ESTCP
Cost and Performance Report

(WP-0308)

Effect of Biodiesel on Diesel Engine Nitrogen Oxide and Other Regulated Emissions

December 2007

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

COST & PERFORMANCE REPORT
ESTCP Project: WP-0308

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ACRONYMS AND ABBREVIATIONS

AFV	alternate fueled vehicle
APG	Aberdeen Proving Ground
AO/AQIRP	Auto/Oil Air Quality Improvement Research Program
ASTM	American Society of Testing and Materials
ATC	Aberdeen Test Center
B20	20% biodiesel
B50	50% biodiesel
B70	70% biodiesel
B100	100% biodiesel by volume
Btu/gal	British thermal units per gallon
CARB	California Air Resources Board
CAT	Caterpillar Corporation
CBC	Construction Battalion Center
CBO	Congressional Budget Office
CCB	Configuration Control Board
CCR	California Code of Regulations
CE-CERT	Bourns College of Engineering–Center for Environmental Research and Technology
CFR	Code of Federal Regulations
CO_2	carbon dioxide
CO	carbon monoxide
CONUS	continental United States
DDIC	Department of Defense identification code
DENIX	Defense Environmental Network and Information Exchange
DESC	Defense Energy Support Center
DLA	Defense Logistics Agency
DNPH	dinitrophenylhydrazine
DoD	Department of Defense
DTBP	ditertiary butyl peroxide
EC	elemental carbon
ECAM	Environmental Cost Analysis Methodology
ECP	engineering chance proposal
EHN	ethyl hexyl nitrate
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FID	flame ionization detector
FTP	Federal Test Procedure
G/bhp-hr	gram per brake horsepower hour
G/mile	gram per mile

ACRONYMS AND ABBREVIATIONS (continued)

GC	gas chromatography
GM	General Motors Corporation
HAP	hazardous air pollutant
HC	hydrocarbon
HMMWV	humvee
HP LC/UV	high-performance liquid chromatography/ultraviolet
JP-8	Jet Propellant No. 8
KW	Kilowatt
NDIR	non-dispersive infrared
NFESC	Naval Facilities Engineering Service Center
NIOSH	National Institute of Occupational Safety and Health
NO_x	nitrogen oxide
NORAD	North American Air Defense Command
NREL	National Renewable Energy Laboratory
NSN	national stock number
OC	organic carbon
PAH	polycyclic aromatic hydrocarbon
PM	particulate matter
PPM	parts per million
PPMW	parts per million by weight
POC	point-of-contact
psi	pounds per sq in
ROVER	Real-time On-road Vehicle Emissions Reporter
TC	total carbon
THC	total hydrocarbon
UCR	University of California, Riverside
ULSD	ultra-low sulfur diesel
US06	EPA Aggressive Certification Cycle
VOC	volatile organic compound
YGA	Yellow Grease Formula A
YGB	Yellow Grease Formula B

ACKNOWLEDGEMENTS

The Project Team would like to thank the dedicated employees at the Camp Pendleton Marine Corps Base for making the arrangements to supply most of the diesel engines tested in this project. Camp Pendleton was able to supply the engines at no cost to the project and accommodate numerous delays in returning the engines. The team would also like to thank Biodiesel Industries, Inc. and the National Renewable Energy Laboratory for supplying 400 gallons of yellow grease biodiesel and emissions testing services, respectively, at no cost to the project. Finally, the Project Team would like to thank the Environmental Security Technology Certification Program (ESTCP) office for providing most of the project funding.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Diesel engines are widely used throughout the Department of Defense (DoD) for powering tactical and nontactical vehicles and vessels, off-road equipment, engine-generator sets, aircraft ground-support equipment and a variety of other applications. Although diesels are the most efficient of internal combustion engines and have favorable characteristics in the reduction of greenhouse gas emissions, concerns with the health effects from particulate matter (PM) and regulated hazardous air pollutants (HAP) emissions have intensified the call for cleaner burning diesels and led to recently proposed and enacted regulations increasing restrictions on diesel exhaust emissions. Because of these developments, many emissions control approaches are being pursued, including the development of cost-effective alternative fuels, such as biodiesel.

Biodiesel is a nontoxic, biodegradable fuel made from organic fats and oils and serves as a replacement, substitute, and enhancer for petroleum diesel. Biodiesel may be blended with petroleum diesel in all existing diesel engines with little or no modification to the engines. It had previously been reported to reduce all regulated air pollutant emissions except emissions of nitrogen oxides (NO_x).[1]

For this project, air emissions testing was performed on eight DoD-operated vehicles and two portable engines. Not all the same test cycles or fuels were used for each test engine. Multiple testing locations with different capabilities were used.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of this project is to establish emissions factors for DoD diesel powered engines of interest fueled with various blends and types of biodiesel, with and without the use of fuel additives that reduce NO_x emissions from biodiesel. Most available biodiesel emissions data are for older heavy-duty engines tested on an engine dynamometer and fueled with a blend of virgin soybean derived biodiesel mixed with low sulfur Diesel Fuel No. 2. Although these data are important, their use in estimating DoD fleet emission factors introduces significant uncertainties. By targeting the emissions from actual DoD-operated heavy-duty engines fueled with either soybean or yellow grease derived biodiesel, relevant DoD emissions factors have been determined.

1.3 REGULATORY DRIVERS

Mobile-source diesel emissions are regulated by both federal (40 Code of Federal Regulations [CFR] 86, 89) and California (13 California Code of Regulations [CCR] Chapter 3) equipment and vehicle standards. These standards are applied to equipment and vehicles at the time of manufacture. In the last 6 years, the Environmental Protection Agency (EPA) has pursued a program to dramatically tighten these regulations. Likewise, the EPA has also pursued a program to dramatically tighten the regulations for non-road diesel engines. These regulations, unlike their on-road counterparts, are based on the size of the engine, with larger engines having tighter standards.

Stationary-source diesel emissions are regulated by state and local regulations. Currently, most regulations limit only NO_x, carbon monoxide (CO), and opacity. However, the California Air Resources Board (CARB) recently proposed guidance that, if adopted by local air districts, would require the reduction of HAP emissions.

In addition to air emissions regulations, federal policymakers have also established initiatives that require the use of alternative transportation fuels such as biodiesel. The purpose of these initiatives is to reduce the nation's oil imports. The Federal Fleet Acquisition Requirement in the Energy Policy Act (i.e., Title III) requires 75% of annual DoD light-duty vehicle acquisitions to be capable of operating on alternative fuels. This law pertains to federal vehicle fleets consisting of 20 or more centrally fueled vehicles. Executive Order 13149, "Greening the Government through Federal Fleet and Transportation Efficiency," requires that by 2005 federal fleets reduce petroleum consumption by 20%, compared with the 1999 levels.

1.4 DEMONSTRATION RESULTS

The project results for the regulated emissions of CO, hydrocarbon (HC), NO_x and PM as well as the unregulated HAP emissions were that, at the 20% biodiesel (B20) level, there were no consistent trends over all applications tested. Within the context of the test matrix, no emissions differences were found between a B20 biodiesel blend manufactured from various yellow grease or soy feedstocks and a CARB-approved ultra-low sulfur diesel (ULSD) fuel. The tested NO_x reduction additives also proved to be ineffective. Therefore, the air pollution performance objectives outlined in the project's demonstration plan were not met. Although these results were not expected, they are not necessarily a disappointment since the baseline USLD fuel proved to be greatly superior to existing on-road Diesel No. 2.

1.5 STAKEHOLDER/END-USER ISSUES

DoD fleet operators are under increasing pressure to reduce both diesel air emissions and petroleum consumption. Unfortunately, many alternate fuels that have been shown to reduce emissions either have fuel costs higher than petroleum diesel or require significant engine modifications and/or infrastructure upgrades. Ideally, an alternate fuels program must be cost-effective and universally applicable and must provide significant measurable environmental benefits. Currently, only biodiesel derived from yellow grease meets these requirements. It is cost-effective, it can be used without any engine modifications, and it does not require any infrastructure upgrades. One of the important factors that limits B20 biodiesel use with DoD is a concern about its effect on air pollution regulatory compliance. By providing emissions testing results for multiple types of biodiesel, this project will address this customer concern.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Biodiesel is a renewable, clean burning, oxygenated fuel for diesel powered engines or boilers that is made from soybean oil, other vegetable oils, or animal fats. Chemically, biodiesel consists of a small number of alkyl esters. It contains no sulfur or aromatics and already meets the EPA's 2006 on-road standard for sulfur content in diesel fuel. Because it has properties similar to petroleum-based diesel fuel, biodiesel can be blended in any ratio with petroleum diesel and used in diesel engines without major modifications. Biodiesel is registered as a fuel and fuel additive with the Environmental Protection Agency (EPA) and meets clean diesel standards established by CARB. Neat biodiesel, i.e., 100% biodiesel (B100) has been designated as an alternative fuel by the Department of Energy and the Department of Transportation.

