Comments of Growth Energy on the Air Resources Board Staff Presentations at a Public Consultation Meeting on Regulations for Commercialization of Alternative Diesel Fuels

These comments respond to the CARB staff's request for comments on the staff's presentations at the April 17, 2014 public consultation meeting on the proposed adoption of regulations to govern commercialization of alternative diesel fuels, including as part of compliance strategies for the California low-carbon fuel standard ("LCFS") regulation.

1. CARB-Sponsored and Related Emissions Testing and Research

During the April 17th meeting, CARB staff indicated that the agency had an "ongoing" study of the emission impacts of B5 and B10 blends underway and that data from that study would be released to the public and incorporated into the rulemaking process. Incorporation of this data into the rulemaking process is essential in order to comply with the Global Warming Solutions Act of 2006 and other statutes that apply to CARB's implementation of the 2006 Act.[1] CARB must provide not only a full report on that study, but also all data that it has obtained in connection with the study and related materials. Nearly four weeks have passed since the April 17th public meeting and, to Growth Energy's knowledge, the CARB staff has not met its commitments.[2] Growth Energy and other stakeholders will need sufficient time to review the data and related materials in order to participate effectively in the ADF and LCFS rulemakings. Also during the course of the workshop, CARB staff indicated that two other agency-sponsored studies of biodiesel blends had been conducted but not yet released to the public. Again, all

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1 *See, e.g.*, Cal. Health & Safety Code § 38562(e) ("The state board shall rely upon the best available … scientific information … when adopting regulations required by this section."); *see also id*. § 38563(b)(4) (regulations to implement the 2006 Act must not "interfere with[] efforts to achieve and maintain federal and state ambient air quality standards."). The California Environmental Quality Act's requirements likewise cannot be met unless CARB considers all relevant data on the potential of biodiesel usage to increase NOx emissions.

2 Much of the data from this study and related materials may also be responsive to a Public Records Act request that Growth Energy has filed with CARB, but no data and very few related materials have been released to date.

reports as well as underlying data and other relevant materials must be made publicly available. All these materials, from each study, must be placed in a public rulemaking file without further delay, pursuant to subsections 6 and 7 of section 11347.3(a) of the Government Code.

2. Methodology to Establish a Significance Threshold and Related Issues

To date, CARB staff has indicated that it has attempted to identify a significance threshold for biodiesel blends by comparing emissions results when engines are tested on nominally specific biodiesel blends, and when the same engines are tested in similar ways on fuel containing no diesel. The defect in such a method is that it does not permit assessment of emissions when engines are operated on biodiesel blends other than those tested, including, for example, biodiesel blends below B5. The appropriate method to determine the significance threshold is contained in an analysis prepared for Growth Energy by Mr. Robert Crawford and placed in the rulemaking file last year.[3] After evaluating the linearity and statistical significance of the relationship between NOx emissions and biodiesel content, Mr. Crawford demonstrates that use of biodiesel even at levels below B5 will result in increased NOx emissions. CARB should adopt Mr. Crawford's approach to establishing the significance threshold for biodiesel, or explain in full any reasons for not doing so.

Despite the fact that CARB staff has correctly chosen to propose mitigation of biodiesel NOx impacts on a per-gallon basis in extreme ozone non-attainment areas, this issue is important because the use of the current methodology for establishing the significance level will not prevent significant increases in NOx emissions in these areas.

[3] Crawford, R., "NOx Emission Impact of Soy- and Animal-based Biodiesel Fuels: A Re-Analysis," December 10, 2013.

3. Protection of the Environment on a Statewide Basis

Based on the presentation at the recent public consultation meeting, CARB staff continues to propose the highly flawed "effective blend" approach for determining the point at which mitigation of biodiesel NOx impacts would be required under the proposed ADF regulation. Instead, CARB staff should also require the per-gallon mitigation concept proposed for extreme ozone nonattainment areas and the appropriate significance threshold to be used in all other areas of the state.

4. Minimum Requirements to Determine and Report Blend Levels

The CARB staff's presentation at the recent meeting did not clarify how the proposed ADF regulation will ensure that the biodiesel content of blends sold in California will be accurately known to fuel purchasers or reported to CARB. At present, CARB appears to have no requirement for determining the biodiesel content of diesel fuels being imported or distributed in the state that contain biodiesel up to the B5 level. Given this, a party interested in blending 5% biodiesel into a "diesel" fuel may be unaware of the fact that the "diesel" fuel could already contain up to 5% biodiesel and that the resulting blend would therefore be B10, not B5. Similarly, a party interested in blending 20% biodiesel into a "diesel" could in fact produce a B25 blend, instead of the intended B20 blend. Obviously, both circumstances have substantial ramifications with respect to potential NOx increases associated with the use of biodiesel in California.

Given the above, CARB must modify as necessary its existing diesel fuel regulations as well as the proposed ADF regulations to ensure that the biodiesel content of all blends of biodiesel and diesel sold in California is accurately known and reported to both CARB as well as the Division of Measurement Standards. This could easily be accomplished by requiring that all "diesel" fuels used in biodiesel blends be tested before blending for Fatty Acid Methyl Ester ("FAME") content using appropriate test procedures such as the EN14103:2011 procedure already referenced in the proposed ADF regulations or the ASTM D7371 procedure. Alternatively, CARB could require testing of final blends for FAME content. Again, failure by CARB to require accurate measurement and reporting of the biodiesel content of biodiesel-diesel blends will lead to unmitigated increases in NOx emissions along with other potential issues, including violations of pump labeling and vehicle manufacturer warranty requirements.

Respectfully submitted,

GROWTH ENERGY

NOx Emissions Impact of Soy- and Animal-based Biodiesel Fuels: A Re-Analysis

December 10, 2013

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NOX EMISSIONS IMPACT OF SOY- AND ANIMAL-BASED BIODIESEL FUELS: A RE-ANALYSIS

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NOX IMPACT OF SOY- AND ANIMAL-BASED BIODIESEL FUELS: A RE-ANALYSIS

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1. EXECUTIVE SUMMARY

1.1 Background on the Proposed Rule

The California Air Resources Board (CARB) has proposed regulations on the commercialization of alternative diesel fuel (ADF) that were to be heard at the December 2013 meeting of the Board. The proposed regulations seek to "… create a streamlined legal framework that protects California's residents and environment while allowing innovative ADFs to enter the commercial market as efficiently is possible."[1] In this context ADF refers to biodiesel fuel blends. Biodiesel fuels are generally recognized to have the potential to decrease emissions of several pollutants, including hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM), but are also recognized to have the potential to increase oxides of nitrogen (NOx) unless mitigated in some way. NOx emissions are an important precursor to smog and have historically been subject to stringent emission standards and mitigation programs to prevent growth in emissions over time. A crucial issue with respect to biodiesel is how to "… safeguard against potential increases in oxides of nitrogen (NOx) emissions."[2]

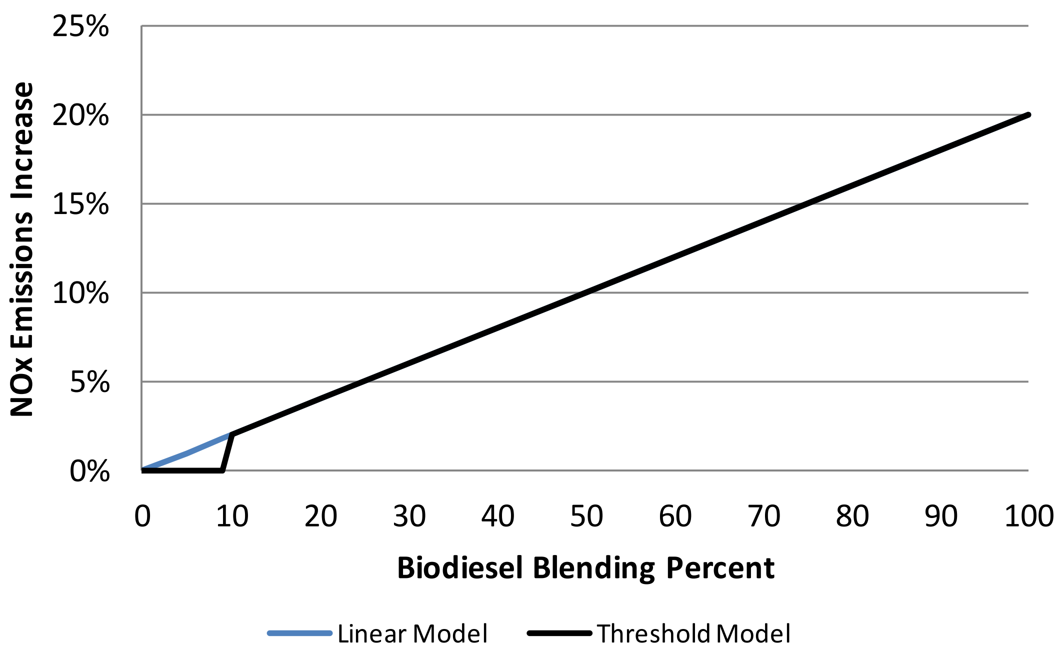
The proposed regulations are presented in the Staff Report: Initial Statement of Reasons (ISOR) for the Proposed Regulation on the Commercialization of New Alternative Diesel Fuels[3] (referenced as ISOR). Chapter 5 of the document describes the proposed regulations, which exempt diesel blends with less than 10 percent biodiesel (B10) from requirements to mitigate NOx emissions:

> *There are two distinct blend levels relative to biodiesel that have been identified as important for this analysis. Based on our analysis to date, we have found that diesel blends with less than 10 percent biodiesel by volume (<B10) have no significant increase in any of the pollutants of concern and therefore will be regulated at Stage 3B (Commercial Sales not Subject to Mitigation). However, we have found that biodiesel blends of 10 percent and above (≥B10) have potentially significant increases in NOx emissions, in the absence of any mitigating factors, and therefore those higher blend levels will be regulated under Stage 3A (Commercial Sales Subject to Mitigation).*[4]

[1] "Notice of Public Hearing to Consider Proposed Regulation on the Commercialization of New Alternative Diesel Fuels." California Air Resources Board, p. 3. *http://www.arb.ca.gov/regact/2013/adf2013/adf2013notice.pdf.*
[2] Ibid. p. 3.
[3] "Proposed Regulation on the Commercialization of New Alternative Diesel Fuels. Staff Report: Initial Statement of Reason." California Air Resources Board, Stationary Source Division, Alternative Fuels Branch. October 23, 2013. *http://www.arb.ca.gov/regact/2013/adf2013/adf2013isor.pdf.*
[4] Ibid, p. 22.

Existing research on the NOx emission effects of biodiesel has consistently been conducted under the hypothesis that the emission effect will be linearly proportional to the blending percent of neat biodiesel (B100) with the base diesel fuel. The Linear Model that has been accepted by researchers is shown as the blue line in Figure 1-1. The Staff position cited above is that biodiesel fuels do not increase NOx emissions until the fuel blend reaches 10% biodiesel. This so-called Staff Threshold Model departs from the Linear Model that underlies past and current biodiesel research by claiming that NOx emissions do not increase until the biodiesel content reaches 10 percent.

Figure 1-1
Linear and Staff Threshold Models for Biodiesel NOx Impacts



The Staff Threshold model is justified by the statement: "*Based on our analysis to date, we have found that diesel blends with less than 10 percent biodiesel by volume (<B10) have no significant increase in any of the pollutants of concern.*" Other portions of the ISOR state that Staff will track "… the effective blend level on an annual statewide average basis until the effective blend level reaches 9.5 percent. At that point, the biodiesel producers, importers, blenders, and other suppliers are put on notice that the effective blend-level trigger of 9.5 percent is approaching and mitigation measures will be required once the trigger is reached."[5] Until such time, NOx emission increases from biodiesel blends below B10 will not require mitigation.

Section 6 of the ISOR presents a Technology Assessment that includes a literature search the Staff conducted to obtain past studies on the NOx impact of biodiesel in heavy-duty

[5] Ibid, p. 24.

engines using California diesel (or other high-cetane diesel) as a base fuel. Section 6.d presents the results of the literature search with additional technical information provided in Appendix B. The past studies include the Biodiesel Characterization and NOx Mitigation Study[6] sponsored by CARB (referenced as Durbin 2011).

