sierra research
1801 J Street
Sacramento, CA 95811
Tel: (916) 444-6666
Fax: (916) 444-8373
Ann Arbor, MI
Tel: (734) 761-6666
Fax: (734) 761-6755

DELIVERED BY HAND

February 18, 2015

Tracy Jensen
Clerk of the Board
California Air Resources Board
1001 I Street
Sacramento, CA 95814

RE: "Comments on the LCFS and ADF rulemaking proposals."

Dear Clerk of the Board:

I have discovered that one attachment to my Declaration included in electronic filing for Growth Energy that Josh Wilter of my staff made yesterday was not included in the upload. I am enclosing the attachment here and am emailing it to Jim Aquila and Lex Mitchel who are listed as the staff contacts for this item in the Hearing Notice. The contents of this attachment do not differ from the content of my Declaration, and the bulk of the analysis in the attachment was provided to the ARB staff on October 24, 2014 as workshop comments.

Sincerely,

Jim Lyons
Senior Partner

Attachments:

NOx EMISSIONS IMPACTS OF BIODIESEL BLENDS

Prepared by:

Rincon Ranch Consulting
2853 S. Quail Trail
Tucson, AZ 85730

Prepared for:

Sierra Research
1801 J. Street
Sacramento, CA 95811

February 10, 2015

NOx EMISSIONS IMPACTS OF BIODIESEL BLENDS

Table of Contents

List of Figures

List of Tables

NOx EMISSION IMPACTS OF BIODIESEL BLENDS

1. EXECUTIVE SUMMARY

The purpose of the Alternative Diesel Fuels (ADF) rulemaking, according to the Air Resources Board (ARB), is to create a regulatory framework that will permit biodiesel and other low-carbon, alternative diesel fuels to "enter the commercial market in California, while mitigating any potential environmental or public health impacts." [1]

The work presented in this report assesses the impacts of biodiesel use on NOx emissions from conventional and new technology diesel engines. It was performed by Rincon Ranch Consulting under subcontract to Sierra Research at the request of Growth Energy.

At present, most diesel fuel and biodiesel is consumed in conventional diesel engines that do not have exhaust gas after-treatment to reduce NOx emissions. The consensus of the literature is that biodiesel will increase NOx emissions by amounts that depend on the blending percentage (how much biodiesel is present in the diesel fuel) and the type of biodiesel feedstock (soy versus animal sources). NOx increases of 1-2% are expected from soy biodiesel at blend levels of B5 to B10 with smaller increases expected, in general, from animal biodiesel at the B5 to B10 level.

Over time, new technology diesel engines (NTDEs) equipped with exhaust gas after-treatment controls for NOx will increasingly make up the heavy duty fleet in response to other ARB programs. While baseline emissions from these engines will be reduced compared to conventional engines, the consensus of the literature available today is that use of biodiesel will still increase NOx emissions above the reduced baseline. At the B20 level, the NOx increase appears to be greater on a percentage basis than would be expected in conventional diesel engines.

The results of this work indicate the following with respect to conventional diesel engines:

- Soy biodiesels will increase NOx emissions at the B5 and B10 levels by approximately 1% and 2%, respectively. This work and Staff's analysis concur in both the conclusion and the estimated levels of NOx increase at B5 and B10. Soy biodiesels in this blend range require NOx mitigation on a per-gallon basis in order to prevent increases in NOx emissions.

- The consensus of the research community is that the effect of soy biodiesel on NOx emissions is continuous and linear with respect to the blending percentage. NOx

[1] "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. January 2, 2015. http://www.arb.ca.gov/regact/2015/adf2015/adf15isor.pdf. Page 11.

increases have been observed at levels as low as B1.[2] The statistical analysis performed for ARB by Rocke supports this conclusion and estimates that soy biodiesel will increase NOx emissions by about 0.2% for each 1% biodiesel in the blend (0.99% for each 5% biodiesel).

In spite of this consensus, the Staff proposal requires NOx mitigation for soy-based biodiesel only above the B5 level in summer months and above the B10 level in winter months. Soy biodiesel blended at the B5 and lower levels would not require mitigation in any circumstance. The ADF regulatory framework must require mitigation of soy-based biodiesels at all blend levels if it is to ensure that such fuels do not increase NOx emissions.

- The effect of animal-based biodiesel on NOx emissions is more complicated than for soy-based blends. As the available literature demonstrates, some animal-based biodiesels will increase NOx emissions while other animal biodiesels will not. While Staff's proposal would establish B10 as the control level for animal-based biodiesel (e.g., mitigation would be required year-round for blends above B10), the available data do not support Staff's conclusion that there will not be increases in NOx emissions from B10 and lower blends. Given the Staff proposal, the only way to ensure that animal-based biodiesel does not increase NOx emissions is to require mitigation at all blend levels.

- Staff presents information indicating that animal biodiesels decrease NOx by 0.2% on average and that the emissions change in comparison to CARB diesel fuel is not statistically significant. The average and the test for statistical significance are both flawed by the failure to consider the varying effects that animal feedstocks have on Cetane Number (CN). The absence of CN as a variable in Staff's analysis leads Staff to wrongly conclude that animal biodiesels will not increase NOx below the B10 level.

- It is well established that increasing CN will reduce NOx emissions from diesel engines. Whether an animal biodiesel will increase NOx depends primarily on the extent to which the feedstock blending increases the CN of the blended fuel. Soy and animal biodiesel blends are not categorically different fuels once the differing effect of soy- and animal-feedstocks on CN is taken into account.

With respect to new technology diesel engines (NTDEs):

- Staff is incorrect in concluding that biodiesel use will not increase NOx in NTDEs. This conclusion is based on a highly selective reading of the technical literature (choosing one of four available studies) and relies on the one study in which the laboratory was not well equipped to measure the low levels of tailpipe NOx emissions from NTDEs.

- A fair reading of the technical literature indicates that B20 biodiesel will increase NOx emissions by about 20% in NTDEs. The four best studies estimate that B20 biodiesel

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[2] McCormick 2002 tested a Fisher-Tropsch (FT) base fuel blended at the B1, B20, and B80 levels. Although the very high FT cetane number (≥75) takes it out of the range of commercial diesel fuels, the study nevertheless measured higher NOx emissions at the B1 level than it did on the FT base fuel.

increases NOx by 18-22% in NTDEs and that the increase is statistically significant. This is a greater percentage NOx increase in proportion to blend level than the increase caused by soy biodiesel in conventional diesel engines (1% at B5, 2% at B10 and ~4% at B20).

- The technical literature also indicates that one should expect NOx emissions to increase at blend levels below B20, with the size of the NOx increase being proportionate to blend level. At the B5 level, NOx emissions from NTDEs are expected to increase by about 5%.

- Staff makes no mention of the concern that use of biodiesel fuels in NTDEs may lead to the loss of NOx conversion efficiency in urea-SCR systems by shifting the NO_2/NOx ratio to lower values. Staff's proposal to allow B20 biodiesel to be used in NTDEs without mitigation potentially places at risk the investment in NOx after-treatment systems to meet the stringent NOx certification levels now in effect.

This analysis demonstrates that the proposed regulations will not "ensure that the use of biodiesel due to LCFS will not result in increases in NOx emissions in California." In fact, the regulations will result in increased NOx emissions in California from the following:

- B5 and lower soy biodiesels year round;
- B6 to B10 soy biodiesels in winter;
- At least some B10 and lower animal biodiesels year-round; and
- B20 and lower biodiesels of all types in NTDEs.

