APPENDIX G

SUPPLEMENTAL STATISTICAL ANALYSIS

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1. Analysis of Diesel Engine Test Data Comparing CARB Soy and Animal Biodiesel Blends to CARB Standard Diesel Fuel

David M. Rocke, PhD

Background:

As part of its Alternative Diesel Fuel rulemaking, ARB has done an extensive literature search and sponsored multiple studies examining the effect of biodiesel blends on NOx emissions using California diesel fuel as the baseline. In 2011 a report was completed for ARB that included an in depth analysis of NOx emissions, primarily on higher blends of B20 and above. The 2011 study, as well as the results of the literature search, showed that biodiesel blends B20 and above increase NOx relative to California diesel. However, it was determined additional study was necessary on the effects of biodiesel blends below B20.

ARB has sponsored two studies in the interim that examined B5 and B10 blends using soy and animal based feedstocks. ARB opted to contract with an independent statistician to determine whether the results of these studies, as well other studies included in its literature search, show a statistically significant impact on NOx from these lower biodiesel blend levels.

Summary

In this report, data from six studies comparing biodiesel blends to CARB standard diesel fuel are analyzed. These comprise 556 measurements in 40 experiments within the six studies on various combinations of test engine and test cycle, with measurements of NOx emissions from each run in each experiment in grams per brake-horsepower-hour. Each experiment was a head-to-head comparison of one of the biodiesel blends with CARB standard diesel fuel.

After a series of analyses of these data, using a range of methods on data comparing each biodiesel fuel to CARB standard diesel, as well as on combined data sets, including one with all six studies of all five fuels (5% and 10% soy biodiesel blends, 5% and 10% animal biodiesel blends, and CARB standard diesel), the following conclusions were reached:

1) Both the 5% and 10% blends of soy biodiesel with CARB diesel have increased NOx emissions compared to CARB diesel. The 5% blend has approximately 1% higher NOx emissions and the 10% blend has approximately 2% higher NOx emissions.
2) Neither the 5% nor 10% blends of animal biodiesel with CARB diesel have been shown to increase NOx emissions over CARB standard diesel. The difference in NOx emissions between the 5% and the 10% blends of animal biodiesel is not statistically significant.
3) The 10% blend of soy biodiesel with CARB diesel has higher NOx emissions than either the 5% or 10% animal biodiesel. The 5% blend of soy biodiesel with CARB diesel has higher NOx emissions than the 5% animal biodiesel.

The difference in NOx emissions between the 5% blend of soy biodiesel and the 10% blend of animal biodiesel is not statistically significant.

Data Sets Analyzed

The data sets used in this analysis are as follows:

Author	Title	Published	Year	Code
Durbin	Biodiesel Characterization and NOx Mitigation Study	Final Report Prepared for ARB	2011	D11
Durbin	CARB B5 Preliminary and Certification Testing	Final Report Prepared for ARB	2013	D13
Karavalakis, Durbin	CARB Comprehensive B5/B10 Biodiesel Blends Heavy-Duty Engine Dynamometer Testing	Final Report Prepared for ARB	2014	KD14
Nikanjam	Performance and emissions of diesel and alternative diesel fuels	SAE 2010-01-2281	2010	N10
Thompson	Neat fuel influence on biodiesel blend emissions	Int J Engine Res Vol. 11, 61-77.	2010	T10

In each case, the fuels tested were CARB ULSD or CARB-like (all coded as CARB), B5 and B10 Soy Biodiesel Blend and B5 and B10 Animal Biodiesel Blend (coded as B5 Soy, B10 Soy, B5 Animal, B10 Animal). Each of these data sets can be further divided into experiments, defined by the test cycle and the test engine type. The number of experiments in each Study and by Fuel comparison, engine, and test cycle is shown below.

Experiments by Biodiesel Blend and Study						
	D11	**D13**	**KD14**	**N10**	**T10**	**Total**
B5 Soy	5	1	6	2	—	14
B10 Soy	1	—	6	—	2	9
B5 Animal	3	2	6	—	—	11
B10 Animal	—	—	6	—	—	6
Total	9	3	24	2	2	40

Experiments by Test Engine and Study						
	D11	**D13**	**KD14**	**N10**	**T10**	**Total**
1991 DDC60	—	—	12	2	—	14
1992 DDC60	—	—	—	—	2	2
1999 Kubota TRU	1	—	—	—	—	1
2006 Cummins ISM	5	3	12	—	—	20
2007 MBE 4000	2	—	—	—	—	2
2009 John Deere 4045HF	1	—	—	—	—	1
Total	9	3	24	2	2	40

Experiments by Test Cycle and Study						
	D11	**D13**	**KD14**	**N10**	**T10**	**Total**
Cruise 40mph	1	—	—	—	—	1
Cruise 50mph	1	—	—	—	—	1
FTP	5	3	8	1	1	18
ISO 8178-4 C1	2	—	—	—	—	2
SET	—	—	8	1	1	10
UDDS	—	—	8	—	—	8
Total	9	3	24	2	2	40

Modeling Strategy

There are a number of possible statistical approaches to the analysis of these data. In order to achieve the highest level of robustness of conclusions, we will apply several approaches, so that any potential dependence on a particular set of assumptions is minimized.

One choice concerns the level of aggregation of the data sets we analyze. This can be at the following levels:

1. The experiment level (40 of them), comparing in each case a biofuel with the measurements of the CARB standard diesel taken in the same experiment
2. The fuel level, aggregating all the experiments comparing a given biodiesel fuel with CARB standard fuel. There are four such data sets, one each for B5 Soy, B10 Soy, B5 Animal, and B10 Animal. In each data set, we will estimate the effect of biodiesel vs. CARB diesel on NOx emissions, and also the effect of the particular experiment.
3. The biosource level, aggregating all the experiments comparing soy biodiesel with CARB standard diesel or comparing animal biodiesel with CARB standard diesel. There are two of these; in each one we will estimate the effect of biodiesel vs. CARB diesel on NOx emissions, the effect of the level of admixture of biodiesel on NOx emissions, and also the effect of the particular experiment.
4. A fully aggregated data set of all 40 experiments. Here we can estimate the various differences among the five fuels (B5 Soy, B10 Soy, B5 Animal, B10 Animal, CARB), as well as those due to the experiment, including choice of test engine and test cycle.

We will begin with analyses of each fuel vs the CARB standard fuel (items 1 and 2 above), then analyze all of the soy biofuel data together, all of the animal biofuel data together (item 3 above), and the full database (item 4 above). In all cases, we use the natural logarithm of the NOx measurement as the response variable, as is usual in emissions response models. The log transformation is needed because the variability of the repeat measurements rises with the mean.

For most of the analyses (except for item 1 above), we use a mixed model framework in which some parameters are fixed effects and some are random. Fixed effects are reproducible changes due to the conditions of the experiment. These would include the Engine Type and the Cycle, which are the same within an experiment, and Fuel, which is the parameter of interest. We can have fixed effects due to Experiment (which includes effects of Engine and Cycle) and Fuel, and possibly an Experiment*Fuel interaction. There are two possible random effects: variability of emissions by experiment, and variability of the effect of the fuel difference across experiments. These random effects are random events specific to an experiment and may encompass the particular instance of an engine, the ambient temperature, variations in the protocol within the test cycle parameters, operator differences and possibly others.

We use the `lme4` package in R (version 3.1.0) for the computations (R Core Team 2014; Bates et al. 2014a, 2014b). Following the procedures in the first report, as confirmed by similar analyses for the other three fuels, we use the model

```
lmer(log(NOx) ~ Exp + Fuel + (1 | Exp), data = ***)
```

where *** is one of the four fuel databases, b5s, b10s, b5a, and b10a, corresponding to B5 Soy, B10 Soy, B5 Animal, and B10 Animal. This has fixed effects due to Experiment and Fuel and a random intercept depending on the experiment.

