

# Real World Cycle Measurement Instrumentation Capability at Low NO<sub>x</sub> Levels for 2027 and Beyond

SOUTHWEST RESEARCH INSTITUTE®

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POWERTRAIN ENGINEERING

# Objectives for Low NO<sub>x</sub> Real World Duty Cycle Testing

1. Characterize Performance of the Low NO<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> Levels Using Representative Emission Signatures

Experimental Approach – Replay Field Duty Cycles on Stage 3RW Low NO<sub>x</sub> Engine in Lab with PEMS and Sensors

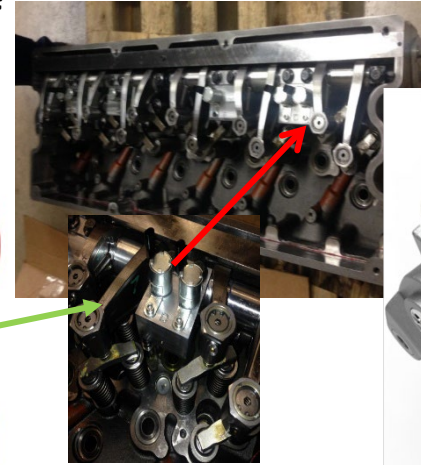
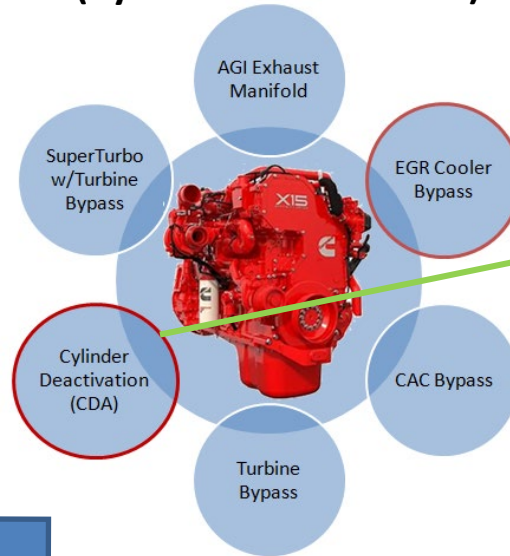
# EPA Stage 3RW Low NO<sub>x</sub> Demonstration Engine

2017 Cummins X15 Engine

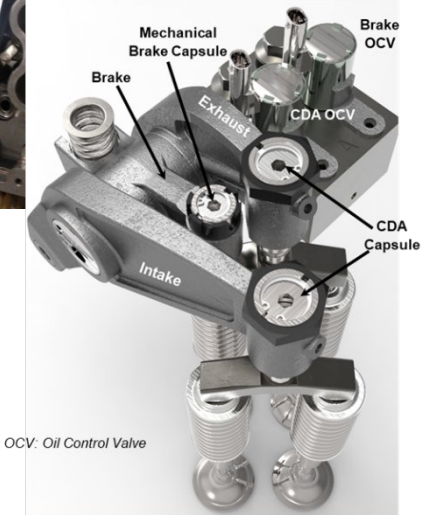


Additional Engine Hardware  
(Cylinder Deactivation)

SAE Paper  
2021-01-0589

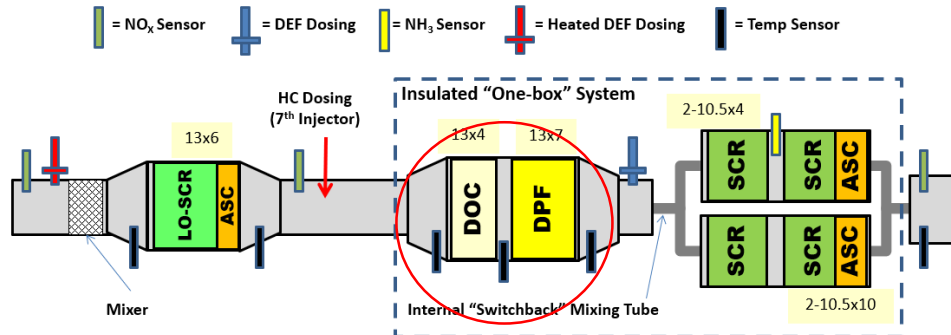


Eaton CDA Hardware



OCV: Oil Control Valve

Advanced Low NO<sub>x</sub> Aftertreatment  
(Dual SCR-Dual Dosing)



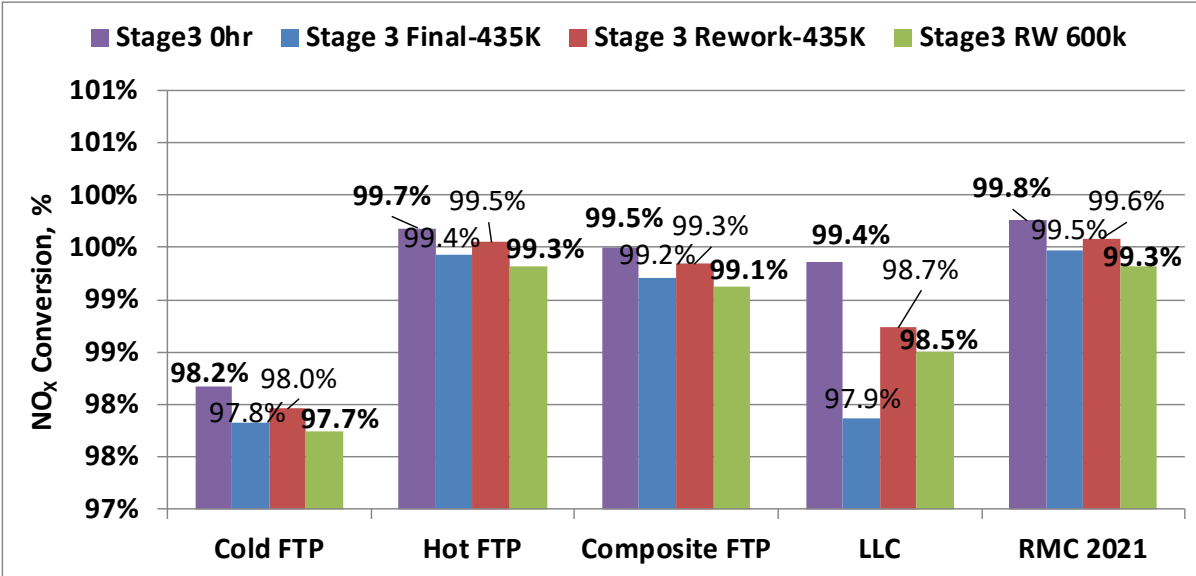
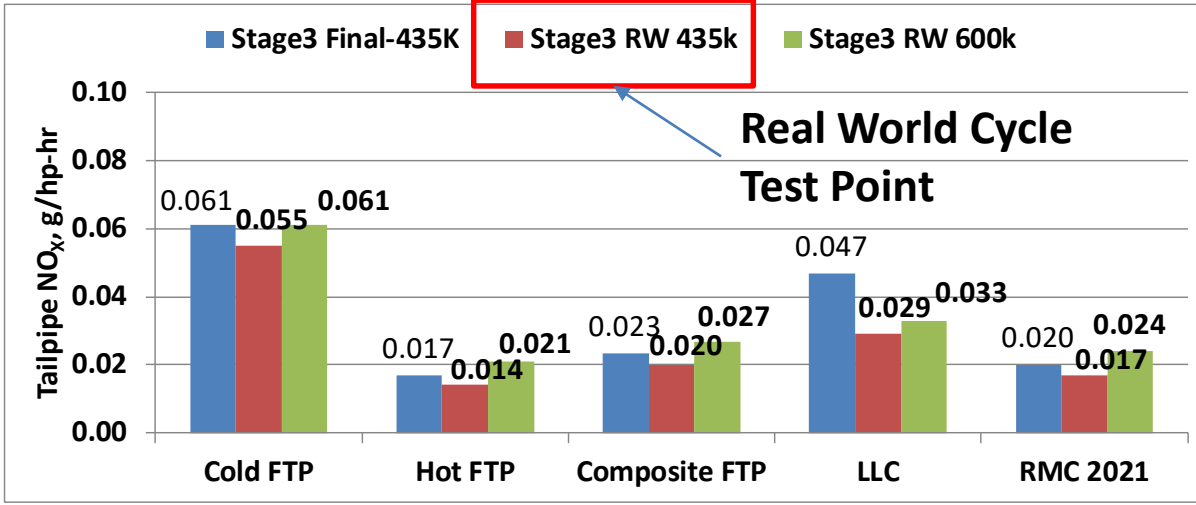
Targets:

- FTP/RMC NO<sub>x</sub> 0.02 g/hp-hr at 435k miles
- Lowest feasible LLC and in-use NO<sub>x</sub>
- No adverse GHG impact

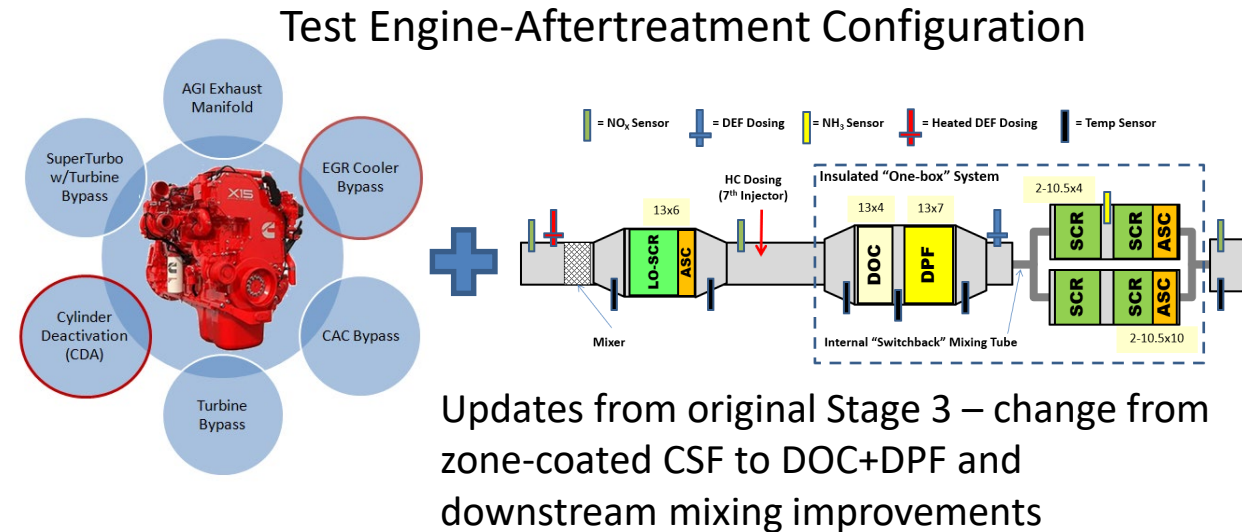
EPA Updates

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



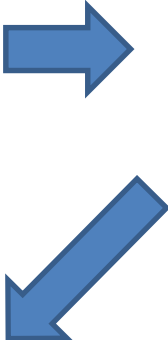
<sup>1</sup> DAAAC = Diesel Accelerated Aftertreatment Aging Cycles

<sup>2</sup> UAF = infrequent Regeneration Upward Adjustment Factor

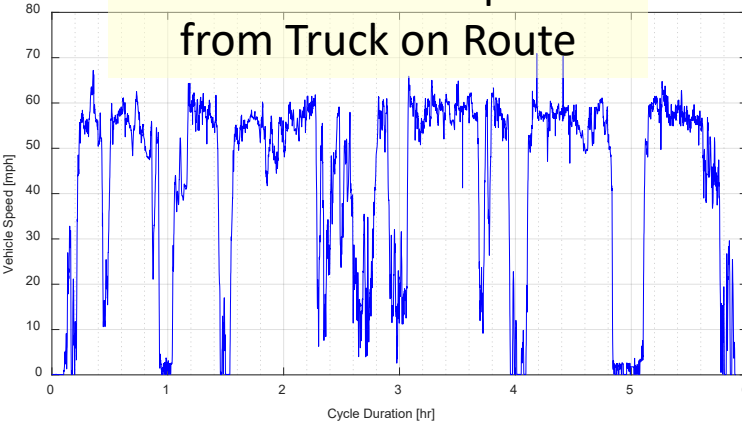
# Cycle Development Process Example – Southern NTE Route



