Real World Cycle Measurement Instrumentation Capability at Low NO_X Levels for 2027 and Beyond

SOUTHWEST RESEARCH INSTITUTE®

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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

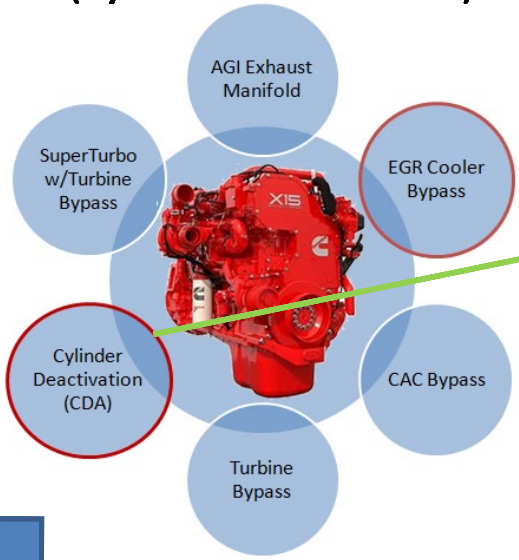
Experimental Approach – Replay Field Duty Cycles on Stage 3RW Low NO_X Engine in Lab with PEMS and Sensors

EPA Stage 3RW Low NO_X Demonstration Engine

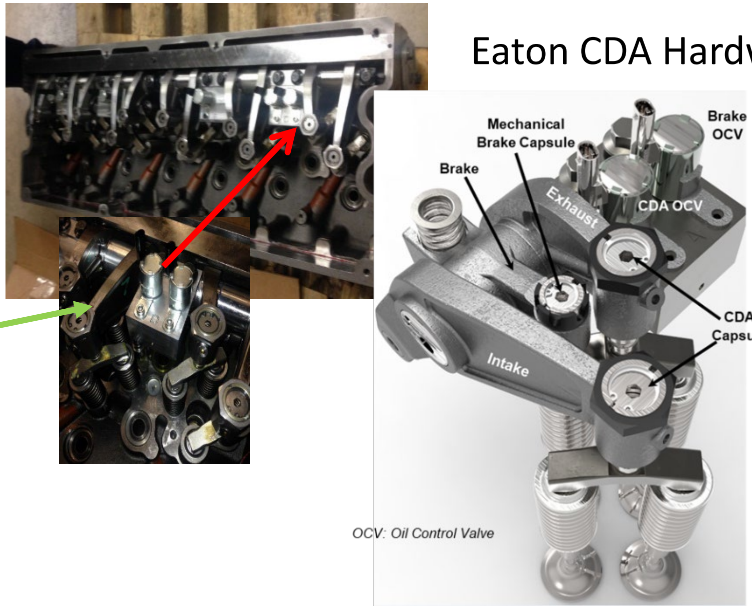
2017 Cummins X15 Engine

SAE Paper 2021-01-0589

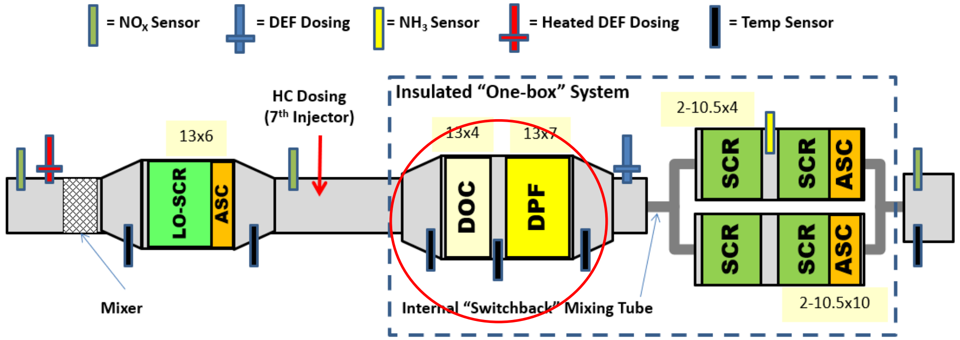
Additional Engine Hardware (Cylinder Deactivation)



Eaton CDA Hardware



Advanced Low NO_X Aftertreatment (Dual SCR-Dual Dosing)



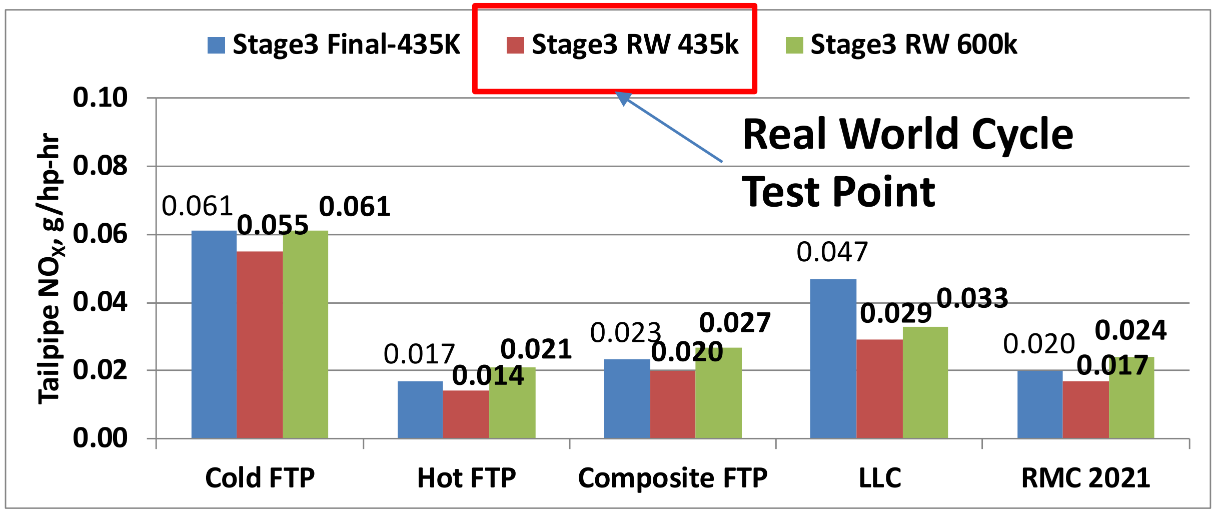
Targets:

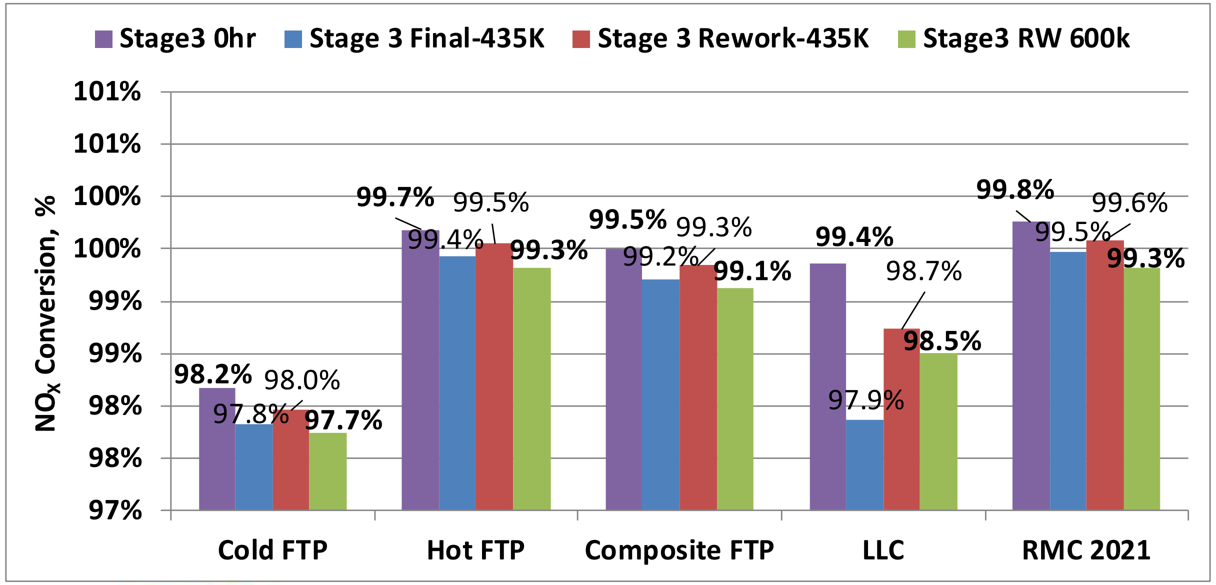
- FTP/RMC NO_X 0.02 g/hp-hr at 435k miles
- Lowest feasible LLC and in-use NO_X
- No adverse GHG impact

EPA Updates

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

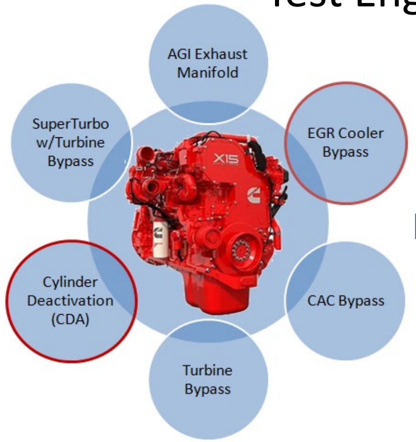
Latest Results on EPA Stage 3RW Platform After 600,000 miles Aging (1,000,000 km) – Regulatory Cycle Results

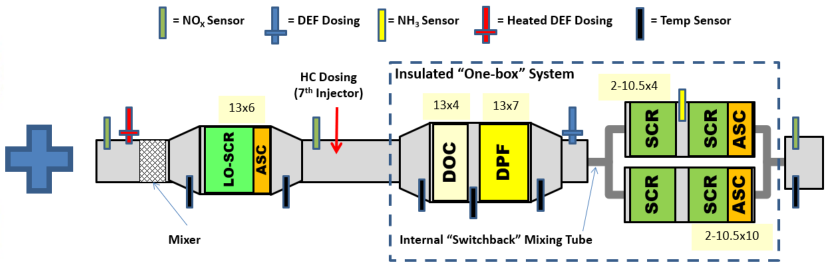




- DAAAC[1] Aging (thermal + chemical) ~13,800 equivalent hours
- **435,000-mile** results compared to <u>*0.020 (FTP-RMC) / 0.050 (LLC)*</u> standard – **At standard but no margin (LLC below standard with margin)**
- **600,000-mile** results compared to <u>*0.035 (FTP-RMC) / 0.090 (LLC)*</u> standard – **Below standard but is margin enough ? (LLC yes)**
- *Note values do not include UAF[2] (0.002 FTP-RMC, 0.005 LLC)*

Test Engine-Aftertreatment Configuration





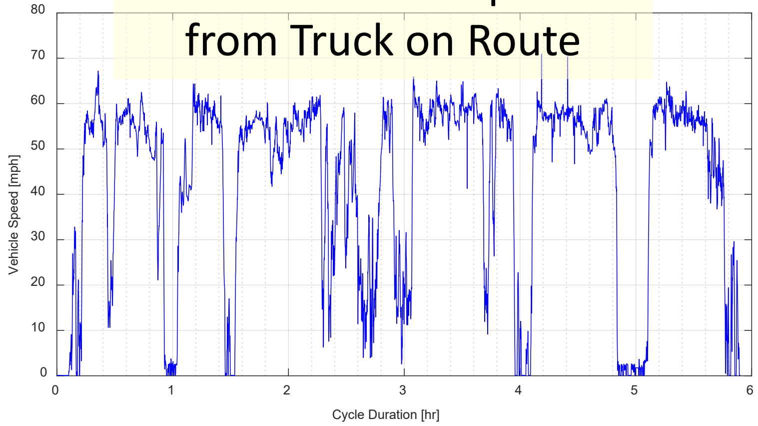
Updates from original Stage 3 – change from zone-coated CSF to DOC+DPF and downstream mixing improvements

[1] DAAAC = Diesel Accelerated Aftertreatment Aging Cycles
[2] UAF = infrequent Regeneration Upward Adjustment Factor

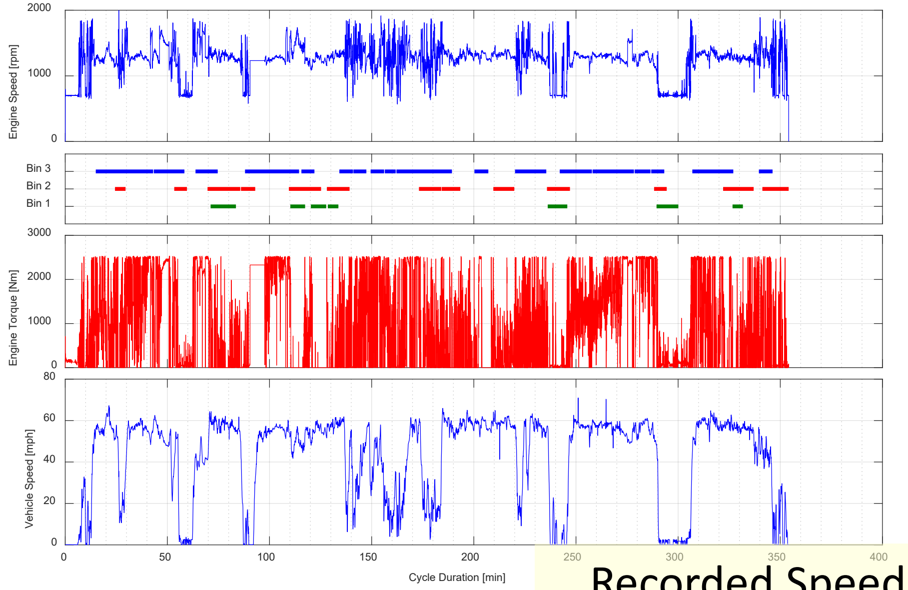
Cycle Development Process Example – Southern NTE Route

Field Route

Actual Vehicle Speed from Truck on Route

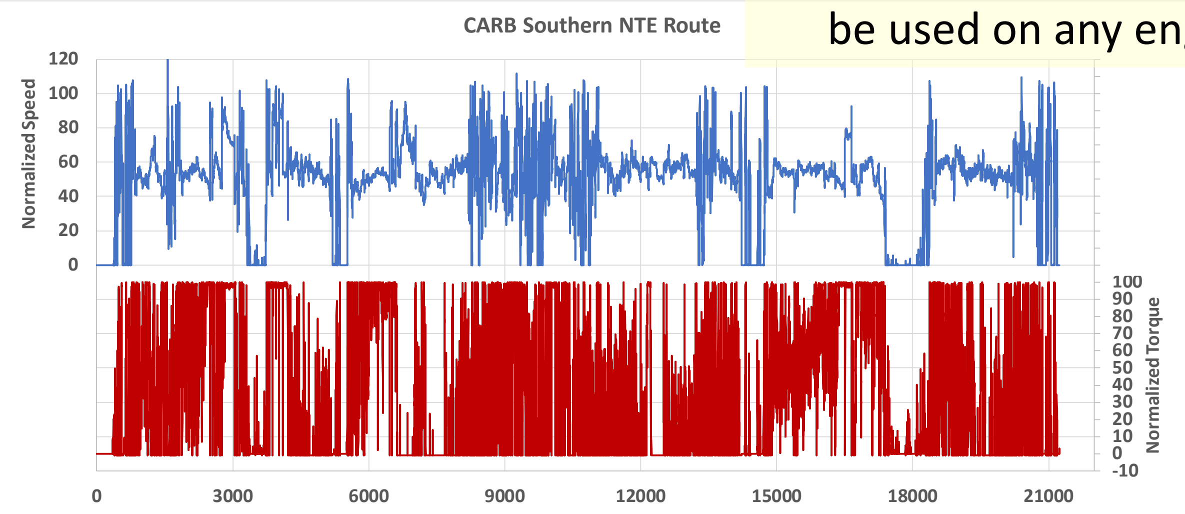


- WVU drove trucks on real-world routes
- Recorded vehicle data used along with engine torque curve information to generate Normalized engine-dyno replay cycle for Lab use



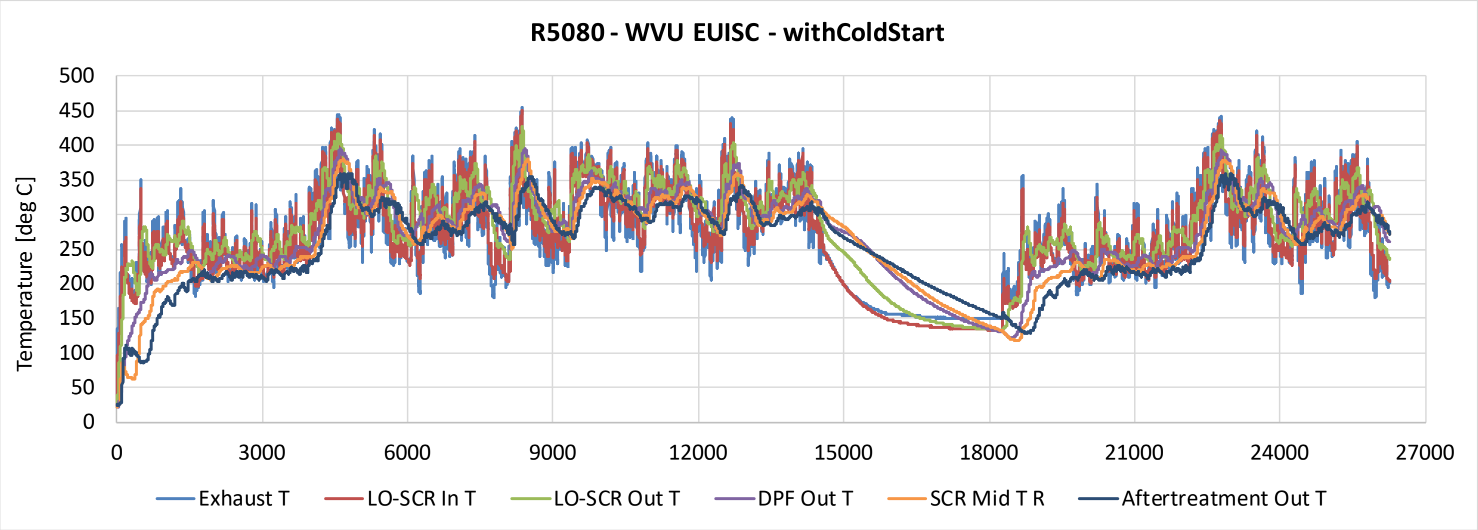
Recorded Speed/Load Data from Drive

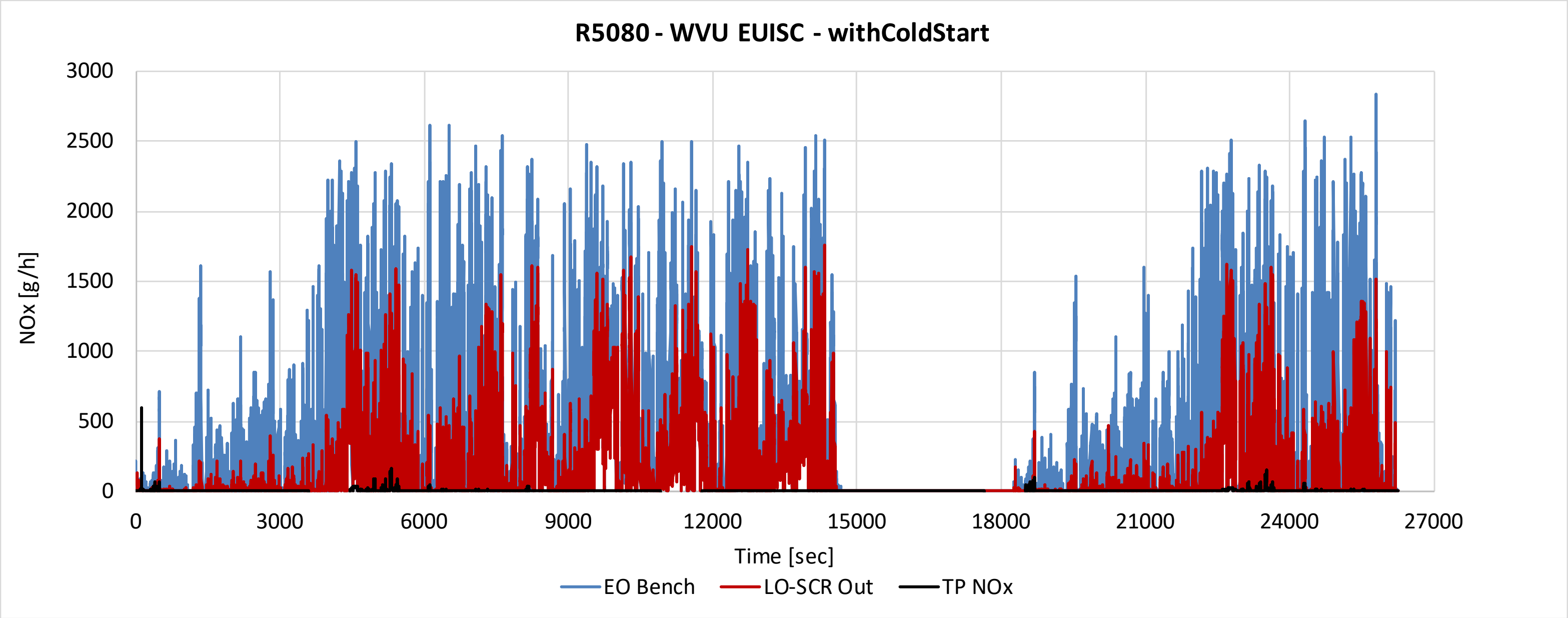
Normalized Engine Cycle (can be used on any engine)



Cycles run for a full shift as they were run in the field, including cold-start and engine shutdowns where they happened

Temperature and 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

3-bin Moving Average Window (3B-MAW) – Short Description

Binning of windows by load (normalized CO_2)

$$window\ normalized\ average\ CO2\ rate = \frac{\left(\sum_{t=1}^{n} \dot{m}_{CO2}(t)\right)}{FCL \times \left(P_{max} \times \frac{n}{3600}\right)}$$

	Bin	Engine Type	Normalized Average Window CO2 Rate
Bin 1	Idle	Diesel Cycle	$CO2_{normalized} \leq 6\%$
Bin 2	Low	Diesel Cycle	$6\% < CO2_{normalized} \leq 20\%$
Bin 3	Med/High	Diesel Cycle	$20\% < CO2_{normalized}$
	All Operation	Otto-Cycle	na

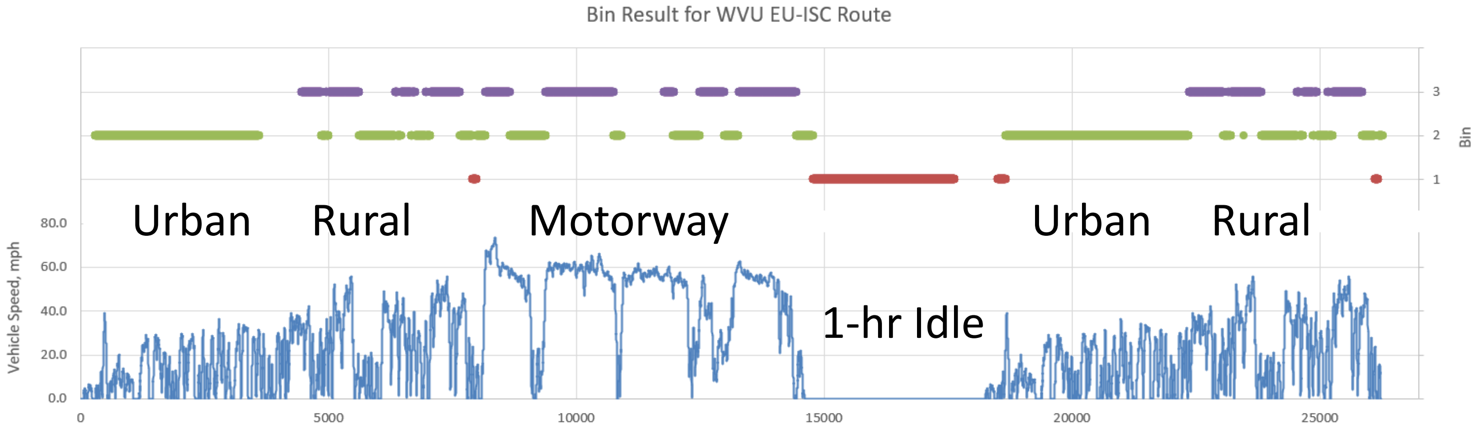
Emission Calculations - summed totals for each bin (Bin 2/3 use sum-over-sum NO_X / CO_2)

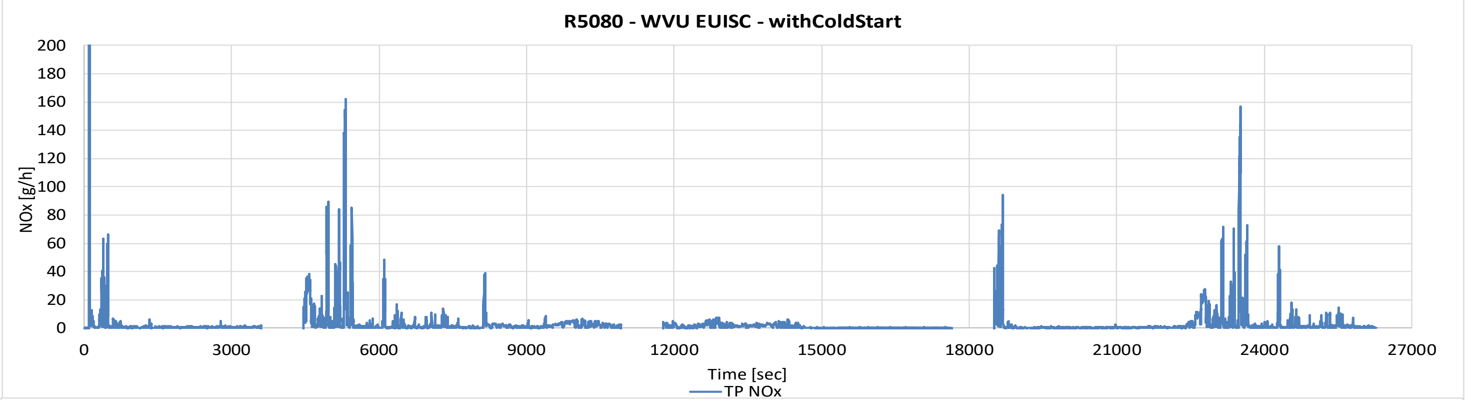
Bin 1 $$e_{sos\ NOx,idle} = \frac{\sum_{k=1}^{n} \dot{m}_{NOx} \times \Delta t}{\sum_{k=1}^{n} \Delta t} \times \frac{3{,}600\ sec}{1\ hr}$$

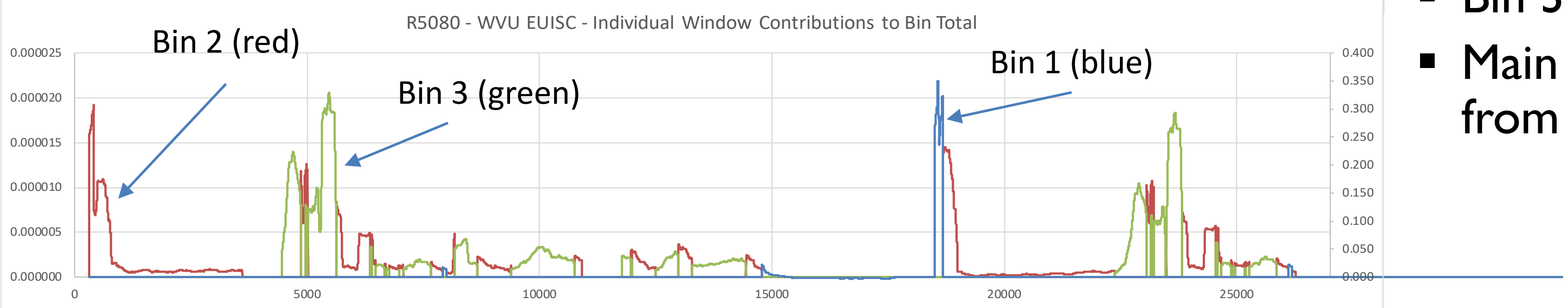
Bin 2/3 $$e_{sos\ a,b} = \frac{\sum_{k=1}^{n} \dot{m}_{a} \times \Delta t}{\sum_{k=1}^{n} \dot{m}_{CO2} \times \Delta t} \times e_{CO2,FTP,FCL}$$

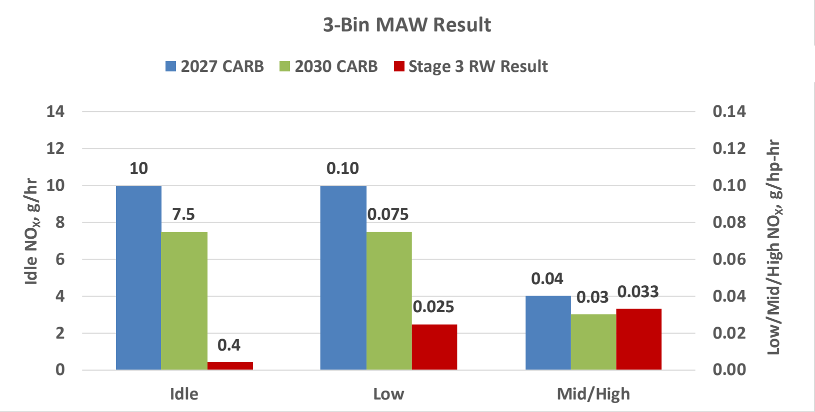
- All operation is used (including cold-start starting 2027)
- 300-second Moving Average Window (MAW) – increments 1 second at a time
- NO_X and CO_2 emissions from each window sorted into bins by normalized CO_2 (load surrogate)
- Bin 1 (Idle) emissions calculated as average mass rate for the entire bin
- Bin 2 / 3 (Low / Med-High) emissions calculate as sum-over-sum (NO_X/CO_2) for the bin
  - multiplied by FTP $BSCO_2$ to translate emissions to $BSNO_X$ in g/hp-hr

Example of 3B-MAW and Emissions – EU ISC Route (Stage3RW-435Kmi System)







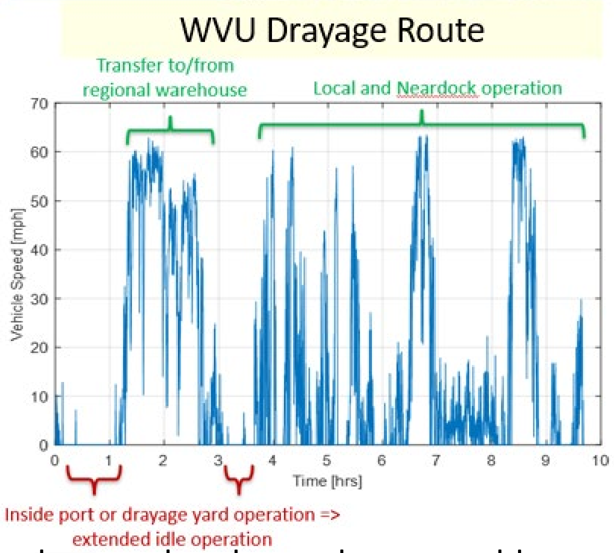


Bin	2027	2030	Result g/hp-hr	Result g/hr	Windows %	Windows Number
Idle (< 6%)	*10*	*7.5*	0.035	**0.4**	13.6%	3180
Low (6%-20%)	*0.10*	*0.075*	**0.025**	1.5	52.6%	12300
Mid-High (> 20%)	*0.04*	*0.03*	**0.033**	5.1	33.8%	7906
Total Cycle			0.030			23386
Total Sum-over-Sum			0.031			
Cycle CO2 % Max					16.3%	

- Large margins for Bin 1/ 2
- Bin 3 is between 2027 and 2030 thresholds
- Main Bin 3 emissions occur at transition from Urban to Rural segment

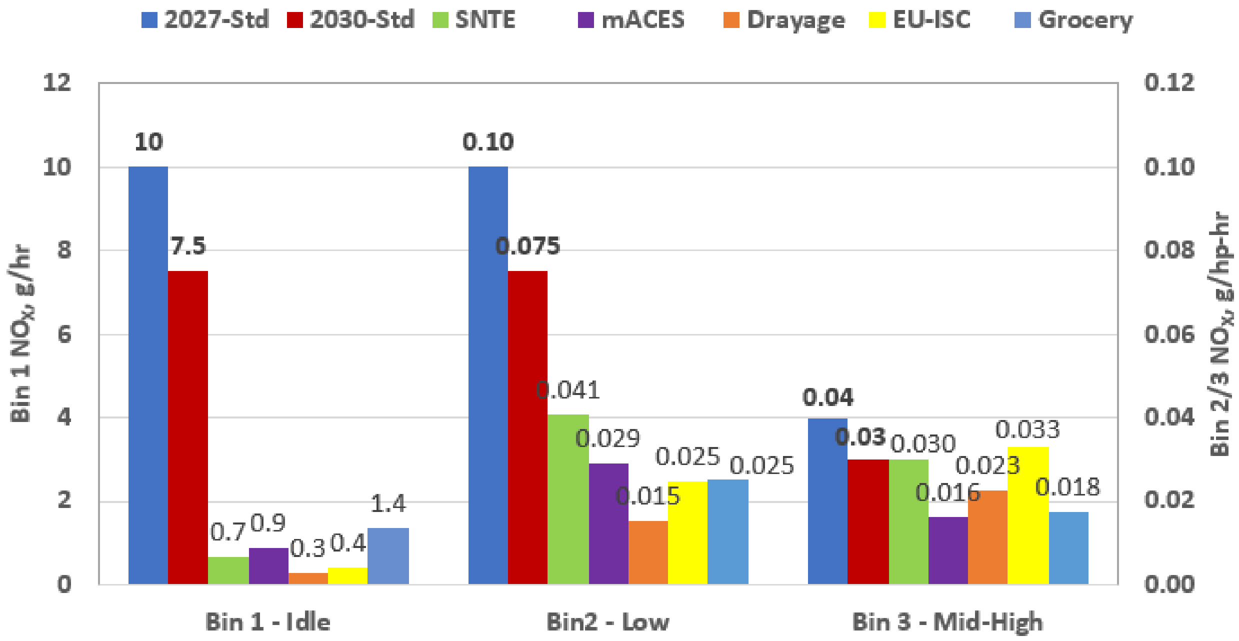
Real World Duty Cycle Results on EPA Stage 3RW Platform

435,000 miles Aging



Real-world routes run by WVU on trucks, translated to cycles we could run on engine-dyno using Stage 3RW system (stock system performed similarly to field data…we are duplicating the field duty cycle accurately)

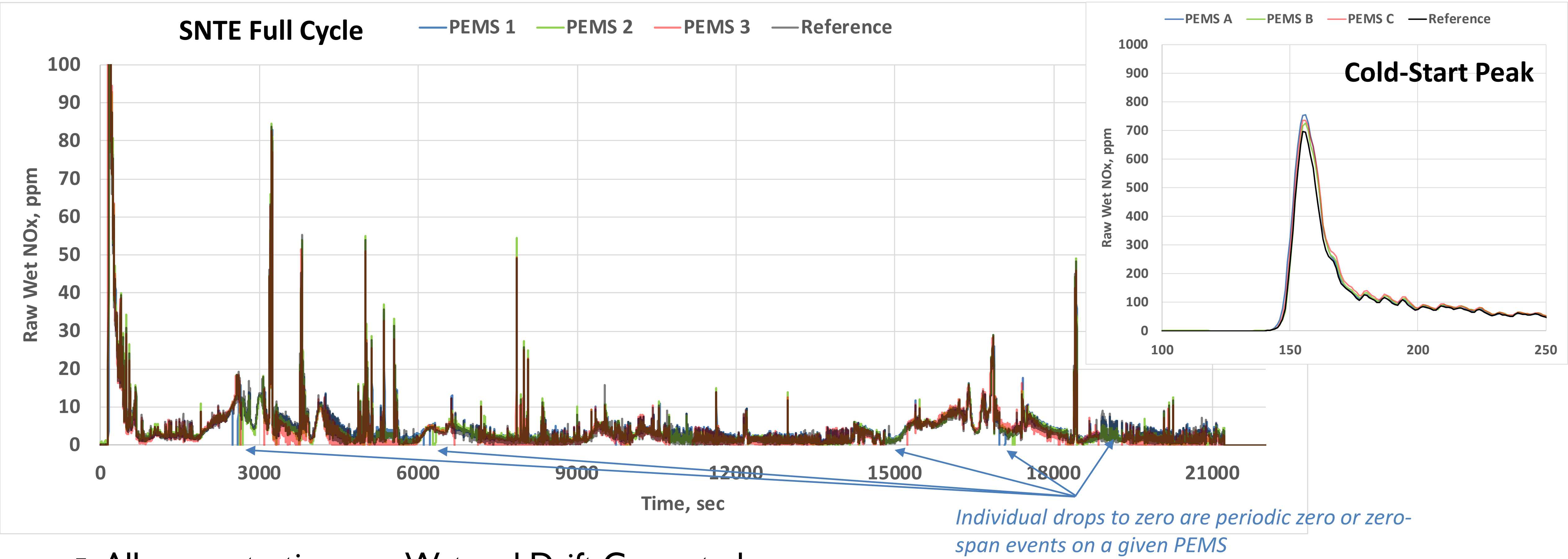
3-bin MAW* In-Use Method Results



- Regulatory Cycle performance (with LLC) does translate to real-world performance for this system
- Bin 1 / 2 – below 2030 thresholds with margin
- Bin 3 – some duty cycles in but some were at or above 2030 thresholds, below 2027 but little margin

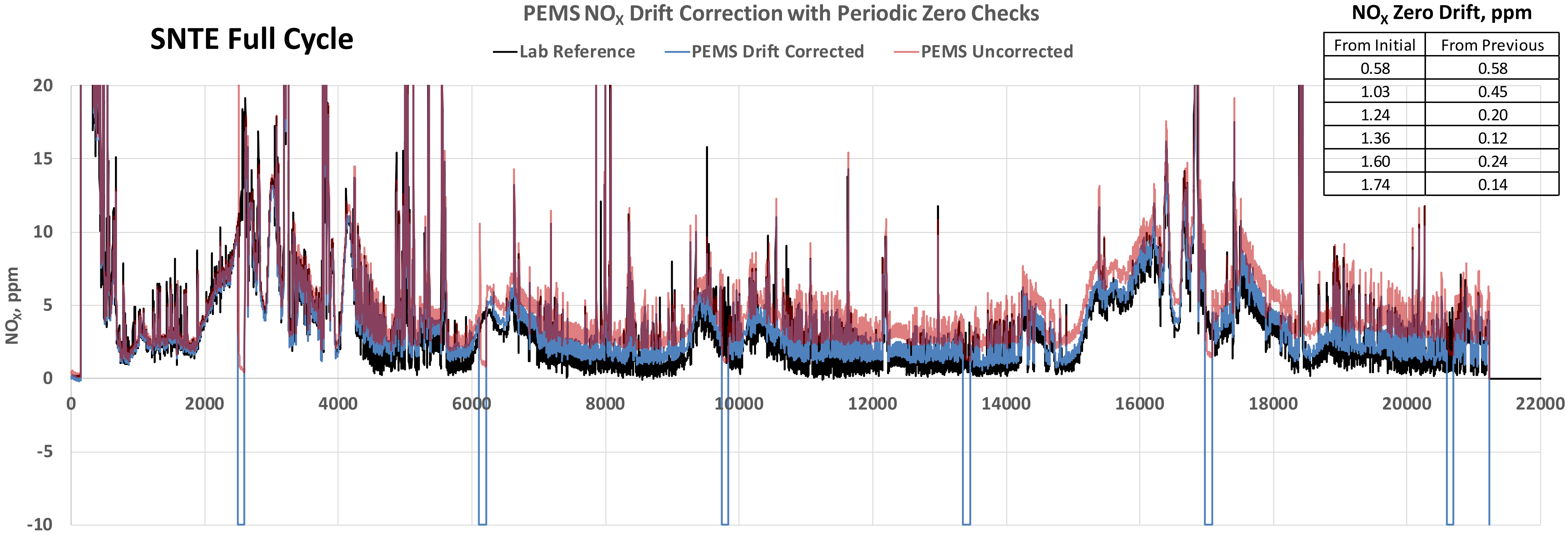
* 3-bin MAW is the new in-use testing protocol (EPA/CARB), considers all operation including cold-start, 5-min averaging window results sorted into three "load" bins

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

Importance of Periodic Zero or Zero-Span and Drift Correction



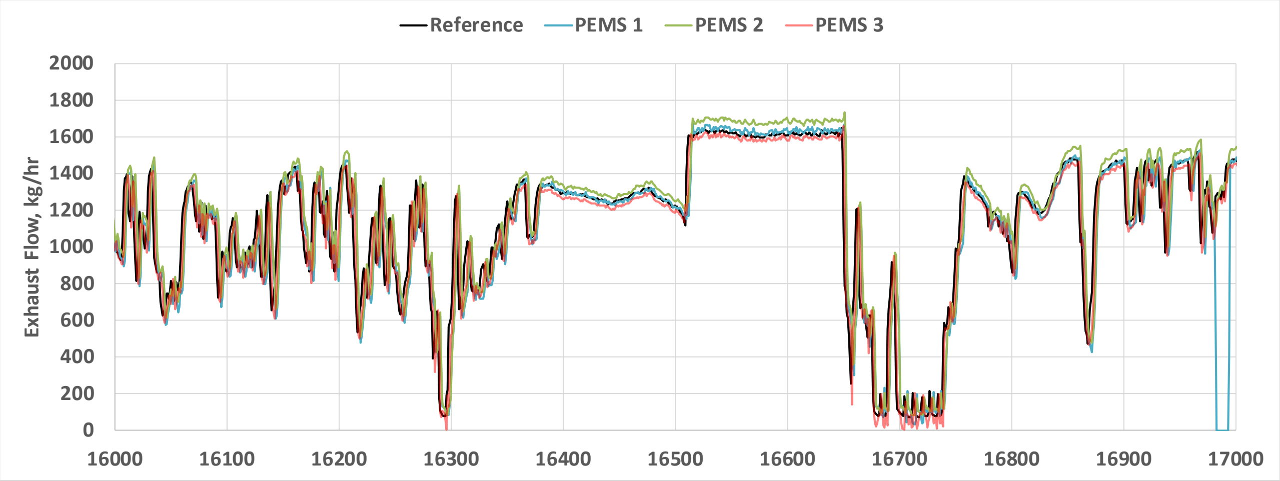
NO_X Zero Drift, ppm

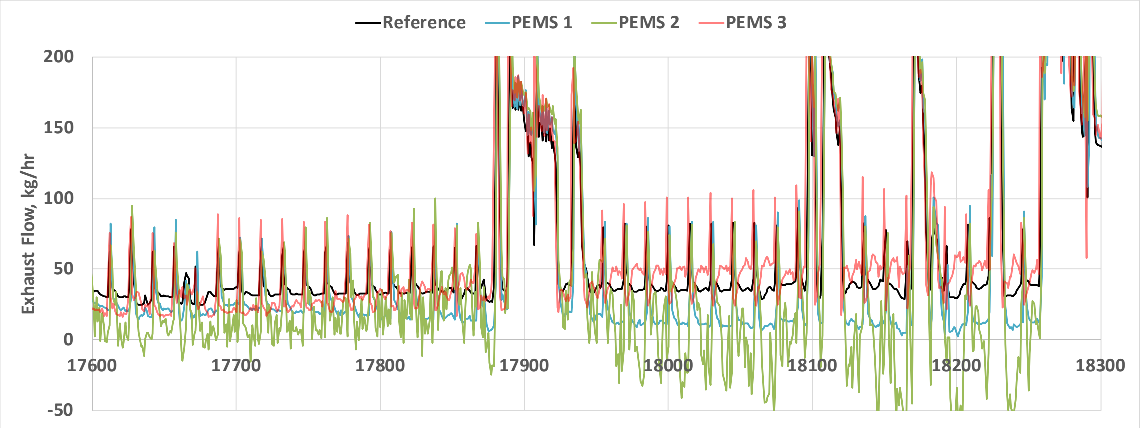
From Initial	From Previous
0.58	0.58
1.03	0.45
1.24	0.20
1.36	0.12
1.60	0.24
1.74	0.14

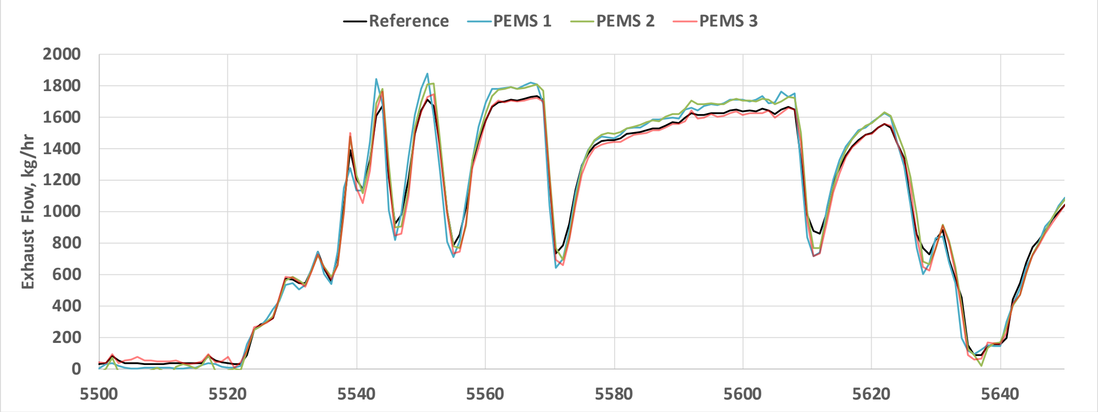
- In this case, drift was observed over test day of ~ 1.7ppm
- Periodic zero observations allowed appropriate drift correction
- <u>Significant reduction in PEMS delta versus Lab Reference</u>

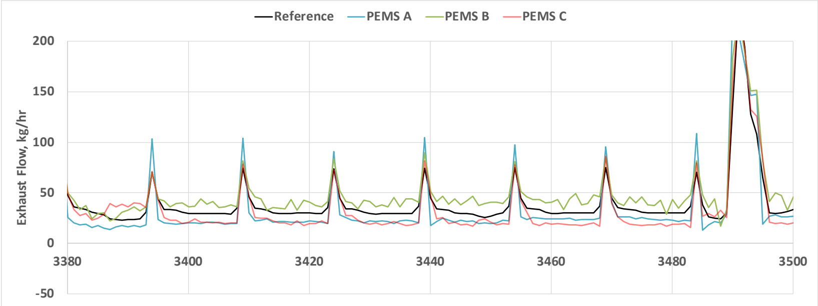
3B-MAW Results	PEMS		Lab
	DC	not DC	Reference
Bin 1, g/hr	0.9	1.2	0.8
Bin 2, g/hp-hr	0.049	0.062	0.040
Bin 3, g/hp-hr	0.035	0.042	0.034

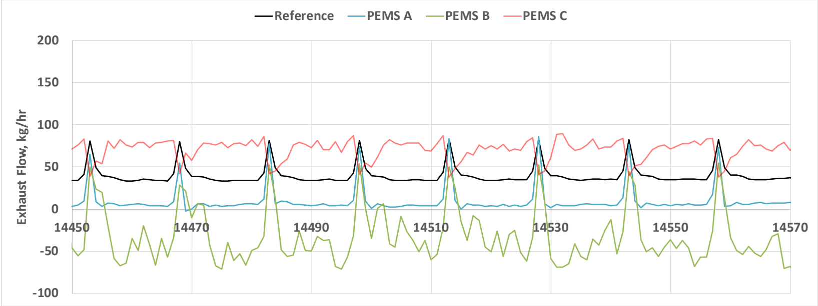
PEMS Exhaust Flow Comparisons – SNTE Example











- Overall similar response between Lab and PEMS flow meters
- Span errors up to 5% observed
- Intermittent issues observed at low flow rates near idle

Selected 3B-MAW Cycle Results – PEMS versus Lab

SNTE Cycle – Stage 3RW, 435k

Bin	Lab	PEMS A	PEMS B	PEMS C
Idle (< 6%)	**0.7**	0.9	0.8	0.3
Low (6%-20%)	**0.041**	0.049	0.043	0.037
Mid-High (> 20%)	**0.030**	0.035	0.034	0.031

Drayage Cycle – Stage 3RW, 435k

Bin	Lab	PEMS A	PEMS B	PEMS C
Idle (< 6%)	**0.3**	0.3	0.3	0.4
Low (6%-20%)	**0.015**	0.018	0.020	0.019
Mid-High (> 20%)	**0.023**	0.020	0.029	0.029

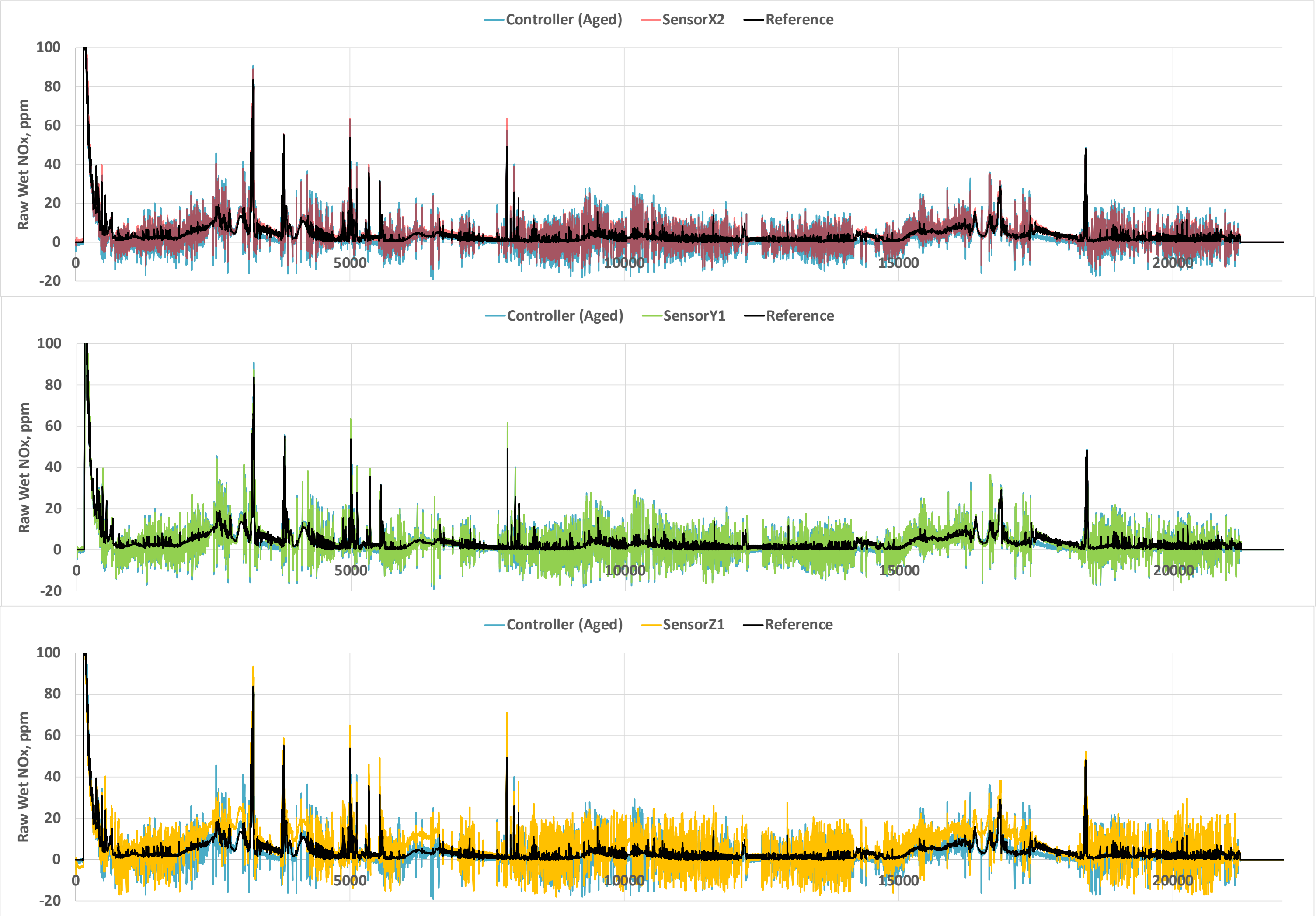
SNTE Cycle – Detuned Controls at Higher Emissions
(0.04 g/hp-hr FTP, 0.1 g/hp-hr LLC)

Bin	Lab	PEMS A	PEMS B	PEMS C
Idle (< 6%)	**5.2**	4.3	5.5	4.9
Low (6%-20%)	**0.183**	0.163	0.162	0.175
Mid-High (> 20%)	**0.047**	0.051	0.048	0.049

- Differences between PEMS and Lab are observed
  - Note that multiple Lab Reference benches were also used
  - PEMS differences were larger than difference among Lab benches
- No consistent trend in PEMS versus Lab comparison across all duty cycles or at different emission levels
  - No clear bias or offset was observed
  - This was true both across different PEMS and from PEMS to Lab

Individual NO_X Sensor Comparisons versus Lab Reference

SNTE Full Cycle



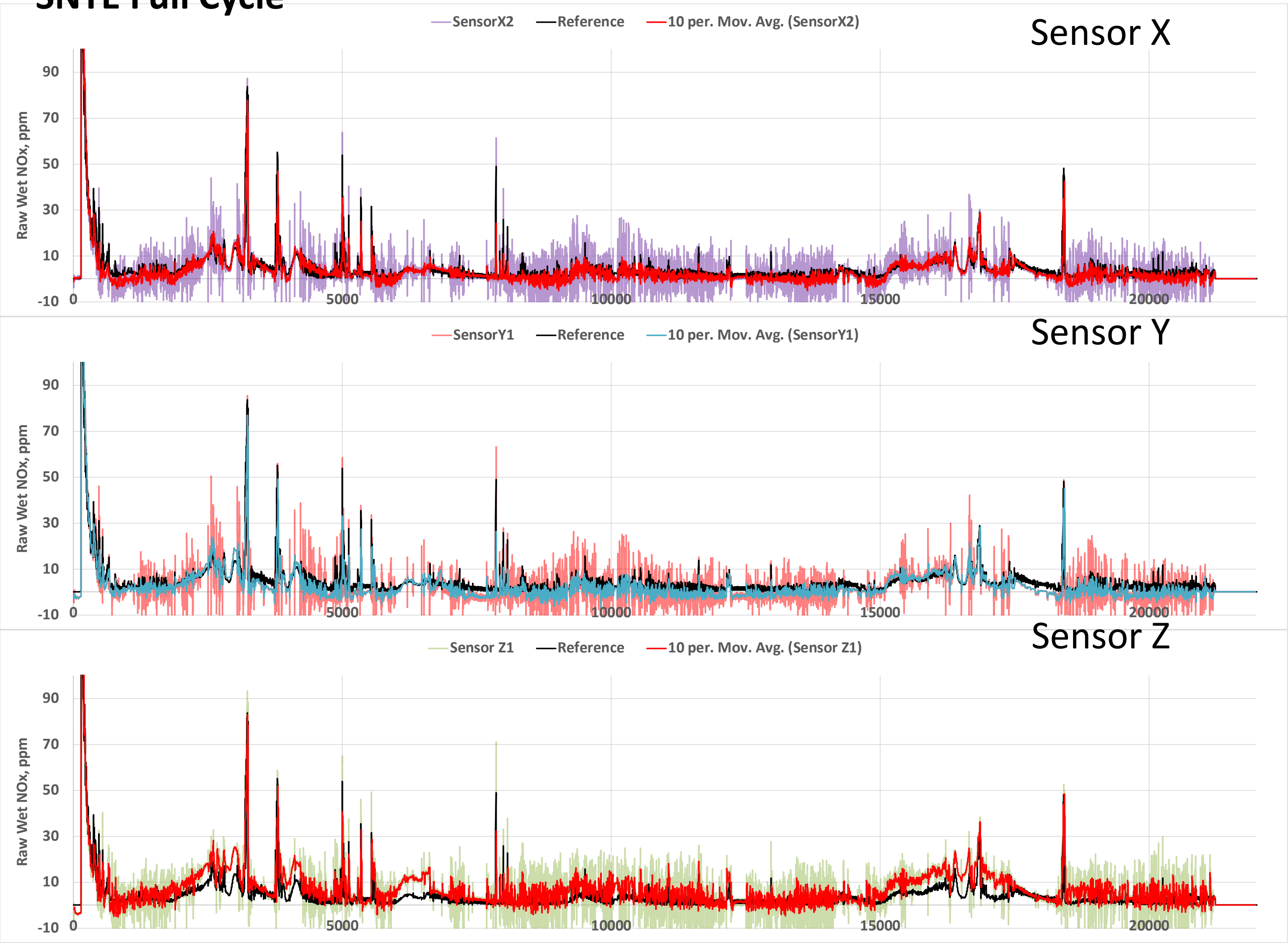
- Data is from same SNTE field cycle as PEMS examples
- Controller is tailpipe NO_X sensor from test article (~1200 hours)
- Sensor X/Y/Z examples from different suppliers
  - Not Aged Sensors
- Lab Reference is same as for PEMS comparisons
- At this scale data appears to be very "noisy" compared to 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…

Impact on 3B-MAW (nic Aging or Batch variability)

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

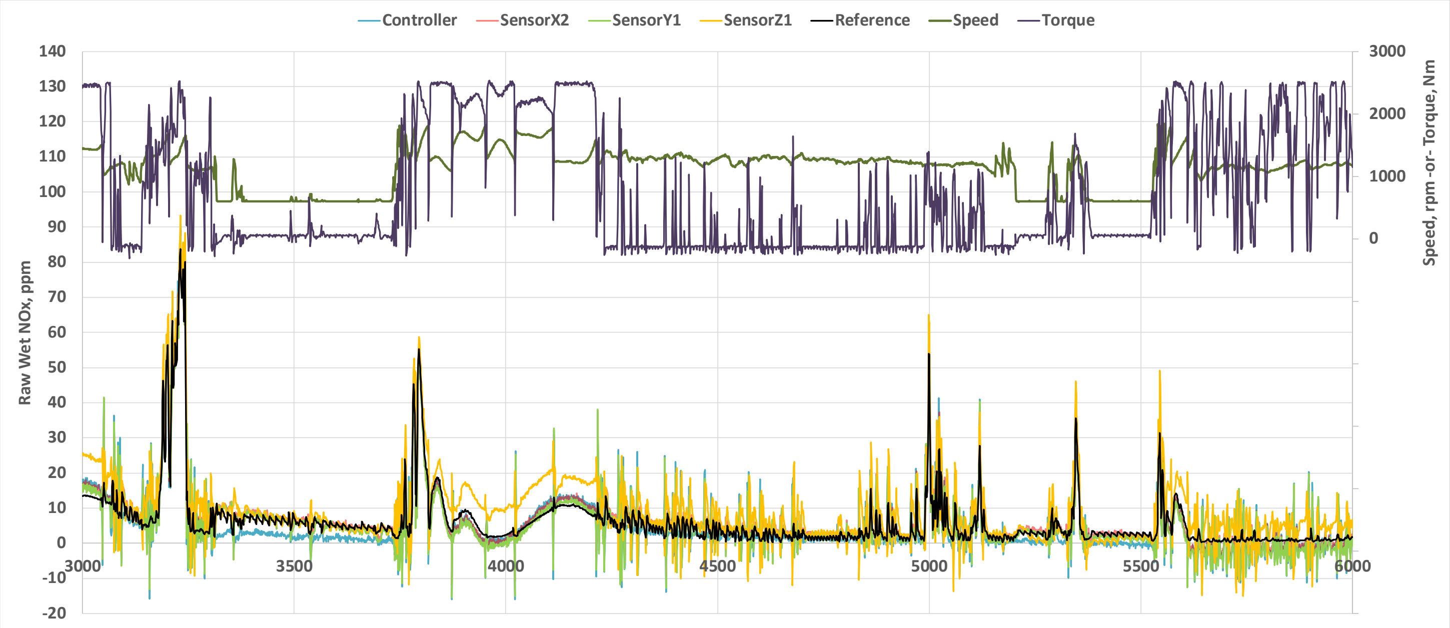
Filtered Sensor Data Comparisons and Impact on Results

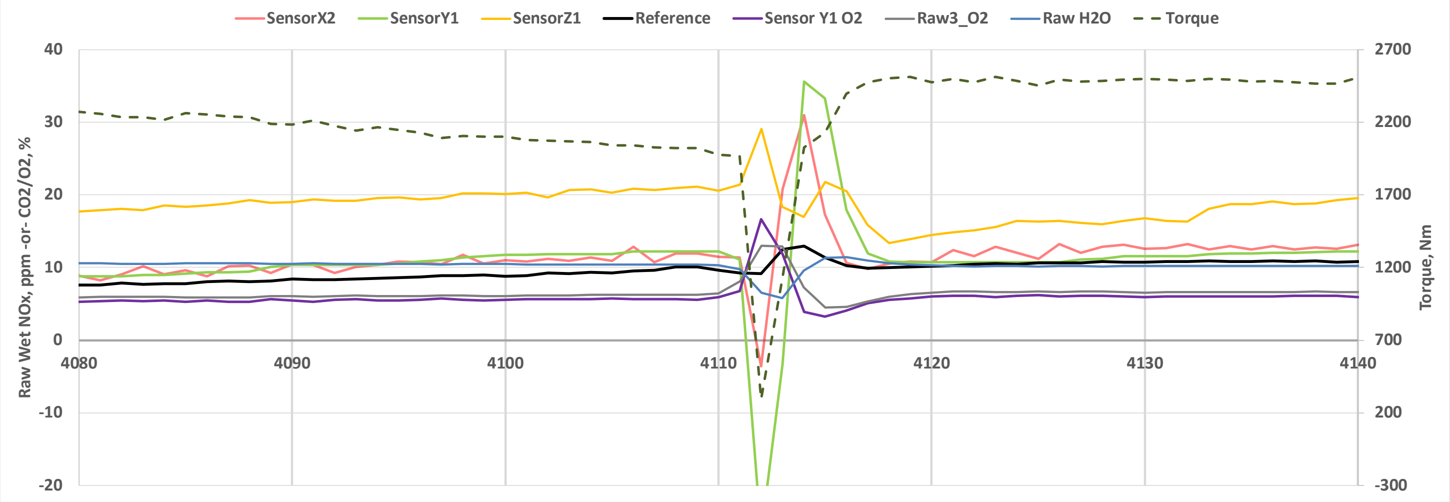
SNTE Full Cycle



- High Frequency sensor behavior makes it difficult to see where sensor is overall compared to Lab
- Added 10-sec moving average filter to sensor data
- Filtered data shows offsets more clearly
- No overall pattern
  - positive and negative offsets are observed compared to Lab data
- Could these lower frequency errors be addressed by zero "drift" correction ?

NO_X Sensor Behavior versus Engine Operation

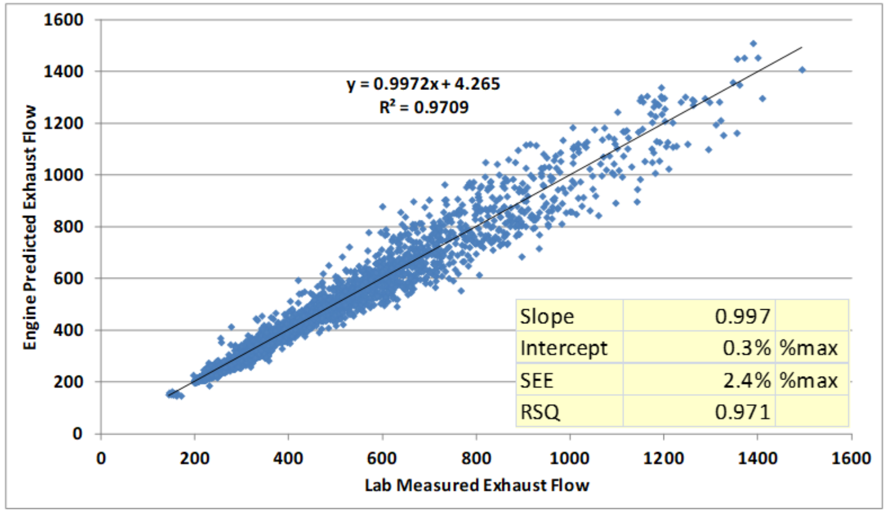




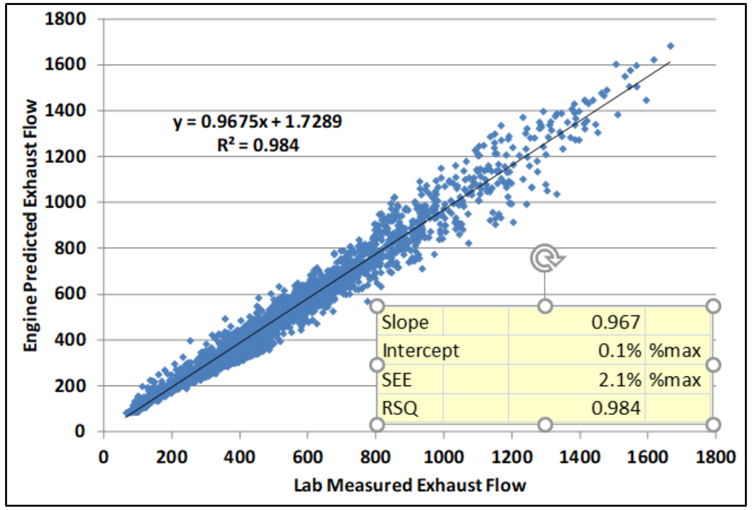
- A variety of different behaviors are seen for different kinds of engine operation
- Rapid changes in speed and/or torque result in significant "noise"
- Sensor behavior impacted by rapid rates of change in load
  - this event show a large but momentary load drop (but not quite a fuel cut event)
- Large swings in O_2 and/or H_2O appear to cause disturbance in NO_X sensor reading
  - this can cause positive or negative errors

Engine ECM Exhaust Flow – CAN J1939 versus Lab

Engine 1



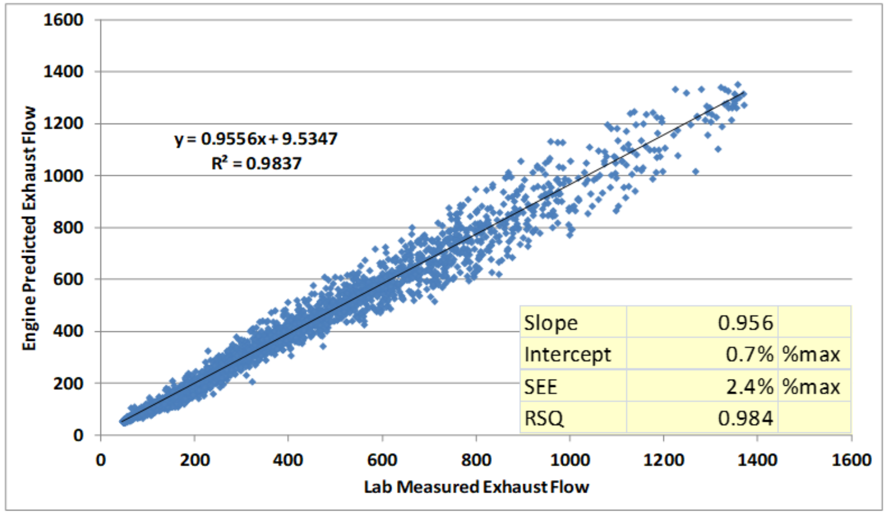
Engine 2



Data from CARB Stage 2
Low NO_X Program

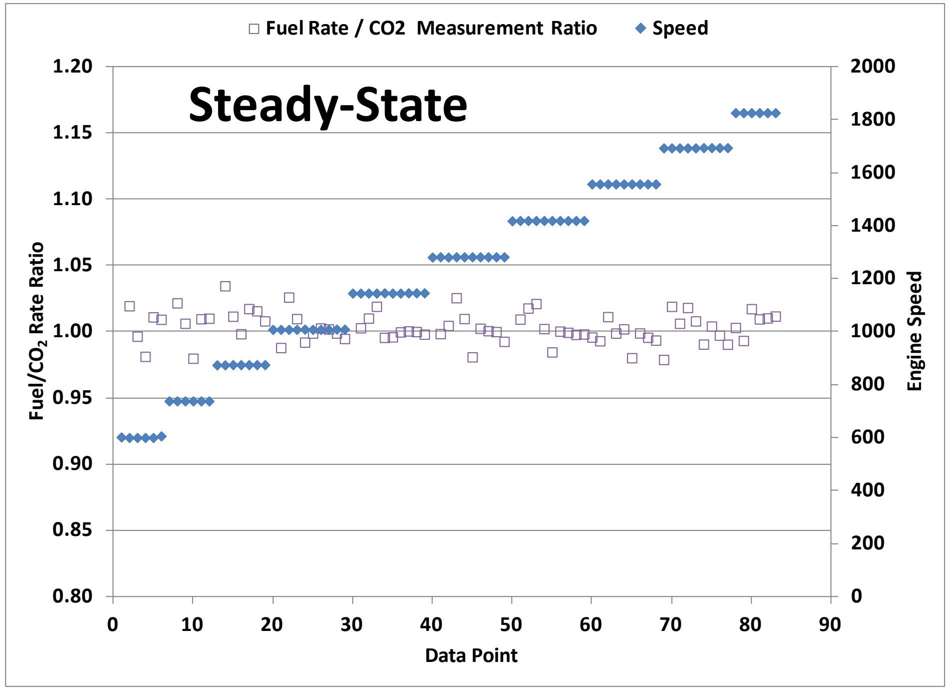
Multiple Production 2018
Heavy-Duty Engines

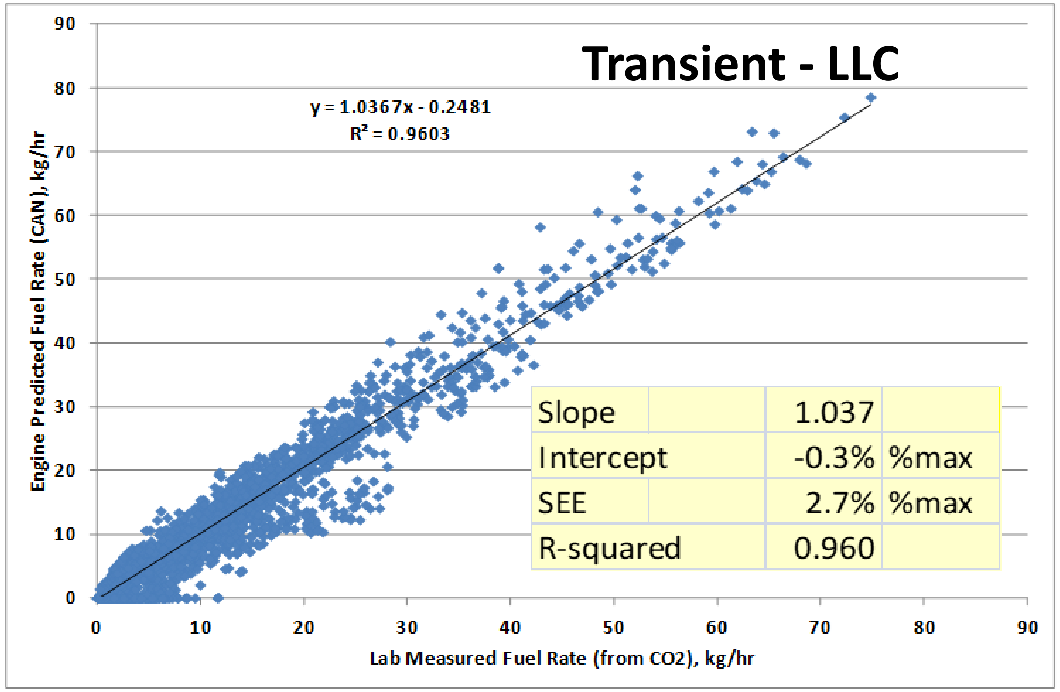
Engine 3



- ECM Exhaust Flow – sum or recorded air flow and fuel flow recorded from J1939 broadcast
  - EngInletAirMassFlowRate (kg/hr)
  - EngFuelRate (L/hr converted to kg/hr using 0.851 kg/L)
- Compared to Lab Reference
  - Measure Intake Air Flow (LFE) + 1065 Chemical Balance
- Standard Error ~ 2-3%, Span Errors < 5%

CO_2 from Engine ECM Fuel Rate – J1939 versus Lab





Slope	1.037	
Intercept	-0.3%	%max
SEE	2.7%	%max
R-squared	0.960	

- ECM Fuel Rate (J1939 EngFuelRate)
- CO_2 can be calculated from Fuel Rate
  - There will be some added error due to varying fuel carbon fraction – small for diesel
  - Likely good enough for purposes of binning
- Flow rate SEE within 3% and slope within 5%

Data from CARB Stage 2 Low NO_X Program

Multiple Production 2018 Heavy-Duty Engines

What Do These Results Indicate About In-Use Measurement ?

- PEMS
  - Overall results look relatively good – no significant biases present with automated zero or zero-span checks active and drift correction applied
  - Spread does appear wider than Lab Reference, but more analysis is needed to say how much
    - SwRI is working on a model of PEMS measurement error to allow analysis via Monte Carlo simulation approach
  - Note these are current generation PEMS, significantly better than previous evaluations
  - These results do not consider environmental impacts on PEMS
    - Are current generation PEMS better than previous equipment ?
- 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…
  - There may be potential for improvement in compensating for sensor drift and/or engine transients
  - 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