Laboratory Investigation of Exhaust NO_X/NH_3 Sensors Under Steady-State and Transient Operation Using ECTO-LAB

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10th PEMS Conference, CE-CERT, March 17-18, 2022

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.

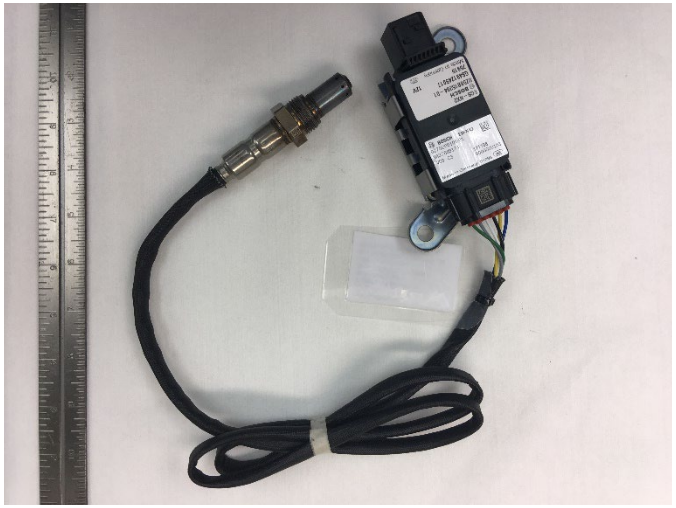
Background

- 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 NOx 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