To our knowledge, ARB has not formulated a position on the level of NOx increase from alternative diesel fuel that is too small to warrant concern. A point of comparison for the NOx increases permitted by the proposed ADF regulations is the ARB program for Reformulated Gasoline (RFG). The RFG program permits alternative gasoline formulations to be sold in the California market provided they are demonstrated to be emissions equivalent to a reference gasoline using the Predictive Model for RFG. The emissions analysis differs somewhat for winter and summer gasoline, but in no instance may the alternative formulation increase emissions of the pollutants considered by more than 0.05%.

The biodiesel NOx emission increases permitted under the proposed ADF regulations dwarf the 0.05% threshold applied to RFG. Soy biodiesel will increase NOx by more than 0.05% at blend levels above 0.25% biodiesel (B0.25). Some animal biodiesels will increase NOx by 0.05% or more at blend levels twice as high (B0.5). The NOx emissions increase in NTDEs appears to be substantially greater on a percentage basis, so that biodiesels will exceed the 0.05% threshold at much lower blend levels.

In the ISOR, Staff uses the term "low saturation" to refer to soy and other feedstocks with $CN < 56$ and "high saturation" to refer to feedstocks, including animal sources, with $CN \geq 56$. Classification based on saturation is useful because of its association with CN. By itself, however, it does not alleviate the concerns regarding NOx increases from unmitigated fuels.

The analysis presented here indicates that CN changes induced by biodiesel blending have a large influence on the size of the NOx increase that is observed. Soy (low saturation) biodiesels adversely affect CN leading to larger NOx increases; animal (high saturation) biodiesels increase CN leading to smaller NOx increases. In fact, soy and animal biodiesels are not categorically different fuels once their differing effect on blend CN is taken into account.

It is strongly recommended that ARB consider as part of the ADF rulemaking a regulatory structure in which the NOx impacts of soy and animal biodiesel are accounted for using a statistical model analogous to the Predictive Model for RFG. The analysis documented in this report provides a possible form for a biodiesel predictive model.

2. NOX EMISSIONS FROM CONVENTIONAL DIESEL ENGINES

2.1 ARB Analysis in Support of the Proposed Regulations

In support of the proposed regulations, ARB commissioned an analysis of the available NOx emissions data by David M. Rocke, PhD. The results of the analysis are reported in Appendix G: Supplemental Statistical Analysis[3] to the ISOR. The analysis used NOx emission measurements on ULSD, B5, and B10 fuels in conventional diesel engines from five studies. The dataset is substantially the same as that used by Rincon Ranch Consulting in the analysis presented later in this section.

The Rocke analysis formulated a series of statistical models involving log(NOx) as the dependent variable and used a statistical approach termed Mixed Effects modeling to estimate the coefficient values. The Mixed Effects approach has statistical advantages over more commonly used methods when dealing with unbalanced datasets, as is the case here. A number of different models were specified, estimated, and the results compared in order to ensure that conclusions drawn from the analysis do not depend upon the model specifications.

For soy-based biodiesel, the Rocke study concludes that soy fuels increase NOx by 1% at B5 and by 2% at B10. The study also demonstrated that the NOx increase is linearly related to the blend level. The slope was estimated to be 0.99% for each 5% biodiesel in a blend and was highly significant statistically ($p \ll 0.001$). These results agree with the Rincon Ranch analysis presented later in this report. <u>There is no controversy with regard to the NOx impact of soy-based biodiesel.</u> Soy biodiesel will increase NOx emissions at all blend levels by about 0.2% for each 1% biodiesel in the blend.

With respect to animal biodiesel, the Rocke study concludes that animal biodiesel does not increase NOx emissions at B5 or B10. The emission changes that are observed are not statistically significant. <u>There is controversy here because the Rocke analysis did not account for the effect of feedstock blending on the CN of the tested fuels</u>. The CN change compared to ULSD is a fixed effect that must be accounted for because the four animal feedstocks that have been used in the technical literature show substantially different cetane behavior in blending.

[3] http://www.arb.ca.gov/regact/2015/adf2015/adf15appg.pdf.

The case for cetane as an explanatory variable for NOx emissions in animal blends is made in Section 2.2.4 of this report. It is well established that increasing CN will reduce NOx emissions from diesel engines. For example, ARB has shown that the additive DTBP can be used to raise CN and mitigate NOx increases caused by biodiesel blending. Whether an animal biodiesel will increase NOx depends primarily on the extent to which the feedstock blending increases CN of the blended fuel. The two animal blends that showed the smallest CN gain over ULSD caused statistically significant NOx increases in the engines tested. The one animal blend that showed the largest CN gain was certified to be NOx neutral, while the animal blend with the next largest CN gain may or may not be NOx neutral. Cetane appears to blend linearly when using soy feedstocks, so that the CN gain over ULSD is highly correlated with blend level. The same is not true for animal feedstocks, where highly non-linear blending behavior has been observed.

The Rocke analysis used a Mixed Effects model to estimate the NOx emissions change at B5 and B10. For animal blends, it concluded that the observed emission changes are not statistically significant. Implicit in the approach is the assumption that the fuels being tested are different, individual realizations from a homogenous population. In this instance, the residual variation not accounted for by the blend level is a random effect representing the scatter in test results due to a variety of factors. The statistical significance of the blend level effect (a fixed effect) is judged in comparison to the residual variation. When the residual variation is large in comparison to the fixed effect, the latter is said to be not statistically significant.

The assumption of a homogenous population is appropriate for soy-based biodiesels. One soybean is much like the next, and the only appreciable differences among soy fuels will result from the methods of preparation. However, the assumption of homogeneity is not appropriate for animal-based biodiesels, which can be drawn from a variety of animal sources and prepared in different ways. The non-homogeneity is seen most readily in the greatly different cetane responses of biodiesel fuels:

- In the McCormick 2005 and Durbin 2011 studies, the animal feedstocks increased the CN of the biodiesel blends by small amounts. These fuels led to statistically significant increases in NOx.
- In the Durbin 2013A study, blending at the B5 level was sufficient to raise the CN of the blend by 8 numbers to reach the cetane level of the feedstock itself. This fuel was certified as NOx neutral at B5.
- The animal feedstock used in the Karavalakis 2014 study was intermediate in its CN effect and also intermediate in its NOx effect.

Because the ARB and Rocke studies have not included cetane as an explanatory variable for animal-based biodiesels, the residual variation term has been enlarged since a portion of it could be accounted for by including a fixed-effects term for cetane. With an enlarged estimate of the residual variance, the studies more easily find that the fixed effect of blend level is not statistically significant.

The absence of cetane as an explanatory variable also affects other methods of analysis used by Rocke. In a t-test comparison of emission differences between biodiesel and ULSD, Rocke finds two cases in which animal B5 changes NOx by statistically significant amounts (one increasing NOx and the other decreasing NOx) and one such case in animal B10 (decreasing NOx), while the other cases show no statistically significant change compared to the base fuel. The study wrongly concludes that these results demonstrate no or little systematic evidence for B5 or B10 animal to increase NOx emissions. In fact, these cases are systematically related to the CN gain of the animal blends in comparison to the base fuel.

