innospec
specialty chemicals

April 23, 2018

VIA ELECTRONIC SUBMISSION & UNITED STATES MAIL

Clerk of the Board
California Air Resources Board
1001 "I" Street, 23rd Floor
Sactramento, CA 95814

Re: Proposed Regulation on the Commercialization of Alternative Diesel Fuels

Dear Mr. Corey:

Innospec Inc. ("Innospec") appreciates the opportunity to comment on the California Air Resources Board's ("CARB") proposed amendments to (i) the low carbon fuel standard regulation (the "LCFS regulation") and (ii) the regulation on commercialization of alternative diesel fuels (the "ADF regulation"). Innospec submits these comments to provide CARB with its suggestions to help ensure the ADF regulation is effective in reducing emissions of oxides of nitrogen ("NOx") from projected increases in biodiesel usage.

Innospec is a global specialty chemicals business. Our Fuel Specialties unit is responsible for the development of fuel additive technology across the complete range of fuels, from petroleum-based, to coal and biofuels. As an entity engaged directly in the development of additives for alternative diesel fuels, Innospec has a strong interest in the development of additives that will help CARB achieve its goal of reducing criteria pollutant and greenhouse gas emissions.

A. Executive Summary

Innospec understands Appendix 1 to the ADF regulation approved in 2015 contained a typographical error in the amount of polycyclic aromatic content in the reference fuels used for testing fuel additives. Specifically, the table suggested applicants for new alternative fuel additives could use reference fuels with a polycyclic aromatic content of less than or equal to 10%, when the maximum level should have been 1.4%. Unfortunately, this error has a direct impact on NOx and PM emissions, because fuels with a higher aromatic content have been shown to require smaller amounts of additives to reduce such emissions.

Innospec appreciates the fact that CARB has recognized this problem, and is seeking to correct this issue in the current rulemaking. However, to ensure the LCFS regulation and the ADF regulation will not result in increases in NOx emissions, it is important that CARB review additives previously certified under Appendix 1, and confirm whether those additives were certified using a reference fuel containing a polycyclic aromatic content of less than 1.4%. Likewise, CARB should consider further amendments designed to revisit the certification of any additive approved using a reference fuel with a polycyclic aromatic content higher than 1.4%.

B. Regulatory Background

In 2009, CARB adopted the LCFS regulation to reduce the carbon intensity of transportation fuels used in California. During the rulemaking process for the original LCFS regulation, CARB staff recognized that the increased use of biodiesel incented by the LCFS regulation could result in an increase in NOx emissions. (See, e.g., ISOR, Appx. G at G-12.) As a result, CARB adopted the ADF regulation in 2015 "to require NOx-reducing measures, such as fuel additives, for biodiesel use above specified control levels." (*Id.*)

To ensure fuel additives would actually achieve the desired NOx reductions, and would not result in other negative environmental effects, the 2015 ADF regulation included in-use requirements for pollutant emissions control. These requirements are included in Appendix 1, which provides specifications for the certification of biodiesel additives, and emissions testing protocols. (ADF Regulation, Appendix 1, subds. (a)(2)(D), (a)(2)(F).) As part of the testing process, the ADF regulation requires tests using a "reference fuel" containing the properties and specifications identified in Subdivision (a)(2)(E), Table A-9. The Executive Officer may only certify additives that have complied with these rigorous testing requirements. (*Id.*, subd. (a)(2)(H).)

C. Maximum Polycyclic Aromatic Content of Reference Fuels

The 2015 regulations contained a typographical error in Table A-9. In the 2015 regulation, Table A-9 incorrectly stated the reference fuel could include a maximum "Polycyclic Aromatic Content, Weight %" of 10%:

Table A.9: Reference Fuel Specifications

Property	Test Method	Fuel Specifications
Sulfur Content	ASTM D5453-93	15 ppm maximum
Aromatic Hydrocarbon Content, Volume %	ASTM D5186-03(2009)	10 % maximum
Polycyclic Aromatic Content, Weight %	ASTM D5186-03(2009)	10 % maximum
Nitrogen Content	ASTM D4629-12	10 ppm maximum
Unadditized Cetane Number	ASTM D613-14, ASTM D6890-13be1, ASTM D7170-14; or ASTM D7668-14a	48 minimum
API Gravity	ASTM D287-12b	33 – 39
Viscosity at 40°C, cSt	ASTM D445-14e2	2.0 – 4.1
Flash Point, °F, minimum	ASTM D93-13e1	130
Distillation, °F	ASTM D86-12	
Initial Boiling Point		340 – 420
10 % Recovered		400 – 490
50 % Recovered		470 – 560
90 % Recovered		550 – 610
End Point		580 – 660

(ADF Regulation, Appendix 1, subdivison (a)(2)(E), Table A. 9 [emphasis added].)

The maximum Polycyclic Aromatic Content should have been listed as 1.4%, consistent with the existing standards adopted in 2004 for diesel reference fuel specifications. (*Cf.* 13 Cal. Code Regs., § 2282(g)(3)(A).) This was recognized in CARB's November 2017 ADF FAQs, No. 36, which states:

> **36. What CARB diesel reference fuel properties must be met for NOx control certification?**
>
> The reference CARB diesel must meet the specifications in Table A.9 of Appendix 1 in the ADF regulation, must be produced using normal refinery processes, including distillation and hydrotreating, but not cracking, and must not include any chemical blendstocks. ***Please note that the Polycyclic Aromatic Content listed in Table A.9 is a typo, it should be 1.4% maximum, not 10% maximum.***

(See Exhibit "A" at 8/9 [emphasis added].)

Increased aromatic or polycyclic aromatic content in a fuel has a direct effect on the amount of NOx and PM emissions associated with the combustion of a fuel. Specifically, the higher the aromatic content of a fuel when blended with biodiesel, the less additive, such as 2 ethyl-hexyl nitrate (2EHN), that is needed to reduce NOx emissions from the fuel. (See, e.g., Exhibit "A.") This affect is increased further with increased polycyclic aromatic content because it increases the number of aromatic rings. The effect is in part that fuels become more NOx neutral as aromatics increase and the dilution factor of 20% biodiesel could reduce polynuclear aromatics by 20%. In addition, the reference fuel itself would have higher baseline emissions and provide a lower barrier to passing the test. Thus, any additives that were approved based on the use of a reference fuel with a polycyclic aromatic content of greater than 1.4% could significantly undermine the efficacy of the additive in reducing NOx emissions associated with biodiesel.

For instance, Innospec understands CARB recently has certified additives based primarily on 2EHN. The Executive Orders for those additives are silent on the issue of whether the testing underlying the certifications using primarily 2EHN additives were performed using reference fuels with polycyclic aromatic content of less than or equal to1.4%. (See *id.*) This does not in fact appear to be the case. For example, one of the Executive Orders approved 2EHN additives with a minimum volume percent of 1,500 ppm (0.150), and having an NOx reduction of 0.9%. (See Executive Order G-714-ADF03 at 2.) This strongly implies that the reference fuel had a very high base line NOx which upon dilution polycyclic aromatics would be much lower. As such, to ensure the one of the fundamental underpinnings of CARB's environmental findings in this rulemaking relating to biodiesel is correct, CARB should confirm whether the testing for 2EHN based additives was performed using a reference fuel with a polycyclic aromatic content of less than or equal to1.4%. If not, CARB should review Executive Order G-714-ADF03 and confirm the appropriate minimum volume percent sufficient to reduce NOx emissions at the expected levels.[1]

CARB should also confirm any other biodiesel additive certified prior to the promulgation of the Proposed Amendments complied with the requirements for reference fuels contained in Appendix 1, Subdivisoin (a)(2)(E), Table A-9. (See, e.g., February 22, 2018, Executive Order G-714-ADF04; July 20, 2017, Executive Order G-714-ADF01.)

D. Proposed Amendments to Appendix 1, Subd. (a)(2)

To ensure the ADF regulation will achieve its purpose in reducing NOx emissions from biodiesel usage incented by the LCFS regulation, and to promote fairness for companies like Innospec that have attempted to comply with the rigorous testing requirements specified under Appendix 1, Subdivision (a)(2), CARB should also consider the following common sense modifications to the ADF regulation:

> (H) If the Executive Officer finds that a candidate fuel has been properly tested in accordance with (a)(2)(F) of this appendix, and makes the determinations specified in (a)(2)(G) of this appendix, then he or she shall issue an Executive Order certifying the alternative

---

[1] Page 3 of Executive Order G-714-ADF03 clarifies that CARB may revisit the 2EHN additives based on the use of an incorrect reference fuel: "CARB reserves the right in the future to review this Executive Order and the certification provided herein to assure that the certified fuel meets the standards and procedures of Title 13, California Code of Regulation, section 2293, et seq."

> diesel fuel or additive formulation represented by the candidate fuel. The Executive Order shall identify all of the characteristics of the candidate fuel determined pursuant to (a)(2)(C) of this appendix. The Executive Order shall provide that the certified alternative diesel fuel formulation has the following specifications: [1] a sulfur content, total aromatic hydrocarbon content, polycyclic aromatic hydrocarbon content, and nitrogen content not exceeding that of the candidate fuel, [2] a cetane number and API gravity not less than that of the candidate fuel, [3] any additional fuel specification required under (a)(2)(C) of this appendix, and [4] presence of all additives that were contained in the candidate fuel, in a concentration not less than in the candidate fuel, except for an additive demonstrated by the applicant to have the sole effect of increasing cetane number. Additionally the Executive Order shall contain a table mirroring Table A.5 in Appendix 1 (a)(1)(A) listing the required concentration of additive at each 5 percent interval of blend level, if applicable. All such characteristics shall be determined in accordance with the test methods identified in (a)(2)(C) of this appendix. The Executive Order shall assign an identification name to the specific certified biodiesel fuel formulation. <u>To the extent any alternative diesel fuel or additive formulation was certified by the Executive Officer based on testing that included the use of a reference fuel that no longer meets the Reference Fuel Specifications in Table A.9, such certification shall be suspended until such time as the applicant demonstrates compliance with Table A.9.</u>

Innospec strongly believes the above amendments are necessary to ensure biodiesel fuel additives actually achieve the desired reductions in NOx emissions from biodiesel usage. Without such protections, there is a significant danger that additives certified under the existing ADF regulation will not be used in volumes sufficient to reduce such NOx emissions.

Innospec appreciates the opportunity to submit comments on the ADF Regulation. If you have any questions regarding our comments, please contact David Daniels, Innospec's Director of Research & Development, at (303) 947-9405.

Respectfully Submitted,

David Jones
General Counsel
Innospec Inc.

Enclosure

Subcontractor Report

February 2003 • NREL/SR-510-31465

NO_x Solutions for Biodiesel

Final Report
Report 6 in a series of 6

R.L. McCormick, J.R. Alvarez, and M.S. Graboski
Colorado Institute for Fuels and Engine Research
Colorado School of Mines
Golden, Colorado

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

Exhibit "A"

February 2003 • NREL/SR-510-31465

NO_x Solutions for Biodiesel

Final Report
Report 6 in a series of 6

R.L. McCormick, J.R. Alvarez, and M.S. Graboski
Colorado Institute for Fuels and Engine Research
Colorado School of Mines
Golden, Colorado

NREL Technical Monitor: K.S. Tyson

Prepared under Subcontract No. XCO-0-30088-01

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

♲ Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

ACKNOWLEDGEMENT

The authors of this report wish to acknowledge the assistance of CIFER staff members Jim Macomber, Bruce Sater, and Roger Ridley in the completion of the test work described here. Short chain fatty acid ester and TBHQ fuel additives were supplied by Dr. Michael Haas and Dr. Thomas Foglia of the Eastern Regional Research Center, Agricultural Research Service, USDA, Wyndmoor, PA.

SUMMARY

This study has examined a number of approaches for NO_x reduction from biodiesel. Blending FT diesel at very high percentages can produce a NO_x neutral fuel. Lowering the base fuel aromatic content from 31.9% to 7.5% (nominally 10% aromatic fuel) was very successful at lowering NO_x. If all other factors are equal, and if the effect of aromatic content is linear, using a base fuel having 25.8% aromatics should provide a NO_x neutral B20 (relative to certification diesel having nominally a 30% aromatic content). The results also suggest that using kerosene as the base fuel could lead to a NO_x neutral blend (this occurs at 40% biodiesel, assuming linearity). The cetane enhancers di-tert-butyl peroxide (DTBP) and ethyl-hexyl nitrate (EHN) are both effective at reducing NO_x from biodiesel. The antioxidant TBHQ is also effective but NO_x reduction was small at the level tested and TBHQ may cause an increase in PM emissions. The idea of using antioxidants as NO_x reduction additives is clearly something that should be explored in more detail. Blending of 2% short chain fatty acid esters was not effective for reducing NO_x. The A1 additive obtained from Bioclean Fuels was effective at NO_x reduction but caused an unacceptably large increase in PM. Based on these results, use of the additives DTBP and EHN is the most practical approach at the present time. Using DTBP at 1 volume percent produces an incremental cost increase of $0.16 per gallon. For EHN at 0.5 volume percent the incremental cost increase per gallon is $0.05.

A nominally 10% aromatic fuel was used as a reference point to determine if B20 blends (blends of either biodiesel with certification diesel or 10% aromatic diesel) might have emissions levels allowing CARB certification. The 10% aromatic fuel met the requirements for sale of diesel fuel in California based on composition, it was not a CARB reference diesel. All of the B20 blends exhibited PM emissions below those for the CARB diesel. Fuels based on certification diesel did not in any case produce NO_x emissions equal to or below those of the 10% aromatic fuel. Even B20 fuels treated with DTBP have NO_x emissions that significantly exceed those of the 10% aromatic diesel. For B20 blends based on the 10% aromatic fuel, adding DTBP is effective at reducing NO_x to the base fuel level. Thus blending biodiesel with a California compliant diesel and treating with DTBP may be a route to a CARB certifiable B20.

Degree of unsaturation appears to be the key difference between soy and yellow grease (YG) based biodiesels from the standpoint of emissions performance. The iodine numbers of these fuels were 127 and 79, respectively. The cetane number of the YG fuel was correspondingly higher. For the B20 blends a significant (about 2%) NO_x increase relative to certification diesel was observed for soy but no significant increase was observed for YG. Treatment with 1% DTBP lowered NO_x by about the same amount for both blends. For B100 fuels, the PM emissions are approximately the same but YG (Bio3000) exhibits NO_x emissions that are lower, relative to soy diesel, by nearly 0.4 g/bhp-h. Treatment of B100 fuels with DTBP is effective at reducing NO_x, but not in proportion to the NO_x reduction observed for B20 blends. The facts that the NO_x reduction for DTBP is the same independent of biodiesel source, and decreases with increasing biodiesel content of the fuel seem important. These results may suggest that DTBP acts largely to lower the NO_x produced by burning the petroleum diesel fuel.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Biodiesel is an oxygenated diesel fuel made from vegetable oils and animal fats by converting the tri-glyceride fats to esters via various esterification processes. A number of studies have shown substantial particulate matter (PM) reductions for biodiesel and biodiesel blended with petroleum diesel (1) relative to petroleum diesel. However, most studies also show a significant increase in nitrogen oxides (NO_x) emissions (1). The cause of this increase in NO_x and solutions to this problem have been the subject of a considerable body of research under the DOE Biodiesel Program at the National Renewable Energy Laboratory (NREL).

In a previous study for NREL (2,3), we examined biodiesels produced from a variety of real-world feedstocks as well as technical grade fatty acid methyl and ethyl esters. Emissions performance in a heavy-duty truck engine using the U.S. heavy-duty federal test procedure (transient test) was measured. The objective was to understand the impact of biodiesel chemical structure, specifically fatty acid chain length and number of double bonds, on emissions of NO_x and PM. It was found that the molecular structure of biodiesel could have a substantial impact on emissions. For neat biodiesels (B100), PM emissions were essentially constant at about 0.07 g/bhp-h as long as density was less than 0.89 g/cm^3 or cetane number was greater than about 45. NO_x emissions increased with increasing fuel density or decreasing fuel cetane number. Increasing the number of double bonds, quantified as iodine number, correlated with increasing emissions of NO_x. The properties of density, cetane number, and iodine number were highly correlated with one another. This result cannot be explained by the well-known NO_x/PM tradeoff because PM remained constant but NO_x changed with fuel properties. Thus the increase in NO_x emissions observed for some biodiesels and for blends of biodiesel in petroleum diesel is not driven by thermal NO formation. The study additionally found that for fully saturated fatty acid chains NO_x emissions were lower than those for petroleum diesel. NO_x increased with decreasing fatty acid chain length for tests using fuels with 18, 16, and 12 carbon chains. Biodiesel composed of technical grade C12 saturated carbon chains (methyl laurate) was NO_x equivalent to certification diesel. Also, there was no significant difference in NO_x or PM emissions for the methyl and ethyl esters of identical fatty acids.

The results of the previous study suggest a number of approaches to reduce NO_x emissions by modifying biodiesel properties. These might be implemented through chemical modification of the fatty acid chain or through plant breeding to develop oils with more suitable properties. In the present study, we have examined a number of potential fuel additive and fuel blending solutions to the NO_x problem. These include blending with Fischer-Tropsch diesel and low aromatic diesel, as well as using several fuel additives. The goal of the study was to identify an approach for reducing the NO_x emissions of soy-based biodiesel by 4% for a B20 blend. The additives tested include the cetane improvers di-tert-butyl-peroxide (DTBP) and 2-ethyl-hexyl-nitrate (EHN), short chain fatty acid esters, tert-butyl-hydroquinone (TBHQ, a food antioxidant), and a proprietary additive called A1 provided by BioClean Fuels. Tests were conducted with biodiesels produced from both soy and yellow grease. There were significant differences between the two biodiesel-fuels with respect to degree of saturation, cetane number, iodine number, and fuel density. Base fuels were certification diesel and a California compliant 10% aromatic diesel.

