Fuel quality varied with methyl esters from different suppliers. Engine dynamometer tests identified significant trends in exhaust emissions. When compared to the ARB diesel baseline, higher blend percentages of methyl esters led to increased emissions of oxides of nitrogen (6%-10%), carbon dioxide (2%-3%) and soluble particulate matter (19%-35%). Also noted were reductions in total hydrocarbons (16%-32%), carbon monoxide (8%-22%) and insoluble particulate matter (10%-37%). Chassis dynamometer tests showed similar trends in exhaust emissions. Field tests consisted of daily refuelling (using 20/80 and 25/75 methyl ester/ARB fuel blends) and operation of a mass transit passenger vehicle within the Los Angeles basin. These tests were conducted to determine the blends' effects on engine performance and wear. Drivers' comments and periodic engine oil analyses indicated no adverse effects. This project demonstrated that 20% soya oil-based methyl esters/ARB diesel blends do not lower emissions to merit utilization by the heavily regulated California mass transit industry. However, the results do indicate that soya oil-derived methyl esters, coupled with known technologies that reduce the soluble fraction of particulate emissions, deserves further exploration as a possible transition fuel option for the Southern California mass transit sector. This project did not develop any new jobs within the Los Angeles basin.

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BACKGROUND

Recent research on plant oil and/or animal fat derived fuels indicated that these biofuels reduce emissions of certain criteria pollutants when utilized in a compression ignition (diesel) engine (Reed, 1993). Research using raw, degummed vegetable oils was conducted with farm tractors during the early 1980's in Illinois, Idaho, Missouri and North Dakota. This work proved that diesel engines could be fuelled with vegetable oils. At the same time certain difficulties were encountered (e.g. injector coking). Additional research, in the US, as well as abroad, showed that methyl esters of various vegetable oils created fewer difficulties than the use of the vegetable oils themselves in heavy duty diesel engines. It was therefore suggested that testing on on-road vehicles (e.g. mass transit buses) be conducted using vegetable oil methyl esters. A vegetable oil derivative that has recently received extensive attention is a soya bean oil derivative, soya methyl ester (methyl ester). Produced through a catalysed reaction between soya bean oil and methanol, it was demonstrated that methyl ester could be used to fuel a diesel engine. Because methyl ester contains less usable energy per unit volume, a compression ignition engine fuelled on 100% methyl ester will develop approximately five percent less power than a similar engine fuelled on diesel fuel. Although a power loss was noted, there was no significant reduction in the torque. Also, most exhaust emissions were observed to be slightly lower than emissions from a similar engine fuelled with #2 diesel (Schumacher, 1993).

The present study was concerned with applied research on the development of methyl ester as a fuel in diesel engines. It was proposed to evaluate, from a commercial user's perspective, the benefits and common-use problems, if any, of a domestically produced "transition fuel" for diesel engines that would cost-effectively provide an overall emissions reduction. Methyl ester presented the potential to be this transition fuel because of the progress of previous research with this fuel and because of the economic forces driving this area of research. There is ongoing concern among the soya bean producers in the US due to considerable oversupply of soya oil. It is important to note that the soya farmer "check-off" dollars have funded much of the recent methyl ester research and demonstration projects. Due to the relatively high price of soya methyl ester and because of suspected materials compatibility problems it was decided that this project would focus on fuels made up of methyl ester and diesel fuel blends rather than on methyl esters alone.

It was originally anticipated, based on data available in mid-1992, that from an engine fuelled on a methyl ester #2 diesel blend, criteria pollutant emissions could decrease by from 5% to 27% as compared to a regular No. 2 diesel baseline. In early 1993, however, it was demonstrated (School and Sorenson, 1993) that NO_x emissions resulting from a methyl ester/diesel blend actually increased. The same study also showed that NO_x emissions were affected by changes in engine timing. We assumed timing would have a greater relative effect on NO_x than on PM. We therefore decided to pursue a "trade-off" during the engine dynamometer testing: NO_x emissions reductions were to be achieved through judicious engine timing delays at the expense of some of the reduced PM's. Lower emissions would be then produced across the spectrum of relevant criteria pollutants.

California mass transit authorities were given a limited period during which to reduce a range of vehicle emissions to prescribed levels. One possible strategy for effectively reducing emissions was to replace diesel with a cleaner fuel option. Available options include propane, natural gas, electricity, methanol, ethanol and other biofuels. All of these fuels had demonstrated, under specific test conditions, some capacity to reduce emissions. There were prohibitive costs associated with the Clean Air Act's ultimate goal of zero-emission vehicles within a specified time frame. With the possible exception of some biofuels, all these fuels required extensive and expensive engine and/or infrastructure retrofits. It was therefore suggested that a biofuel might become that cost-effective "transition fuel" that would help the resource-limited mass transit properties navigate the difficult path between low emissions mandates and higher operating costs. The biofuel selected for the project was a soya bean oil derivative, soya methyl ester (methyl ester), commonly known as "biodiesel".

Project Objectives

The primary goals of this project were to:

1. Investigate the potential for emissions reductions using a methyl ester/ARB diesel blend.
2. Quantify these emissions reductions via engine and chassis dynamometer tests.
3. Establish optimal methyl ester/ARB diesel blend parameters.
4. Verify the feasibility of methyl ester/ARB diesel blend as a cost-effective interim fuel for use in California transit and trucking applications.

Based on data available in mid-1992, our initial proposal anticipated that an engine fuelled on a methyl ester #2 diesel blend could produce the following emissions reductions, as compared to a regular No. 2 diesel baseline:

- particulate matter (PM) by 21%
- oxides of nitrogen (NO_x) by 5%
- carbon dioxide (CO_2) by 9%
- total hydrocarbons (THC) by 27%

In late 1993, however, our engine dynamometer work demonstrated that *both $_{NOx}$ and PM emissions increased.* The "trade-off" concept was therefore invalidated: no engine timing delay trade-off benefits could be realized. Subsequent engine dynamometer data analysis showed that while total particulate emissions did increase, the insoluble fraction of PM markedly decreased with an increased methyl ester percentage. This is significant in that with utilization of a methyl ester/ARBdiesel blends in combination with current oxidation catalyst technology (which reduces the soluble fractions of PM), *total* PM emissions (insoluble as well as soluble) could be cost-effectively reduced. This would then facilitate the PM/NO_X emissions "trade-off" outlined above.