The Rocke analysis was well planned and executed, and we concur with the conclusions drawn for soy-based blends. Because the analysis for animal-based blends is flawed by omission of a cetane variable, it should be revised to address CN gain. We expect that a revised analysis will shed further light on the circumstances in which animal-based biodiesels will and will not increase NOx emissions.

2.2 Rincon Ranch Analysis of ARB NOx Emissions Data

In July 2014, ARB released two datasets that represent the fruit of its efforts to compile the available biodiesel NOx emissions test data on conventional heavy-duty truck (HDT) engines. This report and the companion file *"Biodiesel Emissions Analysis Technical Summary 102014.pdf,"* which is attached to and incorporated in this report, present the results of a statistical analysis of the data sets released by ARB that was performed by Rincon Ranch Consulting at the request of Growth Energy.

The analysis presented below focused on whether soy and animal blends will increase NOx at low blend levels in conventional diesel engines. The following issues were examined:

- The NOx impacts of soy and animal blends at B5 and B10;
- The NOx emission differences observed among animal feedstocks and blends;
- For animal blends, the effect on NOx emissions of the CN change relative to base fuel that is caused by blending of the animal feedstock; and
- The development of a cetane-based model of the biodiesel NOx impacts of soy and animal blends.

2.2.1 Data Used in the Analysis

As noted above, in July 2014, ARB released two datasets of NOx emissions data from testing of biodiesel blends in HDT engines. One file ("B5 & B10 Raw NOx Data") contains the subset of testing for B5 and B10 blends (soy and animal). The test data generated in the four ARB-sponsored UCR studies are present in the form of the individual test run measurements. Because test run information was not reported in their publications, the B5 soy data from Nikanjam 2010 and the B10 soy data from Thompson 2010 are present in the form of emission averages. No animal blends have been tested at the B5 or B10 levels except in the ARB-sponsored emissions testing. A second file ("2014 Biodiesel Literature Search Database") contains all of the biodiesel testing available in the literature through the B20 level (soy and animal), including ARB-sponsored testing and the literature search. The data are in the form of emission averages by engine, test cycle, feedstock type, and blend level.

For purposes of this analysis, the following information was added to the ARB datasets:

- The number of test replications for emissions averages for each study (estimated when the source did not report the number);
- The CN for CARB diesel, the biodiesel blends, and the biodiesel feedstocks; and
- Additional NOx emissions testing at the B50 and B100 levels (where available).

Appendix Table A presents a list of the studies included in the dataset and the author references used in citations here.

2.2.2 NOx Emissions from Soy Biodiesel Blends

Most past research on biodiesel emissions has focused on soy blends. As a result, the literature is relatively large and diverse. The dataset assembled by ARB is derived from 10 different studies, covers 13 different vegetable feedstocks (10 soy, 2 used cooking oil [UCO], 1 canola), and was conducted using 7 different test cycles on a wide variety of engines in different labs. Most of the data, in terms of number of data points, are derived from the three UCR studies (Durbin 2011, Durbin 2013B, and Karavalakis 2014) sponsored by ARB.

We subjected the soy dataset to a number of different analyses using different statistical techniques and selections of the data to ensure that the conclusions we drew were robust. The statistical analyses included the t-test for the difference in mean values (e.g., between B5 and CARB diesel) and linear regression analysis using several different models. The data subsets were selected to use either individual test runs or emission averages and to contain testing through maximum blend levels of B5, B10, B20, B50, and B100.

Our analyses show that there is a consensus among the studies on the NOx impact of soy biodiesel without regard to the specific analytical methods or data used. Soy biodiesel increases NOx emissions by amounts that can be estimated with good statistical confidence because of the large size of the available dataset. The key conclusions are as follows:

- Soy biodiesel increases NOx emissions by ~1% at B5 and ~2% at B10;
- NOx emissions increase in a linear fashion with increasing blend level to reach ~4% at B20 and proportionately larger values at higher blend levels; and
- There is no evidence in the data for a threshold level below which soy biodiesel does not increase NOx.

These conclusions are supported by all of the available studies and data. None of the studies disagree substantially, and while the results for individual blends, engines, and test cycles will vary to some extent, the evidence across a wide range of engines and test cycles is clear. NOx increases can be expected for UCO, canola, and other vegetable biodiesels, but the data are very limited and it is not possible to draw definitive conclusions for these blends.

2.2.3 NOx Emissions from Animal Biodiesel Blends

The literature on NOx emissions from animal blends is much smaller—it consists of only four studies, three of which (Durbin 2011, Durbin 2013A, and Karavalakis 2014) were sponsored by ARB. Except for the McCormick 2005 study, the emissions testing was conducted at the UCR CE-CERT lab. A variety of test cycles were used, but most of the testing was conducted on the hot-start FTP cycle. Table 1 presents a summary of the emissions studies for animal biodiesel.

Table 1. Scope of Emissions Testing for Animal Biodiesel

	McCormick 2005	Durbin 2011	Durbin 2013A	Karavalakis 2014
Biodiesel Feedstock	Animal #1	Animal #2	Animal #3	Animal #4
Blend Levels Tested	B20	B5, B20, B50, B100	B5	B5, B10
Engines Tested	2 on-road	3 on-road, 1 off-road	1 on-road	1 on-road
Test Cycles	FTP	FTP, UDDS, 50 mph, ISO 8178	FTP	FTP, SET, UDDS
Test Replications on Biodiesel	6	126	26	80
Is NOx Increase Observed?				
At / Below B10	–	Yes	No	No
Above B10	Yes	Yes	–	–

It is important to understand the limitations of this small dataset. Without the ARB-sponsored testing, we would have only the six test replications (individual runs) conducted in the McCormick 2005 study. While the three UCR studies accumulated 232 test replications, the work involved only three different animal feedstocks. Including the McCormick 2005 study, the entire literature on NOx emissions from animal biodiesel is based on only four different animal feedstocks. The small number is an important limitation because animal feedstocks are much less homogenous than soy due the greater variety possible in animal sources and compositions. Further, there are notable differences among the four studies as to whether animal biodiesel increases NOx at the B5 and B10 levels (as indicated by the red circles in the table).

As in the soy analysis, we subjected the animal biodiesel data to a number of different analyses using different statistical techniques and selections of the data to ensure that the conclusions we drew were robust. The t-test is the most direct method to assess whether NOx emissions are higher at B5 compared to CARB diesel. Using the individual test run data available from the three UCR studies, we find the following for animal biodiesel at the B5 blend level:

- The animal feedstock used in Durbin 2011 increases NOx in 2 of 3 engines. The increase is highly significant[4] statistically for one engine.

- The animal feedstock used in Durbin 2013A decreases NOx in one engine. The decrease is statistically significant at the p=0.05 level, and the blend was certified as NOx neutral at B5.

- The animal feedstock used in Karavalakis 2014 increases NOx in three of six cases and decreases NOx in the other three cases. None of the changes are statistically significant. The blend may or may not change NOx.

Contrary to Staff's assertion that no NOx increase occurs in B5 animal blends, it is clear that some animal blends will significantly increase NOx emissions, while other animal blends will not. The fundamental issue is then understanding what the NOx impact of a particular animal biodiesel blend will be.