Results Using the Mixed Model for Individual Fuel Comparisons

The full output is given in Appendix 1, but for the crucial Fuel parameter, we obtain estimates as shown below. Since the analysis is on the natural log scale, the results indicate that on the average the NOx emissions on the CARB fuel is about 1.1% lower than the emissions of the B5 fuel. Since the standard errors are approximate, the `lme4` package provides three methods of determining the (95%) confidence interval of a parameter of this kind, with results as shown in the following table. Also shown is the p-value from the ANOVA test.

Fuel Comparison	Estimate	Method	Lower CI	Upper CI	p-value
B5 Soy vs. CARB	−0.01135	Wald	−0.01648	−0.00622	1.044×10^{-5}
		Profile	−0.01629	−0.00641	
		Bootstrap	−0.01681	−0.00657	
B10 Soy vs CARB	−0.01896	Wald	−0.02466	−0.01326	3.721×10^{-10}
		Profile	−0.02447	−0.01345	
		Bootstrap	−0.02447	−0.01296	
B5 Animal vs. CARB	0.003629	Wald	−0.000172	0.007431	0.05354
		Profile	−0.000056	0.007315	
		Bootstrap	−0.000400	0.007675	
B10 Animal vs. CARB	−0.003000	Wald	−0.009522	0.003523	0.3467
		Profile	−0.009306	0.003306	
		Bootstrap	−0.009405	0.003339	

These results suggest that soy biodiesel has higher NOx emissions than the standard CARB fuel, about 1% higher for B5 and about 2% higher for B10. The animal biodiesel shows no significant increase in NOx at either level.

Alternative Analysis 1: Fixed Effects Analysis

For each fuel comparison, we can perform a simpler analysis using fixed effects models, though it does not allow for some complexities that may in fact characterize these data. In this approach, we consider effects of experiment, fuel, and possibly the interaction. The interaction effect is negligible in all four cases, so the additive model was used. The test of the Fuel effect is quite similar to the test in the mixed model—highly significant for soy biodiesel and not significant for animal biodiesel— and the estimated differences in NOx emissions are the same as in the mixed model. The full output for each fuel comparison is given in Appendix 2.

Alternative Analysis 2: t-tests by Experiment

Instead of analyzing the whole set of experiments for a given fuel comparison, we can conduct separate t-tests, one for each experiment. There are two experiments in the B5 Soy and two in the B10 Soy for which we cannot calculate a t-statistics because there are no replicates given—these are from the N10 and T10 studies. This leaves 12 studies for B5 Soy, 7 for B10 Soy, 11 for B5 Animal and 6 for B10 Animal.

For B5 Soy, there are 12 t-statistics comparing B5 Soy biodiesel to CARB diesel. Of these 12 comparisons, 11 have negative t-statistics indicating that the CARB fuel has lower NOx emissions. Of the 12 t-statistics, 5 are large enough in magnitude to be statistically significant at $p < 0.05$. All five of these are negative, showing that in all cases where the comparison was individually statistically significant, the CARB diesel had lower NOx emissions.

For B10 Soy, there are 7 t-statistics comparing B10 Soy biodiesel to CARB diesel. Of these 7 comparisons, 6 have negative t-statistics indicating that the CARB fuel has lower NOx emissions. Of the 7 t-statistics, 5 are large enough in magnitude to be statistically significant at $p < 0.05$. All five of these are negative, showing that in all cases where the comparison was individually statistically significant, the CARB diesel had lower NOx emissions.

For B5 Animal, there are 11 t-statistics comparing B5 Animal biodiesel to CARB diesel. Of these 11 comparisons, 6 have negative t-statistics and 5 have positive t-statistics. Of the 11 t-statistics, 2 are large enough in magnitude to be statistically significant at $p < 0.05$. Of these, one has a negative t-statistic and one has a positive t-statistic. This shows no evidence of a systematic tendency for the B5 biodiesel to have higher NOx emissions.

For B10 Animal, there are 6 t-statistics comparing B10 Animal biodiesel to CARB diesel. Of these 6 comparisons, 4 have negative t-statistics and 2 have positive t-statistics. Of the 6 t-statistics, only one is large enough in magnitude to be statistically significant at $p < 0.05$, and this t-statistic is negative. This shows little evidence of a systematic tendency for the B10 biodiesel to have higher NOx emissions.

Overall, the results from this approach support the conclusion that there is higher NOx emissions on 5% and 10% soy biodiesel, but not on 5% or 10% animal biodiesel, compared to CARB standard diesel.

Results for Mixed Model Analysis of Combined Data Sets for Soy Biodiesel

Here we analyze the results for the combined data sets of B5 Soy vs. CARB and B10 Soy vs. CARB. We expect fixed effects of Fuel and of the combination of Engine and Test Cycle and a random effect of experiment within the Engine and Cycle combination. The full results are given in Appendix 3.

1) A test of the model including the fixed effects of EC (Engine-Cycle combinations) and Fuel (3 types), with a random effect of experiment vs. the model omitting Fuel types shows that the simpler model is rejected ($p = 1.17 \times 10^{-11}$), meaning that the type of fuel does influence NOx emissions.

```
lm.obj0: log(NOx) ~ EC + (1 | Exp)
lm.obj: log(NOx) ~ EC + Fuel + (1 | Exp)

        Df     AIC     BIC logLik deviance  Chisq Chi Df Pr(>Chisq)
lm.obj0 14 -1572.7 -1520.5 800.33  -1600.7
lm.obj  16 -1619.0 -1559.4 825.50  -1651.0 50.343      2   1.17e-11 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

2) The estimated coefficients for the Fuel parameters are

```
Fixed effects:
                                  Estimate Std. Error t value
FuelB5-Soy                       -0.008303   0.003762   -2.21
FuelCARB                         -0.019076   0.003020   -6.32
```

showing that both the CARB fuel and the B5 Soy fuel have lower NOx emissions than the B10 Soy fuel.

3) To compare all three fuels, we use a post-hoc comparison by the Tukey HSD method showing that the CARB fuel has lower NOx emissions than either of the B5 Soy or B10 Soy fuels. The evidence that the B5 fuel has lower emissions than the B10 fuel is less strong.

```
Multiple Comparisons of Means: Tukey Contrasts


Fit: lmer(formula = log(NOx) ~ EC + Fuel + (1 | Exp), data = df1)

Linear Hypotheses:
                       Estimate Std. Error z value Pr(>|z|)
B5-Soy - B10-Soy == 0 -0.008303   0.003762  -2.207   0.0662 .
```

```
CARB - B10-Soy == 0   -0.019076   0.003020  -6.316   <1e-04 ***
CARB - B5-Soy == 0    -0.010773   0.002437  -4.421   <1e-04 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

4) The three fuel effects (2df) can be separated into a linear effect and a quadratic effect. The quadratic effect is not significant, but the linear effect is highly significant ($p = 1.32\times10^{-12}$). The linear coefficient is 0.00986, corresponding to a 0.99% increase in NOx emissions for each 5% admixture of soy biodiesel.[1]

This analysis supports the conclusion that 5% and 10% blends of soy biodiesel with CARB diesel increase NOx emissions at about a 1% increase in NOx emissions for each 5% admixture of soy biodiesel.

Results for Mixed Model Analysis of Combined Data Sets for Animal Biodiesel

Here we analyze the results for the combined data sets of B5 Animal vs. CARB and B10 Animal vs. CARB. We expect fixed effects of Fuel and of the combination of Engine and Test Cycle (EC) and a random effect of experiment within the Engine and Cycle combination. The full results are given in Appendix 4.

