NOx Emission Impacts of Biodiesel Blends:
Technical Summary

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Issues Addressed

- Biodiesel NOx impact
  - How large is it?
  - Does it depend on dataset selection (which blend levels and studies to include)?
- Differences by blendstock type
  - Soy-based blends
  - Animal-based blends
- Emissions differences among animal-based feedstocks
- Are soy- and animal-based blends categorically different in their impact on NOx?
- Some implications for allowing biodiesels into California market

References to Literature

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

Datasets Used in Analysis

- ARB Individual Test Run Dataset ("raw data")
  - 4 tables: B5-soy, B10-soy, B5-animal, B10-animal
  - Individual test run measurements for the 3 UCR studies
  - Emission averages for other literature sources
- ARB Literature Dataset
  - Emission averages by engine, test cycle, and blend
  - Through B20 blend level
- We have added the following
  - Number of test replications for emission averages (estimated in some cases)
  - Cetane number for CARB Diesel, biodiesel blends, biodiesel feedstocks
  - Additional testing at B50 and B100 levels (where available).

NOx Impact of Soy-based Biodiesels

- The literature on soy-based blends is large and diverse (see Table 1):
  - 10 different studies (3 UCR studies sponsored by ARB)
  - 13 different vegetable feedstocks (10 soy, 2 UCO, 1 canola)
  - Conducted on a wide variety of engines in different labs
  - 7 different test cycles
- In spite of the diversity, the 3 UCR studies dominate the dataset.
  - The number of test replications (NReps) is used as a weighting factor in this analysis to reflect the better precision of results based on more tests.
  - When this is done, the UCR studies account for 82.5% of the literature dataset. The weight is even larger at the B5 and B10 levels, which come almost solely from the UCR studies.
- It is important to recognize that the effective diversity is less as a result of the weighting. The UCR studies examine only 3 different soy feedstocks.

Table 1: Scope of Emissions Testing for Soy-based Biodiesel

	Clark 1999	McCormick 2002	McCormick 2005	Eckerle 2008	Nuszkowski 2009	Nikanjam 2010	Thompson 2010	Durbin 2011	Durbin 2013A/B	Karavalakis 2014
Biodiesel Feedstocks	Soy	Soy, UCO	Soy, Canola	Soy	Soy	Soy	Soy	Soy	Soy, UCO	Soy
Blend Levels Tested	B20	B20	B20	B20	B20	B5, B20	B10, B20	B5, B20, B50, B100	B5, B20	B5, B10
Engines Tested	One	One	Two	One	Three	One	One	Two On-Road Two Off-Road	One	Two
Test Cycles	FTP	FTP	FTP	FTP	FTP	FTP, ESC	FTP, ESC	FTP, UDDS, 40mph, 50mph, ISO 8178	FTP	FTP, SET, UDDS
Test Replications on Biodiesel	3	9	9	3	9	16	12	172	36	80

NOx Impact of B5 Soy Blends Compared to CARB Diesel

- All B5 blends are soy-based
- The T-Test is the most direct method to assess the difference in mean NOx emissions (B5 vs. CARB Diesel) for individual engines
  - Requires that individual test runs (or standard deviations) be available. Cannot be applied to the Nikanjam data.
- B5 Soy blends clearly increase NOx emissions (see Table 2):
  - In 9 of 12 cases, NOx emissions are observed to increase
  - The NOx emission increases are statistically significant in 6 of the 9 cases (highly significant in 5 cases)
  - All NOx emission increases on the FTP cycle are statistically significant (when the test can be made)
  - None of the 3 observed NOx decreases is statistically significant.
- Conclusion: B5 Soy blends increase NOx emissions across a range of engines and test cycles.

Table 2. T-Test Results for NOx Impact of B5 Soy-based Blends

Source	Feedstock ID	Engine	Cycle	NReps (total)	ΔNOx (gm/bhp-hr)	Prob > |t|	Statistical Significance
Nikanjam 2010	Soy	1991 DDC 60	FTP	8	T-Test not applied. Requires test runs or standard deviations.		
Nikanjam 2010	Soy	1991 DDC 60	ESC	8	T-Test not applied. Requires test runs or standard deviations.		
Durbin 2011	Soy #1	1999 Kubota TRU	ISO 8178-4 C	19	+ 0.084	p = 0.41	Not significant
Durbin 2011	Soy #1	2006 Cummins ISM	40mph Cruise	5	+ 0.034	p = 0.14	Not significant
Durbin 2011	Soy #1	2006 Cummins ISM	50mph Cruise	12	- 0.020	p = 0.59	Not significant
Durbin 2011	Soy #1	2006 Cummins ISM	FTP	39	+ 0.046	p < 0.001	Highly significant
Durbin 2011	Soy #1	2007 MBE4000	FTP	12	+ 0.011	p = 0.001	Highly significant
Durbin 2013A	Soy #2	2006 Cummins ISM	FTP	12	+ 0.026	p = 0.002	Highly significant
Karavalakis 2014	Soy #3	1991 DDC 60	FTP	16	+ 0.045	p < 0.001	Highly significant
Karavalakis 2014	Soy #3	1991 DDC 60	SET	8	- 0.030	p = 0.36	Not significant
Karavalakis 2014	Soy #3	1991 DDC 60	UDDS	16	+ 0.035	p = 0.05	Significant
Karavalakis 2014	Soy #3	2006 Cummins ISM	FTP	16	+ 0.021	p < 0.001	Highly significant
Karavalakis 2014	Soy #3	2006 Cummins ISM	SET	8	- 0.011	p = 0.16	Not significant
Karavalakis 2014	Soy #3	2006 Cummins ISM	UDDS	17	+ 0.066	p = 0.23	Not significant

Note: The t-test analysis uses the ARB dataset of individual test runs (“raw data”)

Composite NOx Impact of B5 Soy Blends Compared to CARB Diesel

- To estimate a composite impact across engines, a different statistical approach is needed that will account for the varying NOx emission levels of the engines and test cycles.
- Weighted regression analysis with dummy variables for N-1 engine/test cycle combinations "*i*" has been used to estimate Regression Model 1:

$$\log NOx = a + \sum_{i=2}^{N} \delta_i + b \cdot \delta_{B5}$$

where:

  - Coefficients a and δ_i represent the average log *NOx* emission level on CARB Diesel for each engine/test cycle combination. (These values are not reported in the summary of results that follows.)
  - δ_{B5} = 0 for CARB Diesel tests; δ_{B5} = 1 for B5 Soy tests
  - Coefficient b gives the composite NOx impact of B5 Soy across engines/test cycles.
- The log *NOx* formulation assumes that the emissions impact on a percentage basis is proportional to blend level. The percentage impact on NOx emissions equals $100 \cdot [\exp(b)-1]$

Result for Composite B5 Soy Impact on NOx

- Based on the ARB test run dataset ("raw data")
  - The Nikanjam 2010 B5 testing (with weight of 4 for its NOx averages) can be included with the UCR testing (with weight of 1 for each test run).
- Regression Model 1 Result:
  - R^2 = 0.9995 (dominated by the dummy variables that represent the differing NOx emission levels among engines and test cycles)
  - Coefficient b for the δ_{B5} effect has the value: +0.0096 ± 0.0026. The statistical significance is p = 0.0003 (highly significant).
- The equivalent percentage NOx increase is **+0.96%** at the B5 level
  - or 0.19% for each 1 percent biodiesel in a blend.