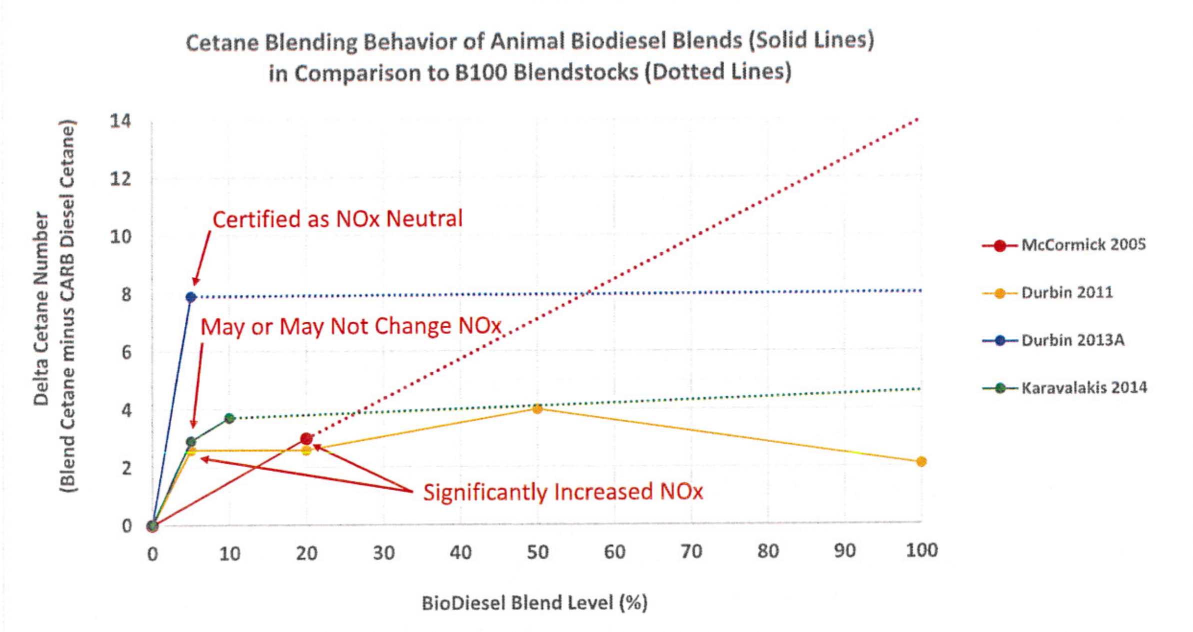
The effect of feedstock blending on the CN of the resulting animal blend is the reason for the apparently discordant results among the studies. Figure 1 plots the four series of animal blends used in the studies, with blend level on the horizontal axis and the change in blend CN (relative to CARB diesel) on the vertical axis. CN blended linearly to B20 for the McCormick feedstock, which showed a much smaller CN benefit than the feedstocks used by UCR—only three numbers at B20 (0.6 numbers at B5). In contrast, all three UCR animal blends achieve a large CN boost at low blending levels in which most or all of the CN benefit of the feedstock is achieved at B5.

In Durbin 2011, the CNs for the blends are above that of the B100 feedstock. This result is probably caused by lab-to-lab differences (blend CN was determined at CE-CERT, while CN for CARB diesel and the B100 feedstock were determined by an outside lab). The actual CN changes are surely lower than shown here—at or below +2 CNs.

The two animal feedstocks that caused statistically significant NOx increases have the smallest CN benefits: McCormick 2005 (red) at B20 and Durbin 2011 (yellow) at B5. The animal B5 blend that passed certification testing as NOx neutral in Durbin 2013A (blue) has the highest CN benefit, where it achieved the entire B100 CN at just 5% blending. The Karavalakis 2014 B5 blend (green) had an intermediate CN benefit and may or may not change NOx.

[4] The term "significant" is used in this report only to refer to statistical significance. When a result reaches the p=0.05 level, we can be 95 percent confident that it is real. In such case, and at smaller p values, the result is said to be statistically significant.

Figure 1. Cetane Blending Behavior of Animal Blends (Solid Lines) Compared to B100 Feedstocks (Dotted Lines)



The blending behavior of the UCR blends is surprising in comparison to the McCormick study, and we find relatively little research on the CN blending behavior of animal feedstocks. All conclusions from this dataset will be influenced by the CN blending behavior of the specific animal feedstocks involved. For such conclusions to be reliable, we must be confident that the large CN boost reported for the UCR blends is both real and representative of all animal feedstocks in California. Also, only limited information is available on the sources and characteristics of the animal feedstocks.

To permit all parties to better understand the animal feedstocks that were tested, ARB should release all information that it has on the following:

- CNs (methods of determination and measured values) for the Durbin 2011 and other UCR studies;
- Physical and chemical properties of the animal feedstocks and biodiesel blends tested;
- The distribution of sources, characteristics, and properties in the population of animal feedstocks that are available for use in the California market; and
- How the specific animal feedstocks tested at UCR were selected, including any information that would demonstrate that the feedstock properties and their CN blending behavior are representative of the animal feedstock population available for use in California.

Staff's use of the terms low saturation (for soy) and high saturation (for animal) to classify biodiesel is useful to differentiate between feedstocks that will tend to decrease CN and those that will tend to increase it. However, it is not a sufficient step in that the CN change at each blend level is the determinative factor for NOx emissions, not the CN of the feedstock itself. Soy feedstocks appear to blend linearly with respect to cetane; however, animal feedstocks often lead to a highly non-linear CN response, as shown in Figure 1.

2.2.4 Development of a Cetane-based Model of NOx Impacts from Soy and Animal Biodiesel

The results presented above indicate the important role that CN plays in determining the NOx response for animal blends. Animal feedstocks tend to increase the CN of the blend above that of the CARB diesel and the CN change can be large at low blend levels. Soy feedstocks generally decrease the CN of the blend below that of the CARB diesel; for soy, the CN change at low blend levels can be smaller than the uncertainty in determining CN. The result of our work on a cetane-based model demonstrates that soy and animal blends are not categorically different fuels once their differing effect on CN is taken into accounted. Their NOx impacts can be represented by the same model as a function of blend level and the change in CN compared to CARB diesel.

The document that accompanies this report explains the development of the cetane-based model in some detail. In brief, it was developed using conventional linear regression analysis with log(NOx) emissions as the dependent variable. Intercept terms were included to represent the varying emission levels on CARB diesel for each combination of study, feedstock type, engine, and test cycle. A b coefficient was included to represent the change in NOx emissions for each one percent biodiesel in a blend at constant CN. A c coefficient was included to represent the change in NOx emissions for each one number change in CN compared to CARB diesel at constant blend level. Both soy and animal blends were included in the estimation, along with the small number of canola and UCO data points, at blend levels up to (and including) B20.

The model estimation shows that the b and c coefficients are highly significant statistically ($p < 0.0001$). The estimation results also show the following:

- The b coefficient has a value of +0.00156, which estimates that soy and animal biodiesel will increase NOx emissions by 0.16% for each one percent biodiesel at constant CN or by 0.8% at B5.
- The c coefficient estimates that +5 CNs will decrease NOx emissions by 1.5% at constant blend level. This result is completely consistent with earlier work[5] on the relationship between CN and NOx emissions in HDT engines, which also found that +5 CNs will decrease NOx emissions by 1.5% in base fuels with CN ~50.