Biodiesel use as a fuel is as old as the diesel engine. Rudolph Diesel, inventor of the diesel engine in 1892, used peanut oil as the original engine fuel. The use of petroleum fuels for diesel engines did not come into widespread use until the 1920s. This fuel substitution was the result of a significant drop in the price of petroleum. Starting in the 1970s after the oil crisis, interest in the use of domestically produced biofuels returned, and in the 1990s, the biodiesel industry organized to promote its use. Recently, biodiesel demand has mostly come from fleet operators affected by the 1998 Energy Policy Act (EPAct) Amendment.

Two recent successes have helped advance the widespread use of biodiesel. First, the American Society of Testing and Materials (ASTM) issued a specification (D 6751) for B100 biodiesel fuel used for blending in December 2001. ASTM is the premier standard-setting organization for fuels and additives in the United States. This development is crucial in standardizing fuel quality for biodiesel in the U.S. market and increasing the confidence of consumers and engine makers. The ASTM specification was developed so that approved fuels could be consistently manufactured using any vegetable oil or animal fat as the raw material. Second, biodiesel became the only alternative fuel in the country to have successfully completed the EPA's Tier I and Tier II Health Effects testing under Section 211(b) of the Clean Air Act in May 2000. The Tier I testing conclusively demonstrated biodiesel's significant reductions in most currently regulated emissions as well as most unregulated emissions—especially those associated with cancer and lung disease. Tier II testing demonstrated biodiesel's nontoxic effect on health.

2.2 PROCESS DESCRIPTION

The production of biodiesel mostly is based on the process of base-catalyzed transesterification at low temperature (150°F), low pressure (20 pounds per sq in [psi]) and with a high conversion factor (98%). As depicted in Figure 1, a fat or oil reacts with an alcohol (like methanol) in the presence of a catalyst to produce glycerine and methyl esters or biodiesel. The methanol is charged in excess to assist in quick conversion and unconverted methanol is recycled. The catalyst is usually sodium or potassium hydroxide that has already been mixed with the methanol.

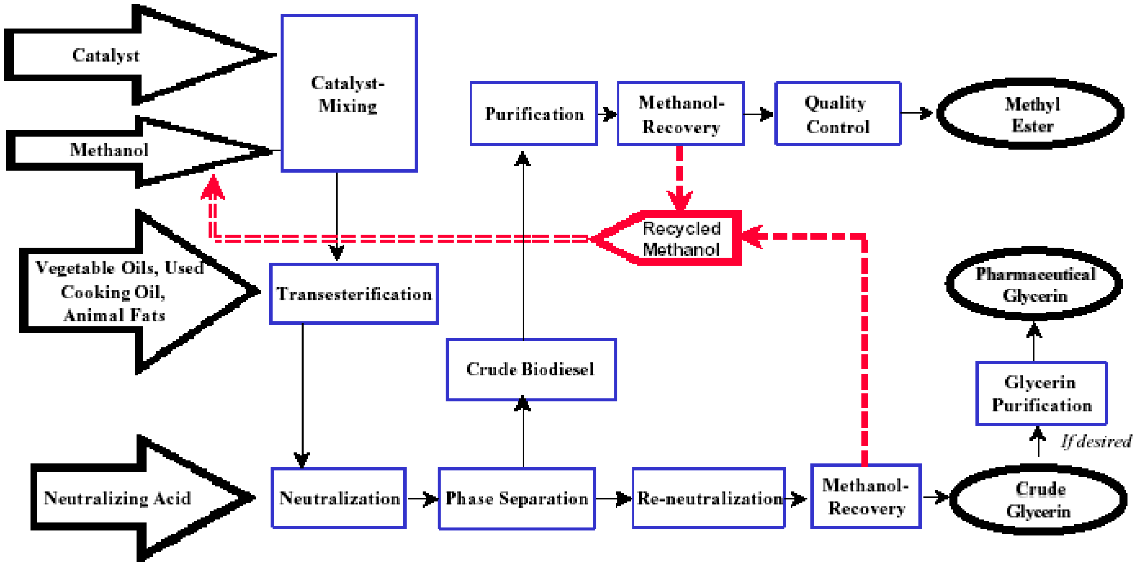

Figure 1. Biodiesel Production Diagram.

The key chemical reaction is the biodiesel reaction with the alcohol are shown below:

CH_2OCOR'''				CH_2OH		$R'''COOR$
|			Catalyst	|		
CH_2OCOR''	+	3 ROH	------>	CH_2OH	+	$R''COOR$
|				|		
CH_2OCOR'				CH_2OH		$R'COOR$
100 pounds Oil or Fat		10 pounds Alcohol (3)		10 pounds Glycerin		100 pounds Biodiesel (3)

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

During the past 20 years, more than 80 scientific studies have been conducted to measure the emissions from heavy-duty diesel engines fueled with biodiesel. Although the studies had many different focuses, most of the work was done using older engines (i.e., pre-1998), with testing performed on an engine dynamometer as opposed to an actual diesel powered vehicle. These studies primarily tested biodiesel derived from soybean oil since it is the most common form of the fuel.

In October 2002, EPA issued the draft technical report EPA 420-P-02-001 *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions*.[1] In this report, EPA used various statistical analytical tools to compile the results from 39 studies. Wherever sufficient information was available, EPA attempted to develop models to predict how biodiesel emissions would be affected by various duty-cycle, engine age/type, and fuel properties. They summarized the results to identify the average expected emissions reductions. For use of B20, Table 1 provides the expected criteria pollutants emissions reductions for virgin soybean-based 20% biodiesel (B20) biodiesel added to an average low sulfur (i.e., <500 parts per million [ppm]) base fuel.

Table 1. Emission impacts of B20 for Soybean-Based Biodiesel Added to an Average Base Fuel.

Regulated Pollutant	Change in Emissions for Soy
NO_x	+ 2.0%
PM	- 10.1%
HC	- 21.1%
CO	- 11.0%

The EPA analysis noted that biodiesel impacts on emissions varied depending on the type of biodiesel (e.g., manufactured from soybean, rapeseed, or animal fats) and on the type of conventional diesel to which the biodiesel was added. For example, biodiesel based on yellow grease provided a greater environmental benefit in that the reduction was greater for carbon monoxide (CO), hydrocarbon (HC), and particulate matter (PM) and the increase in nitrogen oxide (NO_x) was less than with soy-based biodiesel. With one minor exception, emission impacts of biodiesel did not appear to differ by engine model year.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The use of biodiesel fuel has been reported to reduce the overall air pollution resulting from diesel engine operations.[1] Of the criteria pollutants regulated by EPA, biodiesel is reported to reduce CO, HC, PM, and sulfur dioxide emissions while causing only a small increase in NO_x emissions. It also reduces life-cycle greenhouse gas emissions since the engine CO_2 emissions are partially offset by the carbon dioxide (CO_2) removed from the atmosphere by the growing oilseed plants. In addition to its pollution reduction advantages, biodiesel also has economic and strategic advantages. Biodiesel can be made from domestically produced agricultural raw materials that are produced in surplus in the United States. The use of biodiesel will reduce the use of imported oil, much of which is supplied by potentially unstable Middle Eastern suppliers.

Although biodiesel produced from virgin raw materials such as soybean oil is more expensive than petroleum, its use has significant economic benefits. By employing the surplus of raw agricultural products, the cost of government crop support programs can be reduced. In addition, biodiesel production facilities produce employment opportunities, particularly in rural areas.

