January 10, 2020

Mr. Lex Mitchell
California Air Resources Board
1001 I ST
Sacramento, CA 95814

<u>Subject: Comment Submittal</u>
<u>1/7/20 ISOR – Addressing Appendix B</u>

Dear Lex:

CARB's documented "reproducibility" concerns seem to be the underlying motivation to modify the Alternate Diesel Fuel (ADF) Regulation's testing requirements as evidenced in CARB's December 13, 2019 presentation[1], slide 8, which says that CARB "seek to reinforce the certification test procedures" so that the "overall pass/fail results are more reproducible". CARB seems to be basing their "reproducibility" concerns on their recent CE-CERT ADF NOx mitigant verification testing program, the associated results and are now focused on implementing a more robust process capable of reproducing engine emission test results across different fuels and different test facilities.

Provided below are four (4) examples, all based on actual emissions testing data, identical or similar to the ADF's requirements, that address reproducibility and repeatability. Based on such, there are additional factors which CARB should consider prior to modifying the current ADF's testing requirements. For example, CE-CERT's engine emissions results' <u>repeatability</u> is two (2) times higher than other engine to engine <u>reproducibility</u> which we can only technically reconcile by questioning CE-CERT's engine process control procedures. Following are the facts behind this conclusion.

1. The attached paper entitled "Evaluation of the NOx emissions from heavy-duty diesel engines with the addition of cetane improvers" documents the evaluation of emissions produced from several base fuels and a B20, using the ADF's Alternative 3 method while evaluating the cetane improvers 2-ethylhexyl nitrate (2EHN) and di-tertiary butyl peroxide (DTBP) in **<u>three (3)</u>** separate Detroit Diesel Series 60 (S60) at West Virginia University (WVU), a CARB approved emissions engine testing facility. Following are our takeaways specific to CARB's stance on NOx emissions testing "reproducibility".

- <u>In the same fuels at the same facility in different engines</u>, cetane improver NOx emission's reductions, versus a reference fuel, ranged from 0.9 percent to 3.5 percent.

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[1] https://ww2.arb.ca.gov/sites/default/files/2019-12/ADF_Workshop_Presentation_12-13-19.pdf

  - 2100 ppm of 2EHN reduced NOx <u>0.9% in one S60</u> and <u>3.2% in a second S60</u> (range of **2.3%**).

  - 2600 ppm of DTBP reduced NOx 1.0% in one S60, 3.2% in a second S60 and 3.5% in a third S60 (range of 2.5%).

  - Such data speaks to the engine-to-engine variability of, for all intents and purposes, "identical circumstances". CARB should consider this information in the context of their voiced concerns regarding "reproducibility". In our view, 2-2.5% reproducibility is within the expected range.

- If CARB would have taken engine to engine variability into consideration when commenting publicly about VESTA®'s performance, CARB would have fully confirmed VESTA®'s NOX mitigation capabilities.

- On top of engine to engine, facility to facility variability, we advised CARB prior to the CE-CERT testing that the fuels CARB selected[1] (see slide 11) appear to have been selected either in an effort to maximize the chances of NOx mitigant failure. We have separately presented CARB with our views on this matter.

Conclusion: the WVU data indicates when testing cetane improvers, S60 engine to engine NOx emissions <u>reproducibility (different engines, same facility) ranges from 2.3-2.5%</u>.

Further supporting the above, an additional study, a copy of which is attached, entitled "Biodiesel Emissions Data from Series 60 DDC Engines", Leon G. Schumacher, 1995 American Public Transit Association Bus Operations and Technology Conference Reno, Nevada May 10, 1995", documents a reproducibility of **<u>2.2%</u>** (two fuels, no cetane improvers, different facilities, same engine type).

2. A comparative analysis of <u>all</u> VESTA® SwRI NOx emissions certification test data (Alternative 3) was conducted. Reference and candidate fuels' NOx emissions results were independently compared, the results for which are provided below. For each independent fuel evaluation, the first hot start NOx emission result was used as the basis to determine the percent change (see footnotes 1 and 2).

Fuel		C-C-C[1] % change	R-R-R[2] % change
VESTA® 1000 ppm	Min	-0.76	-0.57
	Max	0.46	0.20
	Range	1.22	0.77
VESTA® 1500 ppm	Min	-0.45	-0.37
	Max	0.22	0.22
	Range	0.68	0.69
VESTA® 3000 ppm	Min	-0.64	-0.47
	Max	0.00	0.02
	Range	0.64	0.50

[1] $[(C_n - C_{[illegible]})/C_n]$ X 100%, where n=4,7,16,19,28,31,40

[2] $[(R_n - R_{[illegible]})/R_n]$ X 100%, where n=1,10,13,22,25,34,37

Conclusion: SwRI Reference Fuel repeatability (same fuel, same engine) ranged from 0.50-0.77%; and for the Candidate Fuel ranged from 0.64-1.22%.

3. A similar comparative analysis of CARB's recent CE-CERT NOx emissions test data (Alternative 1) was conducted. Following is a summary of the CE-CERT results for all VESTA® concentrations tested. As with the SwRI analysis, the first hot start was used as the basis for comparison (see footnotes 3 and 4).

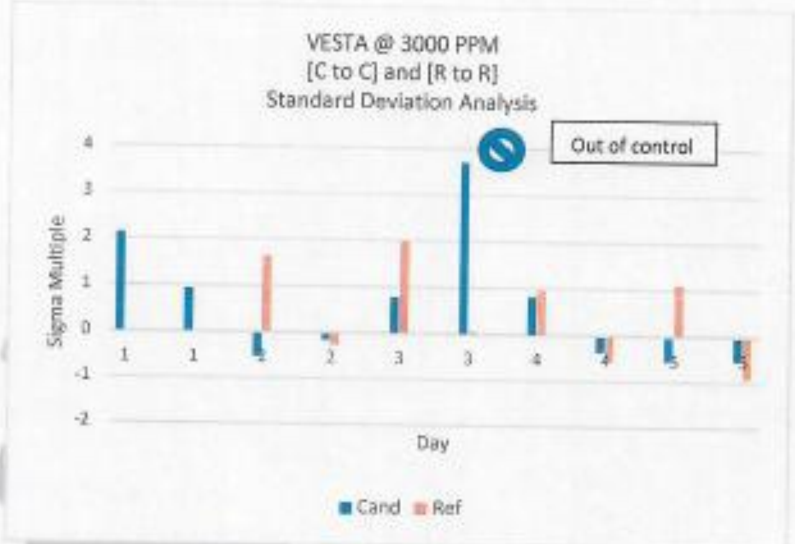
Fuel		C-C[3] % change	R-R[4] % change
VESTA® 1000 ppm	Min	-1.30	-1.13
	Max	0.64	1.83
	Range	1.94	2.96
VESTA® @ 2200 ppm[5]	Min	-0.61	-0.72
	Max	0.47	0.52
	Range	1.09	1.25
VESTA® 3000 ppm	Min	-0.38	-0.76
	Max	2.63	1.70
	Range	3.00	2.46

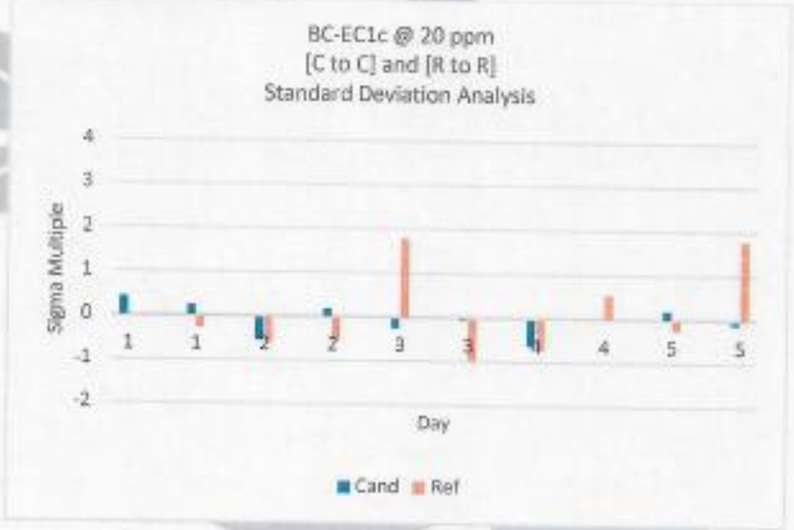
[3] $[(C_n - C_{n+1})/C_n]$ X 100%, where n=2,6,10,14,18,22,26,30,34,38

[4] $[(R_n - R_{n+1})/R_n]$ X 100%, where n=4,8,12,16,20,24,28,32,36

[5] Limited Data

- A further standard deviation based statistical analysis (see below) was conducted on the CE-CERT certification run emission data for VESTA® and BC-EC1c which shows a stark analysis – one process (BC-EC1c) is in control (within ± 3-sigma), the other (VESTA®) isn't (>± 3-sigma).





- Why did the CE-CERT process go out of control is a question that hasn't been answered, but needs to be understood because the basis for CARB's wholesale ADF testing requirement changes are based on faulty data. The recent CE-CERT data is flawed and yet CARB is seeking to rely on such as justification to overhaul the ADF's already robust testing requirements.

- The repeatability issues identified raise significant concerns as to whether the CE-CERT data should be relied upon in CARB's rulemaking process. If CARB excluded the CE-CERT data from its analysis, would they be proposing the same changes and if so why and based on what?

- When evaluating the CE-CERT emissions test results, CARB should have, given the ramifications of its findings as first communicated in their Product Alert[2] and then again at its December 13, 2019 workshop, considered the above noted information when making broad conclusive public statements about VESTA®. CARB chose to place more confidence in the CE-CERT NOx emissions data than that of SwRI. We don't understand why; CARB should answer this question.

- At the same workshop, CARB stated that "Staff is concerned that the UCR [CE-CERT] additive test program results did not align with certification test program results", that "[a]ll tested additives failed statistical tests" and that "VESTA additives showed partial NOx mitigation"[1]. All these statements are misleading and inaccurate. If CARB had conducted a thorough statistical analysis of the CE-CERT emissions' results, CARB would have considered repeatability and reproducibility but did neither. The statistical analysis CARB conducted was a t-test, as required by the ADF, but isn't a rigorous enough statistically in the context of a two-facility different fuels comparison.

- At the same workshop, CARB also stated their "[t]est was conducted using Federal Test Procedure (FTP) heavy-duty transient cycle and Alternative 1 (RCCR), which requires more fuel changes but gives more statistical reproducibility". We cannot reconcile this statement with the actual CE-CERT data. It's abundantly clear that CE-CERT (a) struggled with the fuel changes which impacted the accuracy of their results and (b) produced data that has far worse repeatability than SwRI's both of which call into question CARB's view on Alternative 1. We would appreciate if CARB could clarify what they mean by "reproducibility" in the context of their differing views.

Conclusion: CE-CERT Reference Fuel repeatability (same fuel, same engine) ranged from 1.25-2.96% and for the Candidate Fuel ranged from 1.09-3%. CE-CERT's repeatability range is 2-3 times that of SwRI.