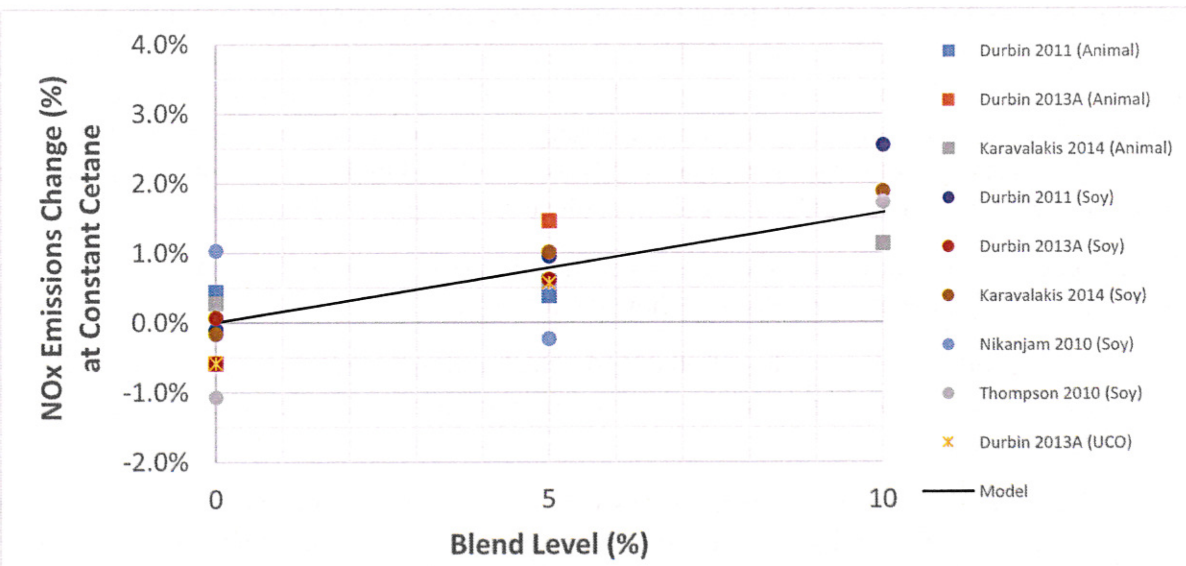
[5] The Effect of Cetane Number Increase Due to Additives on NOx Emissions from Heavy-Duty Highway Engines. EPA420-R-03-002. February 2004. Figure IV.A-1.

- An increase of -b/c = 0.5 CNs is needed to offset the NOx increase expected from each 1% biodiesel added. For B5, an increase of 2.5 CNs is required to offset the expected NOx increase.

The results explain why soy and animal blends appear to be different fuels. Soy blends have an additional, adverse CN effect that increases their NOx impact to ~1% at B5. Animal blends will generally increase CN and that reduces their NOx impact to about one-half the soy level or less, depending on the CN change caused by blending. The results also explain why some animal blends do not increase NOx emissions. If an animal feedstock increases CN by more than ~0.5 numbers for each 1% biodiesel blended, then the resulting fuel may not increase NOx emissions.

To demonstrate these conclusions, Figure 2 presents NOx emissions as a function of blend level for all fuels used to estimate the model once NOx emissions are adjusted for the CN change observed for each blend. For example, if an animal blend increased CN, then its NOx impact is <u>increased</u> as we return it to the base fuel CN. If a soy blend decreases CN, then its NOx impact is <u>decreased</u> as we return it to the base fuel CN. Once adjusted, percent changes in emissions are calculated. As seen in the figure, there is no discernable difference among feedstock types once CN changes are taken into account. Animal and soy blends scatter on both sides of the regression line, indicating that they obey the same blend level model.

Figure 2. There Are No Detectable Differences Among Feedstock Types Once NOx Emissions Are Adjusted to Constant CN



Note: Animal blends are plotted as squares, soy blends as circles, and the non-soy vegetable blends as asterisks.

Note the scatter of points around the regression line (which gives the "average" response). Some of the scatter is due simply to emissions measurement error; however, other factors may be involved in determining the NOx impact for a given feedstock, including differences in the

FAME (fatty acid methyl ester) composition and uncertainty in determining CN for the blends. If ARB were to adopt a predictive model to determine the CN improvement needed to mitigate NOx, it should use the model to evaluate a "worst case" feedstock, meaning a point near the upper end of the range at each blend level.

The most important conclusion of this work is that soy and animal biodiesel blends are not categorically different fuels. Their emissions effects are similar, but they show different NOx impacts because they have different effects on CN. Furthermore, this work provides a potential answer to the problem that some animal blends will significantly increase NOx emissions, while other blends will not, by indicating what individual blends may do.

3. NOX EMISSIONS IN NEW TECHNOLOGY DIESEL ENGINES

Staff's position is that biodiesel will not increase NOx emissions in NTDEs at levels up to and including B20. Its assessment is stated in the ISOR as follows:

> *Engines that meet the latest emission standards through the use of Selective Catalytic Reduction (SCR) have been shown to have no significant difference in NOx emissions based on the fuel used. A study conducted by the NREL looked at two Cummins ISL engines that were equipped with SCR, and found that NOx emissions control eliminates fuel effects on NOx, even for B100 and even in fuels compared against a CARB diesel baseline.*[20] *However, a recent study at UC Riverside tested B50 blends and found a NOx increase with a 2010 Cummins ISX.*[21] *The UC Riverside study did not look at blends below B50. Staff proposes to take a precautionary approach and in the light of data showing there may be a NOx impact at higher biodiesel blends but not at lower biodiesel blends, Staff is limiting the conclusion of no detrimental NOx impacts in NTDEs to blends of B20 and below. Additional studies on NTDEs have been completed, however since they included either retrofit engines or non-commercial engines Staff did not include their results in this analysis.*[22,23,24] (Page 24)

Staff's reliance on Lammert 2012 (Ref. 20) is misplaced because the NREL lab was not equipped to measure the low NOx emission levels of the test vehicles, as the abstract of the Lammert paper clearly notes.[6] In fact, none of the emission changes observed in the study (with one exception) were statistically significant due to the high standard errors that necessarily exist when measurements are made close to the level of detection. In this instance, the failure to observe statistically significant NOx emissions increases from biodiesel at the B20 level is not a demonstration that such increases do not exist.

This specific shortcoming of the Lammert study is why its negative results are in conflict with the finding of the UC Riverside study (Gysel 2014) cited by Staff and the three other studies (Walkowicz 2009, McWilliam 2010, Mizushima 2010) that Staff dismissed. With respect to the

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[6] "SCR systems proved effective at reducing NOx to near the detection limit on all duty cycles and fuels, including B100." Lammert 2012, Abstract.

three other studies, we see no reason why they should be dismissed. It is not the case that factory-designed NOx after-treatment systems will reduce NOx levels to below the detection limit of well-equipped labs (see Gysel 2014 and engine certification testing). Testing conducted using retrofit NOx after-treatment systems that achieve representative levels of NOx control, as in these studies, is entirely suitable for determining whether biodiesel increases tailpipe NOx emissions on a percentage basis. Having a different absolute level of emissions does not preclude reliable measurement of a percentage change.

