

# Laboratory Investigation of Exhaust $\text{NO}_x/\text{NH}_3$ Sensors Under Steady-State and Transient Operation Using ECTO-LAB

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Imad Khalek, Vinay Premnath, Chris Sharp & Travis Kostin

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# Acknowledgements

- Work is funded by US EPA with contribution from the Truck & Engine Manufacturers Association (EMA).
- Sensors were provided in-kind by Bosch, Denso, and Vitesco.

# Background

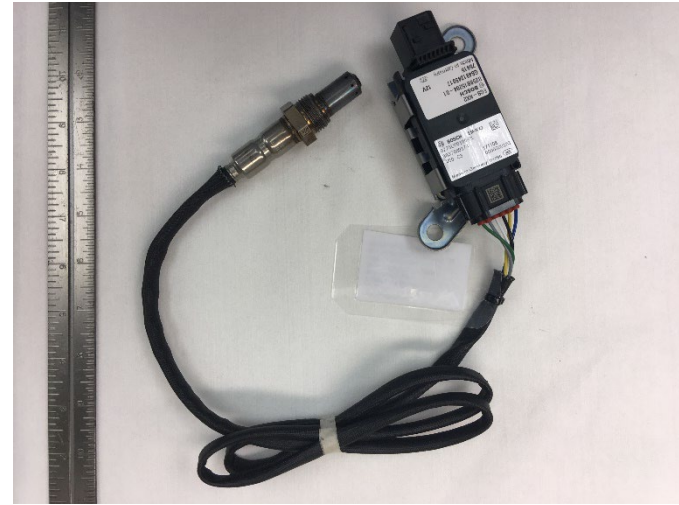
- This work includes three phases
  - Phase 1 was done on a flow bench to determine sensor bias, accuracy, reproducibility, noise and response time
    - It was reported at CE-CERT last conference
- **Phase 2 is covered in this presentation and uses sensors in the exhaust of SwRI Diesel Burner ECTO-LAB**
- Phase 3 was done on an ultra low NO<sub>x</sub> engine platform and will be covered in future conferences
  - **One example is given in this presentation from Phase 3**