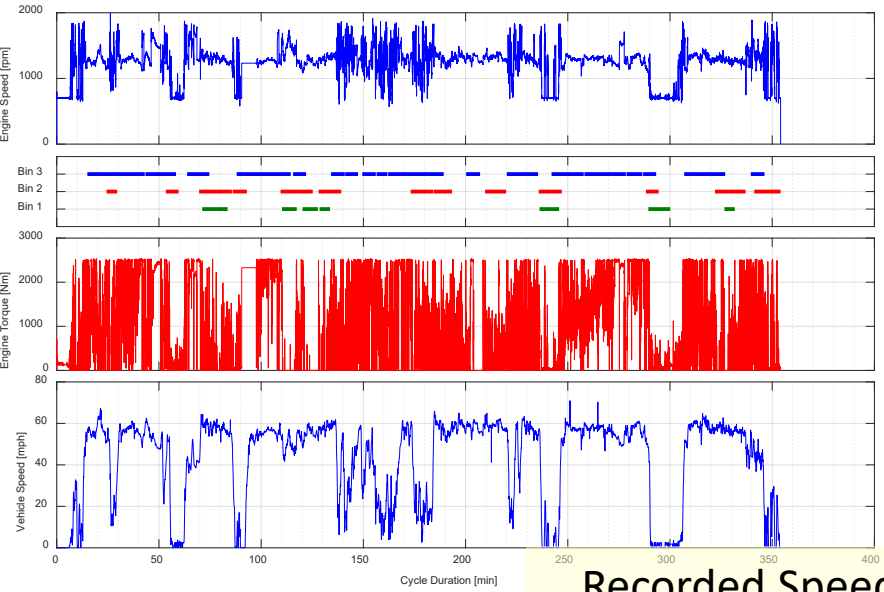
Field Route



Actual Vehicle Speed from Truck on Route

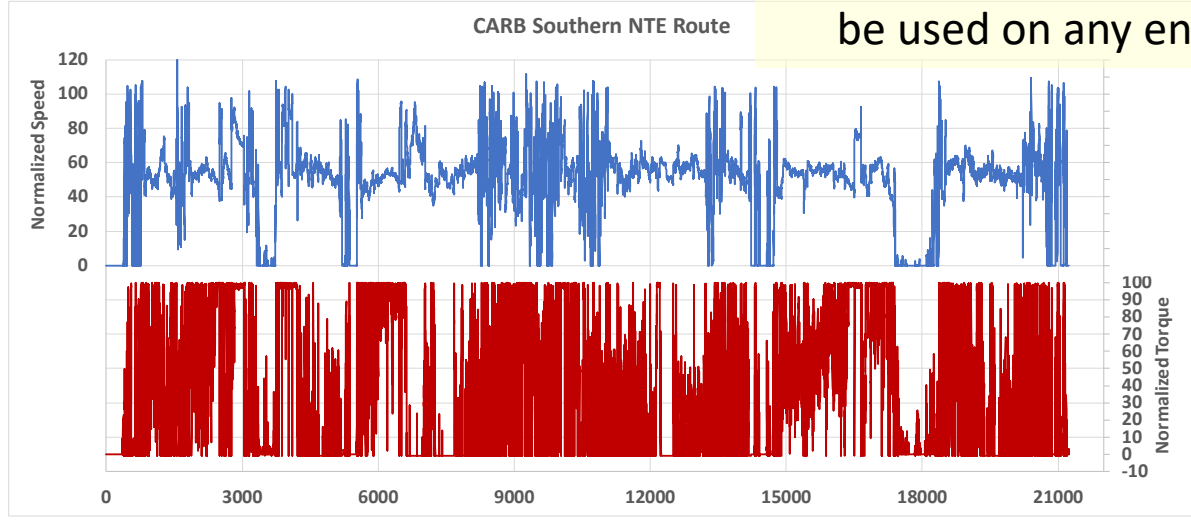


- WVU drove trucks on real-world routes
- Recorded vehicle data used along with engine torque curve information to generate Normalized engine-dyno replay cycle for Lab use



Recorded Speed/Load Data from Drive

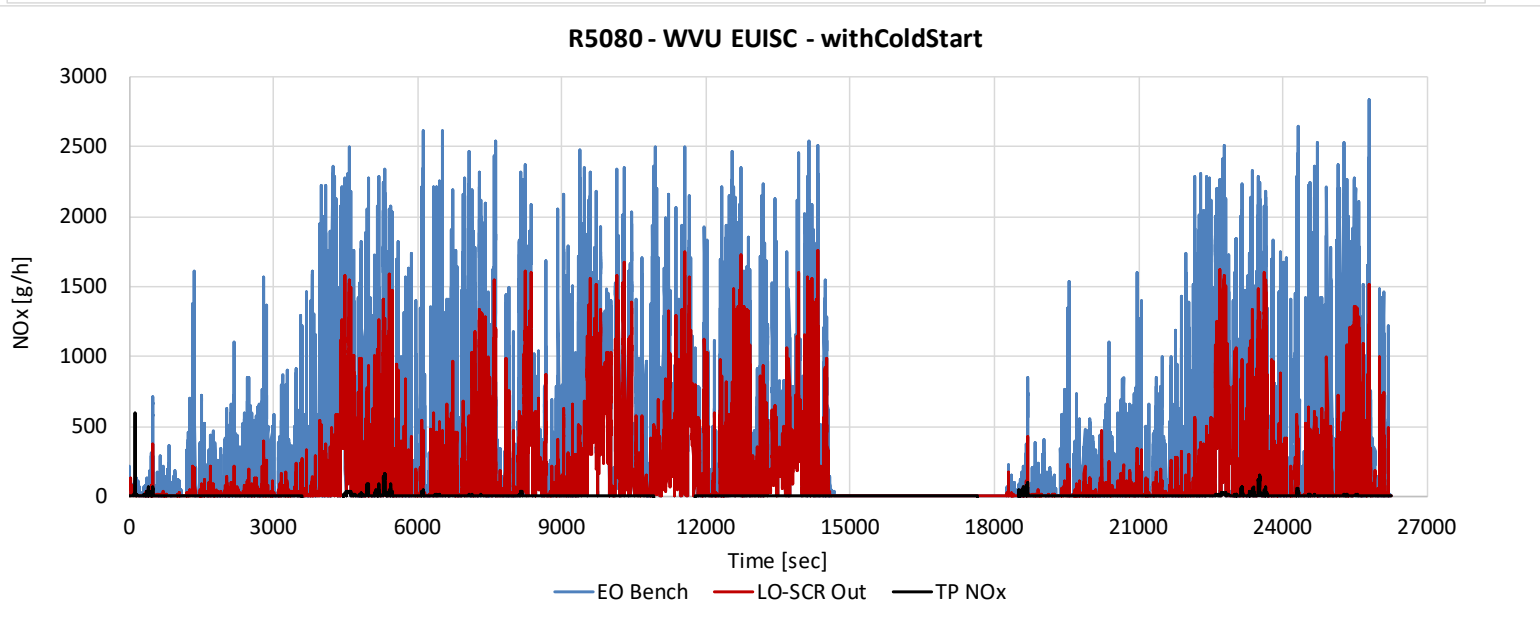
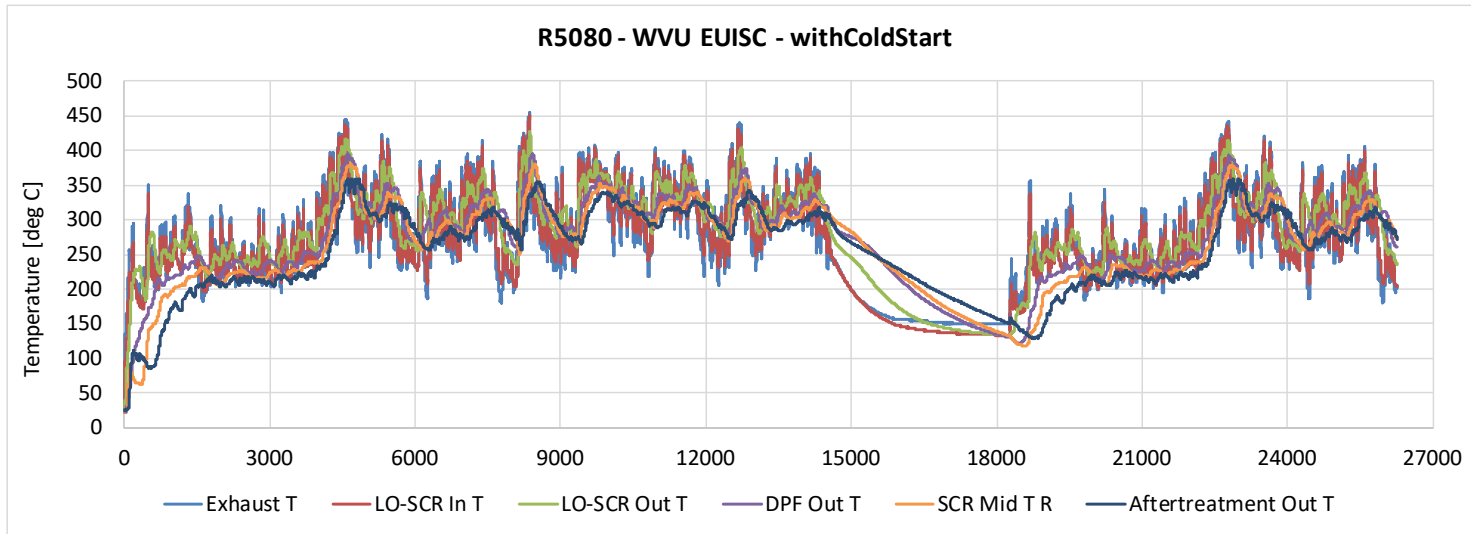
Normalized Engine Cycle (can be used on any engine)