Testing and Demonstration Protocol

A Detroit Diesel 6V92TA Mechanical Unit Injection (MUI) engine was utilized during the course of this project for emissions and performance testing purposes. An older MUI engine (as opposed to a more modern DDEC design) was chosen because MUI technology represented the present state of diesel engine technology in use by the majority of mass transit properties at this time. It is these older, less clean burning engines that would stand to benefit from a cost-effective, relatively low emission interim fuel. Testing concentrated on five key areas:

- fuels characterization,
- engine dynamometer tests,
- chassis dynamometer tests,
- on-road vehicle engine performance testing and field use issues in a mass transit application,
- materials compatibility.

Fuel characterization measurements and tests were conducted on ARB diesel, EPA diesel (diesel fuel subject to October 1, 1993 US EPA Standards), methyl ester, and methyl ester/ARB diesel blends in an effort to fully document and compare fuel composition and quality. These tests included gross heating value, distillation curve, pour point, API gravity, flash point, Cetane numbers and viscosity measurement. In addition, gas chromatographic (GC) analyses were performed on three batches of methyl ester obtained from two suppliers, as well as on three methyl ester/ARB diesel fuel blends. Variations in methyl ester fuel qualities were discovered.

Engine and chassis dynamometer tests were conducted for the purpose of monitoring and defining engine performance and emissions parameters. Engine dynamometer work was performed and ARB and EPA diesel emissions baselines were established. To focus on California mass transit emissions compliance targets, methyl ester/ARB diesel blends were studied. These blends ranged from 20% to 40% methyl ester. For each blend, emissions monitored included: PM (total and soluble), CO_2, CO, $_{NOX}$, THC and brake specific fuel consumption (BSFC). Significant trends in exhaust emissions were demonstrated (a difference of 5% or more from baseline measurements). With increasing percentage of methyl esters came reductions in THC, CO and insoluble PM in comparison to the ARB diesel baseline. Increases in $_{NOX}$, CO_2 and total particulates (both the soluble and insoluble fractions of particulate matter) were also observed (see *Figure 1*). Data from chassis dynamometer testing exhibited trends similar to those found through engine dynamometer tests.

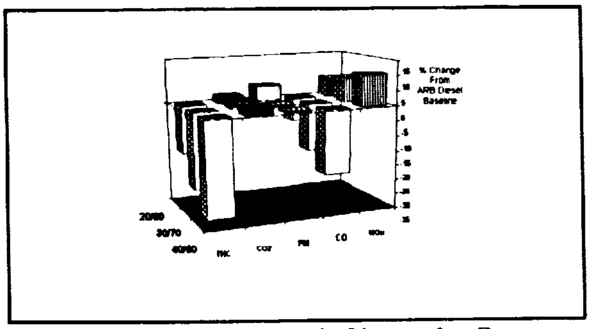


Figure 1. Emissions Trends Observed in Engine Dynamometer Testing

Limited on-road vehicle durability/compatibility tests (10,000 miles in duration) were performed at Gardena Municipal Bus Lines (GMBL) to study the effects of a methyl ester/ARB diesel blend on engine performance and wear. These tests consisted of the daily refuelling and operation of a mass transit passenger bus with a 20/80, and later with some 25/75 methyl ester/ARB diesel blends. Engine oil was regularly sampled to monitor for abnormal engine wear. Components surveyed in the oil samples included twenty chemical elements (metals and metalloids) that are commonly assumed to indicate engine wear. All oil analyses were within normal specifications. Vehicle operators noted no difference in engine power between buses fuelled with ARB diesel and the test bus fuelled with methyl ester/ARB diesel blends.

Material compatibility tests were conducted at ADEPT's facilities and at the GMBL bus refuelling station. Previous research had shown that certain materials, including neoprene, vinyl and vinyl/PVC blends were incompatible with methyl ester. It was understood that these components could not be used in the assembly and operation of the fuel blending and dispensing station.

It had been reported that polyurethane hoses had been successfully used by methyl ester researchers, though no documentation for this assertion was available. For a period of five months a sample of methyl ester was sealed inside a ten-inch long section of polyurethane hose material at room temperature. After two months the outside surface of the hose began to "sweat," indicating that the ester was penetrating through the hose material.

It was also observed that sealed plastic containers used to store methyl ester would deflate over time. We assumed this was caused by gradual polymerization occurring in the presence of O_2. In addition, methyl ester stored in metal containers and exposed to air changed colour and became less clear over a five-month period.

METHODOLOGY

This study concentrated on five key areas:

- fuels characterization,
- engine dynamometer tests,
- chassis dynamometer tests,
- on-road vehicle engine performance testing and field use issues in a mass transit application,
- materials compatibility.

A list of the testing facilities used in this project appears in *Table 1*.

TABLE 1. TESTING FACILITIES

Laboratory	Testing Conducted
ORTECH International, Inc.	Engine Dynamometer
MTA-ETF	Chassis Dynamometer
CORE Laboratories	Fuels Characterization
US Dept. of Agriculture	Fuels Characterization
State of California Division of Measurement Standards	Fuels Characterization
Titan Laboratories	Oil Analysis

TABLE 2. LIST OF COMPONENTS FOR UPGRADE #16-C BY VDDA TO A 6V92 TA MUI ENGINE

Component	Description
90F80(T) Injectors	Special new Transit Spec., low emission, optimized output.
Blower	Changed to 100% by-pass. Blower output self modulates according to turbocharger output. Lower flow at top end. Reduced NOX, smoke, PM_{10}.
Turbocharger	Improved efficiency, quicker response. Matched to blower to output. Better fuel consumption. Lower PM_{10}, NOX, smoke.
Oil Filter Element	Changed to 12 micron to improve filtration, less wear.
Hose Clamps	Proper hose installation.
Air Inlet Housing	Changed to accommodate new turbocharger.
Lock Plate	Prevents Cam Bolt from losing torque after installation.
Cylinder Kit	High tension oil expander rings, barrel faced fire ring, dome to skirt seals, close clearance skirts. Reduced oil consumption.