Composite NOx Impact of Soy Blends Through B10

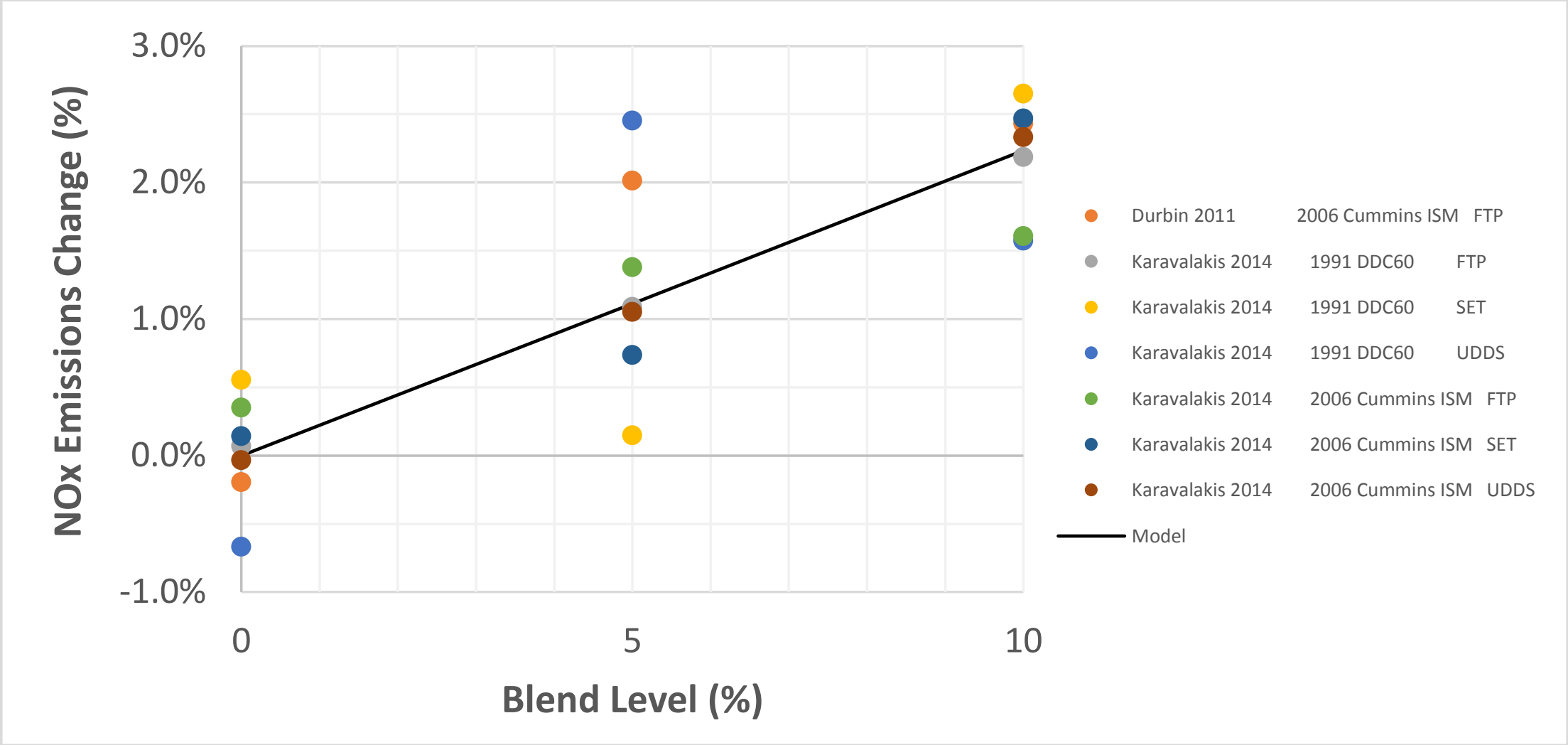
- To assess the composite NOx impact through B10, the regression model is modified to use blend level as the predictive variable. Here, the revised model is fit using the subset of data where individual tests are available ("raw data").
- Unweighted regression analysis with dummy variables for N-1 engine/test cycle combinations "*i*" has been used to estimate Regression Model 2:

$$\log NOx = a + \sum_{i=2}^{N} \delta_i + b \cdot BioPct$$

where:

- Coefficients a and δ_i represent the average log *NOx* emission level on CARB Diesel for each engine/test cycle combination. (These values are not reported in the summary of results that follows.)
- BioPct is the blend level (percentage biodiesel in the blend). CARB Diesel is BioPct = 0; B5 is BioPct = 5.
- Coefficient b gives the composite NOx impact across engines/test cycles for each 1 percent biodiesel in a blend.

Soy biodiesels cause statistically significantly increases in NOx emissions at B10, B5 and Lower blend levels



NOx Impact of Vegetable Biodiesels At Higher Blend Levels

- To include more sources, blends and feedstocks, we shift to analysis of the literature dataset with blend levels above B5. NOx emissions are reported as averages on CARB Diesel and for each BioPct blend level tested.
- Regression Model 2 is fit using emission averages weighted by the number of replications on each blend:

$$\log NOx = a + \sum_{i=2}^{N} \delta_i + b \cdot BioPct$$

where:

- Coefficients a and δ_i represent the average log *NOx* emission level on CARB Diesel for each engine/test cycle combination. (These values are not reported in the summary of results that follows.)
- BioPct is the blend level (percentage biodiesel in the blend). CARB Diesel is BioPct = 0; B5 is BioPct = 5.
- Coefficient b gives the composite NOx impact across engines/test cycles for each 1 percent biodiesel in a blend.

Composite Soy Impact on NOx at Higher Blend Levels

- Including all data through B100 gives the greatest diversity in sources, blends and feedstock.
- Result:
  - $R^2 = 0.9990$ (dominated by the dummy variables that represent the differing NOx emission levels among engines and test cycles)
  - Regression coefficient b for the BioPct effect has value: +0.00220 ± 0.00016. The statistical significance is $p < 0.0001$ (highly significant).
- The equivalent percentage NOx increase is **+1.10%** at the B5 level
  - Or, 0.22% for each 1 percent biodiesel in a blend.
- This result is nearly the same as given by the regression analysis of the individual runs dataset through B5.