# Test Sensors Received By SwRI

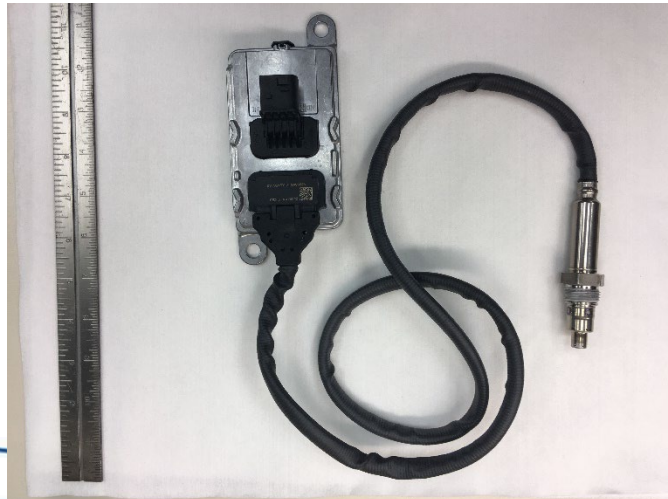
Denso NOx sensor/Prototype



Bosch NOx sensor



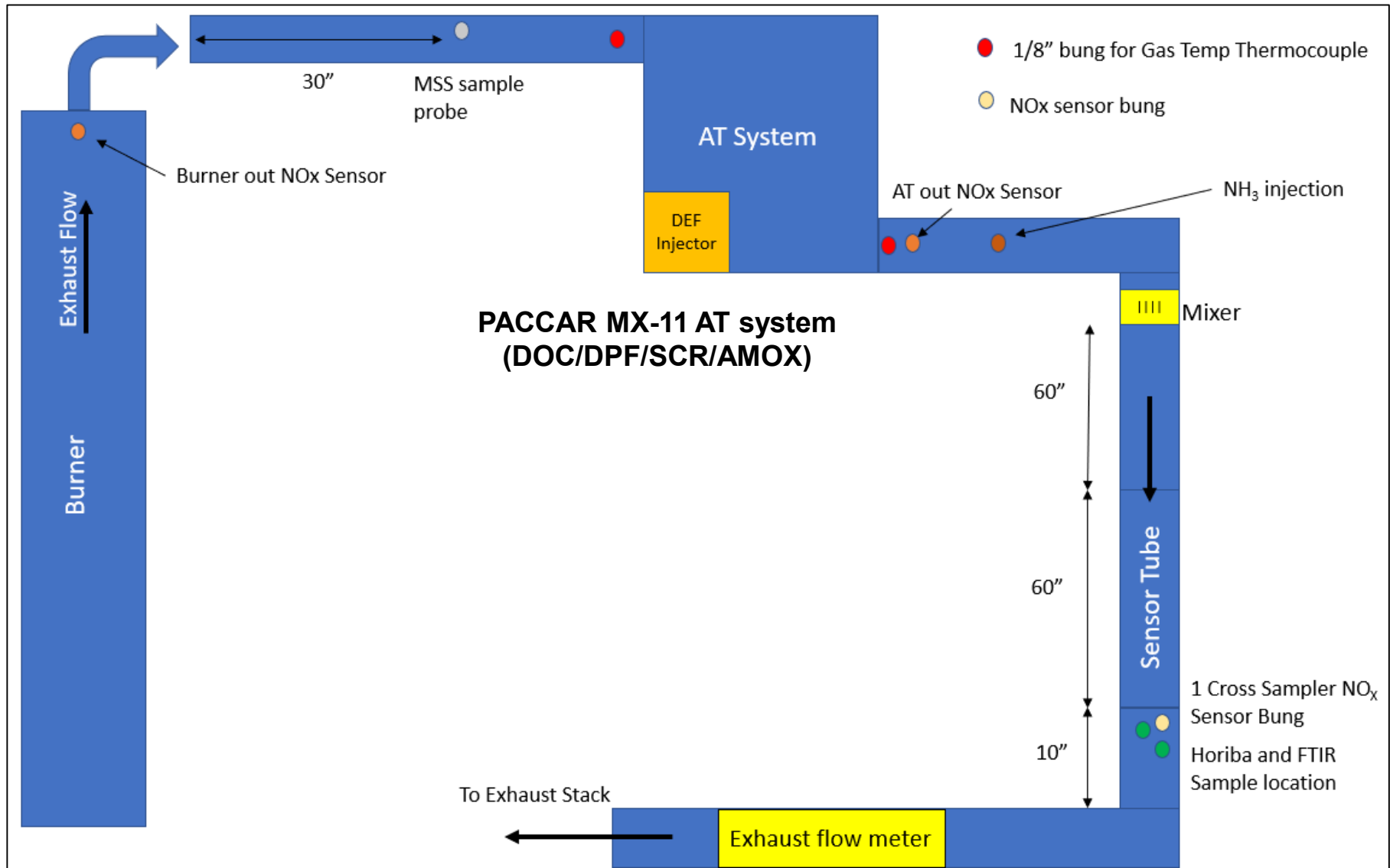
Vitesco NOx sensor/Prototype



Delphi NH<sub>3</sub> sensor

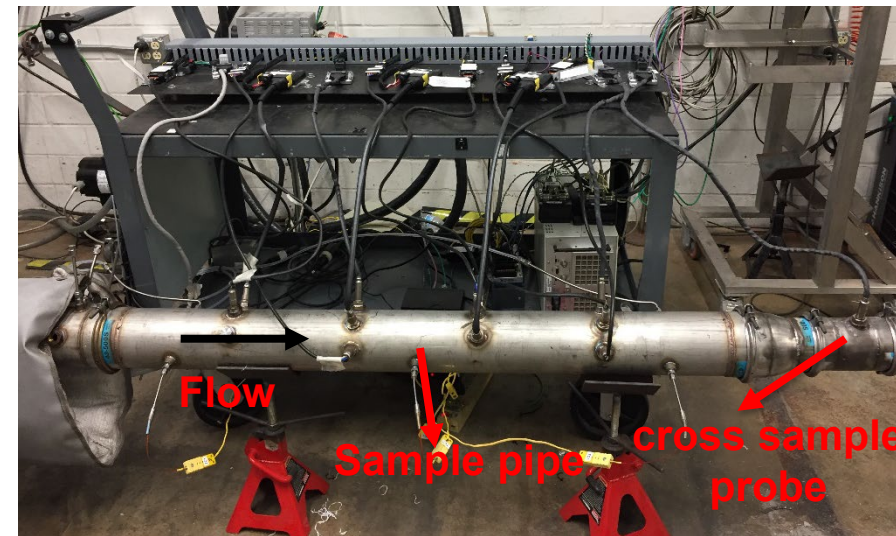
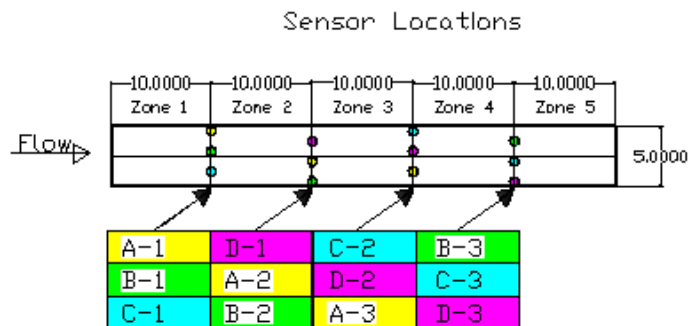
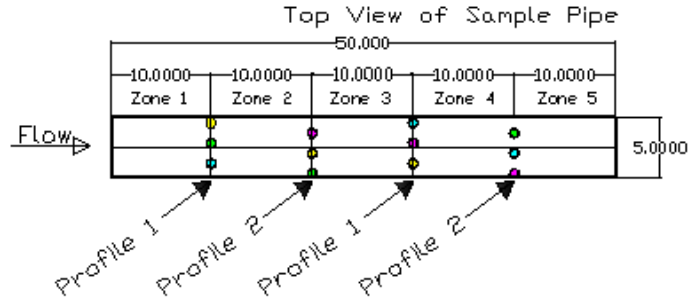
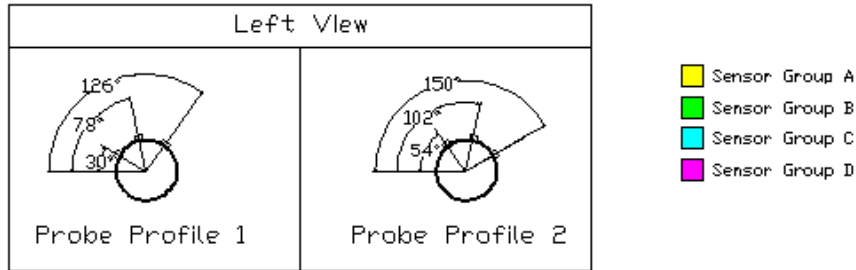


