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ETHYL ESTER OF RAPESEED USED AS A BIODIESEL FUEL—A CASE STUDY*

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Abstract—A 1994 Dodge 2500 turbocharged and intercooled diesel pickup fueled with 100% ethyl ester of rapeseed oil was driven by personnel representing the University of Idaho, Agricultural Engineering Department from Moscow, Idaho to Los Angeles, California and back to Moscow and then from Moscow to Ocean City, Maryland, east of Washington, D.C. and back to Moscow, Idaho. These trips covered a total of 14,069 km (8742 miles). The truck averaged 7.76 km/l (18.7 mile/gal) using 1772 l (468 gal) of ethyl ester of rapeseed oil fuel. No problems or unusual events were encountered with the truck's operation. The truck was completely unmodified as to the engine and fuel system. The fuel required for the trip was all processed in the Agricultural Engineering Laboratory at the University of Idaho and was carried on-board as no refueling facilities were available away from Moscow, Idaho. This is believed to be the first coast-to-coast and back run on 100% biodiesel. Copyright © 1996 Elsevier Science Ltd.

1. INTRODUCTION

Alternative fuels which will improve the environment, reduce the use of petroleum reserves, reduce foreign imports and increase the use of renewable fuels, is a U.S. priority. As part of this process University of Idaho personnel have, since 1979, researched the use of locally produced rapeseed oil as a diesel fuel substitute. Past research has shown that transesterified vegetable oils are very acceptable diesel fuel substitutes.[1]

Transesterification is the process of reacting a trigylceride, such as rapeseed oil, with an alcohol, such as ethanol, in the presence of a catalyst, potassium hydroxide or sodium hydroxide, to produce an ester and glycerol. The process produces two phases: a heavier glycerol phase and the lighter ethyl ester phase. The glycerol has many industrial uses. The ethyl ester, following washing, can be used directly as a diesel fuel, either in blends with diesel or, as in this test, as the only fuel component.

While most biodiesel, a name often used with vegetable oil diesel fuel substitutes, is produced with methanol and vegetable oil, over the past three years research at the University of Idaho has been directed toward perfecting recipes for using ethanol and rapeseed oil to produce ethyl esters. While additional challenges exist in producing ethyl esters compared to the methyl esters, solutions are possible. University of Idaho personnel have produced more than 6000 l (1600 gal) of ethyl esters from rapeseed oil and other lipids in the last year.[2]

In the latter half of 1993, the Pacific Northwest and Alaska Regional Bioenergy Program funded a program with the University of Idaho, Agricultural Engineering Department to examine many aspects of the production and use of ethyl esters. As part of this program, funds were provided to lease a diesel powered vehicle and to operate that vehicle on 100% ethyl ester of rapeseed oil fuel. An addendum to that project also provided funding for emissions tests of the vehicle at the Los Angeles Metropolitan Transit Authority Emissions Test Facility (LA-MTA). It was in the context of meeting the need to accumulate mileage on the vehicle, the requirement for travelling to Los Angeles with the truck, and the necessity of attending meetings in Kansas City and Milwaukee that provided the incentive for the coast-to-coast-to-coast run with the pickup.

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2. DETAILS OF TRAVEL

The western leg of the trip began on 9 March 1994. The starting point was in Moscow, Idaho. The estimated 3800 km (2400 miles) of the trip required approximately 570 l (150 gal) of fuel. In addition, fuel was required for the emission tests at LA-MTA, so nearly 1134 l (300 gal) of fuel was on-board during the trip. A log with stop-over points, miles travelled and liters (gallons) of fuel used for each leg of the trip was as follows:

1. March 9—Moscow, Idaho to Jordan Valley, Oregon; 649 km (403 miles); 73.4 l (19.4 gal) of fuel
2. March 10—Jordan Valley, Oregon to Victorville, California; 801 km (498 miles); 106.0 l (28.0 gal) of fuel
3. March 11—Victorville, California to the Pacific Ocean at Santa Monica Beach; 566 km (352 miles); 68.9 l (18.2 gal) of fuel
4. March 12–16—Testing at LA-MTA
5. March 16—Los Angeles to Carson City, Nevada; 727 km (452 miles); 85.2 l (22.5 gal) of fuel
6. March 17—Carson City, Nevada to Moscow, Idaho; 1209 km (751 miles); 157.1 l (41.5 gal) of fuel
7. Total travel distance 3953 km (2456 miles); 490.6 l (129.6 gal) used; 7.85 km/l (18.9 mpg) average.