Composite Soy Impact on NOx at Higher Blend Levels

- The composite soy impact is also robust with respect to data selection (see Figure 1)
- Different choices for the dataset (test runs versus emissions averages) and the highest blend level to include (through B10, through B20, through B50, and through B100) give different results for the NOx slope with BioPct blending level. However, the results all fall within the errors bars of the estimate based on the B5 test runs alone.
- This indicates that the NOx response is linear with BioPct through high blend levels and that systematic differences among the studies are not large.
- Statistical tests show no difference among soy, UCO, and canola in their NOx impact. However, the UCO and canola samples are small and capable of detecting only large differences.

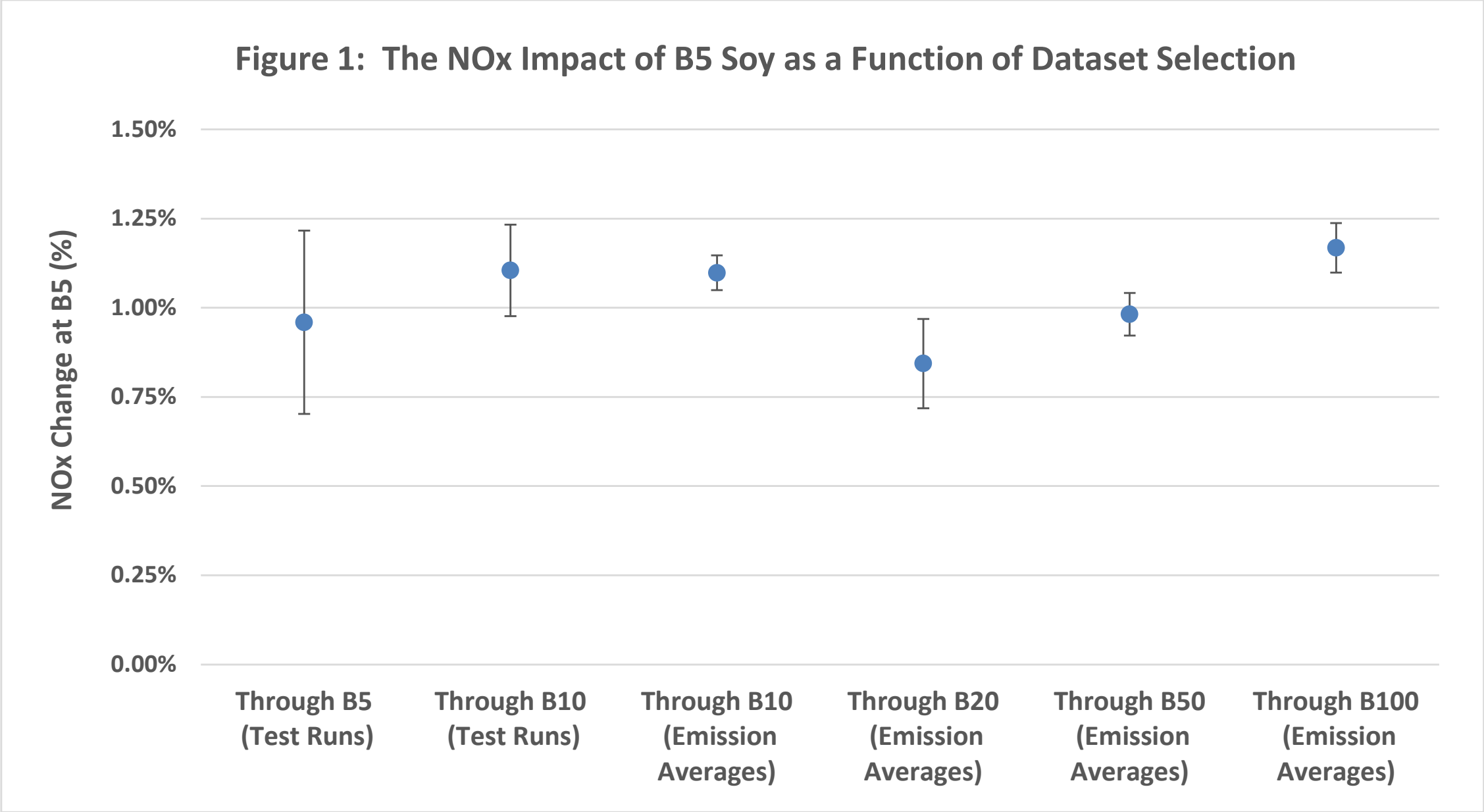


Figure 1: The NOx Impact of B5 Soy as a Function of Dataset Selection
NOx Change at B5 (%)
1.50%
1.25%
1.00%
0.75%
0.50%
0.25%
0.00%
Through B5 (Test Runs)
Through B10 (Test Runs)
Through B10 (Emission Averages)
Through B20 (Emission Averages)
Through B50 (Emission Averages)
Through B100 (Emission Averages)

Conclusions for Soy-based Biodiesels

- Soy biodiesel increases NOx emissions by amounts that can be estimated with good statistical confidence.
- NOx will increase ~1% on average at the B5 level and ~2% at B10.
- The NOx response is linear with the BioPct blend level. <u>There is no threshold level where soy biodiesel does not increase NOx.</u>
- This result is supported by all of the available studies and data (none disagree substantially)
  - Individual blends, engines and test cycles may still vary to some extent.
- NOx increases may be expected for UCO, canola and other vegetable biodiesels, but the data are very limited.

NOx Impact of Animal-based Biodiesel

- The literature on animal-based blends is much smaller than for soy (see Table 3):
  - Only 4 studies (3 UCR studies sponsored by ARB)
  - Only 4 animal feedstocks in total
  - Conducted primarily on engines at UCR CE-CERT (only 6 test replications conducted elsewhere)
  - A variety of test cycles
- The 3 UCR studies dominate the animal-blend dataset to a greater extent than for soy:
  - Counting test replications, the UCR studies account for 97.5% of the dataset. All of the data at the B5 and B10 levels comes from the UCR studies.
- There are notable differences among the four studies on the size of the NOx impact and its relationship to BioPct.
  - *The available studies may not permit a reliable, general understanding of the impacts of animal-based feedstocks*.