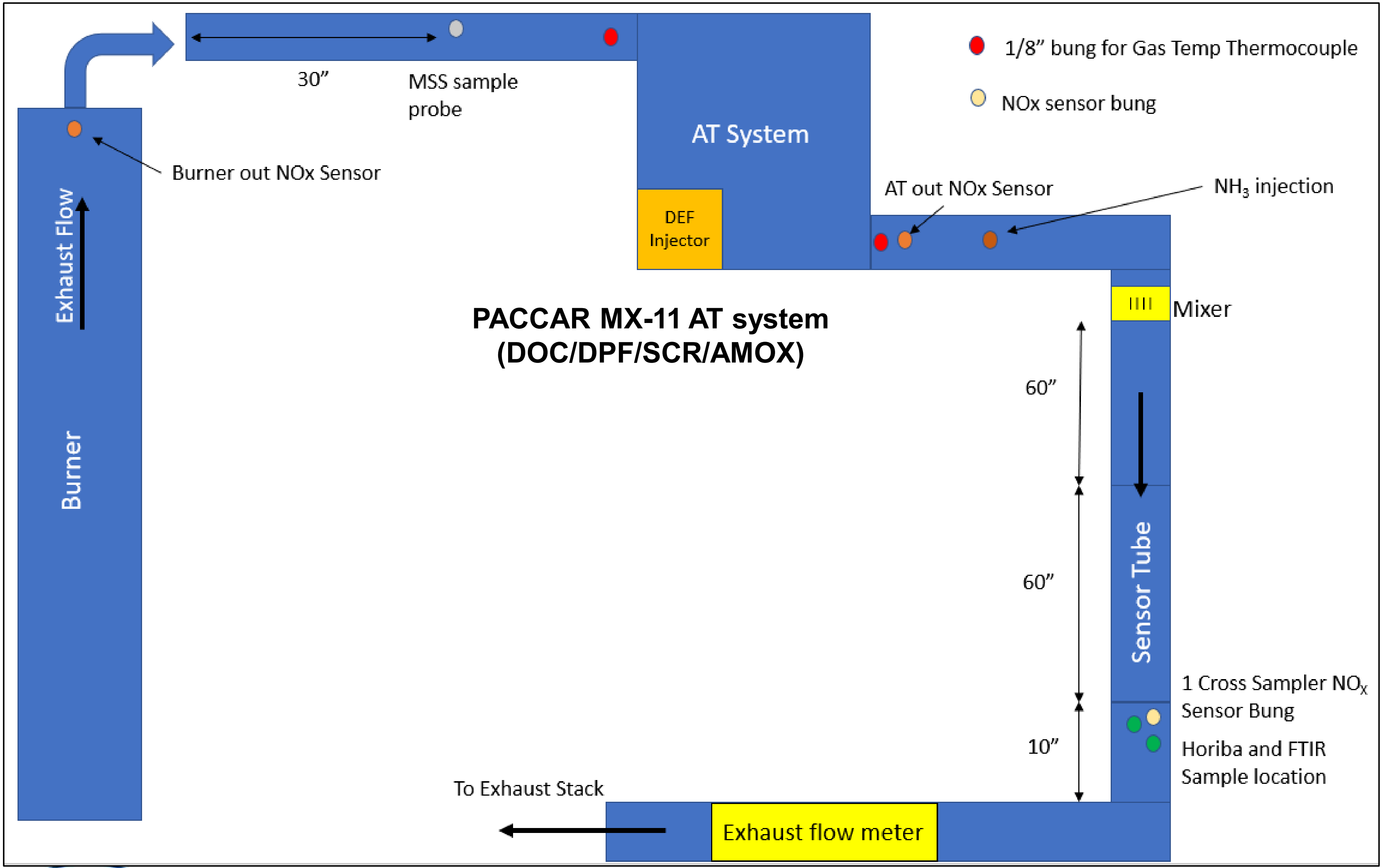
Bosch NOx sensor



Vitesco NOx sensor/Prototype

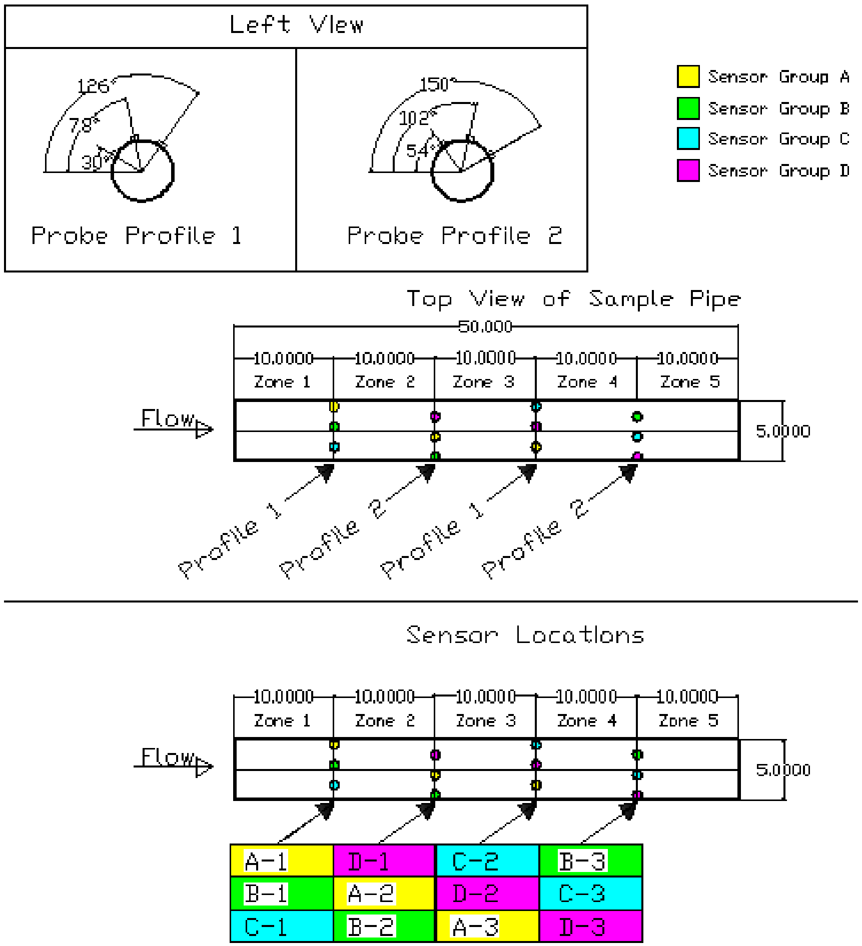
Delphi NH_3 sensor

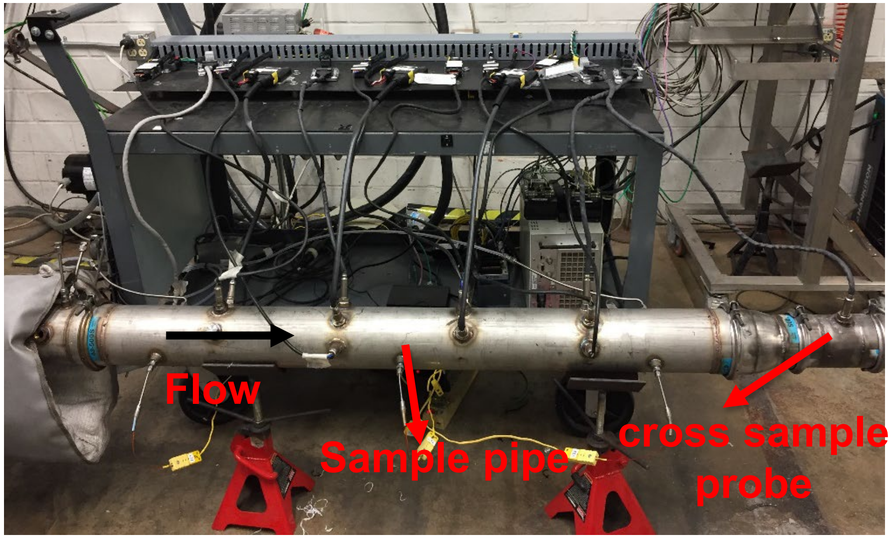
ECTO-LAB Test Cell Setup



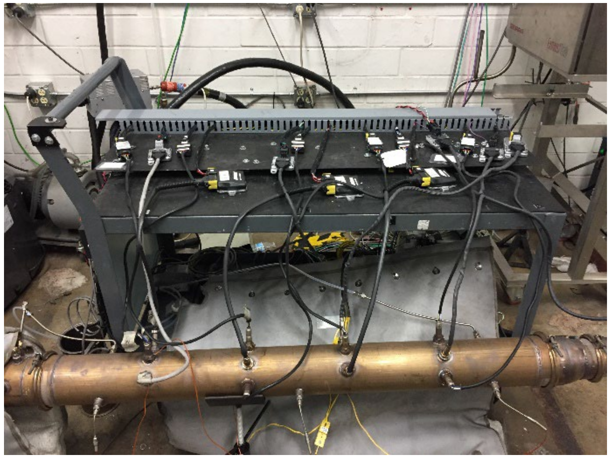
Sample Pipe Schematic/Layout

Total of 12 Sensors





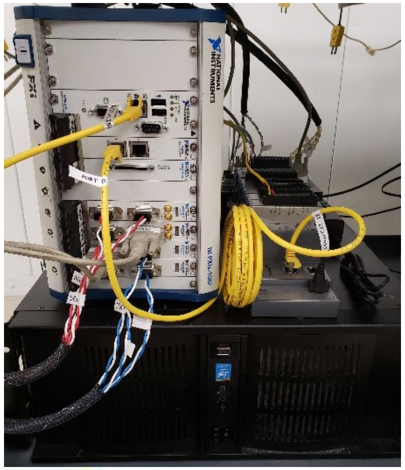
Sensor Layout/Test Cell Setup



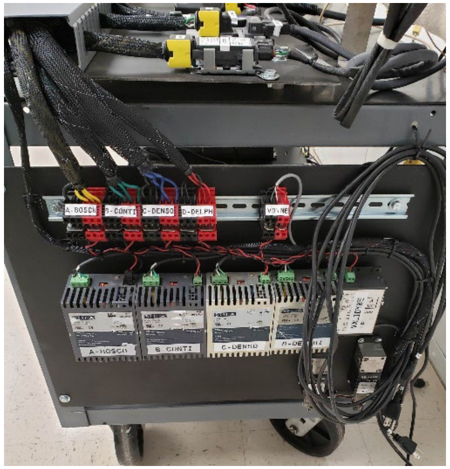
Sensors installed on the sample pipe