**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<sub>2</sub>)

$$\text{window normalized average CO}_2 \text{ rate} = \frac{(\sum_{t=1}^n \dot{m}_{CO_2}(t))}{FCL \times (P_{max} \times \frac{n}{3600})}$$

	Bin	Engine Type	Normalized Average Window CO <sub>2</sub> Rate
Bin 1	Idle	Diesel Cycle	CO <sub>2</sub> normalized ≤6%
Bin 2	Low	Diesel Cycle	6% < CO <sub>2</sub> normalized ≤20%
Bin 3	Med/High	Diesel Cycle	20% < CO <sub>2</sub> normalized
	All Operation	Otto-Cycle	na

## Emission Calculations - summed totals for each bin (Bin 2/3 use sum-over-sum NO<sub>x</sub> / CO<sub>2</sub>)

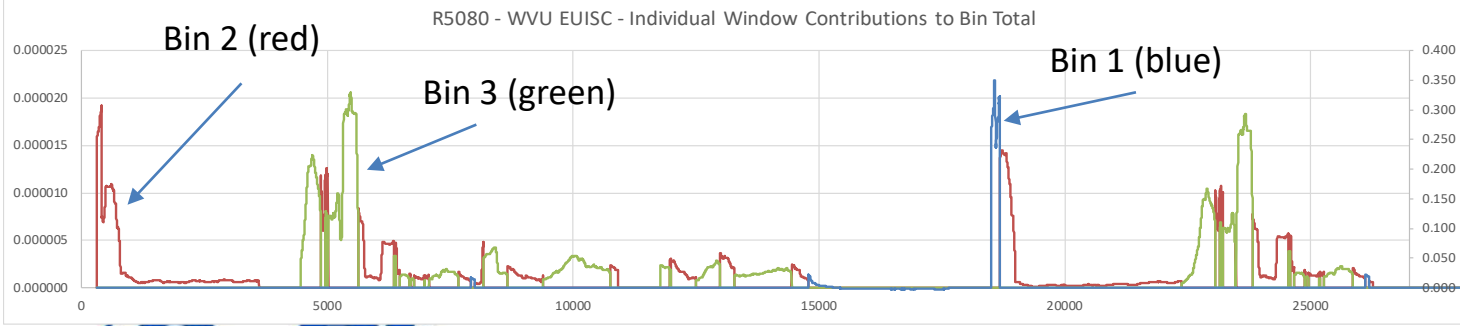
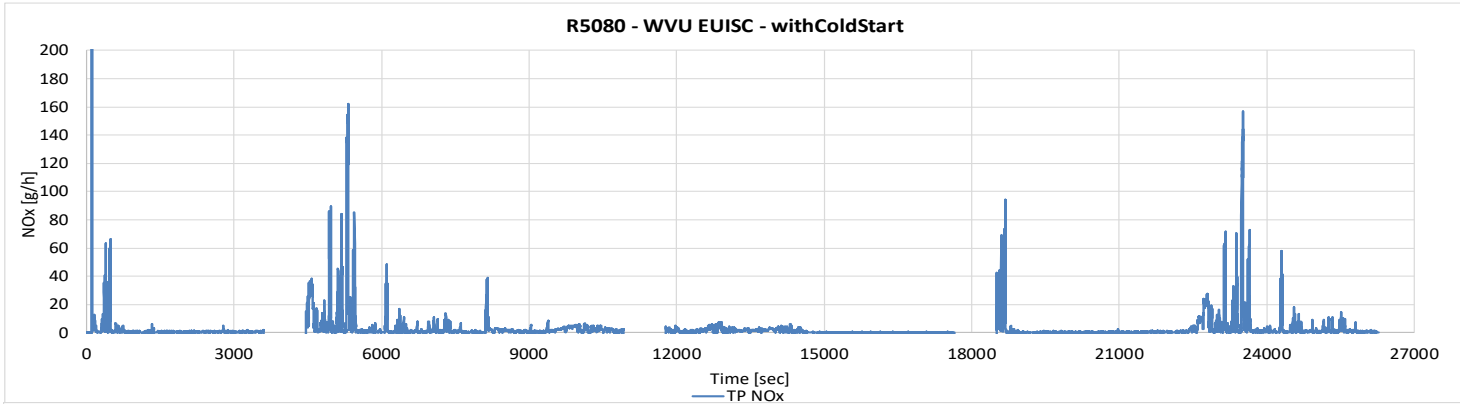
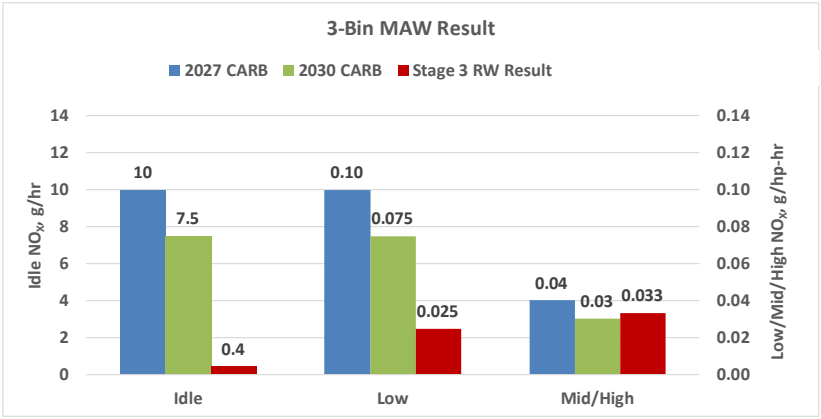
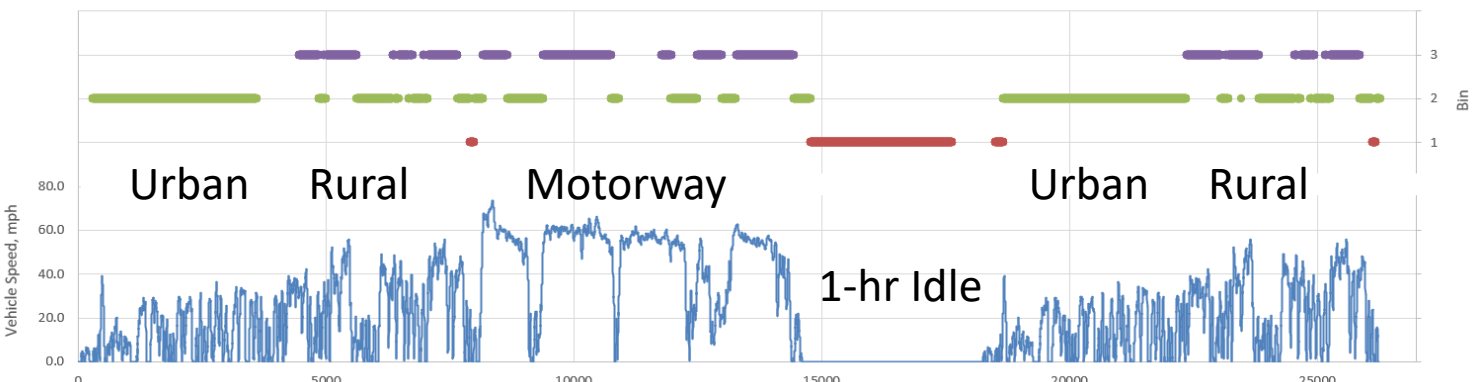
$$\text{Bin 1 } e_{sos NOx, idle} = \frac{\sum_{k=1}^n \dot{m}_{NOx} \times \Delta t}{\sum_{k=1}^n \Delta t} \times \frac{3,600 \text{ sec}}{1 \text{ hr}}$$

$$\text{Bin 2/3 } e_{sos a,b} = \frac{\sum_{k=1}^n \dot{m}_a \times \Delta t}{\sum_{k=1}^n \dot{m}_{CO_2} \times \Delta t} \times e_{CO_2, FTP, FCL}$$

- All operation is used (including cold-start starting 2027)
- 300-second Moving Average Window (MAW) – increments 1 second at a time
- NO<sub>x</sub> and CO<sub>2</sub> emissions from each window sorted into bins by normalized CO<sub>2</sub> (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<sub>x</sub>/CO<sub>2</sub>) for the bin
  - multiplied by FTP BSCO<sub>2</sub> to translate emissions to BSNO<sub>x</sub> in g/hp-hr

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

Bin Result for WVU EU-ISC Route



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

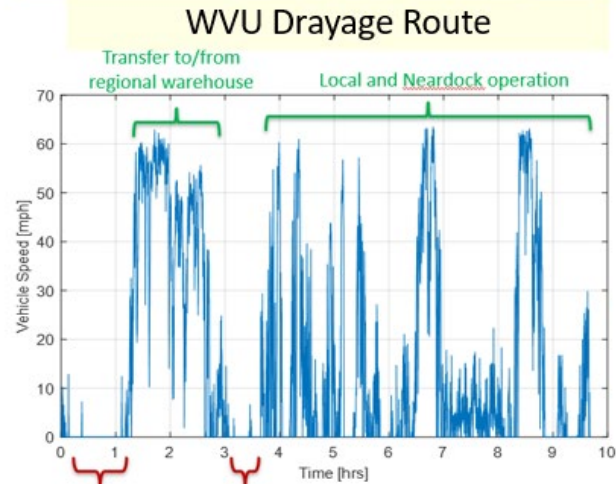
- Large margins for Bin 1 / 2
- Bin 3 is between 2027 and 2030 thresholds
- Main Bin 3 emissions occur at transition from Urban to Rural segment