Table 3: Scope of Emissions Testing for Animal-based Biodiesels

	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
NOx Increase Observed?				
At / Below B10	–	Yes	No	No
Above B10	Yes	Yes	–	–

NOx Impact of B5 Animal Compared to CARB Diesel

- The T-Test is the most direct method to assess differences in mean NOx levels between B5 and CARB Diesel for individual engines.
- The McCormick 2005 study tested the Animal #1 feedstock at the B20 level and found a statistically significant increase in NOx, but did not test at the B5 level considered here.
- Table 4 reports this comparison for animal-based biodiesels. Results:
  - Animal #2 *increases* NOx in 2 of 3 engines. The increase is highly significant for 1 engine.
  - Animal #3 *decreases* NOx in one engine. The increase is statistically significant at the p=0.05 level. The blend was certified as NOx neutral at B5.
  - Animal #4 *increases* NOx in 3 of 6 cases and *decreases* NOx in the other 3 cases. The results are inconclusive as none of the changes are statistically significant. The blend may or may not change NOx.

T-Test for NOx Impact of B5 Animal Blends

Source	Feedstock ID	Engine	Cycle	NReps (total)	ΔNOx (gm/bhp-hr)	Prob > |t|	Statistical Significance
Durbin 2011	Animal #2	2006 Cummins ISM	FTP	12	+ 0.0067	p = 0.29	Not Significant
Durbin 2011	**Animal #2**	**2007 MBE4000**	**FTP**	**12**	+ 0.0168	p < 0.001	Highly Significant
Durbin 2011	Animal #2	2009 John Deere	ISO 8178	13	- 0.0342	p = 0.21	Not Significant
Durbin 2013A	**Animal #3**	**2006 Cummins ISM**	**FTP**	**52**	- 0.0072	p = 0.054	Significant
Karavalakis 2014	Animal #4	1991 DDC 60	FTP	16	+ 0.0031	p = 0.81	Not Significant
Karavalakis 2014	Animal #4	1991 DDC 60	SET	8	+ 0.0095	p = 0.77	Not Significant
Karavalakis 2014	Animal #4	1991 DDC 60	UDDS	16	- 0.1119	p = 0.31	Not Significant
Karavalakis 2014	Animal #4	2006 Cummins ISM	FTP	16	- 0.0073	p = 0.61	Not Significant
Karavalakis 2014	Animal #4	2006 Cummins ISM	SET	8	+ 0.0025	p = 0.90	Not Significant
Karavalakis 2014	Animal #4	2006 Cummins ISM	UDDS	16	- 0.0993	P = 0.16	Not Significant

Notes: The t-test analysis uses the ARB dataset of individual test runs ("raw data")

NOx Impact of Animal Biodiesels Through B10

- Only Karavalakis 2014 reports testing on B5 and B10 to support an assessment of NOx impacts through B10. This involves a single animal feedstock (Animal #4) and cannot be generalized to a wider range of biodiesels.
- The analysis is based on Regression Model 2 which is linear in BioPct.
- For Animal #4, the NOx trend with BioPct is relatively flat through B10 (see Table 5).
  - The NOx slope is positive (NOx is increased) in 3 of 6 cases and negative (NOx is decreased) in 3 of 6 cases.
  - One slope (1991 DDC 60 on SET cycle) is positive and statistically significant.
- Conclusion: Animal #4 increases NOx through B10 in at least one engine and test cycle.

Table 5. NOx Trend Results Through B10 for An Animal Feedstock

Regression Model 2: $\log NOx = a + \sum_{i=2}^{N} \delta_i + b \cdot BioPct$

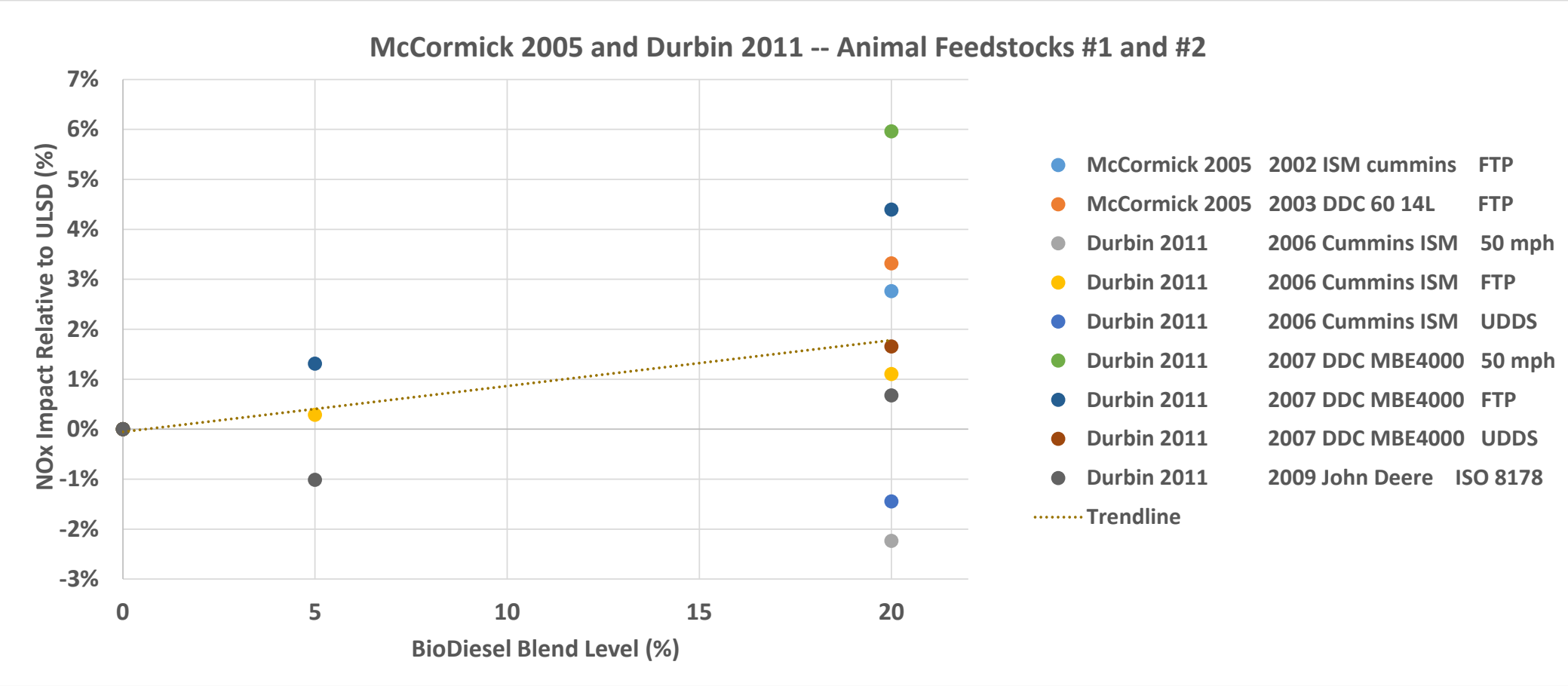
Source	Feedstock ID	Engine	Cycle	BioPct Slope (B) (gm/bhp-hr per % Biodiesel)	Prob > |t|	Statistical Significance
Karavalakis 2014	Animal #4	1991 DDC 60	FTP	+ 0.0012	p = 0.33	Not Significant
Karavalakis 2014	Animal #4	1991 DDC 60	SET	+ 0.0069	p = 0.05	Significant
Karavalakis 2014	Animal #4	1991 DDC 60	UDDS	- 0.0051	p = 0.67	Not Significant
Karavalakis 2014	Animal #4	2006 Cummins ISM	FTP	- 0.0006	p = 0.59	Not Significant
Karavalakis 2014	Animal #4	2006 Cummins ISM	SET	+ 0.0006	p = 0.77	Not Significant
Karavalakis 2014	Animal #4	2006 Cummins ISM	UDDS	- 0.0088	p = 0.19	Not Significant