The results of the Staff literature search are summarized in Table 1-1, which has been reproduced from Table 6.1 of the ISOR. For B5 and B20, the data represent averages for a mix of soy- and animal-based biodiesels, which tend to have different impacts on NOx emissions (animal-based biodiesels increase NOx to a lesser extent). For B10, the data represent an average for soy-based biodiesels only. Staff uses the +0.3% average NOx increase at B5 in comparison to the 1.3% standard deviation to conclude:

> *Overall, the testing indicates different NOx impacts at different biodiesel percentages. Staff analysis shows there is a wide statistical variance in NOx emissions at biodiesel levels of B5, providing no demonstrable NOx emissions impact at this level and below. At biodiesel levels of B10 and above, multiple studies demonstrate statistically significant NOx increases, without additional mitigation.*[7]

Table 1-1
Results of Literature Search Analysis

Biodiesel Blend Level	NOx Difference	Standard Deviation
B5	0.3%	1.3%
B10[a]	2.7%	0.2%
B20	3.2%	2.3%

Source: Table 6.1 of Durbin 2011
Notes:
[a] Represents data using biodiesel from soy feedstocks.

The Staff conclusion is erroneous because it relies upon an apples-to-oranges comparison among the blending levels. Each of the B5, B10, and B20 levels include data from a different mix of studies, involving different fuels (soy- and/or animal-based), different test engines, and different test cycles. The B5 values come solely from the CARB Biodiesel Characterization study, while the B10 values come solely from other studies. The B20 values are a mix of data from the CARB and other studies. The results seen in the table above are the product of the uncontrolled aggregation of different studies that produces incomparable estimates of the NOx emission impact at the three blending levels.

[6] "CARB Assessment of the Emissions from the Use of Biodiesel as a Motor Vehicle Fuel in California: Biodiesel Characterization and NOx Mitigation Study." Prepared by Thomas D. Durbin, J. Wayne Miller and others. Prepared for Robert Okamoto and Alexander Mitchell, California Air Resources Board. October 2011.
[7] ISOR, p. 32.

As will be demonstrated in this report, the Staff conclusion drawn from the data in Table 1-1 is not supported by past or current biodiesel research, including the recent testing program sponsored by CARB. In fact, past and current studies indicate that biodiesel blends at any level will increase NOx emissions in proportion to the blending percent unless specifically mitigated by additives or other measures.

1.2 Summary and Conclusions

The following sections of this report examine the studies cited by CARB one-by-one. As evidenced from this review, it is clear that the data do not support the Staff conclusion and, indeed, the data refute the Staff conclusion in some instances. Specifically:

- There is no evidence supporting the Staff conclusion that NOx emissions do not increase until the B10 level is reached. Instead, there is consistent and strong evidence that biodiesel increases NOx emissions in proportion to the biodiesel blending percent.

- There is clear and statistically significant evidence that biodiesel increases NOx emissions at the B5 level in at least some engines for both soy- and animal-based biodiesels.

Considering each of the six past studies obtained from the technical literature and their data on high-cetane biodiesels comparable to California fuels, we find the following:

1. None of the six studies measured the NOx emissions impact from biodiesel at blending levels below B10. Only two studies tested a fuel at the B10 level. All other testing was at the B20 level or higher. Because none tested a B5 (or similar) fuel, none of them *can* provide direct evidence that NOx emissions are not increased at B5 or other blending levels below B10.

2. These studies provide no data or evidence supporting the validity of the Staff's Threshold Model that biodiesel below B10 does not increase NOx emissions. In fact, all of the studies are consistent with the contention that biodiesel increases NOx emissions in proportion to the blending percent.

3. Two of the studies present evidence and arguments that the NOx impact from biodiesel is a continuous effect that is present even at very low blending levels and will increase at higher levels in proportion to the blending percentage.

Considering the CARB Biodiesel Characterization report, we find that:

4. For the three engines where CARB has published the emission values measured in engine dynamometer testing, all of the data demonstrate that biodiesel fuels significantly increase NOx emissions for both soy- and animal-based fuels by amounts that are proportional to the blending percent. This is true for on-road and off-road engines and for a range of test cycles.

5. Where B5 fuels were tested for these engines, NOx emissions were observed to increase. NOx emission increases are smaller at B5 than at higher blending levels and the observed increases for two engines were not statistically significant by themselves based on the pair-wise t-test employed in Durbin 2011.[8] However, the testing for one of the engines (the 2007 MBE4000) showed statistically significant NOx emission increases at the B5 level for both soy- and animal-based blends.

By itself, the latter result is sufficient to disprove the Staff's contention that biodiesel blends at the B5 level will not increase NOx emissions.

Based on examination of all of the studies cited by CARB as the basis for its proposal to exempt biodiesels below B10 from mitigation, it is clear that the available research points to the expectation that both soy- and animal-based biodiesel blends will increase NOx emissions in proportion to their biodiesel content, including at the B5 level. CARB's own test data demonstrate that B5 will significantly increase NOx emissions in at least some engines.

Based on data in the CARB Biodiesel Characterization report, soy-based biodiesels will increase NOx emissions by about 1% at B5 (and 2% at B10), while animal-based biodiesels will increase NOx emissions by about one-half as much: 0.45% at B5 (and 0.9% at B10). All of the available research says that the NOx increases are real and implementation of mitigation measures will be required to prevent increases in NOx emissions due to biodiesel use at blending levels below B10.

Finally, we note that CARB has not published fully the biodiesel testing data that it relied on in support of the Proposed Rule and thereby has failed to adequately serve the interest of full public disclosure in this matter. The CARB-sponsored testing reported in Durbin 2011 is the sole source of B5 testing cited by CARB as support for the Proposed Rule. Durbin 2011 publishes only portions of the measured emissions data in a form that permits re-analysis; it does not publish any of the B5 data in such a form. It has not been possible to obtain the remaining data through a personal request to Durbin or an official public records request to CARB and, to the best of our knowledge, the data are not otherwise available online or through another source.

CARB should publish all of the testing presented in Durbin 2011 and any future testing that it sponsors in a complete format that allows for re-analysis. Such a format would be (a) the measured emission values for each individual test replication; or (b) averages across all test replications, along with the number of replications and the standard error of the individual tests. The first format (individual test replications) is preferable because that would permit a full examination of the data including effects such as test cell drift over time. Such publication is necessary to assure that full public disclosure is achieved and that future proposed rules are fully and adequately informed by the data.

[8] As discussed in Section 3.3, the pair-wise t-test is not the preferred method for demonstrating statistical significance.

1.3 Review of 2013 CARB B5 Emission Testing

In December 2013, after the release of the ISOR and in response to an earlier Public Records Act request, CARB released a copy of new CARB-sponsored emission testing conducted by Durbin and others at the University of California CE-CERT[9]. The purpose of the study was "*... to evaluate different B5 blends as potential emissions equivalent biodiesel fuel formulations for California.*"[10] Three B5 blends derived from soy, waste vegetable oil (WVO), and animal biodiesel stocks were tested on one 2006 Cummins ISM 370 engine using the hot-start EPA heavy-duty engine dynamometer cycle. A preliminary round of testing was conducted for all three fuels followed by emissions-equivalent certification testing per 13 CCR 2282(g) for two of the fuels. As noted by Durbin: "*[t]he emissions equivalent diesel certification procedure is robust in that it requires at least twenty replicate tests on the reference and candidate fuels, providing the ability to differentiate small differences in emissions.*"[11]

Soy and WVO B5 Biodiesel

The B5-soy and B5-WVO fuels were blended from biodiesel stocks that were generally similar to the soy-based stock used in the earlier CARB Biodiesel Characterization Study (Durbin 2011) with respect to API gravity and cetane number. In the preliminary testing, the two fuels "*...showed 1.2-1.3% statistically significant [NOx emissions] increases with the B5-soy and B5-WVO biodiesel blends compared to the CARB reference fuel.*"[12] The B5-WVO fuel caused the smaller NOx increase (1.2%) and was selected for the certification phase of the testing. There, it "*... showed a statistically significant 1.0% increase in NOx compared to the CARB reference fuel*"[13] and failed the emissions-equivalent certification due to NOx emissions.

Animal B5 Biodiesel

The B5-animal derived fuel was blended from an animal tallow derived biodiesel that was substantially different from the animal based biodiesel used in the earlier Durbin study, and was higher in both API gravity and cetane number. The blending response for cetane number was also surprising, in that blending 5 percent by volume of a B100 stock (cetane number 61.1) with 95% of CARB ULSD (cetane number 53.1) produced a B5 fuel blend with cetane number 61.

In preliminary testing, the B5-animal fuel showed a small NOx increase which was not statistically significant, causing it to be judged the best candidate for emissions-equivalent certification. In the certification testing, it "*...showed a statistically*

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[9] "*CARB B5 Biodiesel Preliminary and Certification Testing*." Prepared by Thomas D. Durbin, G. Karavalakis and others. Prepared for Alexander Mitchell, California Air Resources Board. July 2013. This study is not referenced in the ISOR, nor was it included in the rule making file when the hearing notice for the ADF regulation was published in October 2013.
[10] Ibid, p. vi.
[11] Ibid, p. viii.
[12] Ibid, p. 8.
[13] Ibid, p. 9.

significant 0.5% reduction in NOx compared to the CARB reference fuel"[13] and passed the emissions-equivalent certification. The NOx emission reduction for this fuel blend appears to be real for this engine, but given the differences between the blendstock and the animal based biodiesel blendstock used in the earlier Durbin study it is unclear that it is representative for animal-based biodiesels in general..

Summary

The conclusions drawn in the preceding section are not changed by the consideration of these new emission testing results. For plant-based biodiesels (soy- and WVO-based), the new testing provides additional and statistically significant evidence that B5 blends ***will*** increase NOx emissions at the B5 level. The result of decreased NOx for the B5 animal-based blend stands out from the general trend of research results reviewed in this report. However:

- The same result – reduced NOx emissions for some fuels and engines – has sometimes been observed in past research, as evidenced by the emissions data considered by CARB staff in ISOR Figure B.3 (reproduced in Figure 2.1 below). As shown, some animal-based B5 and B20 fuels reduced NOx emissions while others increased NOx emissions with the overall conclusion being that NOx emissions increase in direct proportion to biodiesel content of the blends and that there is no emissions threshold.

- Increasing cetane is known to generally reduce NOx emissions and has already been proposed by CARB as a mitigation strategy for increased NOx emissions from biodiesel[14]. The unusual cetane number response in the blending and the high cetane number of the B5-animal fuel may account for the results presented in the recently released study.

Considering the broad range of plant- and animal-based biodiesel stocks that will be used in biodiesel fuels, we conclude that the available research (including the recently released CARB test results) indicates that unrestricted biodiesel use at the B5 level will cause real increases in NOx emissions and that countermeasures may be required to prevent increases in NOx emissions due to biodiesel use at blending levels below B10.

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[14] For example, see Durbin 2011 Section 7.0 for a discussion of NOx mitigation results through blending of cetane improvers and other measures.

2. CARB LITERATURE REVIEW

The Staff ISOR explains that the Appendix B Technology Assessment is the basis for CARB's conclusion that biodiesels below B10 have no significant impact on NOx emissions. The assessment is based on data from seven studies (identified in Table 2-1) that tested high-cetane diesel fuels. The first study (Durbin 2011) is the Biodiesel Characterization Study that was conducted for CARB, while the others were obtained through a literature search.