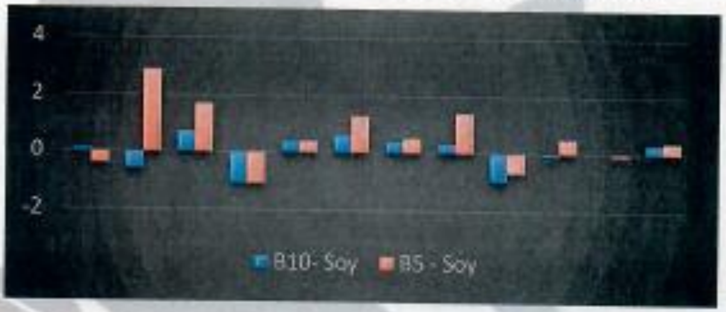
In November, we informed CARB that certain of the CE-CERT data was "out of control" and that given the contrast noted in the two previous graphs, a "special cause" might be that CE-CERT did not take proper care when switching back and forth from reference to candidate fuels. We provided CARB with a description of the careful process SwRI follows with which to compare to CE-CERT's. We then followed up in a December 5, 2019 email to you with a copy to Gabriel Monroe, wherein we requested CE- CERT's standard operating test procedures, specifically those employed for the fuel switch out flushing process. Such information will shed light on whether there is a special cause/effect impacting CE-CERT's repeatability or if CE-CERT's NOx

[2] https://ww2.arb.ca.gov/resources/documents/alternative-diesel-fuels-product-alert-fuel-additives

emissions results vary 1-3% in its S60. We again formally request such information. In either case, this is a matter that CARB should have addressed prior to issuing the Product Alert, followed by a workshop presentation wherein broad unsupported conclusions were documented and voiced.

4. In order to further investigate CE-CERT's repeatability, because of the significant comparative difference to SwRI's repeatability results, we reviewed CARB's June 2014 B5/B10 CE-CERT S60 NOX emissions data[3] to determine if CARB's most recent CE-CERT testing repeatability was an anomaly or the norm. Following is a graphical summary of the study's NOx emissions results (data taken directly from the report).

NOX PERCENTAGE DIFFERENCES VS CARB REF FUEL



Conclusions: Standard deviations ranged between 1.1 (B5) and 0.6 (B10) which are, in comparison, both very high. B5 NOx emissions varied from +2.9% to -1.1% (range: 4%) versus the Reference Fuel; B10 varied from +0.7% to -1.1% (range: 1.8%). The B5 range is especially high. This data further calls into question the quality procedures followed by CE-CERT as previously noted.

- We note in the recent ADF posting that CARB believes B20 increases NOx 4% which appears to be based on CARB's experience. The literature is clear that multiple variables are responsible for different B20 levels of NOx increase including feedstock type, biodiesel cetane number, etc. We ask that CARB (a) articulate the basis for its apparent belief that 4% NOx increase is reflective of market conditions; and (b) clarify whether this 4% is in any way an expectation CARB will apply with NOx mitigant applicants' candidate fuel(s) in the future or in finding "good cause" under its proposed changes to subsection (l) of the ADF's Appendix 1.

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[3] https://ww3.arb.ca.gov/fuels/diesel/altdiesel/20140630carbstudyb5_b10.pdf?_ga=2.98394015.1610438664.1578352889-537003192.1578352794

Summary

- There is a clear disconnect between literature reproducibility (~2%) and CE-CERT's repeatability (as high as 4%). SwRI's repeatability seems more in line with expectations (~2%). The disconnect is that CE-CERT's repeatability is two times the reproducibility documented in the literature.
- We could find no evidentiary support documenting reproducibility of ADF type emissions testing on the same fuels, tested at different facilities using S60's.
- CARB's two facility, two fuel approach, in order to neutralize "reproducibility" concerns, seems unsubstantiated, questionable at best, given the variable nature of emissions testing.
- **Prior to implementing the ADF proposed sweeping testing changes, we believe CARB should conduct an independent statistical analysis of the ADF testing data they have in hand versus the data they used in comparison to determine the best possible path forward. Given what's been presented, there are clearly gaps in knowledge and differing views.**

Aside from any statistical analysis, in attempting to make so many changes to the ADF at once, CARB runs the risk of making the new requirements so overly burdensome that stakeholders may not participate in such a complex certification process given the narrow window of opportunity to recoup any additional testing investments. As is stands presently, the testing CARB is proposing would likely impede biodiesel market development as opposed to advancing it.

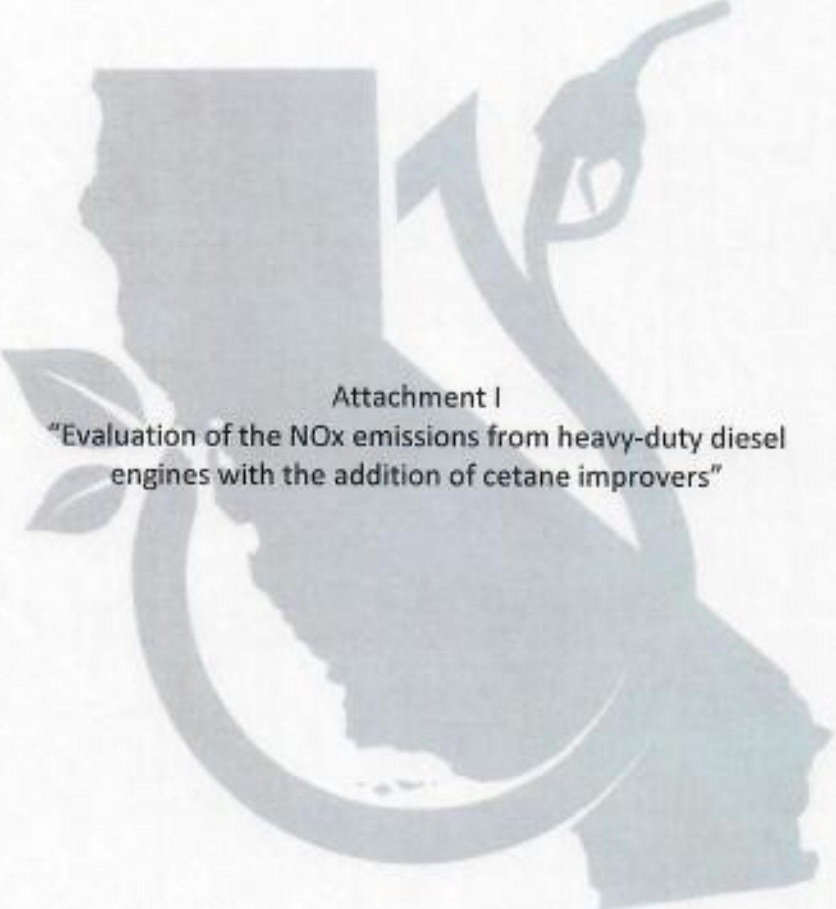
We support all CARB's proposed chain of custody and verification processes, but not the two-facility testing approach. Further, we support modifying the "in-use" requirement, which we have outlined in our December 20th workshop comments submission (attached for the record), to include NOx Mitigant confirmation testing in a "Designated Equivalent Limits Diesel". This modification may be a happy medium as opposed to CARB's proposed two facility two fuel approach.

In addition to any impending changes to the ADF, CARB is also advancing a Low Emission Diesel (LED) program and conducting a separate CE-CERT testing program to evaluate biodiesel's impacts on new technology diesel engine emissions, which might also may require NOx mitigation. As further advancements are made on these efforts and modification to the ADF's chain of custody, verification and observation, etc. are implemented, CARB can take more time to further investigate the issue of engine emissions "reproducibility" which appears to be far more complex than originally estimated.

Please let us know if you require further elaboration on any of the above noted matters. California Fueling will be submitting additional comments on other matters soon. We look forward to working together with CARB through the rules change process.

Respectfully,

Patrick J McDuff
CEO
California Fueling, LLC



Attachment I
"Evaluation of the NOx emissions from heavy-duty diesel engines with the addition of cetane improvers"

CALIFORNIA
FUELING

Evaluation of the NO_x emissions from heavy-duty diesel engines with the addition of cetane improvers

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The manuscript was received on 5 January 2009 and was accepted after revision for publication on 29 April 2009.

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Abstract: The exhaust emissions from heavy-duty diesel engines (HDDEs) contribute to the degradation of ambient air quality; therefore, environmental agencies have created stringent emissions standards. Since the implementation of these standards, overall engine and fuel technology improvements have created a significant reduction in emissions. This study was completed in order to evaluate oxides of nitrogen (NO_x) emissions from fuels with and without cetane-improving additives in recent and early production electronically controlled HDDEs. Five engines spanning the model years from 1991 to 2004 were tested using the Federal Test Procedure (FTP) dynamometer cycle with both petroleum-based diesel and B20 as the neat fuel. It was found that the additives had the most impact on reducing emissions at low engine powers, but the engine power range with an NO_x benefit varied between engines. The cetane improvers were found only to reduce NO_x below a cylinder gas density of 35 kg/m^3 at top dead centre. The lower compression ratio of the 1992 DDC S60 engines reduced the cylinder gas density and provided a larger optimal operating range for the cetane improvers. The cetane improvers reduced NO_x at low engine powers and cylinder gas density for the B20 fuel but were less effective than for the neat petroleum fuels.

Keywords: diesel fuel, additives, cetane improver, nitrogen oxides (NO_x), emissions, heavy-duty diesel engine

1 INTRODUCTION

With ever-increasing concerns about the contribution of heavy-duty diesel engine exhaust constituents, the Environmental Protection Agency (EPA) has created a strict set of emissions regulations from these engines. The regulated diesel emissions include hydrocarbons (HCs), carbon monoxide (CO), oxides of nitrogen (NO_x), particulate matter (PM), and non-methane hydrocarbons (NMHCs). EPA heavy-duty diesel engine emission standards for model years 1988 to 2010 are listed in Table 1 for engines being tested over the transient Federal Test Procedure (FTP) engine dynamometer cycle [**1**]. The years from 2007 to 2010 are a phase-in period for NO_x. In October 1998, a court settlement between the EPA, California Air Resources Board, Department of Justice, and the major diesel engine manufacturers was reached on the issue of high NO_x emissions during certain driving modes [**2**]. As a result, the 2004 emissions standards were moved to October 2002.

Through combined technology improvements in both engine design and fuel processing, a significant reduction in exhaust emissions has been possible. In order for future engines to reach the near-zero emissions mark, external engine technologies will need more development. These external technologies include after-treatment systems, turbocharger design, exhaust gas recirculation (EGR), and diesel particulate traps. Although engine technologies have a greater effect on emissions levels than fuel quality and properties do, the fuel does have an influence on the emissions level generated by the engine.

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Table 1 EPA heavy-duty diesel engine emissions standards [**1**]

Year	Emissions (g/kWh)					
	HCs	CO	NO_x	PM	$NMHCs+NO_x$	NMHCs
1988	1.74	20.79	14.35	0.80	N/A[*]	N/A[*]
1990	1.74	20.79	8.05	0.80	N/A[*]	N/A[*]
1991	1.74	20.79	6.71	0.34	N/A[*]	N/A[*]
1994	1.74	20.79	6.71	0.13	N/A[*]	N/A[*]
1998	1.74	20.79	5.36	0.13	N/A[*]	N/A[*]
2004[†] (option 1)	1.74	20.79	N/A[*]	0.13	3.22	N/A[*]
2004[†] (option 2)	1.74	20.79	N/A[*]	0.13	3.35	0.67
2007–2010	1.74	20.79	0.27	0.01	N/A[*]	0.19

[*] N/A, not applicable.