To address the raw material cost problem, the production of biodiesel manufactured from yellow grease—a food service waste product—is being greatly expanded. Currently, yellow grease is available at little to no cost because most food service operators are required to pay for its disposal. Unfortunately, the supply of yellow grease is not unlimited. It is estimated that up to 800 million gal of yellow grease may be available in the United States per year, a quantity sufficient to produce 700 million gal of B100 biodiesel. This quantity cannot supply all of the potential demand. The Energy Information Administration of the Department of Energy reported in their Annual Energy Review that 2.455 million barrels per day of petroleum diesel fuel was used by the transportation sector in the United States during year 2002. If biodiesel were used for all diesel transportation needs, yellow grease could supply 9.2% of the potential B20 demand.

Three issues potentially limit the widespread and growing usage of biodiesel. The first is the cost of biodiesel which is driven primarily by the feedstock cost. Hence, in this project we are trying to use yellow grease to reduce the fuel cost. A second potential limitation is that there is a small increase in the NO_x emissions, and any increase might not be acceptable in NO_x non-attainment areas. Accordingly, this project will test some additives that claim to reduce the increase in NO_x that is associated with biodiesel. The third issue is the stability and cold weather performance of biodiesel. Currently, there is little information and no recognized test procedure to measure biodiesel's long-term stability. The use of acid number has, however, been suggested as the best simple test method to measure biodiesel stability. Likewise, biodiesel's stability in cold weather is not well understood, although it has been shown that B100 may not be suitable in very cold weather applications, such as winter use in Minnesota. These stability concerns have currently limited Department of Defense (DoD) biodiesel usage to B20 for applications where the fuel will not be stored for extended periods.

To assess the overall potential air pollution control benefit of implementing a biodiesel program, it must be evaluated against the potential alternatives. Biodiesel is a fuel-based solution to controlling emissions from diesel engines. Alternative controls include either expensive add-on devices or replacing the engine with one that meets tougher emission standards. These emission control approaches are much more expensive than a simple fuel change; hence, biodiesel may achieve the targeted reduction in emissions at a lower total cost.

In addition to being a low-cost option to reduce diesel engine emissions, it is also the low-cost option for implementing the EPAct regulations. These regulations require specified fleet operators, including most DoD fleets, to use alternate fueled vehicles (AFV) for at least 75% of their fleet. Using 450 gal of B100 or 2,250 gal of B20 earns the fleet operator one AFV credit. The Congressional Budget Office (CBO) determined in 1998 that using B20 biodiesel is the lowest cost option among the alternative fuel choices available to meet AFV requirements. CBO predicted that the federal government would save $10 million annually by using B20 biodiesel in its fleet vehicles.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Table 2. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance (Future) Objective Met?
Quantitative	Reduce CO emissions	Reduce emissions by 9% minimum with B20	No
	Reduce HC emissions	Reduce emissions by 16% minimum with B20	No
	Reduce PM emissions	Reduce emissions by 8% minimum with B20	No
	Reduce HAP Emissions	Reduce emissions by 16% minimum with B20	No
	Minimize Increase in NO_X emissions	Emissions increase <3%, for B20 (without additive)	Yes
	Reduce NO_x emissions	Reduce emissions by 2%, minimum for B20 (with additive)	No
	Minimize increase in fuel consumption	Increase fuel consumption by 3% maximum with B20	Yes
Qualitative	Drivability	No change	Yes
	Maintain reliability	No breakdowns caused by biodiesel	Yes

Note: The performance objectives are based on a comparison with ultra-low sulfur diesel (ULSD).

3.2 SELECTION OF TEST SITES AND FACILITIES

Biodiesel emissions testing was performed at laboratory test facilities and DoD activities. The laboratory test facilities were selected based on their capabilities, proximity to the Naval Facilities Engineering Service Center (NFESC), costs, and most importantly, their willingness to participate in this testing program. Field-testing sites consist of DoD facilities that operate diesel engines of interest. These sites were selected based on the availability of diesels of interest as well as their willingness to participate in the test program. The decision as to where to perform each of the emissions tests was based on many factors, including the owner's needs, the capability of the test personnel to perform field measurements, and costs.

For this emissions testing program, eight types of diesel-powered vehicles and two portable engines were selected for testing. These engines were selected since they represent a good cross section of diesel engines commonly found at DoD bases as verified during previous NFESC surveys. Test engines were selected to provide the greatest possible array of equipment. They included on-highway, off-highway, military tactical, and portable power equipment. A primary consideration in the selection of the test units was the equipment operating profile and the number of units in the DoD inventory. Here emphasis was placed on equipment that normally operates at medium to high load levels, with long operating times. Information on the selected engines and the tests to be performed is provided in Table 3.

Table 3. Biodiesel Emissions Test Matrix.

Item No.	Test Location	Application Description	Owner/ Operator	Engine Make/Model	Model Year	Fuel Type/ Fuel Additive	Test Cycle/Load	Regulated Emissions	HC and PM Character-ization
1	NREL[1]	Thomas Bus License No. G32 001589	Cheyenne Mountain Air Station	Cummins 5.9L	2002	ULSD B20 (soy)	Cheyenne Mountain Custom Cycle	All	None
	UCR[2] Mobile Lab								
2	UCR	HMMWV[3]	Camp Pendleton	GM[4] 6.5L Model A2	2004	ULSD JP-8[6] B20 (YGA[7]) B50 (YGA) B70 (YGA) B100 (YGA) B20 (soy) B100 (YGA) + Additive 1 B100 (YGA) + Additive 2	FTP[5], US06	All	ULSD B20 (YGA) B100 (YGA) FTP modes only
	ATC		Aberdeen Proving Grounds	GM 6.2L Model A1 M998	1987	ULSD B20 (YGA)	In-use	CO, NO_x	None
3	ATC[10]	Harlan Aircraft Tug	Aberdeen Proving Grounds	Cummins C6 3.9L Engine family XCEXL0239AAA	1999	ULSD B20 (YGA)	In-use	CO, HC, NO_x	None
4	UCR	Stake truck, Ford F700 Series License No. G71 00341	Naval Base Ventura County	Cummins 5.9L – 175HP	1993	ULSD B20 (YGB[11]) B20 (soy)	8-mode	All	None

[1] National Renewable Energy Laboratory (Denver, Colorado)
[2] University of California, Riverside
[3] Humvee
[4] General Motors Corporation
[5] Jet Propellant No. 8
[6] Federal Test Procurement
[7] Yellow Grease Formula A
[8] 50% biodiesel
[9] 70% biodiesel
[10] Aberdeen Test Center (at Aberdeen Proving Ground [APG])
[11] Yellow Grease Formula B
[12] For engine No. 2, two fuel additives are listed. The purpose of both additives is to reduce NO_x by increasing the cetane number of the fuel. Additive No.1 is ethyl hexyl nitrate (EHN), 0.5% by volume, and additive No. 2 is ditertiary butyl peroxide (DTBP), 1% by volume.
[13] Two types of yellow grease were tested, YGA and YGB. These fuels were supplied from independent sources.
[14] None of engines to be tested will have catalyzed soot filters installed. Some of the engines may be equipped with a diesel oxidation catalyst.
[15] Kilowatt
[16] Caterpillar Corporation

Table 3. Biodiesel Emissions Test Matrix (continued).

Item No.	Test Location	Application Description	Owner/ Operator	Engine Make/Model	Model Year	Fuel Type/ Fuel Additive	Test Cycle/Load	Regulated Emissions	HC and PM Character-ization
5	UCR	Tractor, Ford L-9000 License No. MC 288060	Camp Pendleton	Caterpillar 3406C	1992	ULSD B20 (YGA) B20 (YGB) B100 (YGA) 49 State EPA No. 2 Diesel	8-mode	All	ULSD B20 (YGA) B100 (YGA)
6	ATC	Hyster 65 Forklift Model H65XM VIN No. H177B257804	ATC	Perkins 2.6L - 55HP Engine family 1PKXL02.6UB1	2001	ULSD B20 (soy)	In-use	HC, CO, NO_x	None
7	UCR	Ford F-350 Pickup License No. MC 291724	Camp Pendleton	Navistar 7.3 L	1999	ULSD B20 (YGA)	FTP US06	All	None
8	UCR	Thomas Bus License No. G32 00583	Camp Pendleton	CAT[16] 126, 330 HP	2000 Engine 1999	ULSD B20 (YGA) B20 (soy)	8-Mode	All	All
9	UCR	Portable 250 KW[15] Generator	Camp Pendleton	Kamatzu SA60125E-2	2000	ULSD JP-8 B20 (YGA) B100 (YGA)	5-Mode	All	ULSD B20 (YGA) B100 (YGA)
10	UCR	60 KW Tactical Generator	Camp Pendleton	Lippy MEP-806A	1995	ULSD JP-8 B20 (YGA)	5-Mode	All	None

3.3 TEST SITE, FACILITY HISTORY, AND CHARACTERISTICS

The equipment selected for testing is located at the DoD facilities described below:

U.S. Army Aberdeen Test Center, Aberdeen Proving Grounds, Maryland, is a temperate-climate proving ground encompassing 57,000 acres of land and water. It is DoD's lead test center for land vehicles, guns and munitions, and live-fire vulnerability and lethality testing. After more than 80 years, ATC has developed into a world-class, all-purpose test center operating as an outdoor laboratory. The comprehensive array of capabilities, unique facilities, simulators, and models at ATC, combined with an experienced scientific and technical work force, enable testing and experimentation on items ranging from components to entire systems. To support its testing mission, many diesel vehicles used by DoD are found on Aberdeen Proving Grounds.