Table 2-1
List of Studies from High-Cetane Literature Search

Primary Author	Title	Published	Year
Durbin	Biodiesel Mitigation Study	Final Report Prepared for Robert Okamoto, M.S. and Alexander Mitchell, CARB	2011
Clark	Transient Emissions Comparisons of Alternative Compression Ignition Fuel	SAE 1999-01-1117	1999
Eckerle	Effects of Methyl Ester Biodiesel Blends on NOx Emissions	SAE 2008-01-0078	2008
McCormick	Fuel Additive and Blending Approaches to Reducing NOx Emissions from Biodiesel	SAE 2002-01-1658	2002
McCormick	Regulated Emissions from Biodiesel Tested in Heavy-Duty Engines Meeting 2004 Emissions	SAE 2005-01-2200	2005
Nuszkowski	Evaluation of the NOx emissions from heavy duty diesel engines with the addition of cetane improvers	Proc. I Mech E Vol. 223 Part D: J. Automobile Engineering, 223, 1049-1060	2009
Thompson	Neat fuel influence on biodiesel blend emissions	Int J Engine Res Vol. 11, 61-77.	2010

Source: Table B.2 of Durbin 2011

Figure 2-1 reproduces two exhibits from Appendix B that show increasing trends for NOx emissions with the biodiesel blending level. Based on the slopes of the trend lines,

Figure 2-1
NOx Emission Increases Observed in Biodiesel Research Cited in Staff ISOR

Figure B.2: NOx Impact of Soy Biodiesel Blended in High Cetane Base Fuel

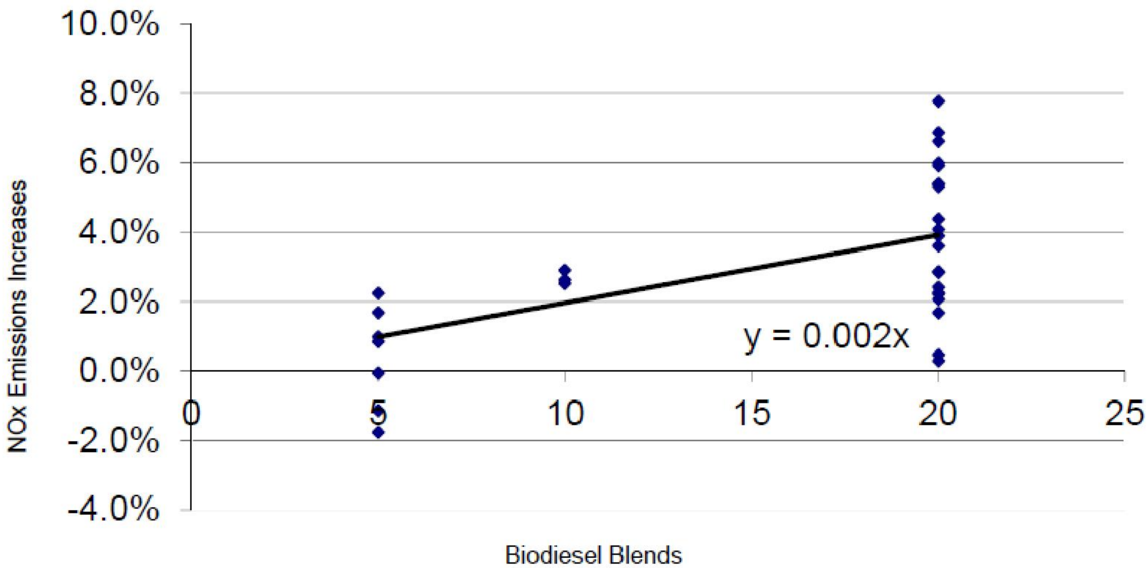
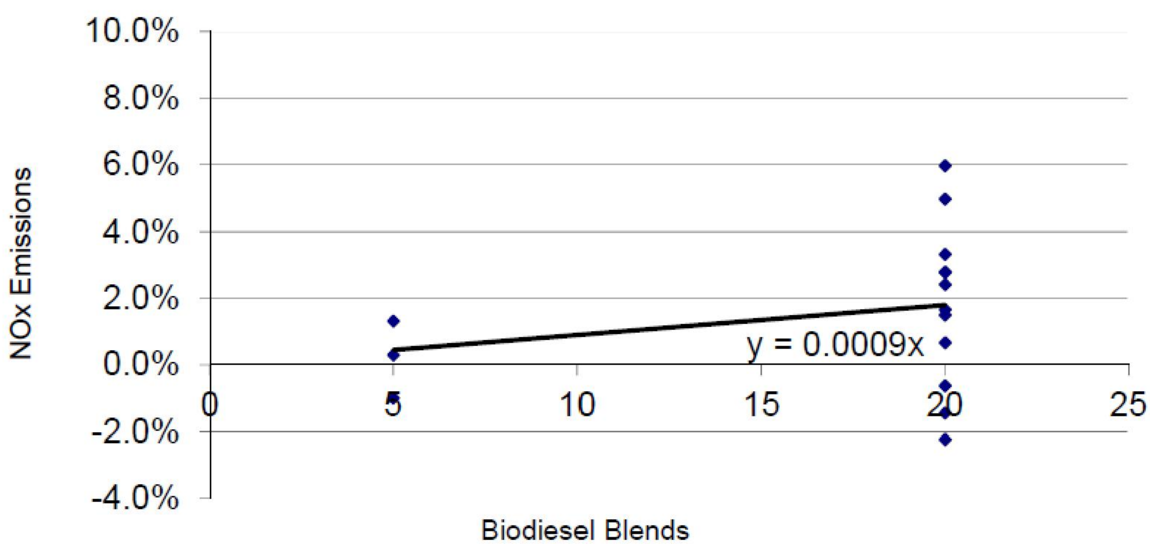


Figure B.3: NOx Impact of Animal Biodiesel Blended in High Cetane Base Fuel



Source: Figures B.2 and B.3 of Appendix B: Technology Assessment soy-based biodiesels are shown to increase NOx emissions by approximately 1% at B5, 2% at B10, and 4% at B20. Animal-based biodiesels are shown to increase NOx emissions by about one-half as much: 0.45% at B5, 0.9% at B10, and 1.8% at B20. Although there is substantial scatter in the results, these data do not appear to support the Staff Threshold Model that biodiesel does not increase NOx emissions at B5 but does so at B10.

We will examine the Durbin 2011 study at some length in Section 3. In this section, we look at each of the other studies cited by the Staff to find out what the studies say about NOx emissions impacts at and below B10.

2.1 Review of Literature Cited in the ISOR

The Staff literature search sought and selected testing that used fuels with cetane levels comparable to California diesel fuels; the Staff does not, however, list those fuels or provide the data that support the tables and figures in Appendix B of the ISOR. Therefore, we have necessarily made our own selection of high-cetane fuels in the course of reviewing the studies. The key testing and findings of each study are summarized below, with a specific focus on what they tell us about NOx emission impacts at B10 and below.

2.1.1 Clark 1999

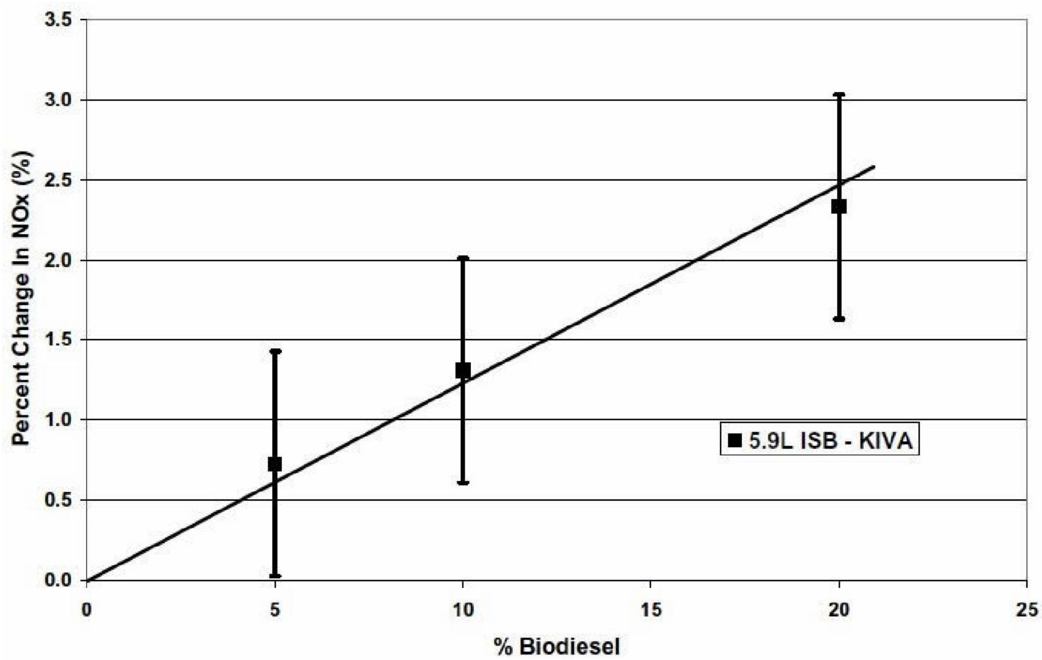
This study tested a variety of fuels on a 1994 7.3L Navistar T444E engine. Of the high-cetane base fuels, one base fuel (Diesel A, off-road LSD) was blended and tested at levels of B20, B50, and B100. NOx emissions were significantly increased for all of the blends. The other base fuel (CA Diesel) was tested only as a base fuel. Its NOx emissions were 12% below that of Diesel A, making it is unclear whether Diesel A is representative of fuels in CA. This study conducted no testing of the NOx emissions impact from biodiesels at the B10 level or below.

2.1.2 Eckerle 2008

This study tested low and mid/high-cetane base fuels alone and blended with soy-based biodiesel at the B20 level. The Cummins single-cylinder test engine facility was used in a configuration representative of modern diesel technology, including cooled EGR. Testing was conducted under a variety of engine speed and load conditions. FTP cycle emissions were then calculated from the speed/load data points. The test results show that B20 blends increase NOx emissions compared to both low- and high-cetane base fuels. This study conducted no testing of the NOx emissions impact from biodiesels at the B10 level or below.

The study notes that two other studies “show that NOx emissions increase nearly linearly with the increase in the percentage of biodiesel added to diesel fuel.” Eckerle’s Figure 21 (reproduced below as Figure 2-2) indicates a NOx emissions increase at B5, which is the basis for the statement in the abstract that “Results also show that for biodiesel blends containing less than 20% biodiesel, the NOx impact over the FTP cycle is proportional to the blend percentage of biodiesel." The authors clearly believe that biodiesel fuels have NOx emission impacts proportional to the blending percent at all levels including B5.

Figure 2-2
Impact of Biodiesel Blends on Percent NOx Change for the 5.9L ISB Engine Operation Over the FTP Cycle



Source: Figure 21 of Eckerle 2008

2.1.3 McCormick 2002

This study tested low- and mid-cetane base fuels alone and blended with soy- and animal-based biodiesel at the B20 level. The testing was conducted on a 1991 DDC Series 60 engine using the hot-start U.S. heavy-duty FTP. NOx emission increases were observed for both fuels at the B20 level. Mitigation of NOx impacts was investigated by blending a Fisher-Tropsch fuel, a 10% aromatics fuel and fuel additives. This study conducted no testing of the NOx emissions impact from commercial biodiesels at the B10 level or below.

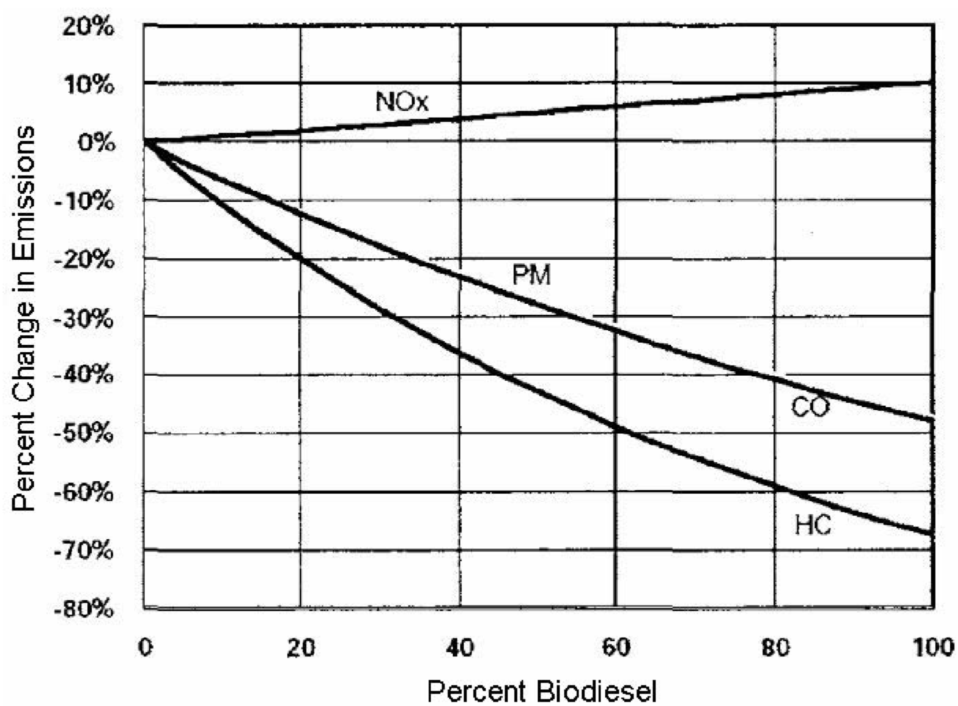
This study also tested a Fisher-Tropsch (FT) base fuel blended at the B1, B20, and B80 levels. Although the very high cetane number (≥75) takes it out of the range of commercial diesel fuels, it is interesting to note that the study measured higher NOx emissions at the B1 level than it did on the FT base fuel and substantially higher NOx emissions at the B20 and B80 levels. While the B1 increase was not statistically significant given the uncertainties in the emission measurements (averages of three test runs), it is clear that increased NOx emissions have been observed at very low blending levels.