METHODS

Fuels and Test Matrix

The fuels examined in this study are listed in Table 1. A 14-task statement of work defined the study design. The fuel testing tasks are outlined below.

Table 1. Fuels utilized in this study.

Fuel	Lot Number	Source
Certification diesel	0KP05202	Phillips Specialty Chemical
10% Aromatic diesel	0LP10A01	Phillips Specialty Chemical
Kerosene (No. 1 diesel)	Not provided	Colorado Petroleum Company
Fischer-Tropsch diesel	Not provided	Shell Oil Company (via NREL)
Soy methyl ester	B4-136	AG Environmental Products (Soygold)
Yellow grease methyl ester	Not provided	Griffin Industries (Bio3000)

Task 1. Fuel Quality Testing:

The base fuels listed in Table 1 were obtained and submitted for analysis to insure that minimum standards were met. The specific standards were ASTM PS121 for the biodiesel fuels, ASTM D975 for the certification diesel, and CARB standards for the 10% aromatic fuel.

Task 2. Baseline Regulated Emissions Tests:

Each of the fuels listed in Table 1 was tested in the DDC Series 60 engine for emissions performance. Tests included one cold start and a minimum of three hot starts for all fuels except the 10% aromatic for which only three hot starts were conducted.

Task 3. Testing Fischer-Tropsch/Biodiesel Blends:

Pure Fischer-Tropsch and blends of 80% FT/20% Soy and 80% Soy/20% FT were tested. Samples of FT diesel containing 1%, 3%, and 5% soy were submitted for lubricity analysis. The sample having the lowest soy diesel level that met the Engine Manufacturers Association recommended maximum High Frequency Reciprocating Rig (HFRR) wear scar maximum of 450 microns was also tested in the engine.

Task 4. Effectiveness of DTBP Additive in Soy B20:

A B20 prepared from soy and certification diesel was tested to demonstrate the NO_x increase typically observed. This fuel was then treated at 0.5, 1.0, and 1.5 volume percent DTBP and these fuels tested in the engine. The objective was to identify a DTBP blending level that reduced NO_x emissions by 4%. Earlier studies at Southwest Research Institute (SwRI) reported that EHN was not effective at reducing NO_x from soydiesel. Tests were also conducted to confirm this result.

Task 5. Effectiveness of DTBP in Other B20 Fuels:

The following B20 fuels were prepared and tested both with and without the DTBP additive at the treat rate determined in Task 4:

- Certification diesel/yellow grease

- 10% aromatic diesel/soy
- 10% aromatic diesel/yellow grease

Task 6. DTBP Effectiveness in Soy B100:
Neat soydiesel was tested using five times the DTBP treat rate determined for B20 in Task 4.

Task 7. DTBP Effectiveness in Yellow Grease B100:
Neat yellow grease biodiesel was tested using five times the DTBP treat rate determined for B20 in Task 4.

Task 8. Additive Testing for the U.S. Department of Agriculture (USDA), Peoria:
This task was not funded and therefore not performed.

Task 9. Additive Testing for USDA Philadelphia:
Dr. Michael Haas and Dr. Thomas Foglia of USDA Eastern Regional Research Center supplied Colorado School of Mines (CSM) with two fuel additives. These were a sample of short chain fatty acid methyl esters (USDA-1) and a food antioxidant, tert-butyl-hyroquinone (USDA-2). A B20 prepared from certification diesel and soy diesel was tested using these additives at treat rates recommended by Drs. Haas and Foglia.

Task 10. Bioclean Fuels A1 Additive:
Bioclean Fuels provided a proprietary additive called A1. A1 was tested in a B20 prepared from 10% aromatic fuel and soy diesel at a treat rate recommended by Bioclean Fuels.

Task 11. Bioclean Fuels A1 Additive-Further Tests:
The A1 additive was tested in a B20 prepared from certification diesel and soy diesel at a treat rate identical to that used in Task 10. A second test using soy B100 was planned. Upon direction from Dr. Shaine Tyson of NREL this second test was not performed.

Task 12. K50 Testing:
A blend of kerosene (No. 1 diesel) with 50% volume percent soydiesel and known as K50 was tested. Neat kerosene was also tested for comparison. K50 was then tested using 2.5 times the treat rate of the best NO_x reducing additive identified in previous tests with B20.

Task 13. Draft Report Preparation:
A draft final report is to be prepared and submitted to NREL as well as to several peer reviewers.

Task 14. Final Report:
Based on reviewers comments, the final report is to be revised and a final version submitted.

Fuel Property Measurement

Williams Laboratory in Kansas City, Missouri performed fuel property measurements with the following exceptions. Core Laboratory in Houston, Texas performed analysis of the FT diesel. Analysis of the soy and yellow grease biodiesels for fatty acid ester content was performed by the Eastern Regional Research Center of the USDA in Wyndmoor, Pennsylvania. Southwest

Research Institute of San Antonio, Texas conducted lubricity tests using the HFRR (high frequency reciprocating rig) test (ASTM-D6079 @ 60°C).

Emissions Testing

The system for emissions measurement for regulated pollutants (THC, CO, NO_x, and PM) includes supply of conditioned intake and dilution air, an exhaust dilution system, and capability for sampling of particulate and analysis of gaseous emissions. All components of the emissions measurement system meet the requirements for heavy-duty engine emissions certification testing as specified in Code of Federal Regulations Title 40, Part 86, Subpart N.

Test Engine:

The engine is a 1991 calibration Series 60 production model loaned by the Detroit Diesel Corporation. The six cylinder, four stroke engine is nominally rated at 345 bhp (257 kW) at 1800 rpm and is electronically controlled (DDEC-II), direct injected, turbocharged, and intercooled. Engine specifications are listed in Table 2. This is the engine model specified in California Code of Regulations Title 13 section 2282, subsection g for certification testing of diesel fuels.

Table 2. DDC Series 60 engine specifications and mapping parameters.

Serial Number	6R-544
Displacement	11.1 L
Rated Speed/Horsepower	1800 rpm/345 bhp
Max Torque Speed/Max Torque	1200 rpm/1335 ft-lb
Idle Speed/CITT	600 rpm/0 ft-lb
High Idle Speed	1940 rpm
Intake Depression	-16 ± 1 in H_2O
Backpressure	32.6 ± 3 in H_2O
Aftercooler Dp	40 ± 3 in H_2O
Intake Manifold Temperature	44±2°C

Regulated Gaseous Emissions Measurement:

All gas mass emissions are determined by background corrected flow compensated integration of the instantaneous mass rates. Tedlar bag samples of background air and exhaust sample are also collected. The exhaust sample is proportionally sampled through a critical flow orifice. The bag compositions are compared with the bag equivalent flow compensated emissions to validate the test runs. Agreement is always within 5% for the individual regulated gaseous emissions.

Particle Sampling for Mass:

Particulate matter is collected on Pallflex T60A20 70 mm filters of a common lot. Particulate matter is sampled through a secondary tunnel that insures a filtered gas temperature below 52°C (126°F). Two independent mass flow controllers are used to regulate the total filtered gas sample and the secondary dilution air rate. The computer determines the total sample volume by integrating the instantaneous flow difference. Flow is made proportional to the diluted exhaust by sending a varying secondary air flow set point from the test manager computer which is based upon the critical flow venturi (CFV) flow rate which in turn is a function of the diluted exhaust temperature at the venturi. The apparent sample flow rate depends on zero flow analog voltage outputs from the transmitters. These are logged before and after the test and the corrected integrated volume is established with a calibration model that considers the voltage offsets.

PM Background. Parallel background samples are not collected. Instead, the intake air is filtered to 95% ASHRAE efficiency and periodic background checks are made. Demineralized water is used for humidity control. The mass collected in the background check made during this program was extremely small. No background correction was made to the particulate determinations.

Weigh Room Conditions. Since the PM mass collected, especially for the biodiesel samples, was small even minor differences in filter weight due to water adsorption can impact the particulate mass emission. Particle filter handling and weighing is conducted in a yellow light, constant humidity weigh room held at 9±2°C (48±4°F) dew point, 50% nominal relative humidity, and 22±1°C (72±2°F).

Quality Control:
The testing is carried out in accordance with 40 CFR Part 86 Subpart N. In addition, a number of additional measures are taken to insure that the NO_x and PM emissions collected in this program are both precise and accurate.

Emission Gas Standards. Emission gases are 1% EPA Protocol Standards. Gas standards were not changed during this test program.

Carbon Balance. As a test quality-assurance check, a carbon balance is performed for each transient test. Diesel mass fuel consumption was monitored with a Micromotion DP-25 mass flow sensor and by weighing the fuel supply tank before and after a test using a load cell. Exhaust carbon is determined from the background corrected THC, CO, CO_2, and PM emissions data. The fuel analysis is used to estimate the H/C ratio of the THC. PM is assumed to be 100% carbon. Runs where carbon balance closure was more than +/-6% in error were generally rejected.

NO_x Humidity Correction. Humidity has a large influence on NO_x emissions. Humidity is measured continuously in the conditioned air inlet by two independently calibrated methods: a dew point meter and a polymer membrane sensor. Furthermore, the intake air is controlled to a 53°F (11.7°C) nominal dew point to insure that the NO_x correction factor (40 CFR 1342-94(d)(8)(iii)) is very near one and essentially constant from test to test. The two humidity measurements do not produce NO_x correction factors that differ by more than 2%.

The Effect of Intake Manifold Temperature on NO_x Emissions. The engine is equipped with a water-cooled turbocharger intercooler. The supply temperature and flow rate of cooling water to the intercooler are adjusted during the engine mapping process to match the manufacturer's design temperature for the intake air at rated speed and wide open throttle. The flow and inlet temperature are feedback controlled so that the temperature history of the manifold from test to test is repeatable. The maximum temperature and stage where it occurred are logged during each test to confirm that NO_x differences are not related to variations from test to test in the intake air temperature profile.

RESULTS

Base Fuel Properties

Base fuel properties and testing methods employed are listed in Table 3. Certification diesel has a cetane number of 47 and an aromatic content of 32%. The nominally 10% aromatic diesel has a cetane number of 48 and an aromatic content of 7.5%. Note that this fuel is not a CARB reference diesel nor is it a fuel certified as emissions equivalent to CARB reference diesel. As a fuel with less than 10% aromatic content it meets the requirements for sale in California based on composition. Comparison of biodiesels and biodiesel blends with this fuel is intended to provide an estimate of suitability of any of these fuels for possible CARB certification. FT diesel has an extremely high cetane number, as is typical for these fuels. While not measured, the aromatic content of FT diesel is zero. For the biodiesel fuels all of the property specifications of ASTM PS121 (shown in Appendix A) are met. Soygold has a cetane number of 47; a value regarded as typical for a soy-derived biodiesel (1). The cetane number of Bio3000 is 56. The kerosene or No. 1 diesel is at the light end of the No. 1 diesel range, and may even meet the specifications of a jet fuel.

The fatty acid makeup of the two biodiesels was also determined and these results are reported in Table 4. As expected, the yellow grease fuel contained significantly higher levels of saturated and monounsaturated compounds. The "other" column in Table 4 includes unidentified peaks in the chromatogram and less than 0.5% of the 20:0 methyl ester.

Certification Fuel Tests and Other Controls

The engine was initially mapped on certification diesel fuel and this map (run 5629) was used to generate the transient test for all testing on all fuels. A plot of the torque map is shown in Appendix B. All emissions testing data for this study are presented in Appendix C, in chronological order. Certification fuel runs were performed periodically throughout the test program to gauge engine drift. A single lot of certification diesel was used. The testing was performed in two campaigns. The first campaign occurred in January 2001 and the second campaign in March and early April 2001. Figure 1 shows daily average NO_x and PM emissions from the certification diesel runs. The two test campaigns are evident. A small (about 2%) difference in NO_x emissions on certification fuel was observed between the two campaigns. This most likely occurred because of repairs made to the NO_x analyzer during February, although drift of the engine itself cannot be ruled out. Certification fuel PM emissions are also slightly higher for the second campaign, although experimental variability is higher in the first campaign.

Tables 5 through 8 present descriptive statistics for the certification fuel runs in both campaigns. Within a given campaign the data are of high repeatability with 95% confidence interval for NO_x of better than ±1% and for PM of better than ±5%. A t-test comparing NO_x emissions for the two campaigns indicates that they are significantly different at better than 99% confidence ($p<0.0001$). PM emissions for the two campaigns are likely identical ($p=0.119$). In analyzing the data, runs will only be compared with certification fuel runs obtained during the same campaign.

Table 3. Results of fuel property testing for base fuels.

Property	Method	Units	Certification Diesel	10% Aromatic Diesel	FT Diesel	Soygold	Bio-3000	No. 1 Diesel
Cetane Number (CN)	ASTM-D613-86		47.4	48.2	>74.8	47.4	55.6	42.8
Cetane Index	ASTM-D975		48.3	49.4	78.3	--	--	45.8
Kinematic Viscosity 40C	ASTM-D445	mm2/s	2.7	2.5	3.34	4.066	4.735	1.3
Iodine Number	ASTM-D1959		--	--	--	127.4	78.8	--
Cloud Point	ASTM-D2500	F	3	-20	40	--	--	-61
Cloud Point	ASTM-D5773	C	--	--	--	-1	7	--
Flash Point	ASTM-D93	F	153	135	228	288	284	130
Cold Filter Plugging Point	ASTM-6371	C	--	--	0	-3	3	--
Pour Point	ASTM-D97	F	0	--	--	--	--	--
Total Sulfur by UVF	ASTM-D5453	wt%	--	--	--	0.000068	0.001468	--
Sulfur	ASTM-D2622	wt%	0.043	0.0057	--	--	--	0.0138
Ash Content	ASTM-D482	wt%	--	--	0.001	--	--	0.001
Sulfated Ash	ASTM-D874	wt%				0.003	0.01	--
Water Content	ASTM-D1796		--	--	<0.05	--	--	--
Specific Gravity	ASTM-D4052		0.8476	0.8302	--	--	--	----
Carbon Residue	ASTM-D189	wt%	--	--	<0.01	--	--	--
Carbon Residue	ASTM-D524	wt%	--	--	--	0.08	0.05	0.06
Corrosion, Copper strip	ASTM-D130		1A	1A	1A	1A	1A	--
Water and Sediment	ASTM-D2709	vol%	--	--	--	<0.005	<0.05	<0.05
Acid Number	ASTM-D664	mgKOH/g	--	--	--	0.03	0.37	--
Hydrocarbon Type:	ASTM-D1319							
Aromatics		%vol	31.9	7.5	--	--	--	--
Olefins		%vol	1.5	2.1	--	--	--	--
Saturates		%vol	66.6	90.4	--	--	--	--
Free Glycerin	ASTM	wt%				0.004	0.016	
Total Glycerin	D6584	wt%				0.184	0.038	
Distillation	ASTM-D86							
IBP		F	352	355	454	--	--	338
10		F	423	421	500	--	--	365
50		F	514	478	556	--	--	407
90		F	599	599	618	--	--	471
EP		F	642	658	638	--	--	515

Table 4. Results of GC-MS analysis of biodiesel samples for specific species.

Fuel	C12:0	C14:0	C16:0	C16:1	C18:0	C18:1	C18:2	C18:3	Other
MW	214.351	242.405	270.459	268.443	298.513	296.497	296.497	294.481	
Unsaturations	0	0	0	1	0	1	2	3	
Soygold	0	0	11.96	0	3.88	22.63	54.52	6.6	0.41
Bio3000	0	0.93	23.30	1.28	9.73	49.65	15.11	0	0

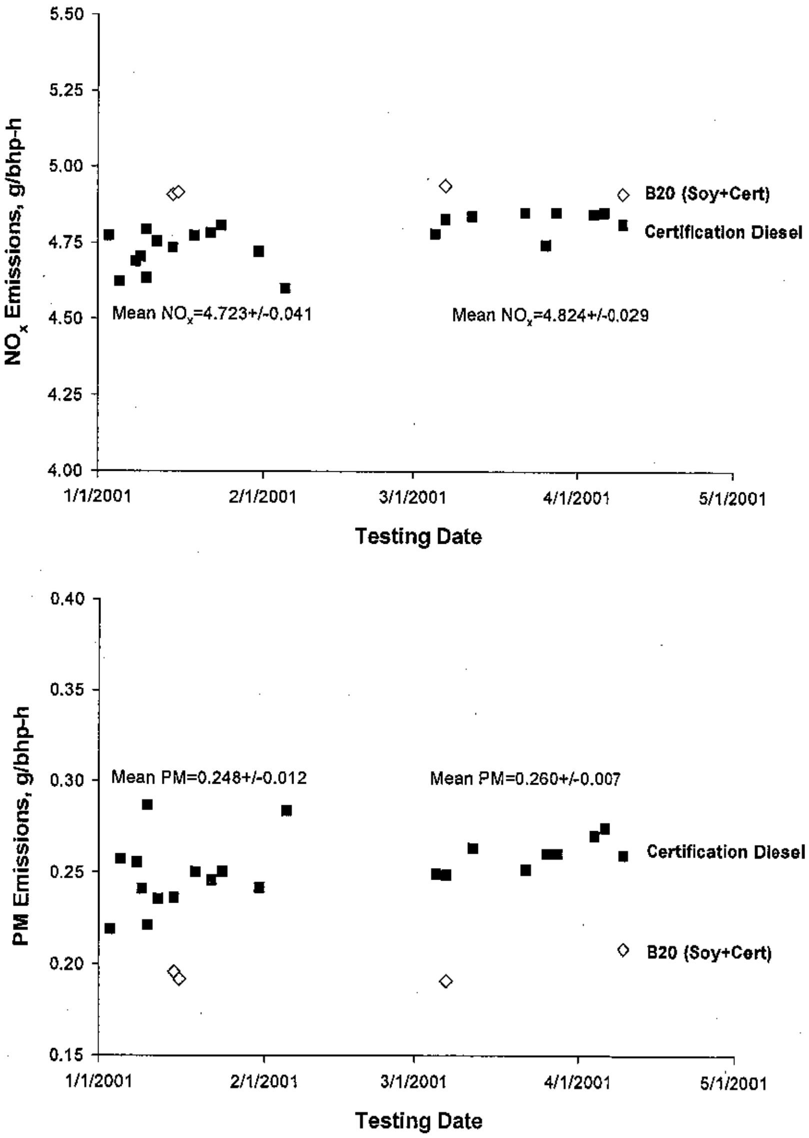


Figure 1. NO_x and PM emissions results for certification fuel runs performed over the study. All data points represent the average of three or more hot start runs.