# ECTO-LAB Test Cell Setup



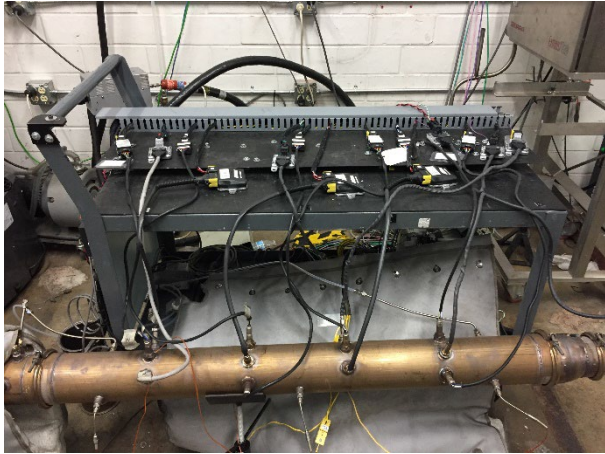
# Sample Pipe Schematic/Layout

Total of 12 Sensors





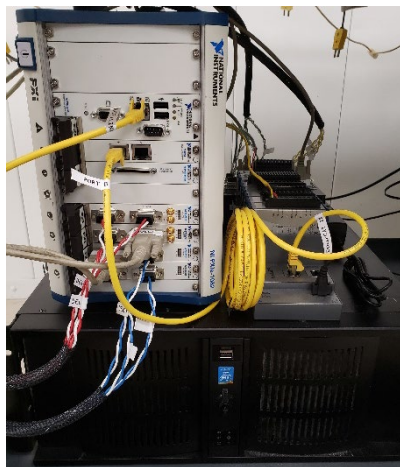
# Sensor Layout/Test Cell Setup



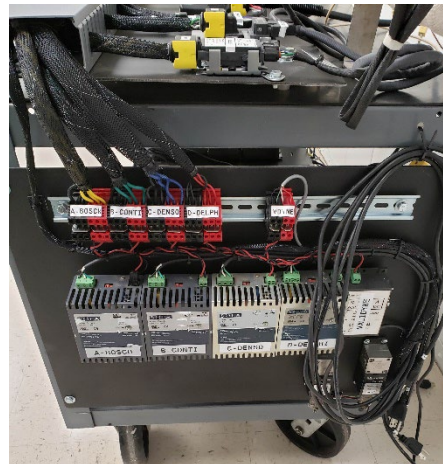
Sensors installed on the sample pipe

- Three sensors per manufacturer are being used
- Horiba MEXA used for reference  $\text{NO}_x$  and  $\text{O}_2$  measurement
- FTIR used for  $\text{NH}_3$  and  $\text{H}_2\text{O}$

DAQ setup



Power supply setup



FTIR



Horiba



# Background - SS DoE

Below are the conditions which were tested during the SS DOE which was designed to give us insight into which variables are the biggest contributors to NO<sub>x</sub> Sensor variability.

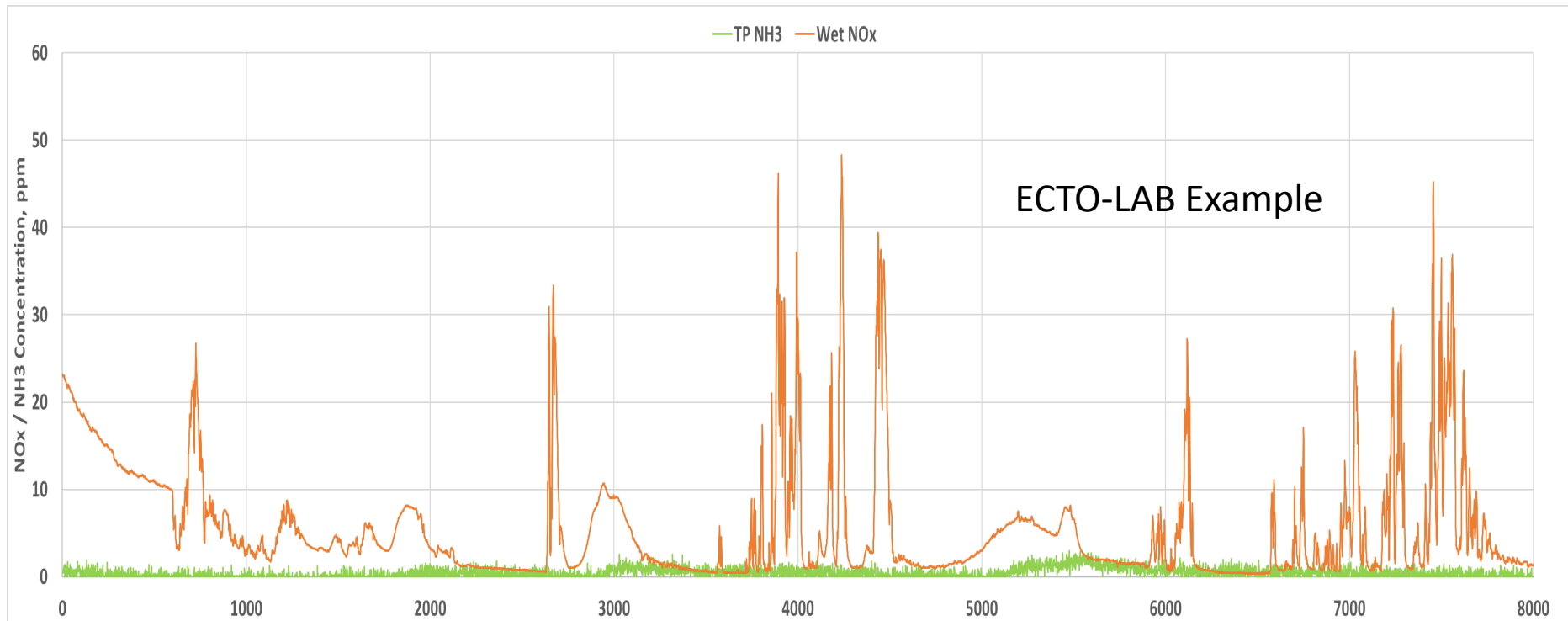
Parameter	No. of Conditions	Units	Condition				
			1	2	3	4	5
Exhaust Flow	3	kg/hr	100	650	1200		
Temperature	2	degC	200	350(a)	500		
Water / O <sub>2</sub>	3	% / %	5 / 11	11 / 8	17 / 4		
TP NO <sub>x</sub>	5	ppm	0	5	10	20	40
NH <sub>3</sub>	2	ppm	0	20			
(a) Limited number of runs							



# Transient DOE

- CARB Southern Route

- Transient Run 1: Low NO<sub>x</sub>, Low NH<sub>3</sub>, ANR of 1.35, baseline
- Transient Run 2: Higher NO<sub>x</sub>, Low NH<sub>3</sub>, ANR of 1.1
- Transient Run 3: Low NO<sub>x</sub>, High NH<sub>3</sub>, ANR of 1.5 with NH<sub>3</sub> injection



# Sensor Y: SS Data Results

# Sensor Y SS

99.5% of the variance in Sensor Y deltas was explained with 6 variables, but most of this comes from NH3 and temperature effects. Recall that temperature only had limited points at midpoint to allow for quadratic curve estimation.