- Three sensors per manufacturer are being used
- Horiba MEXA used for reference NO_X and O_2 measurement
- FTIR used for NH_3 and H_2O

DAQ setup



Power supply setup



FTIR

Horiba

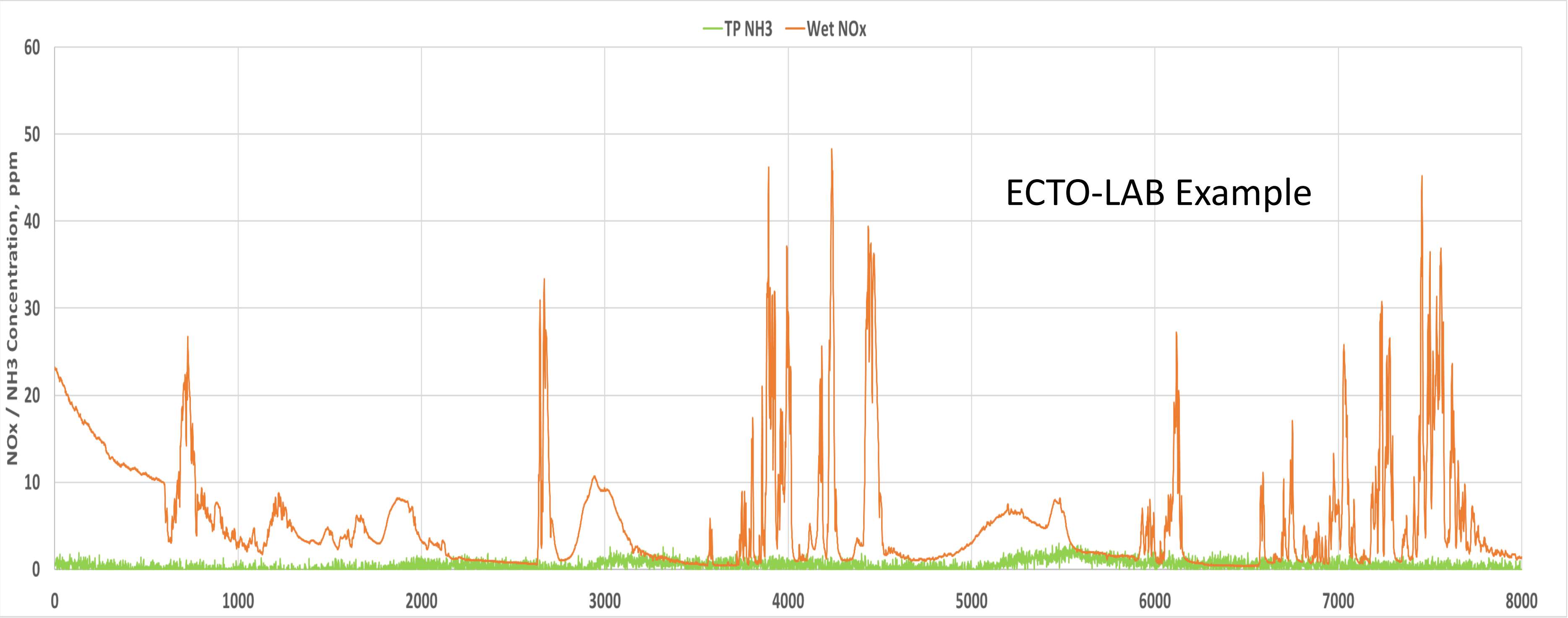
Background - SS DoE

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 NOx 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_2	3	% / %	5 / 11	11 / 8	17 / 4		
TP NO_X	5	ppm	0	5	10	20	40
NH3	2	ppm	0	20			
(a) Limited number of runs							