1) A test of the model including the fixed effects of EC (Engine-Cycle combinations) and Fuel (3 types), with a random effect of experiment vs. the model omitting Fuel types shows that the simpler model is not rejected (p = 0.1037), meaning that the type of fuel does not appear to influence NOx emissions.

```
lm.obj0: log(NOx) ~ EC + (1 | Exp)
lm.obj: log(NOx) ~ EC + Fuel + (1 | Exp)

        Df     AIC     BIC logLik deviance  Chisq Chi Df Pr(>Chisq)
lm.obj0 10 -1399.1 -1363.9 709.55  -1419.1
lm.obj  12 -1399.6 -1357.4 711.81  -1423.6 4.5328      2     0.1037
```

2) The estimated coefficients for the Fuel parameters are

```
Fixed effects:
                                       Estimate Std. Error t value
FuelB5-Animal                         -0.006431   0.003414   -1.88
FuelCARB                              -0.002865   0.002870   -1.00
```

[1] The three fuels can be given a numerical value of x = 0, 5, and 10 for the percentage of soy biodiesel admixture. The linear effect is the regression using x as a predictor. The quadratic effect is the additional explanatory power of x^2 added to the x variable, and this measures curvature of the response. The reason that the linear effect is significant is that the 10% biodiesel has about twice the extra NOx emissions of the 5% biodiesel, which is a straight line relationship. The reason that the quadratic effect is not significant is that the three NOx emissions values line up in very close to a straight line, so there is no measureable curvature.

showing that neither the CARB fuel nor the B5 Animal fuel have provably lower NOx emissions than the B10 Animal fuel.

3) A post-hoc comparison of all three fuels using the Tukey HSD method shows that none of the pairwise differences among the fuels is significant.

```
Multiple Comparisons of Means: Tukey Contrasts


Fit: lmer(formula = log(NOx) ~ EC + Fuel + (1 | Exp), data = df1)

Linear Hypotheses:
                             Estimate Std. Error z value Pr(>|z|)
B5-Animal - B10-Animal == 0 -0.006431   0.003414  -1.884    0.136
CARB - B10-Animal == 0      -0.002865   0.002870  -0.998    0.565
CARB - B5-Animal == 0        0.003566   0.002018   1.767    0.171
```

4) The three fuel effects (2df) can be separated into a linear effect and a quadratic effect. The linear effect is not significant ($p = 0.9027$). The quadratic coefficient has a p-value slightly under 0.05 ($p = 0.03354$), but this is likely due to chance.

This analysis supports the conclusion that 5% and 10% blends of animal biodiesel with CARB diesel have not been shown to increase NOx emissions.

Results for Mixed Model Analysis of Combined Data Sets for Soy and Animal Biodiesel

Here we analyze the results for the combined data sets for all the data sets comparing soy and animal biodiesel to CARB diesel. As before, we expect fixed effects of Fuel and of the combination of Engine and Test Cycle (EC) and a random effect of experiment within the Engine and Cycle combination. The full results are given in Appendix 5.

1) A test of the model including the fixed effects of EC (Engine-Cycle combinations) and Fuel (5 types), with a random effect of experiment vs. the model omitting Fuel types shows that the simpler model is rejected ($p = 1.15\times10^{-15}$), meaning that the type of fuel does appears to influence NOx emissions.

```
lm.obj0: log(NOx) ~ EC + (1 | Exp)
lm.obj: log(NOx) ~ EC + Fuel + (1 | Exp)

        Df     AIC     BIC logLik deviance  Chisq Chi Df Pr(>Chisq)
lm.obj0 15 -2951.8 -2887.0 1490.9  -2981.8
lm.obj  19 -3019.9 -2937.8 1529.0  -3057.9 76.125      4  1.152e-15 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

2) The estimated coefficients for the Fuel parameters are

```
Fixed effects:
                                       Estimate Std. Error t value
FuelB10-Soy                            0.017326   0.004085    4.24
FuelB5-Animal                         -0.006181   0.003737   -1.65
FuelB5-Soy                             0.008740   0.003755    2.33
FuelCARB                              -0.002255   0.003107   -0.73
```

showing that both soy biodiesel fuels likely have higher emissions than the B10 animal biodiesel.

3) To compare all five fuels, we use a post-hoc comparison by the Tukey HSD method showing that B10 Soy has higher emissions than the CARB or either animal biodiesel fuel and that the B5 Soy has higher emissions than the CARB and B5 Animal fuels.

```
       Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lmer(formula = log(NOx) ~ EC + Fuel + (1 | Exp), data = df1)