Also shown in Figure 1 are emissions results for a B20 prepared from soydiesel and certification diesel. These runs serve as an additional control. In all cases B20 NO_x emissions are between 2% and 3% higher than average certification fuel NO_x. B20 PM emissions are always at least 20% lower than certification fuel PM. Analysis of the fuel additive testing data will be based on a comparison of emissions with average B20 runs performed during the same campaign.

Table 5. Descriptive statistics for daily average NO_x emissions from the 1991 DDC Series 60 engine using EPA certification diesel, January campaign.

Mean	4.7228
Standard Error	0.0189
Median	4.7339
Standard Deviation	0.0683
Range	0.206
Minimum	4.6017
Maximum	4.8073
95% Confidence Interval	0.0413
Count	15

Table 7. Descriptive statistics for daily average NO_x emissions from the 1991 DDC Series 60 engine using EPA certification diesel, March campaign.

Mean	4.8241
Standard Error	0.0125
Median	4.8407
Standard Deviation	0.0374
Range	0.1067
Minimum	4.7458
Maximum	4.8525
95% Confidence Interval	0.0288
Count	11

Table 6. Descriptive statistics for daily average PM emissions from a 1991 DDC Series 60 engine using EPA certification diesel, Januray campaign.

Mean	0.2482
Standard Error	5.589e-3
Median	0.2460
Standard Deviation	0.0202
Range	0.0676
Minimum	0.2192
Maximum	0.2868
95% Confidence Interval	0.0122
Count	15

Table 8. Descriptive statistics for daily average PM emissions from a 1991 DDC Series 60 engine using EPA certification diesel, March campaign.

Mean	0.2599
Standard Error	2.981e-3
Median	0.2603
Standard Deviation	8.941e-3
Range	0.0258
Minimum	0.2488
Maximum	0.2746
95% Confidence Interval	0.0069
Count	11

Base Fuel Emissions

The base fuels for this study were tested for emissions in replicate transient tests. Results are reported in Table 9. A lubricity additive called Paradyne 655 was added to the FT diesel at 200 ppm to protect the engine during testing of this fuel. FT diesel is shown to provide significant emissions reductions relative to certification diesel and 10% aromatic diesel. Both soy-based biodiesel (Soygold) and yellow grease-based biodiesel (Bio3000) show a significant NO_x increase relative to certification fuel, as well as the PM decrease typical of these fuels. The kerosene or No. 1 diesel exhibited NO_x emissions similar to the 10% aromatic fuel but had significantly lower PM. Importantly, the coefficient of variation for NO_x measurements was always below 1%.

Table 9. Emissions testing results for base fuels[1].

Fuel		**THC**	**NO_x**	**CO**	**CO_2**	**PM**
		g/bhp-h	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**
Cert Lot # 0KP05202	**Composite**	0.020	4.847	4.865	578	0.232
January 3, 2001	**Average Hot**	**0.020**	**4.773**	**4.604**	**574**	**0.233**
	Coefficient of Variation	16.7%	0.4%	1.0%	0.2%	1.8%
Campaign 1	**Average Hot**	**0.020**	**4.723**	**5.029**	**574**	**0.248**
Campaign 2	**Average Hot**	**0.020**	**4.824**	**5.110**	**571**	**0.260**
Shell FT/Paradyne	**Composite**	0.008	4.093	4.036	551	0.176
	Average Hot	**0.007**	**4.026**	**3.843**	**548**	**0.167**
	Coefficient of Variation	73.8%	0.2%	4.4%	0.2%	4.6%
Soygold	**Composite**	0.014	5.449	3.155	580	0.072
	Average Hot	**0.012**	**5.366**	**2.973**	**576**	**0.068**
	Coefficient of Variation	10.8%	0.2%	2.5%	0.2%	5.5%
Bio3000	**Composite**	0.006	5.065	3.289	580	0.083
	Average Hot	**0.004**	**4.981**	**3.105**	**576**	**0.078**
	Coefficient of Variation	71.0%	0.7%	4.3%	0.5%	8.4%
10%Aro Lot#0LP10A01	**Average Hot**	**0.029**	**4.478**	**4.980**	**569**	**0.231**
	Coefficient of Variation	24.0%	0.2%	3.1%	0.2%	2.8%
Kerosene	**Average Hot**	**0.086**	**4.527**	**4.005**	**554**	**0.199**
	Coefficient of Variation	5.1%	0.3%	1.7%	0.1%	2.4%

[1] Composite is the weighted average (1/7 cold+6/7hot average) and include a minimum of 3 hot start runs. Hot average is for 3 or more hot start runs.

Results for FT Diesel/Soy Diesel Blends

The objective of Task 3 of this project was to quantify the regulated emissions from different blends of biodiesel with Fischer-Tropsch (FT) diesel in compression ignition engines. Based on previous correlations between fuel density and NO_x, blending of a low-density diesel fuel with biodiesel was hypothesized to provide a NO_x reduction. Because Fischer Tropsch diesel also has high cetane and no aromatics, the impact of changing density could not be isolated, but it could be examined. Biodiesel has excellent lubricity properties, while FT diesel has poor lubricity. The combination of the two low-sulfur diesel fuels might provide a very low emission alternative fuel with excellent lubricity properties.

Fuel property testing results for neat FT diesel, biodiesel (Soygold), and certification fuel as well as the different biodiesel-FT blends are presented in Table 10. After blending to 20% soy in FT, the cetane number still exceeds 75. Blending 20% FT into soy increases cetane number to 53.3 and using a linear model suggests a blending cetane number for FT diesel of 77. If this were correct, the 20% soy in FT blend would have a calculated cetane number of 71. Cetane number measurements above about CN=65 are notoriously inaccurate and within this limitation the results are reasonably consistent. Blending soydiesel with FT diesel acts to depress cloud point and cold filter plugging point by a few degrees. Table 11 present HFRR lubricity data for several blends of biodiesel and FT diesel. The Engine Manufacturers Association recommends a maximum HFRR wear scar of 450 microns. A previous report indicates that the Shell FT diesel produces HFRR wear scar of more than 500 microns and that addition of 200 ppm of the

Paradyne 655 lubricity additive reduces this to 210 (4). The average value for 1% biodiesel in FT is 300 micron (or 0.300 mm), well below the manufacturers recommended limit. Based on direction from Mr. Keith Vertin at NREL, a 1% biodiesel/FT diesel blend was selected for testing, along with the FT/B20 and FT/B80 blends specified in our contract.

The emissions testing results for the different runs are presented in Table 12. The coefficients of variation for NO_x and PM measurements were always below 1% and 6% respectively. Emissions of FT diesel and FT diesel with 1% biodiesel are essentially identical, as expected. Adding 20% or larger amounts of biodiesel to FT results in a significant increase in NO_x emissions and decrease in PM emissions. Note, however, that for FT/B20 the NO_x emission is still 0.5 g/bhp-h below the certification diesel level. There is a linear relation for both NO_x and PM emissions as a function of volume percent FT diesel, as shown in Figure 2. The regression equations shown in the figure indicate that a blend of 46% FT with soydiesel would have the same NO_x emissions as certification diesel.

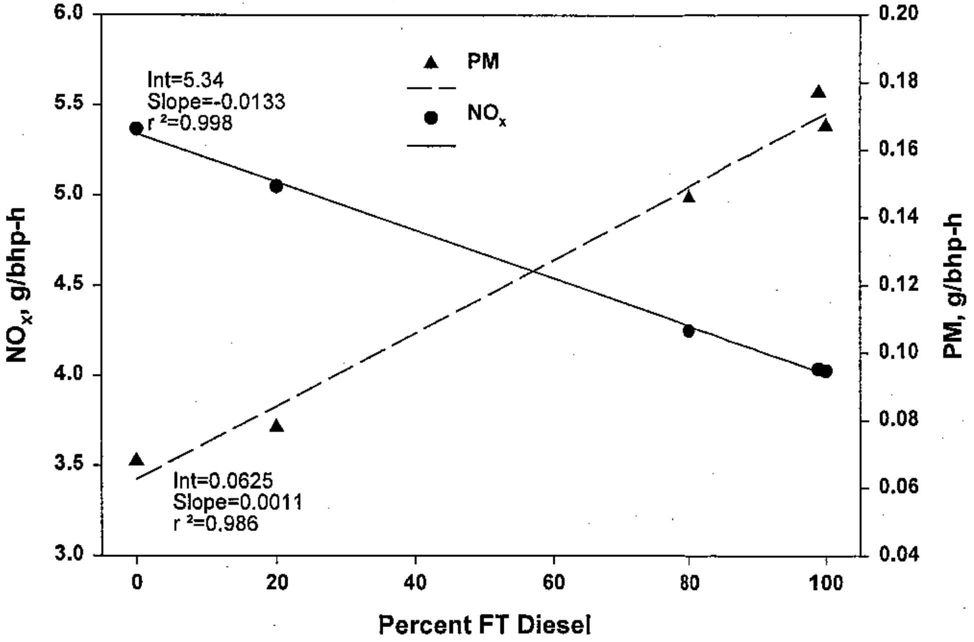


Figure 2. PM and NO_x emissions for blends of FT diesel in soydiesel.

Table 10. Fuel property testing results for FT/Soydiesel blends.

Property	**Method**	**Units**	**Cert fuel**	**F-T**	**Soygold**	**80%FT/20%SG**	**20%FT/80%SG**
Cetane Number	ASTM-D613-86		47.4	>74.8	47.4	>74.8	53.3
Cetane Index	ASTM-D975		48.3	78.3	N/A	70.5	52.2
Kinematic Viscosity at 40 C	ASTM-D445	mm2/s	2.7	3.34	4.066	3.346	3.822
Iodine Number	ASTM-D1959				127.4	29	97.4
Cloud Point	ASTM-D2500	F	3	40		35	31
Cloud Point	ASTM-D5773	C			-1		
Cold Filter Plugging Point	ASTM-6371	C		0	-3	-3	-4
Pour Point	ASTM-D97	F	0				
Flash Point	ASTM-D93	F	153	228	288	219	227
Total Sulfur by UVF	ASTM-D5453	wt%			0.000068		
Sulfur	ASTM-D2622	wt%	0.043			0.0014	0.0024
Ash Content	ASTM-D482	wt%		0.001		0	0
Sulfated Ash	ASTM-D874	wt%			0.003		
Water Content	ASTM-D1796			<0.05			
Specific Gravity	ASTM-D4052		0.8476				
API Gravity	ASTM-D1298					44.6	32.9
Carbon Residue	ASTM-D189	wt%		<0.01			
Carbon Residue Ramsbottom	ASTM-D524	%			0.08	0.03	0.06
Corrosion, Copper strip	ASTM-D130		1A	1A	1A	1A	1A
Water and Sediment	ASTM-D2709	vol%			<0.005	26.6	0
Acid Number	ASTM-D664	mgKOH/g			0.03		
Hydrocarbon Type:	ASTM-D1319	%vol					
Aromatics	ASTM-D1319	%vol	31.9				
Olefins	ASTM-D1319	%vol	1.5				
Saturates	ASTM-D1319	%vol	66.6				
Distillation	ASTM-D86	F					
IBP	ASTM-D86	F	352	454		418	446
10	ASTM-D86	F	423	500		500	570
50	ASTM-D86	F	514	556		576	625
90	ASTM-D86	F	599	618		628	638
EP	ASTM-D86	F	642	638		636	638

Table 11. Lubricity test results (HFRR).

Sample	**Major Axis [mm]**	**Minor Axis [mm]**	**Wear Scar Diameter [mm]**
80% Biodiesel in FT	0.16	0.10	0.130
80% Biodiesel in FT	0.17	0.10	0.135
80% Biodiesel in FT	0.17	0.10	0.135
Average			*0.133*
20% Biodiesel in FT	0.17	0.12	0.145
20% Biodiesel in FT	0.19	0.10	0.145
20% Biodiesel in FT	0.19	0.10	0.145
Average			*0.145*
5% Biodiesel in FT	0.21	0.15	0.180
5% Biodiesel in FT	0.21	0.12	0.165
5% Biodiesel in FT	0.21	0.15	0.180
Average			*0.175*
3% Biodiesel in FT	0.22	0.17	0.195
3% Biodiesel in FT	0.22	0.16	0.190
3% Biodiesel in FT	0.23	0.15	0.190
Average			*0.192*
1% Biodiesel in FT	0.32	0.26	0.290
1% Biodiesel in FT	0.33	0.27	0.300
1% Biodiesel in FT	0.35	0.27	0.310
Average			*0.300*

Table 12. Emissions testing results for soy diesel/FT diesel blends. Reported results are the average of at least three hot start runs.

Fuel		**THC**	**NO_x**	**CO**	**CO_2**	**PM**
		g/bhp-h	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**
Shell FT w/Paradyne	**Average Hot**	**0.007**	**4.026**	**3.843**	**548**	**0.167**
	Coefficient of Variation	73.82%	0.21%	4.41%	0.24%	4.64%
99%FT/1%Soygold	**Average Hot**	**0.004**	**4.035**	**3.915**	**550**	**0.177**
	Coefficient of Variation	96.75%	0.27%	2.52%	0.53%	3.64%
80%FT/20%Soygold	**Average Hot**	**0.005**	**4.249**	**3.608**	**554**	**0.146**
	Coefficient of Variation	83.47%	0.40%	3.49%	0.29%	5.68%
20%FT/80%Soygold	**Average Hot**	**0.006**	**5.048**	**2.986**	**571**	**0.078**
	Coefficient of Variation	10.17%	0.37%	3.02%	0.33%	5.40%

Results for DTBP Treated Fuels

The objective of Task 4 of this project was to quantify the effects of di-tert-butyl peroxide (DTBP) on regulated emissions from B-20 biodiesel (soy) blends. Tasks 5, 6, and 7 examined DTBP in other B20 blends as well as in the neat biodiesel samples. Previous testing using DTBP by Southwest Research Institute, showed that 0.5% and 1.0% volume DTBP treat rates reduced NO_x emissions by approximately 1.1% and 5.2% compared to untreated B20 respectively (5,6). Unfortunately in neither case were the data useful in determining an effective DTBP treat rate to make the B20 NO_x neutral, since the untreated B20 blend had lower NO_x emissions than the baseline No. 2 diesel fuel.

A baseline of 6 hot starts for B20 soy biodiesel in certification fuel was initially established. Using only the certification fuel runs acquired immediately before and after acquisition of the B20 baseline, which averaged 4.754 g/bhp-h, the NO_x increase is 3.3%. We prepared a series of B20 fuels (certification diesel + soydiesel) containing 0.5, 1.0, and 1.5 volume percent DTBP. Hot transient emissions summary results are presented in Table 13. The coefficients of variation for NO_x and PM measurements were always below 1% and 6% respectively. DTBP was effective at reducing NO_x at all three treatment-levels (all statistically significant at 95% confidence or greater). Figure 3 shows an approximately linear relationship between DTBP treat rate and NO_x emissions.

Percent NO_x reduction (with respect to untreated B20) versus percent volume DTBP is shown in Figure 4 and exhibits an approximately linear relationship (p-value for slope=0.02). Based on the linear regression equation shown in Figure 4, an approximate 4% reduction should be achieved using 1% volume DTBP. The 95% confidence interval on the slope of the regression in Figure 4 ranges from –6.23 to –1.42, thus the estimate of 1% volume DTBP is not very precise.

Table 13. Emissions summary for treatment of B20 (soy+cert) with DTBP, results are averages for three or more hot start runs.