2.1.4 McCormick 2005

This study tested blends of soy- and animal-based biodiesels with a high-cetane ULSD base fuel at B10 levels and higher. Two engines were tested – a 2002 Cummins ISB and a 2003 DDC Series 60, both with cooled EGR. The hot-start U.S. heavy-duty FTP test cycle was used. The majority of testing was at the B20 level with additional testing at the B50 and B100 levels. One soy-based fuel was tested at B10. The study showed NOx emission increases at B10, B20, and higher levels. The study also investigated mitigation of NOx increases. This study conducted no testing of the NOx emissions impact from biodiesels below the B10 level.

The authors present a figure (reproduced as Figure 2-3) in their introduction that shows their summary of biodiesel emission impacts based on an EPA review of heavy-duty engine testing. It shows NOx emissions increasing linearly with the biodiesel blend percentage.

Figure 2-3
Trend in HC, CO, NOx and PM Emissions with Biodiesel Percent



Source: McCormick 2005

2.1.5 Nuszkowski 2009

This study tested five different diesel engines: one 1991 DDC Series 60, two 1992 DDC Series 60, one 1999 Cummins ISM, and one 2004 Cummins ISM. Only the 2004 Cummins ISM was equipped with EGR. All testing was done using the hot-start U.S. heavy-duty FTP test cycle. The testing was designed to test emissions from fuels with and without cetane-improving additives. Although a total of five engines were tested, the base diesel and B20 fuels were tested on only two engines (one Cummins and one DDC Series 60) because there was a limited supply of fuel available. NOx emissions increased on the B20 fuel for both engines. A third engine (Cummins) was tested on B20 and B20 blended with cetane improvers to examine mitigation of NOx emissions. This study conducted no testing of the NOx emissions impact from biodiesels at the B10 level or below.

2.1.6 Thompson 2010

This study examined the emissions impacts of soy-based biodiesel at the B10 and B20 levels relative to low-cetane (42), mid-cetane (49), and high-cetane (63) base fuels using one 1992 DDC Series 60 engine. The emissions results were measured on the hot-start U.S. heavy-duty FTP cycle. The study found that NOx emissions were unchanged (observed differences were not statistically significant) at B10 and B20 levels for the low- and mid-cetane fuels. NOx emissions increased significantly at B10 and B20 levels for the high-cetane fuels. This study conducted no testing of the NOx emissions impact from biodiesels at levels below B10.

2.2 Conclusions Based on Studies Obtained in Literature Search

From the foregoing summary of the studies cited by Staff, we reach the conclusions given below.

1. None of the six studies measured the NOx emissions impact from commercial-grade biodiesel at blending levels below B10, and only two studies tested a fuel at the B10 level. All other testing was at the B20 level or higher. Because none tested a B5 (or similar) fuel, none is capable of providing direct evidence regarding NOx emissions at B5 or other blending levels below B10.

2. These studies provide no data or evidence supporting the validity of Staff's Threshold Model that biodiesel below B10 does not increase NOx emissions. In fact, all of the studies are consistent with the contention that biodiesel increases NOx emissions in proportion to the blending percent.

3. Two of the studies present evidence and arguments that the NOx impact from biodiesel is a continuous effect that is present even at very low blending levels and will increase at higher levels in proportion to the blending percentage. One study tested a Fischer-Tropsch biodiesel blend at B1 and observed NOx emissions to increase (but not by a statistically significant amount).

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3. CARB BIODIESEL CHARACTERIZATION STUDY

3.1 Background

CARB sponsored a comprehensive study of biodiesel and other alternative diesel blends in order "… to better characterize the emissions impacts of renewable fuels under a variety of conditions."[15] The study was designed to test eight different heavy- duty engines or vehicles, including both highway and off-road engines using engine or chassis dynamometer testing. Five different test cycles were used: the Urban Dynamometer Driving Schedule (UDDS), the Federal Test Procedure (FTP), and 40 mph and 50 mph CARB heavy-heavy-duty diesel truck (HHDDT) cruise cycles, and the ISO 8178 (8 mode) cycle. Table 3-1 (reproduced from Table ES-1 of Durbin 2011) documents the scope of the test program. Because the Staff relied only on engine dynamometer testing in its Technology Assessment, only the data for the first four engines (shaded) are considered here.

Table 3-1
A Breakdown of the Test Engines for the Different Categories of Testing

2006 Cummins ISM[a]	Heavy-duty on-highway	Engine dynamometer	
2007 MBE4000	Heavy-duty on-highway	Engine dynamometer	
1998, 2.2 liter, Kubota V2203-DIB	Off-road	Engine dynamometer	
2009 John Deere 4.5 L	Off-road	Engine dynamometer	
2000 Caterpillar C-15	Heavy-duty on-highway	Chassis dynamometer	Freightliner chassis
2006 Cummins ISM	Heavy-duty on-highway	Chassis dynamometer	International chassis
2007 BME4000	Heavy-duty on-highway	Chassis dynamometer	Freightliner chassis
2010 Cummins ISX15	Heavy-duty on-highway	Chassis dynamometer	Kenworth chassis

Source: Table ES-1 of Durbin 2011, page xxvi
Notes:
[a] Data for the first four engines (shaded) are considered in this report.

[15] Durbin 2011, p. xxiv.

The original goal of this report was to subject all of the NOx emission testing in Durbin 2011 to a fresh re-analysis. However, it was discovered that Durbin 2011 did not report all of the data that were obtained during the program and are discussed in the report. The chassis dynamometer testing was conducted at the CARB Los Angeles facility. Emission results for the chassis dynamometer testing are presented in tabular and graphical form, but the report does not contain the actual emissions test data. For the engine dynamometer testing, some of the measured emission values are not reported even though the emission results are reported in tabulated or graphical form. Requests for the missing data were directed to Durbin in a personal request and to CARB through an official records request. No information has been provided in response and we have not been able to obtain the missing data from online or other sources.

For this report, we have worked with the data in the forms that are provided in Durbin 2011 as being the best-available record of the results of the CARB study. Because Staff used only data obtained in engine dynamometer testing, the analysis presented in this report has done the same. Nevertheless, the results of the chassis dynamometer testing are generally supportive of the results and conclusions presented here. Durbin 2011 notes:

> *"… The NOx emissions showed a consistent trend of increasing emissions with increasing biodiesel blend level. These differences were statistically significant or marginally significant for nearly all of the test sequences for the B50 and B100 fuels, and for a subset of the tests on the B20 blends."*[16]

Durbin notes that emissions variability was greater in the chassis dynamometer testing, which leads to the sometimes lower levels of statistical significance. There was also a noticeable drift over time in NOx emissions that complicated the results for one engine.

3.2 Data and Methodology

Table 3-2 compiles descriptive information on the engine dynamometer testing performed in Durbin 2011. The experimental matrix involves four engines, two types of biodiesel fuels (soy- and animal-based), and up to four test cycles per engine. However, the matrix is not completely filled with all fuels tested on all engines on all applicable test cycles. The most complete testing is for the ULSD base fuel and B20, B50, and B100 blends. There is less testing for the B5 blend, and B5 is tested using only a subset of cycles. For this reason, we first examine the testing for ULSD, B20, B50, and B100 fuels to determine the overall impact of biodiesels on NOx emissions. We then examine the more limited testing for B5 to determine the extent to which it impacts NOx emissions.

This examination is limited by the form in which emissions test information is reported in Durbin 2011. A complete statistical analysis can be conducted only for the two on-road engines for which Appendices G and H of Durbin 2011 provide measured emissions, and for a portion of the testing of the Kubota off-road engine for which Appendix I provides

[16] Durbin 2011, p. 126.

<table>
<tr><th colspan="5">Table 3-2
Experimental Matrix for Heavy-Duty Engine Dynamometer
Testing Reported in Durbin 2011</th></tr>
<tr><th>Engine</th><th>Biodiesel Type</th><th>Fuels Tested</th><th>Test Cycles</th><th>Notes</th></tr>
<tr><td colspan="5">On-Road Engines</td></tr>
<tr><td rowspan="2">2006 Cummins ISM</td><td>Soy</td><td>ULSD, B20, B50, B100, B5</td><td>UDDS, FTP, 40 mph, 50 mph</td><td>B5 tested on 40 mph and 50 mph cruise cycles</td></tr>
<tr><td>Animal</td><td>ULSD, B20, B50, B100, B5</td><td>UDDS, FTP, 50 mph</td><td>B5 tested only on FTP.</td></tr>
<tr><td rowspan="2">2007 MBE4000</td><td>Soy</td><td>ULSD, B20, B50, B100, B5</td><td rowspan="2">UDDS, FTP, 50 mph</td><td>B5 tested only on FTP.</td></tr>
<tr><td>Animal</td><td>ULSD, B20, B50, B100, B5</td><td>B5 tested only on FTP.</td></tr>
<tr><td colspan="5">Off-Road Engines</td></tr>
<tr><td rowspan="2">1998 Kubota V2203-DIB</td><td>Soy</td><td>ULSD, B20, B50, B100, B5</td><td rowspan="2">ISO 8178 (8 Mode)</td><td rowspan="2">none</td></tr>
<tr><td>Animal</td><td>Not tested</td></tr>
<tr><td rowspan="2">2009 John Deere</td><td>Soy</td><td>ULSD, B20, B50, B100</td><td rowspan="2">ISO 8178 (8 Mode)</td><td>B5 not tested</td></tr>
<tr><td>Animal</td><td>ULSD, B20, B5</td><td>none</td></tr>
</table>

measured emissions. The data needed to support a full re-analysis consist of measured emissions on each fuel in gm/hp-hr terms, which are stated in Durbin 2011 as averages across all test replications along with the number of replications and the standard error of the individual tests. With this information, the dependence of NOx emissions on biodiesel blending percent can be determined as accurately as if the individual test values had been reported and the appropriate statistical tests for the significance of results can be performed.

Regression analysis is used as the primary method of analysis. For each engine and test cycle, the emission averages for each fuel are regressed against the biodiesel blending percent to determine a straight line. The regression weights each data point in inverse proportion to the square of its standard error to account for differences in the number and reliability of emission measurements that make up each average. The resulting regression line will pass through the mean value estimated from the data (i.e., the average NOx emission level at the average blending percent), while the emission averages for each fuel may scatter above and below the regression line due to uncertainties in their measurement. The slope of the line estimates the dependence of NOx emissions on the blending percentage.

Where the data points closely follow a straight line and the slope is determined to be statistically significant, one can conclude that blending biodiesel with a base fuel will increase NOx emissions in proportion to the blending percent. The regression line can then be used to estimate the predicted emissions increase for a given blending percent. The predicted emissions increase is the value one would expect on average over many measurements and is comparable to the average emissions increase one would expect in a fleet of vehicles.

The same level of analysis is not possible for the testing on B5 fuel, which is reported as a simple average for the on-road engines and is not reported at all for the off-road engines. For the B5 fuel, Durbin 2011 presents emission test results in a tabulated form where the percentage change in NOx emissions has been computed compared to ULSD base fuel. This form supports the presentation of results graphically, but it does not permit a proper statistical analysis to be performed. Specifically, the computation of percentage emission changes will perturb the error distribution of the data, by mixing the uncertainty in measured emissions on the base fuel with the uncertainties in measured emissions on each biodiesel blend, and it can introduce bias as a result of the mixing. Further statistical analysis of the computed percent values should be avoided because of these problems. Therefore, a more limited trend analysis of the NOx emissions data for B5 and the John Deere engine is conducted.

3.3 2006 Cummins Engine (Engine Dynamometer Testing)

Table 3-3 shows the NOx emission results for the 2006 model-year Cummins heavy-duty diesel engine based on a re-analysis of the data for this report. As indicated by highlighting in the table, the relationship between increasing biodiesel content and increased NOx emissions for soy-based biodiesel is statistically significant at >95% confidence level[17] in all cases. For the animal-based biodiesel, the relationship is statistically significant at the 92% confidence level for the UDDS cycle, the 94% confidence level for the 50 mph cruise, and the >99% confidence level for the FTP cycle.

For the soy-based fuels, the R^2 statistics show that the emissions effect of biodiesel is almost perfectly linear with increasing biodiesel content over the range B20, B50, and B100. Although not as high for the animal-based fuels (because the emissions effect is smaller and measurement errors are relatively larger in comparison to the trend), the R^2 statistics nevertheless establish a linear increase in NOx emissions with increasing biodiesel content over the same range. The linearity of the response with blending percent is well supported by the many NOx emissions graphs contained in Durbin 2011.