Linear Hypotheses:
                             Estimate Std. Error z value Pr(>|z|)
B10-Soy - B10-Animal == 0     0.017326   0.004085   4.242   <0.001 ***
B5-Animal - B10-Animal == 0 -0.006181   0.003737  -1.654   0.4359
B5-Soy - B10-Animal == 0      0.008740   0.003755   2.327   0.1239
CARB - B10-Animal == 0      -0.002255   0.003107  -0.726   0.9442
B5-Animal - B10-Soy == 0    -0.023507   0.003466  -6.783   <0.001 ***
B5-Soy - B10-Soy == 0       -0.008586   0.003487  -2.462   0.0903 .
CARB - B10-Soy == 0         -0.019582   0.002763  -7.087   <0.001 ***
B5-Soy - B5-Animal == 0      0.014921   0.003049   4.894   <0.001 ***
CARB - B5-Animal == 0        0.003926   0.002185   1.797   0.3503
CARB - B5-Soy == 0          -0.010995   0.002220  -4.953   <0.001 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)
```

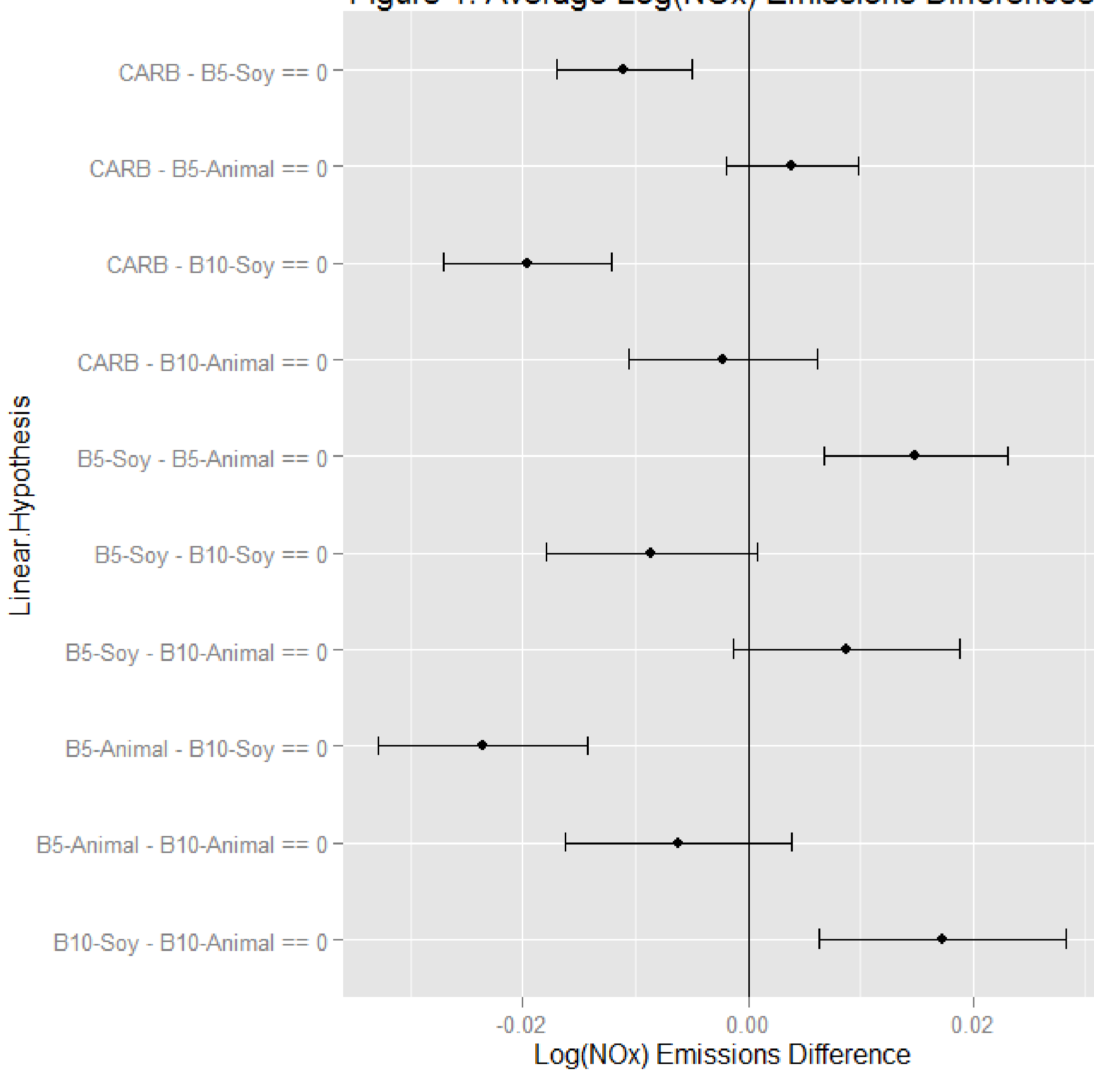
Figure 1 below shows a plot of these emissions differences and confidence intervals. Intervals intersecting the vertical line at 0 indicate that the difference is not statistically significant.

This analysis supports the following conclusions:

1) Both 5% and 10% blends of soy biodiesel with CARB diesel have increased NOx emissions compared to CARB diesel, with an apparently linear trend.
2) Neither 5% nor 10% blends of animal biodiesel with CARB diesel have been shown to increase NOx emissions.
3) The 10% blend of soy biodiesel with CARB diesel has higher NOx emissions than either 5% or 10% animal biodiesel and the 5% blend of soy biodiesel with CARB diesel has higher NOx emissions than the 5% animal biodiesel.

A table of estimated least squares mean emissions values adjusted for engine, cycle, and experiment, is given at the end of Appendix 5 on the log scale, and is graphed below as Figure 2, with the values transformed back to the original scale of gm/bhp-hr.

Figure 1. Average Log(NOx) Emissions Differences



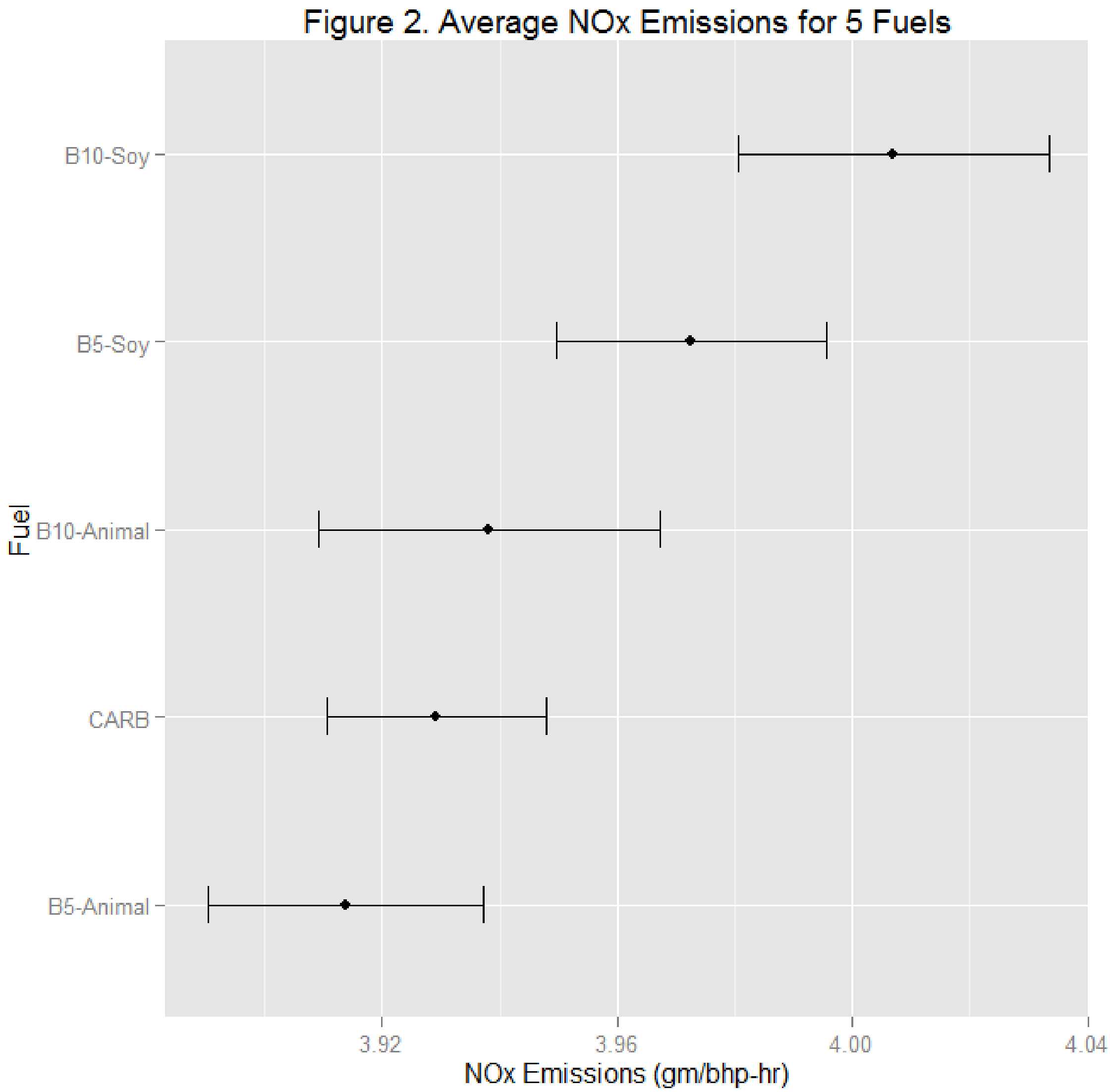


Figure 2. Average NOx Emissions for 5 Fuels
Fuel
B10-Soy
B5-Soy
B10-Animal
CARB
B5-Animal
3.92
3.96
4.00
4.04
NOx Emissions (gm/bhp-hr)

Summary and Conclusions

After a series of analyses of these data, using a range of methods on data comparing each biodiesel fuel to CARB standard diesel, as well as combined data sets, including one with all six studies of all five fuels (5% and 10% soy biodiesel blends, 5% and 10% animal biodiesel blends, and CARB standard diesel, the following conclusions were reached:

1) Both 5% and 10% blends of soy biodiesel with CARB diesel have increased NOx emissions compared to CARB diesel. The 5% blend has approximately 1% higher NOx emissions and the 10% blend has approximately 2% higher NOx emissions.
2) Neither 5% nor 10% blends of animal biodiesel with CARB diesel have been shown to increase NOx emissions over CARB standard diesel.
3) The 10% blend of soy biodiesel with CARB diesel has higher NOx emissions than either 5% or 10% animal biodiesel and the 5% blend of soy biodiesel with CARB diesel has higher NOx emissions than the 5% animal biodiesel.

References

Bates D, Maechler M, Bolker B and Walker S (2014a). lme4: Linear mixed-effects models using Eigen and S4. R package version 1.1-7, http://CRAN.R-project.org/package=lme4.

Bates D, Maechler M, Bolker BM and Walker S (2014b). "lme4: Linear mixed-effects models using Eigen and S4." ArXiv e-print; submitted to Journal of Statistical Software, http://arxiv.org/abs/1406.5823.

R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

2. Supporting Data

A. Results of Mixed Model Analysis by Fuel Comparison

B5 Soy

```
Linear mixed model fit by REML ['lmerMod']
Formula: log(NOx) ~ Exp + Fuel + (1 | Exp)
   Data: b5s

REML criterion at convergence: -865.8

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.0030 -0.3326  0.0196  0.3530  3.3777

Random effects:
 Groups   Name        Variance  Std.Dev.
 Exp      (Intercept) 0.0003923 0.01981
 Residual             0.0002818 0.01679
Number of obs: 184, groups: Exp, 14