Fuel		**THC**	**NO_x**	**CO**	**CO_2**	**PM**
		g/bhp-h	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**
Certification Fuel	**Average Hot**	**0.016**	**4.734**	**5.049**	**574**	**0.236**
January 15, 2001	Coefficient of Variation	29.96%	0.18%	2.43%	0.0	1.32%
B20 Soy in CERT fuel	**Average Hot**	**0.013**	**4.912**	**4.677**	**576**	**0.194**
	Coefficient of Variation	76.55%	0.05%	3.38%	0.12%	4.00%
Certification Fuel	**Average Hot**	**0.012**	**4.774**	**5.005**	**576**	**0.250**
January 18, 2001	Coefficient of Variation	32.09%	0.57%	1.62%	0.0	1.34%
B20 Soy in CERT fuel	**Average Hot**	**0.005**	**4.792**	**4.414**	**574**	**0.197**
w/ 0.5% volume DTBP	Coefficient of Variation	74.64%	0.25%	3.05%	0.22%	1.68%
B20 Soy in CERT fuel	**Average Hot**	**0.016**	**4.754**	**4.436**	**575**	**0.210**
w/ 1.0 % volume DTBP	Coefficient of Variation	11.32%	0.15%	1.01%	0.24%	2.32%
B20 Soy in CERT fuel	**Average Hot**	**0.008**	**4.612**	**4.218**	**571**	**0.196**
w/ 1.5% volume DTBP	Coefficient of Variation	83.58%	0.09%	1.82%	0.29%	2.78%

Because DTBP was successful at reducing NO_x from a B20 composed of soy biodiesel and certification diesel, additional tests were conducted on its effects on NO_x emissions from the following B20 blends:

Soy in 10% aromatic fuel
Yellow grease in certification fuel
Yellow grease in 10% aromatic fuel

Emissions summary results are presented in Table 14, along with some earlier results. The coefficients of variation for NO_x and PM measurements were always below 1% and 4% respectively. DTBP was effective at reducing NO_x emissions to the base fuel level or below (by 3% to 4%) in all cases (significant at 95% confidence or greater).

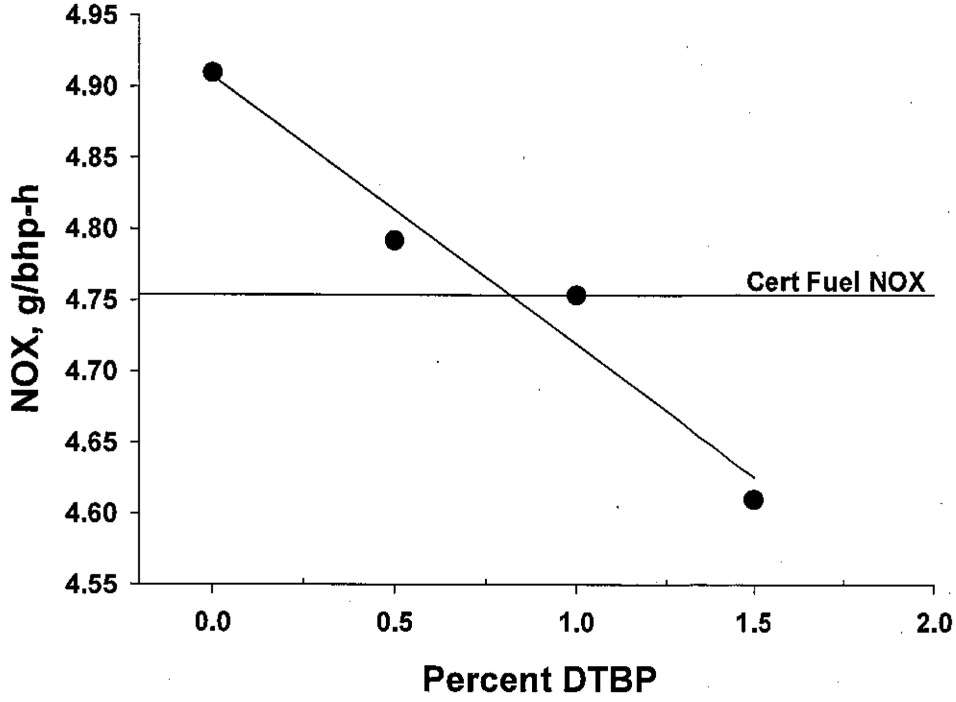


Figure 3. Relationship between DTBP blending level and NO_x emissions in B20 (soy+cert).

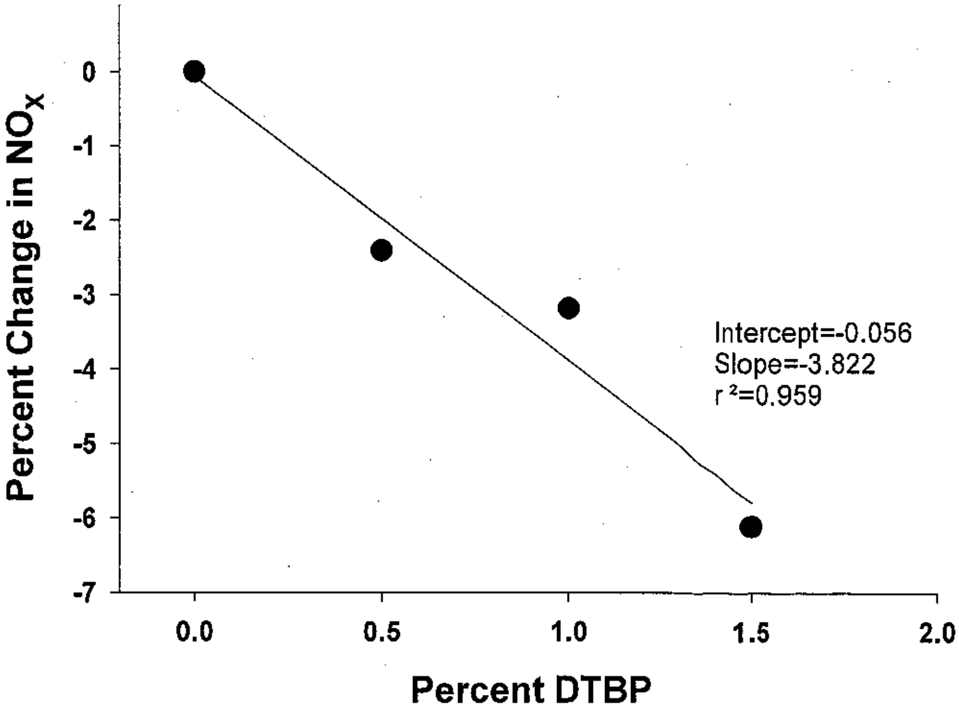


Figure 4. Effect of DTBP blending level on percent NO_x reduction for B20 (soy+cert).

Fuel property testing results for all of these B20 fuels are shown in Table 15. Adding 1% DTBP to B20 (Soy+Cert) increased cetane number from 48 to 60. The results in Table 15 indicate an even larger cetane boost for B20 (Soy+10%) diesel, from 48 to 67, although a cetane number of 67 seems unreasonably high. However, *cetane number for the yellow grease based B20 fuels did not increase significantly*, even though a NO_x reduction was observed. This observation was confirmed by retesting two of the yellow grease containing fuels. Williams Laboratory claims that the same person measures all cetane numbers. This result may imply that DTBP does not reduce NO_x by increasing cetane number but by some other chemical effect.

A 5% DTBP blending level was used for testing B100. Testing results are shown in Table 16, along with other results for completeness. Certification fuel NO_x emissions averaged 4.82 g/bhp-h during Campaign 2 when these tests were conducted. Soy B100 increases NO_x to 5.45 g/bhp-h. Adding DTBP results in a decrease to 5.18 g/bhp-h. This result represents a statistically significant NO_x reduction, but it is still well above the certification fuel level. For yellow grease B100 (Bio3000) NO_x is 5.07 g/bhp-h and adding 5% DTBP reduces NO_x to 4.88 g/bhp-h. Again this NO_x reduction is statistically significant, and has reduced NO_x to the certification fuel level (emissions for the two fuels are the same with 97% confidence).

Table 14. Emissions summary for treatment of various B20 fuels with DTBP (1%), results are averages for three or more hot start runs.

Fuel		**THC**	**NO_x**	**CO**	**CO_2**	**PM**
		g/bhp-h	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**
Certification Fuel	**Average Hot**	**0.02**	**4.723**	**5.011**	**573**	**0.248**
	Coefficient of Variation	0.35%	1.03%	0.20%	1.93%	8.62%
B20 (soy+cert)	**Average Hot**	**0.013**	**4.912**	**4.677**	**576**	**0.194**
	Coefficient of Variation	76.55%	0.05%	3.38%	0.12%	4.00%
B20 (soy+cert) 1.0 % volume DTBP	**Average Hot** Coefficient of Variation	**0.016** 11.32%	**4.754** 0.15%	**4.436** 1.01%	**575** 0.24%	**0.210** 2.32%
B20 (YG+cert)	**Average Hot**	**0.009**	**4.780**	**4.658**	**577**	**0.208**
	Coefficient of Variation	22.83%	0.19%	2.34%	0.0	2.67%
B20 (YG+cert) 1.0 % volume DTBP	**Average Hot** Coefficient of Variation	**0.009** 75.98%	**4.637** 0.14%	**4.498** 4.23%	**574** 0.0	**0.208** 2.75%
10% Aromatic	**Average Hot**	**0.029**	**4.478**	**4.980**	**569**	**0.231**
	Coefficient of Variation	0.240	0.002	0.031	0.002	0.028
B20 (Soy+10%)	**Average Hot**	**0.022**	**4.606**	**4.333**	**567**	**0.189**
	Coefficient of Variation	13.68%	0.09%	4.07%	0.0	4.08%
B20 (Soy+10%) 1.0 % volume DTBP	**Average Hot** Coefficient of Variation	**0.016** 24.00%	**4.469** 0.20%	**4.445** 2.13%	**569** 0.0	**0.201** 1.68%
B20 (YG+10%)	**Average Hot**	**0.017**	**4.586**	**4.427**	**568**	**0.191**
	Coefficient of Variation	17.21%	0.29%	1.61%	0.0	2.51%
B20 (YG+10%) 1.0 % volume DTBP	**Average Hot** Coefficient of Variation	**0.016** 17.22%	**4.414** 0.24%	**4.590** 1.50%	**566** 0.0	**0.203** 0.37%

Table 15. Fuel property testing results for B20 blends.

Property	**Method**	**Units**	**B20 Soy/ CERT**	**B20 Soy/CERT+1 % DTBP**	**B20 Soy/10% Aromatic**	**B20 Soy/10% Aromatic+1% DTBP**	**B20 YG/CERT**	**B20 YG/CERT+ 1%DTBP**	**B20 YG/10% Aromatic**	**B20 YG/10%Aromatic+ 1% DTBP**
Cetane Number (replicate)	ASTM-D613-86		47.7	60	48	67.4	44.7 (46.2)	45.1 (49.2)	47.7	48.2
Cetane Index	ASTM-D976		49.5		50.1		50.2	50.1	50.7	50.9
Specific Gravity	ASTM-D4052			0.852	0.8403	0.8383	0.852	0.8514	0.8388	0.8378
Flash Point	ASTM-D93	F	165		163	147.2	163	150	163	149
Kinematic Viscosity(at 100F)	ASTM-D445	mm2/s	2.88		2.702	5.054	2.918	2.855	2.782	2.744
Corrosion, Copper strip	ASTM-D130		1A		1A	1A	1A	1A	1A	1A
Ash Content	ASTM-D482	wt%	0.001		0	0.001	0.04	0.006	0	0
Carbon Residue Ramsbottom	ASTM-D524	% carbon	0.07		0.04	0.17	0.04	0.43	0.49	0.03
Cloud Point	ASTM-D2500	F	10		-2	-2.2	14	16	18	8
Sulfur	ASTM-D2622	wt%	0.0263		0.0027	0.0037	0.0268	0.0258	0.0035	0.0022
Water and Sediment	ASTM-D2709	vol%	0		<0.05	0.01	<0.05	<0.05	<.05	<.05
API Gravity	ASTM-D1298 /D287				36.8		34.5	34.6	37.1	37.3
Distillation	ASTM-D86	F								
IBP	ASTM-D86	F	365		388	169	375	175	396	176
10	ASTM-D86	F	437		431	433	446	440	432	435
50	ASTM-D86	F	542		511	510	548	545	511	510
90	ASTM-D86	F	631		640	649	632	635	641	647
FBP	ASTM-D86	F	654		658	656	659	652	659	656

Table 16. Emission testing results for B100 fuels with and without DTBP, results are an average of 3 or more hot runs.

Fuel		THC	NO_x	CO	CO_2	PM
		g/bhp-h	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**
Cert Fuel	**Average Hot**	**0.020**	**4.824**	**4.604**	**574**	**0.260**
Campaign 2 Avg	Coefficient of Variation	16.7%	0.4%	1.0%	0.2%	1.8%
Soygold	**Average Hot**	**0.012**	**5.366**	**2.973**	**576**	**0.068**
	Coefficient of Variation	10.8%	0.2%	2.5%	0.2%	5.5%
Soygold+5% DTBP	**Average Hot**	**0.027**	**5.184**	**2.470**	**556**	**0.064**
	Coefficient of Variation	7.73%	0.61%	3.21%	0.06%	6.08%
Bio3000	**Average Hot**	**0.004**	**4.981**	**3.105**	**576.**	**0.078**
	Coefficient of Variation	71%	0.7%	4.3%	0.5%	8.4%
Bio3000+5% DTBP	**Average Hot**	**0.016**	**4.881**	**2.861**	**556**	**0.078**
	Coefficient of Variation	12.43%	0.39%	5.22%	0.04%	6.54%

Results for EHN Treated B20 Blends

Studies conducted in 1994 at SwRI reported that EHN was not effective for NO_x reduction when added to soy-based biodiesel (5,6). However, the biodiesel available at that time was likely of low quality (high methanol, glycerol, and glyceride content) and it would be interesting to repeat those tests using a fuel meeting the requirements of ASTM PS121. Tests were conducted using 0.5% and 1.0% by volume EHN in B20 (soy+cert) and the results are shown in Table 17. Table 18 shows the results of statistical tests to quantify the significance of any differences observed. When comparing B20 to B20 with EHN (0.5%), it clear that the observed 2.3% NO_x reduction has a high degree of statistical significance. When comparing certification fuel emissions to B20+0.5% EHN is seems likely that EHN has reduced NO_x to the certification fuel level. A set of runs was also performed with 1.0% EHN and the NO_x in this case was statistically identical to that observed for 0.5%. Thus, our results do not replicate what was reported by SwRI however the SwRI study only tested EHN in a 2-stroke engine. In the present study with a 4-stroke engine both of the common cetane improvers, EHN and DTBP, reduced NO_x from soydiesel/certification diesel blends.

Table 17. Emissions testing results for EHN in B20 (soy+cert fuel), results are average of three or more hot start runs.

Fuel		THC	NO_x	CO	CO_2	PM
		g/bhp-h	g/bhp-h	g/bhp-h	g/bhp-h	g/bhp-h
B20 (Soy+Cert)	**Average Hot**	**0.018**	**4.909**	**4.674**	**577**	**0.196**
January 15, 2001	Coefficient of Variation	6.95%	0.33%	3.28%	0.0	5.74%
B20 (Soy+Cert)	**Average Hot**	**0.007**	**4.916**	**4.679**	**575**	**0.192**
January 17, 2001	Coefficient of Variation	76.55%	0.05%	3.38%	0.0	4.00%
Certification Diesel	**Average Hot**	**0.041**	**4.830**	**5.106**	**557**	**0.249**
March 7, 2001	Coefficient of Variation	15.02%	0.73%	3.71%	0.31%	2.26%
B20 (Soy+Cert)	**Average Hot**	**0.037**	**4.941**	**4.616**	**558**	**0.191**
March 7, 2001	Coefficient of Variation	18.23%	0.23%	1.36%	0.06%	1.11%
Certification Diesel	**Average Hot**	**0.053**	**4.841**	**5.113**	**554**	**0.264**
March 12, 2001	Coefficient of Variation	2.76%	0.17%	1.37%	0.16%	2.42%
B20 (Soy+Cert)+0.5% EHN	**Average Hot**	**0.024**	**4.834**	**4.529**	**558**	**0.212**
March 13, 2001	Coefficient of Variation	26.99%	0.39%	3.39%	0.11%	2.39%
B20 (Soy+Cert)+1.0% EHN	**Average Hot**	**0.033**	**4.804**	**4.431**	**559**	**0.206**
March 13, 2001	Coefficient of Variation	13.16%	0.56%	1.58%	0.11%	1.90%
Certification Diesel	**Average Hot**	**0.029**	**4.800**	**5.190**	**560**	**0.258**
March 14, 2001	Coefficient of Variation	6.83%	0.55%	2.03%	0.13%	4.00%
Certification Diesel	**Average Hot**	**0.025**	**4.813**	**5.144**	**558**	**0.252**
April 10, 2001	Coefficient of Variation	12.10%	0.18%	2.51%	0.12%	0.68%
B20 (Soy+Cert)	**Average Hot**	**0.023**	**4.913**	**4.784**	**558**	**0.201**
April 10, 2001	Coefficient of Variation	17.82%	0.61%	2.25%	0.12%	2.05%
B20 (Soy+Cert)+0.5% EHN	**Average Hot**	**0.018**	**4.766**	**4.662**	**557**	**0.220**
April 10, 2001	Coefficient of Variation	9.62%	0.74%	2.22%	0.21%	9.59%
B20 (Soy+Cert)	**Average Hot**	**0.018**	**4.877**	**4.714**	**558**	**0.193**
April 19, 2001	Coefficient of Variation	11.28%	0.18%	2.91%	0.18%	1.18%

Table 18. Results of t-test for significance of differences in emissions for EHN containing fuels (Excel t-test tool, two-sample assuming equal variaances).

