An Update on the Examination of In-Use Measurement Variation with PEMS at Low NO_x Levels

SOUTHWEST RESEARCH INSTITUTE®

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Background

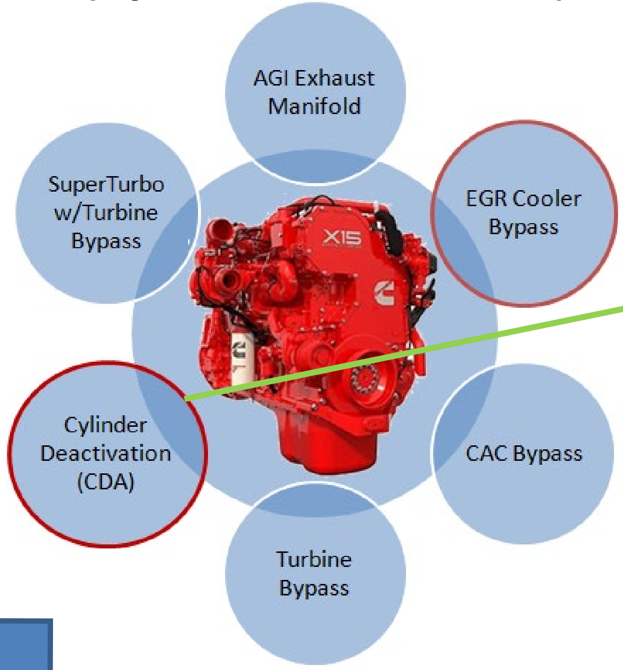
- Low NO_X levels (MY 2027 and beyond) will present new challenges to PEMS
  - Lower levels < 50 mg/hp-hr
  - 2B-MAW analysis method
- PEMS equipment have evolved (and improved) since original Measurement Allowance in 2006
- Objective: Update assessment of PEMS Measurement error and variations
  - Provide information for update of PEMS Accuracy Margins
  - Use a Monte Carlo Model based approach

EPA Stage 3RW Low NO_X Demonstration Engine

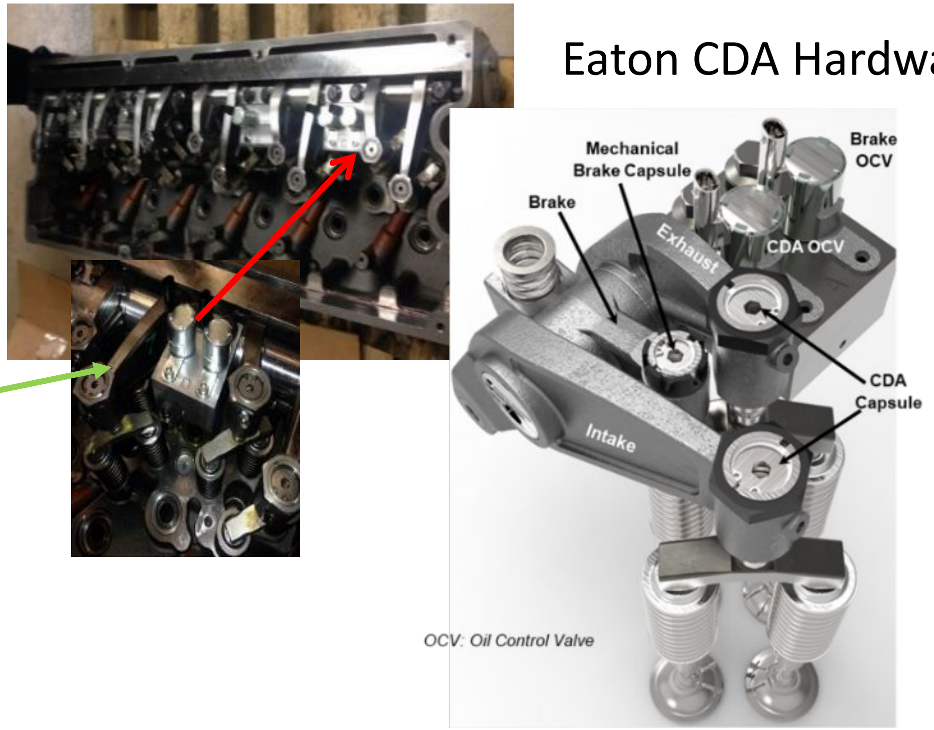
2017 Cummins X15 Engine

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

Additional Engine Hardware (Cylinder Deactivation)

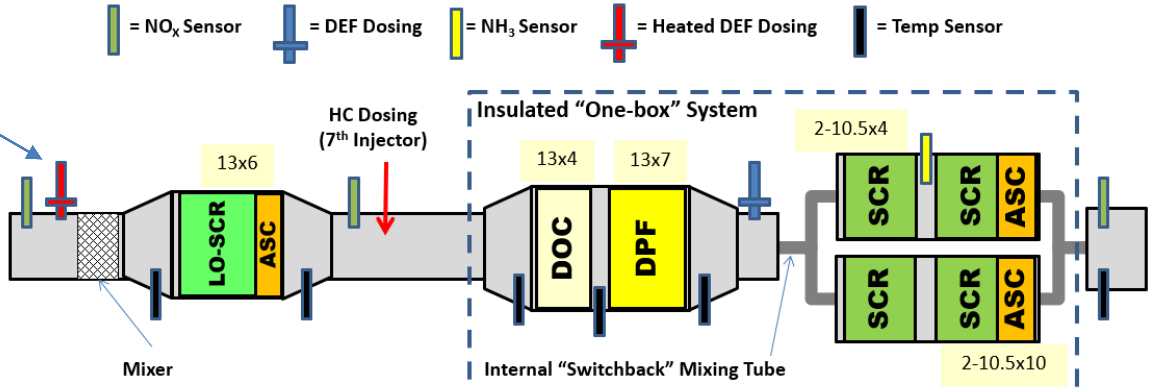


Eaton CDA Hardware



Advanced Low NO_X Aftertreatment (Dual SCR-Dual Dosing)

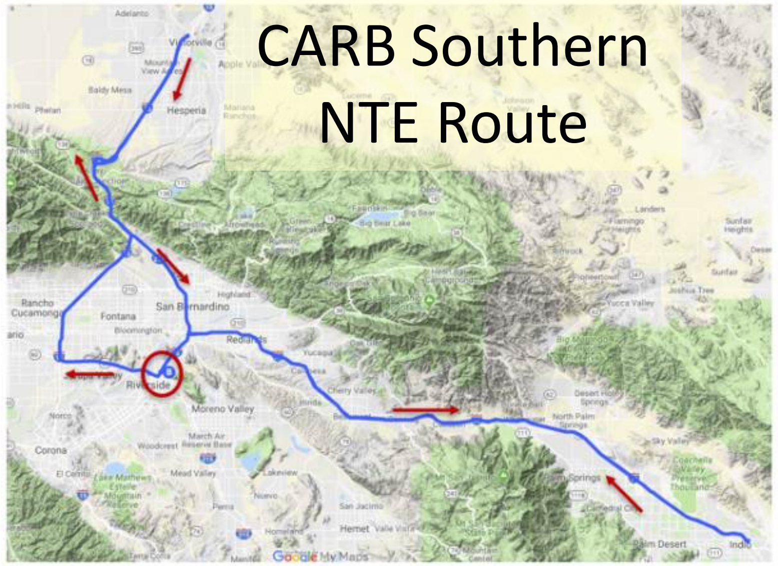
Heated Doser (Forvia)

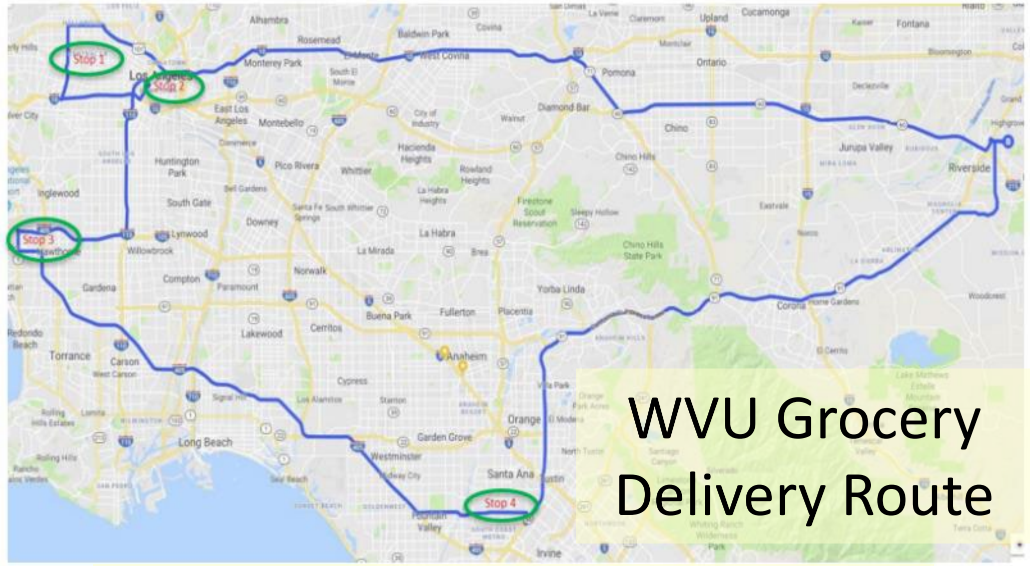


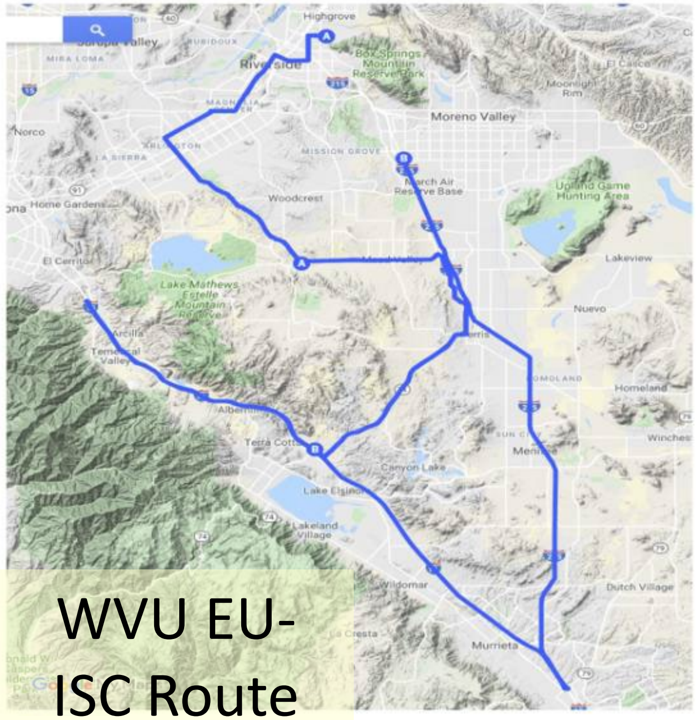
Development Targets:
- FTP/RMC NO_X 0.02 g/hp-hr at 435k miles
- Lowest feasible LLC and in-use NO_X
- No adverse GHG impact

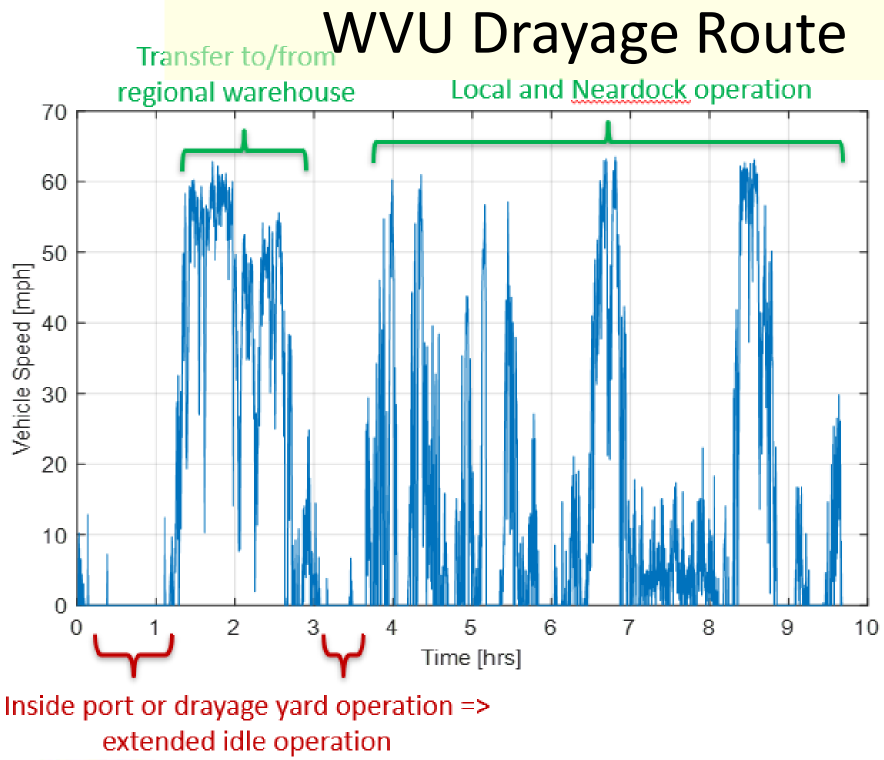
EPA Updates
- Changed zCSF to DOC+DPF
- Improved downstream DEF mixing