Variable	R-Squared W/ Variable Added	Additional R-Squared	Non-NH3 Variability Explained*
NH3	93.5%	-	-
Temp	97.6%	+4.1%	63%
Temp^2	98.3%	+0.7%	11%
H2O	98.7%	+0.4%	6%
Temp*NH3 & Temp^2*NH3	99.1%	+0.4%	6%
H2O*Temp	99.5%	+0.4%	6%

\*= Additional R-squared/6.5%

# Sensor Y: SS Transient Results

# Comparing Variable Levels Across Experiments

The table below compares the transient data levels vs. what was tested in the SS DOE. Other than H2O, all variables appear to fit within the ranges fairly well, with a little bit of a gap on the upper end of the DOE. H2O percentage range extends a little below the lower range of the DOE.

Variable	Range is SS DOE	Transient Data 5 <sup>th</sup> Percentile	Transient Data 95 <sup>th</sup> Percentile
Exhaust Flow (kg/hr)	(100, 1200)	96	899
Temperature (Deg. C)	(200, 500)	194	375
H2O (%)	(5, 17)	1.3	8.9
NOx (ppm)	(0, 40)	0.3	28.0
NH3 (ppm)	(0, 20)	0	19.2



# Variables Studied

The following is a list of variables examined in the transient data set. The word *prime* in this analysis refers the rate of change of a variable from one second to the next. For example,

$$O_2Prime_t = O_{2_t} - O_{2_{t-1}}$$

## Variables Examined:

- Temperature and Temperature Prime
- H<sub>2</sub>O and H<sub>2</sub>O Prime
- O<sub>2</sub> and O<sub>2</sub> Prime
- Exhaust Flow and Exhaust Flow Prime
- NOx and NOx Prime

# SS Variable Importance in Transient

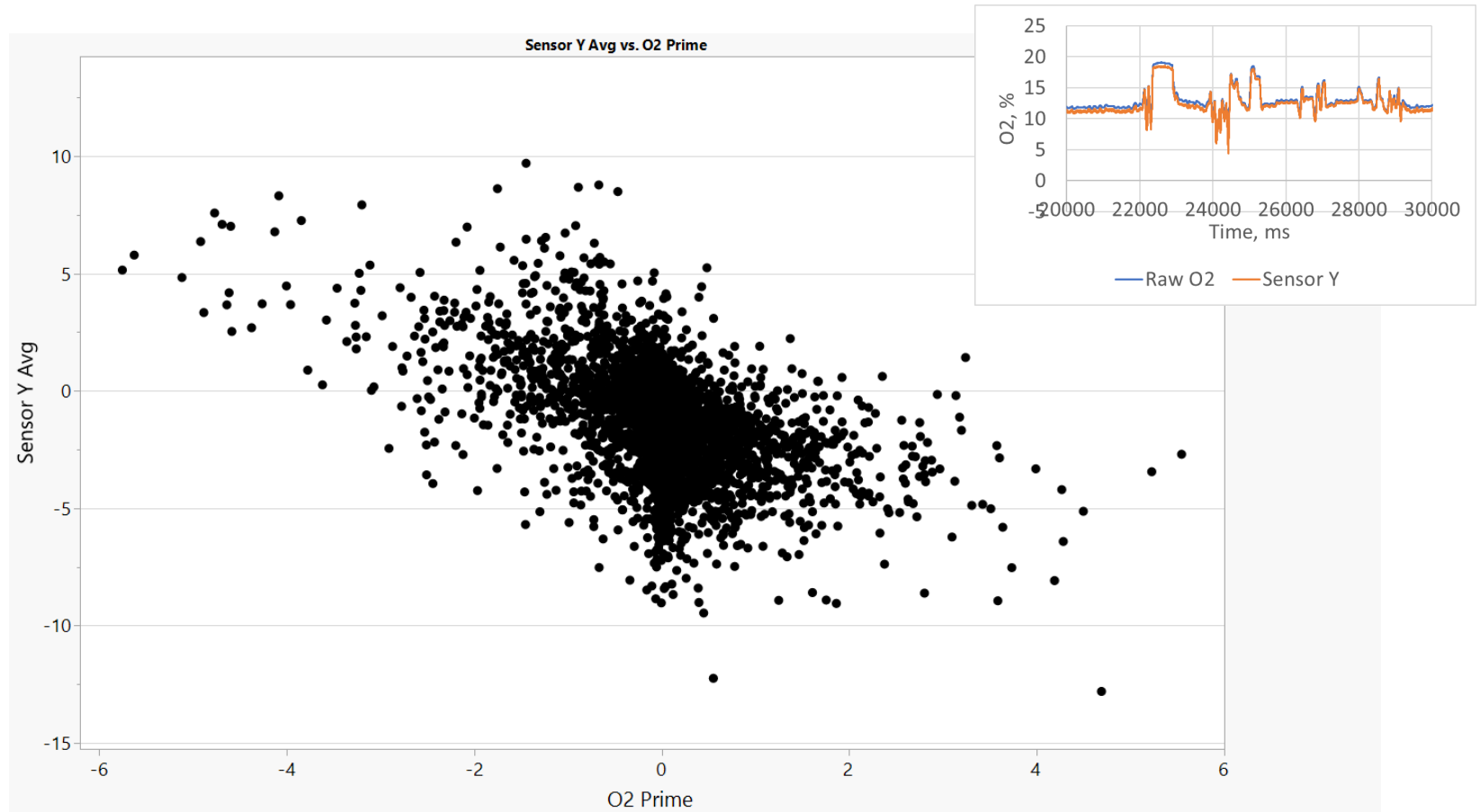
Looking at the variable importance, O2 prime is still the largest non-NH3 impact, followed by the interaction between H2O and NH3. Adding exhaust flow to this list only increases R-squared by 0.2%.