Fixed effects:
             Estimate Std. Error t value
(Intercept)  0.720354   0.021240   33.92
Exp2        -0.163257   0.029403   -5.55
Exp3         0.034603   0.029131    1.19
Exp4        -0.451302   0.029403  -15.35
Exp5         1.449692   0.029254   49.55
Exp6         0.006458   0.029403    0.22
Exp7         0.025543   0.029303    0.87
Exp8         1.081360   0.029285   36.93
Exp9        -0.094923   0.029602   -3.21
Exp10        0.774450   0.029303   26.43
Exp11        1.714500   0.029303   58.51
Exp12        1.282810   0.029602   43.34
Exp13        0.801507   0.031336   25.58
Exp14        1.304217   0.031336   41.62
FuelCARB    -0.011353   0.002617   -4.34
```

Wald Intervals

```
                  2.5 %       97.5 %
(Intercept)  0.67872486  0.761983748
Exp2        -0.22088597 -0.105628542
Exp3        -0.02249316  0.091698895
Exp4        -0.50893083 -0.393673400
Exp5         1.39235408  1.507029054
Exp6        -0.05117037  0.064087054
Exp7        -0.03188932  0.082976160
Exp8         1.02396284  1.138756716
Exp9        -0.15294159 -0.036904241
Exp10        0.71701711  0.831882590
Exp11        1.65706770  1.771933181
Exp12        1.22479126  1.340828616
```

Exp13	0.74009012	0.862924141
Exp14	1.24280010	1.365634129
FuelCARB	-0.01648182	-0.006223831

Profile Likelihood Intervals

	2.5 %	97.5 %
.sig01	0.000000000	0.002571326
.sigma	0.014573370	0.017881624
(Intercept)	0.705873162	0.734835447
Exp2	-0.180135405	-0.146379107
Exp3	0.019498192	0.049707547
Exp4	-0.468180263	-0.434423965
Exp5	1.433760576	1.465622563
Exp6	-0.010419809	0.023336489
Exp7	0.009297084	0.041789754
Exp8	1.065231306	1.097488686
Exp9	-0.112998562	-0.076847273
Exp10	0.758203515	0.790696185
Exp11	1.698254106	1.730746776
Exp12	1.264734295	1.300885584
Exp13	0.774984645	0.828029612
Exp14	1.277694632	1.330739599
FuelCARB	-0.016294087	-0.006411569

Bootstrap Intervals

	2.5 %	97.5 %
sd_(Intercept)|Exp	0.01787507	0.025645641
sigma	0.01520173	0.018570991
(Intercept)	0.67681498	0.766791242
Exp2	-0.22851642	-0.108066583
Exp3	-0.02669412	0.092380808
Exp4	-0.51616964	-0.392100834
Exp5	1.38838188	1.507142149
Exp6	-0.05765814	0.062451597
Exp7	-0.03071517	0.088648612
Exp8	1.01533762	1.145621071
Exp9	-0.15803653	-0.036564436
Exp10	0.71152935	0.826139616
Exp11	1.65423075	1.768359613
Exp12	1.22431381	1.341340831
Exp13	0.73755912	0.861957283
Exp14	1.24033651	1.365964319
FuelCARB	-0.01718376	-0.005705294

B10 Soy

```
Linear mixed model fit by REML ['lmerMod']
Formula: log(NOx) ~ Exp + Fuel + (1 | Exp)
   Data: b10s

REML criterion at convergence: -607.1

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.1119 -0.4474  0.0717  0.4234  5.9910

Random effects:
 Groups   Name        Variance  Std.Dev.
 Exp      (Intercept) 0.0002207 0.01486
 Residual             0.0002207 0.01486
Number of obs: 123, groups: Exp, 9

Fixed effects:
             Estimate Std. Error t value
(Intercept)  0.762029   0.015245   49.99
Exp2        -0.014660   0.021490   -0.68
Exp3         1.043801   0.021490   48.57
Exp4        -0.110819   0.021809   -5.08
Exp5         0.744872   0.021490   34.66
Exp6         1.678719   0.021490   78.12
Exp7         1.260939   0.021809   57.82
Exp8         1.029899   0.023630   43.58
Exp9         1.567553   0.023630   66.34
FuelCARB    -0.018961   0.002909   -6.52
```

Wald Intervals

```
                  2.5 %      97.5 %
(Intercept)  0.73215036  0.79190843
Exp2        -0.05678050  0.02745973
Exp3         1.00168073  1.08592096
Exp4        -0.15356316 -0.06807426
Exp5         0.70275227  0.78699249
Exp6         1.63659888  1.72083910
Exp7         1.21819412  1.30368302
Exp8         0.98358526  1.07621337
Exp9         1.52123890  1.61386701
FuelCARB    -0.02466249 -0.01325910
```

Profile Likelihood Intervals

```
                  2.5 %       97.5 %
.sig01       0.00000000          Inf
.sigma       0.01262902  0.016221814
(Intercept)  0.75554820  0.768510585
Exp2        -0.02322569 -0.006095084
Exp3         1.03523554  1.052366148
Exp4        -0.12190063 -0.099736798
Exp5                 NA           NA
Exp6                 NA           NA
```

```
Exp7         1.24985666  1.272020486
Exp8         1.00941822  1.050380410
Exp9         1.54707186  1.588034050
FuelCARB    -0.02446875 -0.013452837
```

Bootstrap Intervals

```
                            2.5 %      97.5 %
sd_(Intercept)|Exp  0.01087696  0.01726717
sigma               0.01295158  0.01666447
(Intercept)         0.73341137  0.79213353
Exp2               -0.05325343  0.02851264
Exp3                1.00245916  1.08299330
Exp4               -0.15720470 -0.06664186
Exp5                0.70446917  0.78409780
Exp6                1.63742999  1.72330115
Exp7                1.21403802  1.30453569
Exp8                0.98759061  1.07851554
Exp9                1.52234653  1.61564599
FuelCARB           -0.02446762 -0.01296271
```

B5 Animal

```
Linear mixed model fit by REML ['lmerMod']
Formula: log(NOx) ~ Exp + Fuel + (1 | Exp)
   Data: b5a

REML criterion at convergence: -895.1

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.5272 -0.4724 -0.0212  0.5124  3.9241

Random effects:
 Groups   Name        Variance  Std.Dev.
 Exp      (Intercept) 0.0001563 0.01250
 Residual             0.0001589 0.01261
Number of obs: 169, groups: Exp, 11

Fixed effects:
             Estimate Std. Error t value
(Intercept)  0.733465   0.013055   56.18
Exp2        -0.468659   0.018412  -25.45
Exp3         0.242331   0.018385   13.18
Exp4        -0.020035   0.018412   -1.09
Exp5        -0.022702   0.018159   -1.25
Exp6         0.005446   0.018322    0.30
Exp7         1.041211   0.018322   56.83
Exp8        -0.115742   0.018591   -6.23
Exp9         0.755177   0.018322   41.22
Exp10        1.683871   0.018322   91.90
Exp11        1.269021   0.018591   68.26
FuelCARB     0.003629   0.001940    1.87
```

Wald Intervals

	2.5 %	97.5 %
(Intercept)	0.7078770279	0.759053173
Exp2	-0.5047458431	-0.432571833
Exp3	0.2062978655	0.278363960
Exp4	-0.0561215976	0.016052413
Exp5	-0.0582925314	0.012887951
Exp6	-0.0304647613	0.041355995
Exp7	1.0053003963	1.077121153
Exp8	-0.1521793255	-0.079303945
Exp9	0.7192662992	0.791087056
Exp10	1.6479608900	1.719781646
Exp11	1.2325828359	1.305458217
FuelCARB	-0.0001724136	0.007431249

Profile Likelihood Intervals

	2.5 %	97.5 %
.sig01	0.000000e+00	0.00205094
.sigma	1.096112e-02	0.01356971
(Intercept)	7.263103e-01	0.74061991
Exp2	-4.784360e-01	-0.45888172
Exp3	2.327426e-01	0.25191921
Exp4	-2.981171e-02	-0.01025748
Exp5	-3.058485e-02	-0.01481973
Exp6	-3.700039e-03	0.01459127
Exp7	1.032065e+00	1.05035643
Exp8	-1.266728e-01	-0.10481049
Exp9	7.460310e-01	0.76432233
Exp10	1.674726e+00	1.69301692
Exp11	1.258089e+00	1.27995168
FuelCARB	-5.587472e-05	0.00731471

Bootstrap Intervals

	2.5 %	97.5 %
sd_(Intercept)|Exp	0.0110323662	0.014193091
sigma	0.0112355037	0.014004641
(Intercept)	0.7081344205	0.758637283
Exp2	-0.5029651804	-0.432850454
Exp3	0.2078817519	0.277633483
Exp4	-0.0538584151	0.015181759
Exp5	-0.0572778762	0.011708078
Exp6	-0.0285290574	0.040762369
Exp7	1.0077458942	1.077967970
Exp8	-0.1502541601	-0.077928394
Exp9	0.7186375762	0.789088938
Exp10	1.6458534618	1.719348003
Exp11	1.2324843610	1.304232643
FuelCARB	-0.0004002963	0.007675285

B10 Animal