[†] 2004 was moved to October 2002.

Despite having a multitude of experimental data, the influence of the fuel properties on regulated emissions is still not clear [**3**]. The properties of diesel fuels that influence emissions are usually intercorrelated, which means care must be taken to separate the fuel property changes in the test fuel. If multiple fuel properties are changed simultaneously, then it is difficult to pinpoint an exact fuel property to an emission change. Techniques such as non-linear regression and neural network modelling can be used to help to find the effect of changing fuel properties on engine emissions.

The main objective of this study was to evaluate engine emissions with and without cetane-improving additives on recent and early electronically controlled heavy-duty diesel engines (HDDEs). These engines are of interest since their lifetime can be 10–20 years and are the high polluters that are the major contributors to the atmospheric loading of PM and NO_x. The chosen engines were tested using the heavy-duty engine FTP dynamometer cycle. The study examined how the changes in fuel properties due to different fuel additives made an impact on the emissions from older and newer electronically controlled engines. One base fuel was a biodiesel B20 blend, which consisted of 20 vol% soy-derived biodiesel fuel and 80 vol% petroleum diesel fuel. The two other base fuels were petroleum diesel fuels.

2 REVIEW OF THE LITERATURE

Environmental considerations and emissions legislation have both highly influenced current formulation and properties of fuels. In order to have a low-emission diesel engine, the interaction between engine technologies, fuel quality, and emissions needs to be well understood [**3**]. It is fairly evident that improvements in engine technology have a greater impact on reducing emissions than fuel modification does [**4**].

Standards specify the requirements placed on diesel fuels, such as the ASTM D975 in USA, EN 590 in the European Union, and JIS K2204 in Japan [**5**]. The most important parameters specified within these standards that also influence emissions include density or specific gravity, cetane number, distillation temperatures, sulphur content, and aromatics. Research has shown that NO_x and PM both respond to changes in cetane number and aromatic content [**6**]. A reduction in aromatic content leads to a reduction in NO_x and PM, while an increase in cetane number tends to decrease NO_x emissions. When varying the fuel properties, some studies have found that engine calibration changes in EGR rate and injection timing occur and have significant effects on emissions [**7, 8**]. Therefore, when studying the emission effects of changing fuel properties, the EGR rate and injection timing should be held constant between fuels. With a denser fuel, the start of injection occurs earlier because of the compressibility (bulk modulus) of the fuel [**9**] and this earlier start of injection (advanced engine timing) may increase the NO_x emissions [**9**]. This effect is more pronounced with pump-line-nozzle fuel injection and the five engines tested utilized unit injectors, which minimize any bulk modulus effects.

Diesel fuels require certain properties to be sold for on-road heavy-duty diesel engines. As the requirements for fuel properties change, fuel suppliers can use fuel additives to obtain these properties without refinery modification. Some types of fuel additive are ignition, oxygenate, lubricity, combustion, flow, wax anti-settling, anti-foam, detergents, and anti-corrosion. During a study conducted by Shih [**10**], several fuel additives were investigated: ethylhexyl nitrate, di-tertiary butyl peroxide (DTBP), methyl *tert*-butyl ether, dichloromethane, diglyme, monoglyme, and ethanol. It was shown that these additives can have a large impact on the spray penetration of the fuel, air–fuel mixing process, ignition delay, chemical reaction rates, and heat release. Some of the additives had a positive effect on the reduction of regulated emissions, but not necessarily all the constituents. It is known that there is an optimized dosage for each of these additives in order to reduce emissions. Two common ignition improver (or cetane improver) additives are a nitrate-based 2-ethlyhexyl nitrate (2-EHN) and peroxide-based additive (DTBP). Previous diesel emission studies have shown mixed results of NO_x reduction using 2-EHN or DTBP with some having up to 8 per cent reduction in NO_x [**11**, **12**] and with others showing no benefit [**13**] or an increase in NO_x [**14**]. McCormick *et al.* [**15**] effectively blended biodiesel with DTBP and 2-EHN to reduce NO_x and to maintain the PM emissions reduction from the use of biodiesel over its neat petroleum diesel on a 1991 Detroit Diesel Corporation (DDC) series 60 engine, while a 2002 Cummins ISB and 2003 DDC series 60 [**16**] had no effect on NO_x when adding 2-EHN to B20.

There have been many suggestions for diesel fuel alternatives, such as vegetable oils and animal fats. The common sources of oil include soybean, rape, sunflower, coconut, palm, and used frying oil, but methods have also been developed to make biodiesel from such exotic materials as oils produced by certain species of algae [**17**]. Since biodiesel is renewable and a potential greenhouse gas-emissions-reducing fuel, it is one of the most attractive alternative fuels available. High prices present a barrier for a widespread use of biodiesel [**3**]. Since pure biodiesel can be up to twice the price of petroleum diesel, it can be blended with petroleum diesel. The most common blend in the USA is 20 vol % biodiesel and 80 vol % petroleum diesel, which is usually referred to as B20 [**5**].

Some of the characteristics of biodiesel, such as high cetane numbers and low sulphur levels, are advantageous; low heating value and operability problems at low ambient temperatures, especially from saturated feedstocks such as beef tallow and palm oil, are some of the drawbacks [**5**]. An almost sulphur-free biodiesel is attainable through vegetable oils, whereas animal-based biodiesel can contain small amounts of sulphur. Biodiesel is also biodegradable, which is advantageous from an environmental standpoint (fuel spills), but can be a drawback for engine use. A high concentration of biodiesel means the fuel is more susceptible to degradation and water absorption [**3**].

There is wide agreement in the literature that both biodiesel and blends of biodiesel have a decreased amount of CO and HCs [**3**]. This is mostly due to the high oxygen content, which allows for more complete oxidation in the combustion chamber. NO_x emissions have been attributed to the higher oxygen content with a biodiesel [**18**, **19**]. Szybist and Boehman [**20**] observed a crank angle shift of 1° in the injection timing between pure diesel and pure biodiesel with an advance in ignition of up to 4° crank angle, which will influence emissions. The higher bulk modulus of compressibility for biodiesel, which affects the speed of sound, has been shown to create the advanced injection timing [**21**]. Cheng *et al.* [**22**] suggested that a higher flame temperature, which will increase NO_x emissions, is created by a reduction in the radiation heat transfer due to the reduced particulate emissions for biodiesel fuel. A study by Ban-Weiss *et al.* [**23**] attributed the slight NO_x increase for biodiesel to the higher degree of unsaturated HCs in biodiesel. Unsaturated HCs, which have more double bonds, were shown to have a higher adiabatic flame temperature than similar saturated HCs. Typically, owing to the lower energy content of biodiesel, the engine power output is reduced. The power output decreases as the percentage of biodiesel in the fuel increases.

3 EXPERIMENTAL SET-UP

The experimental procedures used in performing this study were conducted at the Center for Alternative Fuels, Engines, and Emissions (CAFEE) at West Virginia University which operates in compliance with Title 40 CFR Part 86, Subpart N and the standards set by ISO 8178 [**1**]. Five engines, namely 1991 DDC S60, 1992 DDC S60, 1992 rebuilt DDC S60, 1999 Cummins ISM 370, and 2004 Cummins ISM 370, were chosen for this study in order to represent a wide spectrum of engine technologies from the CAFEE inventory. In addition, all these engines were rated at approximately 275 kW, allowing a comparison between the engine technologies to be made while holding at least one variable constant. The specifications for these engines can be found in Table 2. The 1991 DDC series 60 engine was turbocharged and had direct injection. This engine was rebuilt to original DDC specifications to meet the EPA emissions standards for 1991. Two 1992 DDC series 60 engines were used for this study. One of the 1992 DDC series 60 engines was rebuilt to manufacturer specifications. This engine will be identified as the 1992 rebuilt DDC series 60 in this study. Two (1999 and 2004) Cummins ISM 370 engines were used to analyse more modern engine technology. The 1999 Cummins ISM 370 engine was turbocharged and had direct injection. The 2004 Cummins ISM 370 engine was similar to the 1999

Table 2 Engine specifications

Engine manufacturer	Engine model	Year	Configuration	Displacement (l)	Power rating (kW)	Torque rating (N m)	Compression ratio	Bore (mm)	Stroke (mm)	Air handling	EGR
DDC	Series 60	1991	Inline six cylinder	11.1	257 at 1800 r/min	1810 at 1200 r/min	16:1	130	139	Turbocharged, after-cooled	N/A
DDC	Series 60	1992	Inline six cylinder	12.7	272 at 1800 r/min	1966 at 1200 r/min	15:1	130	160	Turbocharged, after-cooled	N/A
DDC	Series 60 (rebuilt)	1992	Inline six cylinder	12.7	265 at 1800 r/min	1912 at 1200 r/min	15:1	130	160	Turbocharged, after-cooled	N/A
Cummins	ISM 370 ESP	1999	Inline six cylinder	10.8	276 at 2100 r/min	1830 at 1200 r/min	16.3:1	125	147	Turbocharged, after-cooled	N/A
Cummins	ISM 370	2004	Inline six cylinder	10.8	276 at 2100 r/min	1966 at 1200 r/min	16.1:1	125	147	Turbocharged, after-cooled, VGT	Cooled EGR

Cummins ISM 370 with the exception of a variable-geometry turbocharger (VGT) and cooled EGR.

A full-scale dilution tunnel was used in order to measure the effects of exhaust emissions on a simulated real-world environment. A critical flow venturi was used as the method of measuring the diluted exhaust. The dilute exhaust analysers consisted of a Rosemount analytical model 402 heated flame ionization detector, Rosemount model 955 chemiluminescence detector, Horiba model AIA-210LE non-dispersive infrared (NDIR) analyser, and Horiba model AIA-210 NDIR analyser to measure total hydrocarbons, NO_x, CO, and carbon dioxide (CO_2), respectively. An Eco Physics CLD 844 CM h was used as a secondary NO_x analyser for quality assurance purposes. The PM was gravimetrically measured in accordance with Title 40 CFR Part 86 Subpart N requirements using proportional sampling of the diluted exhaust through a pair of Pallflex 70 mm diameter model T60A20 fluorocarbon-coated glass microfibre filters in series. For fuel measurement, a carbon balance, fuel meter, and gravimetric methods were used to determine the amount of fuel consumed for quality assurance purposes.

Three base fuels were used over the duration of this project, which included two No. 2 diesel fuels and one biodiesel blend (B20). The No. 2 diesel fuels included were fuel A and fuel B (Table 3). The biodiesel blend (fuel C) was prepared by blending 80 vol% of fuel B and 20 vol% of a soy-derived biodiesel. The full fuel analysis for each of the test fuels is located in Table 3 with the ASTM methods used to analyse each property. Although the petroleum fuels, fuels A and B, were similar with cetane numbers of 51.7 and 49.2 respectively, fuel B had a higher sulphur content (340.7 wtppm) and higher aromatic content (34.2 per cent) compared with fuel A (3.7 wtppm and 27.1 per cent).