TABLE 3. TESTS USED IN CORE LABORATORIES FUEL CHARACTERIZATION

Test	Test Method
Distillation curve	ASTM D-86
Heating Value (Gross)	ASTM D-613
Pour Point	ASTM D-97
API Gravity	ASTM D287
Flash Point	ASTM D-93
Cetane # (neat)	ASTM D-613
Viscosity	ASTM D-445

Diesel Engines

Two remanufactured 1983 6V92TA MUI engines were purchased through Valley Detroit Diesel Allison (VDDA) from Detroit Diesel Corporation (DDC). These engines were built to EPA D-bus standards (16-C upgrade, see *Table 2*).

Additional 16-C engine specifications included 9F80(T) injectors times at 1.470, a throttle delay setting of 0.636", a speed rating of 2,000 rpm and a high idle speed of 2,150 rpm.

Fuels Characterization

Fuels characterizations on both ARB diesel and methyl ester were conducted by several laboratories in accordance with ASTM testing standards. These tests included gross heating value, distillation curve, pour Fuels characterizations on both ARB diesel and methyl ester were conducted by several laboratories in accordance with ASTM testing standards. These tests included gross heating value, distillation curve, pour point, API gravity, flash point, Cetane number and viscosity tests (see *Table 3*). In addition, GC analyses were conducted on three batches of methyl ester obtained from two suppliers as well as on the various blends with diesel fuels in an effort to fully document fuel composition and quality.

Additional flash point tests on eleven methyl ester/ARB diesel blends (0% to 100% methyl ester) were conducted by Dr. Jon Van Gerpen, Iowa State University, Department of Mechanical Engineering using a Pensky-Martens I Closed Tester.

Fuels

ARB diesel was donated by Texaco's Bakersfield refinery (material/trade name: Texaco Low Sulfur CARB Diesel 2). Texaco ARB diesel was most suitable for this project as it fully conforms to the 10% maximum aromatics content requirement for ARB diesel (effective October, 1, 1993). Methyl ester was purchased from Calgene Chemical (material/trade name: OLEOCAL ME-130) and from P&G. The P&G methyl ester was initially purchased via Interchem and subsequently via Fosseen Manufacturing.

Engine Dynameter Testing

Engine dynamometer testing was conducted at ORTECH International, Inc. (ORTECH) following the Federal protocol prescribed for the EPA heavy-duty engine transient cycle. Power parameters monitored included: engine speed, torque, brake horse power, and fuel rate. Temperatures monitored included: combustion air, turbocharger out, coolant in, coolant out, oil sump and fuel temperatures. Pressures monitored included: exhaust back pressure, intake restriction, oil and fuel pressures. For each blend, the emissions monitored included: PM (total and soluble), CO_2, CO, NO_x, total hydrocarbons (THC) and brake specific fuel consumption (BSFC).

All instrumentation was calibrated following standard operating procedures. Baseline emissions tests were performed and gaseous and particulate emissions were collected with both EPA and ARB diesel fuels. Prior to running each set of tests, the engines were conditioned on each new fuel by purging the fuel system and operating the engine under a full load for ½ hour. A 2-Point Power Check was performed followed by three hot transient cycles during which gaseous and particulate samples were obtained. The hot transient cycles were run with 20/80, 30/70 and 40/60 methyl ester/ARB diesel blends. For each of the three blends the emissions results from the three hot cycles were averaged.

Chassis Dynamometer Testing

Chassis dynamometer tests were performed at the Metropolitan Transportation Authority Emissions Testing Facility (MTA-ETF) in Los Angeles using an ARB diesel baseline and a 20/80 methyl ester/ARB diesel blend. The same fuels were used for the chassis dynamometer tests as for the engine of a standard road load equation (see Eq. 1). Input parameters were developed by the MTA-ETF based on coast downs conducted by the Southwest Research Institute. The selected inertia weight for the test vehicle was the vehicle tare weight plus 23 passengers and driver times 150 lbs. It was assumed that there were no road gradients. The velocity and acceleration of the vehicle were established by the dynamometer protocol. Emissions were monitored in units of grams per mile and included hydrocarbons, CO, NO_x, particulate matter and CO_2

$$RL = F_0 + F_1 V + F_2 V^n + I\left(\frac{dv}{dt}\right) + mg\sin(\emptyset) \qquad \text{(Eq.1)}$$

where:

RL = Road loads

F_0 = Coefficient of friction (velocity independent)

F_1 = Coefficient of friction (velocity dependant)

V = Velocity at the roller surface

F_2 = Drag coefficient

n = Velocity exponents

I = Vehicle inertia

$^{dv}/_{dt}$ = Acceleration
m = Vehicle mass
g = Acceleration due to gravity
Ø = road gradient (degrees)

The road load equation parameters are as follows:
F_0 = 251 lbf
F_1 = -1.07 lbf-hr/mi
F_2 = 0.1418 lbf-hr^2/mi^2
n = 2
I = 30,050 lbm
Ø = 0.0°

On Road Testing

On-road vehicle compatibility/emissions tests were performed at Gardena Municipal Bus Lines (GMBL) in Gardena, California. These consisted of daily refuelling of a passenger vehicle with a 20/80, and later with some 25/75 methyl ester/ARB diesels blend. Engine oil was sampled on a weekly basis to determine the presence of other than normal engine wear. Elements surveyed in the samples included twenty elements (metals and metalloids) that are commonly assumed to be indicative of engine wear. Material compatibility tests were conducted at ADEPT's facilities and at the GMBL bus refuelling station.

There were challenges inherent in the fuel blending and bus refuelling procedures. Local fire and air quality ordinance requirements dictated the following constraints: no use of electricity nor use of an above ground tank for fuel storage. An automatic dispensing nozzle was mandated. In addition, a flow of at least 14 gallons of fuel per minute was needed so as to not disrupt GMBL's fleet refuelling schedules.

We finally designed and used a solar powered refuelling station. The refuelling system consisted of the following components:

- four interconnected 55-gallon drums,
- a 12-volt drum pump,
- a flow totalizer,
- a deep cycle marine battery connected to a solar panel, and
- sixteen feet of polyurethane hose.