Variable	R-Squared W/ Variable Added	Additional R- Squared	Non-NH3 Variability Explained*
NH3	86.9%	-	
O2 Prime	89.1%	+2.2%	17%
H2O and H2O*NH3	91.3%	+2.2%	17%
Temperature	92.3%	+1.0%	8%
H2O Prime	93.2%	+0.9%	7%

\*= Additional R-squared/13.1%

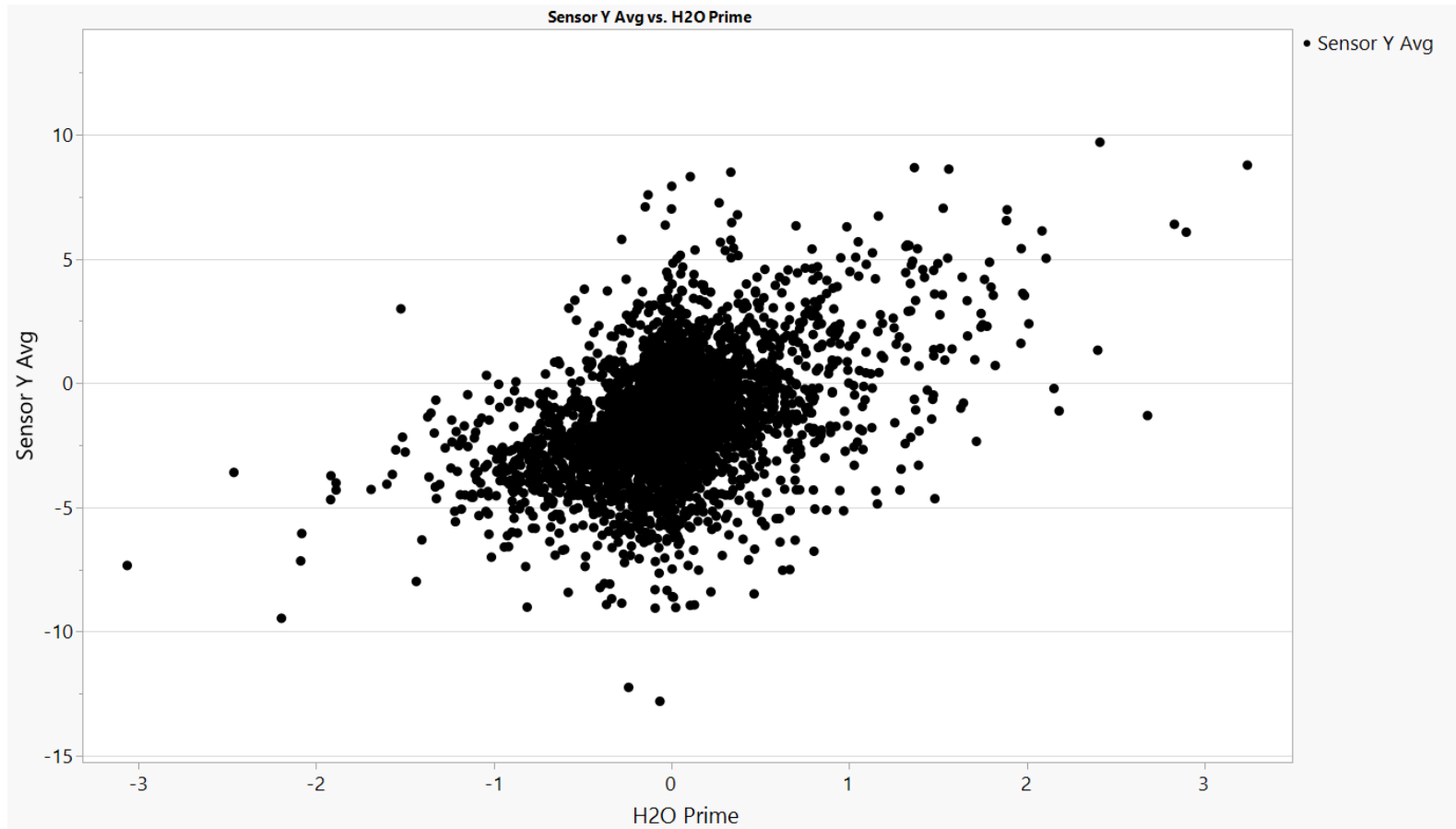
# Sensor Y Delta vs. O2 Prime

The graph below shows the impact of rate of change of O2 on the Sensor Y deltas.



# Sensor Y Delta vs. H2O Prime

The graph below shows the impact of rate of change of H2O on the Sensor Y deltas.



# Applying SS Model to Transient Data

The tables below compare the variability of the deltas of Sensor Y before and after applying the transient model.

All Data, No Model

File	Std. Dev	95 <sup>th</sup> - 5 <sup>th</sup>
Transient #1	2.45	8.51
Transient #2	2.19	6.53
Transient #3	8.77	25.09

All Data, Using SS Model

File	Std. Dev	95 <sup>th</sup> - 5 <sup>th</sup>
Transient #1	1.93	5.94
Transient #2	2.27	6.76
Transient #3	3.00	9.56



# Applying Transient Model

The tables below compare the variability of the deltas of Sensor Y before and after applying the transient model.