When all available studies are included, a consensus of the literature is that biodiesel at the B20 level will increase NOx emissions from NTDEs in most, if not all cases. Lammert 2012 is the one study at odds with the rest of the literature. A range of biodiesel types were used in the studies. NOx increases should be expected at the B20 level for all biodiesel types until such time as additional research indicates differential impacts for biodiesels derived from different sources

3.1 Review of the NTDE Literature

The following sections briefly summarize the NTDE testing conducted in the studies and the conclusions drawn on the NOx emissions impact of biodiesel fuels. Testing of conventional diesel engines without NOx after-treatment is not considered, nor is testing on non-California fuels (low aromatics ULSD was considered equivalent to CARB ULSD). Appendix Table B presents a list of the studies included in the NTDE dataset and the author references used in citations here.

Walkowicz 2009. Chassis dynamometer testing was conducted using a 2005 International 9200i tractor equipped with and without a retrofit diesel oxidation catalyst (DOC) and urea-SCR NOx after-treatment system. On-road emissions measurements also were made using a RAVEM portable emissions measurement system. A ULSD base fuel was tested, as were B20 and B99 biodiesel blends. The type of biodiesel (soy or animal) was not specified, but was mostly likely soy-based as this is the feedstock most common in the market and in engine research.

- Under loaded, on-road conditions, biodiesel increased NOx by 17% at B20 and by about 40% at B99. At B20, the increase was marginally significant ($p=0.10$); at B99, the increase was statistically significant ($p=0.05$).
- Chassis dyno testing was done 24 months later at an ARB lab. The vehicle was determined to have high oil consumption, and lubricating oil was likely present in the exhaust stream. On the UDDS cycle, biodiesel increased NOx by 7% at B20 (marginally significant at $p=0.07$) and by 35% at B99 (highly significant, $p<0.01$).

The authors concluded "The use of biodiesel did result in higher NOx emissions than the use of ULSD (in tests with statistical significance)." The B20 test results did not reach the usual $p=0.05$ level for statistical significance, but were marginally significant ($0.05 < p \leq 0.10$).

McWilliam 2010. A Caterpillar 6.61 engine equipped with DOC and urea-SCR NOx after-treatment was tested using the European non-road transient cycle (NRTC). The fuels used were ULSD plus B20 and B100 biodiesels blended from a rapeseed methyl ester. Figure 9 of the paper shows tailpipe NOx emissions of the vehicle in g/kWh units. Reading from the graph because numerical emission values were not given, tailpipe NOx emissions increase ~15% at B20 and ~150% at B100. Based on the narrow error bars shown in the figure, both of these increases are statistically significant.

This study was conducted by Caterpillar because previous work had highlighted the potential for biodiesel to have an adverse impact on the NOx conversion efficiency of urea-SCR after-treatment systems. Thus, reductions in conversion efficiency have the potential to increase NOx emissions by amounts that exceed that caused by the biodiesel itself. At B20, only a 1% loss of conversion efficiency was noted, but a substantial 6% loss was observed at B100.

The authors of this paper concluded "Additional control strategies will be necessary to correct for NOx increases during biodiesel operation on installations requiring compliance regardless of fuel used."

Mizushima 2010. An inline 4-cylinder diesel engine equipped with DOC, diesel particulate trap (DPT), and urea-SCR NOx after-treatment system was tested using the JE-05 exhaust emissions test cycle used for heavy-duty vehicles in Japan. The fuels used were ULSD plus B20 and B100 blended from waste vegetable oil (WVO). Figure 4 of the paper shows tailpipe NOx emissions of the engine in g/kWh units. NOx emissions are highly linear with biodiesel blending level. Reading from the graph because numerical emission values were not given, tailpipe emissions increase ~20% at B20 and ~100% at B100. The paper does not address the statistical significance of these results.

With respect to NOx conversion efficiency, the study noted a drop from 76% on ULSD to 47% at B100, with a smaller but still measurable drop at B20. The impact on NOx conversion efficiency was linked to the effect of biodiesel in lowering the overall NO_2/NOx ratio at the SCR inlet leading to reduced conversion efficiency.

The authors drew no conclusions regarding the NOx emissions effects of B20 biodiesel as the focus of their research was on the B100 fuel.

Lammert 2012. The NREL study examined NOx emissions from transit buses on both EPA and CARB diesel fuels, B20 soy blends of each, and B100 soy. Chassis dynamometer testing was conducted using the Manhattan Bus (MAN), Orange County Transit Authority (OCTA) and UDDS test cycles. Two of the buses were NTDEs, including a 2010 Cummins ISL and 2011 Gillig/Cummins ISL. Only the 2010 Cummins was tested using the CARB ULSD base fuel and the biodiesel fuels.

NOx emission results for the 2010 Cummins bus are shown in Figure 10 of the paper. For B20, NOx emissions decreased compared to CARB ULSD on all three cycles (MAN, OCTA, and UDDS), and for B100 on the MAN cycle (OCTA and UDDS were not tested). None of the differences were statistically significant except for B20 on the UDDS cycle, and the standard errors plotted in the figure are large in comparison to the emission averages.

The authors explain the non-significance of their results as follows:

> *For much of the cycle NOx would be at or near the detection limit of the laboratory equipment, which resulted in a 95% confidence interval error that was high relative to the value of the cycle emissions.* (Page 6)

One of the authors' conclusions is that SCR NOx after-treatment appears to nearly negate the effect of fuels on NOx emissions. Another conclusion is that SCR NOx after-treatment also negates any duty cycle effect on NOx. (Page 8) For buses without NOx after-treatment, NOx emissions are strongly related to the kinetic intensity (load) of the test cycle. This result is consistent with all past vehicle and engine research studies, which show that NOx emissions are increased when a diesel engine is operated under increased load. However, no such relationship is observed for SCR-equipped buses. Increased load will increase engine-out NOx levels in an SCR-equipped bus. Unless this is accompanied by an increase in NOx conversion efficiency, tailpipe NOx emissions should also increase. Neither conclusion is reliable because of the study's problems in measuring NOx emissions even on ULSD fuel.

Gysel 2014. A 2010 Cummins ISX-15 equipped with DOC, DPF and urea-SCR NOx after-treatment was tested on CARB ULSD and B50 biodiesel blended from soy, waste cooking oil (WCO) and animal fat feedstocks. Chassis dynamometer testing was performed at CE-CERT using the UDDS test cycle.