The eastern leg of the run was carried on between 14 June and 3 July 1994. For the estimated 9600 km (6000 miles) of the trip, approximately 1135 l (300 gal) of fuel were required. The vehicle started with the main tank full, the auxiliary tank full, four 210 l (55 gal) drums of fuel, and one 19 l (5 gal) emergency supply. This was a total of about 1360 l (360 gal) of fuel weighing over 1180 kg (2600 lb). Approximately 75 l (20 gal) remained at the conclusion of the trip. The log for the eastern leg of the trip was as follows:

1. June 12—Moscow, Idaho to Kadoka, South Dakota; 1751 km (1088 miles); 207.8 l (54.9 gal) of fuel
2. June 13—Kadoka, South Dakota to Kansas City, Kansas; 1149 km (714 miles); 152.6 l (40.3 gal) of fuel
3. June 14—on display at the ASAE Liquid Fuels Conference in Kansas City, Missouri
4. June 16—miscellaneous travel in Missouri; 294.4 km (183 miles); 44.7 l (11.8 gal) of fuel
5. June 22—Kansas City, Missouri to Columbia, Missouri; 209.2 km (130 miles); 28.4 l (7.5 gal) of fuel
6. June 22—Columbia, Missouri to Verona, Vermont; 1402 km (871 miles); 162.8 l (43.0 gal) of fuel
7. June 23—Verona, Vermont to Washington, D.C.; 405.6 km (252 miles); 52.2 l (13.8 gal) of fuel
8. June 24—on display at DOE (Forrestal Building) and the Capital Mall in Washington, D.C.
9. June 25—Washington, D.C. to the Atlantic Ocean at Rehoboth Beach, Delaware to Ocean City, Maryland to Toledo, Ohio; 1243 km (773 miles); 157.8 l (41.7 gal) of fuel
10. June 26—Toledo, Ohio to Milwaukee, Wisconsin; 613.2 km (381 miles); 63.2 l (16.7 gal) of fuel
11. June 28–30—on display at the "Fueling the Future—A Clean Air Transportation and Engine Trade Show," Milwaukee, Wisconsin
12. July 1—Milwaukee, Wisconsin to Rapid City, South Dakota; 1447 km (899 miles); 196.5 l (51.9 gal) of fuel
13. July 2–3—Rapid City, South Dakota to Moscow, Idaho; 1601 km (995 miles); 213.9 l (56.5 gal) of fuel
14. July 7—dynamometer test at Western States Cat facility, Spokane, Washington
15. Total travel distance 10,116 km (6286 miles); 1771 l (338.2 gal) fuel used; 7.76 km/l (18.6 mpg) average.
16. Combined total travel distance 14,069 km (8742 miles); 1771 l (468 gal) total fuel use used; 7.76 km/l (18.7 miles/gal) average.

3. UNIQUE CHARACTERISTICS OF THE RUN

1. The total distance travelled was 14,069 km (8742 miles) with one fueling location in Moscow, Idaho.
2. All of the fuel used in the test was 100% ethyl ester of rapeseed oil produced in the Agricultural Engineering Department Laboratory at the University of Idaho.
3. All of the fuel was carried on-board and was on-board the vehicle when it left Moscow, Idaho. No fuel was shipped and/or delivered to other locations.

Table 1. Properties of ethyl ester and diesel control fuel*

	100REE	Diesel
Gross heat of combustion, MJ/kg (Btu/lb)	40.51 (17,415)	45.42 (19,526)
Flash point, °C (°F)	124 (255)	82 (180)
Cloud point, °C (°F)	− 2 (29)	− 14 (6)
Pour point, °C (°F)	− 10 (14)	− 21 (− 5)
Viscosity cs @ 40°C	6.17	2.98
Sulfur (%, wt)	0.014	0.036
Specific gravity, 60/60	0.876	0.8495
Cetane number	59.7	49.2

*Based on analyses by Phoenix Chemical Lab, Inc. and the Agricultural Engineering Analytical Laboratory, University of Idaho.

4. The vehicle ran normally with no engine or fueling system modifications.

5. No diesel fuel was used on the trip, none was carried or purchased and at no time was it felt necessary to attempt to use diesel fuel.

6. The vehicle was driven at normal highway speeds and no attempt was made to avoid any particular situation. Traffic included heavy city traffic, freeways, tollways, etc. On two different days the vehicle travelled over 1600 km (995 miles).

4. VEHICLE PREPARATION

The vehicle tested was a 1994 Dodge pickup with a direct injected, turbocharged and intercooled, 5.9 liter (360 cu. in.) Cummins diesel engine. Weight used during the emissions tests and for the coast down to match the vehicle and chassis dynamometer was 3590 kg (7900 lb).