Cheyenne Mountain Air Station, Colorado Springs, Colorado, is buried 2,000 feet under Cheyenne Mountain. The facility is situated in underground tunnels that were bored out of the mountain. The air station is a top-secret combat operations center formerly known as the North American Air Defense Command (NORAD). The station contains equipment that provides warning of missile or air attacks against North America and can serve as the focal point for air defense operations in the event of an attack. The station's mission is to provide Canadian and U.S. National Command authorities with accurate air, space, missile, and nuclear detonation information. The major units of the station are the North American Aerospace Defense Command, U.S. Space Command, and Air Force Space Command. To access the main operational areas, diesel powered vehicles are used in the underground tunnels. Exhaust from these vehicles is the major source of contamination for the facility's air handling system. The Thomas buses selected for the demonstration are used to transport workers down the main access tunnel.

Marine Corps Base, Camp Pendleton, California, is the site of the Corps' largest amphibious assault training facility, encompassing 17 miles of Southern California coastline and 125,000 acres.

The base has a population of nearly 40,000 Marines and sailors. As such, nearly all types of equipment in the Marine Corps inventory are located at this facility. As a functioning training command, the equipment is used almost daily for training and transportation purposes. The buses and trucks selected for testing are used to transport Marines and equipment to the widely separated training ranges within Camp Pendleton and to other Marine Corps activities. These selected buses and trucks are also commonly found at many other DoD facilities.

Naval Base Ventura Country, Port Hueneme Site, Port Hueneme, California, is the home of the Construction Battalion Center (CBC), the command organization for the Navy's Seabees. The site covers approximately 1,600 acres on the southern California coastline and includes a deep-water port facility. To support the Seabees in their field construction mission, the CBC has a wide variety of diesel-powered vehicles and equipment, much of which is used extensively during training exercises. The equipment and vehicle testing will be a good representation of the types of diesel engines encountered at other Navy shore activities.

Laboratory testing facilities to be used for this program are described below:

University of California, Riverside, California, Bourns College of Engineering–Center for Environmental Research and Technology (CE-CERT) is an off-campus air emissions testing and air pollution research facility of the University of California, a state-supported institute of higher education. CE-CERT was founded more than 12 years ago to support California's effort to understand and reduce air pollution. As part of its capabilities, CE-CERT has two emissions testing facilities that will be used during this project—a light-duty chassis dynamometer emissions testing facility and a mobile test laboratory contained in a trailer. Both testing facilities are capable of measuring all the criteria pollutants on various engine-operating cycles in accordance with EPA approved test methods. In addition to providing emissions rate data, these facilities can provide HC and PM speciation measurements and PM size distribution measurements.

The UCR mobile laboratory was designed to be pulled by a heavy-duty tractor, allowing real on-road emissions measurements to be obtained. The mobile laboratory's design also allows it to be used to measure emissions rates from stationary diesel sources such as back-up generators.

National Renewable Energy Laboratory ReFUEL Laboratory, Denver, Colorado, made its debut in 2002 to provide facilities for identifying, testing, and evaluating renewable and synthetic fuels and lubricants for use in ground transportation, with a focus on enabling high efficiency operation while displacing petroleum products. The 4,500 sq ft facility was previously operated by the Colorado School of Mines as the Colorado Institute for Fuels and High Altitude Engine Research. It was designated as the National High Altitude Heavy-Duty Research and Technology Center under the Clean Air Act Amendments of 1990. The facility includes a heavy-duty chassis dynamometer with tandem 40-in rolls capable of testing single or tandem drive axle vehicles up to 80,000 lb and a 24-ft wheelbase. It is the only high altitude facility of its type in North America. The facility provides air pollution measurement equipment to measure all criteria pollutants using EPA-approved test methods and driving cycles. In addition, it has an engine test cell for directly testing engines.

3.4 PHYSICAL SETUP AND OPERATION

The emissions testing program took place at laboratory sites and in the field. Table 3 identifies the test location for each engine test. When the testing was performed at a laboratory, the test engine was transported to the laboratory. As required, fuels were transported to the test site. Fuels and fuel additives for the testing were stored and mixed at UCR. To reduce the variability of the test results due to changes in fuel composition, all fuels required for the project were purchased and blended at the beginning of the project and stored at UCR. To ensure that the quality of the biodiesel remains the same throughout the project, 200 parts per million by weight (ppmw) of Tenox 21 (active ingredient is t-butyl hydroquinone) was added to the YGA manufactured by NFESC in Port Hueneme, as recommended by NREL.

Since similar DoD vehicles may be operated under different conditions (i.e., different loads and routes) compared to the rest of a fleet, the testing program was developed to incorporate multiple test cycles and load points for each engine tested. Generally, multiple test cycles or load points were tested using the same dynamometer, test track, or load bank.

3.5 SAMPLING AND MONITORING PROCEDURES

To verify the suitability of biodiesel in reducing air emissions from in-service DoD diesel engines, a comprehensive test program was developed. As shown in Table 3, the proposed test program included a wide variety of test engines, fuels, operating conditions and NO_x improvement additives. The project included emissions testing for criteria pollutants as well as hazardous air pollutants (HAPs). EPA-approved test methods were used for applicable tests. To ensure data quality, testing using test cycles and static points was repeated; data points were recorded continuously during the tests and reported as the integrated result over the whole test period; and three testing organizations were employed. Testing results from each engine were compared with the previously completed testing and with similar work performed by other test programs.

At a minimum, all engines were tested using a JP-8 or ULSD base diesel fuel and a B20 biodiesel fuel. Additional tests were performed using B20, B50, B70 and B100 biodiesel fuels manufactured from either soybean oil or yellow grease. In addition, one engine was selected for demonstrating the effectiveness of the EHN and DTBP cetane improvers in reducing NO_x emissions. These additives were chosen based on an investigation reported on in a National Renewable Energy Laboratory Report (McCormick et al).

Gaseous criteria pollutants including CO, HC and NO_x were measured during all tests. The total weight of PM2.5 emissions were measured for all engines tested by NREL and UCR. On a subset of engines, full chemical and physical characterization of the HAP and PM emissions was performed. Test results were reported in the form of emission factors and reported as grams per mile (g/mile), grams per gallon of fuel consumed or grams per brake horsepower hour (g/bhp-hr). The emissions tests used a combination of various standardized stationary and transient driving test cycles as well as static and actual on-road testing. Emissions testing results reported in the scientific literature show that air emissions vary with a number of parameters, the most important variable being the engine operating conditions. The testing conditions were chosen to come as close as possible to the expected certification or to representative in-use conditions as selected by other investigators for similar applications.

Since the purpose of our test program is to provide emissions factors for existing DoD engines installed in various types of DoD operated vehicles or equipment, all testing was performed with the engine installed in the applicable vehicle or equipment. Engine testing in an engine test cell was not part of the test program. Vehicle emission testing was performed either on-road or with the vehicle placed on a chassis dynamometer. Portable generator testing was performed using an electrical resistance load bank. The load bank was adjusted so that testing could be performed at various percentages of full engine load as specified in the EPA test method.