Transient DOE

- CARB Southern Route
  - Transient Run 1: Low NOX, Low NH3, ANR of 1.35, baseline
  - Transient Run 2: Higher NOx, Low NH3, ANR of 1.1
  - Transient Run 3: Low NOx, High NH3, ANR of 1.5 with NH3 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 H20, all variables appear to fit within the ranges fairly well, with a little bit of a gap on the upper end of the DOE. H20 percentage range extends a little below the lower range of the DOE.

Variable	Range is SS DOE	Transient Data 5th Percentile	Transient Data 95th 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,

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

<u>Variables Examined:</u>

- Temperature and Temperature Prime
- H_2O and H_2O Prime
- O_2 and O_2 Prime
- Exhaust Flow and Exhaust Flow Prime
- NOx and NOx Prime

SS Variable Importance in Transient

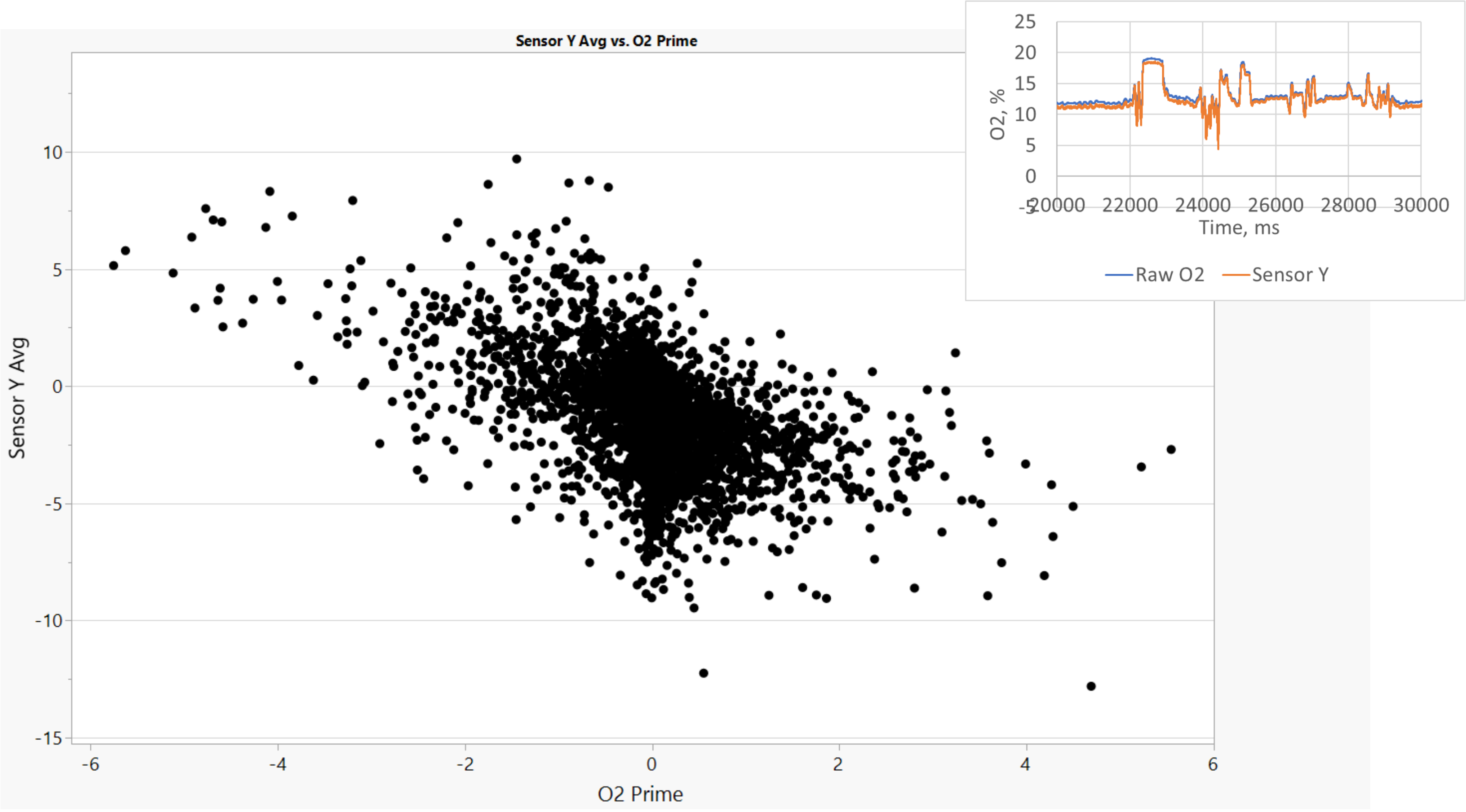
Looking at the variable importance, O2 prime is still the largest non-NH3 impact, followed by the interaction between H2O and NH3. Adding exhaust flow to this list only increases R-squared by 0.2%.