The table also gives the estimated NOx emission increases for B5 and B10 as predicted by the regression lines. For soy-based fuels, the values are 1% for B5 (range 0.8% to 1.3% depending on the cycle) and 2% for B10 (range 1.6% to 2.6% depending on cycle).

[17] A result is said to be statistically significant at the 95% confidence level when the p value is reported as $p \le 0.05$. At the $p \le 0.01$ level, a result is said to be statistically significant at the 99% confidence level, and so forth.

Table 3-3
Re-Analysis for 2006 Cummins Engine (Engine Dynamometer Testing)
Model: NOx = A + B · BioPct
Using ULSD, B20, B50, and B100 fuels

Biodiesel Type	Test Cycle	R^2	Intercept A	BioPct Slope B		Predicted NOx Increase for B5	Predicted NOx Increase for B10
			Value	Value	p value	Pct Change	Pct Change
Soy-based							
	UDDS	0.997	5.896	0.0100 [a]	0.001	0.8%	1.7%
	FTP	0.995	2.024	0.0052	0.003	1.3%	2.6%
	40 mph	1.000	2.030	0.0037	<0.0001	0.9%	1.8%
	50 mph	0.969	1.733	0.0028	0.016	0.8%	1.6%
Animal-based							
	UDDS	0.847	5.911	0.0021 [b]	0.080	0.2%	0.4%
	FTP	0.981	2.067	0.0031	0.001	0.7%	1.4%
	50 mph	0.887	1.768	0.0011	0.058	0.3%	0.6%

Notes:
[a] Blue highlight indicates result is statistically significant at the 95% confidence level or better.
[b] Orange highlight indicates result is statistically significant at the 90% confidence level or better.

For animal-based fuels, the values are approximately one-half as large: 0.4% for B5 (range 0.2% to 0.7%) and 0.8% for B10 (range 0.4% to 1.4%). These predicted increases are statistically significant to the same degree as the slope of the regression line from which they are estimated. That is, the NOx increases predicted by the regression line for soy-based fuels are statistically significant at the 95% confidence level (or better) on all cycles and the predicted NOx increases for animal-based fuels are statistically significant at the 90% confidence level (or better) on all cycles and at the >99% confidence level for the FTP.

Because the limited data on B5 were not used to develop the regression lines for each cycle, and no test data on B10 are available, use of the lines to make predictions for B5 and B10 depends on their linearity over the range between ULSD and B20. Based on the R^2 statistics and the graphs in Durbin 2011, the slopes observed between ULSD and B20 are the same as the slopes observed between B20 and B100 for each of the test cycles. We believe that the linearity of the response with blending percent for values over the range ULSD to B100 would be accepted by the large majority of researchers in the field, as would the use of regression analysis to make predictions for B5 and B10.

The Durbin 2011 report takes a different approach for determining the statistical significance of NOx emission increases for each fuel. For each fuel tested, it computes a percentage change in emissions for NOx (and other pollutants) relative to the ULSD base fuel. It then determines the statistical significance of each observed change using a conventional t-test for the difference of two mean values (2-tailed, 2 sample equal variance t-test). The t-test is conducted on the measured emission values before the percentage emission change is computed.

The t-test would be the appropriate approach for determining statistical significance if only two fuels were tested. However, it is a simplistic approach when three or more fuels are tested because it is applied on a pair-wise basis (B5 vs. ULSD, B20 vs. ULSD, etc.) and does not make use of all of the data that is available. It will have less power than the regression approach to detect emission changes that are real. This limitation is in one direction, however, in that the test is too weak when 3 or more data points are available, but a finding of statistical significance is valid when it occurs. As long as the linear hypothesis is valid, the regression approach should be the preferred method for analysis and for the determination of whether biodiesel blending significantly increases NOx emissions.

Because emission changes will be smallest for B5 (because of the low blending volume), the pair-wise t-test is most likely to fail to find statistical significance at the B5 level. In cases where the pair-wise t-test for B5 says that the emission change vs. ULSD is not statistically significant – but slope of the regression line is statistically significant – the proper conclusion is that additional B5 testing (to improve the precision of the emission averages) would likely lead to the detection of a statistically significant B5 emissions change using the t-test. In this case, the failure to find statistical significance using the t-test is not evidence that B5 does not increase NOx emissions.

For this engine, soy-based B5 was tested on the 40 mph and 50 mph cruise cycles and animal-based B5 was tested on the FTP. To examine this matter further, Table 3-4 reproduces NOx emission results reported in Tables ES-2 and ES-3 of Durbin 2011. Soy-based B5 was shown to increase NOx emissions on the 40 mph cruise cycle, but not on the 50 mph cruise cycle. Animal-based B5 was shown to increase NOx emissions on the FTP. Durbin 2011 noted (p. xxxii) that "[t]he 50 mph cruise results were obscured, however, by changes in the engine operation and control strategy that occurred over a segment of this cycle." Therefore, we discount the 50 mph cruise results and do not consider them further. Neither of the remaining B5 NOx emission increases (for the 40 mph Cruise and FTP cycles) were found to be statistically significant using the t-test, although the 40 mph cruise result for soy-based fuels comes close to being marginally significant (it would be statistically significant at an 86.5% level). The NOx emission increases at higher blending levels were found have high statistical significance (>99% confidence level).

This format, used throughout Durbin 2011 to report emission test data and to show the effect of biodiesel on emissions, is subject to an important statistical caveat. The percent changes are computed by dividing the biodiesel emission values by the emissions measured for the ULSD base fuel. Therefore, measurement errors in the ULSD measurement are blended with the measurement errors for each of the biodiesel fuels. The blending of errors in each computed percent change can bias the apparent trend of emissions with increasing biodiesel content. As will be shown in Section 3.3.2, we can see this problem in the animal-based B5 test data for this engine.

Table 3-4 Percentage Change in NOx Emissions for Biodiesel Blends Relative to ULSD: 2006 Cummins Engine (Engine Dynamometer Testing)						
	Soy-based Biodiesel				Animal-based Biodiesel	
	40 mph Cruise		50 mph Cruise		FTP	
	NOx % Diff	p value	NOx % Diff	p value	NOx % Diff	p value
B5	1.7%	0.135	-1.1%	0.588	0.3%	0.298
B20	3.9% [a]	0.000	0.5%	0.800	1.5%	0.000
B50	9.1%	0.000	6.3%	0.001	6.4%	0.000
B100	20.9%	0.000	18.3%	0.000	14.1%	0.000

Source: Table ES-2 and ES-3 of Durbin 2011, p. xxviii

Notes:

[a] Blue highlight indicates result is statistically significant at the 95% confidence level or better based on the pair-wise t-test.

3.3.1 NOx Impact of Soy-based Biodiesel at the B5 Level

Figures 3-1a and 3-1b display the trend of NOx emissions with blending percent for the soy-based biodiesel on the 40 mph cruise cycle. Figure 3-1a plots the percentage increases as reported by Durbin 2011 in contrast to two different analytical models for the relationship:

- The Linear Model shown by the blue line; and
- The Staff Threshold model (black line), in which the NOx emission change is zero through B9 and then increases abruptly to join the linear model.

In Figure 3-1a, the linear model is an Excel trendline for the computed percent changes. While the data violate a key assumption for the proper use of regression analysis, this approach is the only way to establish a trendline given the form in which Durbin 2011 tabulates the data and presents the results of its testing.

Figure 3-1b plots the actual measured emission values in g/bhp-hr terms in contrast to the same two analytical models. Here, the linear model line is determined through a proper use of regression analysis, in which each emission average in g/bhp-hr terms is weighted inversely by the square of its standard error, using the data for ULSD, B20, B50 and B100 (i.e., excluding the B5 data point). In the case of this engine and biodiesel fuel, both forms of assessment show generally the same trend for NOx emissions as a function of blending percent. Although the NOx emission increases for B5 may fail the t-test for significance, emissions are increased at B5 and the B5 data point is fully consistent with the Linear Model. The Threshold model is clearly a less-satisfactory representation of the test data.

Figure 3-1a
Durbin 2011 Assessment: 40 mph Cruise Cycle NOx Emissions Increases for Soy-Biodiesel Blends (2006 Cummins Engine)

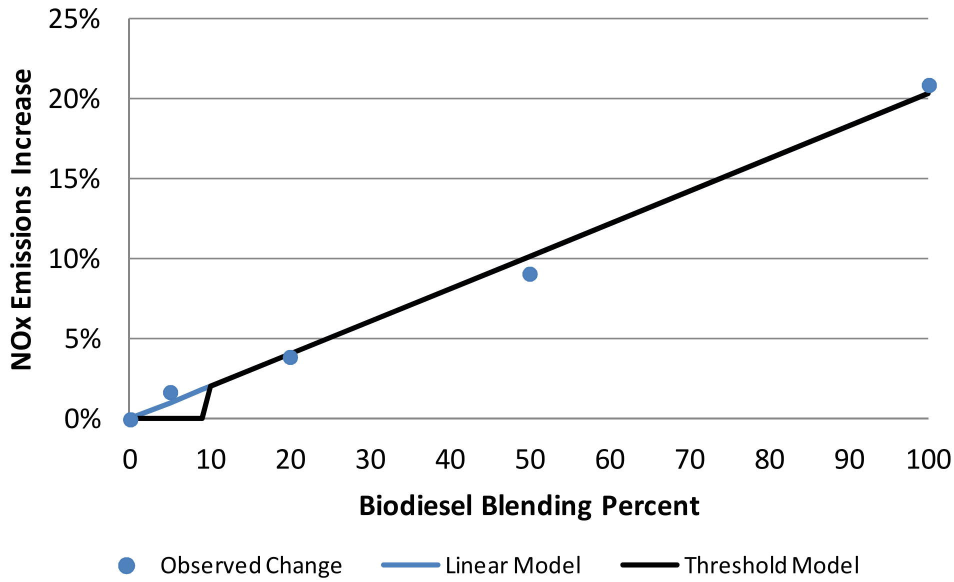
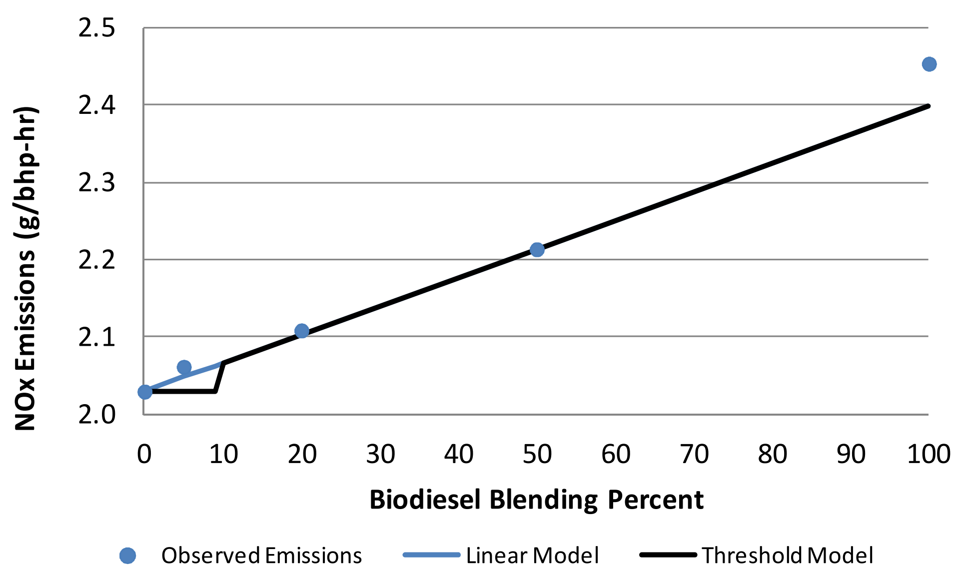


Figure 3-1b
Re-assessment of 40 mph Cruise Cycle NOx Emissions Increases for Soy-Biodiesel Blends (2006 Cummins Engine)



Note that the slope of the trendline (Figure 3-1a) is greater than the slope of the regression line (Figure 3-1b). In the latter figure, the B100 data point stands above the regression line, which passes below it. The regression line (but not the trendline) is fit in a manner that accounts for the uncertainties in each data point, so that the line will pass closer to points that have smaller uncertainties and farther from points that have greater uncertainties. For these data, the B100 data point has the largest uncertainty (±0.026 g/bhp-hr) followed by the B20 data point (±0.025 g/bhp-hr). The other three data points (ULSD, B5, and B50) have uncertainties less than ±0.001 g/bhp-hr. The B20 data point happens to fall on the line, but the B100 data point is found to diverge above. Because the regression analysis can account for the relative uncertainties of the data points, it provides a more accurate and reliable assessment of the impact on NOx emissions.