3.6 ANALYTICAL PROCEDURES

Emissions testing for this project was performed by three testing organizations, ATC, NREL and UCR. The type of data collected is identified in Table 3 and the analytical testing instrumentation used is listed in Table 4. Although each testing organization uses similar analytical testing instrumentation and similar analytical testing procedures specified in federal or recognized standard publications, they each have unique testing capabilities in terms of the types of tests they can perform. These unique capabilities have been fully exploited by this project.

Emissions testing analytical test methods approved by the EPA and found in the Code of Federal Regulations (CFR) were used for testing regulated pollutants. Specifically, testing was performed using the methods contained in 40CFR86 for control of emissions from new and in-use highway vehicles and engines.

For the nonregulated emissions, the analysis methods are not found in the CFR but were performed using industrial specifications and methods that are referenced in the scientific literature. The speciated C1-C12 volatile organic compounds (VOC) were determined using methods developed in collaborative research between the automobile and petroleum industries under the Auto/Oil Air Quality Improvement Research Program (AO/AQIRP) (Siegl et al). For the C1-C12 VOCs, sample collection was performed using Carbowax/molecular sieve packed tubes and/or Tedlar bags followed by gas chromatography—flame ionization detector (FID) analysis using a modified Auto/Oil protocol. For a more detailed discussion of the tube sample collection procedure, see Sha et al, 2005. Aldehydes and ketone emission rates were collected using dinitrophenylhydrazine (DNPH) cartridges and analyzed using a high-performance liquid chromatograph with ultraviolet detection, as per an AO/AQIRP method (Siegl et al). Elemental carbon/organic carbon (OC) samples were collected on quartz filters and analyzed using a Thermooptical carbon aerosol analyzer from Sunset Laboratories, a National Institute of Occupational Safety and Health (NIOSH) recognized method (Birch and Cary, Shah et al, 2004). Semi-volatile hydrocarbons were collected for analysis using a Poly Urethane Foam/Experimental and Developmental (PUF/XAD) cartridge immediately downstream of the quartz fiber media.

Characterization of gaseous HAP compounds, including the mobile source air toxics identified in Table 5, were performed using gas chromatography (GC) where the samples were collected on DNPH cartridges. Acetaldehyde, formaldehyde, benzene, and 1,3-butadiene are the four main gas-phase HAPs specified in the Clean Air Act for mobile sources. Acrolien is another gas-phase chemical targeted by EPA for its toxicity and ambient levels. Naphthalene is the polycyclic aromatic hydrocarbon (PAH) with the highest concentration in vehicle exhaust.

Table 4. Test Methods and Analysis of Exhaust Emissions.

Instrument/Method	Measurement	Sample Duration	Lower Quantifiable Limit (Expressed in terms of fundamental measurement)
Pierburg NDIR[1]	CO_2, CO	1 s	50 - 500 ppm
California Analytical Instruments/FID	HC, Methane	1 s	10 - 30 ppm
California Analytical Instruments/ Chemiluminescence	NO, NO_2	1 s	10 ppm
Various/Filter[2]	$PM_{2.5}$ mass and chemistry	0.25 - 2 hrs	Various
Tedlar Bag/GC-FID	VOCs ($C_2 – C_{12}$)	0.25 - 2 hrs	10 ppb C
DNPH Cartridges/Shimadzu HPLC/UV[3]	Aldehydes and ketones	0.25 - 2 hrs	0.02 µg/mL

[1] non-dispersive infrared
[2] includes Teflon and quartz media for mass, metals, ions, elemental/organic carbon and PAHs by GC/MS on extracts from filters
[3] high-performance liquid chromatography/ultraviolet

Table 5. Partial List of EPA's Recognized Mobile Source Air Toxics.

Acetaldehyde	1,3-Butadiene
Acrolein	Formaldehyde
Benzene	Naphthalene

The measurement of PM emissions is more difficult and in the testing program consisted of mass measurements as well as chemical characterization of the particles. Mass measurements were made by collecting particulates on a filter media and weighing the media before and after exposure to the exhaust. For these measurements, it is critical that the CFR methods be applied in using an upstream classifier to remove the large particles and that the filter face temperature be maintained at 47°C ±5°C. Chemical characterization of the PM involved chemically testing the particles collected on quartz filter media for elemental and organic carbon as these measurements can be directly related to the information gained with the ambient PM monitors.

Most of the emissions testing program was performed by UCR's use of their mobile heavy-duty testing laboratory (test trailer) (Cocker et al). This laboratory was designed for testing diesel powered generators and heavy-duty vehicles. The test trailer perform on-road tractor testing, test a generator connected to an electric load bank, or test a vehicle placed on a separate chassis dynamometer.

For emissions measurements on light or medium duty vehicles, UCR has a Burke E. Porter 48-in single-roll electric dynamometer. For emissions testing with this dynamometer, UCR utilizes standard bag measurements for CO, CO_2, HC, and NO_x and conducts these measurements with a Pierburg AMA-4000 bench. HC is measured modally through a line heated to 190°C using a Pierburg AMA-2000 emission bench.

was performed by ATC used EPA's Real-time On-road Vehicle Emissions Reporter (ROVER) to perform in-use testing. The ROVER system is presently used by ATC to perform tests for the EPA's program to monitor in-use, heavy-duty diesel engines. The ROVER (including all of its components) is mounted on or in the vehicle.

The NREL laboratory features a heavy-duty chassis dynamometer that simulates operation of a vehicle on the road. The dynamometer, which can accommodate vehicles with a wheelbase between 89 and 293 in, is connected with two 40-in diameter rolls that are capable of testing all highway-ready single or twin-axle vehicles. The distance between the rolls can be varied between 42 and 56 in.

In the NREL lab, simulations of vehicle loads, including rolling resistance, air resistance, desired road grade, and acceleration of vehicle inertia, are performed with the dynamometer and controller software. Vehicles of weights between 8,000 to 80,000 lb can be simulated via electrical inertial simulation. For each vehicle test, standard or customized driving test cycles are used that match the duty cycle of the test vehicle, ranging in speeds from idle up to 60 miles per hour. The dynamometer is equipped to run automated warm-up and coast-down routines to verify that dynamometer parasitic loads are stabilized and that road load simulations are accurate.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

This section summarizes the emissions factors from the tested DoD-operated diesel engines. As identified in Table 3, the testing matrix included 10 types of vehicles and portable equipment, 10 types of fuel, three testing organizations, and several different driving/testing cycles Testing was performed for the regulated emissions of CO, HC, NO_x and PM as well as the unregulated emissions of elemental and organic carbon, carbonyls, and specified hazardous gas-phase hydrocarbons. Not every engine was tested for each pollutant. In general, significantly less data was collected for unregulated emissions since the cost to obtain this data was much higher. Table 6 provides emission factors relative to those for ULSD for the regulated emissions. Table 7 provides a similar for the unregulated emissions. Since multiple test runs were performed at each test condition, the results presented in the two tables represent average values. A more complete discussion of the project results and graphs of the data for each tested engine may be found in the project's final report.

4.2 PERFORMANCE CRITERIA

Expected and actual engine performance from the demonstration and the applicable performance confirmation methods are shown in Table 7, which is identical to the table in the project's demonstration Plan. Since emission testing provides quantitative results, this project did not have any primary qualitative performance objectives.

As shown in Table 8, the actual emissions factors did not meet the expected values except for minimizing the increase in NO_x emissions. In summary, there was no statistically significant difference between the emissions factors for ULSD and any of the B20 biodiesels.

In addition to the collection of emissions data, Table 7 also identifies secondary performance criteria, the collection of fuel economy, drivability and reliability information. Based on energy content data reported in EPA's Draft Technical Report EPA 420-p-02-001, the project team did not expect that any fuel economy differences would be observable between the USLD, YGA, and JP-8 fuels. This expectation proved to be correct. A fuel analysis showed that the ULSD had a 1.6% higher energy content than the YGA fuel and the JP-8 fuel had a 0.9% higher energy content. These differences were less than the expected 3-5% difference.

For the drivability and reliability performance criteria, information was collected from fleet and vehicle maintenance management personnel at Camp Pendleton and from the emissions testing drivers. Based on interviews of these personnel, the project team concluded that vehicle drivers and maintenance mechanics experience no difference when operating or repairing B20-fueled vehicles. This result matched our expectation.