	B20 NO_x	B20+EHN NO_x	p-value
Compare untreated B20 to B20+0.5%EHN	4.9113	4.8002	6.87E-07
	Cert NO_x	**B20+EHN NO_x**	**p-value**
Compare cert to B20+0.5% EHN	4.8257	4.8002	0.159907

Testing of USDA Philadelphia Additives

Dr. Michael Haas and Dr. Thomas Foglia of USDA supplied two fuel additives:

USDA-1: A fuel composed of 90% soy biodiesel and 10% short chain fatty acid esters. The USDA fuel was tested as a B20 blend, with the final fuel composed of 80% certification diesel, 2% short chain esters, and 18 % soy diesel. The composition of the short chain ester mixture was:

Methyl butyrate	411 ml	(41.1 volume %)
Methyl caproate	265 ml	(26.5 volume %)
Methyl caprylate	92 ml	(9.2 volume %)
Methyl decanoate	233 ml	(23.3 volume %)

This mixture was selected because in our previous study (2) it was demonstrated that shorter chain, saturated esters had lower NO_x emissions than the long chain unsaturated esters that are dominant in soy diesel. This was true even though NO_x emissions increased for saturated esters when the chain length was shortened.

USDA-2: A fuel composed of 100% soy biodiesel and 1% tert-butyl-hydroquinone, a food antioxidant (also known as TBHQ). The fuel was tested as a B20 with certification diesel; the blended fuel contained 0.2 wt% TBHQ. This additive was selected because in our previous study (2) it was shown that the increase in NO_x is not driven by thermal or Zeldovich NO_x formation and therefore may involve some pre-combustion chemistry of hydrocarbon free radicals. An anti-oxidant might react with these free radicals preventing their participation in a NO_x forming sequence of reactions.

Emissions summary results for these two fuel blends are presented in Table 19, along with some additional results for completeness. The coefficients of variation for NO_x and PM measurements were always below 1.4% and 4% respectively. The statistical analysis of the results reported here utilizes only certification fuel runs and untreated B20 runs from March and early April, 2001.

USDA-1: Certification fuel runs performed before and after testing of this additive in B20 averaged 4.85 g/bhp-h. The NO_x emission for the USDA-1 fuel was 5.012. The average untreated B20 NO_x was 4.93. The 3% increase in NO_x observed for USDA-1 is statistically significant at 98% confidence (p=0.01608). PM emissions are unchanged relative to B20. Thus, USDA-1 was not effective for NO_x reduction. USDA-1 had no significant impact on PM emissions.

USDA-2. Certification fuel runs performed before and after testing this B20 averaged 4.840 g/bhp-h of NO_x. The NO_x emission for the USDA-2 fuel was 4.894 g/bhp-h, 0.044 g/bhp-h higher than the bracketing certification fuel mean which is significantly higher at 99% confidence. The USDA-2 NO_x is 0.035 g/bhp-h lower than the mean B20 NO_x of 4.93. This NO_x reduction is significant at 99.5% confidence (p=0.005532) but apparently the treat rate of 0.2wt% is not adequate to reduce NO_x to the certification fuel level. TBHQ also had a negative effect on PM, causing PM to increase by 9% relative to the average B20 PM emission for the second testing campaign (significant at 99% confidence). This level of PM is still significantly below the PM emission level of certification diesel. Additional testing of TBHQ and other antioxidants is clearly warranted.

Table 19. Emissions summary results for testing of USDA addtives in B20 (soy+cert), results are averages of three or more hot start runs.

Fuel		THC	NO_x	CO	CO_2	PM
		g/bhp-h	g/bhp-h	g/bhp-h	g/bhp-h	g/bhp-h
B20 Soy/Cert fuel	**Average Hot**	**0.037**	**4.941**	**4.616**	**558**	**0.191**
March 7, 2001	Coefficient of Variation	18.23%	0.23%	1.36%	0.06%	1.11%
Cert Fuel	**Average Hot**	**0.036**	**4.853**	**5.283**	**560**	**0.260**
March 28, 2001	Coefficient of Variation	3.36%	0.07%	3.53%	0.07%	1.39%
B20 (Soy)/USDA-1	**Average Hot**	**0.030**	**5.012**	**4.719**	**562**	**0.192**
March 28, 2001	Coefficient of Variation	8.23%	1.31%	2.30%	0.22%	2.16%
Cert Fuel	**Average Hot**	**0.034**	**4.847**	**5.102**	**559**	**0.238**
April 4, 2001	Coefficient of Variation	13.15%	0.04%	2.26%	0.24%	2.15%
B20 (Soy)/USDA-2	**Average Hot**	**0.028**	**4.894**	**4.846**	**560**	**0.214**
April 5, 2001	Coefficient of Variation	9.74%	0.26%	2.84%	0.18%	3.35%
Cert Fuel	**Average Hot**	**0.030**	**4.852**	**5.386**	**559**	**0.232**
April 6, 2001	Coefficient of Variation	11.31%	0.59%	4.09%	0.23%	3.16%
B20 Soy/Cert fuel	**Average Hot**	**0.023**	**4.913**	**4.784**	**558**	**0.201**
April 10, 2001	Coefficient of Variation	17.82%	0.61%	2.25%	0.12%	1.98%

Testing of Bioclean Fuels Additive

The objective of Task 10 of this project was to test a B20 produced from soy and 10% aromatic diesel and containing the A-1 additive from Bioclean Fuels. Task 11 was to perform similar tests on B20 produced from soy and certification diesel, and on B100 soy. Based on the testing results, the NREL technical monitor (Dr. Shaine Tyson) directed us not to perform the B100 test. This section presents emissions results for the two fuels tested with A-1.

The B20 fuels were prepared, as directed by Bioclean Fuels, to contain 1 part in 40 of the liquid A-1 additive. The emissions summary results are presented in Table 20 along with some results from other tasks for completeness. The coefficients of variation for NO_x and PM measurements were always below 1% and 4% respectively.

A-1 in CARB/B20: NO_x emissions from CARB diesel were 4.48 g/bhp-h and increased to 4.61 g/bhp-h upon addition of 20-volume percent soy diesel. Adding A-1 produced NO_x emissions of 4.56 g/bhp-h, which represents no change in NO_x emissions at the 99% confidence level. Adding A-1 caused PM to increase from 0.189 to 0.237 g/bhp-h; essentially eliminating any PM benefit from the biodiesel.

A-1 in Cert/B20: NO_x emissions for certification diesel ran about 4.85 g/bhp-h during late March and early April. Adding 20% soy diesel increased this to 4.91 g/bhp-h. Adding A-1 produced a NO_x emission of 4.84 g/bhp-h, indicating that A-1 successfully reduced NO_x by about 2% for this fuel. However, PM emissions were about 0.23 g/bhp-h. This is identical to PM emissions from certification diesel on bracketing runs and significantly higher than the 0.201 g/bhp-h measured for B20 shortly thereafter. This indicates that A-1 eliminates the PM benefit of using biodiesel.

Table 20. Emissions summary for testing of Bioclean Fuels additive A-1; results are an average of three or more hot start runs.

Fuel		**THC**	**NO_x**	**CO**	**CO_2**	**PM**
		g/bhp-h	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**
10% Aromatic	**Average Hot**	**0.029**	**4.478**	**4.980**	**569**	**0.231**
January 12, 2001	Coefficient of Variation	24.05%	0.17%	3.13%	0.0	2.84%
B20 Soy/10% Aro	**Average Hot**	**0.022**	**4.606**	**4.333**	**567**	**0.189**
January 23, 2001	Coefficient of Variation	13.68%	0.09%	4.07%	0.2%	4.08%
B20 Soy/Cert fuel	**Average Hot**	**0.037**	**4.941**	**4.616**	**558**	**0.191**
March 7, 2001	Coefficient of Variation	18.23%	0.23%	1.36%	0.06%	1.11%
Cert Fuel	**Average Hot**	**0.034**	**4.746**	**5.091**	**555**	**0.260**
March 26, 2001	Coefficient of Variation	16.63%	0.42%	2.23%	0.14%	1.40%
B20 Soy/10% Aro+A1	**Average Hot**	**0.040**	**4.563**	**4.949**	**554**	**0.237**
March 26, 2001	Coefficient of Variation	6.54%	0.10%	1.79%	0.26%	2.30%
Cert Fuel	**Average Hot**	**0.036**	**4.853**	**5.283**	**560**	**0.260**
March 28, 2001	Coefficient of Variation	3.36%	0.07%	3.53%	0.07%	1.39%
Cert Fuel	**Average Hot**	**0.034**	**4.847**	**5.102**	**559**	**0.238**
April 4, 2001	Coefficient of Variation	13.15%	0.04%	2.26%	0.24%	2.42%
B20 Soy/Cert+A1	**Average Hot**	**0.033**	**4.848**	**5.324**	**563**	**0.233**
April 4, 2001	Coefficient of Variation	12.34%	0.35%	0.75%	0.18%	1.08%
Cert Fuel	**Average Hot**	**0.030**	**4.852**	**5.386**	**559**	**0.232**
April 6, 2001	Coefficient of Variation	11.31%	0.59%	4.09%	0.23%	3.68%
B20 Soy/Cert fuel	**Average Hot**	**0.023**	**4.913**	**4.784**	**558**	**0.201**
April 10, 2001	Coefficient of Variation	17.82%	0.61%	2.25%	0.12%	2.05%
Cert Fuel	**Average Hot**	**0.025**	**4.813**	**5.144**	**558**	**0.252**
April 10, 2001	Coefficient of Variation	12.10%	0.18%	2.51%	0.12%	0.68%

Testing of K50

The objective of Task 12 of this project is to test a blend of No. 1 diesel (also known as kerosene) and 50 volume percent soy diesel (this blend is referred to as K50). The best NO_x reduction additive identified under this project is to then be blended with K50 and tested. The best NO_x reduction additive identified was di-tert-butyl-peroxide (DTBP). For B20 produced from soy diesel and certification diesel 0.93, volume percent DTBP was sufficient to reduce NO_x to the certification fuel level. For K50 we elected to employ 2.5 times as much DTBP (2.3%) because the fuel contains 2.5 times as much biodiesel. This is the most conservative way to insure that a NO_x reduction occurs. As the data will show, 2.3% DTBP is more than was needed to achieve NO_x neutrality with certification diesel. A better approach may have been to note that the desired percent NO_x reduction was 2.55%. For B20 this could be obtained with 0.624% DTBP suggesting that 2.5 times this level, or 1.456% DTBP, might have been adequate for the K50 fuel.

The kerosene was obtained locally. Emissions results for the kerosene without biodiesel were obtained for completeness. All emissions results are shown in Table 21. Kerosene produced a NO_x level of 4.53 g/bhp-h. Testing of 50% soy/50% kerosene produced a NO_x emission of 4.94 g/bhp-h, essentially the same level observed for B20 from certification diesel and 20% soy.

Addition of 2.3% DTBP reduced NO_x to 4.70 g/bhp-h. This is well below the certification fuel level of 4.85 g/bhp-h and suggests that between 1% and 1.5% DTBP would have been adequate. Fuel analysis results are reported in Table 22. Addition of 2.3% DTBP to K50 was very effective at increasing cetane number, causing an increase of 28 cetane units.

Table 21. Emissions summary for testing of kerosene/soydiesel blends; results are average of three or more hot starts.

Fuel		**THC**	**NO_x**	**CO**	**CO_2**	**PM**
		g/bhp-h	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**	**g/bhp-h**
B20 Soy/Cert fuel	**Average Hot**	**0.037**	**4.941**	**4.616**	**558**	**0.191**
March 7, 2001	Coefficient of Variation	18.23%	0.23%	1.36%	0.06%	1.11%
Cert Fuel	**Average Hot**	**0.034**	**4.852**	**5.091**	**555**	**0.260**
March 22, 2001	Coefficient of Variation	16.63%	0.42%	2.23%	0.14%	1.40%
Kerosene	**Average Hot**	**0.086**	**4.527**	**4.005**	**554**	**0.199**
March 27, 2001	Coefficient of Variation	5.06%	0.27%	1.66%	0.09%	2.41%
K50	**Average Hot**	**0.046**	**4.940**	**3.611**	**556**	**0.115**
March 28, 2001	Coefficient of Variation	6.03%	1.06%	3.51%	0.24%	3.47%
Cert Fuel	**Average Hot**	**0.036**	**4.853**	**5.283**	**560**	**0.260**
March 28, 2001	Coefficient of Variation	3.36%	0.07%	3.53%	0.07%	1.39%
Cert Fuel	**Average Hot**	**0.030**	**4.852**	**5.386**	**559**	**0.232**
April 6, 2001	Coefficient of Variation	11.31%	0.59%	4.09%	0.23%	3.68%
K50+2.3%DTBP	**Average Hot**	**0.029**	**4.701**	**3.252**	**556**	**0.084**
April 6, 2001	Coefficient of Variation	2.41%	0.69%	3.84%	0.09%	8.56%

Table 22. Fuel property testing results for kerosene and K50 fuels.

Property	**Method**	**Units**	**No. 1 Diesel**	**Soygold**	**K50**	**K50+2.3%DTBP**
Cetane Number (CN)	ASTM-D613-86		42.8	47.4	44.3	72.2
Cetane Index	ASTM-D975		45.8	--	51.2	48.7
Kinematic Viscosity 40C	ASTM-D445	mm2/s	1.3	4.066	2.2	2.2
Iodine Number	ASTM-D1959		--	127.4	--	--
Cloud Point	ASTM-D2500	F	-61	--	17	16
Cloud Point	ASTM-D5773	C	--	-1	--	--
Flash Point	ASTM-D93	F	130	288	144	126
Cold Filter Plugging Point	ASTM-6371	C	--	-3	--	--
Pour Point	ASTM-D97	F	--	--	--	--
Total Sulfur by UVF	ASTM-D5453	wt%	--	0.000068	--	--
Sulfur	ASTM-D2622	wt%	0.0138	--	0.0062	0.0071
Ash Content	ASTM-D482	wt%	0.001	--	--	--
Sulfated Ash	ASTM-D874	wt%	--	0.003	--	--
Water Content	ASTM-D1796		--	--	--	--
Specific Gravity	ASTM-D4052		--	--	--	--
Carbon Residue	ASTM-D189	wt%	--	--	--	--
Carbon Residue	ASTM-D524	wt%	0.06	0.08	0.01	0.06
Corrosion, Copper strip	ASTM-D130		--	1A		
Water and Sediment	ASTM-D2709	vol%	<0.05	<0.005	<0.05	<0.05
Acid Number	ASTM-D664	mgKOH/g	--	0.03	--	--
Hydrocarbon Type:	ASTM-D1319					
Aromatics		%vol	--	--	--	--
Olefins		%vol	--	--	--	--
Saturates		%vol	--	--	--	--
Free Glycerin	ASTM D6584	wt%		0.004		
Total Glycerin		wt%		0.184		
Distillation	ASTM-D86					
IBP		F	338	--	347	251
10		F	365	--	381	380
50		F	407	--	522	518
90		F	471	--	644	648
EP		F	515	--	651	648

DISCUSSION

Effect of Various NO_x Reduction Strategies

This study has examined a number of approaches for NO_x reduction from biodiesel. These are compared in Table 23 for B20 (soy+cert). Blending FT diesel at very high percentages can produce a NO_x neutral fuel. Lowering the base fuel aromatic content from 31.9 to 7.5% (nominally 10% aromatic fuel) was very successful at lowering NO_x. If all other factors are equal and if the effect of aromatic content is linear, using a base fuel having 25.8% aromatics should provide a NO_x neutral B20. The results also suggest that using kerosene as the base fuel could lead to a NO_x neutral blend (this occurs at 40% biodiesel, assuming linearity). The cetane enhancers DTBP and EHN are both effective at reducing NO_x from biodiesel. The antioxidant TBHQ is also effective, but may cause an increase in PM emissions. The idea of using antioxidants as NO_x reduction additives is clearly something that should be explored in more detail. It may be that other antioxidants also reduce NO_x but have no negative impact on PM emissions. The Bioclean Fuels A1 additive is effective at NO_x reduction but causes an unacceptably large increase in PM.

Table 23. Effect of various fuel additives on NO_x reduction for B20 (soy+cert).

Additive	NO_x, g/bhp-h	% Reduction[‡]	Significance (p-value)
Certification Diesel	4.85	--	--
B20 (soy+cert) no additive	4.93	--	--
46% FT diesel	4.85	1.62	Predicted[*]
10% Aromatic base stock	4.61	6.49	<0.001
1% DTBP	4.75	3.65	0.030
0.5% EHN	4.83	2.03	<0.001
2% Short Chain FA Esters (USDA-1)	5.01	-1.62	<0.001
0.2% TBHQ (USDA-2)	4.89	0.08[+]	0.001
2.5% A1	4.85	1.62[+]	0.018

[‡] Relative to B20 (soy+cert)

[*] Predicted from model shown in Figure 2

[+] These additives also caused an increase in PM

Use of Cetane Improvers for Biodiesel NO_x Reduction

Perhaps the most practical strategy for NO_x reduction in the short term is the use of cetane improvers. This is because altering the base fuel properties may severely limit the marketability of biodiesel, and the other additives caused an increase in PM or had no effect. A recently obtained quotation (7) indicates that DTBP can be obtained in truckload quantities for $2.45 per lb. Assuming B20 has a density of 7.1 lb/gal, and DTBP has a density of 6.59lb/gal, 1 volume percent is 0.066 lb of DTBP. This translates into an incremental cost of $0.162 per gallon. For EHN the density is 8.0 lb/gal and 0.04 lb is required to make 0.5 volume percent. EHN has recently been quoted on the internet spot market for $1.25/lb or an incremental cost per gallon of $0.05. Biodiesel is currently selling at between $1 and $1.70 per gallon (8) while petroleum diesel sells for an average of $1.42 per gallon in 49 states and $1.55 per gallon in California (9).