Figure 7 of the paper shows the NOx emissions measured on ULSD and the three B50 biodiesel blends. The soy and WCO B50 blends increased NOx by 43% and 101%, respectively, with both increases being highly statistically significant ($p<0.01$). The animal B50 blend increased NOx by 47%, which was marginally significant ($p=0.065$). The authors' conclude that "Overall, NOx emissions exhibited increases with biodiesel for both vehicles with the differences in NOx emissions relative to CARB ULSD being statistically significant for the new Cummins ISX-15 engine." (Page 6)

The authors note the negative results reported by Lammert 2012 as being in contrast to those of their study, "which shows that there is a relatively strong fuel effect with the B50 blends compared to CARB ULSD from the Cummins ISX-15 engine with SCR." (Page 6). They also note the following:

> *The NOx increase with biodiesel for SCR-equipped engines is usually attributed by a reduction of exhaust temperature and the change of NO_2/NO ratio in NOx emissions [38]. In general, the lower exhaust temperatures with biodiesel will lower the oxidation rates of NO to NO_2 from the DOC. It has been shown that a NO_2/NOx ratio below 0.5 significantly changes SCR reaction chemistry lowering the SCR removal efficiency of NOx [39]. Walkowicz et al. [40] found increases in NOx emissions of 7% with B20 and 26% with B99 compared to ULSD for a heavy-duty diesel vehicle equipped with a 2004 Caterpillar 400 hp C13 engine. For the same vehicle equipped with a urea-based SCR system, NOx increases were very similar on a percentage basis, with B20 and B99 having 7% and 27%, respectively, higher NOx than ULSD.* (Page 6)

The authors continue to say:

> *The trend of increasing NOx emissions for biodiesel blends is consistent with a wide range of studies found in the literature. Comprehensive investigations conducted by Mueller et al. [41] and Sun et al. [42] confirmed that biodiesel promotes a combustion process that is shorter and more advanced than conventional diesel, which contributes to the formation of thermal NOx. The higher NOx emissions with biodiesel for both vehicles could also be a consequence of the higher oxygen content in biodiesel, which enhances the formation of NOx. The lower volatility of biodiesel compared to diesel fuel could also contribute to decreased fractions of premixed burn, as a result of fewer evaporated droplets during the ignition delay period [43]. Another contributing factor for NOx emissions increase could be the engine control module (ECM), which may dictate a different injection strategy based on the lower volumetric energy content of biodiesel. Eckerle et al. [44] suggested that a higher fuel flow is required with biodiesel compared to diesel fuel for an engine to achieve the same power. The ECM interprets this higher fuel flow as an indicator of higher torque, and therefore makes adjustments to engine operating parameters that, under certain operating conditions, increase NOx emissions.* (Page 6).

The engineering mechanisms described by the authors indicate that biodiesel should be expected to increase NOx emissions in NTDEs at blend levels below the B50 examined in the study. There is no basis in these mechanisms to believe that biodiesel will not increase NOx emissions at B20 but will increase NOx emissions at B50.

3.2 Consensus on Biodiesel NOx Impacts

Table 2 presents a summary of the available literature on the NOx emissions impact of biodiesel at the B20 blend level. Four of the five studies tested B20 fuels on NTDEs. Staff choose to rely on the one study in which NOx emissions were at or near the detection limit of the laboratory equipment for much of the test cycle on each fuel and to dismiss the other three studies "... since they included either retrofit engines or non-commercial engines ...". The study that was retained did not observe a NOx increase because it had trouble measuring NOx emissions from the NTDE tested. The studies that were dismissed showed consistent NOx emission increases in the range of 10-20% at B20.

Staff notes the Gysel study, which found significantly increased NOx emissions at B50 compared to CARB ULSD, as its reason for setting the biodiesel control level at B20 for NTDEs. However, Staff did not note the study's discussion indicating that the Lammert results were in contrast to their results and to the results of other studies in the literature. Nor did Staff note the discussion of mechanisms by which biodiesel is believed to increase NOx emissions in NTDEs. These mechanisms include a reduction of the NO_2/NOx ratio that leads to loss of NOx conversion efficiency in urea-SCR systems, promotion of a combustion process that contributes to increased formation of thermal NOx, higher NOx emissions due to the oxygen content of biodiesel, and the lower volatility and lower volumetric energy content of biodiesel. These mechanisms indicate that biodiesel can be expected to increase NOx emissions in NTDEs at blend levels below the B50 examined in the study.

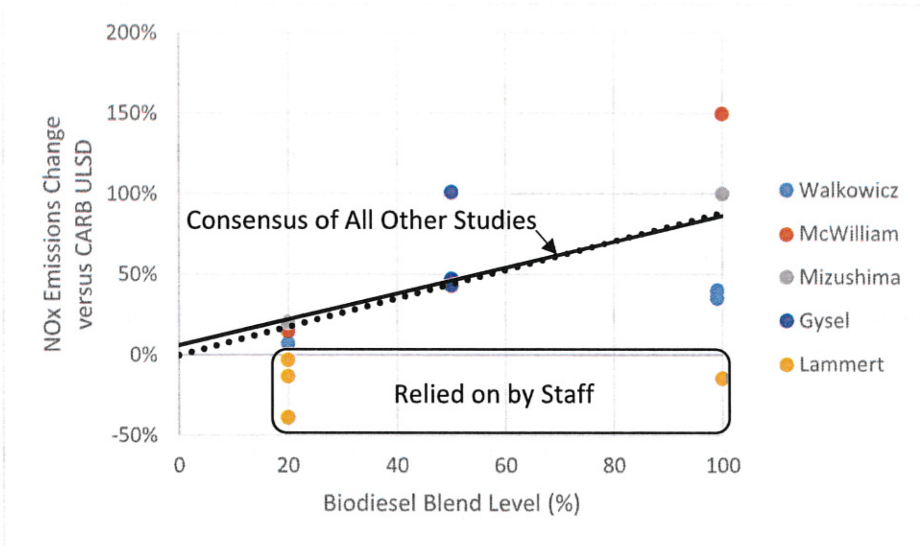
Table 2. Summary of NTDE Literature on NOx Emissions Impact of B20

	B20 NOx Emissions Change (%) versus CARB ULSD	Comments
Studies Relied on by Staff		
Lammert 2012	NOx emissions decrease on three cycles	UDDS cycle decrease is statistically significant. NOx emissions on all fuels were at or near the detection limit of the laboratory equipment.
Gysel 2014	B20 not tested	The paper discusses how biodiesel effects NOx emissions. These mechanisms suggest that biodiesel should increase NOx emissions at levels below B50.
Studies Dismissed by Staff		
Walkowicz 2009	+17% on-road + 7% chassis dyno	Both results are marginally significant ($0.10 \le p < 0.05$)
McWilliam 2010	~15% increase	European transient cycle
Mizushima 2010	~20% increase	Japanese heavy-duty test cycle

Figure 3 summarizes the impact of biodiesel on NTDE NOx emissions at all blend levels. The four studies (excluding Lammert 2012) establish a linear relationship between NOx emissions and blend level. The first trend line (solid black) passes very nearly through the origin without being constrained to do so. The second trend line (dotted black) is constrained to pass through the origin. While there is substantial scatter around the trend lines, the consensus of the four studies is that biodiesel increases NOx by 18-22% at B20, by 45-50% at B50, and by 90-100% at B100.

In spite of this consensus, Staff chose to rely only on the Lammert 2012 study, which shows that biodiesel decreases NOx emissions at both the B20 and B100 blend levels. This is the study that had difficulty measuring NOx emissions because NOx was at or near the detection limit of the laboratory equipment for much of the test cycle on all fuels.

Figure 3. The Impact of Biodiesel on NTDE NOx Emissions



To test the statistical significance of the trend lines shown in the figure, conventional regression analysis was conducted using the data reported by four of the studies (Lammert 2012 excluded) as summarized in Table 3. Regression A corresponds to the figure's solid trend line and is not constrained to pass through the origin. Its slope is +0.80% increase per 1% biodiesel in the blend; it is statistically significant at the $p=0.035$ level. Regression B corresponds to the dotted trend line and is constrained to pass through the origin. Its slope is +0.89% increase per 1% biodiesel, and it is statistically significant at the $p<0.001$ level. The two regression models predict a 22% and 18% increase, respectively, in NOx emissions at B20 in NTDEs.