Table 6. Summary of Emissions Changes Relative to ULSD for Individual Engines.
(Reported as percent change from ULSD values)

Vehicle	Cycle	YGA - B20				Soy - B20				YGB - B20				JP-8				YGA - B100			
		HC	CO	NO_x	PM	HC	CO	NO_x	PM	HC	CO	NO_x	PM	HC	CO	NO_x	PM	HC	CO	NO_x	PM
F350	FTP	-19%	-6%	0%	-15%																
	US06	-18%	-3%	24%	-13%																
Model A2 Humvee	FTP	93%	17%	1%	0%	113%	26%	-1%	-9%					265%	133%	3%	35%	133%	24%	-2%	-38%
	US06	2%	19%	2%	-44%	3%	44%	-1%	-57%					80%	113%	4%	-37%	29%	54%	0%	-70%
F700	AVL 8-mode					4.8%	2.7%	3.2%	5.6%	0.4%	-2.1%	-0.9%	8.4%								
F9000	AVL 8-mode	3.2%	-6.7%	11.7%	-19.4%					-9.5%	-13.5%	8.6%	-35.5%					-31.6%	-30.6%	40.8%	-74.9%
Camp Pendleton Bus	AVL 8-mode	1.3%	-6.8%	-0.4%	-10.8%	13.3%	-6.7%	-3.7%													
250 kW Generator	5 -mode	-6.6%	5.8%	2.3%	17.1%									31.8%	28.9%	1.5%	14.3%	-61.4%	-0.7%	8.3%	13.3%
60 kW Generator	5-mode	6.3%	13.0%	8.2%	10.9%									42.0%	97.5%	15.6%	-48.1%				
Cheyenne Mountain Bus (UCR results)	Custom					-22.0%	-17%	3.0%	-29%												
Cheyenne Mountain Bus (NREL results)	Custom					-11.2%	-1.3%	0.2%	-8.4%												
Aircraft tow	In-use	9%	-18%	-1%																	
Forklift	In-use					-10%	20%	-8%													
Model A1 Humvee	In-use	NA	5%	6%																	
Vehicle	**Cycle**	**YGA - B50**				**YGA - B70**				**YGA - B100 + Additive #1**				**YGA - B100 + Additive #2**							
		HC	**CO**	**NO_x**	**PM**	**HC**	**CO**	**NO_x**	**PM**	**HC**	**CO**	**NO_x**	**PM**	**HC**	**CO**	**NO_x**	**PM**				
Model A2 Humvee	FTP	73%	23%	1%	-28%	100%	28%	-1%	-33%	120%	21%	-3%	-38%	50%	11%	-2%	-42%				
	US06	12%	30%	2%	-63%	24%	52%	2%	-68%	23%	62%	-2%	-75%	15%	57%	0%	-75%				

Table 7. Summary of Emissions Changes Relative to ULSD for HAPs.

(Reported as percent change from ULSD values)

	Engine	EC[1]	OC[2]	TC[3]	Acet-aldehyde	Acrolein	Benzene	Buta-diene	Formal-dehyde	Naph-thalene
YGA 20%	Camp Pendleton Bus	-11.834	4.459	-3.697	21.702				14.704	
	F9000	5.808	-16.481	-1.979	-36.934	1110.738	538.116		-46.037	547.751
	250 kW Generator				44.218	-39.649			36.667	36.767
	Humvee				17.68	21.86	-9.69	55.97	13.06	
YGA 100%	F9000	-79.174	-31.298	-64.190	-47.235	235.889	411.028		-53.932	214.207
	250 kW Generator				36.300	-6.526			44.306	31.096
	Humvee						-16.13	83.48		
Soy B20	Camp Pendleton Bus	-11.834	4.459	-3.697	21.702	29.551			14.704	48.443

[1] elemental carbon
[2] organic carbon
[3] total carbon

Table 8. Expected Performance and Performance Confirmation Methods.

Performance Criteria	Expected Performance (Pre-Demo)	Performance Confirmation Method	Actual (Post-Demo) (Future)
Primary Criteria (Performance Objects) (Quantitative)			
Reduce CO emissions	Reduce emissions by 9% (min.) with B20	40 CFR 86	No change
Reduce HC emissions	Reduce emissions by 16% (min.) with B20	40 CFR 86	No change
Reduce PM emissions	Reduce emissions by 8% (min.) with B20	40 CFR 86	No change
Reduce HAP emissions	Reduce emissions by 16% (min.) with B20	Various EPA methods	No change
Secondary Performance Criteria (Quantitative)			
Minimize increase in NO_x emissions	Emissions increase <3% for B20 (without additive)	40 CFR 86	No change
Minimize increase in NO_x emissions	Reduce emissions by 2% (min.) for B20 (with additive)	40 CFR 86	No change
Fuel economy	Similar to petroleum diesel	40 CFR 86	No change
Secondary Performance Criteria (Qualitative)			
Drivability	No change	Driver response	No change
Reliability	No change	Driver response	No change

4.3 DATA ASSESSMENT

The primary fuels of interest for this study were the 20% biodiesel blends since these are the blends of biodiesel used in military vehicles. The project results for the regulated emissions indicated that, at the B20 level, there were no consistent trends over all applications tested. Within the context of the test matrix, no differences were found between the various YGA, YGB, and soy-based biodiesel feedstocks. The results indicated no statistically significant differences in CO, HC, NO_x and PM emissions between the B20-YGA and the ULSD. The tested NO_x reduction additives also proved to be ineffective. Thus, the air pollution performance objectives outlined in the project's demonstration plan were not met. Although these results were not expected, they are not necessarily a disappointment since the baseline USLD fuel proved to be greatly superior to existing on-road Diesel No. 2.

The project results showed that over the range of vehicle and equipment types, emission factors could vary significantly depending on application or type of usage. Table 6 provides a comparison of the emissions differences for all vehicle and fuel combinations.

Although there were no overall trends, there were trends for individual engines. For the Ford F9000 tractor, there was a trend of lower PM emissions for the B20-YGA, and B20-YGB fuels. There was some trend of higher HC emissions with the biodiesel blends for the Humvee, considering also the higher blend levels. The B20-YGA and B20 YGB also showed a trend of higher CO emissions on the Humvee.

To provide a better understanding of the effects of B20 over the entire fleet, a statistical analysis was performed. Since the vehicles and equipment represent a variety of applications and test protocols, the results were normalized into units of grams of emissions per either gallons of fuel used, kg of fuel used, or British thermal units per gallon Btu/gal of fuel used to provide a mechanism for comparing the results of the fleet as a whole on a consistent basis. These analyses were performed comparing ULSD to B20-YGA since this was the blend utilized with nearly all of the test vehicles. For this analysis, a two-tailed, paired t-test was performed using only the average values for a particular vehicle/fuel combination. For this analysis, we considered $p \leq 0.05$ as statistically significant and $p \leq 0.10$ as being marginally statistically significant. As such, this analysis does not account for the variability of testing within a specific vehicle/fuel combination. The results for HC, CO, NO_x and PM all showed no statistically significant differences between the ULSD and the B20-YGA for either the calculations based on gallons of fuel used, emissions per kg of fuel used, or Btu/gal of fuel used. Statistical comparisons for fuel consumption were also made with the results showing no statistically significant difference in fuel consumption between the ULSD and the B20-YGA. Table 9 provides a summary of these statistical analysis results.

Table 9. Fleetwide Statistical Analysis Results for B20-YGA vs. ULSD.

		HC	CO	NO_x	PM	Fuel Use
Emissions per kg of fuel used	%	-8.6%	-5.1%	0.0%	-9.2%	
	p-value	0.14	0.28	0.97	0.27	
Emissions per gal of fuel used	%	-7.6%	-4.1%	+1.1%	-8.2%	
	p-value	0.16	0.36	0.19	0.32	
Emissions per Btu of fuel used	%	-7.3%	-3.8%	+1.4%	-7.9%	
	p-value	0.16	0.39	0.11	0.33	
Gal per work or activity unit						+1.7%
						0.18

The higher biodiesel blends (B50 to B100) were only tested on the Humvee, and with the B100 on the 250 kW generator and a single test on the Ford F9000. On the Humvee, the higher biodiesel blends did show a trend of higher CO emissions with the higher biodiesel blends, consistent with the B20 blends. There was also a general trend of higher total hydrocarbon (THC) emissions, at least on the FTP cycle, for this vehicle. Finally, there were some trends of lower PM emissions on the Humvee for the higher biodiesel blends and on the F9000 for the B100. This is consistent with the larger body of literature, although consistent PM reductions are not found at the B20 blend levels. NO_x emissions for the single test on the F9000 with B100-YGA were also higher than that found for ULSD.