3.3.2 NOx Impact of Animal-based Biodiesel at the B5 level

Figures 3-2a and 3-2b display the trend of NOx emissions with blending percent for the animal-based biodiesel on the FTP test cycle as reported by Durbin 2011 and as re-assessed in this report using regression analysis, respectively. As Figure 3-2a shows, the NOx percent change values reported by Durbin 2011 appear to follow the Staff Threshold model in that NOx emissions are not materially increased at B5, but are increased significantly at B20 and above. As a result, the blue trendline in the figure (fit from the B20, B50 and B100 data points) has a negative intercept.

Figure 3-2b paints a very different picture from the data. Here, the ULSD and B5 data points stand above the weighted regression line (blue) developed from the data for ULSD, B20, B50 and B100. In the data used to fit the regression line, the ULSD data point has the largest uncertainty (±0.013 g/bhp-hr) while the other three data points (B20, B50, and B100) have uncertainties of ±0.002 g/bhp-hr (one case) and ±0.001 g/bhp-hr (two cases). Considering all of the data, the B5 data point has the second highest uncertainty (±0.007 g/bhp-hr). The regression line closely follows a linear model with a high R^2 (0.981) considering the weighted errors, while the ULSD and B5 points lie above it.

Because the ULSD data point is subject to more uncertainty and appears to be biased high compared to the regression line, the NOx percent changes computed by Durbin 2011 are themselves biased. The trendline result in Figure 3-2a that appeared to be supportive of the Staff Threshold model now appears to be the result of biases in the ULSD and B5 emission averages.

Two important conclusions can be drawn from the foregoing:

1. Accurate and reliable conclusions regarding the impact of B5 on NOx emissions cannot be drawn from the computed percent changes that are reported in Durbin 2011. Nor can accurate and reliable conclusions be drawn from visual inspection of graphs that present such data. Weighted regression analysis of the measured emission values (g/bhp-hr terms) must be performed so that the uncertainties in emissions measurements can be fully accounted for.

2. When a weighted regression analysis is performed using the testing for this engine, there is no evidence that supports the conclusion that B5 blends will not increase NOx emissions. In fact, the data are consistent with the conclusion that biodiesel increases NOx emissions in proportion to the blending percent.

Figure 3-2a
Durbin 2011 Assessment: FTP NOx Emissions Increases for Animal-based Biodiesel Blends (2006 Cummins Engine)

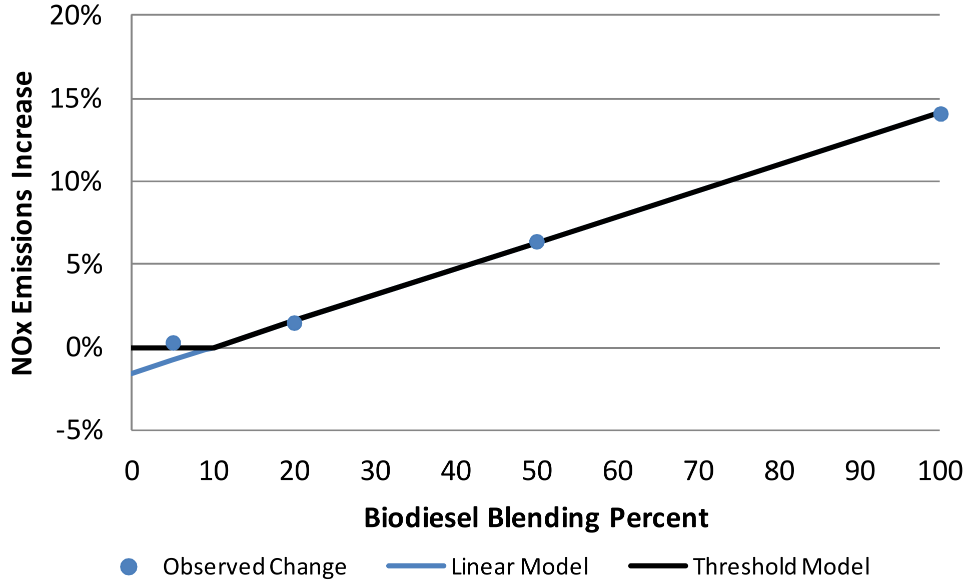
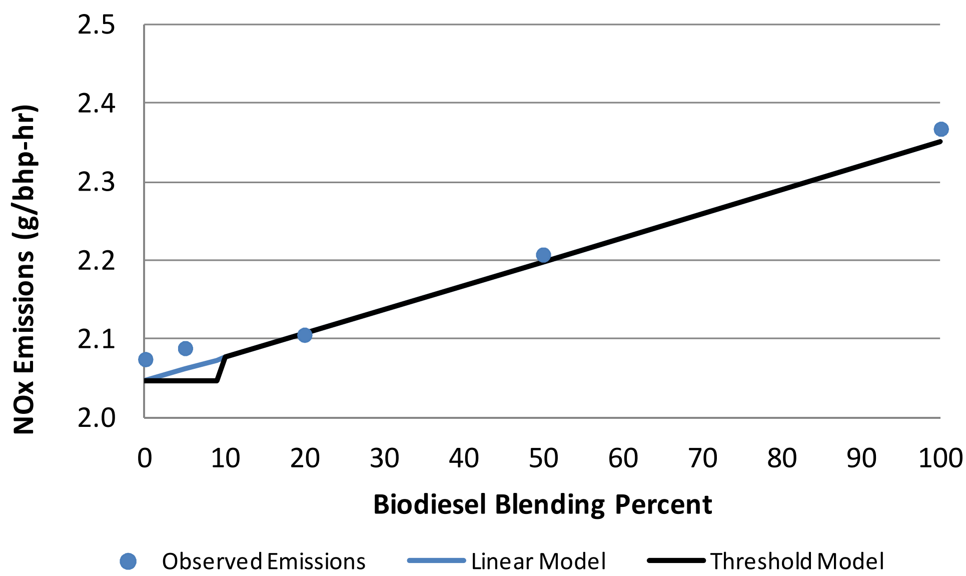


Figure 3-2b
Re-assessment of FTP NOx Emissions Increases for Animal-based Biodiesel Blends (2006 Cummins Engine)



3.4 2007 MBE4000 Engine (Engine Dynamometer Testing)

To analyze the data for the 2007 MBE4000 engine, it has proved necessary to remove two data points, one for the soy-based B20 fuel on the 50 mpg cruise cycle and one for the animal-based B50 fuel on the FTP test cycle:

- Appendix H reports the 50 mph cruise emission average for soy-based B20 to be 0.014 ± 0.020 g/bhp-hr. This value is implausible and wholly inconsistent with the NOx emission change of +6.9% reported in Table ES-4 of Durbin 2011, which would imply a NOx emission average of 1.21*1.069 = 1.30 g/bhp-hr.

- Appendix H reports the FTP emission average for the animal-based B50 fuel to be 2.592 ± 0.028 g/bhp-hr, which stands well above the other test data on animal-based biodiesel. This value is also inconsistent with the NOx emission change of +12.1% reported in Table ES-4 of Durbin 2011, which would imply a NOx emission average of 1.29*1.121 = 1.45 g/bhp-hr.

We believe these reported values are affected by typographical errors and have deleted them from the dataset used here.

With these corrections, Table 3-5 shows the results of the NOx emissions analysis for the 2007 model-year MBE4000 heavy-duty diesel engine. As indicated by highlighting in the table, the relationship between increasing biodiesel content and increased NOx emissions is statistically significant at >99% confidence level in two cases for soy-based biodiesel (the UDDS and FTP cycles) and at the 90% confidence level in one case (the 50 mph cycle). For the animal-based biodiesel, the relationship is statistically significant at the 96% confidence level for the UDDS cycle, the 98% confidence level for the FTP cycle, and >99% confidence level for the 50 mph cycle.

Durbin 2011 again notes a problem with the 50 mph cruise test results, saying (p. xxxii) that "[the NOx] trend was obscured, however, by the differences in engine operation that were observed for the 50 mph cruise cycle." Therefore, we will focus the discussion on the UDDS and FTP results.

For the soy-based fuels, the R^2 statistics show that the emissions effect of biodiesel is almost perfectly linear with increasing biodiesel content over the range from ULSD to B20, B50, and B100 for all cycles (including the 50 mph cruise). That is, the NOx emissions increase between ULSD and B20 shares the same slope as the NOx emissions increase between B20 and B100. For the animal-based biodiesel, the R^2 statistics also establish a linear increase in NOx emissions with increasing biodiesel content over the same range. The linearity of the response with blending percent is also well supported by the many NOx emissions graphs contained in Durbin 2011.

Table 3-5
Re-Analysis for 2007 MBE4000 Engine (Engine Dynamometer Testing)
Model: NOx = A + B · BioPct
Using ULSD, B20, B50, and B100 fuels

Biodiesel Type	Test Cycle	R^2	Intercept A	BioPct Slope B		Predicted NOx Increase for B5	Predicted NOx Increase for B10
			Value	Value	p value	Pct Change	Pct Change
Soy-based							
	UDDS	0.989	2.319	0.0090 [a]	0.005	4.6%	9.1%
	FTP	0.998	1.268	0.0049	0.006	2.5%	5.0%
	50 mph	0.979	1.198	0.0054 [b]	0.092	2.7%	5.5%
Animal-based							
	UDDS	0.913	2.441	0.0036	0.044	2.0%	4.0%
	FTP	0.999	1.288	0.0038	0.020	2.5%	5.0%
	50 mph	0.994	1.205	0.0049	0.003	2.5%	5.0%

Notes:
[a] Blue highlight indicates result is statistically significant at the 95% confidence level or better.
[b] Orange highlight indicates result is statistically significant at the 90% confidence level or better.

The table also gives the estimated NOx emission increases for B5 and B10 as predicted by the regression lines. For soy-based fuels, the values are ~3.5% for B5 (range 2.5% to 4.6% depending on the cycle) and ~7.5% for B10 (range 5.0% to 9.1% depending on cycle). For animal-based fuels, the values are approximately two-thirds as large: ~2.3% for B5 (range 2.0% to 2.5%) and ~4.5% for B10 (range 4.0% to 5.0%). The predicted increases are statistically significant to the same degree as the slope of the regression line from which they are estimated. That is, the predicted NOx increases are statistically significant at the >99% confidence level for soy-based fuels on the UDDS and FTP cycles and at the >95% confidence level for animal-based fuels on all cycles. The predicted NOx increase is statistically significant at the 90% confidence level for soy-based fuels on the 50 mph cruise cycle.

For this engine, soy- and animal-based B5 were tested on the FTP. Table 3-6 reproduces the NOx emission results reported in Tables ES-4 and ES-5 of Durbin 2011. While there are caveats on use of the pair-wise t-test, the FTP test data for this engine show NOx emissions at the B5 level for both soy- and animal-based fuels that are statistically significant at the 99% confidence level (or better) in this case. That is, the test data for this engine as reported by Durbin 2011 refute the Staff Threshold Model that biodiesel blends below B10 do not increase NOx emissions.

Table 3-6 **Percentage Change in NOx Emissions for Biodiesel Blends Relative to ULSD: 2007 MBE4000 Engine (Engine Dynamometer Testing)**				
	Soy-Based Biodiesel FTP		Animal-Based Biodiesel FTP	
	NOx % Diff	p value	NOx % Diff	p value
B5	0.9% [a]	0.007	1.3%	0.000
B20	5.9%	0.000	5%	0.000
B50	15.3%	0.000	12.1	0.000
B100	38.1%	0.000	29%	0.000

Source: Table ES-4/5 of Durbin 2011, p. xxix
Notes:
[a] Blue highlight indicates result is statistically significant at the 95% confidence level or better based on pair-wise t-test.

Figures 3-3a and 3-3b below compare the FTP data for this engine to the regression line representing the linear model (blue) and the Staff Threshold model (black) for both soy- and animal-based biodiesel. In both cases, the regression line was developed using the data for ULSD, B20, B50, and B100 (i.e., excluding the B5 data point). For both soy- and animal-based biodiesels, the data point for B5 falls on the established line, while the Staff Threshold model is inconsistent with the data. For this engine, it is clear that soy- and animal-based biodiesels increase NOx emissions at all blending levels.