Real-World Duty Cycles

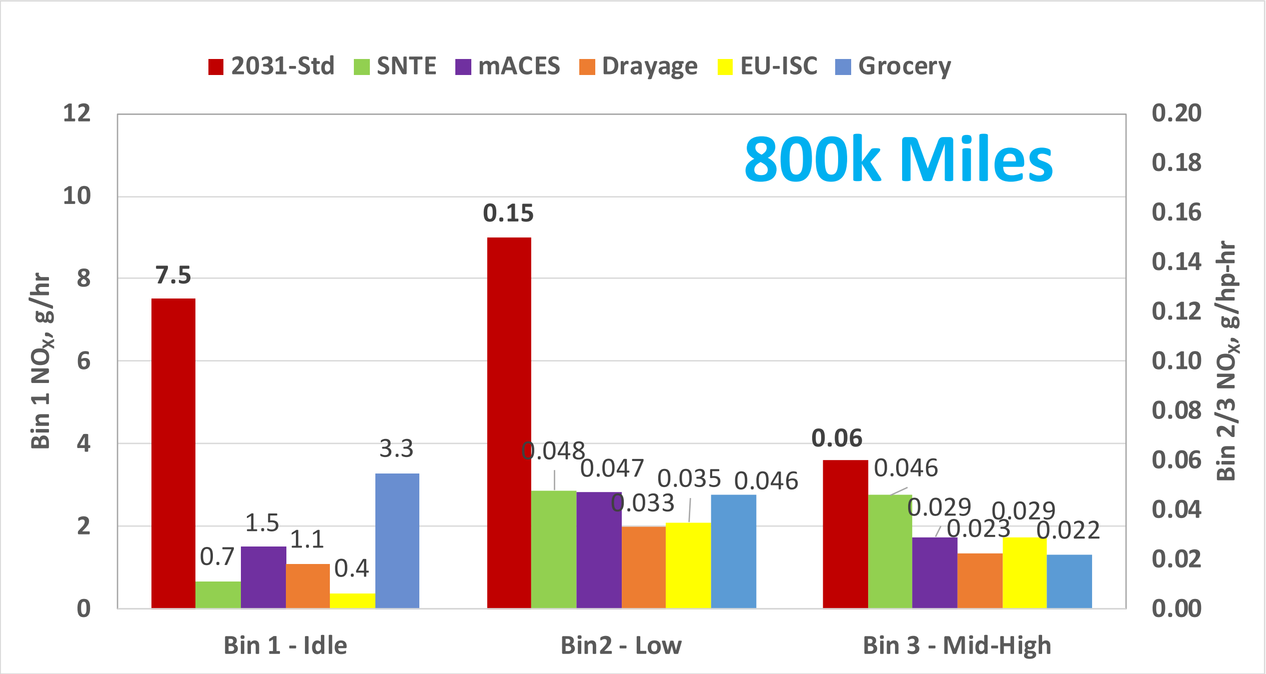




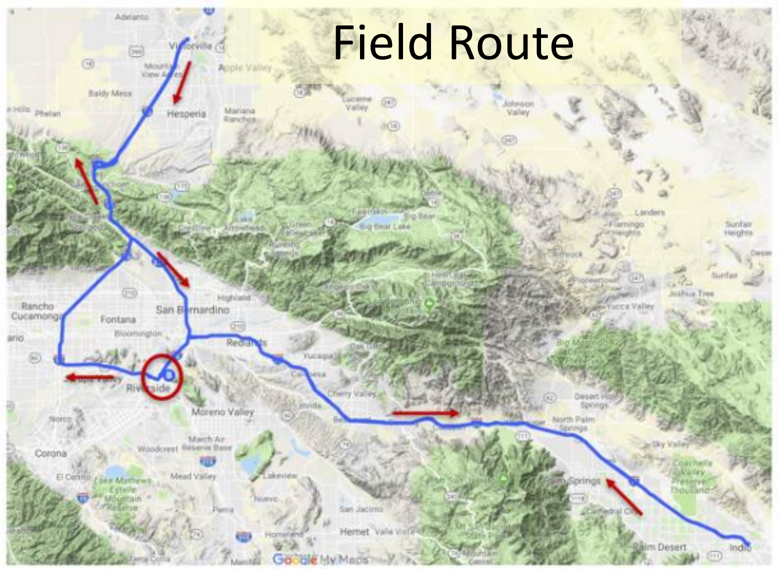




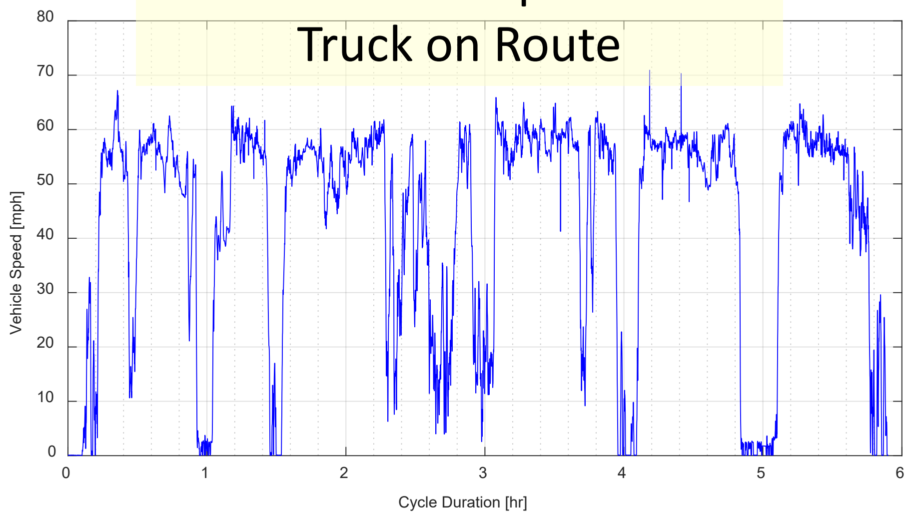
- Each of these cycles is a real working route that was driven with multiple actual Class 7 and Class 8 trucks
- Cycles represented a wide variety of different kinds of vehicle operations
- Recorded Vehicle Data was used to develop speed/load profiles that could be translated for Laboratory use



Cycle Translation Process Example – CARB Southern Route

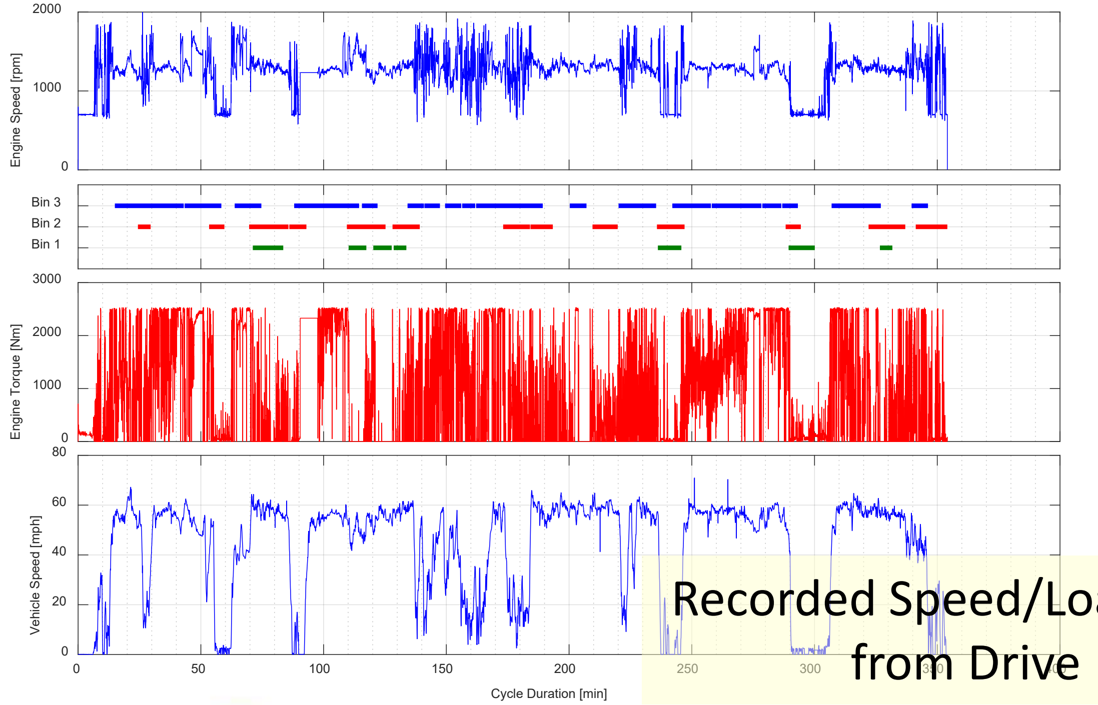


Field Route

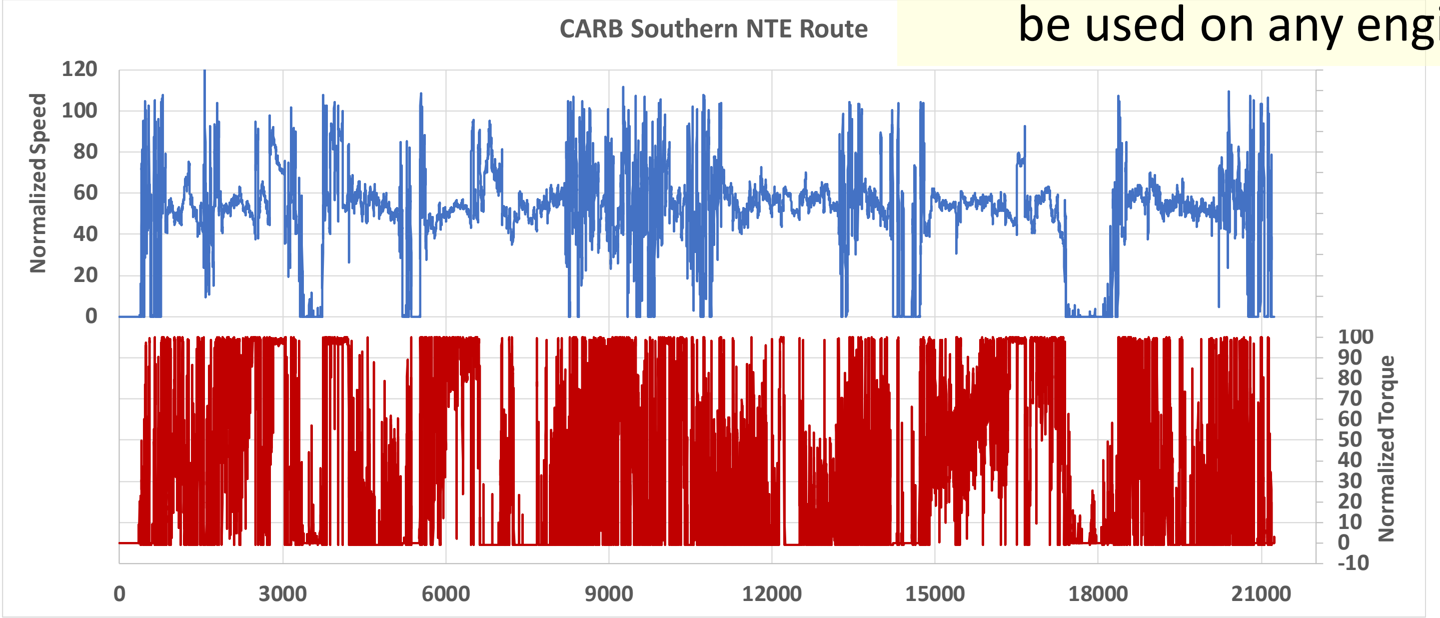


Actual Vehicle Speed from Truck on Route

- 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



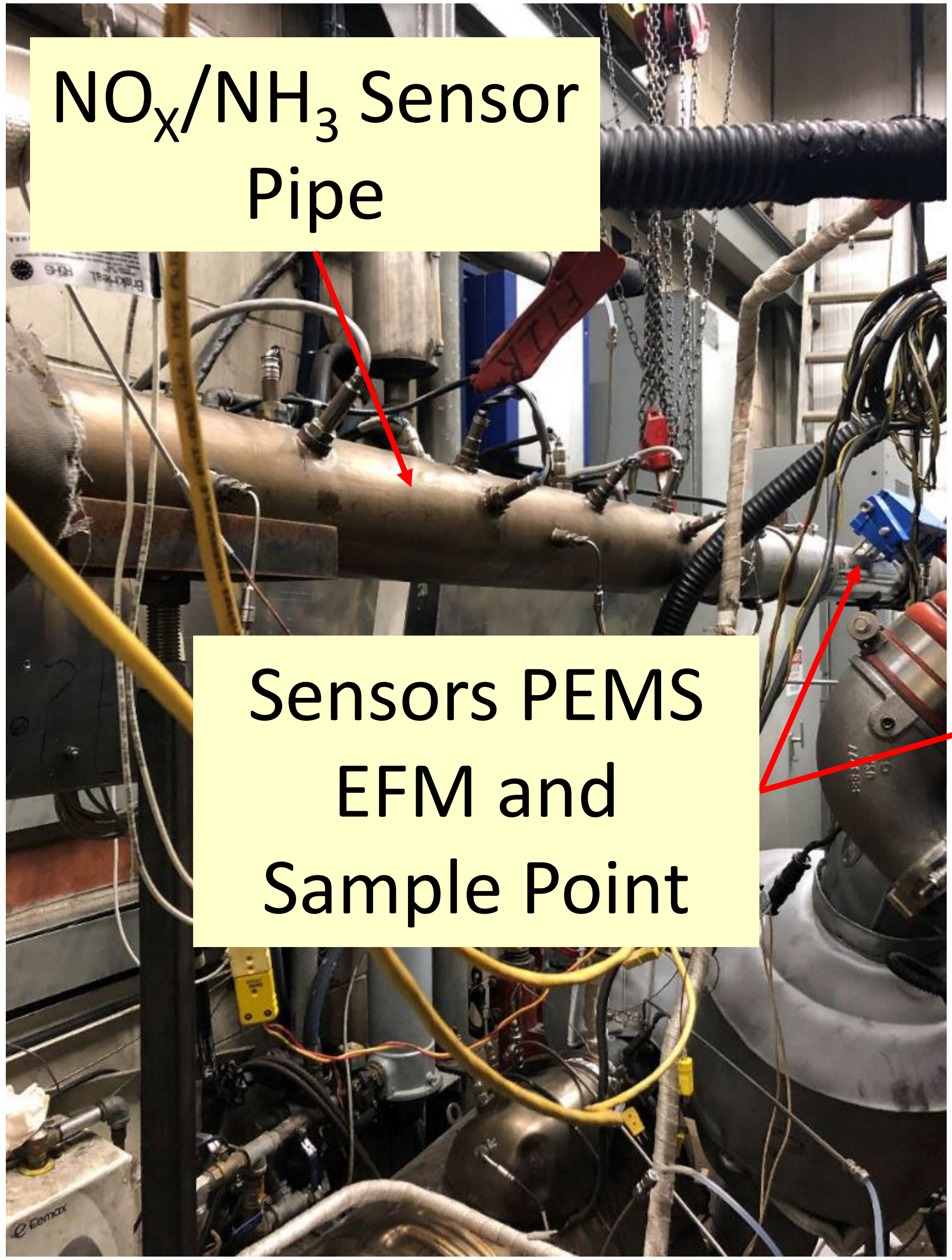
Normalized Engine Cycle (can be used on any engine)