Two different diesel additives were used throughout the duration of the study in order to create different additive blend ratios of the base fuel. Each of the additives was known as a cetane improver, which reduced the ignition delay time to provide proper starting, smooth operation, and efficient combustion [5]. The additive fuel blends were mixed prior to the start of testing. The two additives were 2-EHN and DTBP.

4 RESULTS AND DISCUSSION

The primary petroleum fuel was fuel A, which was tested on all three DDC engines and the 1999 Cummins engine. Fuel B was the base petroleum

Table 3 Neat fuel analysis

Test method	Fuel property	Units	Value for the following		
			Fuel A	Fuel B	Fuel C (B20)
D613	Cetane number	—	51.7	49.2	51.1
D4052s	Density at 15 °C	kg/m^3	833.5	848.1	855.6
D445 40c	Viscosity	mm^2/s	2.47	2.69	2.96
D5186	Total aromatics	wt %	27.1	34.2	27.4
	Monoaromatics	wt %	21.2	24.8	19.8
	Polyaromatics	wt %	5.9	9.4	7.5
D5291	Carbon	wt %	85.9	86.8	84.8
	Hydrogen	wt %	13.2	13.0	12.9
	Oxygen	wt %	0.00	0.00	1.96
	Hydrogen-to-carbon ratio	—	1.84	1.79	1.81
	Oxygen-to-carbon ratio	—	0.000	0.000	0.017
D4629	Nitrogen	wtppm	6.4	70.6	39.9
D5453	Sulphur	wtppm	3.7	340.7	254.1
D86	Initial boiling point	°C	176.1	179.4	195.7
	5%	°C	190.5	198.0	214.5
	10%	°C	203.7	212.6	229.5
	15%	°C	210.9	222.2	237.9
	20%	°C	219.1	230.8	244.2
	30%	°C	233.6	245.1	256.3
	40%	°C	246.5	256.4	267.0
	50%	°C	256.8	265.9	277.7
	60%	°C	266.7	275.4	290.5
	70%	°C	276.4	286.7	304.5
	80%	°C	288.2	300.9	318.8
	90%	°C	305.4	320.0	331.3
	95%	°C	320.8	333.7	338.4
	Final boiling point	°C	338.1	346.8	347.9
	Recovered	ml	98.3	98.6	98.3
	Residue	ml	0.1	0.5	0.5
	Loss	ml	1.6	0.9	1.2
D93	Flash point	°C	67.8	70.6	82.8
West Virginia University	Lower heating value	MJ/kg	42.49	42.54	41.50

fuel for the 2004 Cummins engine tests and the base component for the B20 fuel (fuel C). The B20 biodiesel blend (fuel C) was tested on only the two Cummins engines and the rebuilt 1992 DDC S60 since there was a limited supply available. The test matrix for the tested fuels and engines is seen in Table 4. The table shows which fuels and additive concentrations were completed for each. It is noted that not every fuel–additive combination was tested on each engine. There were two reasons why this occurred. First, there were limited quantities of fuel and test cell time. Second, additional additives or additive concentrations were added as the testing progressed on the basis of knowledge gained throughout the campaign. As a result of these two reasons, the test matrix was filled in to provide the widest range of fuels and additives possible.

The transient FTP test was chosen for analysis since heavy-duty diesel engines used in on-road vehicles are tested and certified in the USA using the FTP and supplemental emissions test engine test cycles. It is noted that engine manufacturers are now required to perform in-use emissions testing. The FTP is the transient test cycle used to certify HDDEs and to analyse the emissions formed to simulate on-road driving conditions in the USA. The test cycle includes four main segments: New York non-freeway, Los Angeles non-freeway, Los Angeles freeway, and a repeat of the New York non-freeway. The first and fourth segments represented light urban traffic with frequent stops and starts. The second segment represented crowded urban traffic with very few stops, and the third segment represented crowded freeway traffic [1, 3]. For each fuel evaluation, three repeat hot-start FTP tests were conducted to obtain an average value and some indication of run-to-run variation.

4.1 NO_x emissions

With the use of cetane improvers, the brake specific NO_x emissions over the FTP tests showed significant reductions of 1.0 per cent, 3.5 per cent, 3.2 per cent, and 1.9 per cent for the 1991 DDC engine, 1992 DDC engine, rebuilt 1992 DDC engine, and 1999 Cummins engine respectively (Table 5). The 2004 Cummins engine had a significant increase in the brake specific NO_x emissions of 1.3 per cent with the addition of 0.32 vol % 2-EHN and had no significant difference from 0.16 vol % 2-EHN and 0.26 vol %

Table 4 Fuels examined for each test engine

		Fuels examined[*]				
Base fuel	Additive	1991 DDC S60	1992 DDC S60	1992 rebuilt DDC S60	1999 Cummins ISM 370	2004 Cummins ISM 370
Fuel A	None	X	X	X	X	—
	0.16 vol % 2-EHN	—	—	—	X	—
	0.21 vol % 2-EHN	X	—	X	—	—
	0.26 vol % DTBP	X	X	X	X	—
Fuel B	None	—	—	X	X	X
	0.16 vol % 2-EHN	—	—	—	—	X
	0.32 vol % 2-EHN	—	—	—	—	X
	0.40 vol % DTBP	—	—	—	—	X
Fuel C (B20)	None	—	—	X	X	X
	0.16 vol % 2-EHN	—	—	—	X	—
	0.26 vol % DTBP	—	—	—	X	X

[*] X, tested fuels; —, non-tested fuels.

DTBP. Significant differences were determined with a Student t test at a p value of 0.95. The concentration levels of 2-EHN and DTBP added were determined on the basis of experience with these additives to obtain similar brake specific NO_x emissions between the two cetane improvers.

Typically, when a transient test cycle is studied, only the integrated brake specific emissions are reported. For this study an additional approach was taken to give a more complete indication of the emission effects throughout the whole test cycle. The effectiveness of each fuel additive was studied by creating an NO_x percentage difference with respect to their neat fuel comparison as a function of engine power. To create the NO_x percentage difference, the continuous NO_x mass emission rate from each FTP test was averaged and time shifted to match the power curve, since the analysers measure the emissions with a time delay. Then, a sixth-order polynomial was fitted between engine power and the NO_x emissions rate to obtain an empirical relation (Fig. 1). The engine power was normalized by the

Table 5 Integrated brake specific NO_x over the FTP cycle

			Value for the following[*]				
Base fuel	Additive	Parameter	1991 DDC S60	1992 DDC S60	1992 rebuilt DDC S60	1999 Cummins ISM 370	2004 Cummins ISM 370
Fuel A	None	NO_x (g/kWh)	5.98	6.81	6.77	5.24	—
	0.16 vol % 2-EHN	NO_x (g/kWh)	—	—	—	5.14	—
		Difference (%)	—	—	—	−1.9	—
		p	—	—	—	0.0000	—
	0.21 vol % 2-EHN	NO_x (g/kWh)	5.93	—	6.55	—	—
		Difference (%)	−0.9	—	−3.2	—	—
		p	0.0125	—	0.0008	—	—
	0.26 vol % DTBP	NO_x (g/kWh)	5.92	6.57	6.56	5.15	—
		Difference (%)	−1.0	−3.5	−3.2	−1.8	—
		p	0.0077	0.0003	0.0009	0.0010	—
Fuel B	None	NO_x (g/kWh)	—	—	6.88	5.41	3.15
	0.16 vol % 2-EHN	NO_x (g/kWh)	—	—	—	—	3.17
		Difference (%)	—	—	—	—	0.5
		p	—	—	—	—	0.2170[†]
	0.32 vol % 2-EHN	NO_x (g/kWh)	—	—		—	3.20
		Difference (%)	—	—	—	—	1.3
		p	—	—		—	0.0238
	0.40 vol % DTBP	NO_x (g/kWh)	—	—	—	—	3.17
		Difference (%)	—	—	—	—	0.4
		p	—	—	—	—	0.3759[†]
Fuel C (B20)	None	NO_x (g/kWh)	—	—	6.90	5.53	3.32
	0.16 vol % 2-EHN	NO_x (g/kWh)	—	—	—	5.50	—
		Difference (%)	—	—	—	−0.6	—
		p	—	—	—	0.0259	—
	0.26 vol % DTBP	NO_x (g/kWh)	—	—	—	5.47	3.24
		Difference (%)	—	—	—	−1.0	−2.5
		p-value	—	—	—	0.0113	0.0302

[*] —, non-tested fuels.

[†] No significant difference at a 95 per cent confidence level.

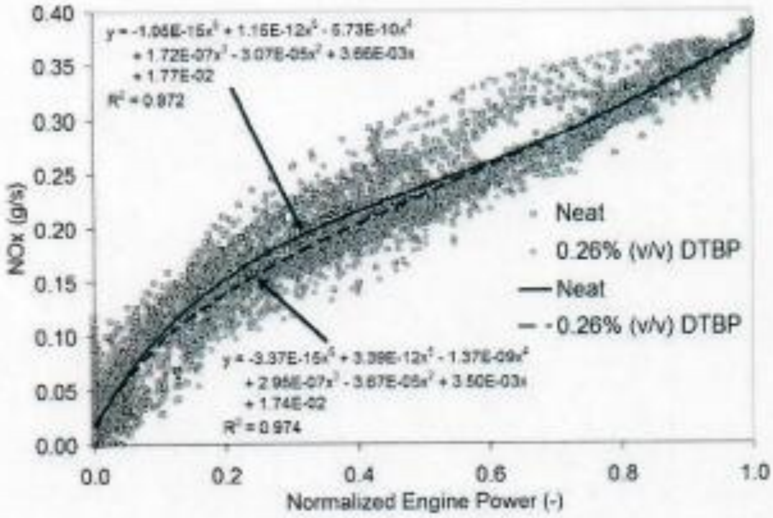

Fig. 1 NO_x trend lines for 1992 rebuilt DDC S60

maximum power achieved during the FTP test. The sixth-order polynomials from the tested fuel with and without cetane improver were then used to find the NO_x percentage difference as a function of the normalized engine power (Fig. 2). A negative percentage difference is an NO_x reduction and a positive percentage difference is an NO_x increase based on the neat fuel emissions levels. The bars shown in Figs 2 to 7 are the 95 per cent confidence interval, which is from the three repeat FTP tests for each fuel. The R^2 value between NO_x mass emissions and engine power was typically greater than 0.9 for the DDC engines and the 1999 Cummins engine. The 2004 Cummins engine had an R^2 range of 0.81–0.84, which was lower than the other engines owing to the influence of the changing EGR rate at different engine powers over an FTP test.