```
Linear mixed model fit by REML ['lmerMod']
Formula: log(NOx) ~ Exp + Fuel + (1 | Exp)
   Data: b10a

REML criterion at convergence: -388.9

Scaled residuals: 
    Min      1Q  Median      3Q     Max 
-2.8844 -0.3454  0.0822  0.4784  3.5163 

Random effects:
 Groups   Name        Variance  Std.Dev.
 Exp      (Intercept) 0.0002214 0.01488 
 Residual             0.0002215 0.01488 
Number of obs: 80, groups: Exp, 6

Fixed effects:
             Estimate Std. Error t value
(Intercept)  0.736722   0.015426   47.76
Exp2         1.035428   0.021689   47.74
Exp3        -0.116300   0.022006   -5.28
Exp4         0.753768   0.021689   34.75
Exp5         1.687508   0.021689   77.80
Exp6         1.274192   0.022006   57.90
FuelCARB    -0.003000   0.003328   -0.90
```

Wald Intervals

```
                   2.5 %       97.5 %
(Intercept)  0.706486265  0.766956923
Exp2         0.992918135  1.077937673
Exp3        -0.159430248 -0.073168904
Exp4         0.711258665  0.796278202
Exp5         1.644998188  1.730017726
Exp6         1.231061326  1.317322670
FuelCARB    -0.009521882  0.003522589
```

Profile Likelihood Intervals

```
                   2.5 %       97.5 %
.sig01       0.000000000  0.003758564
.sigma       0.012268458  0.016739245
(Intercept)  0.728998478  0.744444710
Exp2         1.025457404  1.045398403
Exp3        -0.128510894 -0.104088258
Exp4         0.743797934  0.763738933
Exp5         1.677537458  1.697478457
Exp6         1.261980679  1.286403316
FuelCARB    -0.009305544  0.003306251
```

Bootstrap Intervals

```
                          2.5 %       97.5 %
sd_(Intercept)|Exp  0.011053596  0.019206150
sigma               0.012364723  0.017223225
(Intercept)         0.706666465  0.765434228
Exp2                0.992474673  1.078945202
Exp3               -0.160472138 -0.072604440
Exp4                0.712494082  0.795363205
Exp5                1.645601839  1.728599030
Exp6                1.232957558  1.317027936
FuelCARB           -0.009405357  0.003339215
```

B. Fixed Effects Analysis by Experiment and Fuel

B5 Soy

```
Call:
lm(formula = log(NOx) ~ Exp + Fuel, data = b5s)

Residuals:
      Min        1Q    Median        3Q       Max 
-0.050407 -0.005582  0.000328  0.005925  0.056696 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)    
(Intercept)  0.720354   0.007669  93.928  < 2e-16 ***
Exp2        -0.163257   0.008939 -18.264  < 2e-16 ***
Exp3         0.034603   0.007999   4.326 2.59e-05 ***
Exp4        -0.451302   0.008939 -50.489  < 2e-16 ***
Exp5         1.449692   0.008437 171.825  < 2e-16 ***
Exp6         0.006458   0.008939   0.723  0.47097    
Exp7         0.025543   0.008604   2.969  0.00342 ** 
Exp8         1.081360   0.008542 126.599  < 2e-16 ***
Exp9        -0.094923   0.009573  -9.916  < 2e-16 ***
Exp10        0.774450   0.008604  90.010  < 2e-16 ***
Exp11        1.714500   0.008604 199.267  < 2e-16 ***
Exp12        1.282810   0.009573 134.005  < 2e-16 ***
Exp13        0.801507   0.014046  57.062  < 2e-16 ***
Exp14        1.304217   0.014046  92.852  < 2e-16 ***
FuelCARB    -0.011353   0.002617  -4.338 2.46e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.01679 on 169 degrees of freedom
Multiple R-squared:  0.9995,  Adjusted R-squared:  0.9994 
F-statistic: 2.265e+04 on 14 and 169 DF,  p-value: < 2.2e-16

Analysis of Variance Table

Response: log(NOx)
           Df Sum Sq Mean Sq   F value    Pr(>F)    
Exp        13 89.351  6.8731 24393.873 < 2.2e-16 ***
```

```
Fuel        1  0.005  0.0053    18.821 2.464e-05 ***
Residuals 169  0.048  0.0003
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

B10 Soy

```
Call:
lm(formula = log(NOx) ~ Exp + Fuel, data = b10s)

Residuals:
      Min        1Q    Median        3Q       Max
-0.046228 -0.006646  0.001065  0.006289  0.088999

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.762029   0.003423 222.613  < 2e-16 ***
Exp2        -0.014660   0.004524  -3.241  0.00157 **
Exp3         1.043801   0.004524 230.733  < 2e-16 ***
Exp4        -0.110819   0.005853 -18.934  < 2e-16 ***
Exp5         0.744872   0.004524 164.654  < 2e-16 ***
Exp6         1.678719   0.004524 371.082  < 2e-16 ***
Exp7         1.260939   0.005853 215.434  < 2e-16 ***
Exp8         1.029899   0.010817  95.209  < 2e-16 ***
Exp9         1.567553   0.010817 144.912  < 2e-16 ***
FuelCARB    -0.018961   0.002909  -6.518 2.07e-09 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.01486 on 113 degrees of freedom
Multiple R-squared:  0.9995,  Adjusted R-squared:  0.9995
F-statistic: 2.625e+04 on 9 and 113 DF,  p-value: < 2.2e-16

Analysis of Variance Table

Response: log(NOx)
           Df Sum Sq Mean Sq   F value    Pr(>F)
Exp         8 52.119  6.5149 29521.604 < 2.2e-16 ***
Fuel        1  0.009  0.0094    42.482 2.069e-09 ***
Residuals 113  0.025  0.0002
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

B5 Animal

```
Call:
lm(formula = log(NOx) ~ Exp + Fuel, data = b5a)

Residuals:
      Min        1Q    Median        3Q       Max 
-0.044463 -0.005955 -0.000267  0.006459  0.049465 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)    
(Intercept)  0.733465   0.003766 194.764  < 2e-16 ***
Exp2        -0.468659   0.005146 -91.070  < 2e-16 ***
Exp3         0.242331   0.005047  48.017  < 2e-16 ***
Exp4        -0.020035   0.005146  -3.893 0.000146 ***
Exp5        -0.022702   0.004149  -5.472 1.73e-07 ***
Exp6         0.005446   0.004814   1.131 0.259674    
Exp7         1.041211   0.004814 216.297  < 2e-16 ***
Exp8        -0.115742   0.005754 -20.116  < 2e-16 ***
Exp9         0.755177   0.004814 156.878  < 2e-16 ***
Exp10        1.683871   0.004814 349.801  < 2e-16 ***
Exp11        1.269021   0.005754 220.562  < 2e-16 ***
FuelCARB     0.003629   0.001940   1.871 0.063195 .  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.01261 on 157 degrees of freedom
Multiple R-squared:  0.9996,  Adjusted R-squared:  0.9996 
F-statistic: 3.774e+04 on 11 and 157 DF,  p-value: < 2.2e-16