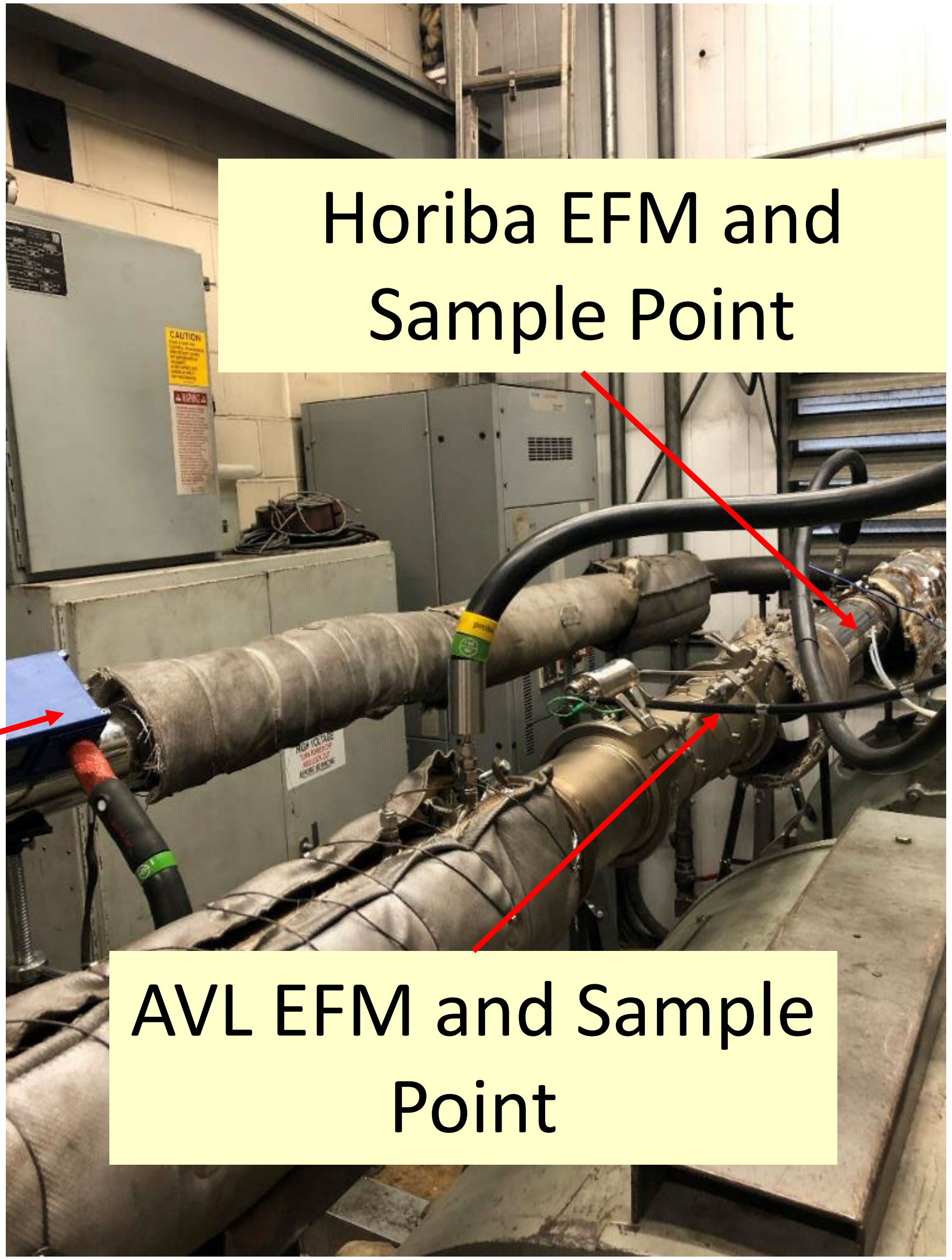
Input Data Source for Model Calibration

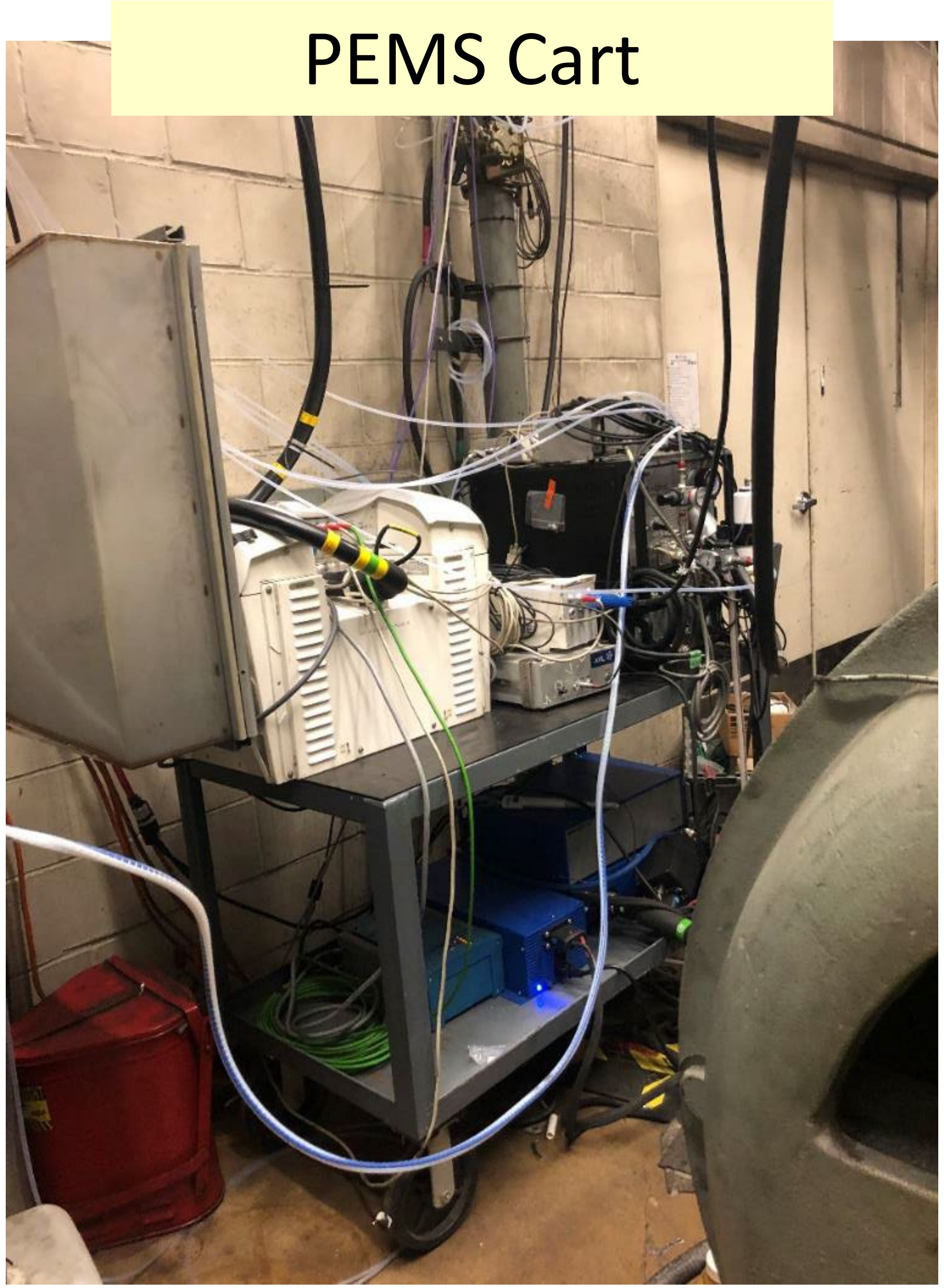
- Parallel data with Lab and PEMS taken on 19 different field cycle runs
  - 5 duty cycles
  - 3 test configurations
  - repeat cycles
  - ~ 130 hours of driving with Reference measurements to compare

- 3 different PEMS from 3 different manufacturers
- 3 different Raw Lab emissions benches to characterize Lab variability
  - Note only 1 Raw Lab exhaust flow measurement
- *10 NO_X sensors from 3 different manufacturers (not used in PEMS model but available for other work…)*

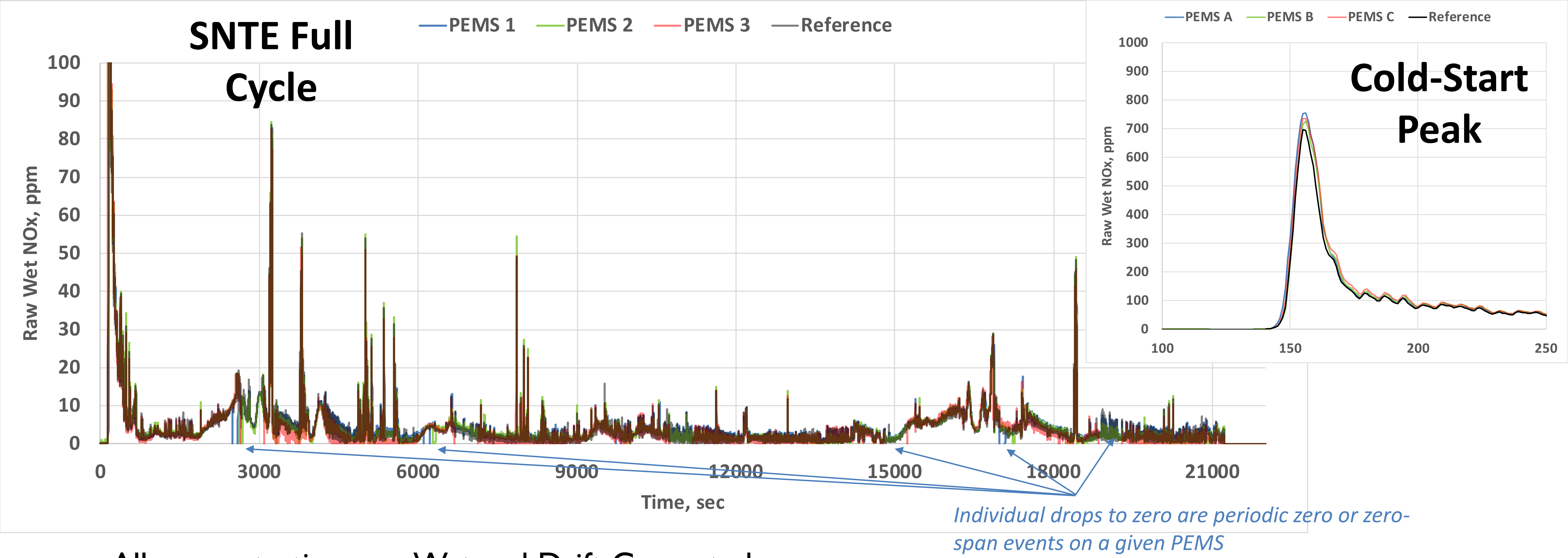
PEMS and Sensor Installation (Lab Reference Upstream)







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 could be used to run a Monte Carlo simulation
  - Model can be run on any set of "Reference" data (a set of NO_X/CO_2/EFM traces)
  - Separate model for each PEMS (or Lab Bench)
  - Model validation against data from CE-CERT in-use experiment
    - PEMS compared to CE-CERT Mobile Emission Laboratory (MEL) Reference

- 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 Analysis from PEMS Experiment Data

	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**

Using these data EPA determined the final PEMS NO_X Accuracy Margins included in HD 2027 FRM

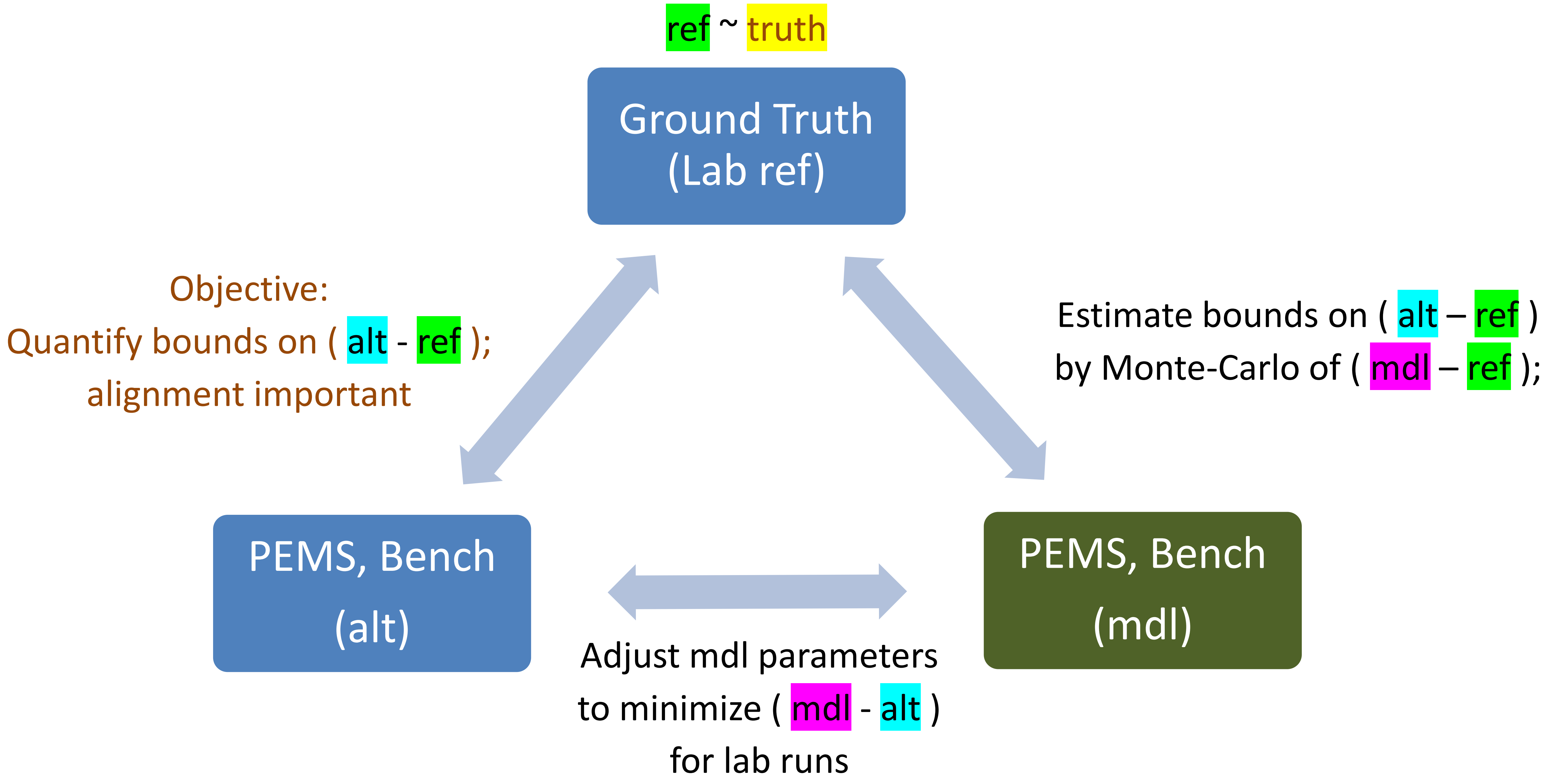
Bin 1 = 0.4 g/hr

Bin 2 = 0.005 g/hp-hr (5 mg/hp-hr)

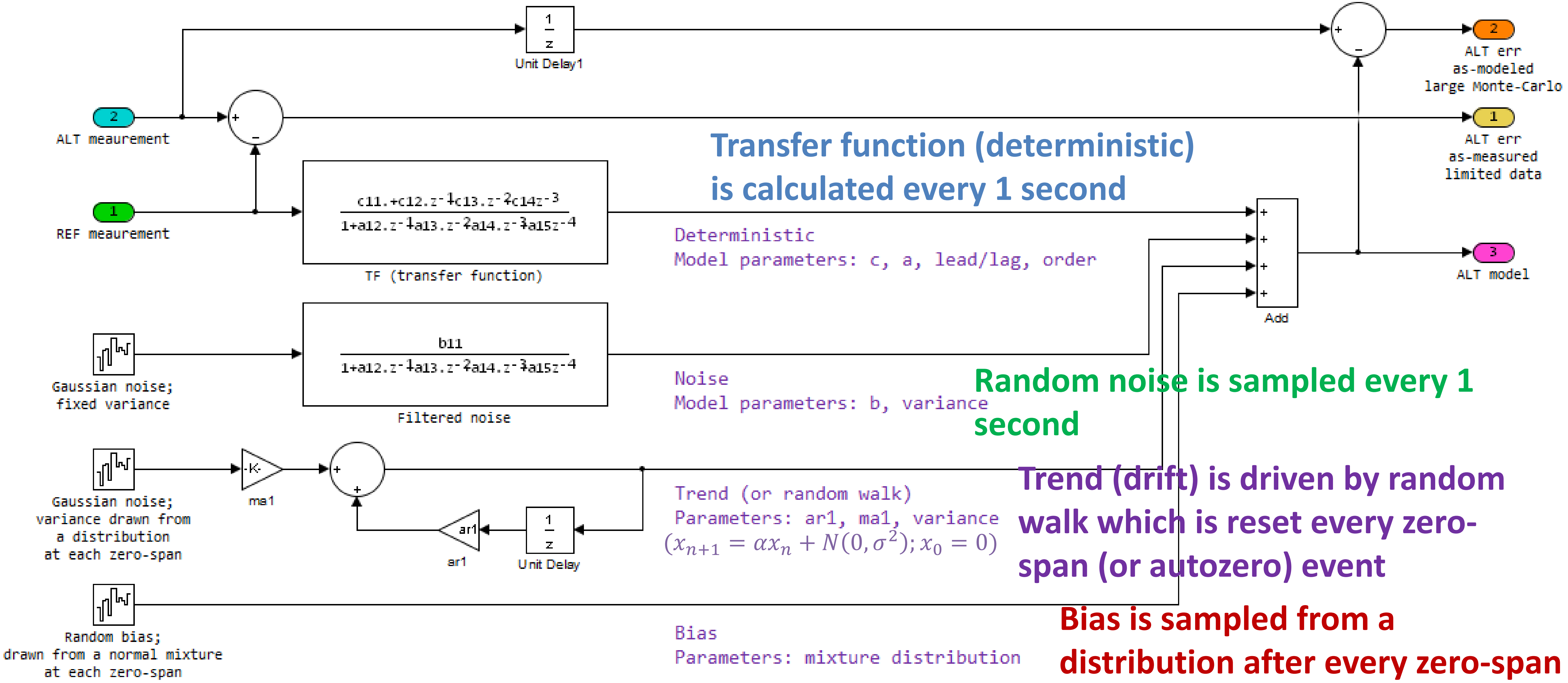
(40 CFR 1036.420(a) Table 1)