DTBP and 2-EHN behaved similarly in the same engine. Figures 2 and 3 display the effect of adding DTBP and 2-EHN respectively to their respective petroleum neat fuel for all five engines. The bars represent the 95 per cent confidence interval of the curve fitted from the three FTP tests. For all five engines, the NO_x reduced on the addition of DTBP and 2-EHN at low engine powers and had an NO_x increase or no change at high engine powers. The engine power at which the NO_x changed from a reduction to an increase or no change varied between the five engines. The 1992 DDC engines changed at a normalized engine power of 0.74–0.76. The NO_x change occurred at a lower normalized engine power of 0.51–0.58 for the 1991 DDC engine. The increased engine power range where an NO_x reduction occurs with the 1992 DDC engines res-

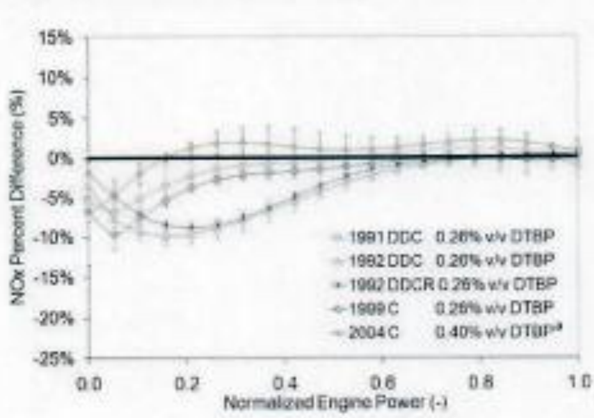

Fig. 2 NO_x percentage difference when adding DTBP to fuel A for the five engines. The superscript a indicates that the neat fuel was fuel B

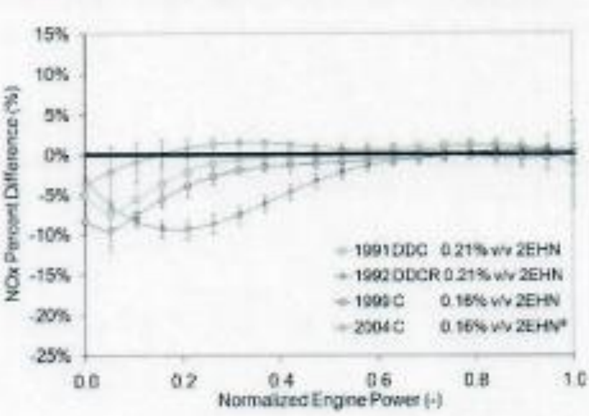

Fig. 3 NO_x percentage difference when adding 2-EHN to fuel A for the five engines. The superscript a indicates that the neat fuel was fuel B

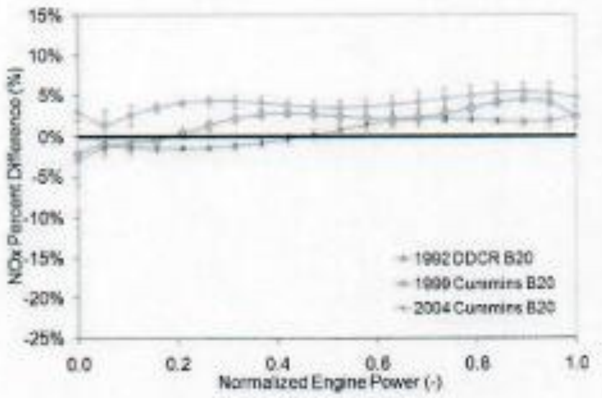

Fig. 4 NO_x percentage difference when adding 20 vol% biodiesel to fuel B (fuel C) for three engines

ulted in a greater NO_x reduction for the integrated brake specific NO_x than with the 1991 DDC engine. The 1999 Cummins engine went from an NO_x reduction to an increase at a normalized engine power of 0.68–0.72. The 2004 Cummins engine had the smallest range of normalized engine power for an NO_x reduction at 0–0.15. An NO_x increase of up to 2 per cent was noticed with the two Cummins engines. The 1992 rebuilt DDC engine showed approximately 1 per cent NO_x increase at high engine powers, but this was within the 1 per cent test-to-test repeatability.

The 20 per cent biodiesel increased the cetane number of the neat fuel from 49.2 to 51.1. This increased cetane number provided a similar NO_x percentage difference trend to that of 2-EHN and DTBP for the rebuilt 1992 DDC engine and 1999 Cummins engine with a reduction at low engine powers and increase at high engine powers (Fig. 4). Less NO_x reduction occurred at low engine powers with the B20 fuel than with the cetane improvers and the location of the change from an NO_x reduction to increase occurred at a lower engine power. In the rebuilt 1992 DDC engine and the 1999 Cummins ISM 370 engine, the B20 fuel (fuel C) reduced NO_x below normalized engine powers of 0.42 and 0.18 respectively, compared with the base fuel (fuel B). The 2004 Cummins engine showed an NO_x increase at all engine powers compared with the base fuel (Fig. 4). These results are similar to those in the study by Eckerle *et al.* [8], which showed no change or a reduction in NO_x at low loads and an NO_x increase at high loads with B20 in 2004 and 2006 5.8 l Cummins ISB engines, which were equipped with EGR. Eckerle *et al.* [**8**] partially attributed the NO_x changes from biodiesel to engine calibration changes with 5–8 per cent change in NO_x due to different intake oxygen concentrations, which will be

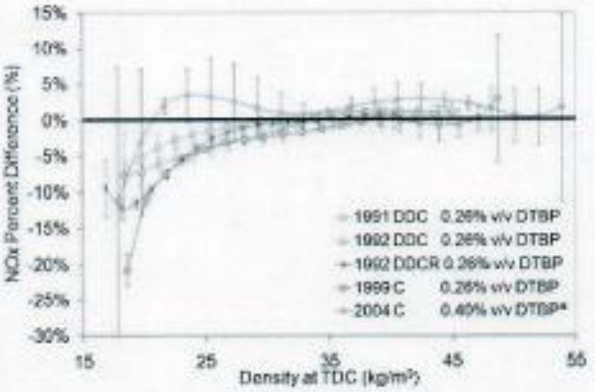

Fig. 6 NO_x percentage difference when adding DTBP to fuel A for the five engines. The superscript a indicates that the neat fuel was fuel B

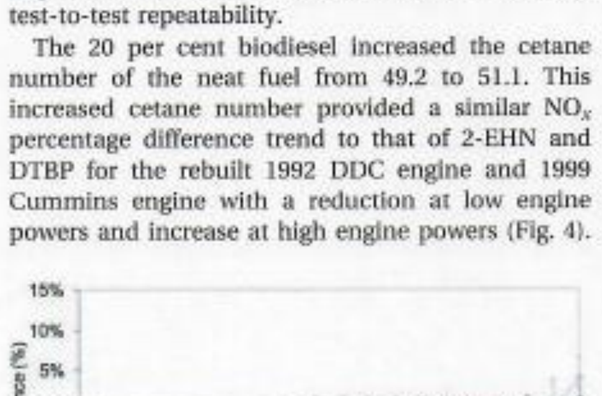

Fig. 5 NO_x percentage difference when adding DTBP or 2-EHN to fuel C (B20 blend) for the two engines

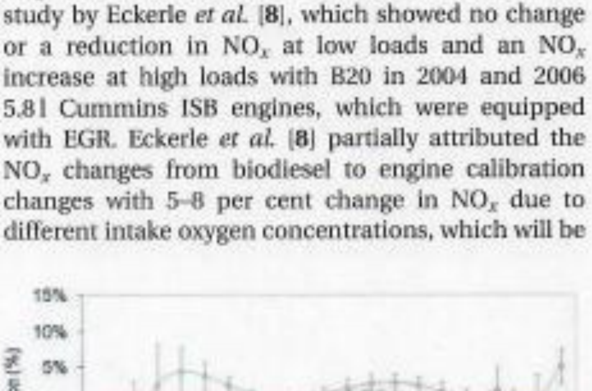

Fig. 7 NO_x percentage difference when adding 2-EHN to fuel A for the five engines. The superscript a indicates that the neat fuel was fuel B

less of an issue with the non-EGR equipped engines used here (the 1992 DDC engines and the 1999 Cummins engine). In the 1998 and 2000 10.8 l Cummins engines without EGR, an NO_x reduction with B20 was shown for a low-load test cycle by Eckerle *et al.* [**8**], which correlates with the NO_x reduction noticed at low engine power (Fig. 4).

The integrated brake specific NO_x emissions over the FTP showed significant reductions of 0.6 per cent and 1.0 per cent when adding 0.16 vol % 2-EHN and 0.26 vol % DTBP respectively to the B20 (fuel C) fuel in the 1999 Cummins engine (Table 5). The 2004 Cummins engine showed a significant reduction of 2.5 per cent in NO_x with 0.26 vol % DTBP added to the B20 fuel. At low engine powers, an NO_x reduction was noticed for both Cummins engines (Fig. 5). The 1999 Cummins engine had no change in NO_x above the normalized engine power of 0.48–0.62. The 2004 Cummins engine showed an increase in NO_x only above 0.96. The dependence of engine year and power on NO_x change when adding a cetane improver to a B20 fuel provides insight into the results reported in the literature [**15**, **16**]. It should be noted that the cetane-improved B20 was compared with the B20 fuel (fuel C) and not the base petroleum fuel (fuel B).

The study by Higgins *et al.* [**24**] using a constant-volume combustion vessel showed that the reduction in ignition delay caused by 2-EHN was more significant under low-temperature and low-density conditions. Kobori *et al.* [**25**] found the same conclusions regarding 2-EHN in a rapid compression machine. In an effort to correlate these fundamental combustion studies with the production engines tested, the NO_x percentage difference with additive was studied as a function of the density at top dead centre (TDC). The density at TDC was calculated from the ideal-gas law, intake pressure, intake temperature, and the compression ratio and is given by

$$\rho_{\mathrm{TDC}} = \rho_{\mathrm{intake}}\,\mathrm{CR} \tag{1}$$

where CR is the compression ratio. Equation (1) was derived from the ideal-gas law and assuming a polytropic process from intake conditions at bottom dead centre to TDC. The charge air was assumed to have no internal EGR. The density at TDC from equation (1) is the density that would occur at TDC during motoring conditions with the same intake pressure and temperature conditions.

Sixth-order polynomials were fitted between the ρ_{TDC} and the NO_x emissions rate from the FTP tests to determine the NO_x percentage difference. The same methods were used as described above for the NO_x percentage difference and engine power. The only change was that the engine operating points at idle were ignored because the measured intake conditions changed more rapidly than the measured emissions. At conditions when the engine goes from high load to idle, the analysers still reported NO_x emissions owing to diffusion and dispersion in the sampling system, but the measured intake conditions (and therefore ρ_{TDC}) have a much faster response. This caused a wide spread in the measured NO_x emissions for ρ_{TDC} during idle.