Analysis of Variance Table

Response: log(NOx)
           Df Sum Sq Mean Sq    F value  Pr(>F)    
Exp        10 65.963  6.5963 41512.6743 < 2e-16 ***
Fuel        1  0.001  0.0006     3.5009 0.06319 .  
Residuals 157  0.025  0.0002                       
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

B10 Animal

```
Call:
lm(formula = log(NOx) ~ Exp + Fuel, data = b10a)

Residuals:
      Min        1Q    Median        3Q       Max 
-0.042926 -0.005141  0.001224  0.007119  0.052330 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)    
(Intercept)  0.736722   0.004076 180.763   <2e-16 ***
Exp2         1.035428   0.005262 196.789   <2e-16 ***
Exp3        -0.116300   0.006444 -18.047   <2e-16 ***
Exp4         0.753768   0.005262 143.258   <2e-16 ***
Exp5         1.687508   0.005262 320.721   <2e-16 ***
Exp6         1.274192   0.006444 197.729   <2e-16 ***
FuelCARB    -0.003000   0.003328  -0.901     0.37    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 

Residual standard error: 0.01488 on 73 degrees of freedom
Multiple R-squared:  0.9995,  Adjusted R-squared:  0.9995 
F-statistic: 2.428e+04 on 6 and 73 DF,  p-value: < 2.2e-16 

Analysis of Variance Table

Response: log(NOx)
          Df Sum Sq Mean Sq   F value Pr(>F)    
Exp        5 32.270  6.4539 2.914e+04 <2e-16 ***
Fuel       1  0.000  0.0002 8.125e-01 0.3703    
Residuals 73  0.016  0.0002                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 
```

C. Results of Mixed Model Analysis of Combined Soy Biodiesel Data Sets

(EC is a variable of all combinations of Engine and Test Cycle)

```
Data: df1
Models:
lm.obj0: log(NOx) ~ EC + (1 | Exp)
lm.obj: log(NOx) ~ EC + Fuel + (1 | Exp)

        Df     AIC     BIC logLik deviance  Chisq Chi Df Pr(>Chisq)
lm.obj0 14 -1572.7 -1520.5 800.33  -1600.7
lm.obj  16 -1619.0 -1559.4 825.50  -1651.0 50.343      2   1.17e-11 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1


Linear mixed model fit by REML ['lmerMod']
Formula: log(NOx) ~ EC + Fuel + (1 | Exp)
   Data: df1

REML criterion at convergence: -1533.8

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.1210 -0.3911  0.0197  0.3641  5.7106

Random effects:
 Groups   Name        Variance  Std.Dev.
 Exp      (Intercept) 7.629e-05 0.008734
 Residual             2.579e-04 0.016058
Number of obs: 307, groups: Exp, 23

Fixed effects:
                                  Estimate Std. Error t value
(Intercept)                       1.509480   0.006618  228.09
EC1991 DDC60SET                   0.510859   0.008979   56.89
EC1991 DDC60UDDS                  0.932357   0.009162  101.76
EC1992 DDC60FTP                   0.282507   0.015626   18.08
EC1992 DDC60SET                   0.820160   0.015626   52.49
EC1999 Kubota TRUISO 8178-4 C1    0.668533   0.011315   59.09
EC2006 Cummins ISMCRUISE - 40mph -0.781170   0.012884  -60.63
EC2006 Cummins ISMCRUISE - 50mph -0.944370   0.011665  -80.96
EC2006 Cummins ISMFTP            -0.756630   0.007460 -101.42
EC2006 Cummins ISMSET            -0.867123   0.009592  -90.40
EC2006 Cummins ISMUDDS            0.298329   0.009149   32.61
EC2007 MBE4000FTP                -1.232414   0.011665 -105.65
FuelB5-Soy                       -0.008303   0.003762   -2.21
FuelCARB                         -0.019076   0.003020   -6.32
```

```
         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lmer(formula = log(NOx) ~ EC + Fuel + (1 | Exp), data = df1)

Linear Hypotheses:
                       Estimate Std. Error z value Pr(>|z|)
B5-Soy - B10-Soy == 0 -0.008303   0.003762  -2.207   0.0662 .
CARB - B10-Soy == 0   -0.019076   0.003020  -6.316   <1e-04 ***
CARB - B5-Soy == 0    -0.010773   0.002437  -4.421   <1e-04 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- single-step method)
```

```
Data: df1
Models:
lm.obj2b: log(NOx) ~ EC + fuel.lin + (1 | Exp)
lm.obj2a: log(NOx) ~ EC + fuel.lin + fuel.quad + (1 | Exp)

         Df   AIC     BIC logLik deviance  Chisq Chi Df Pr(>Chisq)
lm.obj2b 15 -1621 -1565.1 825.48    -1651
lm.obj2a 16 -1619 -1559.4 825.50    -1651 0.0399      1     0.8418

Data: df1
Models:
lm.obj2c: log(NOx) ~ EC + (1 | Exp)
lm.obj2b: log(NOx) ~ EC + fuel.lin + (1 | Exp)

         Df     AIC     BIC logLik deviance  Chisq Chi Df Pr(>Chisq)
lm.obj2c 14 -1572.7 -1520.5 800.33  -1600.7
lm.obj2b 15 -1621.0 -1565.1 825.48  -1651.0 50.303      1  1.317e-12 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
Linear mixed model fit by REML ['lmerMod']
Formula: log(NOx) ~ EC + fuel.lin + (1 | Exp)
   Data: df1

REML criterion at convergence: -1542.1

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.0951 -0.4088 -0.0025  0.3703  5.7327

Random effects:
 Groups   Name        Variance  Std.Dev.
 Exp      (Intercept) 7.317e-05 0.008554
 Residual             2.575e-04 0.016045
Number of obs: 307, groups: Exp, 23

Fixed effects:
                                  Estimate Std. Error t value
(Intercept)                       1.500333   0.006058  247.66
EC1991 DDC60SET                   0.510904   0.008850   57.73
EC1991 DDC60UDDS                  0.932355   0.009010  103.48
EC1992 DDC60FTP                   0.282115   0.015446   18.26
EC1992 DDC60SET                   0.819768   0.015446   53.07
EC1999 Kubota TRUISO 8178-4 C1    0.668848   0.011109   60.21
EC2006 Cummins ISMCRUISE - 40mph -0.780875   0.012703  -61.47
EC2006 Cummins ISMCRUISE - 50mph -0.943983   0.011456  -82.40
EC2006 Cummins ISMFTP            -0.756559   0.007339 -103.09
EC2006 Cummins ISMSET            -0.867126   0.009446  -91.80
EC2006 Cummins ISMUDDS            0.298316   0.008997   33.16
EC2007 MBE4000FTP                -1.232028   0.011456 -107.54
fuel.lin                          0.009860   0.001317    7.49
```