## All Data, No Model

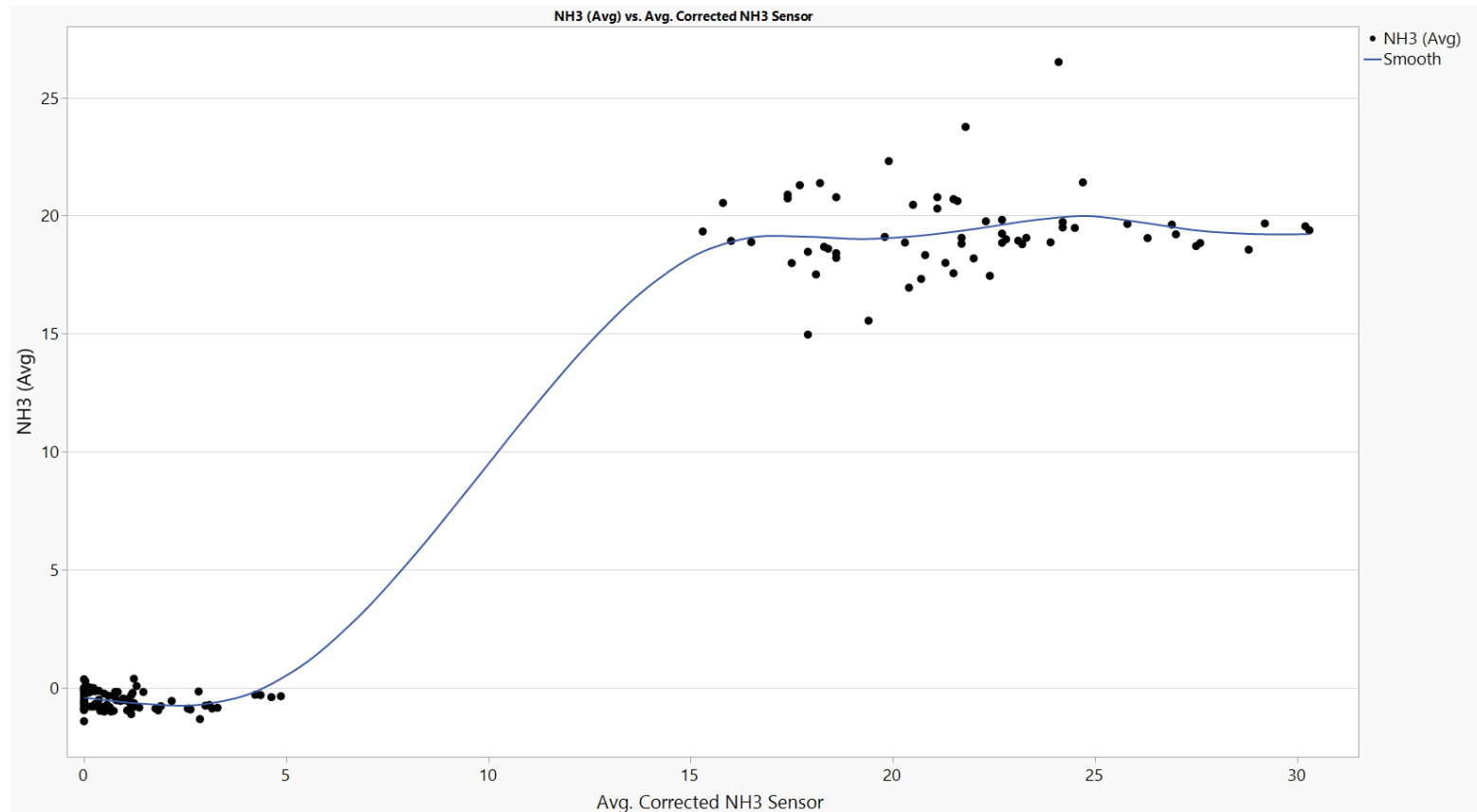
File	Std. Dev	95 <sup>th</sup> - 5 <sup>th</sup>
Transient #1	2.45	8.51
Transient #2	2.50	6.53
Transient #3	8.77	25.09

## All Data, Using Transient Model

File	Std. Dev	95 <sup>th</sup> - 5 <sup>th</sup>
Transient #1	1.50	4.91
Transient #2	1.69	4.97
Transient #3	1.60	4.52