The NO_x percentage difference due to the addition of 2-EHN or DTBP correlated with the ρ_{TDC} for all the engines although the 2004 Cummins engine had large confidence intervals, suggesting that the correlation is not significant for this engine (Figs 6 and 7). Below a ρ_{TDC} of $35\,\mathrm{kg/m^3}$, the NO_x was reduced owing to the cetane improver. The NO_x percentage difference curves were not identical for all engines, but other variables besides the cetane improver affect the ignition delay, such as the injection timing, injection pressure [**25**], temperature at injection [**25**], and injector hole diameter [**25**]. The 2004 Cummins engine incorporates EGR, which affects the intake pressure, intake temperature, and concentration of intake oxygen. A lower concentration of intake oxygen will create a longer ignition delay and the varying EGR rate will minimize the correlation between ρ_{TDC} and the NO_x percentage difference. With the engines having an NO_x reduction at low cylinder densities with cetane improvers, the amount of time operated at these low densities will influence the resulting integrated brake specific NO_x emissions. The frequency of time operated at each density from 12.5 to $57.5\,\mathrm{kg/m^3}$, with density bins of $5\,\mathrm{kg/m^3}$, showed that the 1992 DDC engines operated at low densities more frequently than the other engines (Fig. 8). A third-order polynomial was fitted between the frequency and the density bins to show the trend. The two 1992 DDC engines operated at $12.5–17.5\,\mathrm{kg/m^3}$ for 52 per cent of the FTP, while the 2004 Cummins engine operated in that range only for 42 per cent of the FTP. The maximum density bin was $37.5–42.5\,\mathrm{kg/m^3}$ for the 1992 DDC engines, while the two Cummins operated had a maximum at or above $47.5\,\mathrm{kg/m^3}$. The cetane improvers therefore worked more efficiently at lower densities and the more time operated at these low densities resulted in lower NO_x emissions. The 1992 DDC engines had the lowest compression ratio and no EGR, which

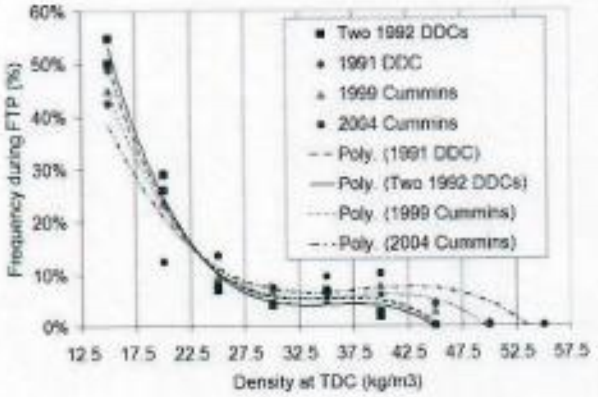

Fig. 8 Frequency distribution of the density at TDC for the five engines

resulted in the most NO_x benefit from cetane improvers. Engines such as refuse trucks or large-bore engines that operate primarily at relatively low engine powers and densities are optimal for cetane improvers.

4.2 PM emissions

The PM reduced significantly for the B20 blends, which is consistent with the literature. One of the most difficult hurdles for engine manufacturers to overcome in reducing the overall NO_x and PM emissions to meet current and future standards is the NO_x–PM trade-off. This trade-off occurs because, when the combustion chamber is cooled, the overall production of NO_x is reduced. In return, owing to the cooler temperatures, the PM is not able to oxidize; therefore, an increase in PM is seen. The two Cummins engines and the 1992 DDC showed this trend, as seen in Fig. 9. The figure includes all the fuels tested including the B20 for the two Cummins engines and the 1992 rebuilt DDC engine. The B20 will change the NO_x–PM trade-off linear fit. Figure 9 illustrates the effect of fuel properties on NO_x and PM, and it is shown that the fuel properties have a large impact on NO_x and PM emissions when keeping the engine control strategy consistent for each engine throughout the testing campaign, by using a production engine calibration. This was also shown by Gibble [**26**].

5 CONCLUSIONS

As the emissions standards continue to become increasingly stringent, engine manufacturers and fuel suppliers have to improve technologies in order to reduce engine-out emissions. The overall emission levels are lower for newer model years of the engines, and this is due to the improved engine technologies. The baseline fuels evaluated in this work showed a decreasing emissions trend with newer model years, with cetane improvers (2-EHN and DTBP) showing a greater impact on the older-technology engines. The additives reduced NO_x up to a normalized engine power of 0.51–0.58, 0.74–0.76, 0.68–0.72, and 0.15 for the 1991 DDC, 1992 DDCs, 1999 Cummins, and 2004 Cummins engines respectively but showed no NO_x change or increased NO_x production above this point. The cetane improvers only showed NO_x reduction at cylinder gas

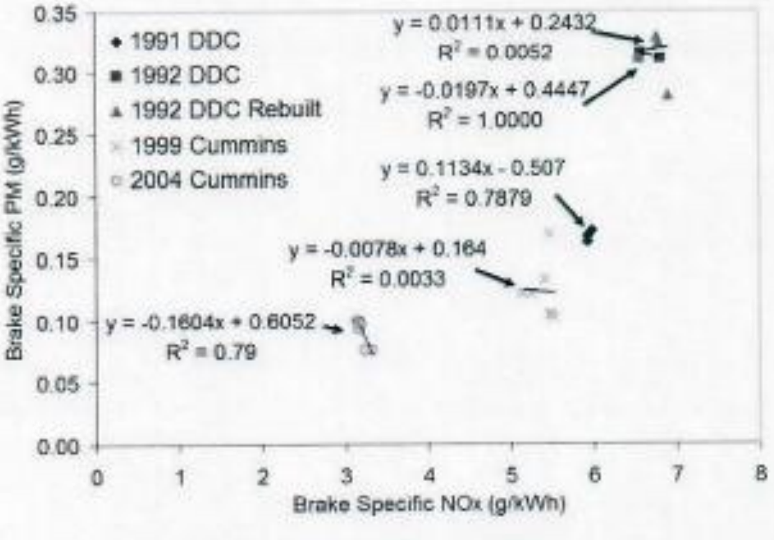

Fig. 9 NO_x–PM trade-off for FTP tests densities below 35 kg/m^3 and 2-EHN is known to be more effective at reducing ignition delay at low pressures and temperatures from fundamental combustion studies.

The data from this study show that cetane-improving additives are beneficial in reducing NO_x in engines with low compression ratios (typically legacy engines) but have less opportunity for NO_x reduction in newer-technology engines (higher compression ratio and EGR). The increased compression ratio of the 1991 DDC, 1999 Cummins, and 2004 Cummins engines increased the cylinder gas density at all operating points, creating less opportunity for NO_x reduction. Although the increased NO_x production with the addition of cetane improvers for the newer engines is less than 3 per cent at high engine powers, this increase negates some of the newer, and possibly future, engine technology benefits.

The B20 did have an increase in NO_x production, but there was a decrease in all the other regulated emissions. Some NO_x reduction (about 1 per cent) was noticeable below a normalized engine power of 0.42 in the 1992 rebuilt DDC engine and below 0.18 in the 1999 Cummins engine, suggesting that the increased cetane number of the biodiesel created a 'cetane effect', but the NO_x increased approximately 2–4 per cent at high engine powers. These NO_x results for B20 are in agreement with the data obtained by Eckerle *et al.* [**8**], which showed no change or a reduction in NO_x at low loads and an NO_x increase at high loads. This emissions impact can be seen as being beneficial considering only NO_x is being increased and, if a cetane-improving additive were used, the NO_x production is only slightly higher than with the petroleum-based diesels from which the blends were created on the basis of the additive treat rates used in this work.

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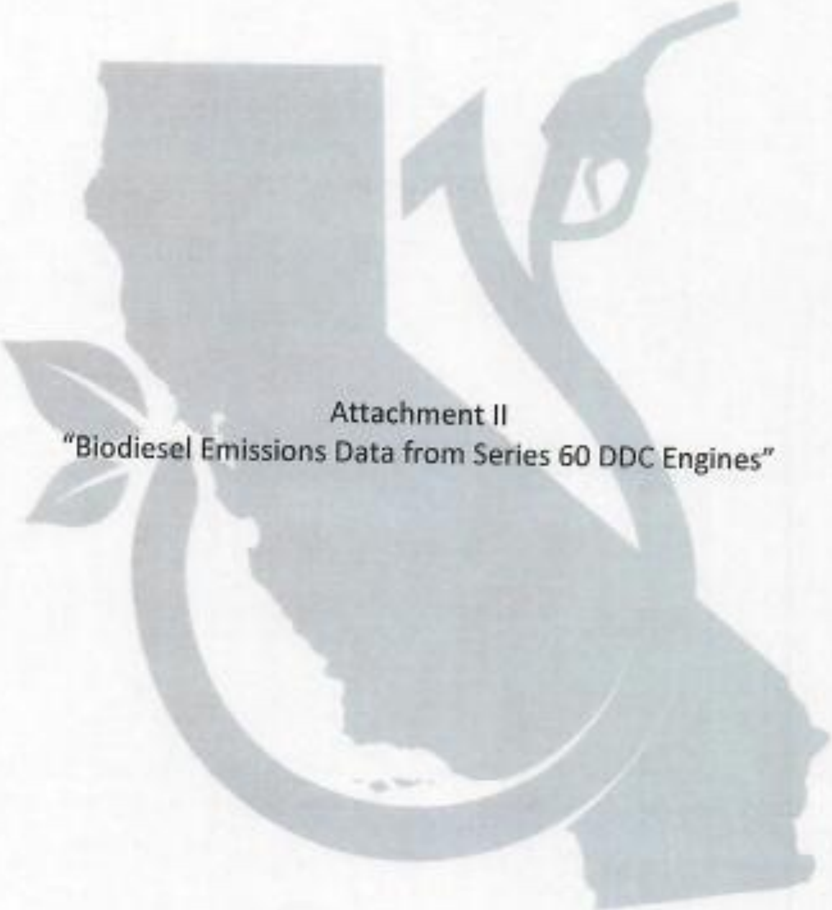

Attachment II
"Biodiesel Emissions Data from Series 60 DDC Engines"

CALIFORNIA
FUELING

Biodiesel Emissions Data From Series 60 DDC Engines

presented at the
1995 American Public Transit Association
Bus Operations and Technology Conference
Reno, Nevada
May 10, 1995

by

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Introduction

Biodiesel was first used in the late 1800s by Rudolph Diesel as he demonstrated the compression engine that he had designed- the diesel engine. Petroleum based diesel fuel has been the fuel of choice for the compression ignition engine designed by Mr. Diesel for many years. However, methyl esters of animal and vegetable oils (biodiesel), due to their cleaner burning tendencies in the compression ignition engine, are again being evaluated for use as a fuel for modern diesel engines.

Purpose and Objectives

The purpose of this study was to analyze and draw comparisons concerning the fueling of Series 60 DDC engines that have been fueled with blends of biodiesel and petroleum diesel fuel. Specifically, two National Biodiesel Board sponsored research efforts were examined to gain a deeper understanding of: 1) regulated EPA exhaust emissions, 2) selected fuel related properties, and 3) power/performance characteristics.

Detroit Diesel Series (DDC) 60 engines were tested in transient test cells at the Southwest Research Institute (SwRI), San Antonio, Texas and the Colorado Institute for Fuels and High Altitude Engine Research (CIFER), Denver, Colorado. The DDC Series 60 engine chosen for this testing is a modern four stroke engine with 1991 calibration. The hardware is typical of current on-road engine technology and has been extensively used for emission studies. The impact of various fuel compositions on emissions from the Series 60 is well established. The 1991 Series 60 is also the engine specified by the California Air Resources Board for California diesel fuel certification.