We were unable to use the automatic dispensing nozzle because the 12-volt drum pump was unable to deliver enough pressure to insure adequate flow through the nozzle. It was necessary to store the methyl ester off-site and to transport it to GMBL on a weekly basis. The bus was refuelled by first calculating (based on daily vehicle mileage and fuel consumption) the amount of methyl ester needed to make up the appropriate blend. Methyl ester was then pumped from the blending and dispensing system into the bus fuel tank, which was then topped off from ARB diesel from GMBL's underground tanks.

RESULTS AND DISCUSSIONS

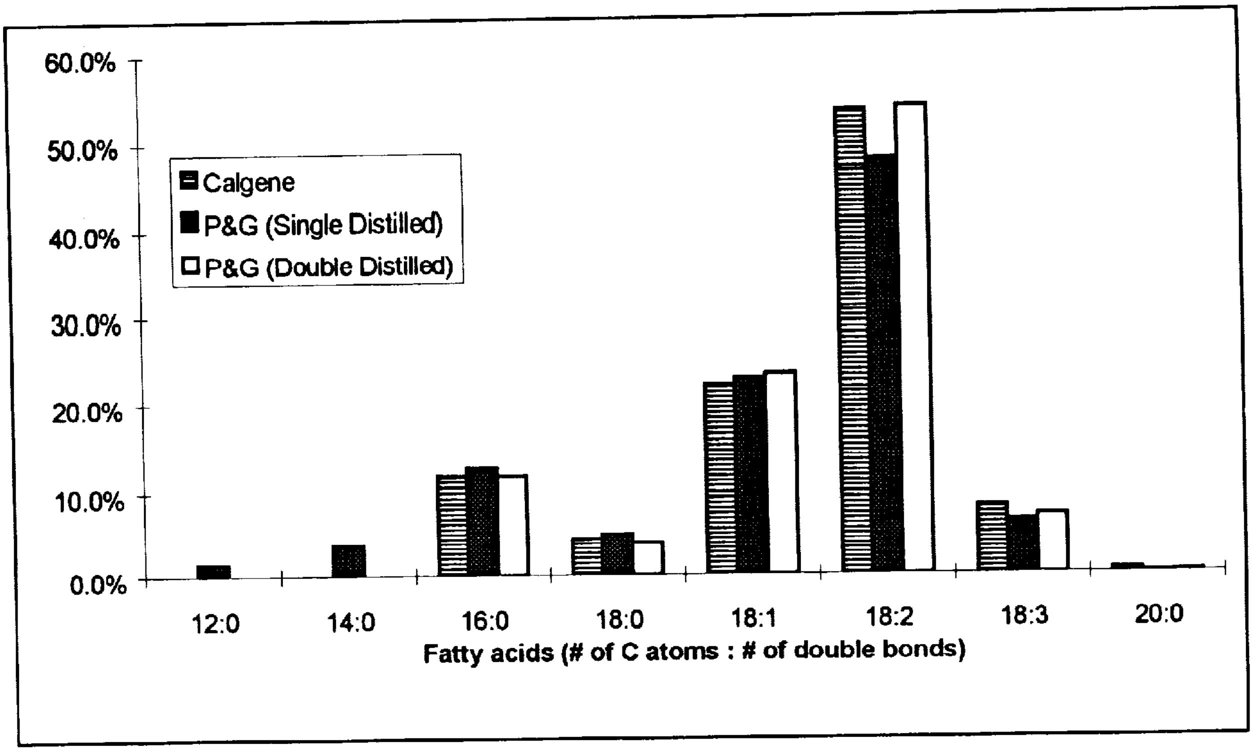
Fuel Characterization

Fuels characterization was conducted on ARB low sulphur, low aromatics diesel, EPA low sulphur diesel and methyl ester fuels to establish data points for key parameters (see *Table 4*). These parameters were used to evaluate differences in fuel quality between methyl esters from various suppliers and to serve as a basis of comparison for other methyl ester/ARB diesel blends. The tests included gross heating value, distillation, pour point, API gravity, flash point, Cetane number and viscosity tests. Gas chromatographic (GC) analyses were also conducted on methyl esters from two sources.

Differences in fuel characteristics between EPA and ARB diesels proved to be minimal. Cetane numbers varied by approximately 0.5% while gross heating values varied as little as 0.25%. Flash points were 74.4°C (166°F) and 75.6 °C (168 °F) respectively.

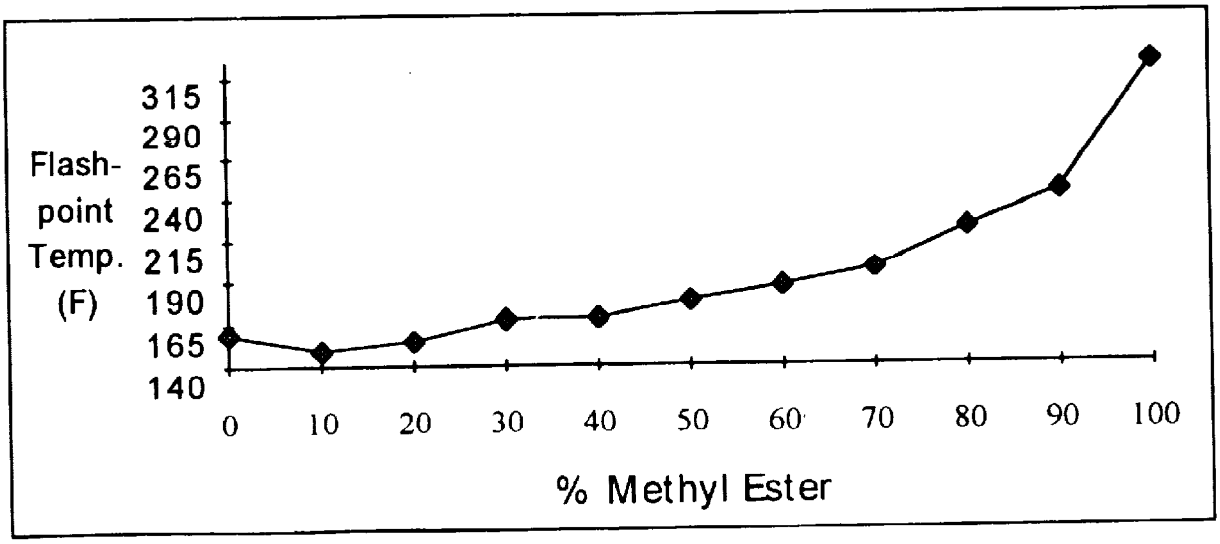
Differences between methyl esters from two different suppliers, Proctor & Gamble (P&G) and Calgene, proved slightly more significant. Prior to 1994, P&G produced soya methyl ester using a "single distillation process." This procedure left too much glycerine, water or methanol in the final product. In spring of 1994, P&G reportedly began using a "double distillation process" in an effort to improve product quality. Though only "doubly distilled" methyl esters were used for the engine and on-road testing portions of this project, GC tests were also conducted on single distilled methyl esters. Results from these tests showed a smaller percentage of doubly and triply saturated fatty acids from soya oil and a greater percentage of lauric and myristic acids (C_{12} and C_{14}) in the singly distilled product than in the doubly distilled esters (see *Figure 2*). No methanol was observed in any of the tested samples. When combined in a 20% blend with ARB diesel, the blends' parameters were essentially the same.