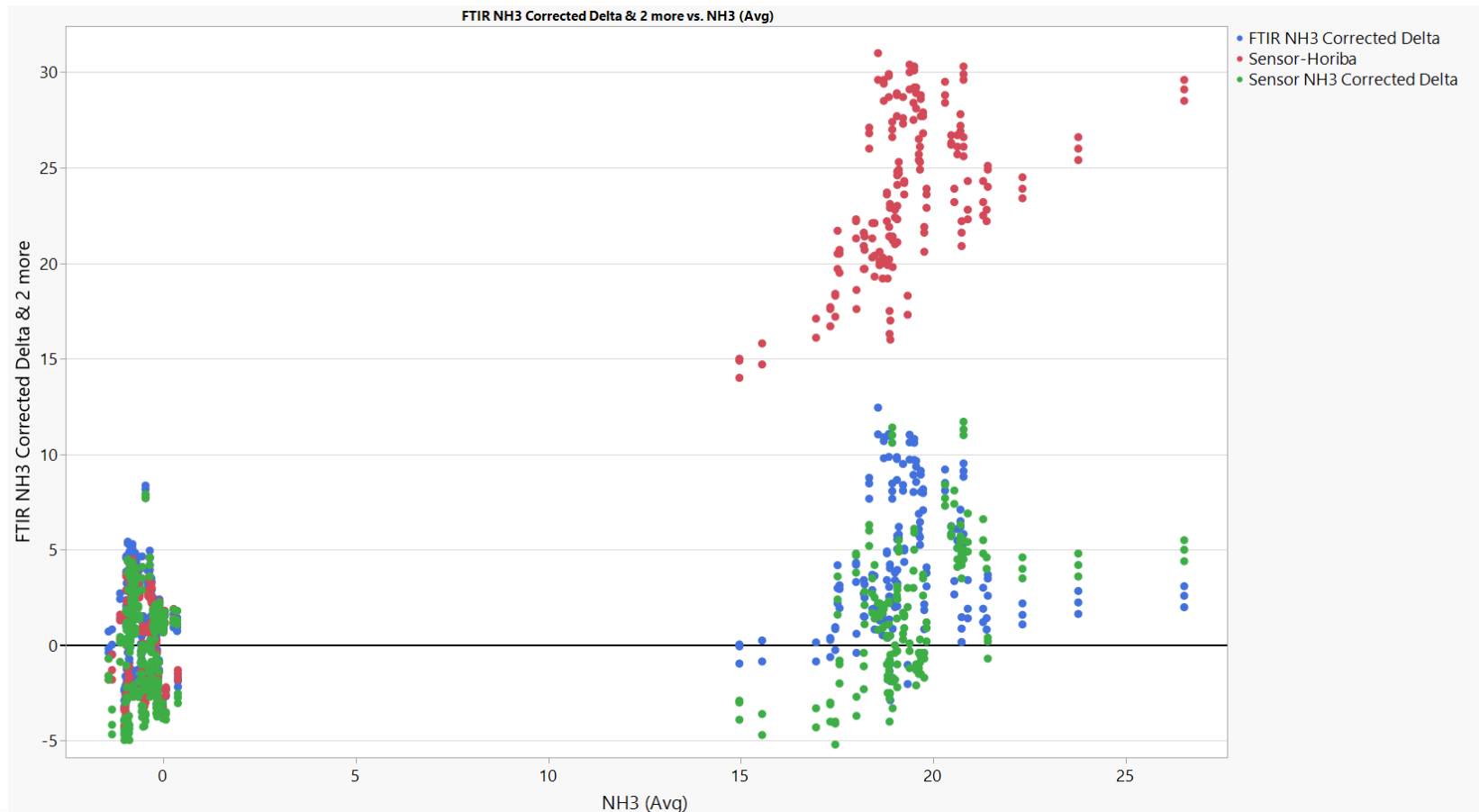
# NH3 Agreement Between Methods

The FTIR ammonia “NH3 (Avg)” does not seem to agree very well with the corrected ammonia sensor data (avg. of 3 sensors used).



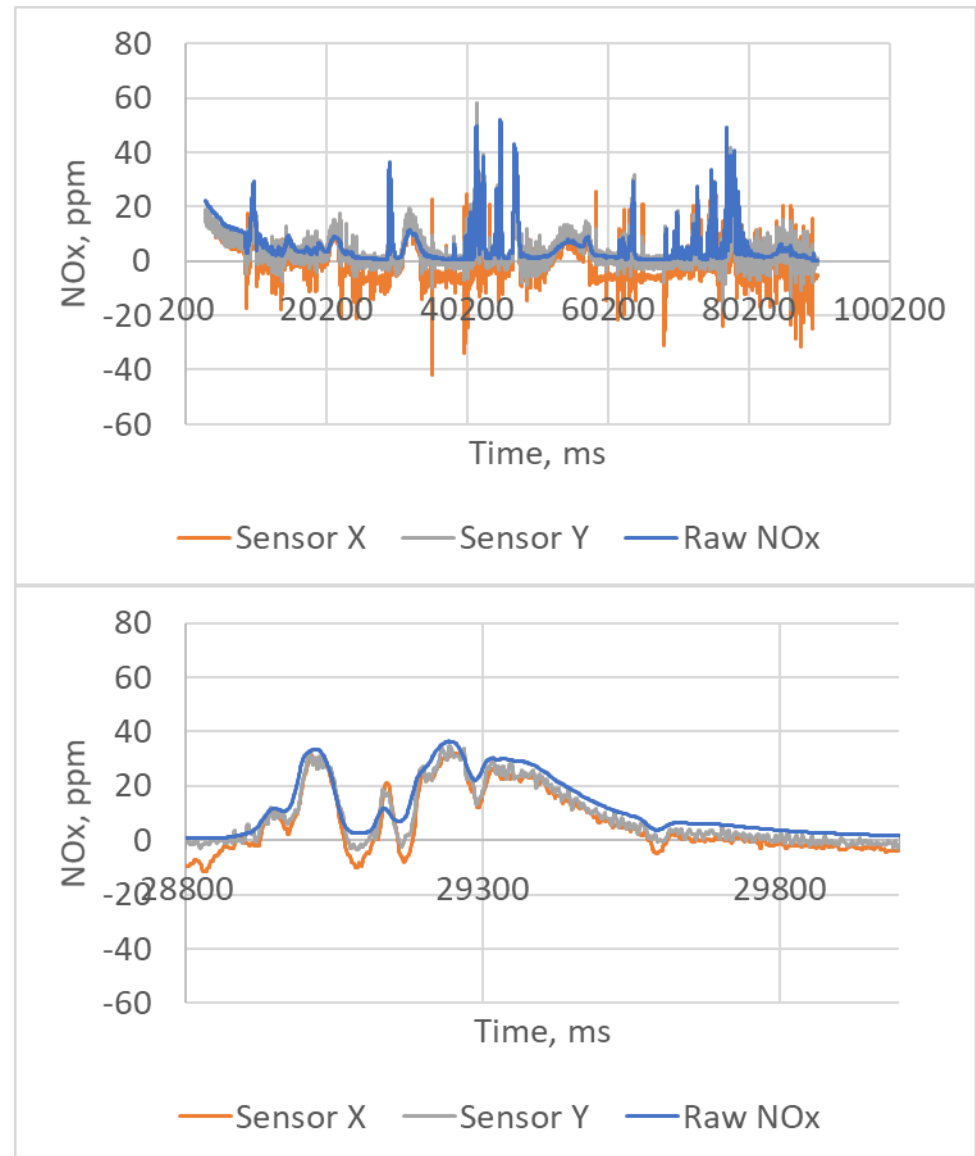
# NH3 Agreement Between Methods

The plot below shows the error for corrected NOx using FTIR NH3 vs. corrected NOx using the average of 3 corrected NH3 sensors. FTIR seems better when looking at NH3 values above and below the DOE noise.