Methods

EPA regulated emissions, oxides of nitrogen (NOx), total hydrocarbons (THC), carbon monoxide (CO), and particulate matter (PM) were recorded for five blends using CFR 40 transient testing procedures. Variables such as air and fuel temperature and relative humidity were carefully monitored and controlled. CIFER performed 1 hot and 3 cold transient tests for 0, 20, 35, 65, and 100 percent blends of biodiesel. SwRI performed 4 hot transient tests for 0 and 20 percent blends of biodiesel. All testing was performed against the reference diesel map. Although this does not conform with the Code of Federal Regulations which requires a separate map for each fuel for engine certification purposes, this has become an accepted way to examine the effect of fuel properties on emissions by the EPA and state agencies like CARB (CIFER, 1994).

Reference Number 2 diesel fuel was secured from Colorado Petroleum, Inc (CIFER) and Phillips Petroleum Company (SwRI). The biodiesel was secured from Midwest Biofuels. The chemical composition of the base fuels can be found in Table 1. The cetane numbers reported by CIFER in Table 1 for the biodiesel blends were measured by Core Laboratories in Houston, Texas.

Other CIFER fuel analyses were conducted by Hauser Laboratories, Boulder, Colorado. Hauser determined the oxygen content directly using oxidative coulometry. The oxygen content of the blends, however, were determined by extrapolation which was based on the oxygen content of the base fuels (diesel fuel and biodiesel) and the known weight percent of each stock in a given blend (CIFER, 1995). CIFER did not analyze the 100% neat biodiesel. Rather, they relied upon an analysis of the fuel made by Proctor and Gamble, the manufacturer of the biodiesel. SwRI analyzed the blends for their testing at SwRI.

The fuels were blended volummetrically by weight to 20%, 35%, and 65% levels at each research facility. For example, a B20 blend represents 20 percent biodiesel and 80 percent petroleum diesel on a volume per volume basis.

At each change of fuel, the fuel filter was changed and the fuel lines were drained. The engine was warmed up on the new fuel to purge any of the remaining previous test fuel from the engine's fuel system. The engine was then torque-mapped and prepared for transient testing. Although a torque-map was run at each fuel change to evaluate engine performance, all testing was run using a transient cycle generated from the first torque-map conducted using the base 2-D fuel on the first day of testing. This was done to minimize day-to-day variability and allow for better comparison between test fuels.

The engine tested was a 1991 DDC Series 60, four-stroke, turbocharged, six-cylinder engine of in-line configuration. The test engine was a 12.7 liter, directed injected engine capable of producing 370 horsepower at 1800 rpm. Peak torque was 1450 lb-ft at 1200 rpm. The engine electronic control system was a standard DDEC II electronic control module used with the Series 60 engine.

Results

Because of the greater energy density of petroleum diesel fuel, the engine is capable of generating both the greatest torque and greatest horsepower while fueled with reference diesel at wide open throttle. As such, running the blends using a different torque-map would reduce the researcher's ability to make equal (as is possible) comparisons between blends. The candidate fuel is not able to generate the same power at wide open throttle as the reference diesel fuel, but all intermediate load set points were met. As noted in Table 2, small differences in power produced per horsepower-hour were noted with B35 and lower blends. Blends greater than 65 percent biodiesel, due to the energy differences previously noted, were unable to produce the same level of power as petroleum diesel.

Table 2. Series 60 power observations in horsepower-hour for biodiesel blend research

conducted at Southwest Research Institute and the Colorado Institute for Fuels and High Altitude Engine Research.

Lab	DF	B20	B35	B65	B100
SwRI	25	25.1	-	-	-
% Change	N/A	+0.4			
CIFER	22.29	22.35	22.23	22.13	21.94
% Change	N/A	+0.3	-0.3	-0.71	-1.57

The engine exhaust emissions analyzers were calibrated using the same set of span gases during the test programs. The results of the testing are in general agreement with biodiesel studies that have been conducted on other two and four stroke diesel engines. As the biodiesel blend concentration increased, the oxides of nitrogen (NOx) emissions increased, while the total hydrocarbons (THC), carbon monoxide (CO) and particulate matter (PM) decreased. Each targeted EPA emission (NOx, THC, CO, & PM) are discussed and compared independently in the text that follows.

The Series 60 engine at SwRI produced higher THC when fueled on B20 at SwRI when compared to B20 fueling at CIFER. Two of the hot runs, however, were significantly different from the other two test runs. Careful review of the raw data found in the final report clearly substantiates this premise. A value of .149 and .1 were observed on the first day of testing as compared to values of .08 and .075 on the second day of testing. Averages computed for the second day of testing parallel the data reported by CIFER. The data reported by CIFER more closely follows the data that has been reported in the literature (Schumacher, et al., 1992, Borgelt, et al., 1994). (Table 3)

The trends observed concerning CO when testing the Series 60 engine clearly indicate that as the level of biodiesel in the blend increases, that CO levels emitted by the engine decline. The data recorded at both labs were quite similar concerning this EPA targeted emissions variable. As noted in Table 4, CO reductions ranged from approximately 7 - 40 percent when fueling with biodiesel and biodiesel blends. These observations are based on data reported in Table 4.

Table 3. Series 60 Total Hydrocarbon engine exhaust emissions for biodiesel blend research conducted at Southwest Research Institute and the Colorado Institute for

Fuels and High Altitude Engine Research. (Note: units are in grams per brake horsepower-hour)

Lab	DF	B20	B35	B65	B100
SwRI (hot only)	0.077	0.095	-	-	-
% Change	N/A	+23.4			
CIFER (hot only)	0.154	0.130	0.139	0.110	0.085
CIFER (composite)	0.164	0.143	0.148	0.120	0.092
% Change (composite)	N/A	-12.8	-10.4	-26.8	-43.9

Table 4. Series 60 Carbon Monoxide engine exhaust emissions for biodiesel blend research conducted at Southwest Research Institute and the Colorado Institute for Fuels and High Altitude Engine Research. (Note: units are in grams per brake horsepower-hour)

Lab	DF	B20	B35	B65	B100
SwRI (hot only)	2.258	2.052	-	-	-
% Change	N/A	-9.1			
CIFER (hot only)	4.270	3.868	3.477	3.005	2.242
CIFER (composite)	4.458	4.141	3.668	3.178	2.633
% Change (composite)	N/A	-7.1	-17.7	-28.7	-40.9

Oxides of nitrogen emissions followed that which is reported in the literature. B20 and B35 blends were not significantly different from baseline diesel, but were approximately one percent higher than the baseline diesel. Blends greater than B35, however were statistically different from baseline diesel and would require engine and/or fuel modifications to meet EPA regulations. As noted in Table 5, the increase in NOx ranged from 1 to 11.5 percent, depending on the blend that was tested.

Table 5. Series 60 Oxides of Nitrogen engine exhaust emissions for biodiesel blend research conducted at Southwest Research Institute and the Colorado Institute for Fuels and High Altitude Engine Research. (Note: units are in grams per brake

horsepower-hour).

Lab	DF	B20	B35	B65	B100
SwRI (hot only)	4.679	4.626	-	-	-
% Change	N/A	-1.1			
CIFER (hot only)	4.577	4.629	4.625	4.789	5.106
CIFER (composite)	4.635	4.688	4.680	4.848	5.166
% Change (composite)	N/A	+1.1	+1.0	+4.6	+11.5

Reductions in PM were substantial when testing an unmodified Series 60 engine. As noted in Table 6, fueling with a B20 blend produced a 9 - 19 percent reduction in PM, depending on which lab did the testing. The 19 percent reduction reported by CIFER has been observed in the literature. The 60 percent reduction noted, although extremely good, is not commonly reported in the literature. The testing at the higher blend levels in the Series 60 must be replicated to substantiate these data. These comments are based on the data reported in Table 6.

Table 6. Series 60 Particulate Matter engine exhaust emissions for biodiesel blend research conducted at Southwest Research Institute and the Colorado Institute for Fuels and High Altitude Engine Research. (Note: units are in grams per brake horsepower-hour).

Lab	DF	B20	B35	B65	B100
SwRI (hot only)	.220	.200	-	-	-
% Change	N/A	-9.1			
CIFER (hot only)	0.295	0.248	0.216	0.158	0.098
CIFER (composite)	0.322	0.259	0.222	0.165	0.102
% Change (composite)	N/A	-19.6	-31.1	-48.8	-68.3

One of two major differences observed in the chemical make-up of biodiesel and biodiesel blends is that oxygen is present in the fuel. The oxygen noted in the blends ranged from 2.4 to 7.2 percent by weight. The addition of oxygen to diesel fuel is believed to be responsible for the reductions in the solid portion of PM.

The second of two major differences concerning the chemical make-up of biodiesel and biodiesel blends is the cetane value of the fuel. Since the chemical make-up of biodiesel and biodiesel blends differs from petroleum diesel fuel, the cetane index is not appropriate to calculate the cetane number of the fuel. Rather, a cetane engine must be used to determine the cetane number of the fuel. Both SwRI and CIFER used a cetane engine to calculate the cetane number of the fuel. As noted in Table 7, the addition of biodiesel to the baseline diesel consistently improved the cetane value of the fuel.

Table 7. Oxygen content and cetane numbers for diesel, biodiesel, and biodiesel blends used to fuel Series 60 engines during engine testing conducted by Southwest Research Institute and the Colorado Institute for Fuels and High Altitude Engine Research.

Item	DF	B20	B35	B65	B100
% Oxygen (SwRI)	0.0	2.2	-	-	-
% Oxygen (CIFER)	0.21	2.4	4.0	7.2	11.1
Cetane (SwRI)	45.8	48.1			
Cetane (CIFER)	46.2	50.2	52.2	54.5	56.4

Summary and Conclusions

As noted previously, the results of the testing are in general agreement with biodiesel studies that have been conducted on other two and four stroke diesel engines. Specifically, as the biodiesel blend concentration increased, the oxides of Nitrogen (NOx) emissions increased, while the total hydrocarbons (THC), carbon monoxide (CO) and particulate matter (PM) decreased. The neat biodiesel exceeded the 1991-1994 NOx emission standard of 5 grams per brake horsepower-hour, however the 1994 PM standard was met using the neat fuel. In general, the amount of PM reductions noted were proportional to the total weight percent of oxygen present in the fuel. CO showed a similar relationship with varying oxygen content.

The increase in THC that were observed within the SwRI data may be an anomaly within the data. The data observed while testing the same engine one month earlier using a high sulfur, high aromatic fuel followed the trends reported by CIFER. In this study Callahan, (1993) reported a 7% reduction in THC when fueling with B20.

An analysis of the PM revealed that the reduction was entirely due to a reduction in insolubles that are primarily composed off carbon soot. However, one should note that a slight increase in the soluble organic fraction of the PM was observed.

Although power remained consistent with the lower level blends (B35 or lower), the pounds of fuel used per brake horsepower-hr increased as the concentration of biodiesel increased. Fueling with B20 increased fuel consumption by 1.3%, B35 by 2.3%, B65 by 7.1%, and B100 by 12.7%. When one compares this data with that reported in the literature, this increase in fuel consumption was normal and expected. Engine efficiency (not to be confused with fuel efficiency) was found to be the same for biodiesel and biodiesel blends as for the reference fuel. Fuel consumption for biodiesel blends should therefore be able to be calculated from diesel fuel economy data based on these findings.