The engine was not modified in any way for use with the vegetable oil fuels. The fuel delivery system was modified for convenience of changing fuels between emissions test runs at the LA-MTA emissions test facility. Fuel delivery and fuel return lines were cut and 3-way, manually operated valves were installed so that a stub line with quick couplers could be installed on one part of the 3-way valves. Individual 19 l (5 gal) fuel tanks were modified with fuel filters and flexible lines added which could be quickly connected to the 3-way valves. During normal operation, fuel was delivered and returned to the vehicle fuel tank. During emissions testing the valves were switched to the external lines to which the correct test fuel was connected. For the emissions 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.

The truck has a factory installed 128 l (34 gal) fuel tank. To extend its range for operation on biodiesel a 375 l (100 gal) auxiliary tank was installed in the bed. The auxiliary tank had an electric dispensing pump with a volume-delivered meter for transferring fuel into the vehicle tank. During the coast-to-coast-to-coast run the additional fuel required was carried in 200 l (55 gal) drums.

5. FUEL USED

Rapeseed oil esterified using ethanol as the alcohol instead of methanol is under study at the University of Idaho. The benefits of ethyl ester are: (a) both ethanol and vegetable oil are environmentally friendly,[3] renewable products; (b) ethyl and methyl esters have similar fuel characteristics; (c) ethanol is safer to handle than methanol: toxic effects to personnel from exposure to the fumes are reduced.

All of the fuel used in this test was produced at the Agricultural Engineering Laboratory at the University of Idaho using recipes and techniques developed at the laboratory.[2] Rapeseed oil was expelled using a small screw press from seed purchased from a local company. The seed was cleaned and bagged and then was expelled in a plant capable of 40 kg/h (100 lb/h) of seed throughput. The oil was filtered and then esterified using ethanol and potassium hydroxide in a small, 760 l (200 gal), biodiesel reactor. The glycerol was discarded and the ethyl ester washed using a process that requires about 1/3 volume of water per volume of ethyl ester. The

Table 2. Results of LA-MTA emissions tests for the arterial cycle (all values are in g/mile)

Volume percent of REE in diesel control fuel	100% Diesel	20% REE	50% REE	100% REE
HC	0.833	0.668*	0.541*	0.332*
CO	3.28	2.38*	1.84*	1.74*
NO_x	6.23	5.98*	5.72*	5.53*
CO_2	651.7	653.4	657.5	658.1*
PM	0.301	0.286	0.337	0.305

*These means, in the same column, are significantly different from diesel ($P < 0.05$).

Table 3. Results of LA-MTA emissions tests for the EPA cycle (all values are g/mile)

Volume percent of REE in diesel control fuel	100% Diesel	20% REE	50% REE	100% REE
HC	1.25	1.021	0.834*	0.592*
CO	4.50	2.92*	2.23*	2.11*
NO_x	6.85	6.44*	6.31*	6.01*
CO_2	698.6	708.2	698.3	707.0
PM	0.411	0.386	0.428	0.480

*These means, in the same row, are significantly different from diesel ($P < 0.05$).

final product was filtered and used as fuel. Table 1 contains data on the properties of both the ethyl ester of rapeseed oil and the low sulfur diesel control fuel used in the tests. For more details on fuel properties refer to Ref. 4.

6. EMISSIONS TEST

In March 1994, University of Idaho personnel conducted a series of transient chassis dynamometer emissions tests in cooperation with the Los Angeles County Metropolitan Transit Authority (LA-MTA). Emissions data generated in this program included EPA regulated emissions: total hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate matter (PM) and also reports carbon dioxide (CO_2). For a more detailed discussion of these tests refer to Ref. 4.

Two test cycles were used in the test program. First, a modified arterial cycle (modified by doubling the length), which consisted of eight replications of accelerating to 64.4 km/h (40 miles/h) and decelerating to 0 km/h (miles/h) and required 758 s. Second was the dynamometer driving schedule for heavy duty vehicles (Code of Federal Regulations 40, Part 86, Appendix I and Cycle D), a 1060 s test.

Table 4. Emissions percent increase (+) or decrease (−) compared to diesel control fuel for the average of the Arterial cycle (Table 1) and the EPA cycle (Table 2)

Volume percent of REE in diesel control fuel	20% REE	50% REE	100% REE
HC	− 19.0*	− 34.3*	− 55.6*
CO	− 31.9*	− 47.6*	− 50.6*
NO_x	− 5.1*	− 8.1*	− 11.8*
CO_2	+ 0.8	+ 0.4	+ 1.1*
PM	− 5.7	+ 7.4	+ 10.3

*These means, in the same column, are significantly different from diesel ($P < 0.05$).