Figure 3-3a
Re-assessment of FTP Cycle NOx Emissions Increases for Soy-based Biodiesel Blends (2007 MBE4000 Engine)

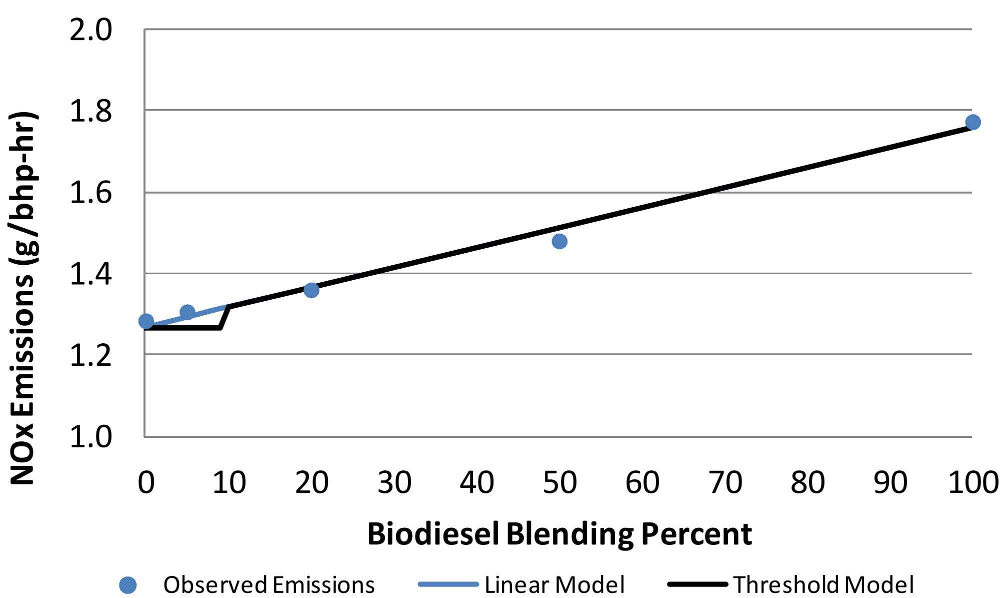
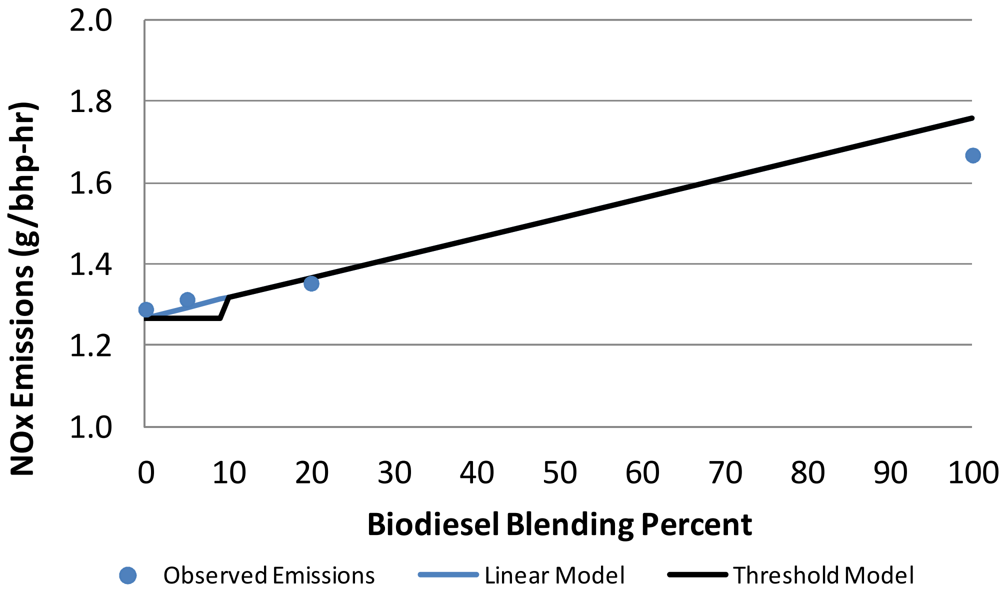


Figure 3-3b
Re-assessment of FTP Cycle NOx Emissions Increases for Animal-based Biodiesel Blends (2007 MBE4000 Engine)



3.5 1998 Kubota TRU Engine (Engine Dynamometer Testing)

The 1998 Kubota V2203-DIB off-road engine was tested on the base fuel (ULSD) and soy-based biodiesel at four blending levels (B5, B20, B50, B100) in two different series using the ISO 8178 (8-mode) test cycle. Appendix I reports the measured emissions data only for the first series (ULSD, B50, B100). Using this subset of data, Table 3-7 summarizes the results of the re-analysis for this engine.

As for the other engines, the results of the analysis demonstrate the following:

- The high R^2 statistic shows that the emissions effect of biodiesel is almost perfectly linear over the range B50 and B100. That is, the slope from ULSD to B50 is the same as the slope from B50 to B100. The slope of the regression line is statistically significant at the 99% confidence level.

- NOx emissions are estimated to increase by 1.0% at the B5 level and by 2.1% at the B10 level. These estimated NOx emission increases are statistically significant to the same high degree as the regression slope on which they are based.

Table 3-7 Re-Analysis for 1998 Kubota V2203-DIB Engine (Engine Dynamometer Testing) Model: NOx = A + B · BioPct Using ULSD, B50, and B100 fuels							
Biodiesel Type	Test Cycle	R^2	Intercept A	BioPct Slope B		Predicted NOx Increase for B5	Predicted NOx Increase for B10
			Value	Value	p value	Pct Change	Pct Change
Soy-based	ISO 8178	0.999	12.19	0.0256 [a]	0.01	1.0%	2.1%

Notes:
[a] Blue highlight indicates result is statistically significant at the 95% confidence level or better.

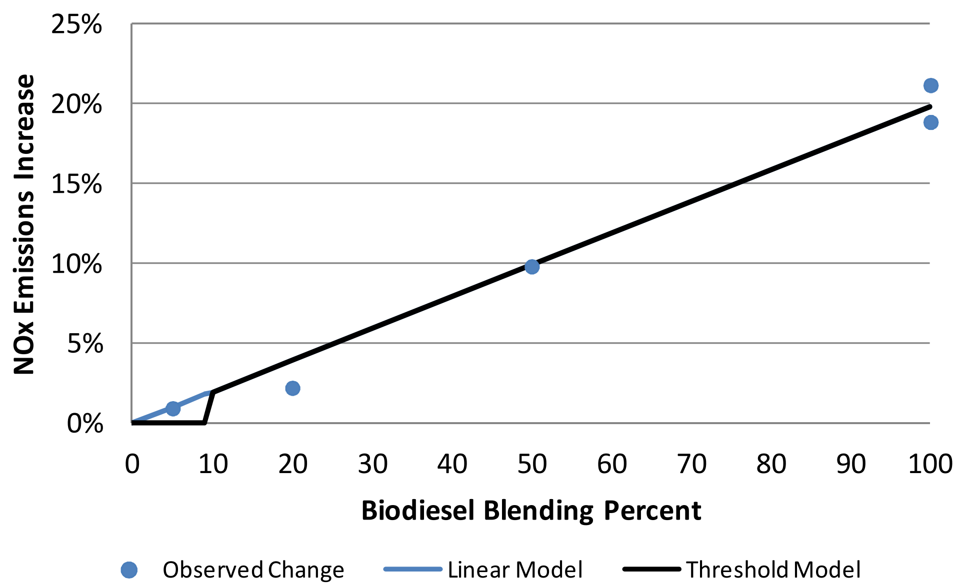
The second test series involved ULSD, B5, B20, and B100 fuels. Measured emissions data are not given in Appendix I, so we must work with the calculated percent changes in NOx emissions tabulated in Durbin 2011. Table 3-8 reproduces the NOx emission results reported in Table ES-8 of Durbin 2011 for the two test series. For the second test series, biodiesel at the B5 level increased NOx emissions, but the result fails the pair-wise t-test for statistical significance. The NOx emission increase at the B20 level was statistically significant at the 90% confidence level, and the increase at the B100 level was statistically significant at the >99% confidence level. The significance determinations use the pair-wise t-test, which is subject to caveats, but this is the only method available to gauge significance because re-analysis of the computed percentage changes is not possible.

Table 3-8 Percentage Change in NOx Emissions for Biodiesel Blends Relative to ULSD: 1998 Kubota TRU Engine (Engine Dynamometer Testing)				
	Soy-Based Biodiesel Series 1 ISO 8178		Soy-Based Biodiesel Series 2 ISO 8178	
	NOx % Diff	p value	NOx % Diff	p value
B5	Not tested		0.97%	0.412
B20	Not tested		2.25% [a]	0.086
B50	7.63% [b]	0.000	Not tested	
B100	13.76%	0.000	18.89%	0.000

Source: Table ES-8 of Durbin 2011, p. xxxviii
Notes:
[a] Orange highlight indicates result is statistically significant at the 90% confidence level or better based on pair-wise t-test.
[b] Blue highlight indicates result is statistically significant at the 95% confidence level or better based on pair-wise t-test

Figure 3-4 displays the trend of NOx emissions with blending percent for the first and second test series combined. As the figure shows, the available data points scatter around the trendline determined from the emission change percentages (not from regression analysis). The B20 data point falls below the trend line while the two B100 data points bracket the trend line. It is not possible to explain the divergence of the B20 data point

Figure 3-4
Durbin 2011 Assessment: ISO 8178 Cycle NOx Emissions Increases for Soy-based Biodiesel Blends (1998 Kubota Engine, Test Series 1 and 2 Combined)



because the emissions data for the second test series are not published in Durbin 2011. The B5 data point clearly supports the Linear Model and is inconsistent with the Staff Threshold Model.

3.6 2009 John Deere Off-Road Engine (Engine Dynamometer Testing)

The only information on the 2009 John Deere off-road engine comes from the tabulation of calculated percentage emission changes. Table 3-9 reproduces these data from Table ES-7 of Durbin 2011. For the soy-based biodiesel, NOx emissions are significantly increased at the B20 and higher blend levels. The increase for B20 is statistically significant at the 90% confidence level and the increases for B50 and B100 are statistically significant at the >99% confidence level based on the pair-wise t-test. A soy-based B5 fuel was not tested.

Table 3-9 **Percentage Change in NOx Emissions for Biodiesel Blends Relative to ULSD: 2009 John Deere Engine (Engine Dynamometer Testing)**				
	Soy-Based Biodiesel ISO 8178		Animal-Based Biodiesel ISO 8178	
	NOx % Diff	p value	NOx % Diff	p value
B5	Not tested		-3.82	0.318
B20	2.82% [a]	0.021	-2.20	0.528
B50	7.63%	0.000	Not tested	
B100	13.76%	0.000	4.57	0.000

Source: Table ES-7 of Durbin 2011, p. xxxviii
Notes:
[a] Blue highlight indicates result is statistically significant at the 95% confidence level or better based on pair-wise t-test.

For animal-based biodiesel, the testing shows the unusual result that B5 and B20 appear to decrease NOx emissions, while B100 increases NOx. The B5 and B20 decreases are not statistically significant, while the B100 increase is statistically significant at the >99% confidence level. Durbin 2011 concludes:

> *The animal-based biodiesel also did not show as great a tendency to increase NOx emissions compared to the soy-based biodiesel for the John Deere engine, with only the B100 animal-based biodiesel showing statistically significant increases in NOx emissions.*[18]

Durbin 2011 does not discuss these results further and does not note any problems in the testing, making further interpretation of the results difficult. Figure 8-1 of Durbin 2011 presents the NOx results for this engine with error bars. First, we note that the figure appears to suggest that NOx emissions were increased on the B20 fuel in contradiction to the table above. Second, it is clear that the error bars are large enough that no difference in NOx emissions can be detected among ULSD, B5, and B20 fuels. Overall, this result could be consistent with the Staff Threshold Model through B5, but the failure to detect a NOx emission increase at B20 is not. Without further information, it is not possible to determine whether the result seen here is a unique response of the John Deere engine to animal-based biodiesel or is the result of a statistical fluctuation or an artifact in the emissions data.

3.7 Conclusions

The Biodiesel Characterization report prepared by Durbin et al. for CARB is an important source of information on the NOx emissions impact of biodiesel fuels in heavy-duty engines. It is the sole source of information on the NOx impact of B5 blends cited in the ISOR. When the engine dynamometer test data are examined for

[18] Durbin 2011, p. xx.

the three engines for which emissions test data have been published, we find clear evidence that biodiesel increases NOx emissions in proportion to the blending percent. Where B5 fuels were tested for these engines, NOx emissions are found to increase above ULSD for both soy- and animal-based blends in all three engines and by statistically significant amounts in one engine.