The researchers reported that future research should focus on activities that allow one to better understand the relationship between fuel composition and emissions in the Series 60 engine. The aromatic content and the cetane number of the fuel should receive further testing. Fuels that have been oxygenated by different oxygenates should be tested and compared with biodiesel blends. The pursuit of these efforts will help develop a deeper understanding of how the diesel engine might best utilize the chemical properties of biodiesel and biodiesel blends.

Table 1. Fuel properties of diesel, biodiesel, and biodiesel blends as reported by the Colorado Institute for Fuels and High Altitude Engine Research and Southwest Research Institute when testing a Series 60 Detroit Diesel engine.

Fuel Variable	DF- SwRI	DF-CIFER	B20 - SwRI	B100- SwRI
Carbon, WT%	N/A	86.64	N/A	76.5
Hydrogen	N/A	12.80	N/A	12.5
Oxygen	N/A	0.21	2.2	11.0
Nitrogen	N/A	0.11	N/A	N/A
Sulfur	0.032	0.032	0.024	0.003
Saturates, Vol %	56.0	64.4	N/A	N/A
Olefins	8.3	1.3	N/A	N/A
Aromatics	35.7	34.3	N/A	N/A
API Gravity	35.7	35.6	34.2	28.0
IBP, F	367	387	373	606
IBP, 10%	429	429	433	626
IBP, 50%	507	527	533	638
IBP, 90%	598	632	627	650
EBP, 100%	638	677	647	664
Flash Point, F	172	N/A	177	307
Viscosity, CST, @ 40 C	2.59	N/A	2.83	4.11
Cetane number	45.8	46.2	48.1	N/A

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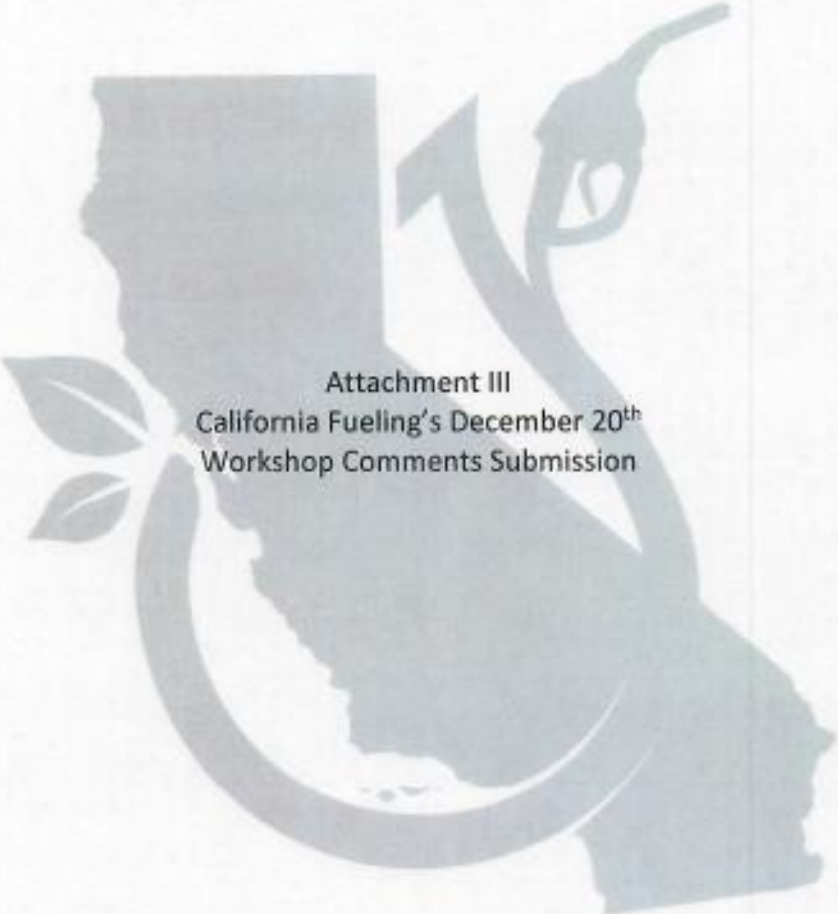


Attachment III
California Fueling's December 20th
Workshop Comments Submission

CALIFORNIA
FUELING

December 20, 2019

Mr. Lex Mitchell
California Air Resources Board
1001 I ST
Sacramento, CA 95814

Sent via email: alexander.mitchell@arb.ca.gov

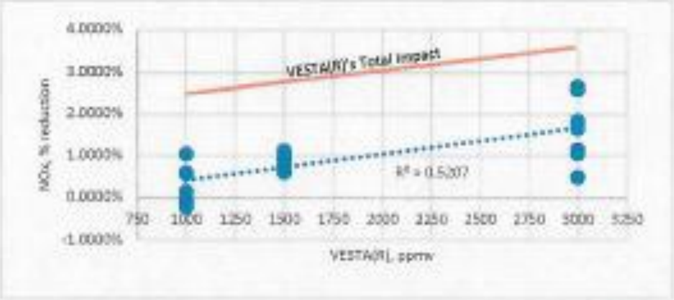
Subject: Feedback on CARB's 12/13/19 "Public Workshop to Discuss Potential Amendments to the Regulation on the Commercialization of Alternative Diesel Fuels"

Dear Lex:

Thank you for the opportunity to comment on the information communicated by CARB at the subject event. **We want to applaud CARB** for documenting what was obvious to most but skirted by one, and formalizing self-evident chain of custody (slide 22) and testing (slide 19) procedures which we believe alone will prevent fraud from occurring. Following are our additional comments by slide:

1. Slide 7 – DTBP has not been evaluated against the current ADF protocol. Additionally, if there are any additional testing requirements, DTBP should be required to meet such. At a minimum, DTBP should be tested and shown to perform against an ADF compliant Reference Fuel, something that has never occurred. If not, DTBP should be removed from the list of approved products.
    a. Question: Will DTBP be subject to any new ADF requirements or any further testing?
2. Slide 8 – CARB's concerns regarding VESTA® engine certification test results and their associated "reproducibility" are unsubstantiated.
    a. Question: Has CARB approached SwRI and CE-CERT and inquired as to whether any joint test programs have been run on identical (a) fuels; and (b) additives?
    b. Following is an overview of our three certification test run's data.

NOx Reduction versus VESTA® Concentration Candidate vs. Reference Fuel



c. A summary of our certification run statistical data is provided following:

Certification Runs, Student's t-Test Data

Run	VESTA® Dose (ppmv)	X_C	δ	S_p	$(2/n)^{0.5}$	t (a, 2n-2)	X_R	X_R Adjusted	% Reduction $X_{R\ Adjusted}$ vs X_C
1	3000	4.463	0.045	0.065	0.447	1.083	4.540	4.554	2.0
2	1500	4.467	0.045	0.021	1.083	1.083	4.506	4.541	1.6
3	1000	4.437	0.045	0.020	1.083	1.083	4.450	4.483	1.0

Our Reference Fuel range was 0.090; Coefficient of Variation (CoV) was 2%. For CARB's CE-CERT run the Reference Fuel range was 0.087, CoV was 1.9%. The CoV for our SwRI Reference Fuel data is almost identical to CARB's CE-CERT Reference Fuel data. Reference Fuel "reproducibility" does not seem to be an issue

d. Based on points b. and c. above, CARB's "reproducibility" concerns must be based on VESTA®'s NOx reduction vs treat rate results (since Best's product did <u>not</u> provide <u>any</u> level of NOx mitigation, which is consistent with the testing of Best's product that we commissioned at SwRI in 2018, and both provided to CARB in December, 2018 and appended to the Complaint in *California Fueling, LLC. v. Best Energy Solutions and Technology Corp., dba "Best Corp.", et al.*, Case No. 18STCV08474).

    i. <u>Question</u>: What, if any, other data or information is CARB basing its "reproducibility" concerns?

e. Statistical analysis of the CE-CERT testing, provided by us and reviewed with CARB at our November 19th meeting, demonstrated that certain of CE-CERT's procedures were "out of control" and indicative of, among other things, a failure to properly flush lines and filters between the frequent fuel changes that go along with the ADF's Alternative 1 procedure (RCCR). As discussed during our meeting, these same concerns can be seen in review of CE-CERT's July 2014 B5/B10 test data.

  i. <u>Question</u>: Why is CARB basing its decision to implement new ADF testing requirements on a flawed additive testing data set?

  ii. <u>Question</u>: Could these faulty CE-CERT procedure issues be the explanation behind CARB's recent "reproducibility" issues?

  iii. <u>Question</u>: If the basis for CARB's recent "reproducibility" issues are beyond points i. and ii. above, can CARB clearly lay out the science behind its concerns?

f. **<u>Question: As opposed to CARB adding the newly proposed ADF test regimen, why not modify the current ADF's "In-Use" language to allow CARB to trigger an Executive Order suspension (temporary then permanent) and require mandatory second round testing (e.g., the Designated Equivalent Limits testing outlined on slide 19) when CARB has reason to believe that previously submitted test results fail to meet established and pre-defined science-based criteria.</u>**

3. Slide 18 – CARB's proposed updated certification program would cost ~$350k, potentially more. Given the narrow window of opportunity between 2021 and the ADF's estimated sunset (2023), a net positive return on investment is questionable given the variables outside of an applicant's control (namely, further regulation changes that could negatively impact NOx mitigant requirements).

  a. <u>Question</u>: Will CARB be addressing the newly proposed ADF testing costs and associated payback in its ISOR? CARB should take into consideration that this process will necessarily increase ADF NOx mitigant costs to the consumers.

4. Slide 23 – During the workshop, CARB indicated the proposed testing regimen is "technically feasible". We believe there are a number or feasibility concerns.

  a. The timeframe to gather fuels and test will take more than 6 months especially considering the potential demand on engine testing facilities.

    i. <u>Question:</u> Will CARB consider allowing more time to meet any potential new testing requirements, and if so, under what circumstances?

b. All approved ADF NOx Mitigants were certified using the DDC Series 60 (S60). The recent EMFAC workshop presentation indicates there is a significant population of pre-1995 vehicles which appear to outweigh the 2004-2006 vehicle population.

    i. <u>Question</u>: Will CARB allow for the continued use of the S60 for either: (a) retesting of previously approved additives; and/or (b) testing of new additives/treat rates under the proposed new testing requirements?

CARB has been placed in the unenviable position of having to make sweeping changes to the ADF as a result of one party not holding themselves to the same standards of every other company that sought certification through the already difficult existing ADF testing requirements. While the ADF needs to be updated and the regulation calls for such, CARB is placing a significant new burden on all stakeholders with the newly proposed testing requirements. Considering the information we've presented regarding CE-CERT's evaluation of VESTA® and the overly harsh reference and candidate fuels selected by CARB for CE-CERT testing, we believe it's in the better interest of all stakeholders to implement three changes at this time:

1. the new chain of custody requirements proposed in slide 22;
2. the new testing requirements proposed in slide 19; and
3. the "in-use" testing "trigger" language proposed above.

Please let us know if you require further elaboration on any of the above noted matters.

Respectfully,

Patrick J McDuff
CEO
California Fueling, LLC