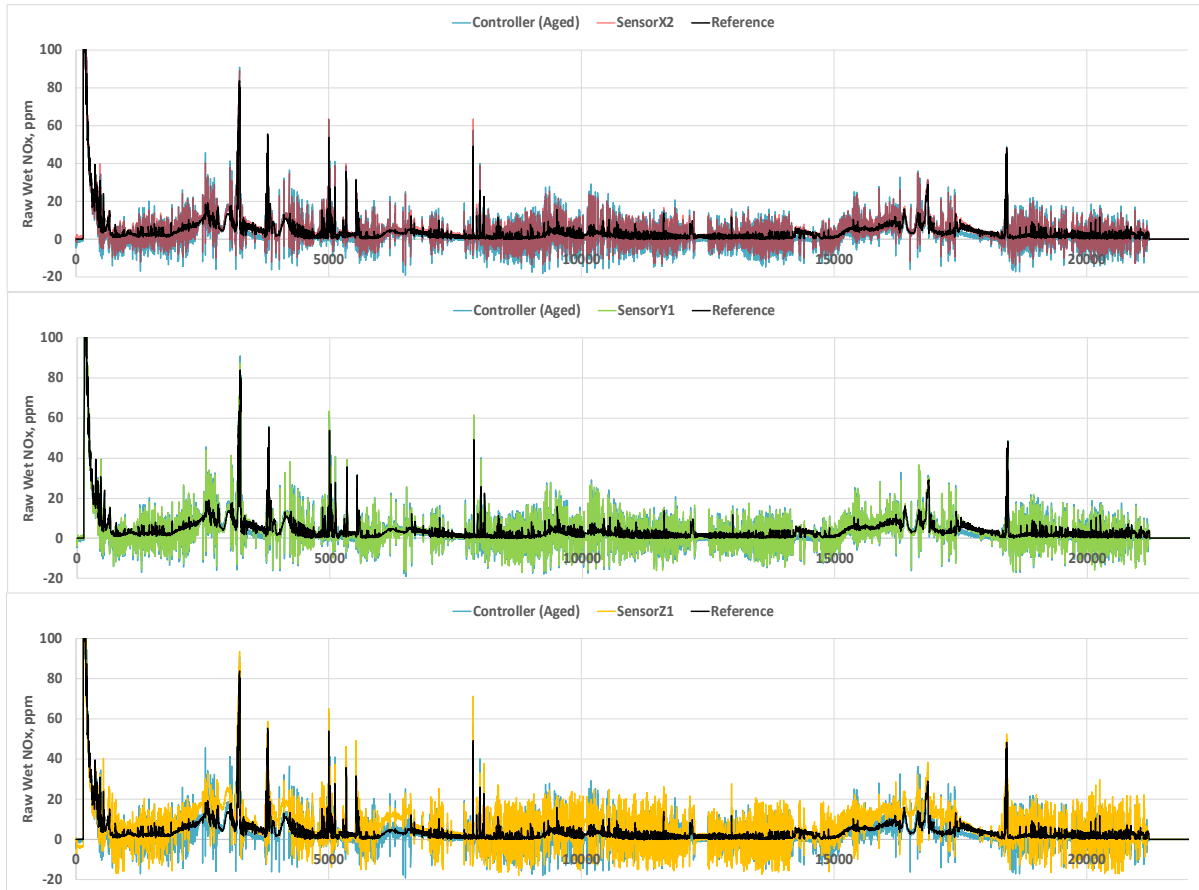
# Negative Values Example

- This is an example for two sensor signals
  - Sensor X bias more negative near zero but reads similar to Sensor Y at higher concentration
  - This could present difficulty on how to treat negative values and it may need to be applied on a case-by-case basis



# Individual NO<sub>x</sub> Sensor Comparisons versus Lab Reference- (Engine Platform, no Sensor Correction)

## SNTE Full Cycle



- Data is from same SNTE field cycle as PEMS examples
- Controller is tailpipe NO<sub>x</sub> sensor from test article (~1200 hours)
- Sensor X/Y/Z examples from different suppliers
  - Not Aged Sensors
- Lab Reference is same as for PEMS comparisons
- At this scale data appears to be very “noisy” compared to Lab
  - Larger features are still captured
- Aged Controller sensor does appear to show a negative offset compared to Lab and other sensors
  - This is just one sample...

### Impact on 3B-MAW

3B-MAW Result	2030 CARB Threshold	Lab Reference	Sensor X	Sensor Y	Sensor Z
Bin 1, g/hr	7.5	0.7	0.9	0.3	1.3
Bin 2, g/hp-hr	0.075	0.040	0.039	0.028	0.068
Bin 3, g/hp-hr	0.03	0.033	0.034	0.032	0.072



# Conclusions

- $\text{NH}_3$  is the most important variable interfering with sensor signal
  - Subtracting the  $\text{NH}_3$  contribution is crucial for accurate  $\text{NO}_x$  measurement. The current  $\text{NH}_3$  sensor suffers accuracy and variability at low level to be used. New  $\text{NH}_3$  sensing technology is needed
- Other variables can impact the sensor performance such as temperature, rate of change of  $\text{O}_2$  and  $\text{H}_2\text{O}$  but the model could account for them
- Applying the SS model on transient data marginally slightly reduced the stdev to  $< \pm 3$  ppm
- Applying the transient model to transient data greatly reduced the stdev to  $< \pm 2$  ppm
- ECTO-LAB proved to be a useful tool to better understand and optimize sensor performance. More ECTO-LAB work with a focus on what we learned from this phase can certainly yield a better sensing technology transfer function addressing accuracy, variability and negative values
- $\text{NO}_x$  sensors may offer a solution for determining 3B-MAW with additional correction to some of the behavior we examined in this program