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%

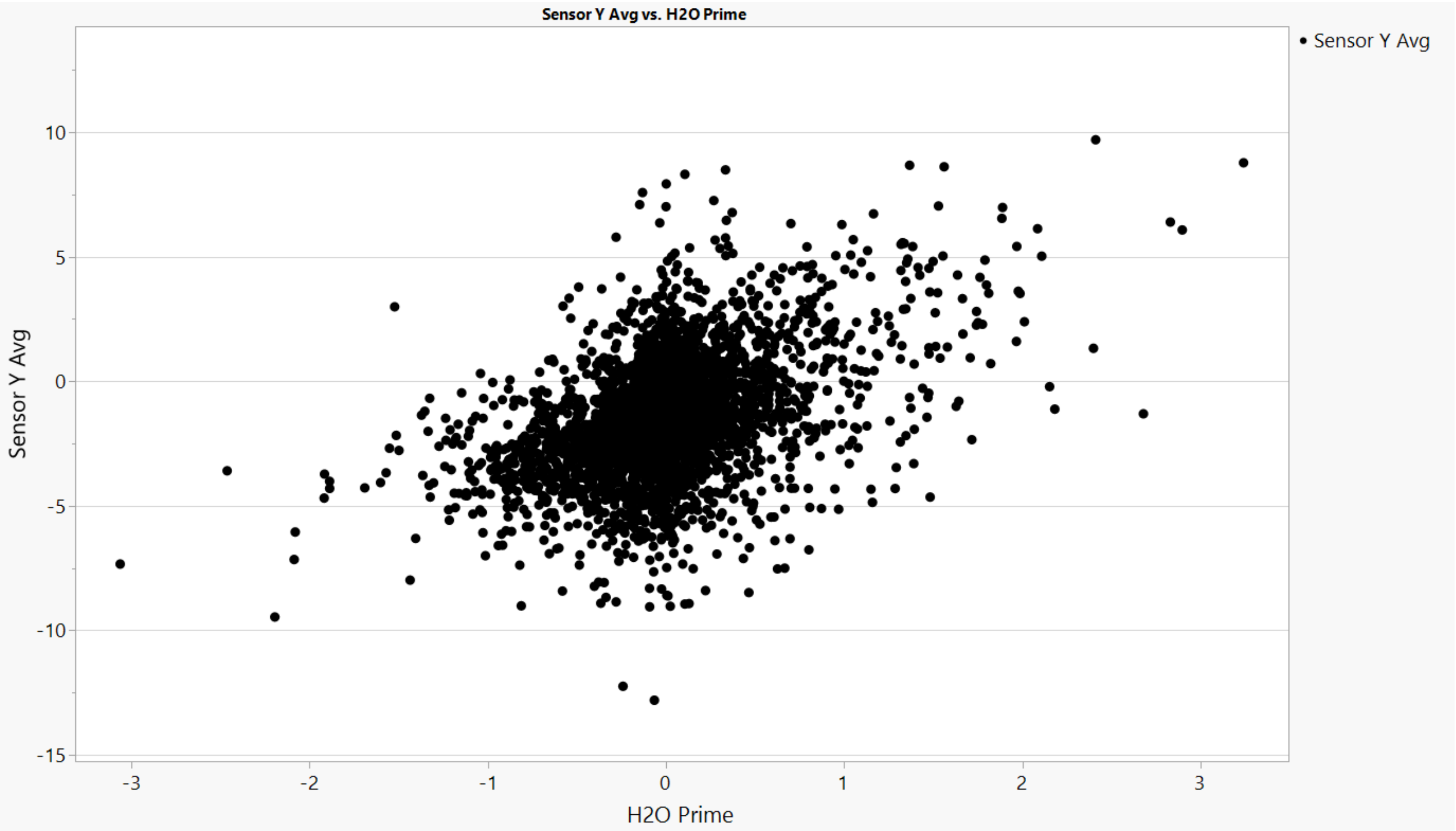
Sensor Y Delta vs. O2 Prime

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^{th} - 5^{th}
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^{th} - 5^{th}
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

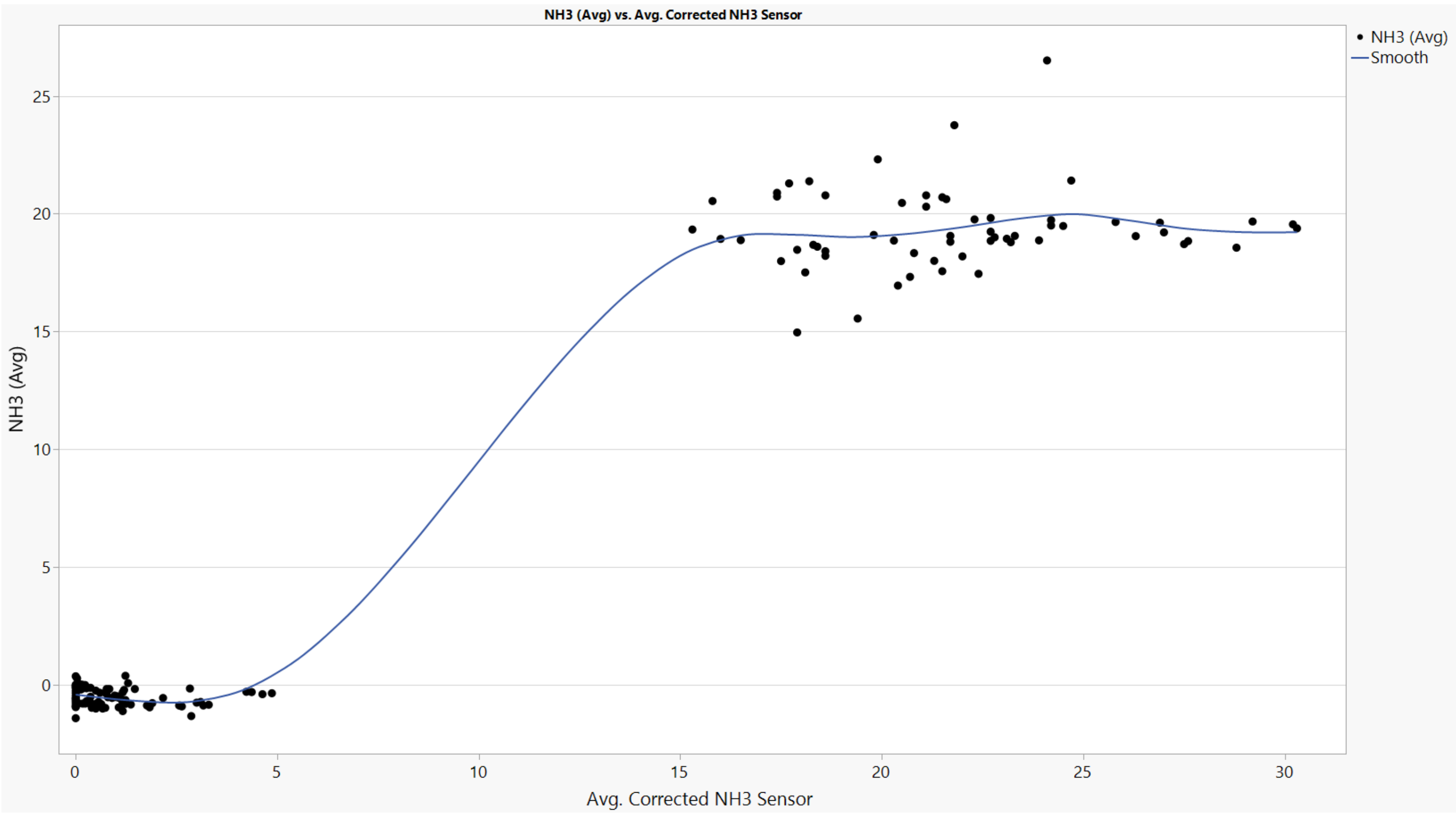
File	Std. Dev	95th - 5th
Transient #1	2.45	8.51
Transient #2	2.50	6.53
Transient #3	8.77	25.09

All Data, Using Transient Model

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

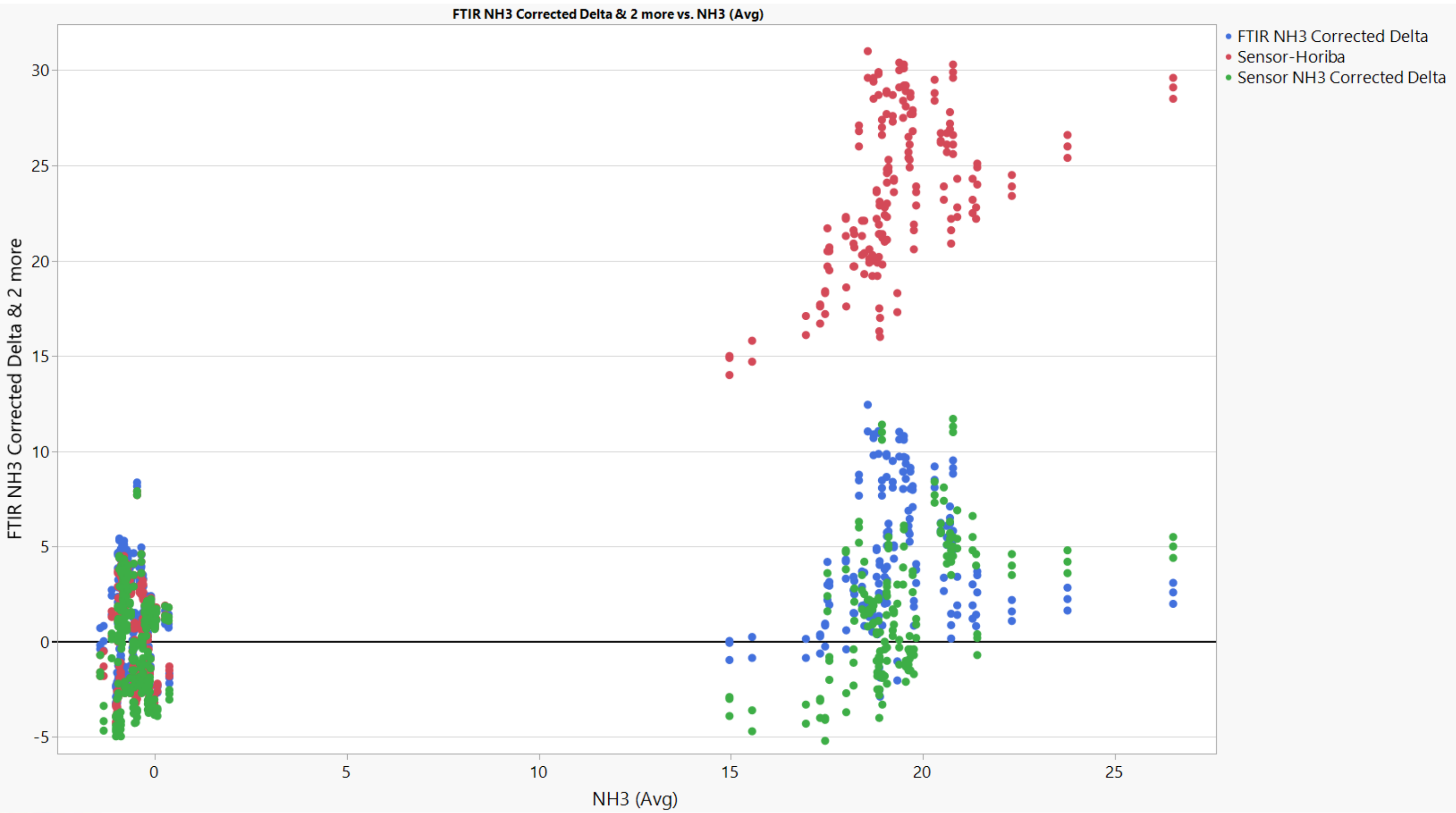
NH3 Agreement Between Methods

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



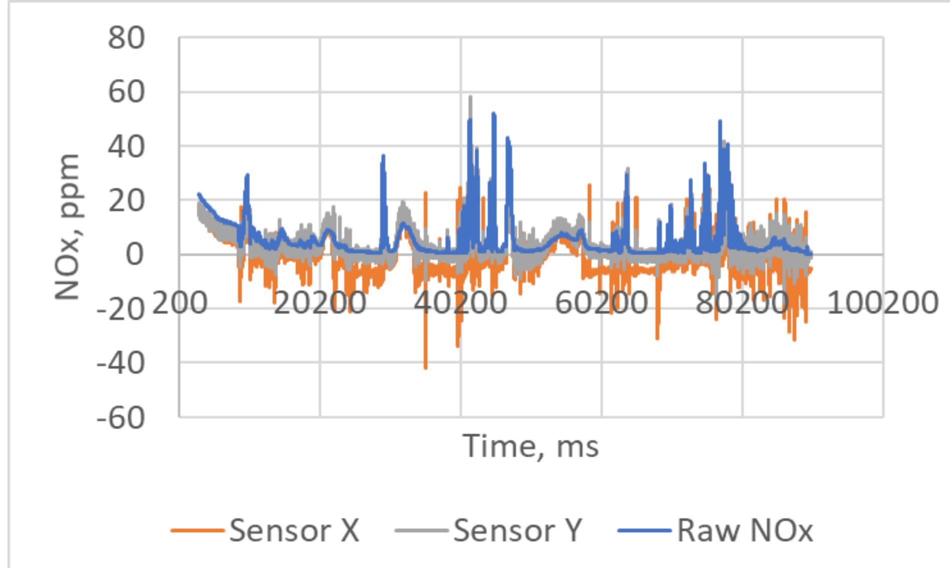
NH3 Agreement Between Methods

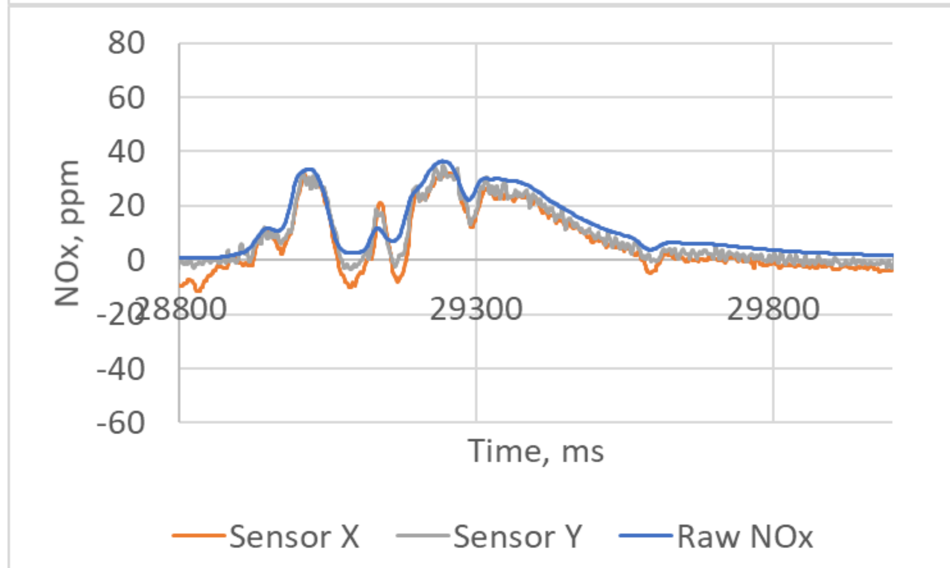
The plot below shows the error for corrected NOx using FTIR NH3 vs. corrected NOx using the average of 3 corrected NH3 sensors. FTIR seems better when looking at NH3 values above and below the DOE noise.