Table 3. Statistical Significance of Biodiesel NOx Effect in NTDEs

	Intercept	Significance	Slope (% NOx Increase per 1% biodiesel)	Significance	Predicted NOx Increase at B20
Regression A	6.4	p = 0.80	+0.80% (±0.32%)	p = 0.035	22%
Regression B	None	n/a	+0.89% (±0.16%)	p <0.001	18%

A fair reading of the technical literature would lead Staff to expect that biodiesel will increase NOx emissions in NTDEs by about 20% at B20 and by proportionately smaller amounts at blend levels below B20. At the B5 level, the impact is expected to be an increase in NOx emissions of about 5%. At the B20 level, the NOx increase appears to be greater on a percentage basis than would be expected in conventional diesel engines (1% at B5, 2% at B10, and ~4% at B20). The loss of NOx conversion efficiency when biodiesel fuels are used is one likely reason for the greater impact.

4. SUMMARY AND CONCLUSIONS

The key conclusions of this study are summarized below with respect to conventional diesel engines and new technology diesel engines.

Conventional Diesel Engines

- Soy and animal blends are not categorically different fuels once their differing effect on blend CN is taken into account.
- There is no evidence in the data of a threshold level below which biodiesel fuels as a group do not increase NOx, whether soy or animal. As shown here, the magnitude of the NOx impact observed depends on both the blend level and the change in CN that results from blending of the biodiesel feedstock.
- Soy blends clearly and significantly increase NOx by ~1% at B5 and by ~2% at B10. The effect is continuous and linear with respect to the blend level at all levels above ULSD. Soy blends require mitigation at all levels to offset increased NOx emissions.
- Staff's proposal requires NOx mitigation in summer months for soy fuels at blend levels greater than B5. Because soy fuels increase NOx at all blend levels, mitigation should be required for B5 and lower blends to prevent increased NOx emissions.
- Animal blends are more complicated. The current research is limited, and the evidence is mixed. At least one B5 animal blend significantly increased NOx, while another has been certified as NOx neutral. Other B5 animal blends may or may not increase NOx depending on their CN effect (and possibly other factors).
- Staff's assertion that no NOx increase occurs at B5 in animal blends is incorrect: some animal blends will significantly increase NOx emissions, while other animal blends will not.
- Animal blends cannot be assumed to have no impact on NOx emissions without a demonstration that feedstock blending raises CN enough to offset potential NOx increases.

New Technology Diesel Engines

- Staff is incorrect in concluding that biodiesels will not increase NOx in NTDEs. The Staff conclusion is based on a highly selective reading of the technical literature that relies on the one study in which the laboratory was not well equipped to measure the low levels of tailpipe NOx emissions from NTDEs.

- There is greater reason to exclude the study Staff relied on than the three studies that Staff excluded. If that is done, there are no test data at the B20 level or below in NTDEs and no basis whatsoever to permit biodiesel fuels in NTDEs in California.
- While the available data are limited, the four best studies (excluding Lammert 2012) support the conclusion that biodiesel increases NOx by 18-22% at B20 and that the increase is statistically significant. Staff has no basis to claim that no NOx impacts are associated with biodiesel at the B20 level and below in NTDEs.
- A fair reading of the technical literature would lead Staff to expect that biodiesel will increase NOx emissions by about 20% at B20 and by proportionately smaller amounts at lower blend levels. This is a greater percentage NOx increase in proportion to blend level than the increase caused by soy biodiesel in conventional diesel engines (1% at B5, 2% at B10, and ~4% at B20).
- Staff makes no mention of the concern that the use of biodiesel fuels may lead to the loss of NOx conversion efficiency in urea-SCR after-treatment systems by shifting the NO_2/NOx ratio to lower values. Conversion losses were observed at B20 in two of the studies.

Based on the results summarized above, it is strongly recommended that ARB consider as part of the ADF rulemaking a regulatory structure in which the NOx impacts of soy and animal biodiesel are accounted for using a statistical model analogous to the Predictive Model for RFG. We see the cetane-based model presented here as a possible draft for a biodiesel predictive model, but substantial additional work is needed to:

- Demonstrate that blends mitigated using DTBP obey the same model; and
- Further assess the impacts of biodiesel produced from animal feedstocks on both CN gain in blends as well as NOx emissions.

Further, more advanced statistical techniques should be used as was done in developing the Predictive Model for California Reformulated gasoline. The dataset used here is unbalanced, meaning that there are varying numbers of data points for each combination of study, feedstock type, engine, and test cycle. In fact, only a fraction of all possible study/feedstock/engine/test cycle cells are represented by one or more data points. Mixed Effects modeling is appropriate in such cases and its use will assure that coefficient estimates are not biased by the unbalanced distribution of the data.

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APPENDIX TABLE A: REFERENCES TO LITERATURE ON CONVENTIONAL DIESEL ENGINES

Author	Title	Feedstocks Studied	Blends Studied
Clark 1999	Transient Emissions Comparisons of Alternative Compression Ignition Fuel	Soy	B20
McCormick 2002	Fuel Additive and Blending Approaches to Reducing NOx Emissions from Biodiesel	Soy, UCO	B20
McCormick 2005	Regulated Emissions from Biodiesel Tested in Heavy-Duty Engines Meeting 2004 Emissions	Soy, Canola, Animal	B20
Eckerle 2008	Effects of Methyl Ester Biodiesel Blends on NOx Emissions	Soy	B20
Nuszkowski 2009	Evaluation of the NOx emissions from heavy duty diesel engines with the addition of cetane improvers.	Soy	B20
Nikanjam 2010	Performance and emissions of diesel and alternative diesel fuels	Soy	B5, B20
Thompson 2010	Neat fuel influence on biodiesel blend emissions	Soy	B10, B20
Durbin 2011	Biodiesel Characterization and NOx Mitigation Study	Soy, Animal	B5, B10, B20
Durbin 2013A	CARB B5 Preliminary and Certification Testing	Animal	B5
Durbin 2013B	CARB B20 Biodiesel Preliminary and Certification Testing	Soy, UCO	B20
Karavalakis 2014	CARB Comprehensive B5/B10 Biodiesel Blends Heavy-Duty Engine Dynamometer Testing	Soy, Animal	B5, B10

APPENDIX TABLE B: REFERENCES TO LITERATURE ON NEW TECHNOLOGY DIESEL ENGINES

Author	Title	Feedstocks Studied	Blends Studied
Walkowicz 2009	On-road and In-Laboratory Testing to Demonstrate Effects of ULSD, B20 and B99 on a Retrofit Urea-SCR Aftertreatment System	Soy?	B20, B99
McWilliam 2010	Emissions and Performance Implications of Biodiesel Use in an SCR-equipped Caterpillar C6.6	Rapeseed	B20, B100
Mizushima 2010	Effect of Biodiesel on NOx Reduction Performance of Urea-SCR System	WVO	B20, B100
Lammert 2012	Effect of B20 and Low Aromatic Diesel on Transit Bus NOx Emissions Over Driving Cycles with a Range of Kinetic Intensity	Soy	B20, B100
Gysel 2014	Emissions and Redox Activity of Biodiesel Blends Obtained from Different Feedstocks from a Heavy-Duty Vehicle Equipped with DPF/SCR Aftertreatment and a Heavy-Duty Vehicle without Control Aftertreatment	Soy, WCO, animal	B50