# Real World Duty Cycle Results on EPA Stage 3RW Platform

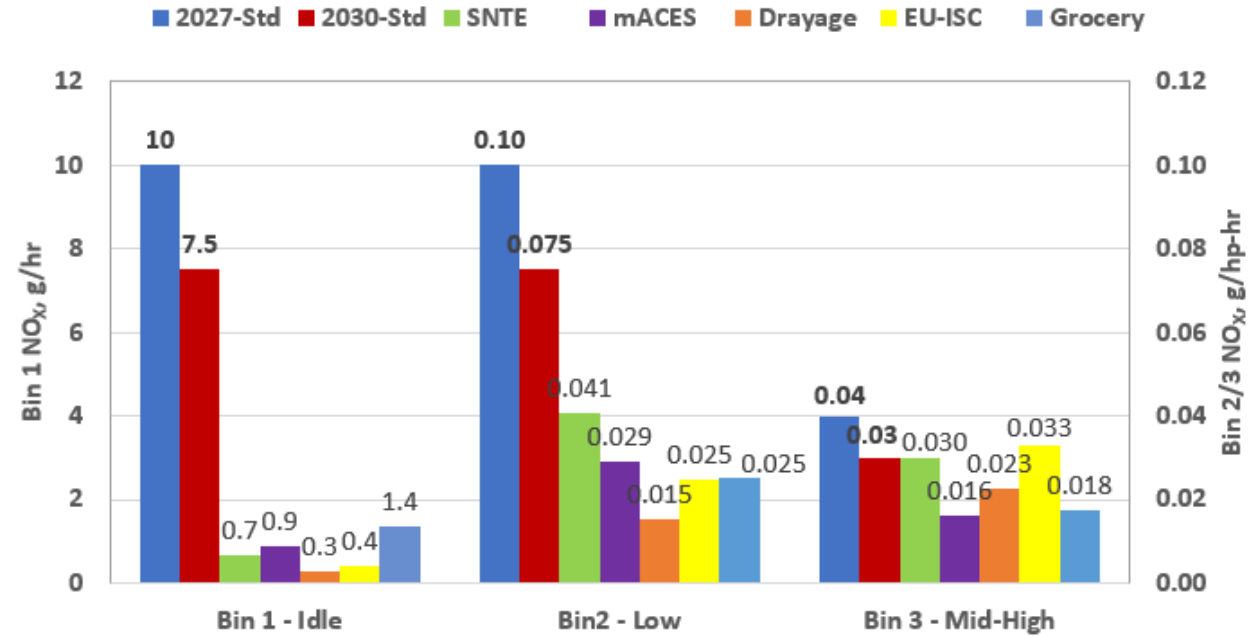
## 435,000 miles Aging



Inside port or drayage yard operation => extended idle operation

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

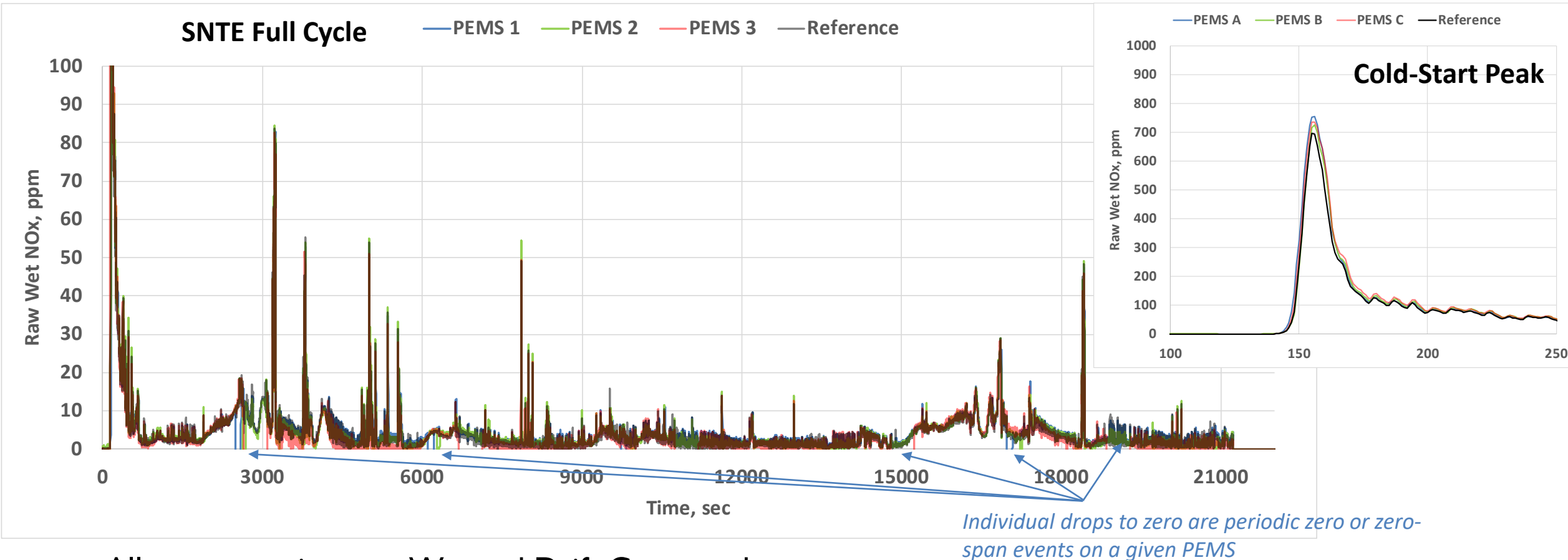


- Regulatory Cycle performance (with LLC) does translate to real-world performance for this system
- Bin 1 / 2 – below 2030 thresholds with margin
- Bin 3 – some duty cycles in but some were at or above 2030 thresholds, below 2027 but little margin