Of particular interest was a possible safety issue regarding a low flash point test result (55.5 °C, 132°F) of a 20/80 methyl ester/ARB diesel blend tested by the California Department of Food & Agriculture, Division of Measurements Standards. Such a low flash point would preclude the blend from use in marine engines and would



*Data supplied by Dr. Marvin O. Bagby, USDA

Figure 2. Percentage of Carbon Atoms in Fatty Acid Chains in Three Methyl Ester Products



* Data supplied by Dr. Marvin O. Bagby, USDA

Figure 3. Flash Point Temperature vs. % Methyl Ester With ARB diesel.

Raise concerns for on-road use. Further tests were conducted by Dr. Jon Van Gerpen of Iowa State University, Department of Mechanical Engineering, on eleven blends ranging from 0% to 100% methyl ester. Results show that there is in fact a previously unknown flashpoint lowering effect of methyl ester and diesel note subsequent tests have shown the drop in flash point not to be significant enough to create a fuel blend safety concern. Additional research is suggested to substantiate these intial results. The above work further suggests a need to establish a commonly accepted fuel standard. In the absence of such a standard, further engine emissions and performance work will be of limited value.

ENGINE DYNAMOMETER TESTING

Engine dynamometer tests were conducted using the EPA heavy-duty engine transient cycle. Analysis of power parameters, including engine speed, torque, brake horse power and fuel rate, indicate a gradual decrease in power as the percentage of methyl ester is increased from 20% to 40% (see *Tables 5* and *6*).

These changes are within expectations. Since the noted changes are relatively small no definitive conclusions were drawn from these particular data.

To focus on exhaust emissions compliance needs for the California mass transit market, methyl ester/ARB diesel blends were studied. Emissions monitored included: PM (total and soluble), CO_2, CO, $_{NOX}$ and total hydrocarbons (THC). With increasing percentage of methyl ester came reductions in THC, CO and insoluble particulates. The 40/60 blend showed a 32.4% drop in THC and a 21.6% drop in CO from the ARB diesel baseline. The 20/80 blend showed 15.9% and 7.9% drops respectively (see *Figures 4 and 5*). Oxides of nitrogen ($_{NOX}$) and soluble particulate emissions increased with increasing methyl ester percentage. The 20/80 blend showed a 6.2% increase in $_{NOX}$ while the 40/60 blend showed a 10.3% increase from the ARB diesel baseline (see *Figure 6*). Total PM emissions increased by 5.1% with the 20/80 blend. Projected emissions reductions vs realized emissions reductions for a 20/80 blend are compared in *Table 7*.

Of some interest was the fact that CO_2 emissions increased by at least 2.3% from the ARB diesel baseline when methyl ester was added (see *Figure 7*). Carbon dioxide is known to be a product of complete combustion. Other exhaust emissions (THC, CO, PM) are products of incomplete combustion. A higher CO_2 ratio juxtaposed with a lower percentage of THC, CO and insoluble PM in the exhaust is thought to indicate a more complete burning of the fuel blends in the combustion chamber.

Complete combustion is a function of conditions in the combustion chamber (temperature, pressure, residence time, *etc.*) and fuel parameters, along with other factors. One of the characteristics of diesel fuel that is considered to be indicative of a specific diesel fuel's auto-ignition capability in the combustion process is its cetane number. Fuels with high cetane numbers have generally shown a greater tendency to auto-ignite than have fuels with lower cetane numbers. In diesel engines this means that high cetane number fuels will begin to combust at lower temperatures and pressures than will low cetane number fuels. Lab work indicated that the cetane numbers of the methyl ester/ARB diesel blends were higher than those of ARB diesel alone. It is possible that because of this difference in cetane number, and because other pertinent engine operating parameters (*e.g.* compression ratio) remained constant, the methyl ester/ARB diesel blends ignited sooner than ARB diesel alone. It is thought that this earlier ignition could cause higher peak temperatures in the combustion chamber and longer residence times. It is generally accepted that higher temperatures and longer residence times lead to more complete fuel combustion. This more complete combustion is typically accompanied by an increase in CO_2 and a decrease in THC, CO and insoluble PM emissions. As it is known that $_{NOX}$ emissions increase with higher temperatures, a rise in $_{NOX}$ emissions would also be expected. The results of the engine and chassis dynamometer tests conducted as part of this project appear to support the above hypothesis.

Particulate matter in the exhaust can be broken down into two fractions, soluble and insoluble. Contrary to expectations, total PM emissions first increased (20/80 blend), then dropped slightly (30/70 blend) and then stabilized (40/60 blend). There did not appear to be an explanation for this until the soluble and non-soluble parts of PM were analysed seperately. It was then found that the soluble particulate fraction increased while the insoluble fraction decreased as the percentage of methyl ester in the blend increased (see *Figure 8*). Insoluble particulates are composed mainly of pure carbons and contribute significantly to visible exhaust smoke. The decrease in insoluble particulates corroborated smoke opacity measurements that showed smoke opacity decreasing with increasing methyl ester percentages.