JP-8 was also tested over a range of test applications and showed relatively consistent higher HC emissions over the Humvee and the two generators ranging from 30 to 265%. Similarly, CO emissions increased with JP-8 on the Humvee and the two generators in the range of 30 to 130%. Some improvement in PM was found with the JP-8 on 60 kW generators.

The results of this study in general show much smaller changes in emissions with B20 than previous studies. A number of other studies have found larger reductions in HC, CO, and PM emissions for biodiesel fuels (EPA; Sharp, 1997; Sharp, 1998a; Sharp, 1998b; Grabowski et al; Smith et al; Spataru and Romig; McDonald et al; Clark et al; Starr). There are some differences between the present and previous studies. In many of the previous studies, however, comparisons were made with Federal No. 2 diesel fuels with higher aromatic contents and lower cetane numbers than the California Air Resources Board (CARB) fuel used in the present work (Sharp, 1997; Sharp, 1998a; Sharp, 1998b; Grabowski et al; Smith et al; Spataru and Romig; McDonald et al). Other previous studies have, however, demonstrated the emissions reduction potential of biodiesel blends in comparison with CARB fuels (Clark et al, Starr). It is worth noting that while ULSD will soon be implemented throughout the country, the nature of the diesel fuel could still differ significantly between different regions of the country. The CARB ULSD probably represents the most stringent fuel requirements that would be met by commercial fuels. In other parts of the country where fuel specification on aromatics and other fuel properties are not as strict, some additional benefits may be found relative to those in this study.

There may also be differences in the operational load in comparison with engine dynamometer tests that affect the magnitude of the changes in emissions. Previous studies have shown that the benefits of biodiesel fuels decrease in magnitude at lower loads (McDonald et al, Choi et al, Akasaka et al). UCR has also observed similar results for previous tests conducted over the light-duty FTP in their laboratory for biodiesel fuels on medium-duty diesel trucks (Durbin et al, 2000; Durbin et al, 2002).

For the unregulated HAP emissions, no consistent trends were identified over the subset of vehicles tested. This result, like those for the regulated emissions, did not meet the air pollution performance objectives outlined in the project's demonstration plan. However, it should be noted that the dataset for HAPs was smaller than that for the regulated emissions. Also, since speciation data was not available for all modes, analyses and comparisons based on weighted values could not be conducted for the species. As such, it is likely that a larger sample set would be needed to statistically evaluate the effects of biodiesel on HAPs against ULSD. While these results were not expected, it is not necessarily a disappointment since, as previously stated, the baseline ULSD fuel proved to be greatly superior to existing on-road Diesel No. 2.

Since the purpose of this demonstration is to obtain air emissions data not currently available for DoD diesel engines of interest, the overall success of this project will be measured in terms of the quality of data acquired and its acceptance by the scientific community. As an additional measure, this project must provide sufficient data to convince DoD diesel fleet operators and fuel suppliers to implement biodiesel programs within their activities. In order for the project's test results to be accepted, standard recognized test methods were employed and the results reported in units consistent with other investigations.

4.4 TECHNOLOGY COMPARISON

As compared with CARB ULSD, this project found that common DoD diesel engines powered with B20 biodiesel have similar drivability, emissions factors, fuel economy, and reliability. These results did not appear to be affected by the source of the biodiesel. Both soy and yellow-grease-based biodiesel produced similar results. It was also found that the two tested NO_x reduction fuel additives are not effective in reducing NO_x emissions.

5.0 COST ASSESSMENT

5.1 COST REPORTING

Implementing a biodiesel fueling program represents new operational costs over existing petroleum diesel fueling activities. The advantage of implementing a biodiesel program over other potential alternative fuels is that biodiesel can be used in most existing diesel engines without modifications to either the engine or fuel storage system, and the fuel can be dispensed from existing fueling stations. Thus, a biodiesel program should have very small start-up costs. These benefits are not available for competing alternate fuels, such as hydrogen or compressed natural gas. The only direct cost for implementing a biodiesel program is the price difference of the fuel, taking into account the slight decrease in fuel economy with biodiesel, which for most fleets will not be noticeable. As of the preparation date of this Environmental Security Technology Certification Program (ESTCP) Cost and Performance Report, the average national difference between the commercial price of petroleum diesel and B20 is $0.17 per gal of fuel. For federal government fleets, the Defense Energy Support Center currently charges a $0.14 per gal premium for B20.

In terms of indirect environmental costs, NFESC has not been able to identify any costs that would change with biodiesel use. For example, permitting and spill-plan requirements for fuel dispensing and storage operations would be the same. The only effect that biodiesel use will have on environmental compliance costs is in the area of AFV credits. Since the federal government is mandated to purchase AFVs, satisfying this requirement through usage of biodiesel can minimize this program's compliance costs. Assigning a value to an AFV is, however, very difficult. NFESC is not aware of any generally acceptable value assigned to an AFV credit.

Since fuel cost is the only identified cost difference between the use of petroleum and biodiesel, neither information is shown in Table 10. The Environmental Cost Analysis Methodology (ECAM) developed by the National Defense Center for Environmental Excellence was not used because it is not required for incorporating the fuel cost information. Cost information for competing alternate fuels is not incorporated into Table 10 since the purpose of this ESTCP project is to obtain air emissions data for biodiesel, not to justify its use in place of another alternative fuel.

Table 10. Types of Costs by Category.

Direct Environmental Activity Process Costs				**Indirect Environmental Activity Costs**		**Other Costs**	
Start-Up		**Operation and Maintenance**					
Activity	$	Activity	$/gal	Activity	$	Activity	$
		Fuel purchase (price difference)	$0.14				

5.2 COST ANALYSIS

Currently many DoD-operated nontactical diesel powered engines are fueled with low sulfur diesel fuel made from petroleum. This is rapidly changing as new B20 biodiesel programs are rolled out throughout DoD. Tactical engines are fueled with JP-8, a higher sulfur containing fuel also derived from petroleum. Starting in 2006, the EPA has mandated that on-road diesel powered vehicles use ULSD. Since this new mandate will be implemented after the completion of this project, the costs for biodiesel will be not be compared to ULSD. As discussed in Section 5.1, cost information for competing alternate fuels will not be incorporated into the final reports since the purpose of this ESTCP project is to obtain air emissions data for biodiesel, not to justify its use in place of another alternate fuel.

The retail price of biodiesel reflects its distribution and manufacturing costs, the profit for the distributors and producers as well as the fact that, given the current biodiesel supply/demand balance, buyers are generally willing to pay a premium over the price of petroleum diesel. The manufacturing costs are primarily driven by the cost of the raw material vegetable oil. At current soybean oil prices, the oil costs a little over one-half the retail price of B100 biodiesel. Generally, the manufacturing cost for making the biodiesel is proprietary information; however, it is believed to be decreasing in recent years as the biodiesel market has developed. This trend is expected to continue for the next few years, at least.

Costs and the difference in cost between petroleum diesel and biodiesel continuously change over the course of time. Petroleum diesel costs are driven by the world cost of crude oil, the oil refining markup, and any local supply/demand imbalances. Since biodiesel consumed in the United States is primarily made from virgin soybean oil, its cost is driven by this commodity's price, as well as any local supply/demand imbalances. Currently, the cost of soybean oil for use in the manufacture of biodiesel has been lowered through a $1.00 per gallon direct federal subsidy. The duration and extent of future subsidies is unknown.

In summary, the life-cycle costs for implementing a biodiesel fueling program are totally dependent on the difference in cost between the two fuels. Assuming that the cost for crude oil increases faster than that of soybean oil, the price premium for biodiesel should decrease in the future. This cost difference between petroleum diesel and biodiesel may or may not be important based on any future mandates to use alternate fuels. In this case, the costs for biodiesel must be compared to that of the other alternate fuels.