\* 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

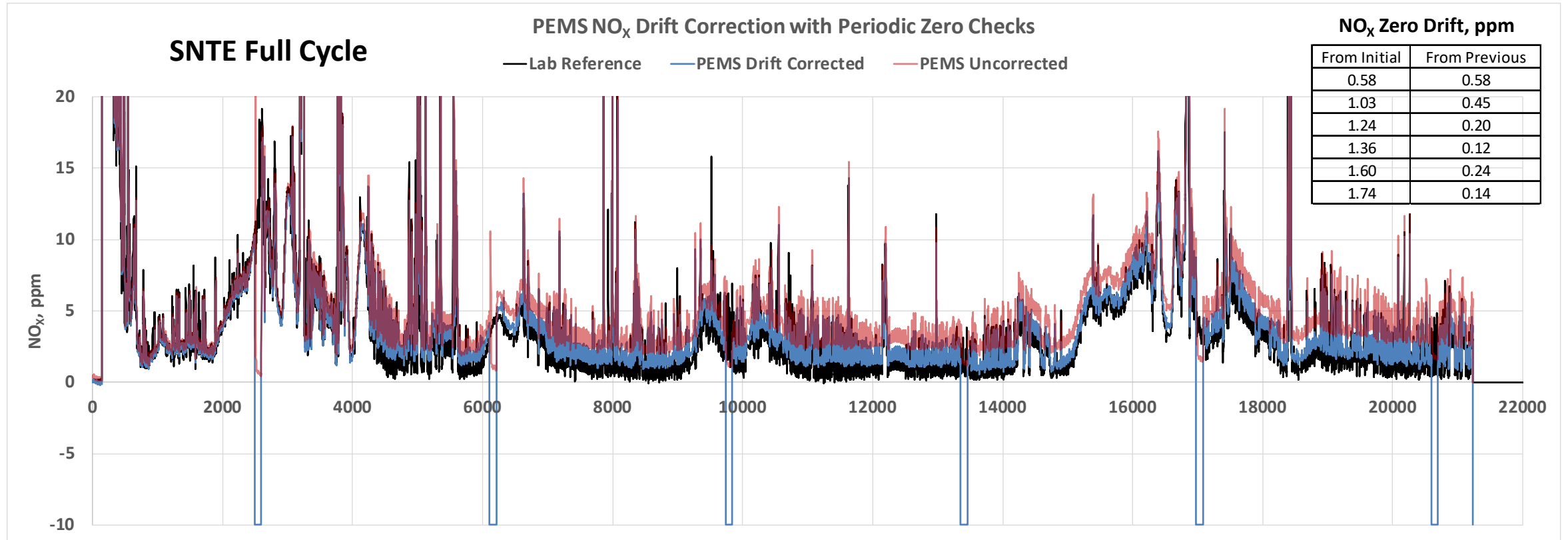


# PEMS vs Lab Reference – NO<sub>x</sub> Concentration



- All concentrations are Wet and Drift Corrected
- Overall PEMS NO<sub>x</sub> behavior very similar to Lab Reference over 6.5 hours