California diesel fuel averages approximately 16% aromatic content (10) and, as discussed above, using a base fuel with less than 25.8% aromatic content should result in B20 NO_x emissions below those for certification diesel. So using a low aromatic California diesel as the blending diesel to lower NO_x relative to certification diesel, if such a fuel was available, would have an incremental cost on the order of $0.13 per gallon.. FT diesel sells for $0.20 to $0.50 more than California diesel so blending high levels of FT with biodiesel to reduce NO_x may not be an economically viable alternative.

Comparisons with 10% Aromatic Diesel

For a diesel fuel to be legal for sale in California it must meet EPA's requirements, and in addition it must be proven to be emissions equivalent to a 10% aromatic CARB reference diesel or have less than 10% aromatic content (California Code of Regulations Title 13 section 2282, subsection g). In this study we tested a nominally 10% aromatic fuel as a reference point for gauging the potential of B20 blends for possible CARB certification. Results for several B20 blends are shown in Figure 5 and compared to emissions from the 10% aromatic fuel. All of the B20 blends exhibited PM emissions below those measured for the 10% aromatic diesel. However, B20 fuels based on certification diesel did not in any case exhibit NO_x emissions at or below the emissions of the 10% aromatic fuel. B20 blends produced from the 10% aromatic fuel and including DTBP were NO_x equivalent or better. Thus blending of biodiesel with a California compliant diesel and treating it with DTBP may be a route to a CARB certifiable B20.

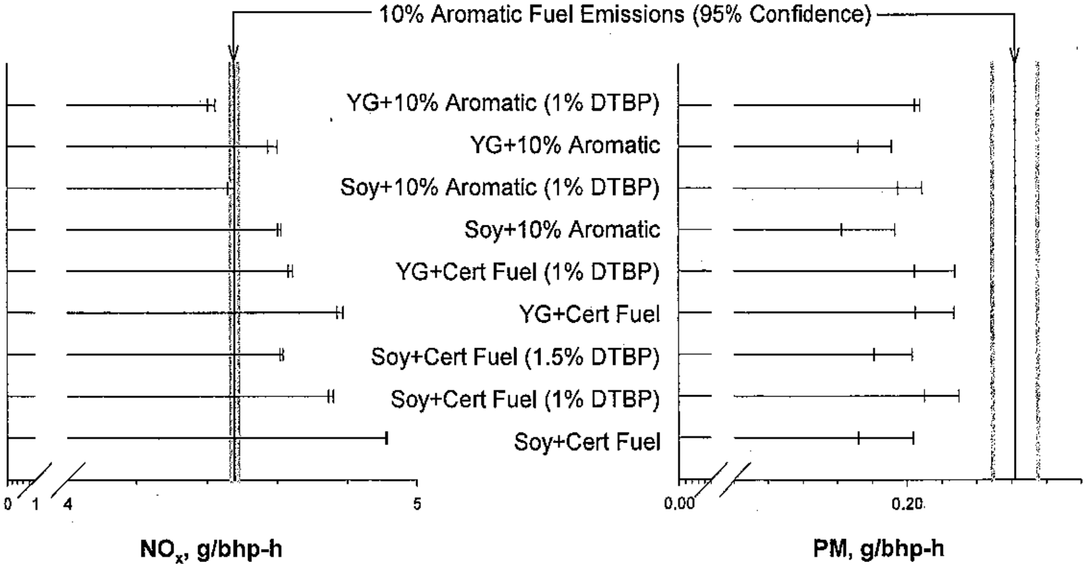


Figure 5. Comparison of B20 emissions with emissions for 10% aromatic diesel.

Comparison of Soy and YG Biodiesels

Degree of unsaturation appears to be the key difference between soy and yellow grease (YG) based biodiesels from the standpoint of emissions performance (2,3). The iodine numbers of these fuels were 127 and 79, respectively. The cetane number of the YG fuel was correspondingly higher. Figure 6 compares emissions for various fuels containing soy and YG biodiesel. For B100 fuels, the PM emissions are approximately the same, but YG (Bio3000) exhibited NO_x emissions that were lower by nearly 0.4 g/bhp-h. Treating B100 fuels with DTBP was effective at reducing NO_x, but not in proportion to the NO_x reduction observed for B20 blends.

For the B20 blends a significant (about 2%) NO_x increase relative to certification diesel was observed for soy but no significant increase was observed for YG. Treatment with 1% DTBP lowered NO_x by about the same amount for both blends. The fact that the NO_x reduction for DTBP is the same independent of biodiesel source, and that it decreases with increasing biodiesel content of the fuel may suggest that DTBP acts largely to lower the NO_x produced by burning the petroleum diesel fuel. The fact that DTBP can reduce NO_x emissions from petroleum diesel is well documented (11).

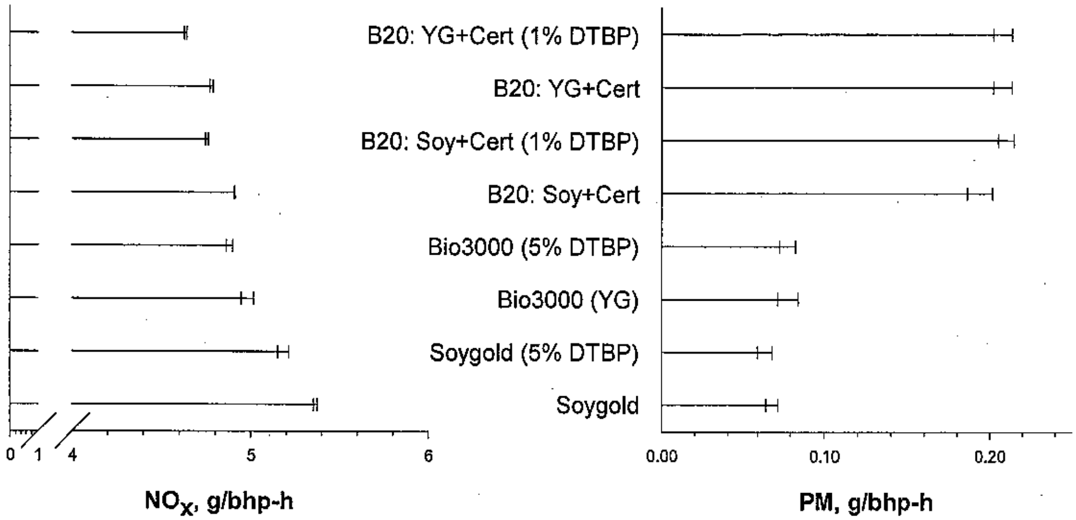


Figure 6. Comparison of emissions for various soy and yellow grease biodiesel fuels.

CONCLUSIONS

This study has examined a number of approaches for NO_x reduction from biodiesel. The following conclusions can be drawn:

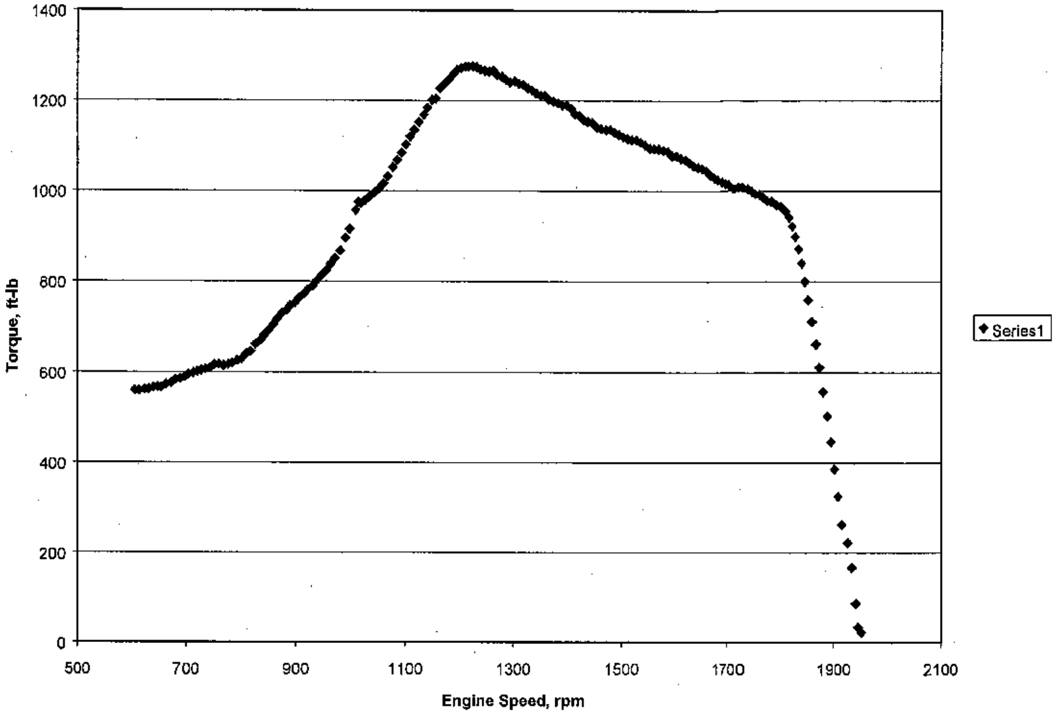
- The cetane improvers DTBP and EHN are effective for reducing NO_x by 4% in B20 blends. DTBP at 1.0 volume percent will add on the order of $0.16 per gallon and EHN at 0.5 volume percent will add on the order of $0.05 per gallon to the cost of biodiesel.
- DTBP is also effective at NO_x reduction for B100 fuels but not in proportion to the NO_x reduction observed for B20 blends. This may indicate that cetane improvers act largely to lower the NO_x produced during burning of the petroleum diesel fuel.
- Blending with a low aromatic diesel, kerosene, or FT diesel is also effective at reducing NO_x.
- The antioxidant TBHQ significantly reduced NO_x but also caused a small increase in PM. The use of antioxidants in general is worthy of further study.
- Short chain fatty acid esters were not effective for NO_x reduction.
- Bioclean Fuels A1 additive is effective at NO_x reduction but also produces a significant increase in PM.
- No combination of biodiesel with certification fuel and fuel additives produced NO_x emissions levels below that observed for a 10% aromatic fuel, suggesting that CARB certification using a 30% aromatic base fuel is not possible. Lowering aromatic content to roughly 25% and addition of cetane improver would be necessary for NO_x neutrality relative to 10% aromatic fuel.

APPENDIX A: ASTM PS121 SPECIFICATION FOR BIODIESEL FUELS

Property		ASTM Method	Limits	Units
Flash Point		93	100 min	°C
Water and Sediment		2709	0.05 max	Vol %
Carbon Residue		4530	0.05 max	Wt %
	or	524	0.09 max	Wt%
Sulfated Ash		874	0.02 max	Wt %
Kinematic Viscosity@40°C		445	1.9-6.0	mm^2/sec
Sulfur		5453	0.05 max	Wt %
Cetane Number		613	40 min	
Cloud Point		2500	Report	°C
Copper Strip Corrosion		130	No. 3 max	
Acid number		664	0.80 max	Mg KOH/gm
Free Glycerine		GC[1]	0.02 max	Wt %
Total Glycerine		GC[1]	0.24 max	Wt %

APPENDIX B: ENGINE TORQUE MAP

The chart below shows the engine map, acquired on certification diesel fuel, that was used to generate the transient cycle for all transient runs in this test program (the map is run number 5629).



APPENDIX C: EMISSIONS DATA

FUEL	Run #	Date		bhp-h	THC g/bhp-h	NOx g/bhp-h	CO g/bhp-h	CO2 g/bhp-h	PM g/bhp-h
Cert Lot # 0KP05202	5746	1/3/01	C	21.791	0.025	5.285	6.430	605.0	0.218
Cert Lot # 0KP05202	5747	1/3/01	H	21.791	0.016	4.769	4.553	575.3	0.214
Cert Lot # 0KP05202	5748	1/3/01	H	21.819	0.023	4.759	4.646	573.2	0.221
Cert Lot # 0KP05202	5749	1/3/01	H	21.836	0.020	4.792	4.612	573.5	0.222
Composite					**0.020**	**4.847**	**4.865**	**578.5**	**0.219**
Hot Average				**21.815**	**0.020**	**4.773**	**4.604**	**574.0**	**0.219**
Coefficient of Variation				**0.10%**	**16.70%**	**0.35%**	**1.03%**	**0.0**	**1.93%**
Shell FT w/ Paradyne 655	5751	1/4/01	C	21.599	0.018	4.491	5.196	573.8	0.231
Shell FT w/ Paradyne 655	5752	1/4/01	H	21.632	0.012	4.033	4.021	549.5	0.174
Shell FT w/ Paradyne 655	5753	1/4/01	H	21.571	0.003	4.017	3.823	547.2	0.169
Shell FT w/ Paradyne 655	5754	1/4/01	H	21.542	0.005	4.029	3.684	547.4	0.159
Composite					**0.008**	**4.093**	**4.036**	**551.7**	**0.176**
Hot Average				**21.582**	**0.007**	**4.026**	**3.843**	**548.1**	**0.167**
Coefficient of Variation				**0.21%**	**73.82%**	**0.21%**	**4.41%**	**0.0**	**4.64%**
Cert Lot # 0KP05202	5755	1/5/01	H	21.814	0.011	4.581	5.077	570.8	0.268
Cert Lot # 0KP05202	5756	1/5/01	H	21.767	0.018	4.635	4.762	571.7	0.248
Cert Lot # 0KP05202	5757	1/5/01	H	21.816	0.018	4.651	5.043	571.8	0.256
Hot Average		1/5/01		**21.799**	**0.015**	**4.622**	**4.961**	**571.4**	**0.257**
Coefficient of Variation				**0.13%**	**25.98%**	**0.79%**	**3.49%**	**0.0**	**3.87%**
80%FT/20%Soygold	5758	1/5/01	H	21.546	0.010	4.268	3.751	556.0	0.155
80%FT/20%Soygold	5759	1/5/01	H	21.492	0.001	4.238	3.557	552.9	0.146
80%FT/20%Soygold	5760	1/5/01	H	21.483	0.004	4.239	3.515	553.6	0.138
Hot Average				**21.507**	**0.005**	**4.249**	**3.608**	**554.2**	**0.146**
Coefficient of Variation				**0.16%**	**83.47%**	**0.40%**	**3.49%**	**0.0**	**5.68%**
Cert Lot # 0KP05202	5761	1/8/01	H	21.752	0.018	4.682	5.208	574.7	0.259
Cert Lot # 0KP05202	5762	1/8/01	H	21.791	0.025	4.696	4.974	573.4	0.252
Hot Average		1/8/01		**21.771**	**0.021**	**4.689**	**5.091**	**574.0**	**0.255**
Coefficient of Variation				**0.13%**	**21.63%**	**0.21%**	**3.25%**	**0.0**	**1.84%**
20%FT/80%Soygold	5763	1/8/01	H	21.419	0.006	5.069	3.089	572.5	0.082
20%FT/80%Soygold	5764	1/8/01	H	21.424	0.007	5.043	2.925	569.3	0.077
20%FT/80%Soygold	5765	1/8/01	H	21.439	0.006	5.033	2.943	572.6	0.074
Hot Average				**21.427**	**0.006**	**5.048**	**2.986**	**571.5**	**0.078**
Coefficient of Variation				**0.05%**	**10.17%**	**0.37%**	**3.02%**	**0.0**	**5.40%**
Cert Lot # 0KP05202	5766	1/9/01	H	21.758	0.014	4.695	5.135	575.4	0.234
Cert Lot # 0KP05202	5767	1/9/01	H	21.797	0.020	4.715	5.211	575.1	0.248
Hot Average		1/9/01		**21.778**	**0.017**	**4.705**	**5.173**	**575.3**	**0.241**
Coefficient of Variation				**0.13%**	**21.35%**	**0.30%**	**1.03%**	**0.0**	**4.01%**