- 2b-MAW data generated for all PEMS and Raw Lab benches for each of the 19 duty cycles
- Difference (delta) between Raw Reference results and PEMS (or bench) result calculated
- Bias and variability of these deltas was determined for each PEMS and Lab bench
- Pooled Lab variation subtracted from each PEMS
- High side risk based on 95th percentile of deltas and average bias for each PEMS
  - across the 19 results

Model: Structure/Parameters/"Calibration"



Model – Structure and Parameters



Transfer function (deterministic) is calculated every 1 second

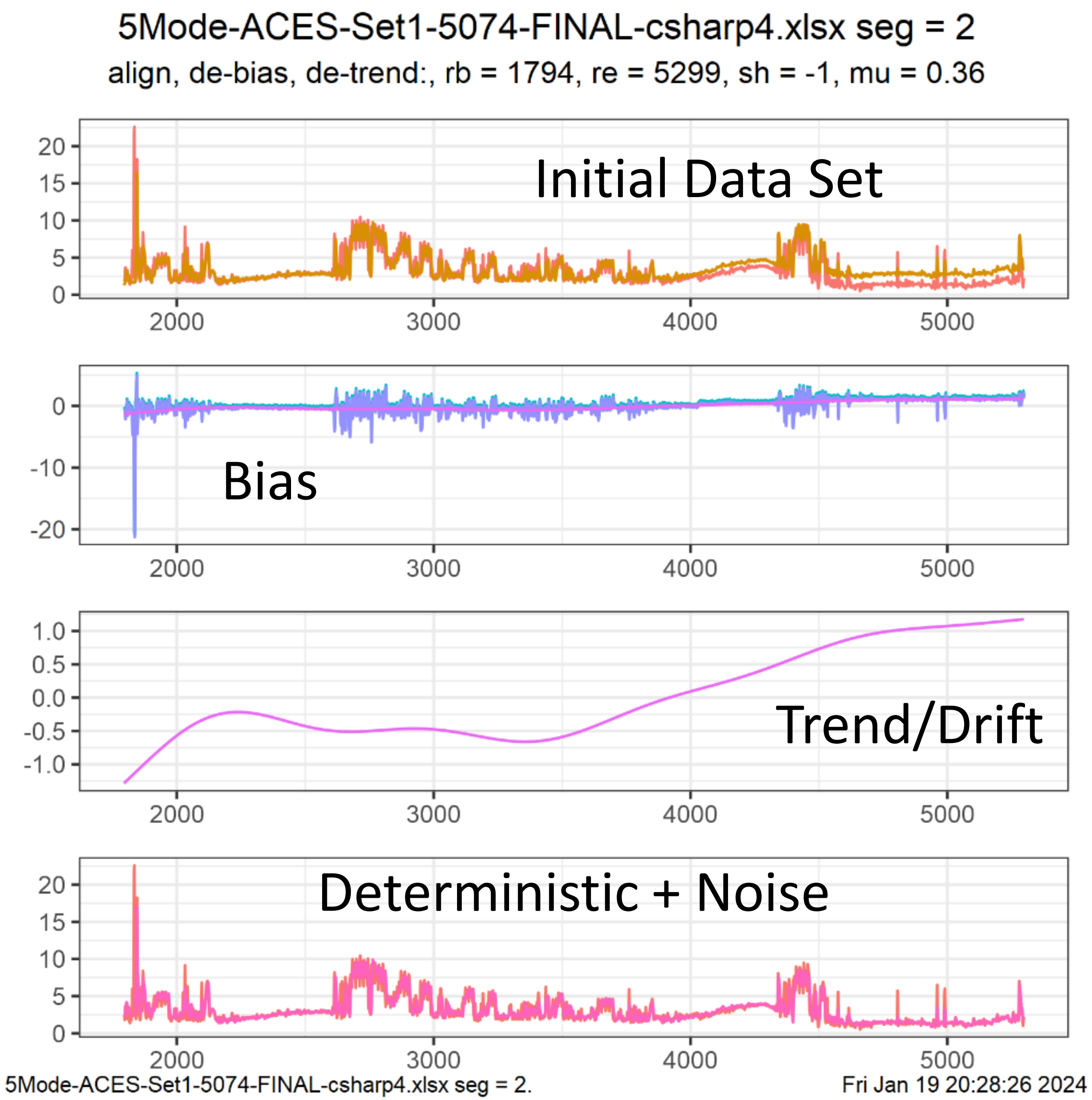
Random noise is sampled every 1 second

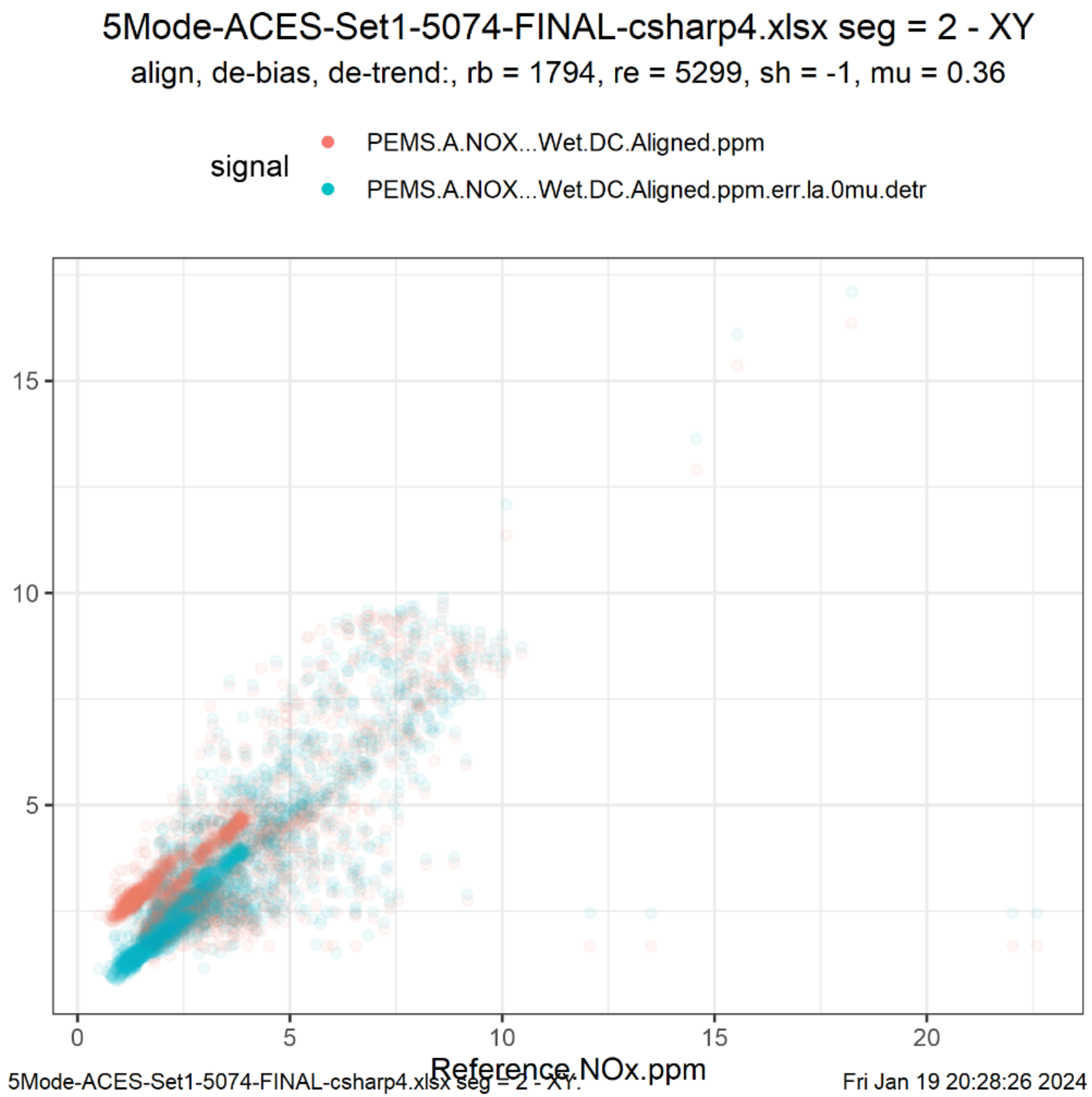
Trend (drift) is driven by random walk which is reset every zero-span (or autozero) event

Bias is sampled from a distribution after every zero-span (or autozero) event

Each of these functions is calibrated for NO_X, CO_2, Exhaust Flow separately for each PEMS (or Bench)

Remove Bias, Align Locally, Remove Drift – Per Segment





Structure of the Transfer Function (TF)

The Transfer Function is an ARMA model (auto-regressive moving average) that depends on both the Reference data and the Model's own running result

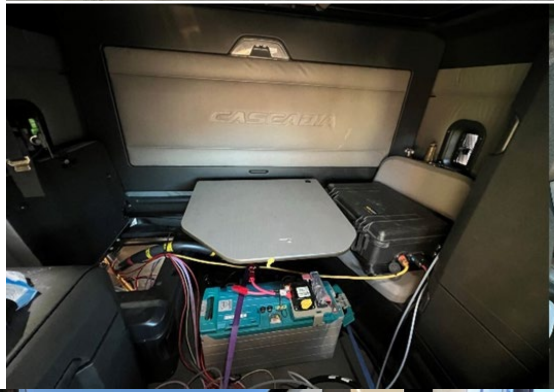
- For our model alt = TF*ref, we assume the following
- The value of alt x_t at time t depends on m future and q past values of ref $r_{t+m}, \dots, r_t, \dots, r_{t-q}$
  - This is the moving average (MA) part of the model
- The value of alt x_t at time t also depends its own p past values $x_{t-1}, \dots, x_{t-p}$
  - This is the auto-regressive (AR) part of the model
- Additionally, the value of alt x_t at time t also depends a random number ϵ_t
- $x_t = a_1 x_{t-1} + \cdots + a_p x_{t-p} + c_0 r_{t+m} + c_1 r_{t+m-1} + \cdots + c_{m+q} r_{t-q} + b_1 \epsilon_t$
  - $\epsilon_t \sim N(0, \sigma_t^2)$ **Noise Term**

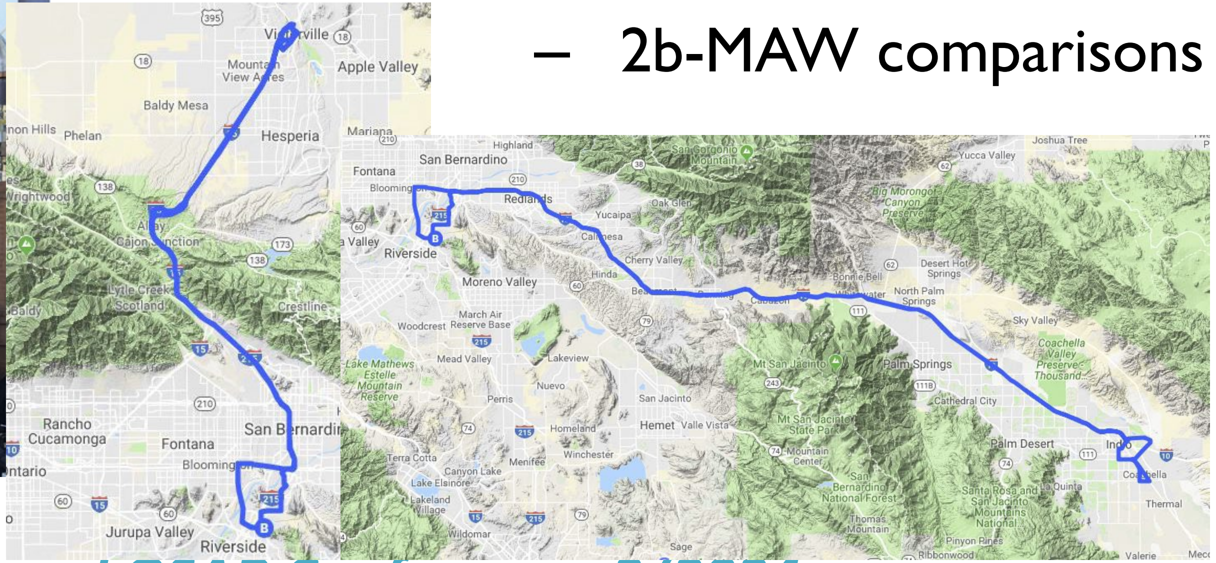
Transfer Function

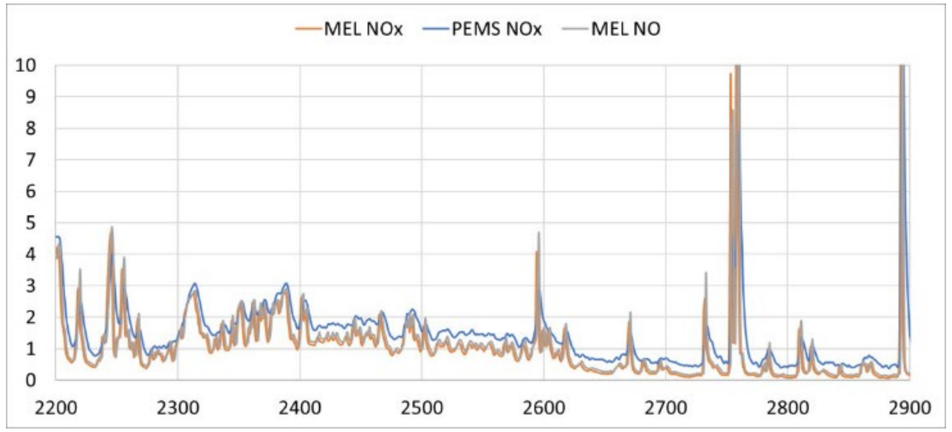
- Choosing TF model means choosing the order (m, q, p) and the corresponding coefficients to minimize the unexplained variance σ_t^2