- Reference is average of 3 separate Lab emission benches

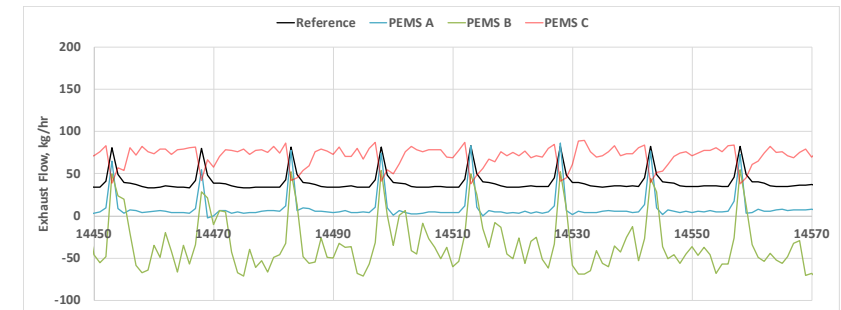
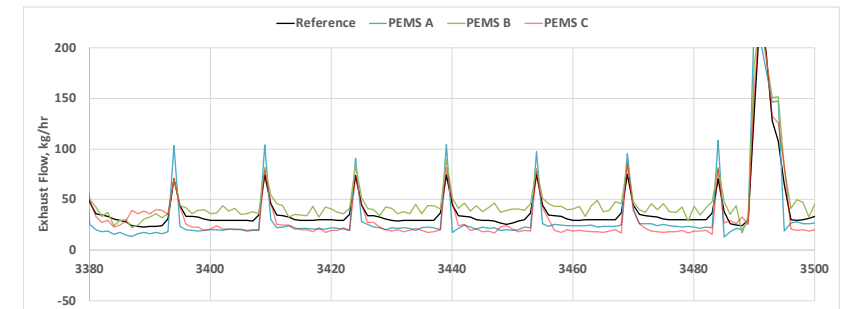
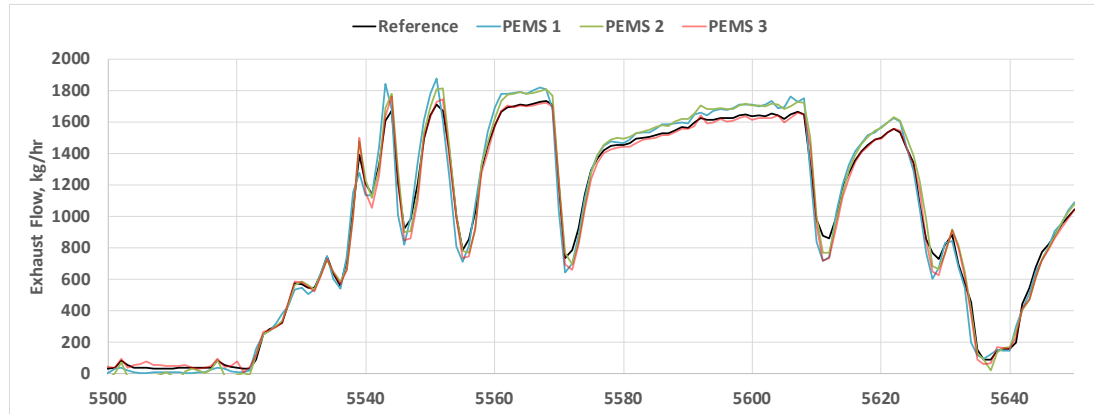
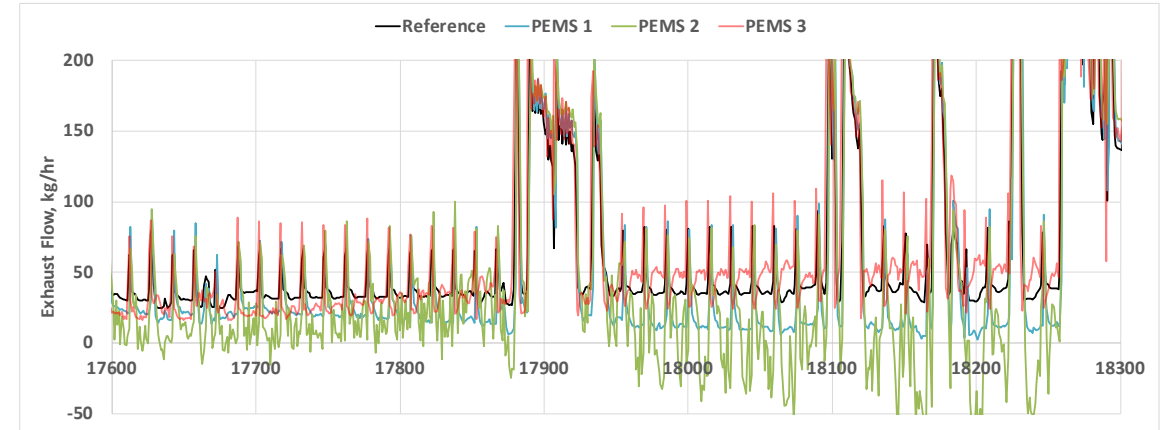
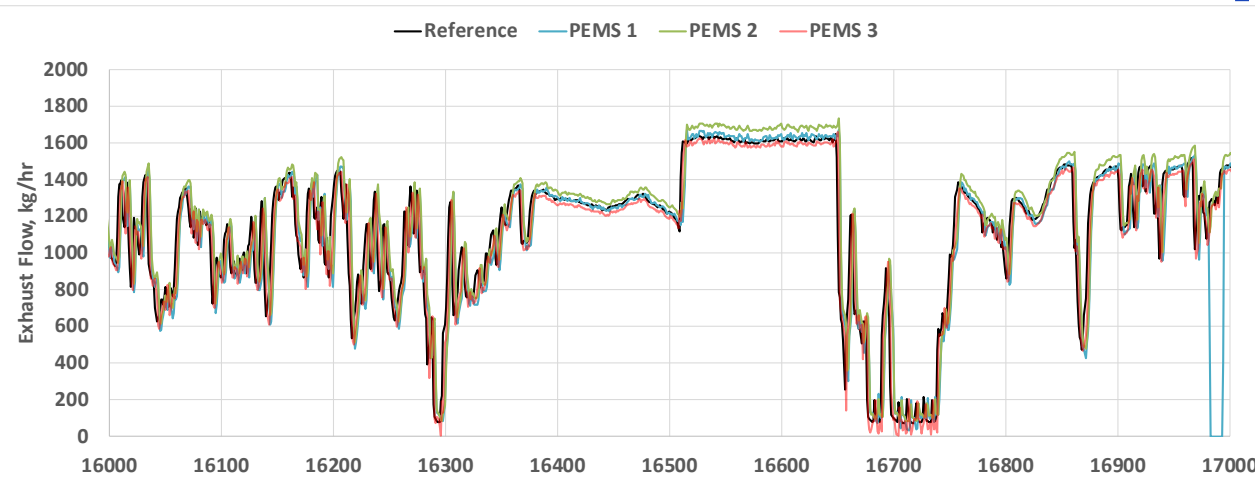
# Importance of Periodic Zero or Zero-Span and Drift Correction