TABLE 5. PEAK POWER COMPARISONS

Test	ARB Diesel	20/80	30/70	40/60
Engine Speed (rpm)	2,003	2,003	2,003	2,002
Engine Power, bkW (bhp)	195 (261)	198 (266)	196 (262)	192 (258)
Engine Torque, N-m (ft-lb)	928 (685)	946 (698)	933 (688)	918 (677)
Fuel Flow, kg/hr (lb/hr)	47.8 (105.4)	49.4 (108.9)	49.3 (108.7)	49.0 (108.0)

TABLE 6. PEAK TORQUE COMPARISONS

Test	ARB Diesel	20/80	30/70	40/60
Engine Speed (rpm)	1,201	1,202	1,202	1,202
Engine Power, bkW (bhp)	144 (193)	145 (194)	144 (193)	143 (191)
Engine Torque, N-m (ft-lb)	1142 (842)	1149 (848)	1143 (843)	1133 (836)
Fuel Flow, kg/hr (lb/hr)	32.9 (72.5)	38.4 (84.7)	33.6 (74.1)	33.8 (74.5)

TABLE 7. PROJECTED VS. REALIZED EMISSIONS REDUCTIONS FOR A 20/80 METHYL ESTER/ARB DIESEL BLEND

Criteria Pollutants	Projected Reductions	Realized Reductions
CO	21%	7.9%
THC	27%	15.9%
NOX	5%	[+6.2%]
CO_2	9%	[+2.5%]
PM	21%	[+5.1%]

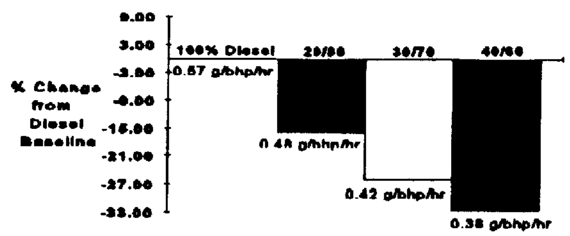


Figure 4. Comparison of Total Hydrocarbon Emissions Between Methyl Ester/ARB Diesel Blends and 100% ARB Diesel

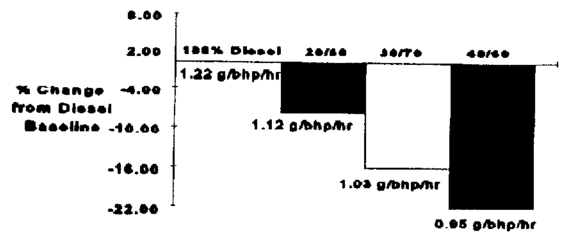


Figure 5. Comparison of CO Emissions Between Methyl Ester/ARB Diesel Blends and 100% ARB Diesel

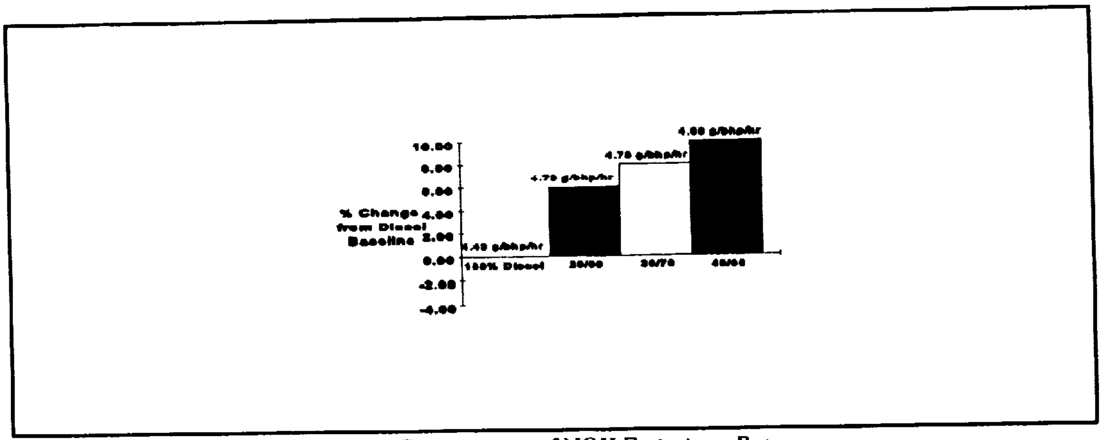


Figure 6. Comparison of NOX Emissions Between Methyl Ester/ARB Diesel Blends and 100% ARB Diesel

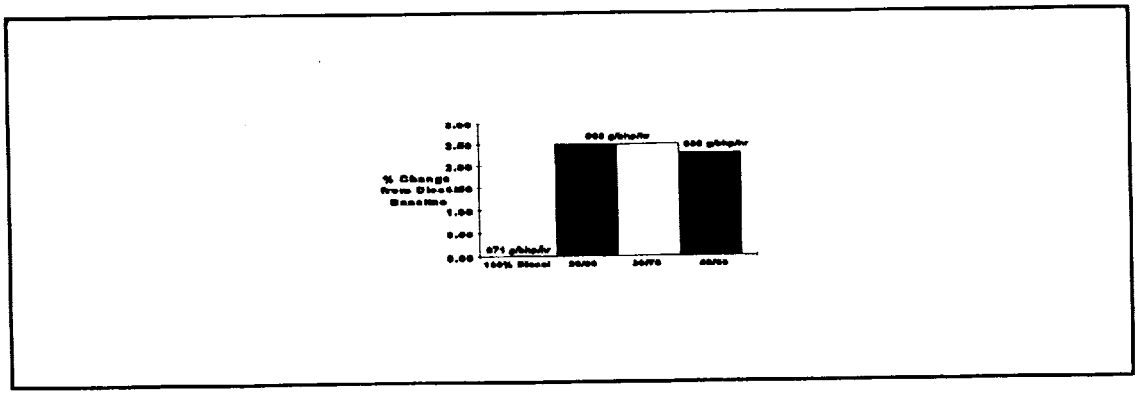


Figure 7. Comparison of CO_2 Emissions Between Methyl Ester/ARB Diesel Blends and 100% ARB Diesel