CE-CERT Validation Data Experiment

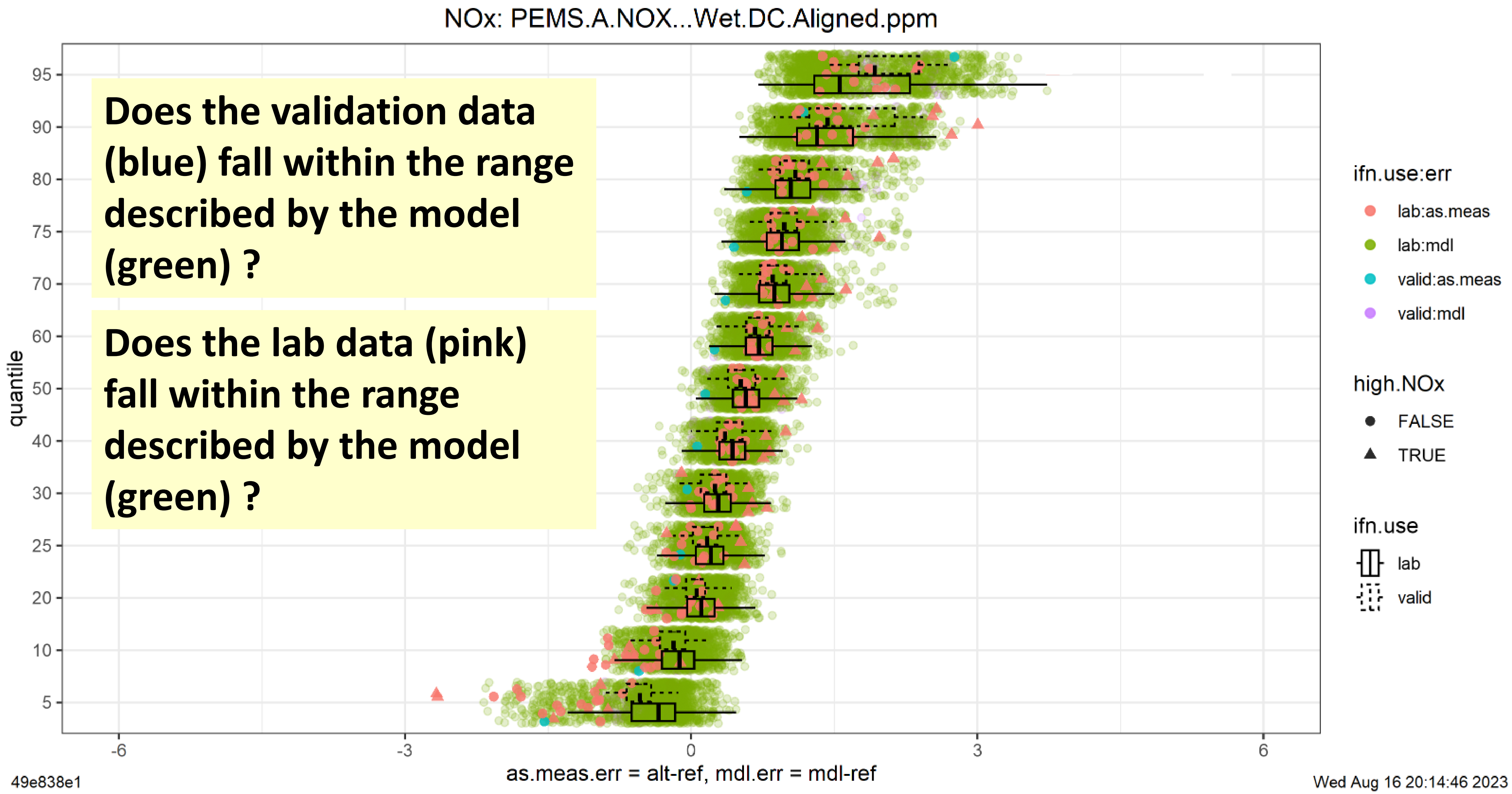
- Used CE-CERT MEL is Reference
- 2019MY Freightliner Truck
  - 2019 DD15 – 505hp
- Three sets of drives (four routes) – one set for each type of PEMS
  - Same three PEMS models but a different example from the one SwRI used in each case
- Deltas generated for NO_X/CO_2/EFM to compare to SwRI model
  - 2b-MAW comparisons also possible







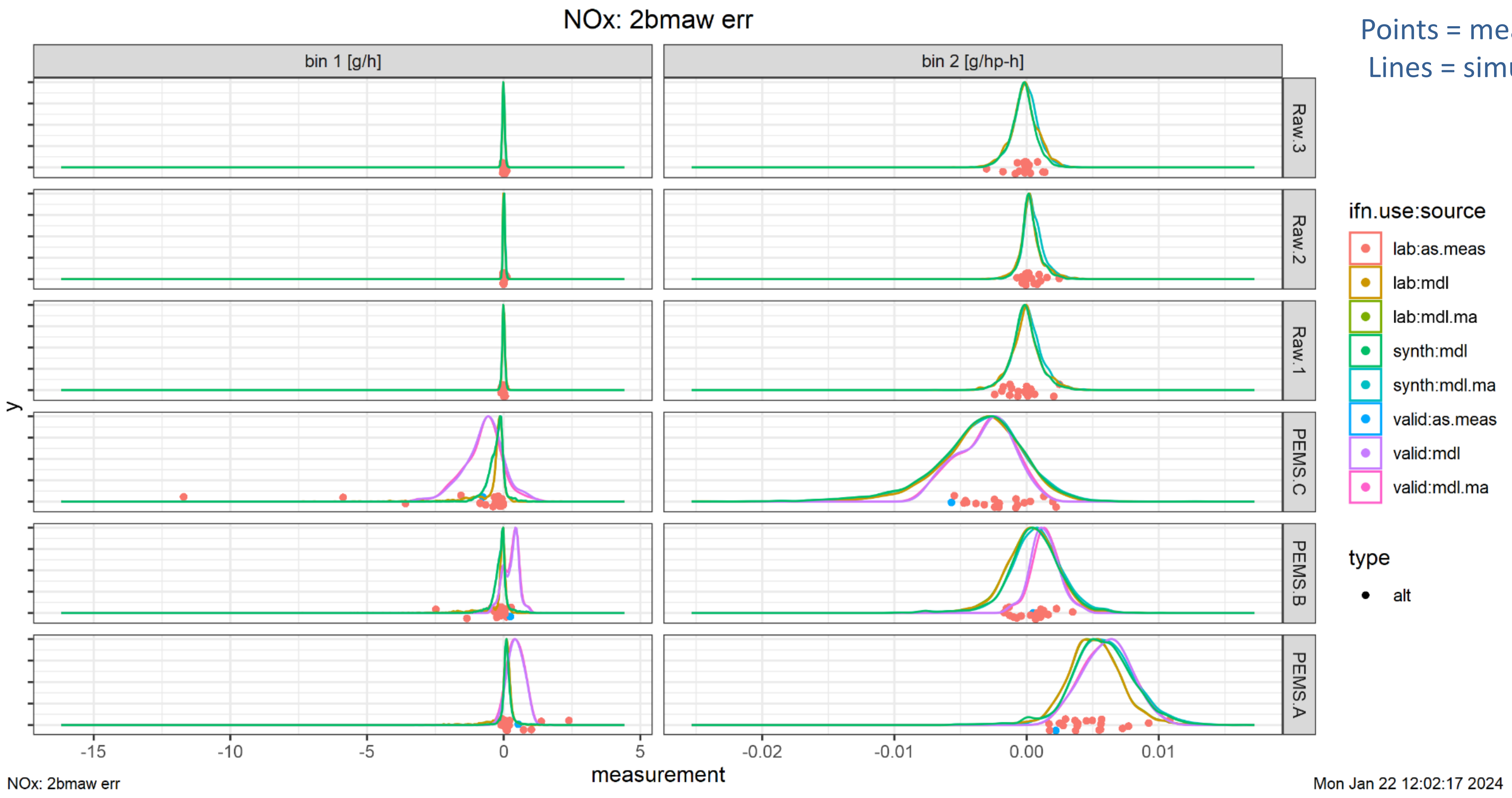
Validation Analysis Example – PEMS A NO_x



Does the validation data (blue) fall within the range described by the model (green) ?

Does the lab data (pink) fall within the range described by the model (green) ?

Dist of 2bmaw Bin-value Err wrt Reference



Points = measured
Lines = simulated

Measurement Delta: Monte Carlo Model Run

- **Models built from SwRI lab data**
- **Models validated using CE-CERT field data**
- **Measurement delta constructed from "third-party reference runs"**

Ground Truth
(36 ref runs)

Bench Model
(alt mdl 1,2,3)

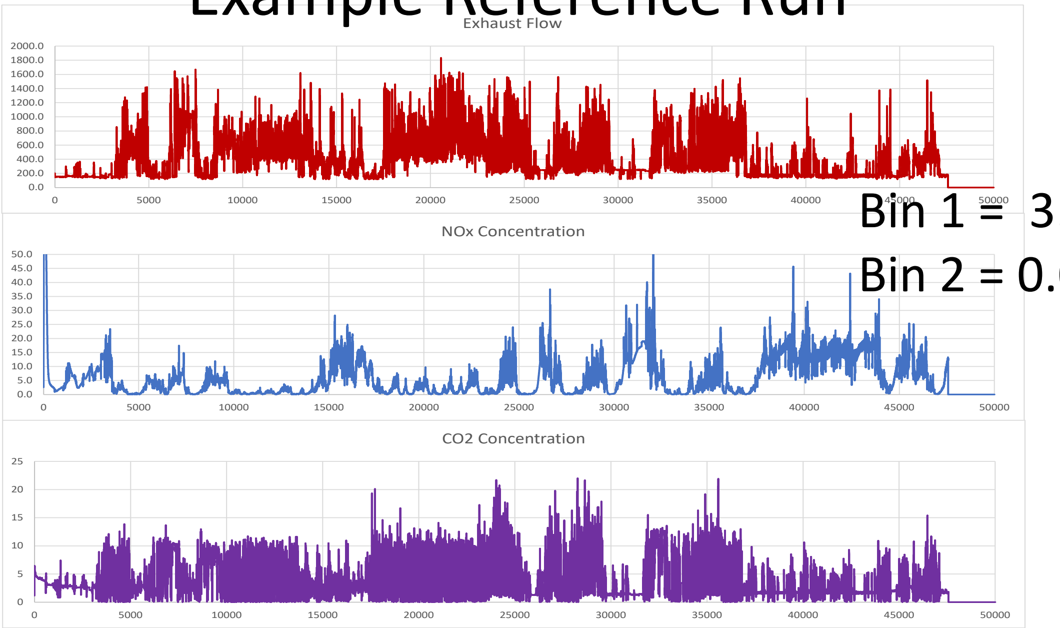
PEMS Model
(alt mdl A, B, C)

Monte-Carlo
36 runs * 401 real * 3 bench = 43308
err = bench mdl – ref; by bin

Measurement delta

Monte-Carlo
36 runs * 401 real * 3 PEMS = 43308
err = PEMS mdl – ref; by bin

Example Reference Run

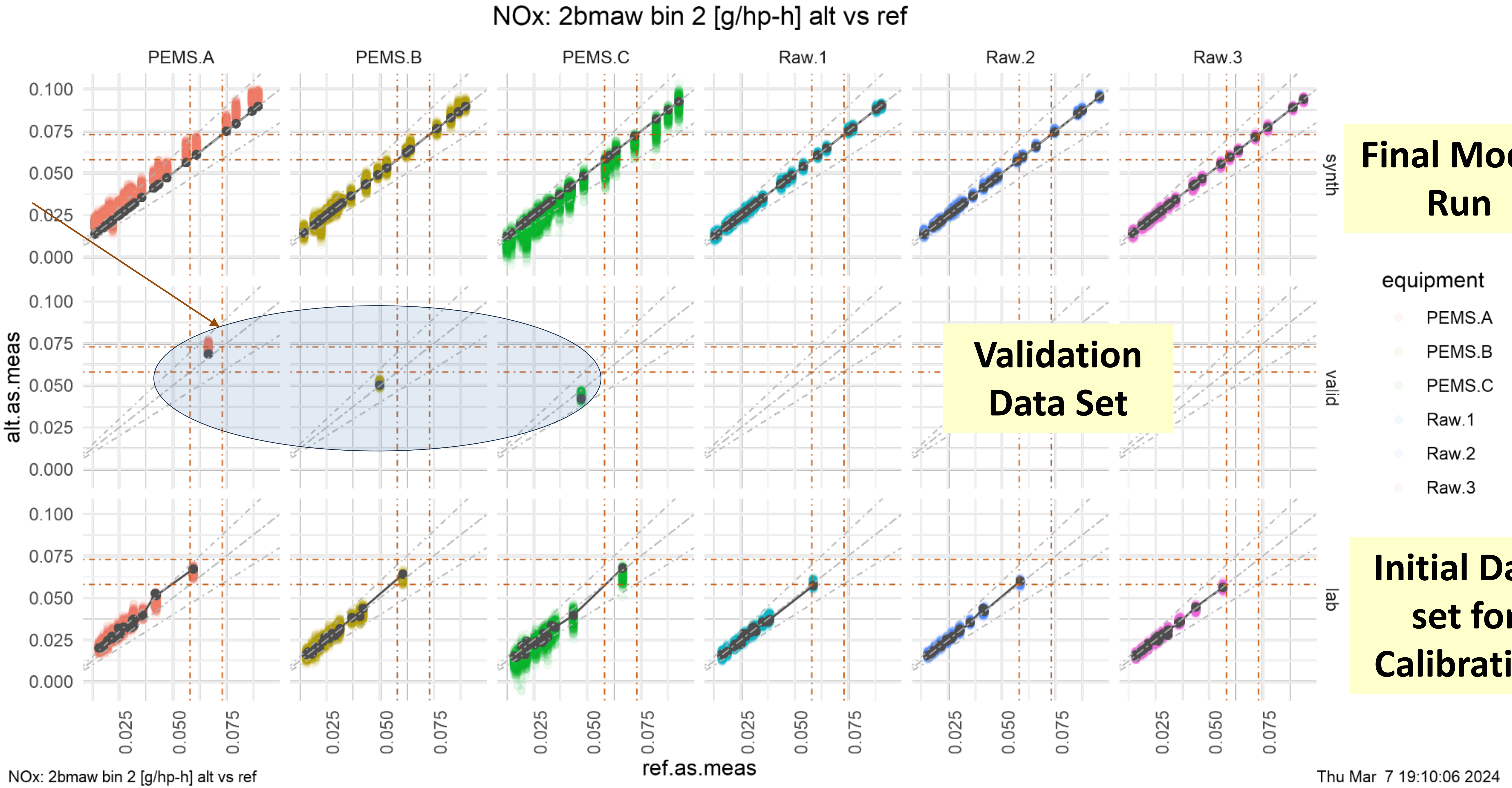


Bin 1 = 3.1 g/hr
Bin 2 = 0.027 g/hp-hr

36 Different "Reference" Runs
- **Supplied by EPA/WVU/Manufacturers**
- **30k-45k secs long (full days)**
- **NO_X data scaled (via SwRI model to Low NO_X)**

Comparing 2bmaw Bin-2 [g/hp-h]: alt vs ref

Note consistency of bias between SwRI and CE-CERT same-label equipment



Final Model Run

Validation Data Set

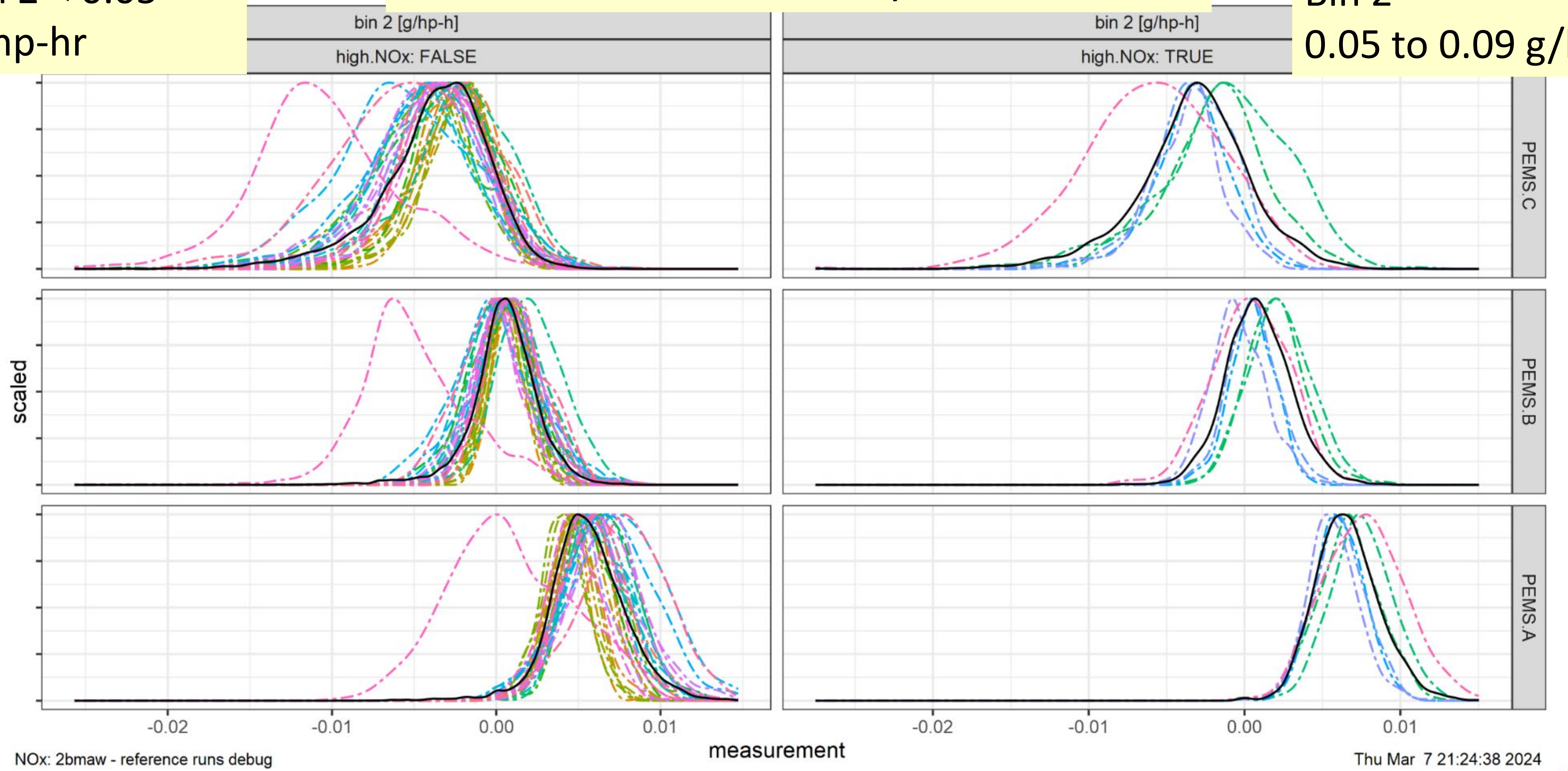
Initial Data set for Calibration

Comparing 2bmaw Bin-2 [g/hp-h]: Measurement Deltas

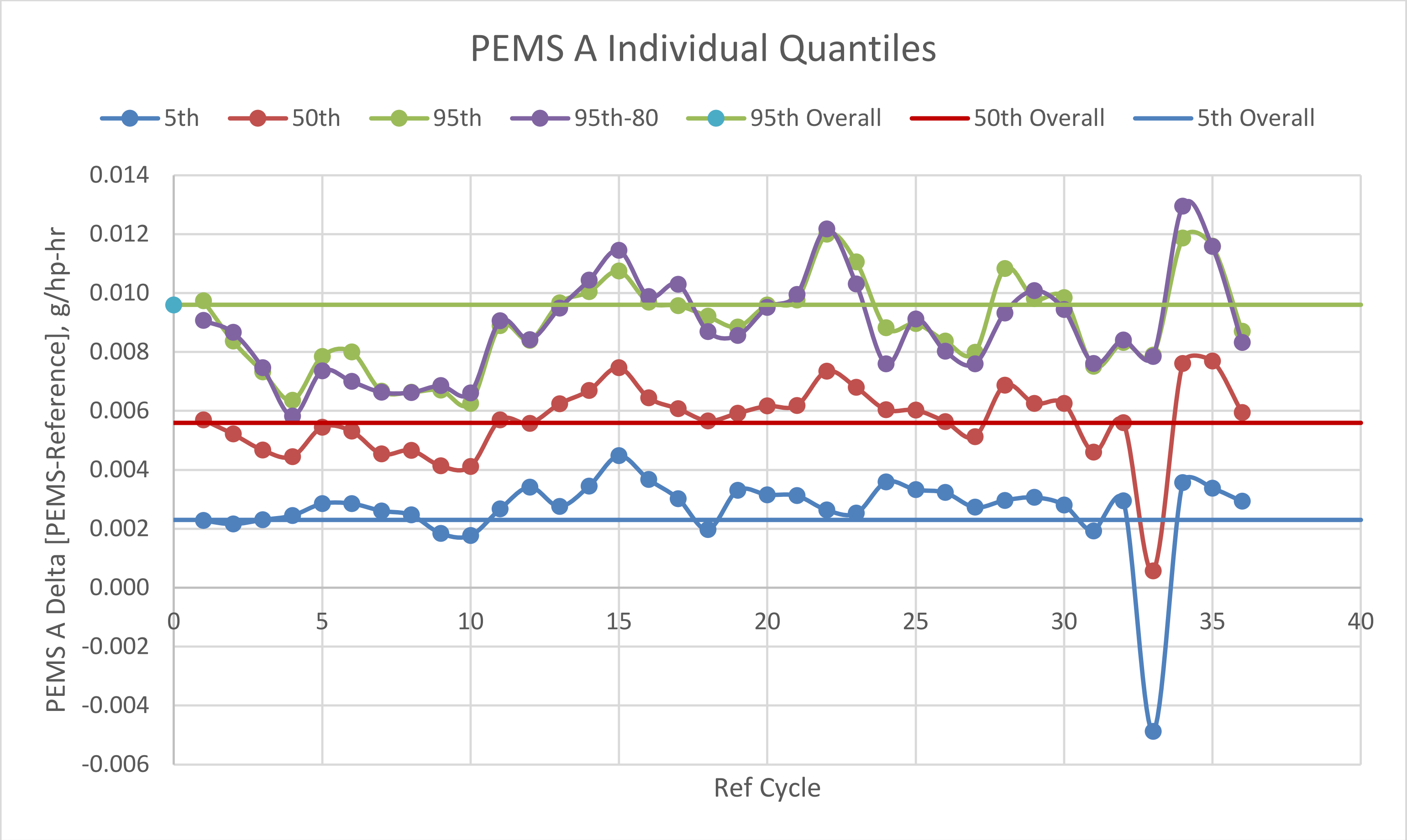
Black = Aggregate Distribution
All others = Individual Ref Cycle Distributions

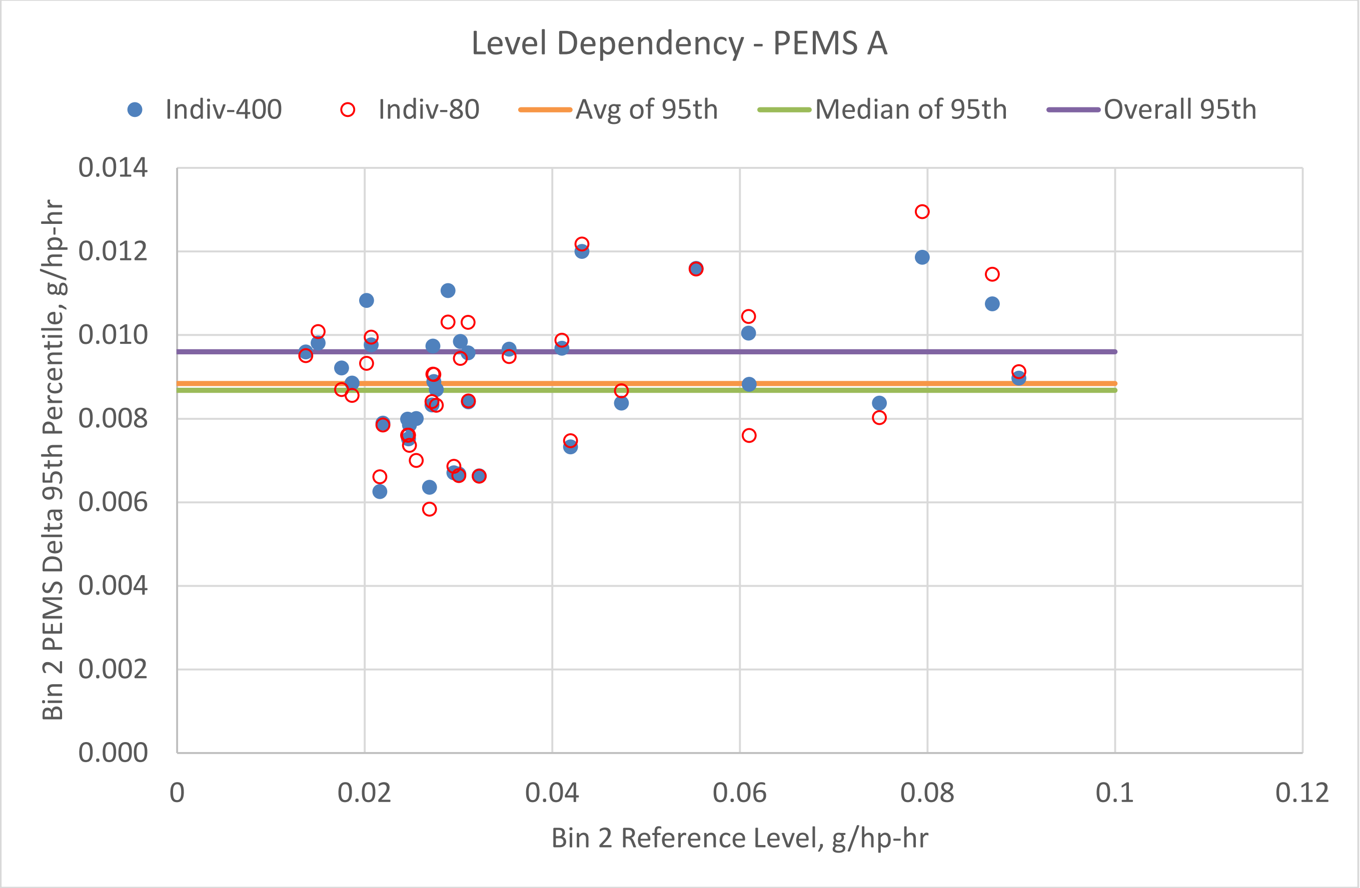
Bin 2 < 0.05 g/hp-hr

Bin 2
0.05 to 0.09 g/hp-hr



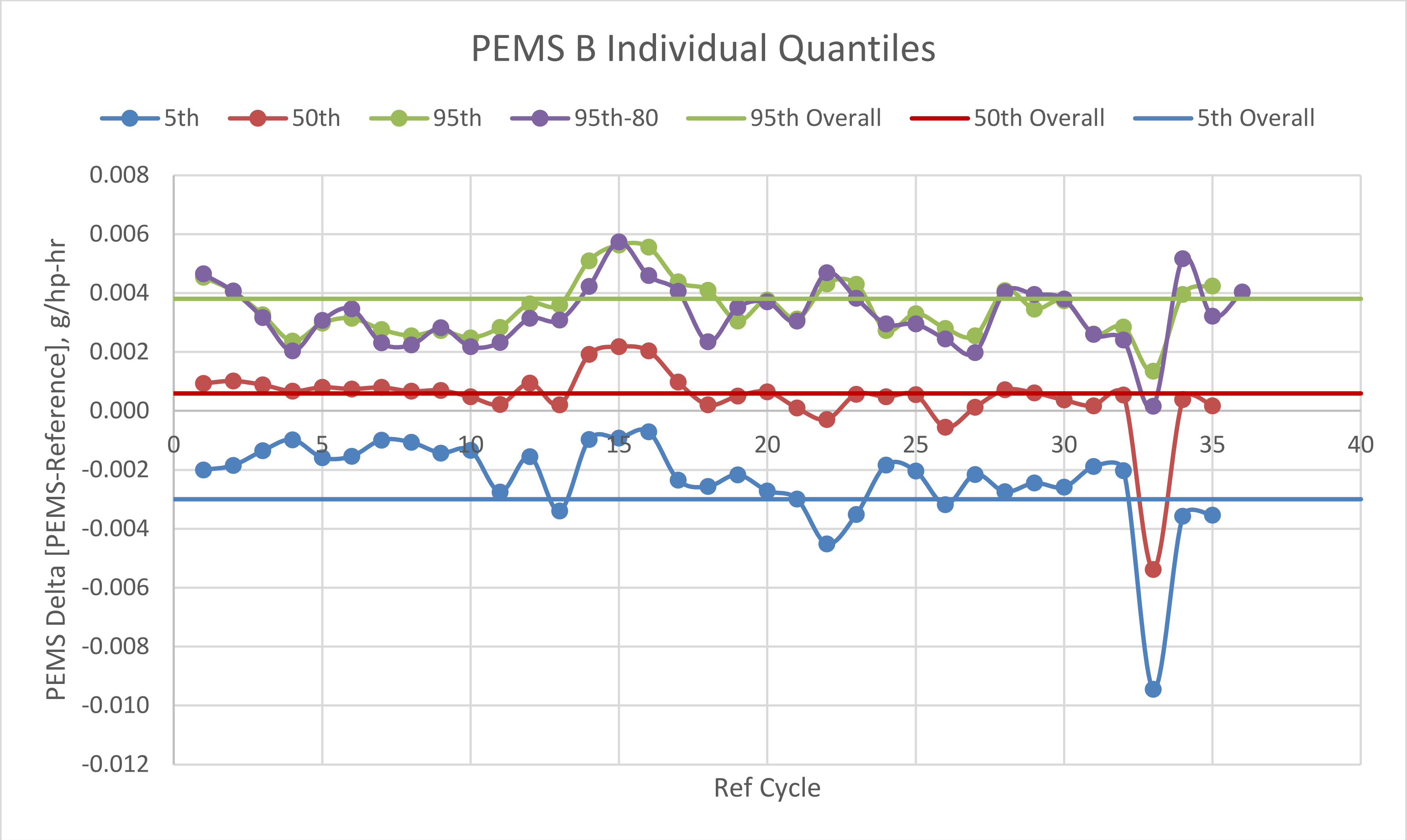
PEMS A Distributions and Level Dependency

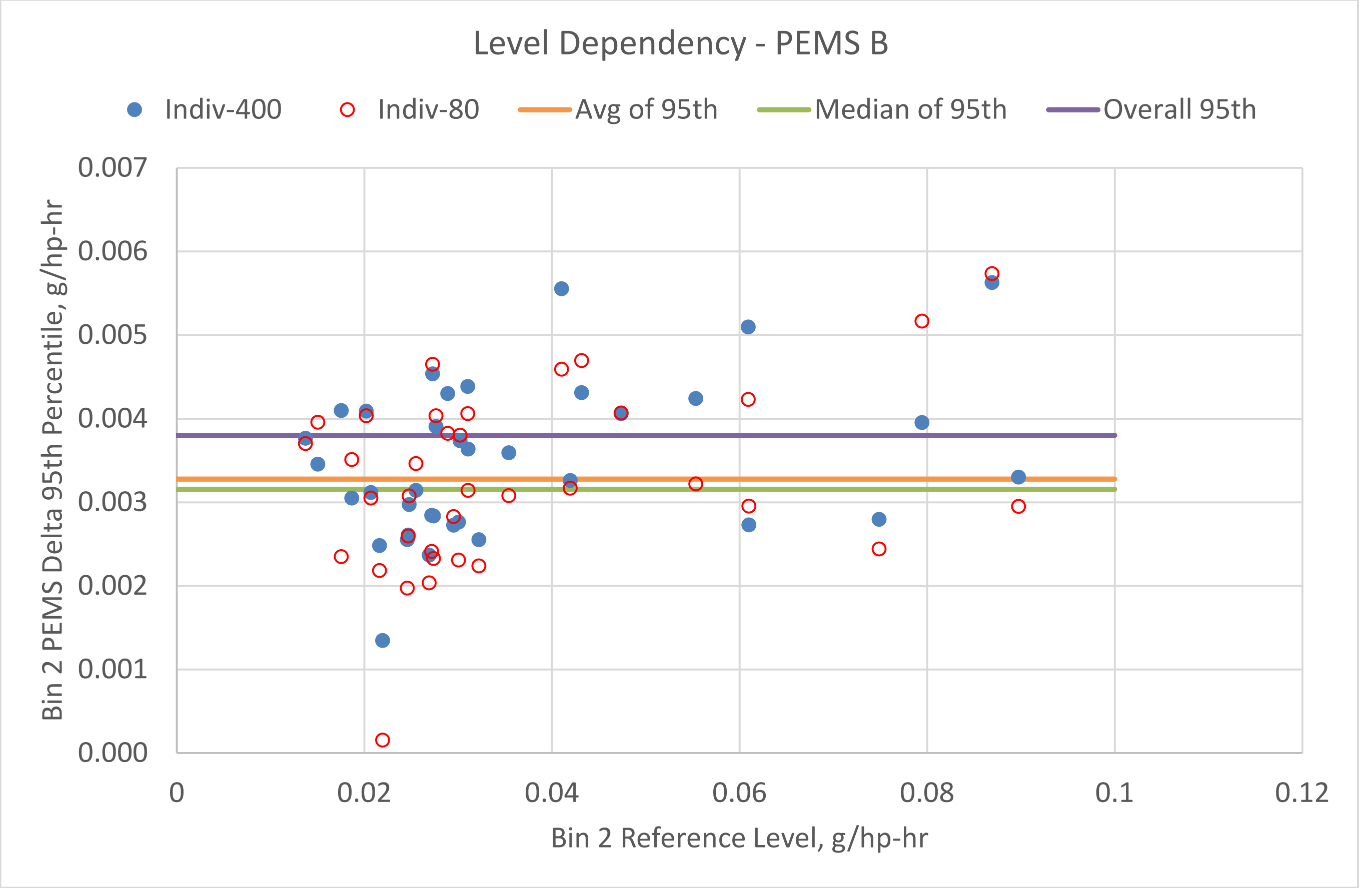




- PEMS A does not indicate any level dependency up to 0.09 g/hp-hr
- PEMS Delta does appear to vary somewhat with duty cycle

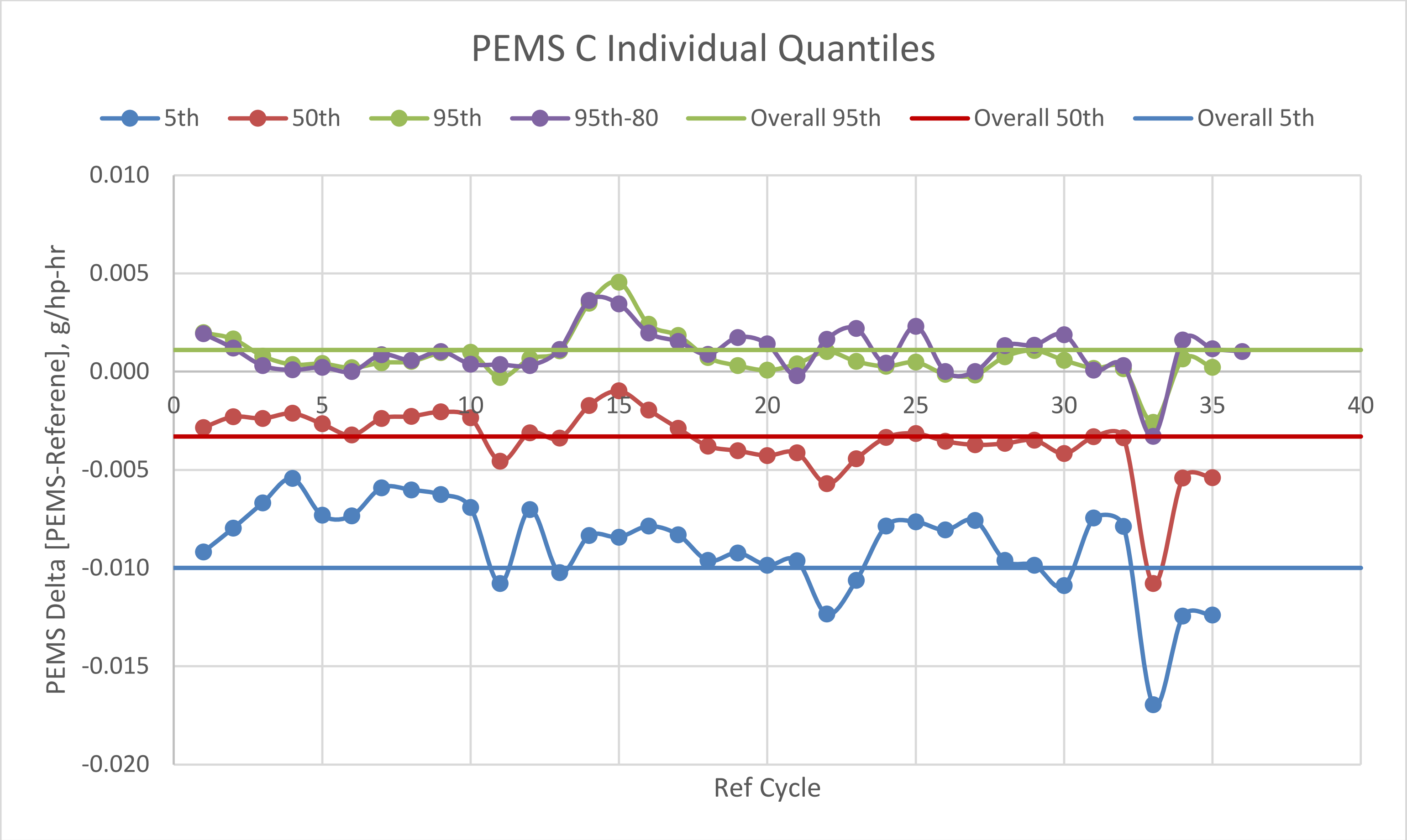
PEMS B Distributions and Level Dependency

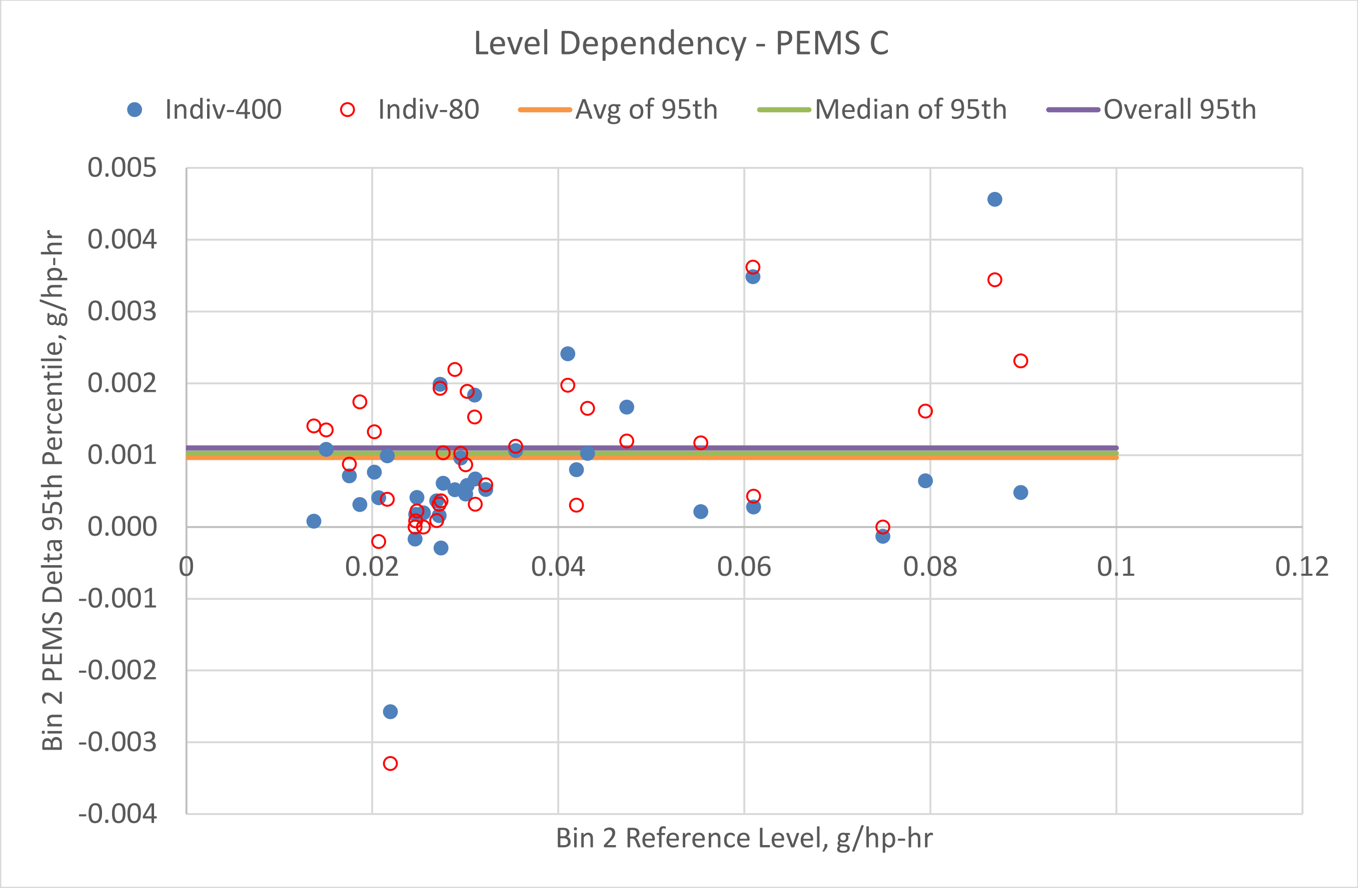




- PEMS B does not indicate any level dependency up to 0.09 g/hp-hr
- PEMS Delta does appear to vary somewhat with duty cycle

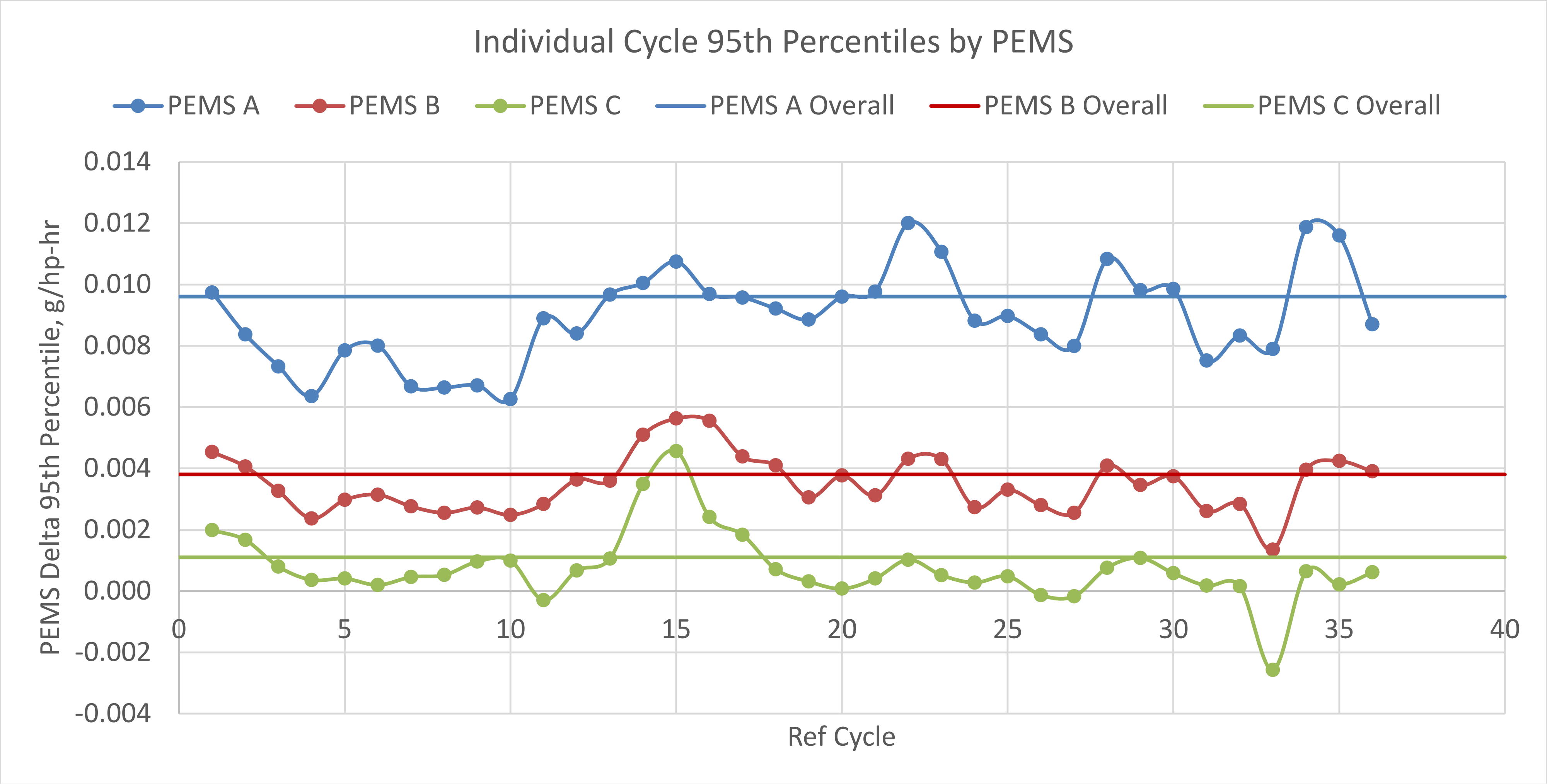
PEMS C Distributions and Level Dependency





- PEMS C does not indicate any level dependency up to 0.09 g/hp-hr
- PEMS Delta does appear to vary somewhat with duty cycle

95th Percentiles for All PEMS by Ref Cycle



- Overall no general trending – A shows more cycle variation than B and C
- Cycle 33 is an outlier low for B/C (note that 5th and 50th show A is as well)
- Cycle15 is an outlier high for B/C

2b-MAW PEMS Absolute Error Distribution Quantiles

							Quantiles							
equipment	bin	ifn.use	source	n.	mu.	sd.	q.0.	**q.5.**	q.10.	**q.50.**	q.90.	**q.95.**	q.100.	**5th to 95th Spread**
					Bin 1 NO_X, g/hr									
PEMS.A	1	synth	mdl	14400	0.14	0.21	-0.98	**-0.10**	-0.02	**0.11**	0.30	**0.48**	2.07	**0.58**
PEMS.B	1	synth	mdl	14400	-0.13	0.27	-1.73	**-0.56**	-0.40	**-0.10**	0.08	**0.26**	1.38	**0.82**
PEMS.C	1	synth	mdl	14400	-0.30	0.36	-3.75	**-0.89**	-0.68	**-0.25**	-0.02	**0.12**	1.58	**1.02**
Raw.1	1	synth	mdl	14400	-0.01	0.04	-0.25	**-0.08**	-0.06	**0.00**	0.04	**0.06**	0.20	**0.14**
Raw.2	1	synth	mdl	14400	0.01	0.03	-0.16	**-0.03**	-0.02	**0.01**	0.05	**0.07**	0.23	**0.10**
Raw.3	1	synth	mdl	14400	-0.01	0.04	-0.23	**-0.07**	-0.05	**-0.01**	0.04	**0.05**	0.29	**0.12**

							Quantiles							
equipment	bin	ifn.use	source	n.	mu.	sd.	q.0.	**q.5.**	q.10.	**q.50.**	q.90.	**q.95.**	q.100.	**5th to 95th Spread**
					Bin 2 NO_X, g/hp-hr									
PEMS.A	2	synth	mdl	14400	0.0057	0.0024	-0.0092	**0.0023**	0.0032	**0.0057**	0.0086	**0.0096**	0.0150	**0.0074**
PEMS.B	2	synth	mdl	14400	0.0005	0.0021	-0.0153	**-0.0029**	-0.0019	**0.0006**	0.0030	**0.0038**	0.0090	**0.0067**
PEMS.C	2	synth	mdl	14400	-0.0037	0.0034	-0.0258	**-0.0100**	-0.0080	**-0.0033**	0.0001	**0.0011**	0.0110	**0.0111**
Raw.1	2	synth	mdl	14400	-0.0001	0.0011	-0.0057	**-0.0019**	-0.0014	**-0.0001**	0.0012	**0.0017**	0.0054	**0.0036**
Raw.2	2	synth	mdl	14400	0.0003	0.0008	-0.0042	**-0.0008**	-0.0005	**0.0002**	0.0012	**0.0016**	0.0059	**0.0024**
Raw.3	2	synth	mdl	14400	-0.0002	0.0009	-0.0048	**-0.0018**	-0.0014	**-0.0002**	0.0009	**0.0012**	0.0042	**0.0030**

- Lab distributions (Raw.1.2.3) are much narrower than PEMS, more consistent, and show almost no bias
- PEMS distributions show varying levels of bias and wider (more varied) spreads

Calculation of Incremental PEMS Error

Values shown for PEMS A/B/C are after subtraction of the Lab

PEMS 95th percentile – Lab 95th percentile (or PEMS 5th – Lab 5th)

Bin 1 NO_X, g/hr

	5th Percentile	50th Percentile	**95th Percentile**
PEMS A	-0.037	0.109	**0.416**
PEMS B	-0.501	-0.101	**0.197**
PEMS C	-0.831	-0.250	**0.061**
Lab Avg	-0.062	-0.001	**0.061**

Bin 2 NO_X, g/hp-hr

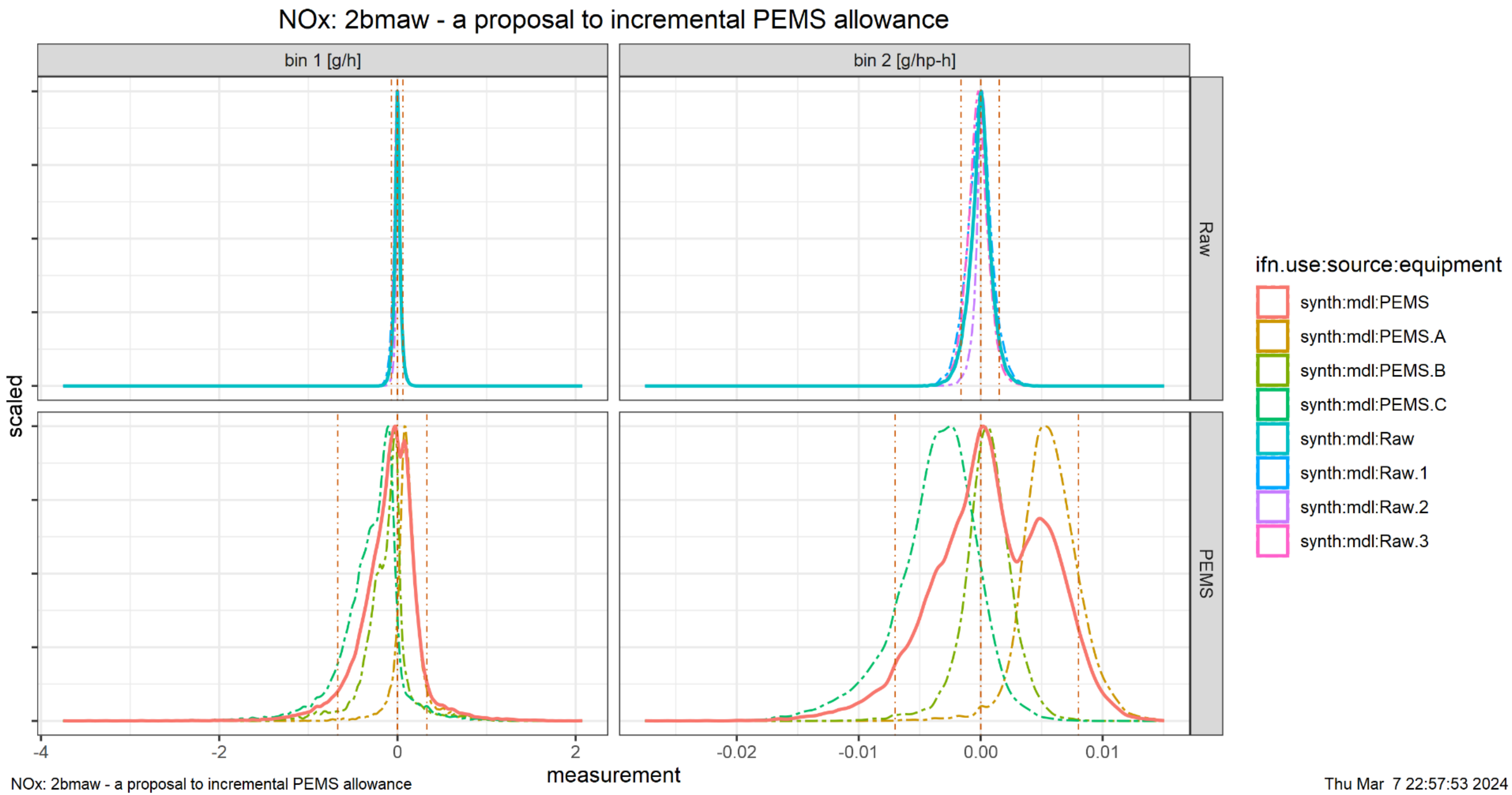
	5th Percentile	50th Percentile	**95th Percentile**
PEMS A	0.0038	0.0057	**0.0081**
PEMS B	-0.0014	0.0006	**0.0023**
PEMS C	-0.0085	-0.0033	**-0.0005**
Lab Avg	-0.0015	0.0000	**0.0015**

Final Incremental Results for Each PEMS

How do we use these to generate a recommendation for accuracy margins ?

Aggregated Distributions for PEMS and Lab

Treat Raw.N and PEMS.X Encounters as Random and Aggregate – Solid Blue and Solid Red



Aggregated Quantiles and Incremental Error

Aggregated Quantiles for PEMS and Lab

bin	bin.txt	generic	n	q.5.	q.50.	q.95.
1	bin 1 [g/h]	PEMS	43308	-0.660	-0.063	0.329
1	bin 1 [g/h]	Raw	43308	-0.06706	0.00023	0.06084
2	bin 2 [g/hp-h]	PEMS	43308	-0.007	0.001	0.008
2	bin 2 [g/hp-h]	Raw	43308	-0.00161	0.00001	0.00152

PEMS Incremental Error for Aggregated Data Sets

	5th Percentile	50th Percentile	**95th Percentile**
Bin 1, g/hr	-0.593	-0.063	**0.268**
Bin 2, g/hp-hr	-0.0054	0.0008	**0.0065**

Acknowledgments

- EPA and EMA for funding of the Field duty cycle and PEMS testing
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- CE-CERT for the validation field runs and data analysis

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

- MECA member companies for providing emission control hardware

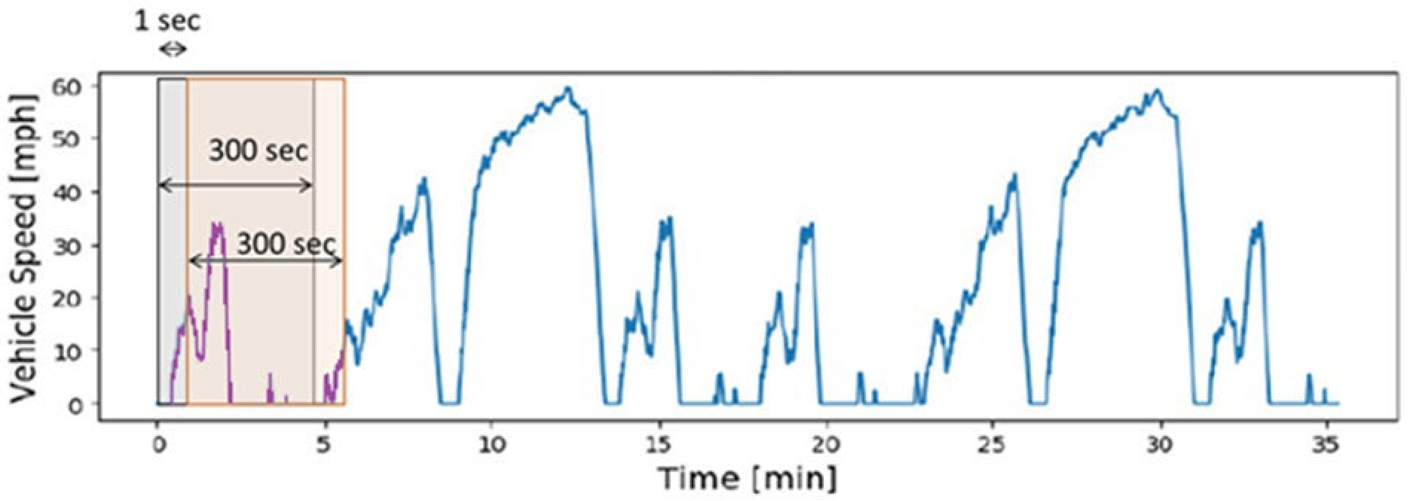
- Cummins for providing the engine and engineering support

- 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 fixed-length 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)
  - For EPA Bins 2 and 3 are combined into a single bin
- 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)



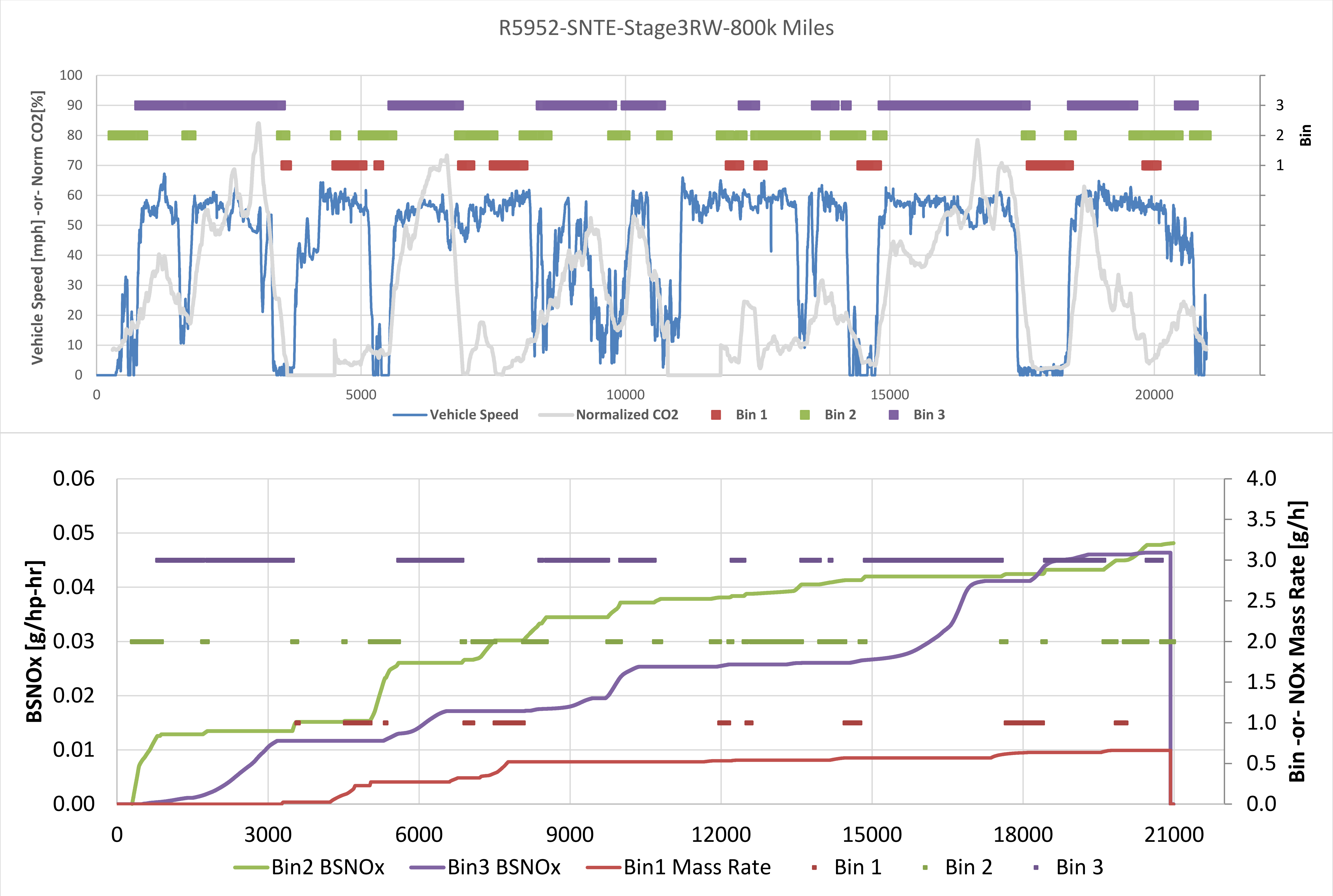
CARB In-Use NO_X Standards

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