Note: The regression analysis uses the ARB dataset of individual test runs ("raw data").

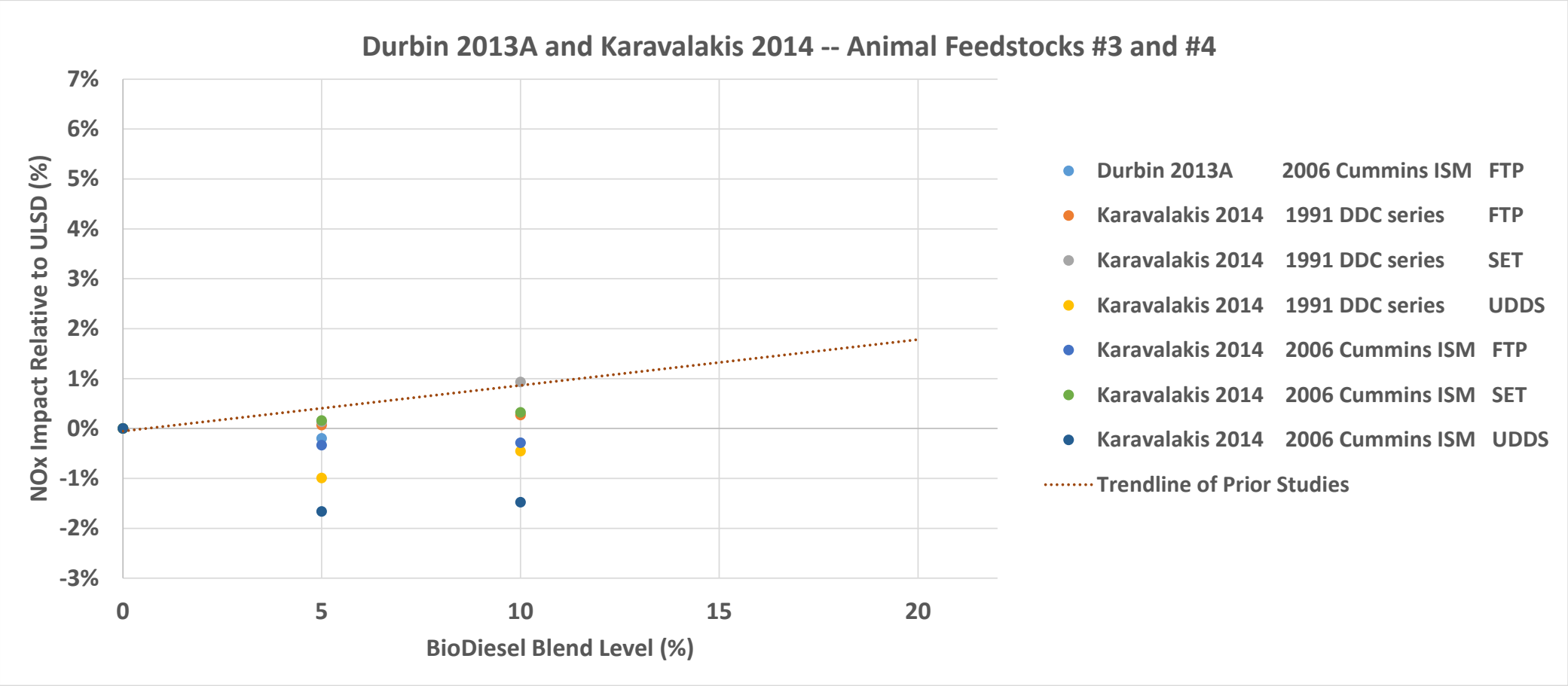
NOx Impact of Animal Biodiesels Through B20

- To include more sources, blends and feedstocks, we shift to analysis of the literature dataset. NOx measurements are reported as averages on CARB Diesel and for each BioPct blend level tested.
- Only graphical analysis is presented through B20 because most sources tested only two blend levels per feedstock (so regression analysis is not useful).
- As the following charts show, the latest ARB studies show substantially lower NOx impacts than the earlier studies and no clear trend with BioPct blend level.
- Each study tested a different animal feedstock. We interpret these results as indicating that the <u>NOx impact can vary in important ways from one animal feedstock to another</u>.

- In the first two studies of animal-based biodiesel:
  - NOx is significantly increased at B20
  - A smaller increase is observed at B5 consistent with a linear model



- In the two most-recent studies of animal-based biodiesel:
  - No appreciable NOx increase is observed through B10
  - NOx impacts are below the trendline of the two prior studies