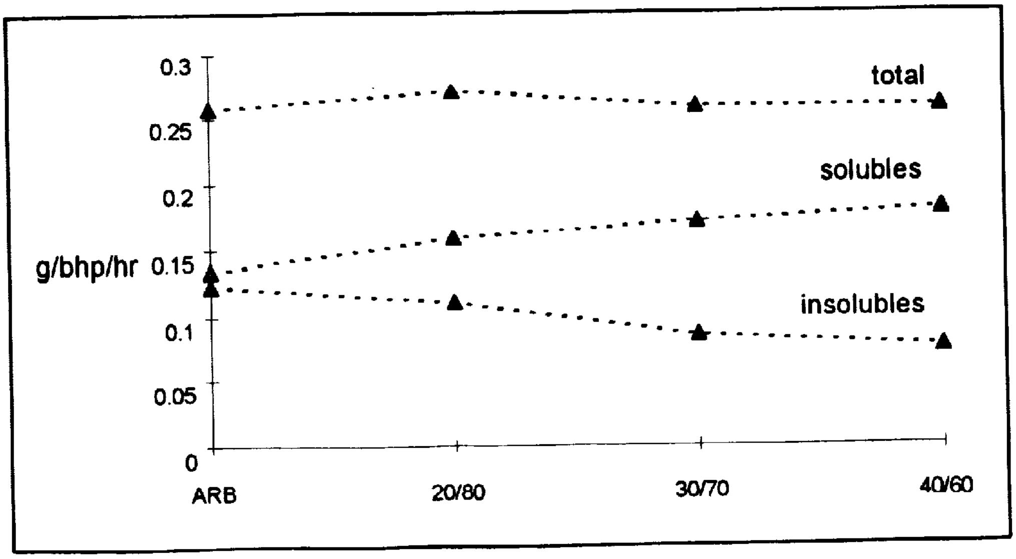
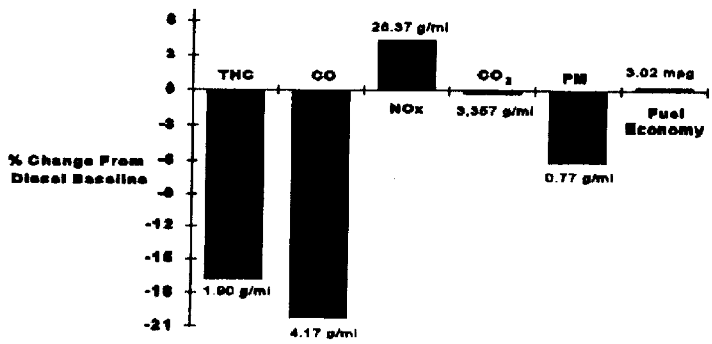


Figure 8. Comparison of Total, Soluble and Insoluble Particulate Emissions Between Methyl Ester/ARB Diesel Blends and 100% ARB Diesel



* Conducted At The Mta-Etf Chassis Dynamometer on The Central Business District Cycle

Figure 9. Chassis dynamometer data: Comparison of Emissions between A20/80 Methyl Ester/ARB Diesel Blend and 100% ARB Diesel.

The fact that PM did not drop as expected curtailed further timing optimization engine dynamometer work. Further work was predicated on a PM drop. The absence of a PM drop was attributed to the mandated reduction in aromatic hydrocarbons in ARB diesel. Research conducted prior to this study had utilized EPA diesels which contain a much higher aromatics content than ARB diesel (35% vs. 10%).

CHASSIS DYNAMOMETER TESTING

Chassis dynameter testing was conducted on a 20/80 methyl ester/ARB methyl ester/ARB diesel blend at the emissions testing facility of the Los Angeles Country Metropolitan Transportation Authority. Although to definitive comparisons can be drawn between chassis and engine dynamometer tests because of the vast differences in procedural parameters and conditions, the results of the chasses test were largely similar to those in the engine dynameter tests (see *Figure 9*). Total hydrocarbons (THC), CO and PM emissions decreased by 16.7 percent, 20.2 percent and 6.1 percent respectively while NO_x emissions increased by 4.5 percent over the ARB diesel baseline. It should be noted that the Central Business District (CBD) chassis dynamometer test is considered to be less stressful on the engine than the EPA engine dynamometer transit cycle test.

ON-ROAD TESTING

On-road testing consisted of the daily refuelling (using 20/80 and 25/75 methyl ester/ARB fuel blends) of a passenger vehicle in an actual mass transit application within the Los Angeles basin. These tests were conducted to determine the blends' effects on engine performance and wear. The vehicle ran approximately 10,000 miles on the two blends. From the weekly oil samples taken, no abnormal engine wear was noted. Drivers of the test bus were surveyed regarding changes in power and handling before and after the bus was fuelled with the blends. The drivers could not tell the difference between before and after conditions.

MATERIALS COMPATIBILITY TESTING

Material's compatibility testing was limited to the components used in the assembly and operation of the fuel blending and pumping station. The material used for hoses was polyurethane ("Superthane," purchased from NewAge Industries). For a period of five months a sample of methyl ester was sealed inside a ten-inch long section of the product at room temperature. After two months the outside surface of the hose began to "sweat," indicating that the ester had penetrated the hose material. It was also observed that sealed plastic containers used to store methyl ester would deflate over time. This seemed to imply the presence of a chemical reaction between the ester and some component of the atmosphere trapped within the vessel. It was also observed that methyl ester degrades upon exposure to air. Methyl ester from drums opened for sampling purposes and left alone changed colour and became cloudy. This "shelf life" was approximately five months.

Methyl ester was also found to be an excellent paint remover. The penetrant qualities of methyl ester are well documented. Because the fuel drums were painted, and because paint dissolved by the methyl ester could have been introduced into the fuel blend through the drums' ventilation holes, care had to be taken in removing any methyl ester spills from the Conducted at the MTA-ETF chassis dynamometer on the Central Business District Cycle tops of the fuelling drums.

Prior to being used as a fuelling station, one set of fuelling drums was contaminated with silicates. These silicates, in the presence of methyl ester and ARB diesel, leached into the fuel blend. It is not clear whether the leaching agent for the silicates was the methyl ester, ARB diesel or a combination of the two materials. Further investigation is advised in this particular area.