FUEL	Run #	Date		bhp-h	THC g/bhp-h	NOx g/bhp-h	CO g/bhp-h	CO2 g/bhp-h	PM g/bhp-h
1% SoyGold in FT	5768	1/9/01	H	21.475	0.004	4.045	3.951	553.7	0.183
1% SoyGold in FT	5769	1/9/01	H	21.464	0.000	4.024	3.990	549.8	0.178
1% SoyGold in FT	5770	1/9/01	H	21.500	0.007	4.037	3.803	547.9	0.170
Hot Average				**21.480**	**0.004**	**4.035**	**3.915**	**550.5**	**0.177**
Coefficient of Variation				**0.09%**	**96.75%**	**0.27%**	**2.52%**	**0.0**	**3.64%**
Cert Lot # 0KP05202	5772	1/9/01	H	21.756	0.014	4.627	5.141	573.0	0.323
Cert Lot # 0KP05202	5773	1/9/01	H	21.695	0.017	4.643	4.939	573.5	0.251
Hot Average				**21.725**	**0.015**	**4.635**	**5.040**	**573.3**	**0.287**
Coefficient of Variation				**0.20%**	**13.99%**	**0.24%**	**2.84%**	**0.0**	**17.78%**
SoyGold	5774	1/10/01	C	21.374	0.024	5.946	4.245	605.7	0.097
SoyGold	5775	1/10/01	H	21.448	0.011	5.367	3.047	577.1	0.073
SoyGold	5776	1/10/01	H	21.391	0.012	5.353	2.899	576.2	0.067
SoyGold	5777	1/10/01	H	21.409	0.013	5.378	2.973	575.0	0.065
Composite					**0.014**	**5.449**	**3.155**	**580.3**	**0.072**
Hot Average				**21.416**	**0.012**	**5.366**	**2.973**	**576.1**	**0.068**
Coefficient of Variation				**0.14%**	**10.82%**	**0.23%**	**2.48%**	**0.0**	**5.46%**
Cert Lot # 0KP05202	5778	1/10/01	H	21.718	0.026	4.804	5.248	573.6	0.229
Cert Lot # 0KP05202	5779	1/10/01	H	21.674	0.018	4.785	4.809	576.3	0.213
Hot Average				**21.696**	**0.022**	**4.794**	**5.029**	**574.9**	**0.221**
Coefficient of Variation				**0.14%**	**27.11%**	**0.28%**	**6.17%**	**0.0**	**5.19%**
Bio3000	5780	1/11/01	C	21.466	0.020	5.570	4.390	602.7	0.112
Bio3000	5781	1/11/01	H	21.426	0.000	4.938	3.047	575.5	0.082
Bio3000	5785	1/11/01	H	21.395	0.004	5.007	3.289	579.6	0.080
Bio3000	5786	1/11/01	H	21.393	0.006	4.971	2.980	573.3	0.068
Bio3000	5787	1/11/01	H	21.394	0.007	5.008	3.106	576.7	0.078
Composite					**0.006**	**5.065**	**3.289**	**580.1**	**0.082**
Hot Average				**21.402**	**0.004**	**4.981**	**3.105**	**576.3**	**0.077**
Coefficient of Variation				**0.07%**	**70.98%**	**0.67%**	**4.28%**	**0.0**	**8.25%**
Cert Lot # 0KP05202	5788	1/12/01	H	21.710	0.019	4.742	5.022	576.6	0.225
Cert Lot # 0KP05202	5789	1/12/01	H	21.747	0.028	4.760	5.113	575.9	0.238
Cert Lot # 0KP05202	5790	1/12/01	H	21.723	0.025	4.760	4.982	574.4	0.244
Hot Average		1/12/01		**21.727**	**0.024**	**4.754**	**5.039**	**575.6**	**0.236**
Coefficient of Variation				**0.09%**	**19.75%**	**0.22%**	**1.32%**	**0.0**	**4.18%**
10% Aro Lot#0LP10A01	5793	1/12/01	H	21.630	0.035	4.474	5.155	570.5	0.238
10% Aro Lot#0LP10A01	5794	1/12/01	H	21.624	0.021	4.473	4.859	568.5	0.225
10% Aro Lot#0LP10A01	5795	1/12/01	H	21.605	0.029	4.486	4.924	569.9	0.229
Hot Average				**21.620**	**0.029**	**4.478**	**4.980**	**569.6**	**0.231**
Coefficient of Variation				**0.06%**	**24.05%**	**0.17%**	**3.13%**	**0.0**	**2.84%**

FUEL	Run #	Date		bhp-h	THC g/bhp-h	NOx g/bhp-h	CO g/bhp-h	CO2 g/bhp-h	PM g/bhp-h
Cert Lot # 0KP05202	5797	1/15/01	H	21.799	0.013	4.728	5.136	574.4	0.238
Cert Lot # 0KP05202	5798	1/15/01	H	21.814	0.020	4.740	4.962	573.7	0.234
Hot Average		1/15/01		**21.806**	**0.016**	**4.734**	**5.049**	**574.1**	**0.236**
Coefficient of Variation				**0.05%**	**29.96%**	**0.18%**	**2.43%**	**0.0**	**1.32%**
20% SoyGold in CERT Lot# 0KP05202	5799	1/15/01	H	21.744	0.019	4.899	4.759	577.6	0.196
20% SoyGold in CERT Lot# 0KP05202	5800	1/15/01	H	21.730	0.017	4.900	4.497	576.6	0.185
20% SoyGold in CERT Lot# 0KP05202	5802	1/15/01	H	21.754	0.019	4.928	4.766	579.3	0.208
Hot Average				**21.743**	**0.018**	**4.909**	**4.674**	**577.9**	**0.196**
Coefficient of Variation				**0.05%**	**6.95%**	**0.33%**	**3.28%**	**0.0**	**5.74%**
20% SoyGold in CERT Lot# 0KP05202	5807	1/17/01	H	21.730	0.002	4.919	4.862	576.1	0.201
20% SoyGold in CERT Lot# 0KP05202	5808	1/17/01	H	21.710	0.005	4.915	4.593	575.7	0.188
20% SoyGold in CERT Lot# 0KP05202	5809	1/17/01	H	21.734	0.012	4.915	4.583	574.8	0.188
Hot Average				**21.725**	**0.007**	**4.916**	**4.679**	**575.5**	**0.192**
Coefficient of Variation				**0.06%**	**76.55%**	**0.05%**	**3.38%**	**0.0**	**4.00%**
20% SoyGold in CERT Lot# 0KP05202 + 0.5%DTBP	5810	1/18/01	H	21.737	0.008	4.781	4.548	576.3	0.198
20% SoyGold in CERT Lot# 0KP05202 + 0.5%DTBP	5811	1/18/01	H	21.747	0.005	4.790	4.279	573.9	0.193
20% SoyGold in CERT Lot# 0KP05202 + 0.5%DTBP	5814	1/18/01	H	21.740	0.001	4.805	4.416	574.4	0.199
Hot Average				**21.741**	**0.005**	**4.792**	**4.414**	**574.9**	**0.197**
Coefficient of Variation				**0.02%**	**74.64%**	**0.25%**	**3.05%**	**0.0**	**1.68%**
Cert Lot # 0KP05202	5815	1/19/01	H	21.820	0.012	4.802	5.036	578.3	0.254
Cert Lot # 0KP05202	5816	1/19/01	H	21.828	0.008	4.748	5.067	576.3	0.251
Cert Lot # 0KP05202	5817	1/19/01	H	21.808	0.016	4.772	4.914	575.1	0.247
Hot Average		1/19/01		**21.819**	**0.012**	**4.774**	**5.005**	**576.5**	**0.250**
Coefficient of Variation				**0.05%**	**32.09%**	**0.57%**	**1.62%**	**0.0**	**1.34%**
20% SoyGold in CERT Lot# 0KP05202 + 1.0%DTBP	5818	1/19/01	H	21.746	0.019	4.758	4.429	576.5	0.205
20% SoyGold in CERT Lot# 0KP05202 + 1.0%DTBP	5820	1/19/01	H	21.778	0.015	4.746	4.485	573.7	0.210
20% SoyGold in CERT Lot# 0KP05202 + 1.0%DTBP	5821	1/19/01	H	21.763	0.016	4.760	4.396	575.3	0.215
Hot Average				**21.763**	**0.016**	**4.754**	**4.436**	**575.1**	**0.210**
Coefficient of Variation				**0.07%**	**11.32%**	**0.15%**	**1.01%**	**0.0**	**2.32%**
20% SoyGold in CERT Lot# 0KP05202 + 1.5%DTBP	5718	11/16/00	H	21.681	0.016	4.615	4.303	573.0	0.190
20% SoyGold in CERT Lot# 0KP05202 + 1.5%DTBP	5719	11/16/00	H	21.677	0.003	4.607	4.155	571.3	0.200
20% SoyGold in CERT Lot# 0KP05202 + 1.5%DTBP	5720	11/16/00	H	21.676	0.007	4.612	4.194	569.7	0.197
Hot Average				**21.678**	**0.008**	**4.612**	**4.218**	**571.3**	**0.196**
Coefficient of Variation				**0.01%**	**83.58%**	**0.09%**	**1.82%**	**0.0**	**2.78%**

FUEL	Run #	Date		bhp-h	THC g/bhp-h	NOx g/bhp-h	CO g/bhp-h	CO2 g/bhp-h	PM g/bhp-h
20% Bio-3000 in CERT Lot# 0KP05202	5822	1/22/01	H	21.772	0.007	4.770	4.783	577.1	0.213
20% Bio-3000 in CERT Lot# 0KP05202	5823	1/22/01	H	21.802	0.012	4.784	4.606	579.0	0.209
20% Bio-3000 in CERT Lot# 0KP05202	5824	1/22/01	H	21.762	0.009	4.786	4.584	574.8	0.202
Hot Average				**21.778**	**0.009**	**4.780**	**4.658**	**577.0**	**0.208**
Coefficient of Variation				**0.10%**	**22.83%**	**0.19%**	**2.34%**	**0.0**	**2.67%**

FUEL	Run #	Date		bhp-h	THC g/bhp-h	NOx g/bhp-h	CO g/bhp-h	CO2 g/bhp-h	PM g/bhp-h
Cert Lot # 0KP05202	5825	1/22/01	H	21.790	0.017	4.759	5.137	577.0	0.250
Cert Lot # 0KP05202	5826	1/22/01	H	21.815	0.018	4.785	4.908	575.8	0.244
Cert Lot # 0KP05202	5827	1/22/01	H	21.812	0.020	4.805	4.863	575.8	0.244
Hot Average		1/22/01		**21.806**	**0.018**	**4.783**	**4.969**	**576.2**	**0.246**
Coefficient of Variation				**0.06%**	**7.15%**	**0.48%**	**2.96%**	**0.0**	**1.37%**
20% Bio-3000 in CERT Lot# 0KP05202 + 1.0%DTBP	5828	1/23/01	H	21.775	0.012	4.630	4.701	576.6	0.211
20% Bio-3000 in CERT Lot# 0KP05202 + 1.0%DTBP	5829	1/23/01	H	21.796	0.001	4.637	4.470	573.2	0.211
20% Bio-3000 in CERT Lot# 0KP05202 + 1.0%DTBP	5830	1/23/01	H	21.774	0.013	4.643	4.324	572.6	0.201
Hot Average				**21.782**	**0.009**	**4.637**	**4.498**	**574.1**	**0.208**
Coefficient of Variation				**0.06%**	**75.98%**	**0.14%**	**4.23%**	**0.0**	**2.75%**
20% SoyGold in 10%AROMATIC lot # 0LP10A01	5831	1/23/01	H	21.719	0.019	4.610	4.491	568.3	0.195
20% SoyGold in 10%AROMATIC lot # 0LP10A01	5832	1/23/01	H	21.680	0.025	4.602	4.366	566.9	0.191
20% SoyGold in 10%AROMATIC lot # 0LP10A01	5833	1/23/01	H	21.695	0.023	4.607	4.143	566.1	0.180
Hot Average				**21.698**	**0.022**	**4.606**	**4.333**	**567.1**	**0.189**
Coefficient of Variation				**0.09%**	**13.68%**	**0.09%**	**4.07%**	**0.19%**	**4.08%**
Cert Lot # 0KP05202	5834	1/24/01	H	21.806	0.016	4.788	5.171	575.3	0.265
Cert Lot # 0KP05202	5835	1/24/01	H	21.834	0.022	4.809	4.804	573.9	0.248
Cert Lot # 0KP05202	5836	1/24/01	H	21.811	0.016	4.825	4.809	573.6	0.239
Hot Average		1/24/01		**21.817**	**0.018**	**4.807**	**4.928**	**574.2**	**0.251**
Coefficient of Variation				**0.07%**	**18.72%**	**0.38%**	**4.26%**	**0.0**	**5.37%**
20% Bio-3000 in 10%AROMATIC lot# 0LP10A01	5837	1/24/01	H	21.723	0.014	4.601	4.508	569.5	0.196
20% Bio-3000 in 10%AROMATIC lot# 0LP10A01	5838	1/24/01	H	21.732	0.019	4.579	4.399	568.2	0.188
20% Bio-3000 in 10%AROMATIC lot# 0LP10A01	5839	1/24/01	H	21.726	0.019	4.578	4.374	567.2	0.187
Hot Average				**21.727**	**0.017**	**4.586**	**4.427**	**568.3**	**0.191**
Coefficient of Variation				**0.02%**	**17.21%**	**0.29%**	**1.61%**	**0.0**	**2.51%**
20% Bio-3000 In 10%Aromatic Lot# 0LP10A01+1.0% DTBP	5840	1/25/01	H	21.652	0.015	4.427	4.659	568.1	0.203
20% Bio-3000 In 10%Aromatic Lot# 0LP10A01+1.0% DTBP	5841	1/25/01	H	21.651	0.019	4.406	4.590	567.4	0.204
20% Bio-3000 In 10%Aromatic Lot# 0LP10A01+1.0% DTBP	5842	1/25/01	H	21.636	0.014	4.410	4.521	565.0	0.204
Hot Average				**21.646**	**0.016**	**4.414**	**4.590**	**566.8**	**0.203**
Coefficient of Variation				**0.04%**	**17.22%**	**0.24%**	**1.50%**	**0.0**	**0.37%**
20% SoyGold in 10%Aromatic lot # 0LP10A01+1.0 %DTBP	5843	1/25/01	H	21.592	0.016	4.480	4.528	570.2	0.198
20% SoyGold in 10%Aromatic lot # 0LP10A01+1.0 %DTBP	5844	1/25/01	H	21.653	0.012	4.465	4.465	569.1	0.205
20% SoyGold in 10%Aromatic lot # 0LP10A01+1.0 %DTBP	5845	1/25/01	H	21.621	0.019	4.463	4.341	570.5	0.201
				21.622	**0.016**	**4.469**	**4.445**	**569.9**	**0.201**
				0.14%	**24.00%**	**0.20%**	**2.13%**	**0.0**	**1.68%**
Cert Lot # 0KP05202	5846	1/31/01	C	21.734	0.003	4.744	5.017	560.8	0.275
Cert Lot # 0KP05202	5847	1/31/01	H	21.766	0.010	4.707	4.766	560.5	0.254
Cert Lot # 0KP05202	5848	1/31/01	H	21.807	0.012	4.704	4.793	561.1	0.248
Cert Lot # 0KP05202	5849	1/31/01	H	21.808	0.013	4.758	4.811	562.4	0.224
Hot Average		1/31/01		**21.793**	**0.011**	**4.723**	**4.790**	**561.3**	**0.242**
Coefficient of Variation				**0.11%**	**12.47%**	**0.64%**	**0.48%**	**0.0**	**6.58%**