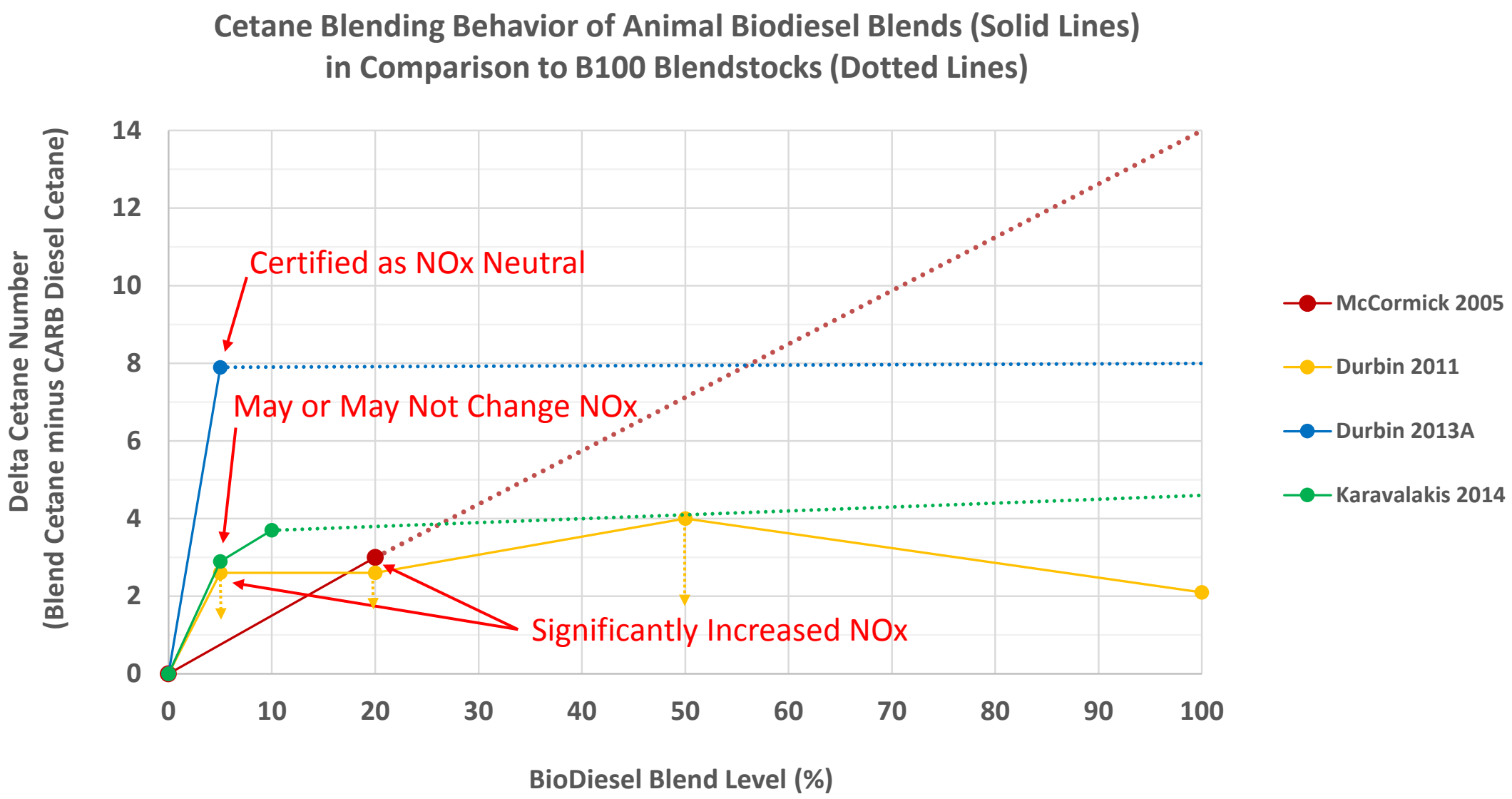
What is the Composite NOx Impact for Animal-based Biodiesel?

- It depends on the <u>blend level range that is considered</u>
- This choice determines the influence given to each study and animal feedstock in the estimate.
- Including higher blending levels (more studies, more feedstocks) gives a better ability to resolve the slope with blend level and may yield a more general result.
- Including only lower blending levels reduces the number of feedstocks and blends considered. Results may not be general.

	Highest Blend Level Considered			
	B10	B20	B50	B100
Weight Given to Studies				
McCormick 2005	0%	2%	2%	2%
Durbin 2011	15%	59%	63%	67%
Durbin 2013A	21%	10%	9%	8%
Karavalakis 2014	65%	30%	27%	24%
Composite BioPct Slope				
ΔNOx (%) per 1% Biodiesel	- 0.03%	+ 0.05%	+ 0.29%	+ 0.16%
Standard Error of Estimate	± 0.03%	± 0.03%	± 0.09%	± 0.06%
Prob > |t|	p = 0.35	p = 0.15	p < 0.01	p = 0.01
Statistically Significant?	No	No	Yes	Yes

A Better Understanding of Cetane Effects is Needed

- The higher cetane number of animal feedstocks is a likely reason that animal-based blends have lower NOx impacts than soy-based blends.
- Cetane is complicated and may or may not blend linearly with volume.
- The following chart shows that <u>all</u> of the UCR animal-based blends have a large cetane benefit, achieving most (or all) of the B100 cetane at low blend levels.
  - Lab differences could be involved. Durbin 2011 measured cetane for the blends at CE-CERT, while cetane for CARB Diesel and B100 was determined by an outside lab.
  - The large cetane boosts at low blend levels help to offset NOx increases.
- The McCormick 2005 animal feedstock behaves differently, with cetane blending linearly with BioPct in the B20 blend. The cetane benefit of this feedstock expected at the B5 level is small compared to the three UCR feedstocks.
- *What is the evidence that the rapid cetane boost observed for the UCR blends is real and representative of the cetane behavior of animal feedstocks available in the California market?*


Cetane Blending Behavior of Animal Biodiesel Blends (Solid Lines)
in Comparison to B100 Blendstocks (Dotted Lines)
Delta Cetane Number
(Blend Cetane minus CARB Diesel Cetane)
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
100
BioDiesel Blend Level (%)
Certified as NOx Neutral
May or May Not Change NOx
Significantly Increased NOx
McCormick 2005
Durbin 2011
Durbin 2013A
Karavalakis 2014

What Do We Know About the Animal-based blends?

- Not enough to fully understand the emissions results. ARB should release all available information on its animal feedstocks and blends, including the distillation curves and the FAME and oxygen content analysis (if performed).
- ARB should clarify how it has determined cetane number in the 3 UCR studies and confirm its animal-blend cetane numbers with outside testing.

	McCormick 2005	Durbin 2011	Durbin 2013A	Karavalakis 2014
Feedstock Description	Beef Tallow	Animal	Animal Tallow	Animal
B100 Cetane Number	65	57.9	61.1	58.0
Flash Point (^oC)	159	164	144	165
Cloud Point (^oC)	14	13	15	–
Kinematic Viscosity 40C (mm^2/s)	4.71	4.41	4.691	4.714
Specific Gravity	0.8754	–	0.8750	0.875
API Gravity	–	28.5	30.2	30.3
Distillation T90 (^oC)	351	348	352	Not Reported
Iodine Number	56	Not Reported	Not Reported	Not Reported

Conclusions on NOx Impact of Animal-based Biodiesel Blends

- Animal-based biodiesels have smaller NOx impacts than soy-based blends. The tendency of animal feedstocks to increase cetane is a likely reason.
- The animal-blends dataset is much more limited than for soy, with only four different feedstocks examined in the entire literature.
- There is disagreement among the studies on the NOx impact of B5 animal blends:
  - One B5 blend has significantly increased NOx on one engine and test cycle.
  - One B5 blend has been certified as NOx neutral on one engine and test cycle.
  - Other B5 blends may or may not increase NOx depending on engine and test cycle
- We need to understand the cetane behavior in the UCR blends and what is representative of animal biodiesels in California before more general conclusions can be drawn for animal-based blends.