Several fuels were tested including ethyl ester of rapeseed oil (REE) produced by the University of Idaho Department of Agricultural Engineering. The diesel fuel used in the tests was Phillips D-2, low sulfur control fuel (D2).

Summaries of the results of these tests showing the average values for the two cycles and for the REE fuel compared with diesel, are given in Tables 2–4. Table 2 is the emissions data for the arterial cycle, Table 3 is the actual emissions data for the EPA cycle and Table 4 is a comparison of the emissions for each of the biodiesel fuels showing the percent increase or decrease in emissions compared to diesel control fuel. Data include 20% REE, which was a blend of 20% REE and 80% diesel control fuel (2 replications of the Arterial cycle and 1 replication of the EPA cycle); 50% REE, which was a blend of 50% REE and 50% diesel control fuel (2 replications of the Arteril cycle and 1 replication of the EPA cycle); 100% REE (4 replications of the Arterial cycle and 3 replications of the EPA cycle); and 100% diesel control fuel (6 replications of the Arterial cycle and 3 replications of the EPA cycle).

Table 5. Results of the dynamometer tests of the biodiesel fueled pickup

	2253 km (1400 miles) Beginning		12,100 km (7520 miles) Middle		25,554 km (16,500 miles) End	
	Diesel	100% REE	Diesel	100% REE	Diesel	100% REE
Power, kW (hp) @ 2500 rpm	108 (145)	108 (145)	108 (145)	105 (141)	109 (146)	106 (142)
Fuel efficiency @ 2500 rpm g/MJ (lb/hphr)	79.6 (0.471)	86 (0.5105)	80.9 (0.4787)	87.9 (0.5205)	78.6 (0.4653)	86.3 (0.5107)
Percent opacity snap idle test (% opacity)	21.5	18.4	26.1	15.5	27	17

7. DYNAMOMETER TESTS

After an initial break-in of 2250 km (1400 miles), the pickup was tested on a dynamometer. Western States Cat in Spokane, WA contributed the use of their Superflow 601 chassis dynamometer facility. The dynamometer was computer controlled and provided a printout of the horsepower to the wheels, torque, fuel consumption, fuel temperature, inlet air temperature, coolant temperature, exhaust temperature, engine blow by, engine rpm, and turbo boost pressure. An opacity meter provided a measure of the amount of smoke in the exhaust.

The pickup was dynamometer tested at three mileages [2253 km (1400 miles); 12,100 km (7520 miles) and 25,554 km (16,500 miles)] on 100% REE and 100% D2. Each fuel was tested in triplicate. The summary given in Table 5 is an average of the triplicated runs at the specified intervals.

8. CONCLUSIONS

In the first half of 1994, a Dodge Cummins turbocharged and intercooled, 5.9 liter (360 cu. in.) diesel powered vehicle was driven 14,069 km (8742 miles) consuming 1771 l (468 gal) of biodiesel and averaged 7.76 km/l (18.7 miles/gal).

The vehicle performed normally and no problems were encountered. All of the fuel for the trip was carried on-board. Fuel transfer was from auxiliary fuel tanks with the use of an electric on-board fuel pump into the stock fuel tank. During the trip, the vehicle was tested for emissions at the Los Angeles Metropolitan Transit Authority, was displayed in Kansas City, Missouri at the ASAE liquid fuels conference, in Washington, D.C. at the Capital Mall and in front of the Department of Energy (Forrestal Building), and in the Wisconsin International Alternative Fuels and Clean Air Conference. Dynamometer tests were conducted before, during and at the conclusion of the test. It should be noted that these tests were conducted in June and July 1994 during mild to warm weather. Cold weather operation, below that of the ethyl ester pour point, would require additional precautions and/or additives to keep the fuel fluid.

Specific conclusions are:

1. Emissions tests with this vehicle showed a reduction in HC (55.6%), CO (50.6%) and NO_x (11.8%) and an increase in CO_2 (1.1%) and PM (10.3%). The results for PM are not significantly different from diesel. The other results were significantly different ($P < 0.05$).
2. The dynamometer test at 2500 rpm showed 1.8% less power, and 8.9% less fuel economy, and 31.8% less opacity when operated on biodiesel in comparison to diesel control fuel.
3. Vehicle performance was extremely good and no problems were noted during this test.

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