CONCLUSIONS

Soya methyl ester, in 20%, 30% and 40% blends with ARB diesel is not deemed at this stage of research to be a viable mass transit "transition fuel" for Los Angeles basin conditions. This statement is based on the following facts:

1. Methyl ester/ARB diesel blends emit greater amounts of PM, $_{NOX}$ and CO_2 when compared to ARB diesel alone. Because of this, no optimal fuel blend/engine timing package could be realized. Current California emissions standards cannot be met using the tested fuel blends.

2. The Southern California delivered soya methyl ester cost was much higher than anticipated ($5 per gallon vis-à-vis an originally estimated $2.50 per gallon), rendering methyl ester/ARB diesel blends non-cost effective under current economic conditions. Fuel cost is a critical operations issue for mass transits.

3. There exist significant variations in methyl ester fuel characteristics. Although it is known that engine performance and emissions will be affected by fuel variations in general, it is not known to what degree methyl ester fuel variations will manifest themselves.

4. There exist unresolved materials compatibility and durability issues. Though limited engine durability testing showed no unacceptable engine wear, materials used in fuel transfer (*e.g.* hoses) exhibited signs of incompatibility with methyl ester.

5. Soya methyl ester appears to have a definite duration "shelf life". More research is suggested in this area.

6. Soya methyl ester has the potential to become part of a broader technology package (*i.e.* high activity oxidizing catalyst, engine timing changes) that could prove to be a cost-effective transition fuel solution.

RECOMMENDATIONS

Given the data collected in this project, we recommend further research, testing and analysis in the following areas:

1. Testing on:
   - Long-term engine performance and wear on various methyl ester blends.
   - Methyl ester/diesel blends plus high activity oxidizing catalysts.
   - Methyl ester/ARB diesel/heavy alkaloids EPA engine dynamometer testing.
   - Materials compatibility.
2. Research on:
   - Methyl ester shelf life.
   - Methyl esters from other feedstocks (i.e. restaurant waste oils, palm oil, almond oil, *etc.*).
   - Methyl ester performance when fungicides are added to the fuel blend. Since methyl esters are biodegradable, they will serve as

energy sources for microbial growth.

3. Development of:
   - Methyl ester fuel standards. In the absence of such a standard, further engine emissions and performance work will be of limited value.

4. Economic analysis of:
   - Pricing for methyl ester as a fuel.

This complex issue merits additional investigation given the following circumstances: potential RECLAIM credits for applications in the South Coast basin area, transportation costs, availability and volume of source feedstock and volatility of both feedstock oil and methyl markets.

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The statements and conclusions in this report are those of the contractor and not necessarily those of the Mobile Sources Air Pollution Reduction Review Committee or the South Coast Air Quality Management District. The mention of commercial products, their sources or their uses in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products.

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GLOSSARY OF TERMS, ABBREVIATION AND SYMBOLS

Organizational Acronyms:

ASTM	American Society of Testing Materials.
Calgene	Calgene Chemical, California based supplier of methyl ester for fuel characterization tests.
CORE	Laboratories California laboratory selected for fuels characterization testing.
DDC	Detroit Diesel Corporation. Producer of the 6V92TA MUI engines used for the project.
GMBL	Gardena Municipal Bus Lines, Gardena, California. Project host site selected for on-road vehicle compatibility/emissions tests.
MTA-ETF	Los Angeles Metropolitan Transportation Authority-Emissions Testing Facility. Facility selected for the chassis dynamometer tests.
ORTECH	ORTECH International, Inc. Canadian facility selected for engine dynamometer tests.
P&G	Procter & Gamble. Supplier of methyl ester for fuels characterization tests.

VDDA	Valley Detroit Diesel Allison. Los Angeles distributor of the 6V92 TA MUI engines purchased for the project.

Symbols, Units and Terms

6V92TA MUI	DDC engine equipped with mechanical unit injectors used for project testing.
API gravity	Relative density scale developed by American Petroleum Industry.
ARB diesel	October 1, 1993 diesel conforming to California Air Resource Board standards.
ASTM D-287	API gravity test
ASTM D-445	Viscosity test
ASTM D-613	Cetane number test
ASTM D-613	Heating value test
ASTM D-86	Distillation curve test
ASTM D-93	Flash point test
ASTM D-97	Pour point test
bhp	Brake horse power. Unit of engine power.
Biofuels	Plant oil and/or animal fat derived fuels.
BSFC	Brake specific fuel consumption. Expresses normalized fuel consumption to brake engine power output.
CBD	Central Business District cycle. Test protocol selected for the chassis dynamometer tests.
Cetane number	Indicator of a fuel's auto-ignition capability. Analogous to octane rating for spark-ignition engines.
CO	Carbon monoxide. Odourless, toxic gas. Product of incomplete combustion.
Distillation curve	Correlation between temperature and volatility of fuel components.
"Double Distillation"	Process reportedly used by Procter & Gamble in the manufacture of methyl ester.
Dynamometer	Device used to load an engine for testing purposes.
Flash point temp.	Measure of lean ignitable limit for a fuel vvapourair mixture. Important in relation to the potential hazards of handling flammable fuel vapours.
ft-lb	Foot-pound. Unit of torque.
GC	Gas chromatography.
Heating value	Measure of a fuel's specific energy.
Hydrocarbon	Compounds based primarily on carbon and hydrogen.
Iodine number	Indicator of polymerization.
kg/hr	Kilogram per hour. Unit of fuel flow.
Lauric acid	Fatty acid with 12 carbon atoms.
Myristic acid	Fatty acid with 14 carbon atoms.
Methyl ester	Defined for the purposes of this report: Soya methyl ester.
Methyl soyate	Soya methyl ester.
	Oxides of nitrogen. Major contributor to photochemicals smog.
OLEOCAL ME-130	Methyl ester purchased Calgene Chemical.
PM	Particulate matter.
Pour point temp.	Lowest temperature to which a fuel can be cooled without impeding the free flow of liquid.
"Single distillation"	Procedure reportedly used prior to 1994 by Procter & Gamble in the manufacture of methyl ester.
rpm	Revolutions per minute. Unit of engine speed.
Soya methyl ester	Soya bean oil-derived fuel similar in properties to diesel f uel.
THC	Total hydrocarbons.
TP	Total particulates.
Viscosity	Measure of a fluids resistance to internal shearing. Influences pumping, lubricity and atomization characteristics of liquid fuels.