FUEL	Run #	Date		bhp-h	THC g/bhp-h	NOx g/bhp-h	CO g/bhp-h	CO2 g/bhp-h	PM g/bhp-h
Cert Lot # 0KP05202	5879	2/15/01	C	21.810	0.018	5.015	5.850	578.3	0.305
Cert Lot # 0KP05202	5880	2/15/01	H	21.842	0.016	4.797	5.382	572.8	0.287
Cert Lot # 0KP05202	5881	2/15/01	H	21.827	0.020	4.832	5.584	574.9	0.305
Hot Average				**21.826**	**0.018**	**4.881**	**5.605**	**575.323**	**0.299**
Coefficient of Variation				**0.07%**	**10.71%**	**2.39%**	**4.19%**	**0.48%**	**3.47%**
Cert Lot # 0KP05202	5883	2/16/01	H	21.842	0.021	4.871	5.039	570.7	0.264
Cert Lot # 0KP05202	5884	2/16/01	H	21.871	0.018	4.902	5.144	571.1	0.266
Cert Lot # 0KP05202	5887	2/16/01	H	21.898	0.017	4.872	4.984	570.6	0.255
Hot Average				**21.870**	**0.018**	**4.882**	**5.056**	**570.802**	**0.262**
Coefficient of Variation				**0.13%**	**10.82%**	**0.36%**	**1.61%**	**0.04%**	**2.33%**
Cert Lot # 0KP05202	5923	3/7/01	H	21.933	0.039	4.869	5.283	557.7	0.252
Cert Lot # 0KP05202	5924	3/7/01	H	21.928	0.048	4.818	4.906	555.1	0.242
Cert Lot # 0KP05202	5925	3/7/01	H	21.927	0.036	4.802	5.129	558.3	0.252
Hot Average				**21.929**	**0.041**	**4.830**	**5.106**	**557.051**	**0.249**
Coefficient of Variation				**0.02%**	**15.02%**	**0.73%**	**3.71%**	**0.31%**	**2.26%**
20% SoyGold in CERT lot:OKPO5202	5926	3/7/01	H	21.815	0.029	4.947	4.687	558.4	0.194
20% SoyGold in CERT lot:OKPO5202	5927	3/7/01	H	21.839	0.040	4.949	4.589	558.9	0.189
20% SoyGold in CERT lot:OKPO5202	5928	3/7/01	H	21.865	0.042	4.928	4.571	559.1	0.191
Hot Average				**21.840**	**0.037**	**4.941**	**4.616**	**558.787**	**0.191**
Coefficient of Variation				**0.11%**	**18.23%**	**0.23%**	**1.36%**	**0.06%**	**1.11%**
Cert Lot # 0KP05202	5930	3/12/01	H	21.885	0.054	4.831	5.107	553.9	0.267
Cert Lot # 0KP05202	5931	3/12/01	H	21.911	0.051	4.844	5.047	554.8	0.256
Cert Lot # 0KP05202	5932	3/12/01	H	21.902	0.053	4.846	5.186	555.6	0.267
Hot Average				**21.900**	**0.053**	**4.841**	**5.113**	**554.770**	**0.264**
Coefficient of Variation				**0.06%**	**2.76%**	**0.17%**	**1.37%**	**0.16%**	**2.42%**
20:1 SoyGold + DTBP	5933	3/12/01	H	21.642	0.027	5.208	2.545	557.1	0.066
20:1 SoyGold + DTBP	5934	3/12/01	H	21.615	0.024	5.148	2.477	556.8	0.066
20:1 SoyGold + DTBP	5935	3/12/01	H	21.630	0.028	5.194	2.387	556.4	0.060
Hot Average				**21.629**	**0.027**	**5.184**	**2.470**	**556.796**	**0.064**
Coefficient of Variation				**0.06%**	**7.73%**	**0.61%**	**3.21%**	**0.06%**	**6.08%**
20% SoyGold + 0.5% EHN in Cert lot # OKPO5202	5936	3/13/01	H	21.841	0.017	4.855	4.672	558.6	0.218
20% SoyGold + 0.5% EHN in Cert lot # OKPO5202	5937	3/13/01	H	21.831	0.028	4.827	4.549	557.4	0.209
20% SoyGold + 0.5% EHN in Cert lot # OKPO5202	5938	3/13/01	H	21.810	0.028	4.820	4.367	558.1	0.209
Hot Average				**21.827**	**0.024**	**4.834**	**4.529**	**558.028**	**0.212**
Coefficient of Variation				**0.07%**	**26.99%**	**0.39%**	**3.39%**	**0.11%**	**2.39%**
20% SoyGold + 1.0% EHN in Cert lot # OKPO5202	5939	3/13/01	H	21.792	0.033	4.834	4.438	559.7	0.202
20% SoyGold + 1.0% EHN in Cert lot # OKPO5202	5940	3/13/01	H	21.868	0.029	4.794	4.498	559.0	0.210
20% SoyGold + 1.0% EHN in Cert lot # OKPO5202	5941	3/13/01	H	21.843	0.038	4.783	4.358	558.5	0.206
Hot Average				**21.834**	**0.033**	**4.804**	**4.431**	**559.085**	**0.206**
Coefficient of Variation				**0.18%**	**13.16%**	**0.56%**	**1.58%**	**0.11%**	**1.90%**

FUEL	Run #	Date		bhp-h	THC g/bhp-h	NOx g/bhp-h	CO g/bhp-h	CO2 g/bhp-h	PM g/bhp-h
20:1 Bio-3000 + DTBP	5942	3/14/01	H	21.430	0.018	4.901	3.033	556.4	0.083
20:1 Bio-3000 + DTBP	5943	3/14/01	H	21.444	0.015	4.863	2.773	556.0	0.079
20:1 Bio-3000 + DTBP	5944	3/14/01	H	21.451	0.014	4.879	2.776	556.3	0.073
Hot Average				**21.442**	**0.016**	**4.881**	**2.861**	**556.253**	**0.078**
Coefficient of Variation				**0.05%**	**12.43%**	**0.39%**	**5.22%**	**0.04%**	**6.54%**
Cert Lot # 0KP05202	5945	3/14/01	H	21.834	0.032	4.776	5.292	560.1	0.248
Cert Lot # 0KP05202	5946	3/14/01	H	21.855	0.028	4.795	5.082	561.1	0.256
Cert Lot # 0KP05202	5947	3/14/01	H	21.864	0.028	4.828	5.196	561.6	0.269
Hot Average				**21.851**	**0.029**	**4.800**	**5.190**	**560.947**	**0.258**
Coefficient of Variation				**0.07%**	**6.83%**	**0.55%**	**2.03%**	**0.13%**	**4.00%**
Cert Lot # 0KP05202	5952	3/22/01	C	21.902	0.032	4.866	5.388	556.2	0.271
Cert Lot # 0KP05202	5953	3/22/01	H	21.918	0.041	4.859	5.072	556.3	0.248
Cert Lot # 0KP05202	5954	3/22/01	H	21.884	0.036	4.855	5.104	555.4	0.245
Cert Lot # 0KP05202	5955	3/22/01	H	21.881	0.037	4.843	5.245	557.7	0.262
Hot Average				**21.894**	**0.038**	**4.852**	**5.140**	**556.460**	**0.252**
Coefficient of Variation				**0.09%**	**7.25%**	**0.17%**	**1.79%**	**0.20%**	**3.60%**
40:1 B-20Soy in 10%Aromatic / A-1	5965	3/26/01	H	21.731	0.037	4.558	5.051	555.7	0.234
40:1 B-20Soy in 10%Aromatic / A-1	5966	3/26/01	H	21.748	0.042	4.568	4.903	554.6	0.244
40:1 B-20Soy in 10%Aromatic / A-1	5967	3/26/01	H	21.750	0.042	4.564	4.893	552.9	0.234
Hot Average				**21.743**	**0.040**	**4.563**	**4.949**	**554.415**	**0.237**
Coefficient of Variation				**0.05%**	**6.54%**	**0.10%**	**1.79%**	**0.26%**	**2.30%**
Kerosene	5968	3/27/01	H	21.486	0.113	5.140	5.837	580.6	0.256
Kerosene	5969	3/27/01	H	21.420	0.082	4.521	4.069	555.3	0.204
Kerosene	5970	3/27/01	H	21.421	0.085	4.520	4.011	554.3	0.198
Kerosene	5971	3/27/01	H	21.401	0.091	4.542	3.937	555.1	0.194
Hot Average				**21.414**	**0.086**	**4.527**	**4.005**	**554.917**	**0.199**
Coefficient of Variation				**0.05%**	**5.06%**	**0.27%**	**1.66%**	**0.09%**	**2.41%**
K50 (50% Kerosene + 50% SoyGold)	5972	3/28/01	H	21.445	0.044	5.000	3.749	555.8	0.119
K50 (50% Kerosene + 50% SoyGold)	5973	3/28/01	H	21.483	0.045	4.915	3.500	557.5	0.112
K50 (50% Kerosene + 50% SoyGold)	5974	3/28/01	H	21.464	0.049	4.904	3.585	554.9	0.112
Hot Average				**21.464**	**0.046**	**4.940**	**3.611**	**556.070**	**0.115**
Coefficient of Variation				**0.09%**	**6.03%**	**1.06%**	**3.51%**	**0.24%**	**3.47%**
Cert Lot # 0KP05202	5976	3/28/01	H	21.775	0.035	4.850	5.151	560.5	0.258
Cert Lot # 0KP05202	5977	3/28/01	H	21.806	0.037	4.855	5.415	561.1	0.263
Hot Average				**21.791**	**0.036**	**4.853**	**5.283**	**560.763**	**0.260**
Coefficient of Variation				**0.10%**	**3.36%**	**0.07%**	**3.53%**	**0.07%**	**1.39%**
18% SoyGold in CERT lot: 0KP05202 + 2% USDA-1	5978	3/28/01	H	21.719	0.032	5.088	4.844	560.8	0.196
18% SoyGold in CERT lot: 0KP05202 + 2% USDA-1	5979	3/28/01	H	21.727	0.030	4.979	4.641	562.1	0.188
18% SoyGold in CERT lot: 0KP05202 + 2% USDA-1	5980	3/28/01	H	21.743	0.028	4.970	4.674	563.2	0.191
Hot Average				**21.730**	**0.030**	**5.012**	**4.719**	**562.012**	**0.192**
Coefficient of Variation				**0.06%**	**8.23%**	**1.31%**	**2.30%**	**0.22%**	**2.16%**

FUEL	Run #	Date		bhp-h	THC g/bhp-h	NOx g/bhp-h	CO g/bhp-h	CO2 g/bhp-h	PM g/bhp-h
Cert Lot # 0KP05202	5989	4/4/01	H	21.839	0.030	4.847	5.235	560.8	0.241
Cert Lot # 0KP05202	5990	4/4/01	H	21.882	0.033	4.846	5.030	558.2	0.231
Cert Lot # 0KP05202	5991	4/4/01	H	21.863	0.039	4.850	5.042	559.1	0.241
Hot Average				**21.861**	**0.034**	**4.847**	**5.102**	**559.377**	**0.238**
Coefficient of Variation				**0.10%**	**13.15%**	**0.04%**	**2.26%**	**0.24%**	**2.42%**
40:1 B-20Soy in Cert / A-1	5992	4/4/01	H	21.761	0.032	4.863	5.284	564.1	0.232
40:1 B-20Soy in Cert / A-1	5993	4/4/01	H	21.765	0.029	4.830	5.364	564.5	0.236
40:1 B-20Soy in Cert / A-1	5994	4/4/01	H	21.799	0.037	4.852	5.325	562.6	0.232
Hot Average				**21.775**	**0.033**	**4.848**	**5.324**	**563.746**	**0.233**
Coefficient of Variation				**0.10%**	**12.34%**	**0.35%**	**0.75%**	**0.18%**	**1.08%**
20% SoyGold in Cert lot OKPO5202 + 0.2%wt USDA-2	5995	4/5/01	H	21.794	0.024	4.904	5.044	558.7	0.225
20% SoyGold in Cert lot OKPO5202 + 0.2%wt USDA-2	5996	4/5/01	H	21.791	0.030	4.879	4.755	561.1	0.209
20% SoyGold in Cert lot OKPO5202 + 0.2%wt USDA-2	5997	4/5/01	H	21.782	0.029	4.887	4.836	560.4	0.213
20% SoyGold in Cert lot OKPO5202 + 0.2%wt USDA-2	5998	4/5/01	H	21.791	0.029	4.904	4.750	560.0	0.210
Hot Average				**21.790**	**0.028**	**4.894**	**4.846**	**560.051**	**0.214**
Coefficient of Variation				**0.02%**	**9.74%**	**0.26%**	**2.84%**	**0.18%**	**3.49%**
Cert Lot # 0KP05202	6000	4/6/01	H	21.825	0.029	4.880	5.473	558.7	0.233
Cert Lot # 0KP05202	6001	4/6/01	H	21.840	0.033	4.822	5.135	558.0	0.223
Cert Lot # 0KP05202	6002	4/6/01	H	21.827	0.027	4.855	5.550	560.5	0.240
Hot Average				**21.831**	**0.030**	**4.852**	**5.386**	**559.078**	**0.232**
Coefficient of Variation				**0.04%**	**11.31%**	**0.59%**	**4.09%**	**0.23%**	**3.68%**
K50 (50% Kerosene + 50% SoyGold) + 2.3% vol. DTBP	6003	4/6/01	H	21.425	0.029	4.739	3.396	556.5	0.092
K50 (50% Kerosene + 50% SoyGold) + 2.3% vol. DTBP	6004	4/6/01	H	21.432	0.030	4.688	3.185	555.5	0.083
K50 (50% Kerosene + 50% SoyGold) + 2.3% vol. DTBP	6005	4/6/01	H	21.442	0.029	4.678	3.175	555.9	0.078
Hot Average				**21.433**	**0.029**	**4.701**	**3.252**	**556.004**	**0.084**
Coefficient of Variation				**0.04%**	**2.41%**	**0.69%**	**3.84%**	**0.09%**	**8.56%**
Cert Lot # 0KP05202	6010	4/10/01	H	21.866	0.024	4.820	5.289	557.6	0.253
Cert Lot # 0KP05202	6011	4/10/01	H	21.849	0.023	4.816	5.044	558.3	0.250
Cert Lot # 0KP05202	6012	4/10/01	H	21.840	0.029	4.803	5.099	558.9	0.254
Hot Average				**21.852**	**0.025**	**4.813**	**5.144**	**558.237**	**0.252**
Coefficient of Variation				**0.06%**	**12.10%**	**0.18%**	**2.51%**	**0.12%**	**0.68%**
20% SoyGold in Cert lot OKPO5202	6013	4/10/01	H	21.810	0.018	4.947	4.660	558.2	0.197
20% SoyGold in Cert lot OKPO5202	6014	4/10/01	H	21.786	0.026	4.895	4.843	559.3	0.206
20% SoyGold in Cert lot OKPO5202	6015	4/10/01	H	21.812	0.025	4.896	4.850	559.4	0.201
Hot Average				**21.803**	**0.023**	**4.913**	**4.784**	**558.961**	**0.201**
Coefficient of Variation				**0.06%**	**17.82%**	**0.61%**	**2.25%**	**0.12%**	**2.05%**
20% SoyGold in Cert lot OKPO5202+0.5%EHN	6025	4/19/01	H	21.832	0.019	4.805	4.781	558.9	0.244
20% SoyGold in Cert lot OKPO5202+0.5%EHN	6026	4/19/01	H	21.816	0.017	4.735	4.615	558.0	0.213
20% SoyGold in Cert lot OKPO5202+0.5%EHN	6027	4/19/01	H	21.811	0.020	4.759	4.591	556.6	0.204
Hot Average				**21.819**	**0.018**	**4.766**	**4.662**	**557.824**	**0.220**
Coefficient of Variation				**0.05%**	**9.62%**	**0.74%**	**2.22%**	**0.21%**	**9.59%**

FUEL	Run #	Date		bhp-h	THC g/bhp-h	NOx g/bhp-h	CO g/bhp-h	CO2 g/bhp-h	PM g/bhp-h
20% SoyGold in Cert lot OKPO5202	6028	4/19/01	H	21.833	0.018	4.887	4.824	557.7	0.195
20% SoyGold in Cert lot OKPO5202	6029	4/19/01	H	21.772	0.015	4.875	4.758	559.6	0.194
20% SoyGold in Cert lot OKPO5202	6030	4/19/01	H	21.782	0.019	4.870	4.560	559.1	0.191
Hot Average				**21.796**	**0.018**	**4.877**	**4.714**	**558.795**	**0.193**
Coefficient of Variation				**0.15%**	**11.28%**	**0.18%**	**2.91%**	**0.18%**	**1.18%**

APPENDIX D: REFERENCES

1. Graboski, M.S., R.L. McCormick "Combustion of Fat and Vegetable Oil Derived Fuels in Diesel Engines" *Progress in Energy and Combustion Science*, 24 125 (1998).
2. Graboski, M.S., McCormick, R.L., Alleman, T.L., Herring, A.M. "Effect of Biodiesel Composition on NO_x and PM Emissions from a DDC Series 60 Engine" Final Report to National Renewable Energy Laboratory, Contract No. ACG-8-17106-02. June 7, 2000.
3. McCormick, R.L., Graboski, M.S., Alleman, T.L., Herring, A.M. "Impact of Biodiesel Source Material and Chemical Structure on Emissions of Criteria Pollutants from a Heavy-Duty Engine" *Environ. Sci. Technol.* 35 1742-1747 (2001).
4. Norton, P., Vertin, K., Bailey, B., Clark, N. N., Lyons, D.W., Goguen, S., Eberhart, J. "Emissions from Trucks using Fischer-Tropsch Diesel Fuel" *SAE Technical Paper No.* 982526 (1998).
5. Sharp, C.A. "Transient Emissions Testing of Biodiesel in a DDC 6V-92TA Engine" Final Report to NBB, SWRI, Oct. 1994.
6. Sharp, C.A. "Transient Emissions Testing of Biodiesel and Other Additives in a DDC Series 60 Engine" Final Report to NBB, SWRI, Dec. 1994.
7. NORAC Company, accessed by telephone 626-334-2908, April 24, 2001.
8. Tyson, K. S. private communication, April 24, 2001.
9. Energy Information Agency, U.S.D.O.E. at www.eia.doe.gov accessed April 24, 2001.
10. *Appendix IV-Fuels Report;* California Air Resources Board: Sacramento, CA, 2000. http://www.arb.ca.gov/diesel/documents/rrpapp4.pdf.
11. Schwab, S.D., Guinther, G.H., Henly, T.J., Miller, K.T. "The Effects of 2-Ethylhexyl Nitrate and Di-tertiary-butyl Peroxide on the Exhaust Emissions from a Heavy-Duty Diesel Engine" *SAE Technical Paper No.* 1999-01-1478 (1999).

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE February 2003	3. REPORT TYPE AND DATES COVERED Subcontract Report

4. TITLE AND SUBTITLE NO_x Solutions for Biodiesel: Final Report; Report 6 in a Series of 6	5. FUNDING NUMBERS XCO-0-30088-01 BBA3.5210
6. AUTHOR(S) R.L. McCormick, J.R. Alvarez, and M.S. Graboski	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Colorado Institute for Fuels and Engine Research Colorado School of Mines Golden, Colorado	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	10. SPONSORING/MONITORING AGENCY REPORT NUMBER NREL/SR-510-31465

11. SUPPLEMENTARY NOTES

NREL Technical Monitor: K.S. Tyson

12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A number of studies have shown substantial particulate matter (PM) reductions for biodiesel, but also a significant increase in nitrogen oxides (NO_x) emissions. This study examines a number of approaches for NO_x reduction from biodiesel.

14. SUBJECT TERMS Biodiesel; heavy duty engine emissions; nitrogen oxides (NO_x); particulate matter (PM)	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL