Assessment of Measurement Variability of New Low NO_x PEMS for Measurement Allowance (and a brief look at Sensors…)

SOUTHWEST RESEARCH INSTITUTE®

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2023 OSAR Conference
March 30, 2023

Objectives for Low NO_X Real World Duty Cycle Testing

1. Characterize Performance of the Low NO_X Test Engine-Aftertreatment System on Real-World Duty Cycles
   - Does Regulatory Cycle Performance Translate to field cycles ?

2. Characterize PEMS Measurement Capability at Low NO_X Levels Using Representative Emission Signatures
   - What is the Incremental Measurement Variability (if any) with PEMS as compared to Lab Reference Measurements ?

3. Examine Sensor-Based Measurements at Low NO_X Levels Using Representative Emission Signatures

Experimental Approach – Replay Field Duty Cycles on Stage 3RW Low NO_X Engine in Lab with PEMS and Sensors

5 field duty cycles, 3 test configurations, 19 total data runs (~ 140 hours of data)

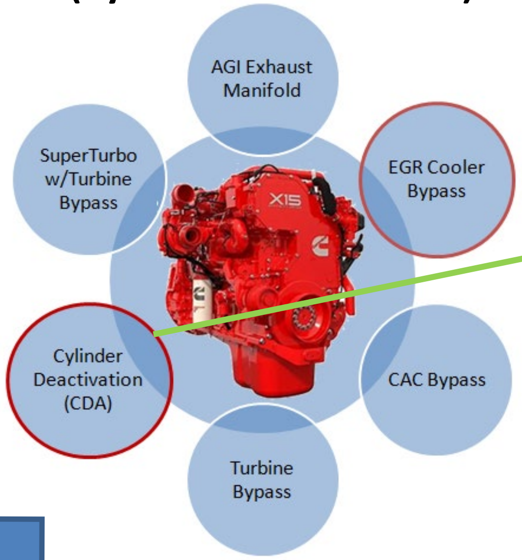
Field Cycle Runs on Low NO_X Engine

EPA Stage 3RW Low NO_X Demonstration Engine

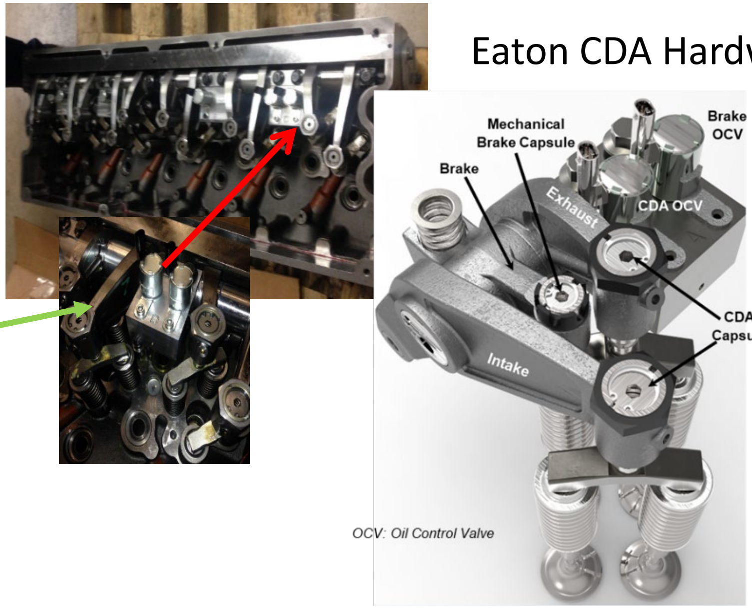
2017 Cummins X15 Engine

SAE Papers
2021-01-0589
2023-01-0357

Additional Engine Hardware (Cylinder Deactivation)

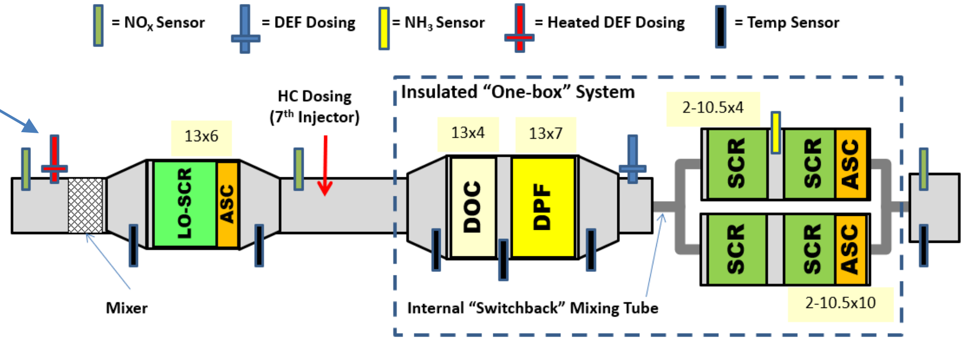


Eaton CDA Hardware



Advanced Low NO_X Aftertreatment (Dual SCR-Dual Dosing)

Heated Doser (Forvia)



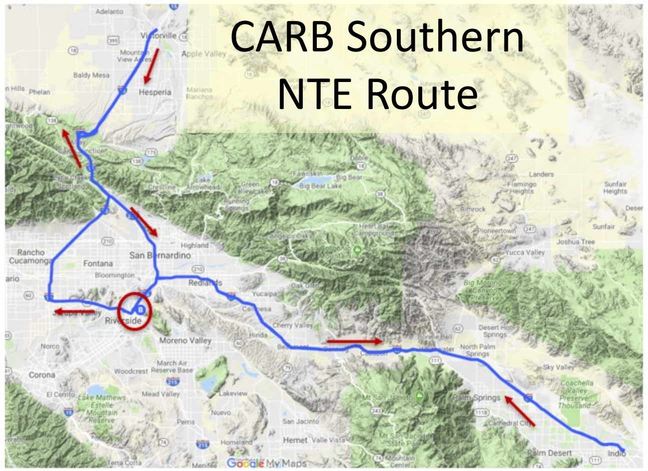
Development Targets:

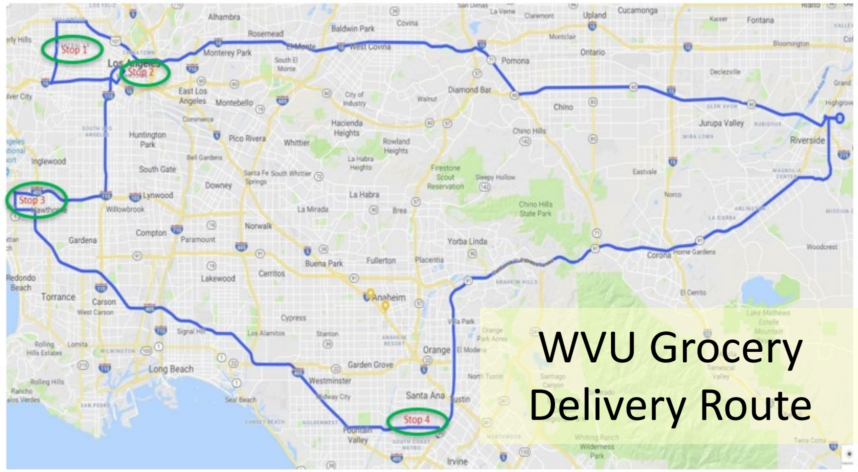
- FTP/RMC NO_X 0.02 g/hp-hr at 435k miles
- Lowest feasible LLC and in-use NO_X
- No adverse GHG impact

EPA Updates

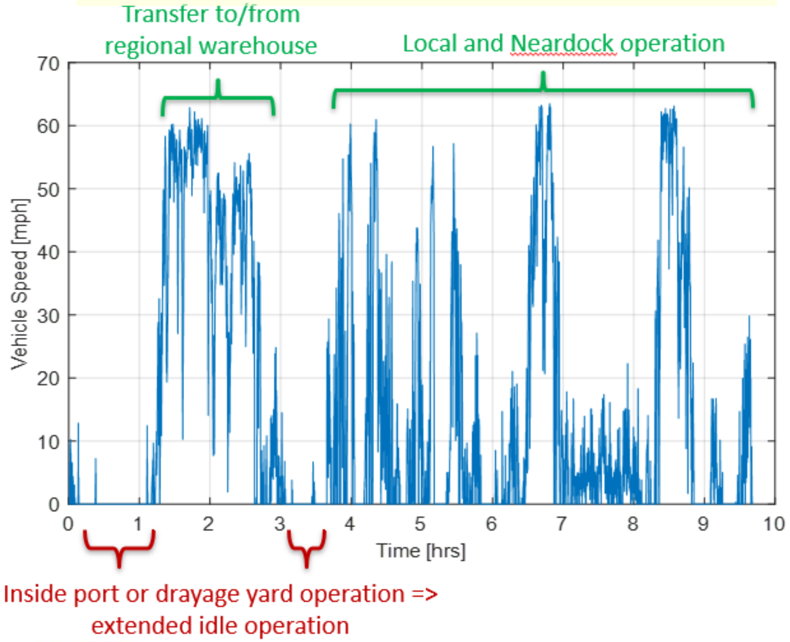
- Changed zCSF to DOC+DPF
- Improved downstream DEF mixing

Real-World Duty Cycles





WVU Drayage Route

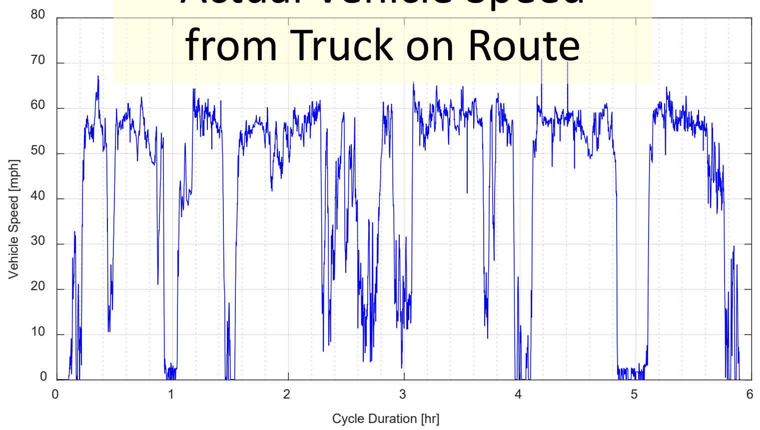


- Each of these cycles is a real working route that was driven with multiple actual Class 7 and Class 8 trucks
  - WVU collected this data on behalf of EMA
- Cycles represented a wide variety of different kinds of vehicle operations
- Recorded Vehicle Data was used to develop speed/load profiles that could be translated for Laboratory use

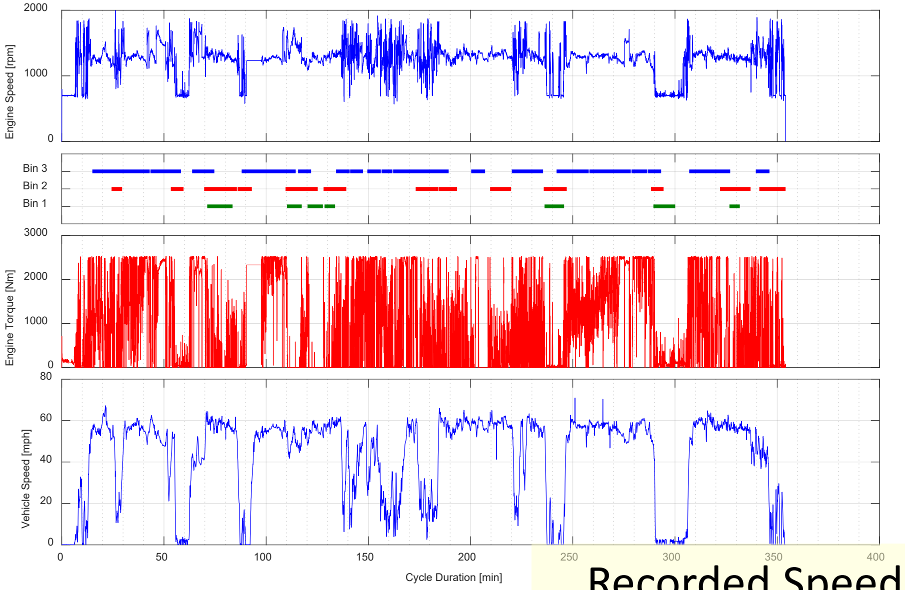
Cycle Translation Process Example – CARB Southern Route

Field Route

Actual Vehicle Speed from Truck on Route

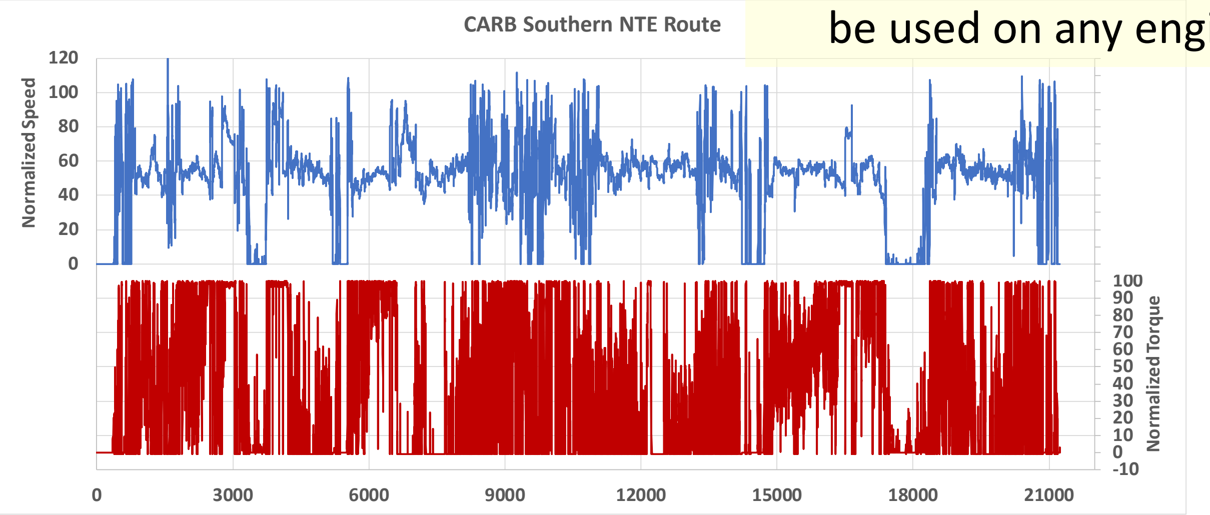


- WVU drove trucks on real-world routes
- Recorded vehicle data used along with engine torque curve information to generate Normalized engine-dyno replay cycle for Lab use

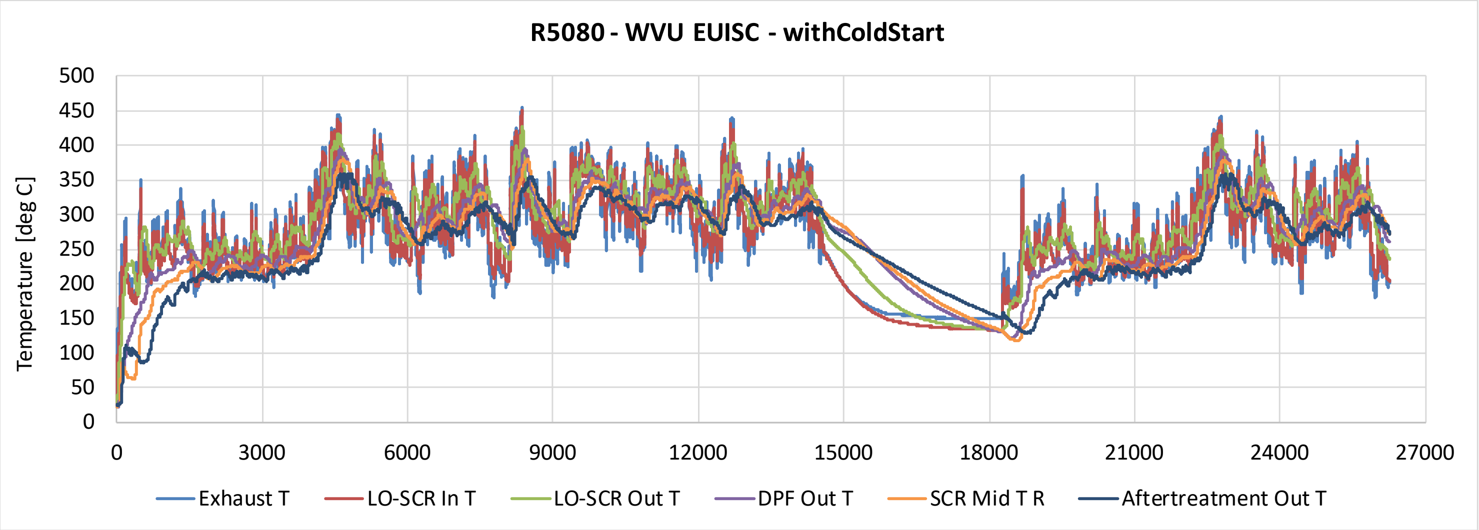


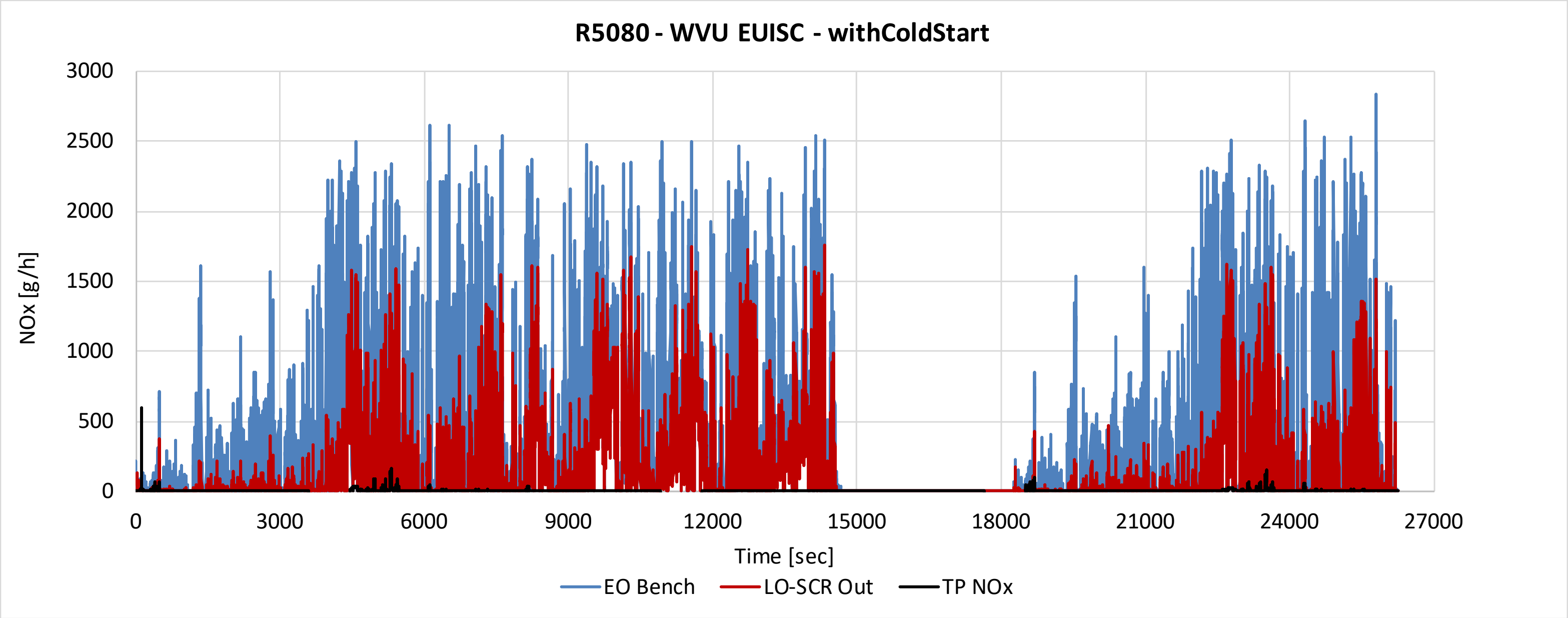
Recorded Speed/Load Data from Drive

Normalized Engine Cycle (can be used on any engine)



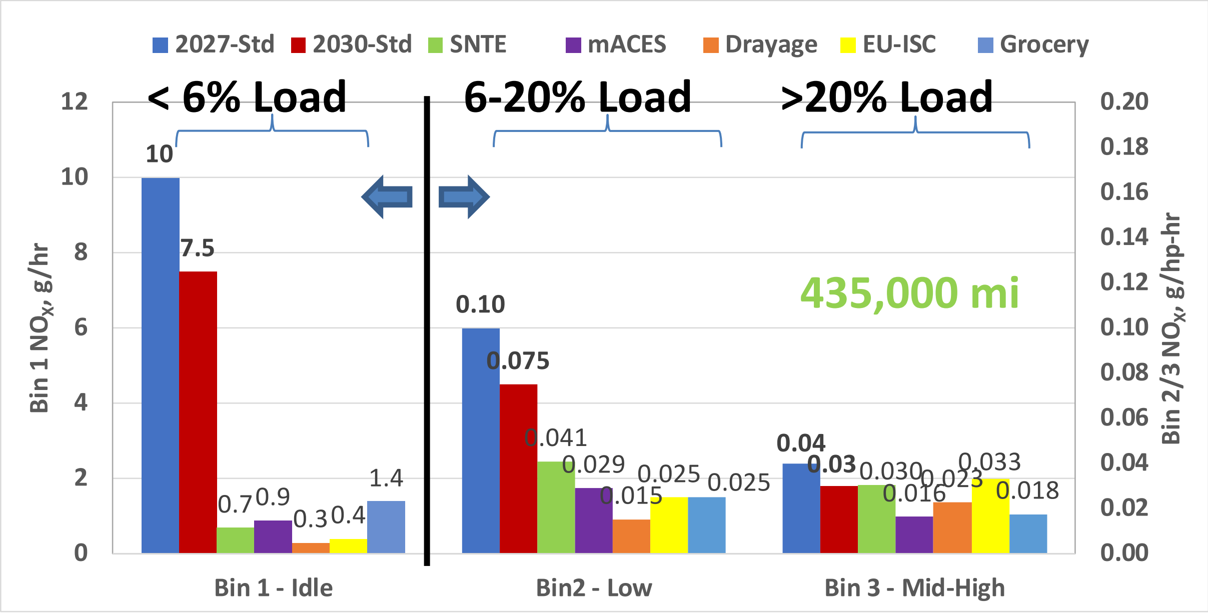
Temperature and NO_x Data on Example Field Cycle (EU-ISC)

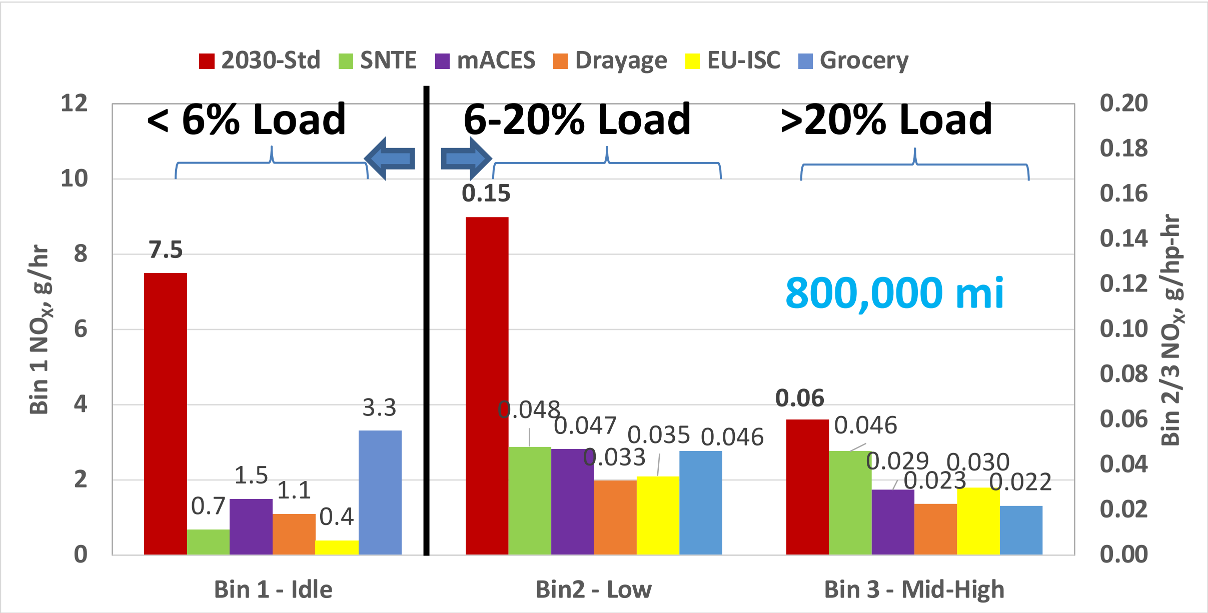




- Cold-start and low load primary control is using LO-SCR
- High-load LO-SCR efficiency reduced by strategy and dsSCR handles most of load
  - enable passive soot oxidation
- Tailpipe behavior is barely visible in black at bottom

Field Duty Cycle Results (3B-MAW) - Stage 3RW



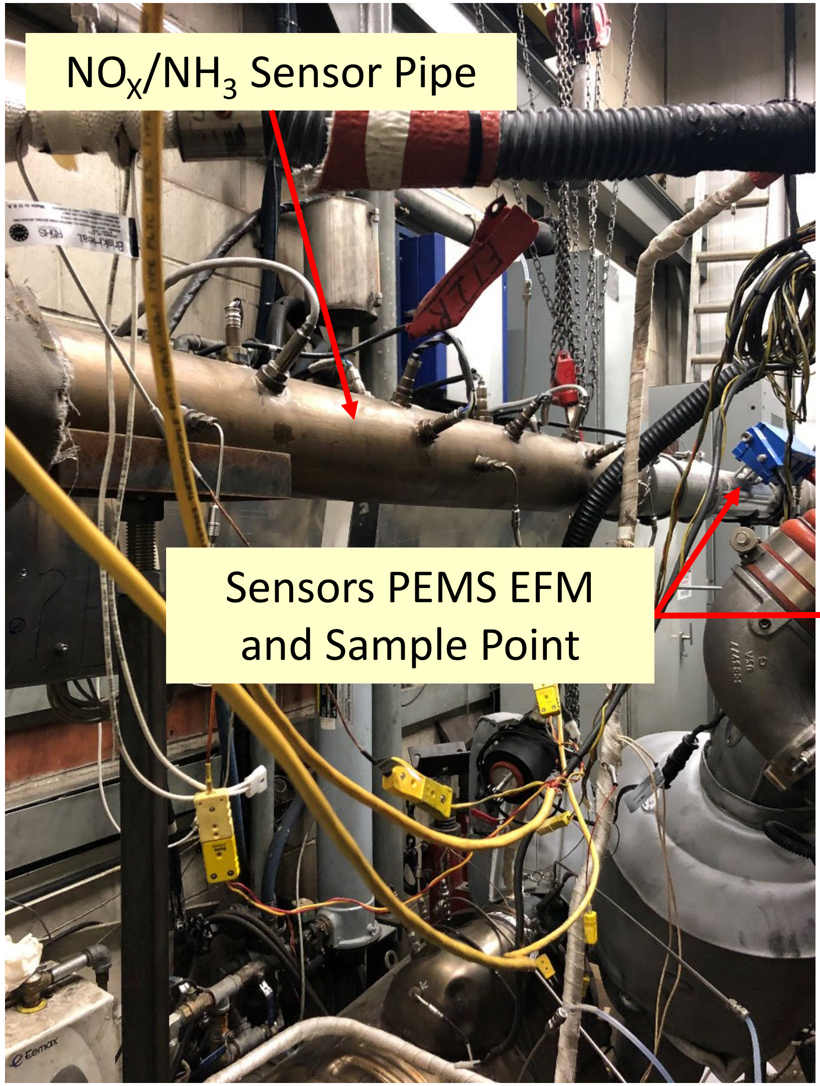


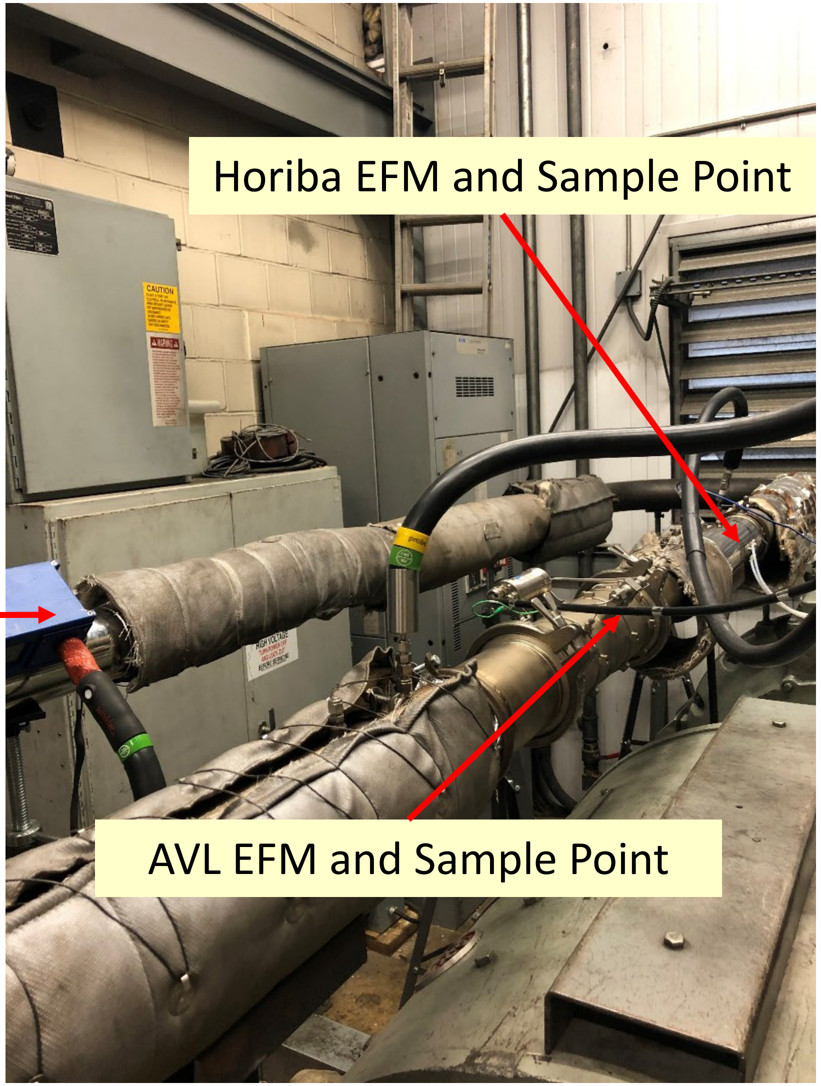
PEMS Experiment Data at this Aging Point

- Emissions are evaluated using new CARB / EPA in-use method (covers all operations, no low power exclusions, includes cold-start)
- Low NO_X emissions shown over a wide variety of Field Cycles
  - Standards (dark blue and red) are CARB 2027 and 2031 in-use compliance thresholds
  - Low NO_X engine generally below targets – some Bin 3 margins are smaller than desired
- Low Load emission problem is no longer present with Low NO_X technology - controlled as well or better than high load
- Emission controls are durable – still below thresholds at 800,000 miles
- **Note that these results are for OCV, with CCV Bin 2 and Bin 3 results are lower by ~ 0.005 to 0.007 g/hp-hr**
  - CCV provides larger margins at all levels

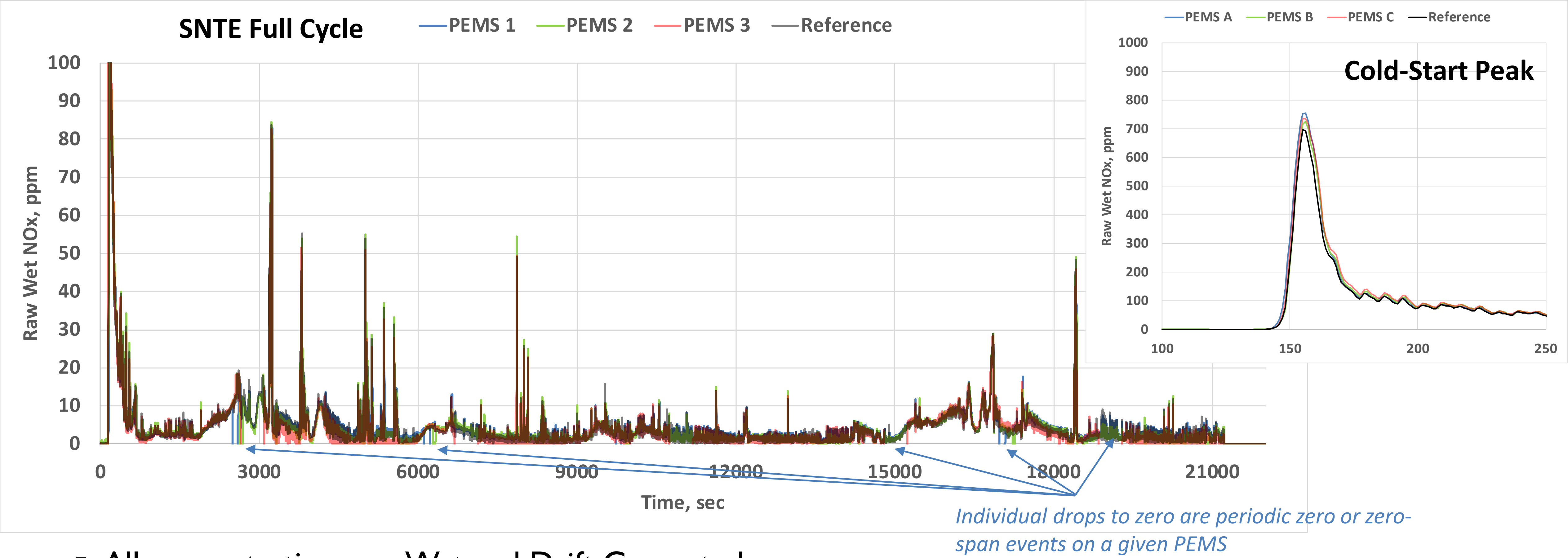
PEMS Data and Analysis

PEMS and Sensor Installation (Lab Reference Upstream)





PEMS vs Lab Reference – NO_X Concentration



- All concentrations are Wet and Drift Corrected
- Overall PEMS NO_X behavior very similar to Lab Reference over 6.5 hours
- Reference is average of 3 separate Lab emission benches

Modeling and Analysis

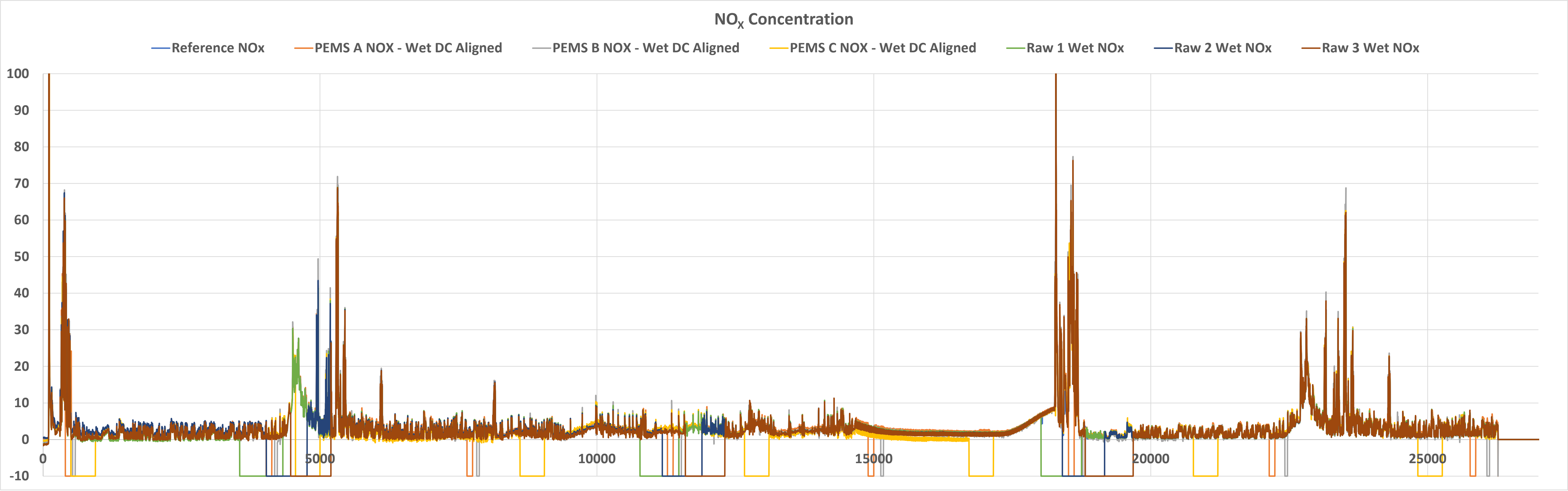
- Prime path for the program is to use the PEMS data to train a model of measurement variation that will be used to run a Monte Carlo simulation
  - Separate model for each PEMS
  - Model validation against data from CE-CERT in use experiment
    - PEMS compared to Mobile Emission Laboratory Reference
  - This effort is still on-going…

- EPA needed guidance for a PEMS Measurement Allowance for the HD-2027 FRM (finalized in December 2022)
  - Directly analyzed the 19 data sets that we had to look at levels of variation observed
    - 3B-MAW analysis of PEMS vs Lab Reference
    - Also conduct 3B-MAW analysis of individual Lab measurement to understand Lab variation

Direct Experimental Data Analysis Methodology

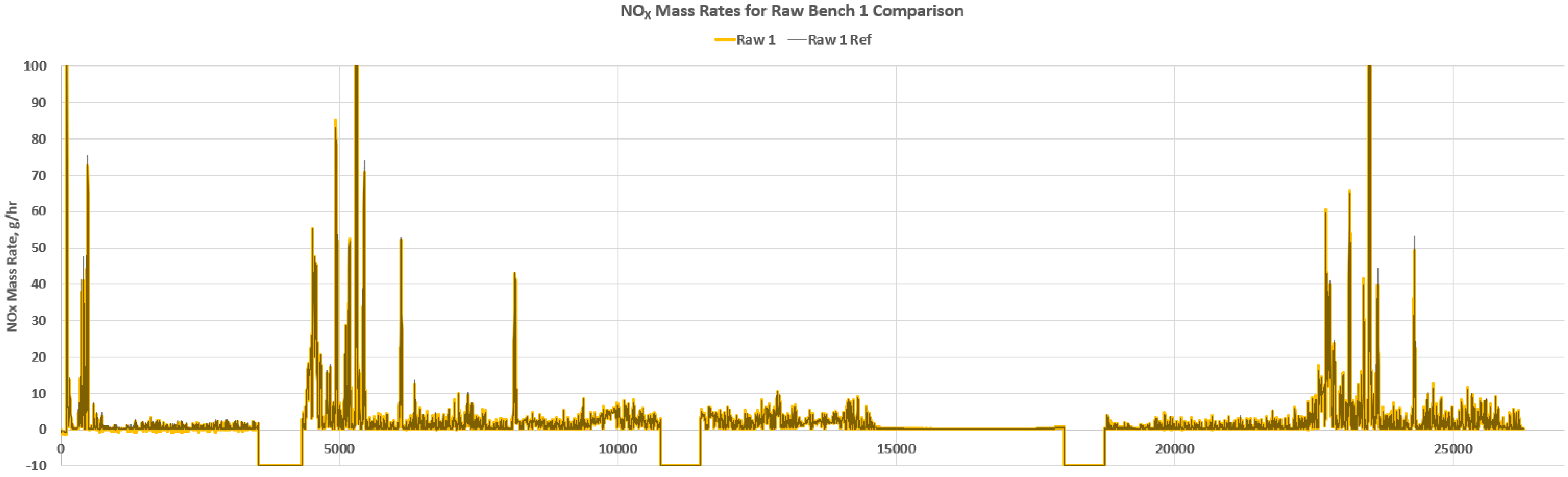
- Use PEMS and Lab data "as Measured"
  - Time Alignment within each instrument only – concentration and flow per 1065
  - We are not generating deltas on a continuous basis
- Calculate 3B-MAW for each PEMS and each Lab Raw measurement
  - 2B-MAW also added later when EPA plans became clear
- Compare each "Candidate" (PEMS or Lab) measurement to the Lab Reference (average of the 3 Lab measurements) on all 3 bins
  - We are comparing only the final bin values
- Note that because of different zero-span schedules for each instrument, it is necessary to generate are matching Reference signal for comparison
  - Otherwise, artificial differences will be generated to do presence and absence of different windows for each instrument
  - Direct comparison across all instruments to each other would require scrubbing away a lot more data or otherwise all combinations between pairs of instruments would require their own analysis (we do not have the resources for this in the timeframe needed)

Example Data Set for NO_X



- Note varying zero-span gaps
- Removing all of these to allow direct comparison would result in loss of ~ 25% of the entire data set including a number of key emission events…

Reference Data Matching Example for NO_x



- For each instrument (PEMS or Lab) a matching Reference is generated with the same zero-span gaps
- This example shows the matching gaps generated for the Raw Lab Bench 1 comparison
- These traces will be used (along with a matching CO_2 mass rate trace) to calculate 3B-MAW values for the desired comparison
- This was done for each instrument separately (PEMS or Lab)

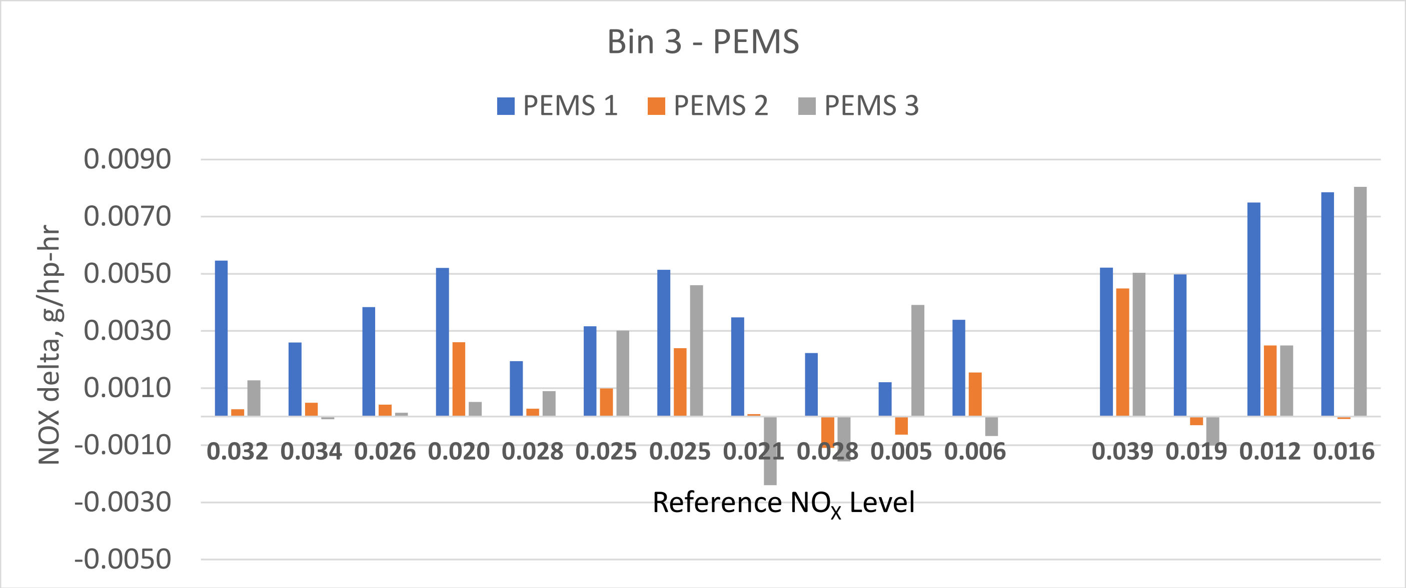
Example Output for Single Duty Cycle

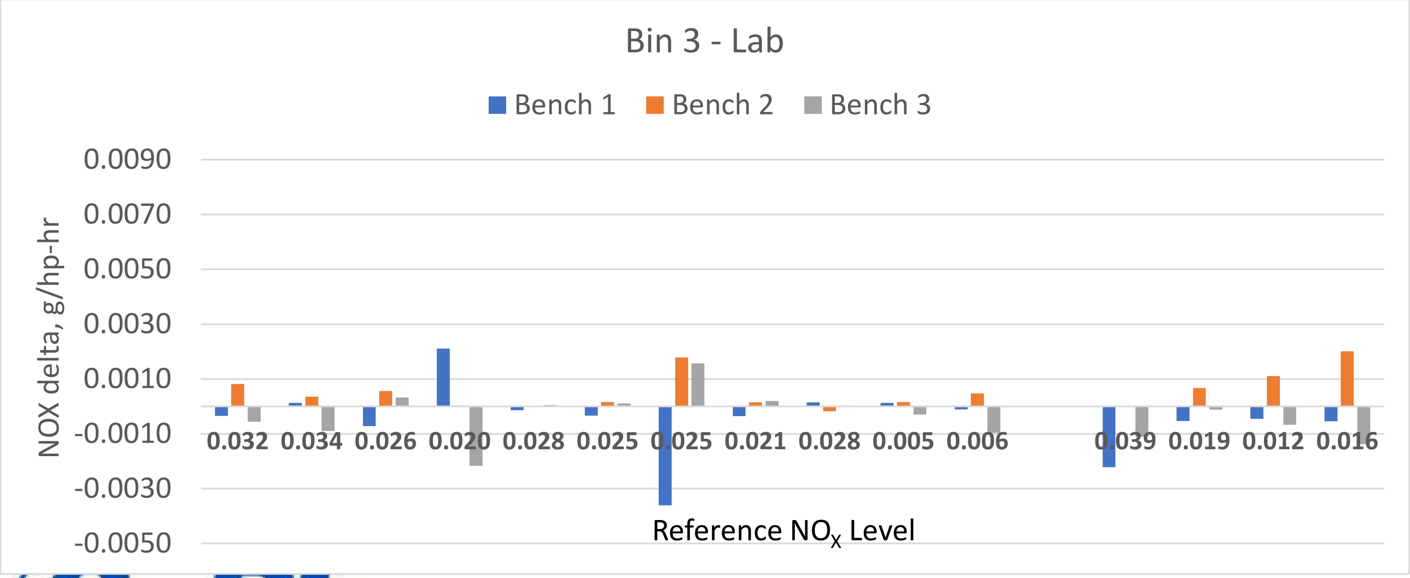
PEMS		PEMS 1				PEMS 2				PEMS 3			
		Reference	PEMS	Delta	% Delta	Reference	PEMS	Delta	% Delta	Reference	PEMS	Delta	% Delta
Bin 1	g/hr	0.80	0.84	**0.0416**	**5.2%**	0.80	0.77	**-0.0233**	**-2.9%**	0.79	0.43	**-0.3529**	**-44.9%**
Bin 2	g/hp-hr	0.0455	0.0497	**0.0042**	**9.2%**	0.0437	0.0465	**0.0028**	**6.5%**	0.0457	0.0402	**-0.0055**	**-12.0%**
Bin 3	g/hp-hr	0.0311	0.0334	**0.0023**	**7.6%**	0.0322	0.0326	**0.0005**	**1.4%**	0.0299	0.0296	**-0.0003**	**-0.9%**
Lab		Raw 1				Raw 2				Raw 3			
		Reference	Bench	Delta	% Delta	Reference	Bench	Delta	% Delta	Reference	Bench	Delta	% Delta
Bin 1	g/hr	0.84	0.79	**-0.0529**	**-6.3%**	0.66	0.65	**-0.0064**	**-1.0%**	0.65	0.61	**-0.0356**	**-5.5%**
Bin 2	g/hp-hr	0.0433	0.0437	**0.0004**	**0.9%**	0.0427	0.0427	**0.0000**	**-0.1%**	0.0408	0.0393	**-0.0015**	**-3.7%**
Bin 3	g/hp-hr	0.0301	0.0302	**0.0001**	**0.4%**	0.0315	0.0318	**0.0003**	**1.1%**	0.0322	0.0313	**-0.0008**	**-2.5%**

PEMS		PEMS 1				PEMS 2				PEMS 3			
		Reference	PEMS	Delta	% Delta	Reference	PEMS	Delta	% Delta	Reference	PEMS	Delta	% Delta
Bin 1	g/hr	0.80	0.84	**0.0416**	**5.2%**	0.80	0.77	**-0.0233**	**-2.9%**	0.79	0.43	**-0.3529**	**-44.9%**
Bin 2	g/hp-hr	0.0328	0.0355	**0.0027**	**8.2%**	0.0337	0.0344	**0.0007**	**2.0%**	0.0319	0.0310	**-0.0009**	**-2.8%**
Lab		Raw 1				Raw 2				Raw 3			
		Reference	Bench	Delta	% Delta	Reference	Bench	Delta	% Delta	Reference	Bench	Delta	% Delta
Bin 1	g/hr	0.84	0.79	**-0.0529**	**-6.3%**	0.66	0.65	**-0.0064**	**-1.0%**	0.65	0.61	**-0.0356**	**-5.5%**
Bin 2	g/hp-hr	0.0317	0.0318	**0.0001**	**0.3%**	0.0329	0.0332	**0.0003**	**0.9%**	0.0331	0.0322	**-0.0009**	**-2.7%**

- Each result is a delta [PEMS – Lab Reference] or [Lab – Lab Reference]
- We will also compare across duty cycles and data files for all 19
  - Note that 5 of them are at a higher NO_X level so we will compare at two NO_X levels
- Both 3B-MAW and 2B-MAW results are shown

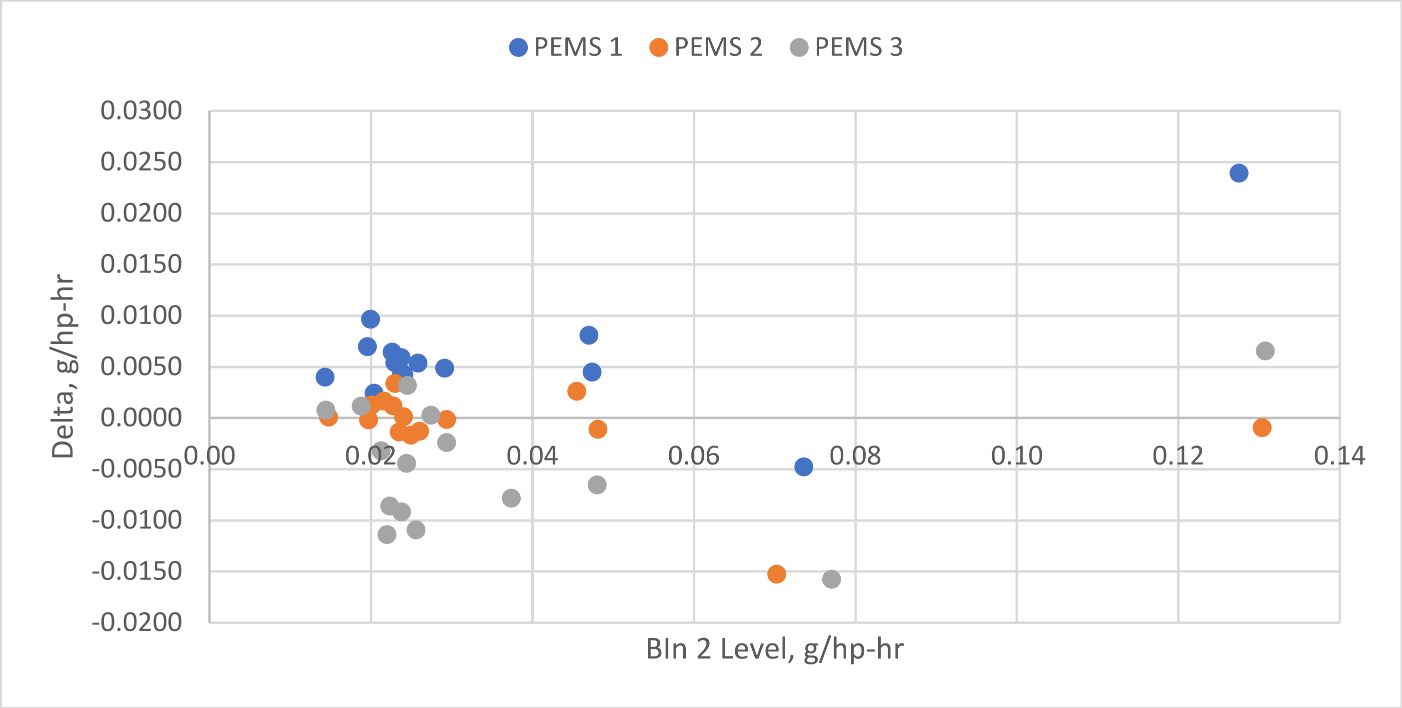
Comparison of NO_X Deltas – PEMS vs Lab, Bin 3





- For Bin 3 note that PEMS deltas are mostly positive
  - This is not true for all bins
- PEMS deltas are generally larger than Lab deltas
  - There is an occasional flier among bench data
- There not a level dependency for these deltas
  - Note that all results are below 0.05 g/hp-hr reference

PEMS Deltas by Level – Bin 2

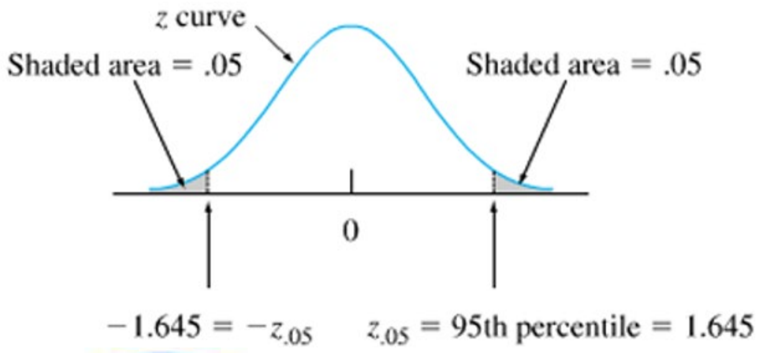


Not enough data > 0.05 g/hp-hr to examine level dependency at higher levels

- Deltas are generally the same below 0.05 g/hp-hr
  - This suggests a minimum absolute accuracy
- PEMS show similar variance in deltas
  - PEMS 3 has slightly higher variance
- Different bias observed for each PEMS (below 0.05 g/hp-hr)
  - PEMS 1 high, PEMS 2 none, PEMS 3 low

Analysis of Collected Deltas for All Runs (2B-MAW Example)

	Bin 1		
SD of PEMS Deltas	0.141065854	0.13533327	0.30959153
Pooled Lab variability	0.021842985		
Incremental SD of PEMS	0.139364483	0.13355889	0.30882001
95th Percentile Incremental Variance	0.229	0.220	0.508
Average Bias	0.059	-0.090	-0.283
Final Value = 95th Percentile+Bias	**0.288**	**0.130**	**0.225**
	Bin 2		
SD of PEMS Deltas	0.001732451	0.00107469	0.00264034
Pooled Lab variability	0.000575709		
Incremental SD of PEMS	0.001633997	0.00090748	0.00257681
95th Percentile Incremental Variance	0.0027	0.0015	0.0042
Average Bias	0.0044	0.0008	0.0003
Final Value = 95th Percentile+Bias	**0.0070**	**0.0023**	**0.0045**



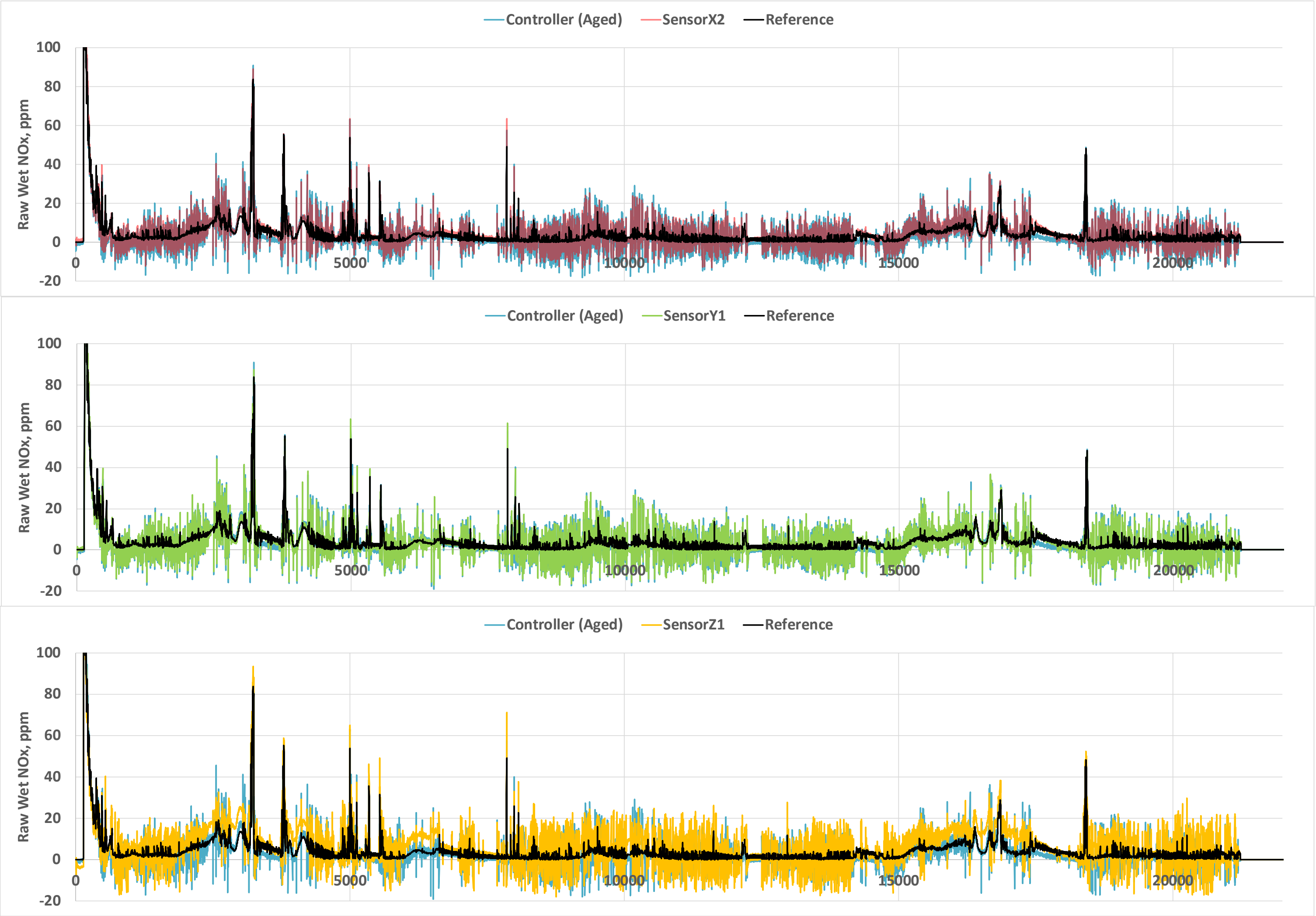
Final Allowance Values
Bin 1 = 0.4 g/hr
Bin 2 = 0.005 g/hp-hr

- Calculations run for each bin and for each of three PEMS
  - Bin 1 units are g/hr
  - Bin 2 units are g/hp-hr
- Pooled standard deviation developed for both PEMS and Lab
- Incremental PEMS variance calculated by subtracting Lab variance from PEMS variance
- Average bias from Reference calculated for each PEMS
- Final values (in bold) are high side risk for each PEMS
- EPA used these values to develop measurement allowance in FRM

Sensor Data and Analysis

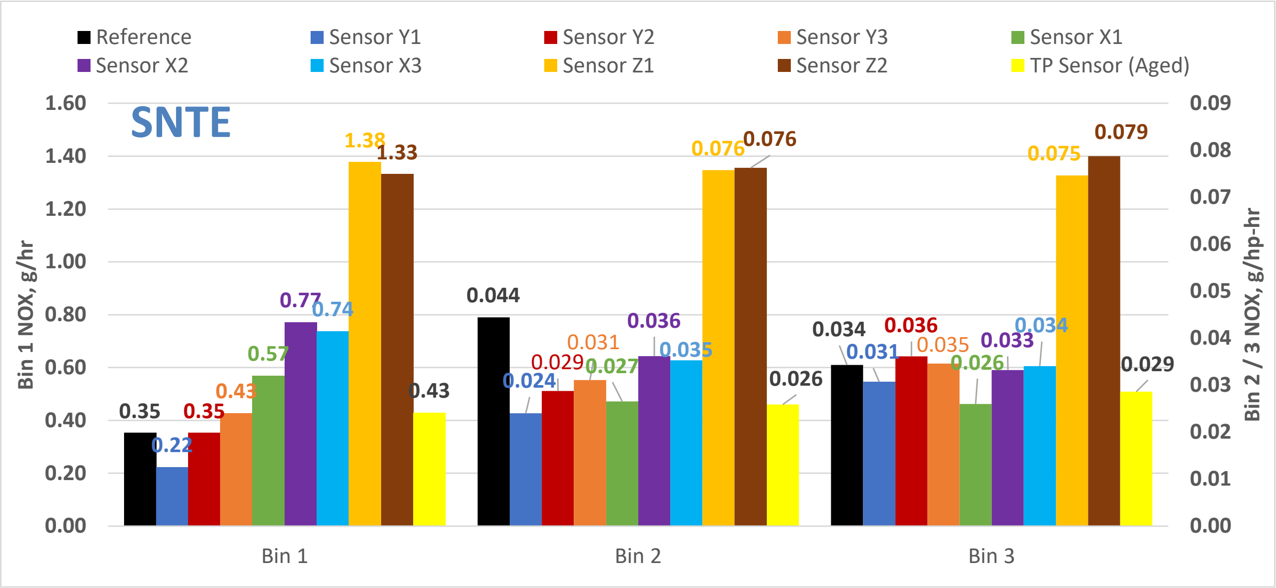
Individual NO_X Sensor Comparisons versus Lab Reference

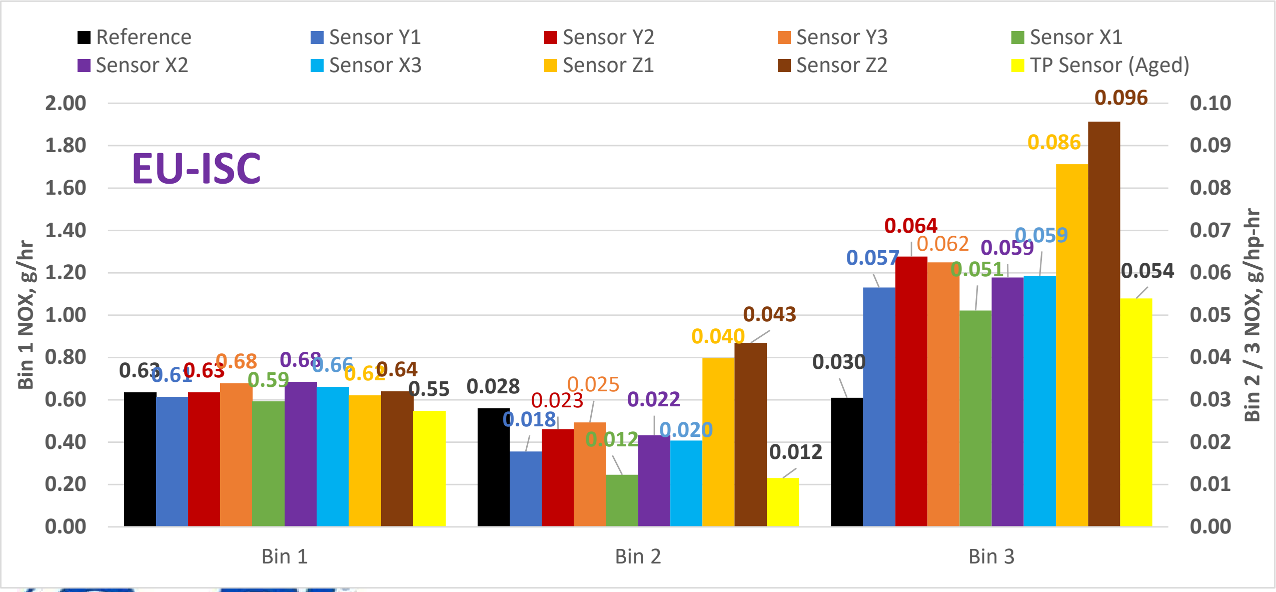
SNTE Full Cycle



- 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…

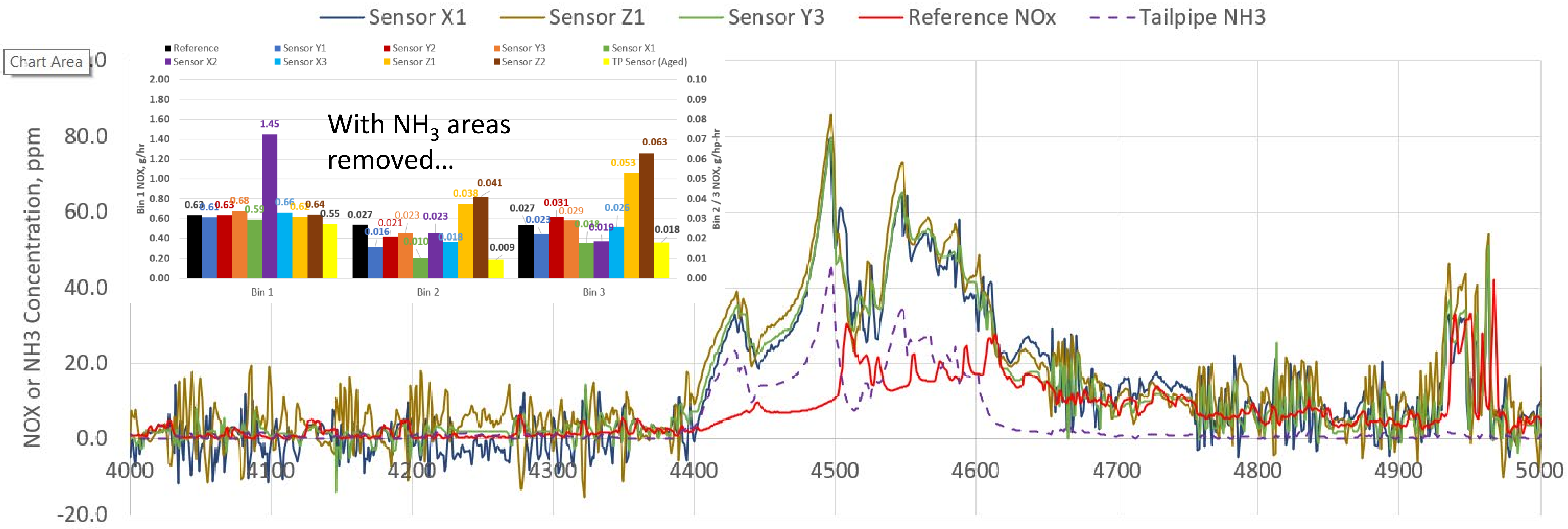
Example 3B-MAW Values for Sensors





- Reference is Lab analyzers and Lab exhaust flow
- All sensors use same engine-based exhaust flow and fuel flow (for CO_2)
- Much larger differences than observed for PEMS
  - Differences by sensor manufacturer
- Note EU-ISC cycle seems to have high bias on Bin 3
  - see next slide…

What Happened on EU-ISC Cycle ?