Specifically, a re-analysis of the NOx emissions test data demonstrates the following:

1. For the 2006 Cummins engine, biodiesel fuels are found to significantly increase NOx emissions for both soy- and animal-based blends by amounts that are proportional to the blending percent. This result indicates that biodiesels will increase NOx emissions at blending levels below B10. When B5 fuels were tested, NOx emissions were observed to increase but by amounts that fail to reach statistical significance according to the pair-wise test.[19] Graphical analysis demonstrates that NOx emissions measured for B5 fuels are consistent with the Linear Model, but not the Staff Threshold Model.

2. For the 2007 MBD4000 engine, biodiesel fuels are found to significantly increase NOx emissions for both soy- and animal-based blends by amounts that are proportional to the blending percent. This result indicates that biodiesels will increase NOx emissions at blending levels below B10. When B5 fuels were tested, NOx emissions were observed to increase and by amounts that are found to be statistically significant using the pair-wise t-test.[13] <u>This result alone is sufficient to disprove the Staff Threshold Model</u>. Graphical analysis demonstrates that NOx emissions measured for B5 fuels are consistent with the Linear Model, but not the Staff Threshold Model.

3. For the 1998 Kubota TRU (off-road) engine, soy-based biodiesel fuels are found to significantly increase NOx missions. Animal-based biodiesel was not tested. When a soy-based B5 fuel was tested, NOx emissions were observed to increase but by amounts that fail to reach statistical significance according to the pair-wise test.[13] Graphical analysis demonstrates that NOx emissions measured for B5 fuels are consistent with the Linear Model, but not the Staff Threshold Model.

The measured emissions test data for the other off-road engine (2009 John Deere) are not contained in the Durbin 2011 report and CARB has not made them publicly available. Thus, a re-analysis was not possible. Based on the tables and figures in Durbin 2011, soy-based biodiesel fuels were shown to significantly increase NOx emissions at B20 levels and higher, but B5 was not tested. Testing of animal-based blends shows no change in NOx emissions at B5 and B20 levels, but B100 is shown to significantly increase NOx emissions. Durbin 2011 discusses this result only briefly, and it is unclear what conclusions can be drawn from it.

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[19] As discussed in Section 3.3, the pair-wise t-test is not the preferred method for demonstrating statistical significance.

APPENDIX A

RESUME OF ROBERT W. CRAWFORD

Education

1978 Doctoral Candidate, ScM. Physics, Brown University, Providence, Rhode Island
1976 B.A. Physics, Pomona College, Claremont, California

Professional Experience

1998-Present Independent Consultant

Individual consulting practice emphasizing the statistical analysis of environment and energy data with an emphasis on how data and statistics are properly used to make scientific inferences. Mr. Crawford provides support on statistical, data analysis, and modeling problems related to ambient air quality data and emissions from mobile and stationary sources.

Ambient Air Quality and Mobile Source Emissions – Mr. Crawford has worked with Sierra Research on elevated ambient CO and PM concentrations in Fairbanks AK and Phoenix AZ, including the effect of meteorological conditions on ambient concentrations, the relationship of concentrations to source inventories, and the use of non-parametric techniques to infer source location from wind speed and direction data. Ongoing work is employing Principal Components Analysis to elucidate the relationship between meteorology and $PM_{2.5}$ concentrations in Fairbanks. In the past year, this work led to creation of the AQ Alert System, a tool used by air quality staff to track $PM_{2.5}$ monitor concentrations during the day and to prepare AQ alerts over the next 3 days based on the meteorological forecast.

In past work for Sierra, he has also conducted studies of fuel effects on motor vehicle emissions for Sierra. For CRC, he determined the relationship between gasoline volatility and oxygen content on tailpipe emissions of late model vehicles at FTP and cold-ambient temperatures. For SEMPRA, he determined the relationship between CNG formulation and tailpipe emissions of criteria pollutants and a range of air toxics. Other work has included the design of vehicle surveillance surveys and determination of sample sizes, development of screening techniques similar to discriminant functions to improve the efficiency of vehicle recruitment, the analysis of vehicle failure rates measured in inspection & maintenance programs, and the statistical evaluation of data collected on freeway speeds using automated sensors.

Stationary Source Emissions – Over the past 5 years, Mr. Crawford has worked with AEMS, LLC on EPA's MACT and CISWI rulemakings for Portland Cement plants, in which significant issues related to data quality, data reliability, and emissions variability are evident. Key issues include the need to properly account for uncertainty and emissions variability in setting emission standards. He also supported AEMS in the current EPA rulemaking on reporting of greenhouse gas emissions from semiconductor facilities, where the proper characterization of emission control device performance was a key issue. He is currently supporting AEMS in a regulatory process to re-determine emission standards for an industrial facility where the new standard will be enforced by continuous emissions monitoring (CEMS). At issue is how to set the standard in such a way that there will be no more than a small, defined risk that 30-day emission averages will exceed the limitations while emissions remain well-controlled .

Advanced Combustion Research – In recent work for Oak Ridge National Laboratory, Mr. Crawford conducted a series of statistical studies on the fuel consumption and emissions performance of Homogenous Charge Compression Ignition (HCCI) engines. One of these studies was for CRC, in which fuel chemistry impacts were examined in gasoline HCCI. In HCCI, the fuel is atomized and fully-mixed with the intake air charge outside the cylinder, inducted during the intake stroke, and then compressed to the point of spontaneous combustion. The timing of combustion is controlled by heating of the intake air. If R&D work can demonstrate a sufficient understanding of how fuel properties influence engine performance, the HCCI combustion strategy potentially offers the fuel economy benefit of a diesel engine with inherently lower emissions.

1979-1997 Energy and Environmental Analysis, Inc., Arlington, VA. Director & Partner (from 1989).

Primary work areas: Studies of U.S. energy industries for private and institutional clients emphasizing statistical analysis, business planning and computer modeling/forecasting. Responsible for the EEA practice area that provided strategic planning and forecasting services to major energy companies. Primary topical areas included: U.S. energy market analysis and strategic planning; gas utility operations; and natural gas supply planning.

U.S. Energy Market Analysis

During 1995-1997, Mr. Crawford directed EEA's program to provide comprehensive energy supply and demand forecasting for the Gas Research Institute (GRI) in its annual *Baseline Projection of U.S. Energy Supply and Demand*. Services included: development of U.S. energy supply, demand, and price forecasts; sector-specific analyses covering energy end-use (residential, commercial, industrial, transportation), electricity supply, and natural gas supply and transportation; and the preparation of a range of publications on the forecasts and energy sector trends.

From 1989 through 1997, he directed the use of EEA's Energy Overview Model in strategic planning and long-term market analysis for a client base of major energy producers, pipelines, and distributors in both the United States and Canada. The Energy Overview Model was used under his direction as the primary analytical basis for the 1992 National Petroleum Council study *The Potential for Natural Gas in the United States*. Mr. Crawford also provided analysis for clients on a wide range of other energy market issues, including negotiations related to an LNG import project intended to serve U.S. East Coast markets. This work assessed the utilization and economic value of seasonal gas deliverability in order to develop LNG pricing formulas and evaluate the project's viability.

Other topical areas of work during his period of employment with EEA include:

Gas Load Analysis and Utility Operations – Principal investigator in a multi-year research program for the Gas Research Institute (GRI) that examined seasonal gas loads, utility operations, and the implications for transmission and storage system reliability and capacity planning.

Gas Transmission and Storage – Principal investigator for a study of industry plans for expansion of underground gas storage capacity in the post-Order 636 environment, including additions of depleted-reservoir and salt-formation storage, an engineering analysis of capital and operating costs for the projects, and unbundled rates for new storage services.

Natural Gas Supply Planning – Mr. Crawford was EEA's senior manager and lead analyst on gas supply planning issues for both pipeline and distribution companies, which included technical and analytic support in development and justification of gas supply strategies; and identification of optimal seasonal supply portfolios for Integrated Resource Planning proceedings.

Transportation Systems Research

Mr. Crawford also had extensive experience in motor vehicle fuel economy and emissions while at EEA. He participated for five years in a DOE research program on fuel economy, with emphasis on the evaluation of differences between laboratory and on-road fuel economy. His work included analysis of vehicle use databases to understand how driving patterns and ambient (environmental) conditions influence actual on-road fuel economy. He also developed a software system to link vehicle certification data systems to vehicle inspection and testing programs and participated in a range of studies on vehicle technology, fuel economy, and emissions for DOE, EPA, and other governmental agencies.

SELECTED PUBLICATIONS (emissions and motor vehicle-related topics)

Statistical Assessment of $PM_{2.5}$ and Meteorology in Fairbanks, Alaska: 2013 Update. Crawford and Dulla. Prepared for the Alaska Department of Environmental Conservation. (forthcoming).

Statistical Assessment of $PM_{2.5}$ and Meteorology in Fairbanks, Alaska. Crawford and Dulla. Prepared for the Alaska Department of Environmental Conservation. March 2012.

Principal Component Analysis: Inventory Insights and Speciated $PM_{2.5}$ Estimates. Crawford. Presentation at Air Quality Symposium 2011, Fairbanks and North Star Borough, Fairbanks, AK. January 2011.

Influence of Meteorology on $PM_{2.5}$ Concentrations in Fairbanks Alaska: Winter 2008-2009. Crawford. Presentation at Air Quality Symposium 2009, Fairbanks and North Star Borough, Fairbanks, AK. July 2009.

Analysis of the Effect of Fuel Chemistry and Properties on HCCI Engine Operation: A Re-Analysis Using a PCA Representation of Fuels. Bunting and Crawford. 2009. Draft Report (CRC Project AFVL13C)

The Chemistry, Properties, and HCCI Combustion Behavior of Refinery Streams Derived from Canadian Oil Sands Crude. Bunting, Fairbridge, Mitchell, Crawford, et al. 2008. (SAE *08FFL 28)*

The Relationships of Diesel Fuel Properties, Chemistry, and HCCI Engine Performance as Determined by Principal Components Analysis. Bunting and Crawford. 2007. (SAE 07FFL 64).

Review and Critique of Data and Methodologies used in EPA Proposed Utility Mercury MACT Rulemaking, prepared by AEMS and RWCrawford Energy Systems for the National Mining Association. April 2004.

PCR+ in Diesel Fuels and Emissions Research. McAdams, Crawford, Hadder. March 2002. ORNL/TM-2002/16.

A Vector Approach to Regression Analysis and its Application to Heavy-duty Diesel Emissions. McAdams, Crawford, Hadder. November 2000. ORNL/TM-2000/5.

A Vector Approach to Regression Analysis and its Application to Heavy-duty Diesel Emissions. McAdams, Crawford, Hadder. June 2000. (SAE 2000-01-1961).

Reconciliation of Differences in the Results of Published Shortfall Analyses of 1981 Model Year Cars. Prepared by Energy and Environmental Analysis, Inc. for the U.S. Department of Energy under Contract DE-AC01-79PE-70045. October 1985

Short Test Results on 1980-1981 Passenger Cars from the Arizona Inspection and Maintenance Program. Darlington, Crawford, Sashihara. August 1984.

Seasonal and Regional MPG as Influenced by Environmental Conditions and Travel Patterns. Prepared by Energy and Environmental Analysis, Inc. for the U.S. Department of Energy under Contract DE-AC01-79PE-70045. March 1983.

Comparison of EPA and On-Road Fuel Economy – Analysis Approaches, Trends, and Impacts. McNutt, Dulla, Crawford, McAdams, Morse. June 1982. (SAE 820788)

Regionalization of In-Use Fuel Economy Effects. Prepared by Energy and Environmental Analysis, Inc. for the U.S. Department of Energy under Contract DE-AC01-79PE-70032. April 1982.

1985 Light-Duty Truck Fuel Economy. Duleep, Kuhn, Crawford. October 1980. (SAE 801387)

PROFESSIONAL AFFILIATIONS

Member, Society of Automotive Engineers.

HONORS AND AWARDS

2006 Barry D. McNutt Award for Excellence in Automotive Policy Analysis. Society of Automotive Engineers.

US Patent 7018524 (McAdams, Crawford, Hadder, McNutt). Reformulated diesel fuels for automotive diesel engines which meet the requirements of ASTM 975-02 and provide significantly reduced emissions of nitrogen oxides (NO_x) and particulate matter (PM) relative to commercially available diesel fuels.

US Patent 7096123 (McAdams, Crawford, Hadder, McNutt). A method for mathematically identifying at least one diesel fuel suitable for combustion in an automotive diesel engine with significantly reduced emissions and producible from known petroleum blend stocks using known refining processes, including the use of cetane additives (ignition improvers) and oxygenated compounds.

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