D. Results of Mixed Model Analysis of Combined Animal Biodiesel Data Sets

(EC is a variable of all combinations of Engine and Test Cycle)

```
Data: df1
Models:
lm.obj0: log(NOx) ~ EC + (1 | Exp)
lm.obj: log(NOx) ~ EC + Fuel + (1 | Exp)

        Df     AIC     BIC logLik deviance  Chisq Chi Df Pr(>Chisq)
lm.obj0 10 -1399.1 -1363.9 709.55  -1419.1
lm.obj  12 -1399.6 -1357.4 711.81  -1423.6 4.5328      2     0.1037


Linear mixed model fit by REML ['lmerMod']
Formula: log(NOx) ~ EC + Fuel + (1 | Exp)
   Data: df1

REML criterion at convergence: -1335.3

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.3315 -0.4452  0.0093  0.5001  3.8668

Random effects:
 Groups   Name        Variance  Std.Dev.
 Exp      (Intercept) 7.073e-05 0.00841
 Residual             1.784e-04 0.01336
Number of obs: 249, groups: Exp, 17

Fixed effects:
                                       Estimate Std. Error t value
(Intercept)                             1.492764   0.006760  220.81
EC1991 DDC60SET                         0.517134   0.009351   55.30
EC1991 DDC60UDDS                        0.931217   0.009048  102.91
EC2006 Cummins ISMFTP                  -0.761175   0.007587 -100.32
EC2006 Cummins ISMSET                  -0.870493   0.009351  -93.09
EC2006 Cummins ISMUDDS                  0.283847   0.009048   31.37
EC2007 MBE4000FTP                      -1.221495   0.011281 -108.28
EC2009 John Deere 4045HFISO 8178-4 C1 -0.510503   0.011227  -45.47
FuelB5-Animal                          -0.006431   0.003414   -1.88
FuelCARB                               -0.002865   0.002870   -1.00
```

```
         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lmer(formula = log(NOx) ~ EC + Fuel + (1 | Exp), data = df1)

Linear Hypotheses:
                             Estimate Std. Error z value Pr(>|z|)
B5-Animal - B10-Animal == 0 -0.006431   0.003414  -1.884    0.136
CARB - B10-Animal == 0      -0.002865   0.002870  -0.998    0.565
CARB - B5-Animal == 0        0.003566   0.002018   1.767    0.171
(Adjusted p values reported -- single-step method)

Data: df1
Models:
lm.obj2b: log(NOx) ~ EC + fuel.lin + (1 | Exp)
lm.obj2a: log(NOx) ~ EC + fuel.lin + fuel.quad + (1 | Exp)

         Df     AIC     BIC logLik deviance  Chisq Chi Df Pr(>Chisq)
lm.obj2b 11 -1397.1 -1358.4 709.55  -1419.1
lm.obj2a 12 -1399.6 -1357.4 711.81  -1423.6 4.5179      1    0.03354 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1


Data: df1
Models:
lm.obj2c: log(NOx) ~ EC + (1 | Exp)
lm.obj2b: log(NOx) ~ EC + fuel.lin + (1 | Exp)

         Df     AIC     BIC logLik deviance  Chisq Chi Df Pr(>Chisq)
lm.obj2c 10 -1399.1 -1363.9 709.55  -1419.1
lm.obj2b 11 -1397.1 -1358.4 709.55  -1419.1 0.0149      1     0.9027
```

```
Linear mixed model fit by REML ['lmerMod']
Formula: log(NOx) ~ EC + fuel.lin + (1 | Exp)
   Data: df1

REML criterion at convergence: -1339.8

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.4437 -0.4700  0.0343  0.4777  3.8349

Random effects:
 Groups   Name        Variance  Std.Dev.
 Exp      (Intercept) 7.192e-05 0.008481
 Residual             1.808e-04 0.013447
Number of obs: 249, groups: Exp, 17

Fixed effects:
                                        Estimate Std. Error t value
(Intercept)                            1.4896732  0.0064577  230.68
EC1991 DDC60SET                        0.5171337  0.0094272   54.86
EC1991 DDC60UDDS                       0.9312171  0.0091225  102.08
EC2006 Cummins ISMFTP                 -0.7621695  0.0076342  -99.84
EC2006 Cummins ISMSET                 -0.8704932  0.0094272  -92.34
EC2006 Cummins ISMUDDS                 0.2838468  0.0091225   31.11
EC2007 MBE4000FTP                     -1.2231525  0.0113442 -107.82
EC2009 John Deere 4045HFISO 8178-4 C1 -0.5120309  0.0112943  -45.34
fuel.lin                              -0.0002006  0.0012078   -0.17
```

E. Results of Mixed Model Analysis of Combined Soy and Animal Biodiesel Data Sets

(EC is a variable of all combinations of Engine and Test Cycle)

```
Data: df1
Models:
lm.obj0: log(NOx) ~ EC + (1 | Exp)
lm.obj: log(NOx) ~ EC + Fuel + (1 | Exp)

        Df     AIC     BIC logLik deviance  Chisq Chi Df Pr(>Chisq)
lm.obj0 15 -2951.8 -2887.0 1490.9  -2981.8
lm.obj  19 -3019.9 -2937.8 1529.0  -3057.9 76.125      4  1.152e-15 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Linear mixed model fit by REML ['lmerMod']
Formula: log(NOx) ~ EC + Fuel + (1 | Exp)
   Data: df1

REML criterion at convergence: -2908.8

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.3726 -0.4285 -0.0124  0.4287  6.2029

Random effects:
 Groups   Name        Variance  Std.Dev.
 Exp      (Intercept) 6.766e-05 0.008226
 Residual             2.218e-04 0.014893
Number of obs: 556, groups: Exp, 40

Fixed effects:
                                       Estimate Std. Error t value
(Intercept)                            1.492477   0.005102  292.50
EC1991 DDC60SET                        0.513614   0.006271   81.90
EC1991 DDC60UDDS                       0.931747   0.006220  149.81
EC1992 DDC60FTP                        0.282436   0.014081   20.06
EC1992 DDC60SET                        0.820090   0.014081   58.24
EC1999 Kubota TRUISO 8178-4 C1         0.668622   0.009910   67.47
EC2006 Cummins ISMCRUISE - 40mph      -0.781077   0.011439  -68.28
EC2006 Cummins ISMCRUISE - 50mph      -0.944299   0.010259  -92.05
EC2006 Cummins ISMFTP                 -0.758930   0.005139 -147.69
EC2006 Cummins ISMSET                 -0.868848   0.006492 -133.83
EC2006 Cummins ISMUDDS                 0.291068   0.006216   46.83
EC2007 MBE4000FTP                     -1.226991   0.007855 -156.21
EC2009 John Deere 4045HFISO 8178-4 C1 -0.510659   0.010194  -50.09
FuelB10-Soy                            0.017326   0.004085    4.24
FuelB5-Animal                         -0.006181   0.003737   -1.65
FuelB5-Soy                             0.008740   0.003755    2.33
FuelCARB                              -0.002255   0.003107   -0.73
```

```
         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lmer(formula = log(NOx) ~ EC + Fuel + (1 | Exp), data = df1)

Linear Hypotheses:
                             Estimate Std. Error z value Pr(>|z|)    
B10-Soy - B10-Animal == 0    0.017326   0.004085   4.242   <0.001 ***
B5-Animal - B10-Animal == 0 -0.006181   0.003737  -1.654   0.4359    
B5-Soy - B10-Animal == 0     0.008740   0.003755   2.327   0.1239    
CARB - B10-Animal == 0      -0.002255   0.003107  -0.726   0.9442    
B5-Animal - B10-Soy == 0    -0.023507   0.003466  -6.783   <0.001 ***
B5-Soy - B10-Soy == 0       -0.008586   0.003487  -2.462   0.0903 .  
CARB - B10-Soy == 0         -0.019582   0.002763  -7.087   <0.001 ***
B5-Soy - B5-Animal == 0      0.014921   0.003049   4.894   <0.001 ***
CARB - B5-Animal == 0        0.003926   0.002185   1.797   0.3503    
CARB - B5-Soy == 0          -0.010995   0.002220  -4.953   <0.001 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)
```

Table of Least-Squares Means

Fuel	Estimate	Standard.Error	Lower.CI	Upper.CI
B5-Animal	1.3645	0.0030	1.3585	1.3705
CARB	1.3684	0.0024	1.3637	1.3732
B10-Animal	1.3707	0.0038	1.3633	1.3781
B5-Soy	1.3794	0.0029	1.3736	1.3852
B10-Soy	1.3880	0.0033	1.3814	1.3946