5.3 COST COMPARISON

As discussed in Section 5.1, implementing a biodiesel fueling program represents additional operational costs over existing practices. Since biodiesel may be used in existing diesel engines and fueled using the existing fueling infrastructure and because it requires no additional environmental permits, the implementation of a biodiesel program should have very small start-up costs. These benefits are not available for competing alternate fuels such as hydrogen or compressed natural gas. Since the purpose of this ESTCP project is to obtain air emissions data for biodiesel and not to justify its use in place of another alternate fuel, an analysis of the cost differences between the various alternate fuels has not been made. The only direct cost for implementing a biodiesel program is the price difference of the fuel, taking into account the slight decrease in fuel economy with biodiesel, which for most fleets will not be noticeable. Currently, for federal government fleets, Defense Energy Support Center (DESC) currently charges a $0.14 per gallon premium for B20.

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6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

For biodiesel manufactured from virgin soybean oil, the feedstock costs account for more than 70% of production costs, including plant capital costs. For example, it takes about 7.5 lb of soybean oil costing approximately $0.21 per lb to produce a gal of B100 biodiesel; thus feedstock costs alone are at least $1.58 per gal. With processing, distribution, marketing, overhead expenses, and the currently high profit level, the cost of the finished biodiesel is more than $2.90 per gal.

Biodiesel producers are trying to reduce these feedstock costs by a variety of methods including developing higher oil-content soy hybrids, using other vegetable oils with a higher oil content or using yellow grease that is often available at low (approximately $0.05 per lb) or no cost. By employing one of these strategies, it is estimated that the future cost of the feedstock can be reduced to approximately $0.35 per gal, thus making biodiesel more competitive with petroleum-based diesel fuel. The Department of Energy forecasted that biodiesel from yellow grease will cost $1.40 per gal and mustard-based biodiesel will cost <$1 per gal by 2010.

6.2 PERFORMANCE OBSERVATIONS

Three performance issues are of primary concern with the use of biodiesel: how it affects the fuel economy of a diesel engine; how it affects engine performance; and how it affects engine maintenance. The average virgin soybean-oil-derived biodiesel has an energy content of 119k Btu/gal, compared with an average 130k Btu/gal for petroleum diesel (EPA). This basic energy content difference may result in a lower fuel economy for biodiesel. The EPA report included a summary of 217 actual fuel economy tests, and results showed that the fuel economy for B20 was 0.9 – 2.1% less than for petroleum diesel. Based on the experience from Marine Corps Base Camp Pendleton, the main supplier of test engines for this project, it is unlikely, however, that most B20 users will notice any difference in fuel economy. It is also unlikely that B20 users will observe any differences in the engine performance and maintenance between diesel engines fueled with B20 or petroleum diesel. These observations are based on the Camp Pendleton use of B20 in more than 600 engines for more than 4 years.

6.3 SCALE-UP

For this project, a representative sample of DoD-operated diesel engines was tested. Air pollution emissions from these types of engines represent a significant portion of the total diesel emissions from a typical DoD activity. Marine, stationary, and large tactical diesels that were outside the scope of this project and were not tested.

6.4 OTHER SIGNIFICANT OBSERVATIONS

Since this project was originally proposed, many additional DoD nontactical fleets have been switched to B20. The Department of Navy Environmental Policy Memorandum 05-01 was issued for Navy and Marine Corps fleets requiring that all applicable nontactical fleets use B20 by June 1, 2005. At this point, there is every reason to believe that most DoD nontactical fleets will be using B20 within the next couple of years since there appears to be significant economic and political pressure to reduce petroleum imports. To further expand the use of B20, the Navy is currently investigating its use in the continental United States (CONUS) ground tactical vehicles and equipment that support training operations.

6.5 LESSONS LEARNED

Based on the experience from Camp Pendleton implementing a B20 biodiesel fueling program for nontactical vehicles is almost a non-event. The only issue of concern is a recommendation that the fuel distribution tanks be cleaned when the switch to B20 is made and that the vehicle fuel filters are changed shortly after the switch to biodiesel. The need to clean the tanks and change the filters occurs because the biodiesel is a much better solvent than petroleum diesel. Failure to take these actions may lead to vehicle breakdowns caused by plugged fuel filters.

For applications where fuel turnover is low, there is an additional concern. The biodiesel industry recommends that biodiesel be used within 6 months of its manufacture. Using old biodiesel may also lead to plugged fuel filters.

6.6 END-USER ISSUES

The end users of this project will be DoD diesel-powered fleet operators and the DoD diesel fuel suppliers, primarily the Defense Logistics Agency (DLA). Their primary concerns in implementing biodiesel fueling programs are fuel availability, cost, performance, and environmental regulation. Negative results in any of these areas will stop an implementation program in its tracks.

Biodiesel may be manufactured from a multitude of agricultural raw materials, but biodiesel fuel made from virgin soybean oil is the most common type. Although this fuel is overwhelmingly manufactured in the midwestern states, where the soybeans are grown, it is widely available throughout the CONUS. Significant increases in DoD use of this fuel are not expected to greatly change its supply/demand balance. Unfortunately, at this time, virgin soybean biodiesel costs more than petroleum diesel.

Another potential source of biodiesel is that made from yellow grease. This fuel has an advantage in that it is currently cost competitive with petroleum. As the market for yellow grease is in its early stage of development, this fuel is not widely available. It is generally not used by DoD, even though its use has been approved by DESC, the primary DoD fuel supplier.

Since B20 biodiesel has approximately 1.7% lower fuel energy content per gal of fuel than petroleum diesel, a small decrease in fuel economy, as measured in miles per gal, may occur with its use. Fleet operators do not, however, expect any noticeable decrease in engine performance nor any increase in required maintenance. Based on previous biodiesel implementation efforts, these performance expectations should be met.

In the area of environmental regulatory compliance, the DoD fleet operator is not expected to face any implementation barriers, just benefits. DoD fleet operators have a requirement that 75% of their light duty vehicles be capable of operating on alternative fuels. For every 2,250 gal of

B20 biodiesel fuel used on vehicles weighing more that 8,500 lb, one AFV credit is allowed. Since the use of biodiesel will not require any infrastructure upgrades, its widespread implementation is an easy way to earn AFV credits and thus avoid other costly options, such as the use of natural gas powered vehicles.

In addition to these current regulatory issues, it is expected that some form of air pollution reductions will be mandated for existing diesel engines, particularly in the area of PM emissions. Since B20 biodiesel has been reported to reduce PM emissions when compared with current low sulfur Diesel Fuel No. 2 (see Table 1), the DoD fleet operator may avoid other more costly retrofit requirements.

To ensure that DoD fleet operators are informed of project results, the transition plan for this project will involve publicizing the test results in various forms readily available to DoD and regulatory decision makers. This effort will include providing a copy of the final report to the National Biodiesel Board and making a presentation of the results at the National Biodiesel Board annual brainstorming session. Since DLA controls the accepted DoD buy list, NFESC will work with that organization to ensure that potential biodiesel users fully understand its potential benefits.

To reach potential DoD interested parties, NFESC has presented project results at the annual Joint Service Environmental Management Conference as well as a regional Air and Waste Management Association and Federal Laboratory Consortium Conference. Currently, NFESC produces products supporting the transition of technologies to the Navy and other DoD customers. These products include generating environmental quality initiative fact sheets, *Currents Magazine* articles, Pollution Prevention Technical Library data sheets, pocket cards, user data packages, technical reports, technology implementation plans and a point of contact (POC) list of potential customers. Project results will also be posted on the Defense Environmental Network and Information Exchange (DENIX). Potential non-DoD interests will be informed of the results of the project by submitting articles for publication in applicable trade publications and technical journals, as by well as using the National Biodiesel Board to disseminate information.

6.7 APPROACHES TO REGULATORY COMPLIANCE AND ACCEPTANCE

The use of biodiesel as a blending stock or substitute for petroleum diesel has been approved by all applicable regulatory agencies. Its use does not require any environmental permitting. For federal government fleets, the use of biodiesel is encouraged. Executive Order 13149, *Greening the Government Through Federal Fleet and Transportation Efficiency,* directs federal agencies to reduce petroleum fuel consumption. Each agency operating 20 or more motor vehicles within the United States was required to reduce its entire vehicle fleet's annual petroleum consumption by at least 20% by the end of FY 2005, compared with FY 1999 petroleum consumption levels. To accomplish this reduction goal while earning alternative vehicle credits in accordance with EPAct (Public Law 102-486), DoD activities may use a 20% blend of biodiesel mixed with petroleum diesel for fueling their diesel engines.

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APPENDIX A

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