The Influence of Cetane on Biodiesel NOx Impacts

Cetane is a Key Driver of the NOx Impact for Biodiesel

- This section presents an analysis that demonstrates that soy- and animal-based blends are <u>not categorically different</u> once their differing effect on blend cetane is accounted for.
  - Soy-based feedstocks have more unsaturated carbon bonds and tend to reduce cetane below that of CARB Diesel, although some soy and other vegetable feedstocks can increase cetane.
  - Animal-based feedstocks are more highly saturated and tend to increase cetane above that of CARB Diesel in most cases.
- When a cetane term is added, soy- and animal-based blends can be represented by the same model.
- The preliminary analysis indicates a method of predicting which biodiesel blends will have the greatest impact on NOx emissions.

Cetane-based Model of the Biodiesel NOx Impact

- The analysis uses the complete literature dataset – all blends at blending levels through B20 – in a modified regression analysis.
- Regression Model 3 is fit using emission averages weighted by the number of replications on each blend:

$$\log NOx = a + \sum_{i=2}^{N} \delta_i + b \cdot BioPct + c \cdot \Delta Cetane$$

where:

- Coefficients a and δ_i represent the average log *NOx* emission level on CARB Diesel for each engine/test cycle combination. (These values are not reported in the summary of results that follows.)
- BioPct is the blend level (percentage biodiesel in the blend). CARB Diesel is BioPct = 0; B5 is BioPct = 5.
- ΔCetane is the change in cetane number of the blend compared CARB Diesel
- Coefficient b gives the composite NOx impact across engines/test cycles for each 1 percent biodiesel in a blend at constant cetane (i.e., ΔCetane = 0).
- Coefficient *c* gives an adjustment to NOx emissions in proportion to ΔCetane.

Result for Cetane-based Model of Biodiesel NOx Impacts

- Result: $R^2 = 0.9948$ (dominated by the dummy variables that represent the differing NOx emission levels among engines and test cycles)

Coefficient	Estimate	Prob > |t|	Statistical Significance
b	+ 0.00156	$p < 0.0001$	Highly Significant
c	- 0.00303	$p < 0.0001$	Highly Significant

- The NOx increase is 0.16% for each 1 percent biodiesel in a blend, or 0.8% for B5 <u>at constant cetane</u>.
  - Soy blends have an additional, adverse cetane effect on average that increases the NOx impact to ~1%.
  - Animal blends tend to increase Cetane, so have reduced NOx impacts in comparison.

Result for Cetane-based Model of Biodiesel NOx Impacts

- The *c* coefficient estimates that +5 Cetane Numbers will decrease NOx emissions by 1.5%.
  - Other work* also finds a 1.5% NOx reduction for +5 Cetane Numbers in base blends with Cetane levels of ~50.
- An increase of -*b/c* = 0.5 Cetane Numbers is needed to offset the NOx increase expected from each 1% biodiesel added. For B5, an increase of 2.5 Cetane numbers is required to offset the NOx increase.
- Statistical tests of the residuals indicate that the model explains all of the observed differences among biodiesel types (animal, soy, UCO, canola) and among studies.

* *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.

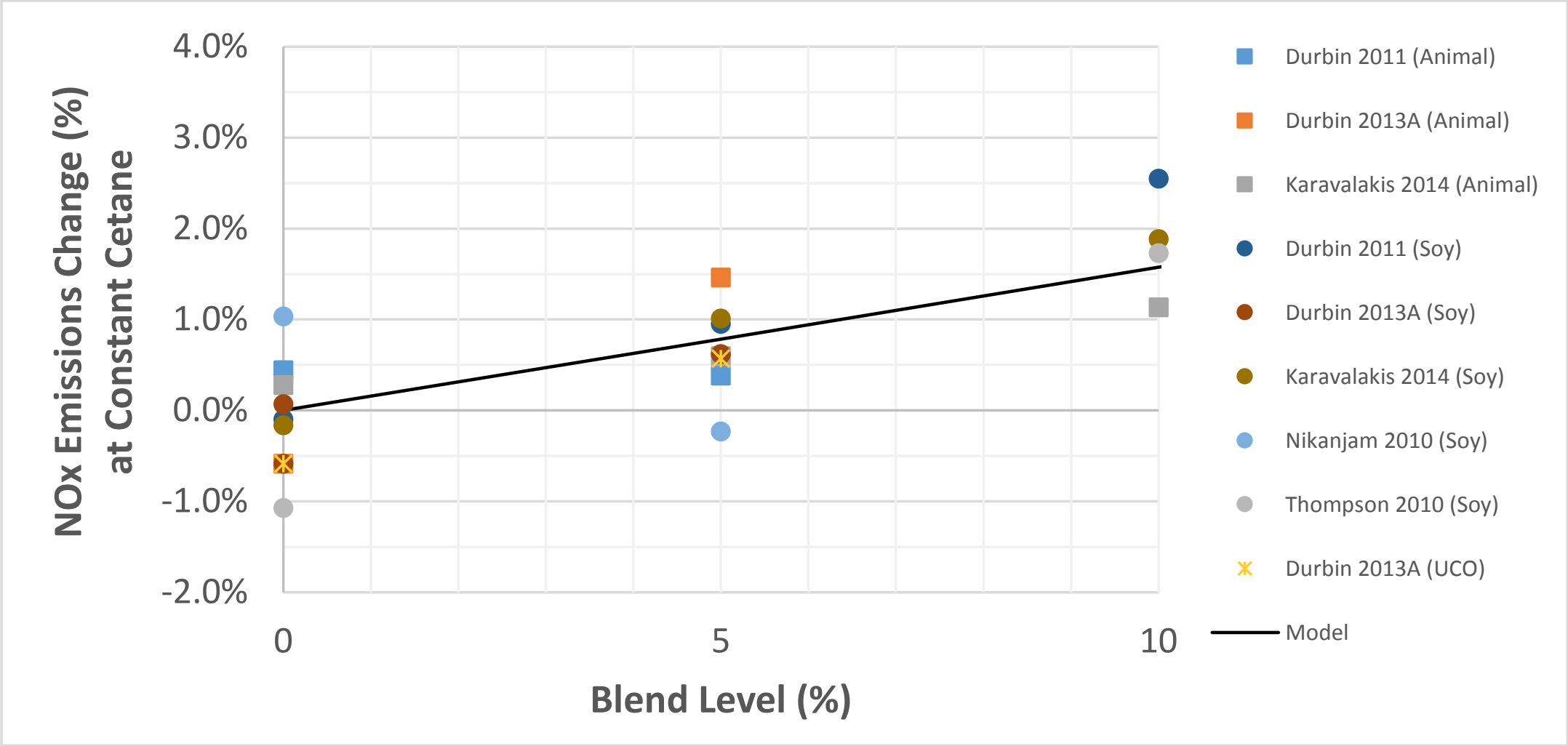
NOx Emission Changes At Constant Cetane

- The *c* coefficient can be used to remove the effect of cetane changes from the measured NOx emission values. The adjustment takes each biodiesel blend back to the cetane number of the CARB diesel used as the base blend in its testing.
- For each combination *i* (study, feedstock, engine, and test cycle), the percent change in NOx emissions at blend level *j* can be estimated as follows:

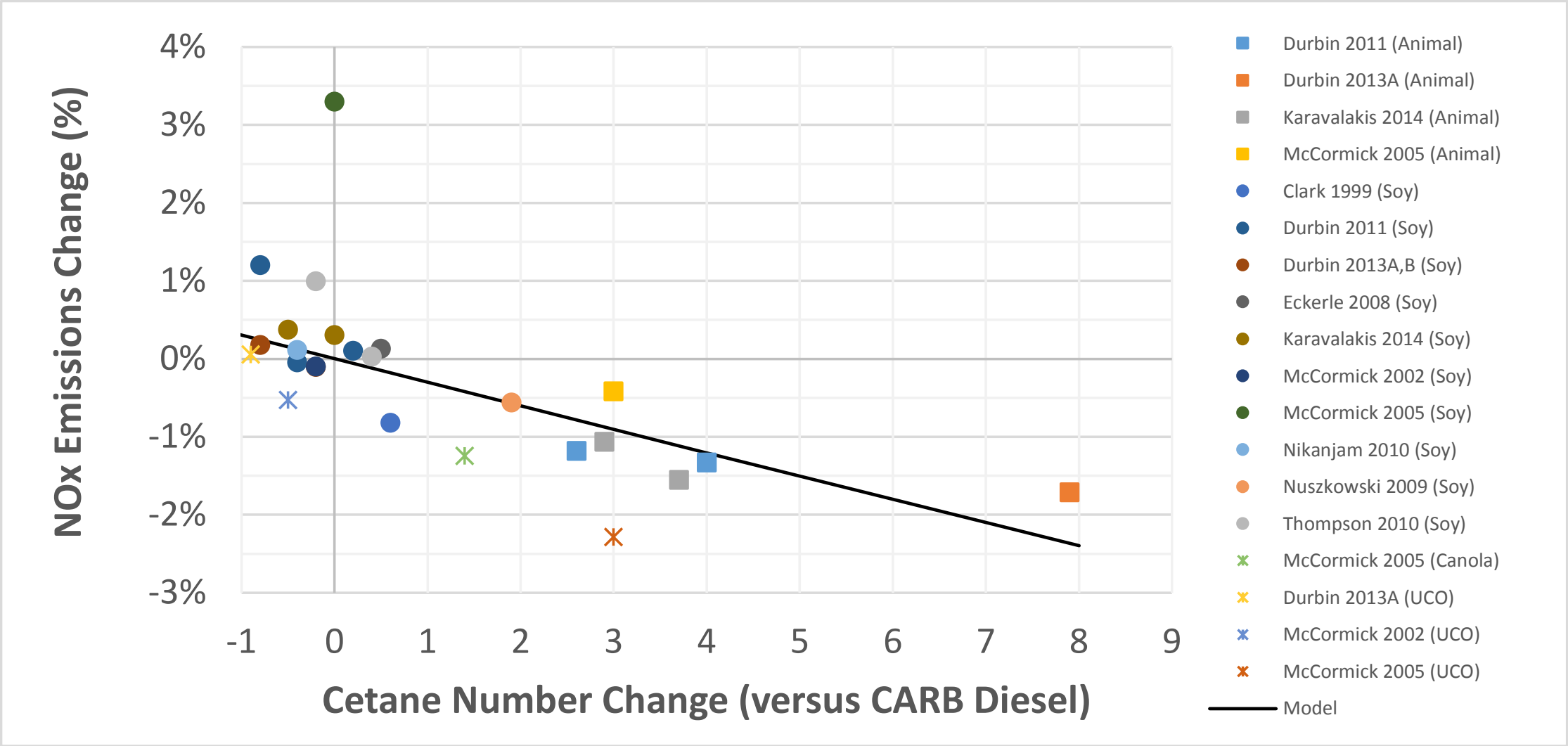
$$\Delta NOx_{i,j} = \exp\left[\ln NOx_{i,j} - \left(a_i + \sum_{i=2}^{N} \delta_i\right) - c \cdot \Delta Cetane_i\right] - 1$$

- This approach references the percent change in NOx to the emission intercept $a_i + \sum_{i=2}^{N} \delta_i$ estimated on CARB diesel for each engine/test cycle.
- Average percentage changes for each study, feedstock, engine, test cycle, and blend level are then plotted in the following figure.

There is no detectable difference among feedstock types when NOx emission changes are adjusted to constant Cetane Number



The Response of NOx to Cetane Number is the Same for Soy- and Animal-based Biodiesel Blends (When Adjusted for Blend Level)



Cetane-based Model of Biodiesel NOx Impacts

- Our preliminary analysis suggests a method of predicting the NOx emission impacts of biodiesel blends.
- Further work is needed:
  - To demonstrate that blends mitigated using DTBP or by co-blending with renewable diesel obey the same model
  - To assess whether the four animal feedstocks that have been tested are representative of all animal feedstocks available in the California market.
  - Additional emissions testing may be needed if we see that the four animal feedstocks are not fully representative.
- More advanced statistical techniques (Mixed Effects modeling) may also be needed, as used in the Predictive Model for gasoline.

Some Implications for Biodiesel in California

- Soy- and animal-based blends are not categorically different fuels once their differing effect on blend Cetane is accounted for.
- There is no threshold blend level where biodiesel fuels as a group do not increase NOx, whether soy- or animal-based.
- Soy-based blends clearly and significantly increase NOx by ~1% at B5 and by correspondingly larger amounts at higher blend levels. Soy blends <u>require</u> mitigation at all levels to offset increased NOx emissions.
- Animal-based blends are more complicated. The current research is limited and the evidence is mixed:
  - At least one B5 animal blend significantly increases NOx, while another has been certified as NOx neutral.
  - Other B5 animal blends may or may not increase NOx depending on their effect on Cetane Number (and possibly other factors).
- Animal-based blends cannot be assumed to have no impact on NOx emissions without an assessment of the impact of feedstock blending on Cetane number.