- On this particular test run and test configuration (after aging) there were a couple of NH_3 breakthrough events at high temperature after aggressive ramps (Bin 3)
- NO_X sensor readings biased high by NH_3 at tailpipe
  - This can happen and must be dealt with…

Analysis of Sensors Compared to PEMS – 2B-MAW Bin 2 (Preliminary)

Bias + 95th Percentile Variance, g/hp-hr			
Sensor Y1	0.017	PEMS 1	0.007
Sensor Y2	0.023	PEMS 2	0.002
Sensor Y3	0.024	PEMS 3	0.005
Sensor X1	0.011		
Sensor X2	0.019		
Sensor X3	0.020		
TP Sensor (aged)	0.013		
Sensor Z1	0.047		
Sensor Z2	0.055		

NONE OF THESE SENSORS ARE AGED EXCEPT THE TP SENSOR

THIS IS A TINY SAMPLE OF PRODUCTION VARIATION FROM ONE BATCH

- Using similar methodology to what was developed for PEMS values used by EPA
- Note that Sensor exhaust flow and fuel flow (CO_2) are fairly close to Reference (and PEMS)
- Even excluding Sensor Z these values are still 2X to 5X PEMS allowance of 0.005 g/hp-hr
  - With Sensor Z as much as 11X
  - Variation even with manufacturers

What Do These Results Indicate About In-Use Measurement ?

- PEMS
  - Current generation PEMS are significantly better than previous evaluations
  - PEMS variation for in-use test articles ~ 0.05 g/hp-hr is about 0.005 mg/hp-hr (10%)
    - EPA Measurement allowance of 5 mg/hp-hr based on this value
    - This appears to be the absolute floor for variation (though at least one PEMS was better in this experiment)
    - More data at higher levels needed to examine level dependency
      - CE-CERT validation data may be able to provide this
- NO_X Sensors
  - Work yet to be done for "compliance level" measurements at Low NO_X levels
    - Can be used to identify significant problems, failures, gross emitters…
  - Variation of current sensors is generally 5X to as much as 10X more
    - NH3 cross sensitivity can make this worse…
  - Impact of sensor aging and batch variability must also be accounted for
- Other Engine Sensor Measurements to support 3B-MAW (Exhaust Flow, CO_2 from Fuel Rate)
  - Relatively close, maybe good enough to support compliance measurements if NO_X can be improved

Acknowledgments

- EPA and EMA for funding of the Field duty cycle and PEMS testing
- CARB, MECA, EPA for funding of Low NO_X test engine development

- PEMS suppliers for providing PEMS equipment
- Sensor suppliers for providing NO_X sensors

- MECA member companies for providing emission control hardware

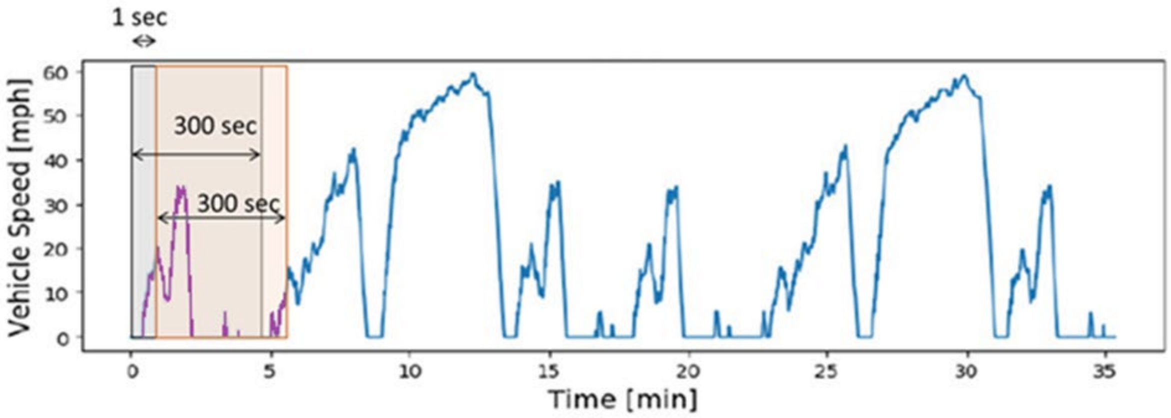
- Cummins for providing the engine and engineering support

- EMTC members for program review, guidance, and program oversight

Appendix – Supporting Slides

U.S. In-Use Compliance - 2B-MAW / 3B-MAW Basics

- Utilized in test runs of nearly any length
  - There are some minimums for number of windows in each bin
  - Still require at least 3 hours of non-idle operation for a valid test day
- The entire data set is utilized including cold-start
- The xB-MAW method uses a <u>fixed-length</u> 300-second average window
- Average window is stepped through the data file in 1-second increments
- Each window is sorted into one of 3 load bins based on "normalized CO_2"
  - NO_X mass (all bins) and CO_2 mass (Bins 2 and 3)
  - <u>For EPA Bins 2 and 3 are combined into a single bin</u>
- A sum-over-sum calculation is done for each bin to generate final numbers (Bin 1 is just NO_X mass rate in g/hr)



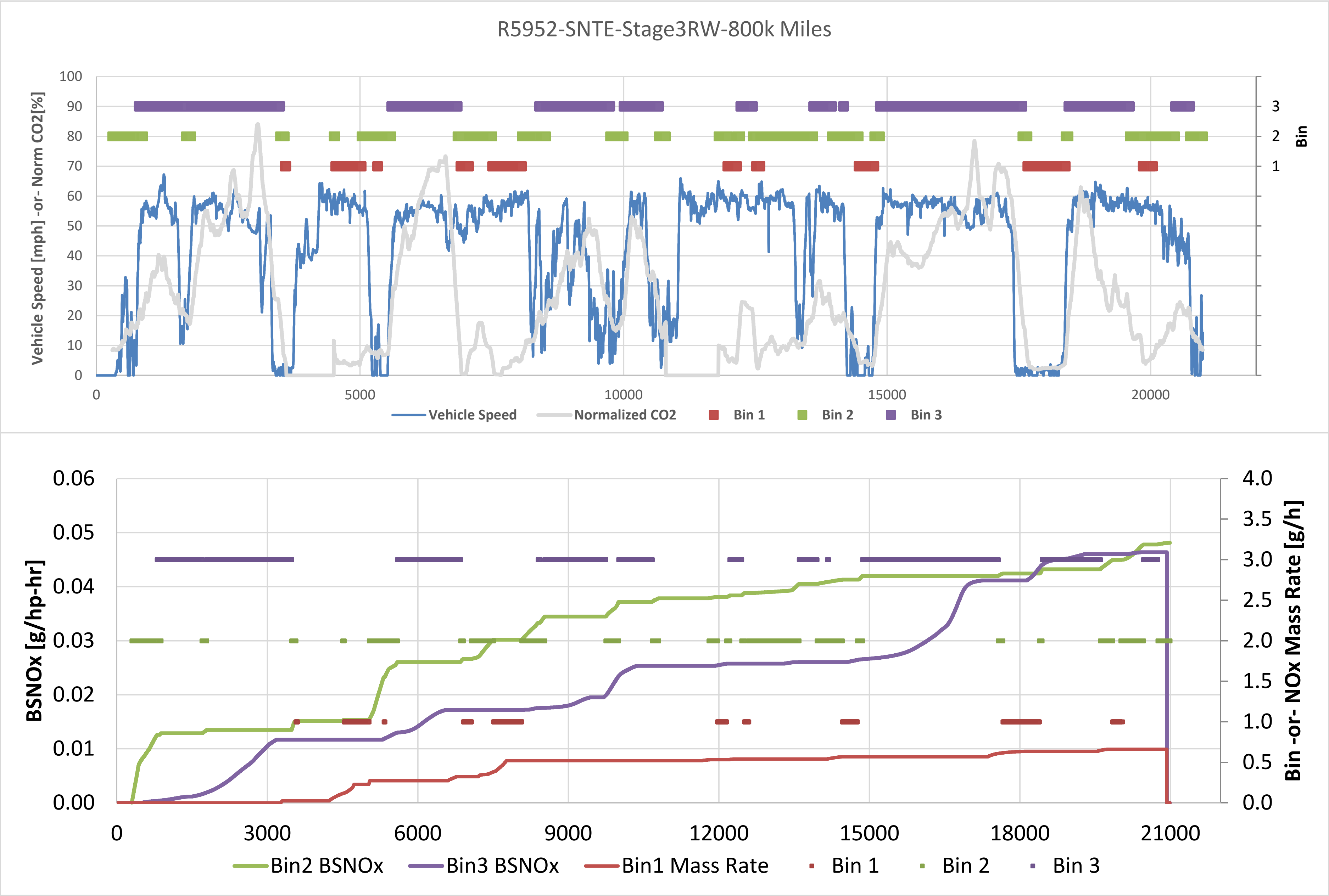
CARB In-Use NO_X Standards

Bin	Normalized CO_2 Range	CARB In-Use Threshold	
		2024-2029	2030+
1 – Idle	< 6%	≤ 2 x Idle Standard	≤ 1.5 x Idle Standard
2 - Low Load	6% to 20%	≤ 2 x LLC Standard	≤ 1.5 x LLC Standard
3 - Mid-High Load	> 20%	≤ 2 x FTP Standard	≤ 1.5 x FTP Standard

EPA In-Use Standards

Off-Cycle Bin	NO_X	Temperature adjustment [a]	HC mg/hp·hr	PM mg/hp·hr	CO g/hp·hr
Bin 1	10.0 g/hr	$(25.0 - \bar{T}_{amb}) \cdot 0.25$	—	—	—
Bin 2	58 mg/hp·hr	$(25.0 - \bar{T}_{amb}) \cdot 2.2$	120	7.5	9

Example of 3B-MAW Window Sorting and Bin Value Accumulation



EPA now combines Bin 2 (green) and Bin 3 (purple) in one bin