Negative Values Example

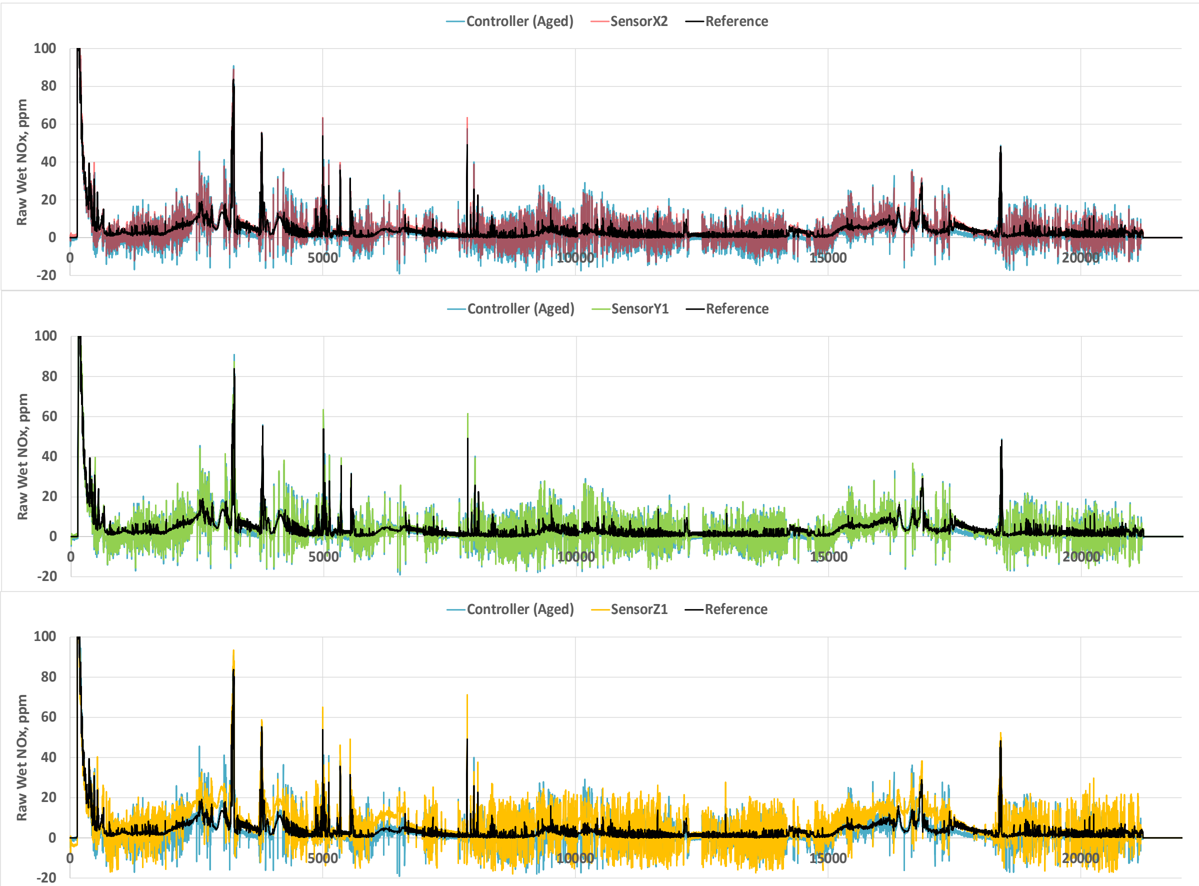
- This is an example for two sensor signals
  - Sensor X bias more negative near zero but reads similar to Sensor Y at higher concentration
  - This could present difficulty on how to treat negative values and it may need to be applied on a case-by-case basis





Individual NO_X 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_X 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

- NH_3 is the most important variable interfering with sensor signal
  - Subtracting the NH_3 contribution is crucial for accurate NOx measurement. The current NH_3 sensor suffers accuracy and variability at low level to be used. New NH_3 sensing technology is needed
- Other variables can impact the sensor performance such as temperature, rate of change of O_2 and H_2O but the model could account for them
- Applying the SS model on transient data marginally slightly reduced the stdev to < ±3 ppm
- Applying the transient model to transient data greatly reduced the stdev to < ±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
- NO_X sensors may offer a solution for determining 3B-MAW with additional correction to some of the behavior we examined in this program