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

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 – SNT E 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%)	<b>0.7</b>	0.9	0.8	0.3
Low (6%-20%)	<b>0.041</b>	0.049	0.043	0.037
Mid-High (> 20%)	<b>0.030</b>	0.035	0.034	0.031

Drayage Cycle – Stage 3RW, 435k

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

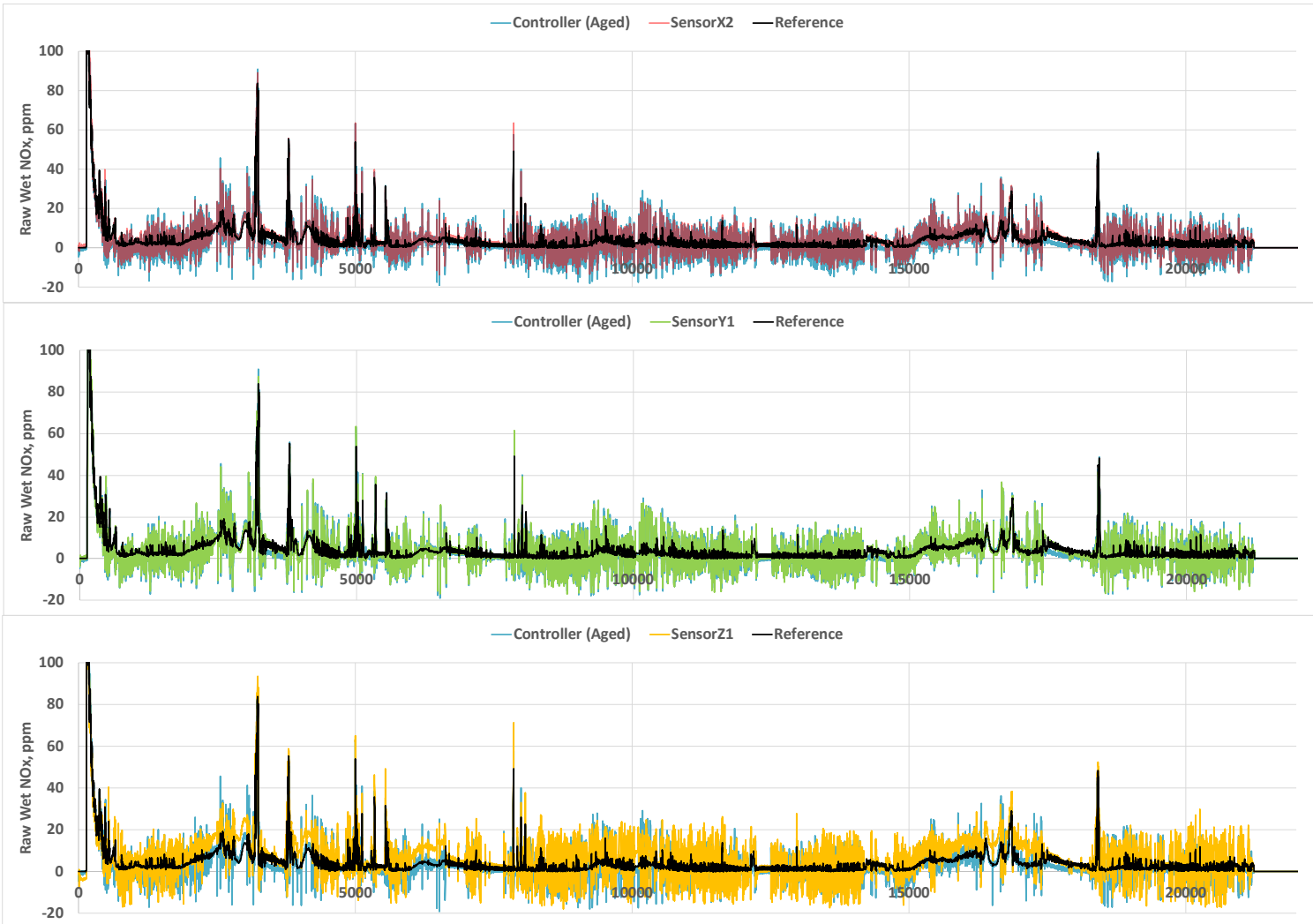
SNTE Cycle – Detuned Controls at Higher Emissions  
(0.04 g/hp-hr FTP, 0.1 g/hp-hr LLC)

Bin	Lab	PEMS A	PEMS B	PEMS C
Idle (< 6%)	<b>5.2</b>	4.3	5.5	4.9
Low (6%-20%)	<b>0.183</b>	0.163	0.162	0.175
Mid-High (> 20%)	<b>0.047</b>	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<sub>x</sub> Sensor Comparisons versus Lab Reference

## SNTE Full Cycle



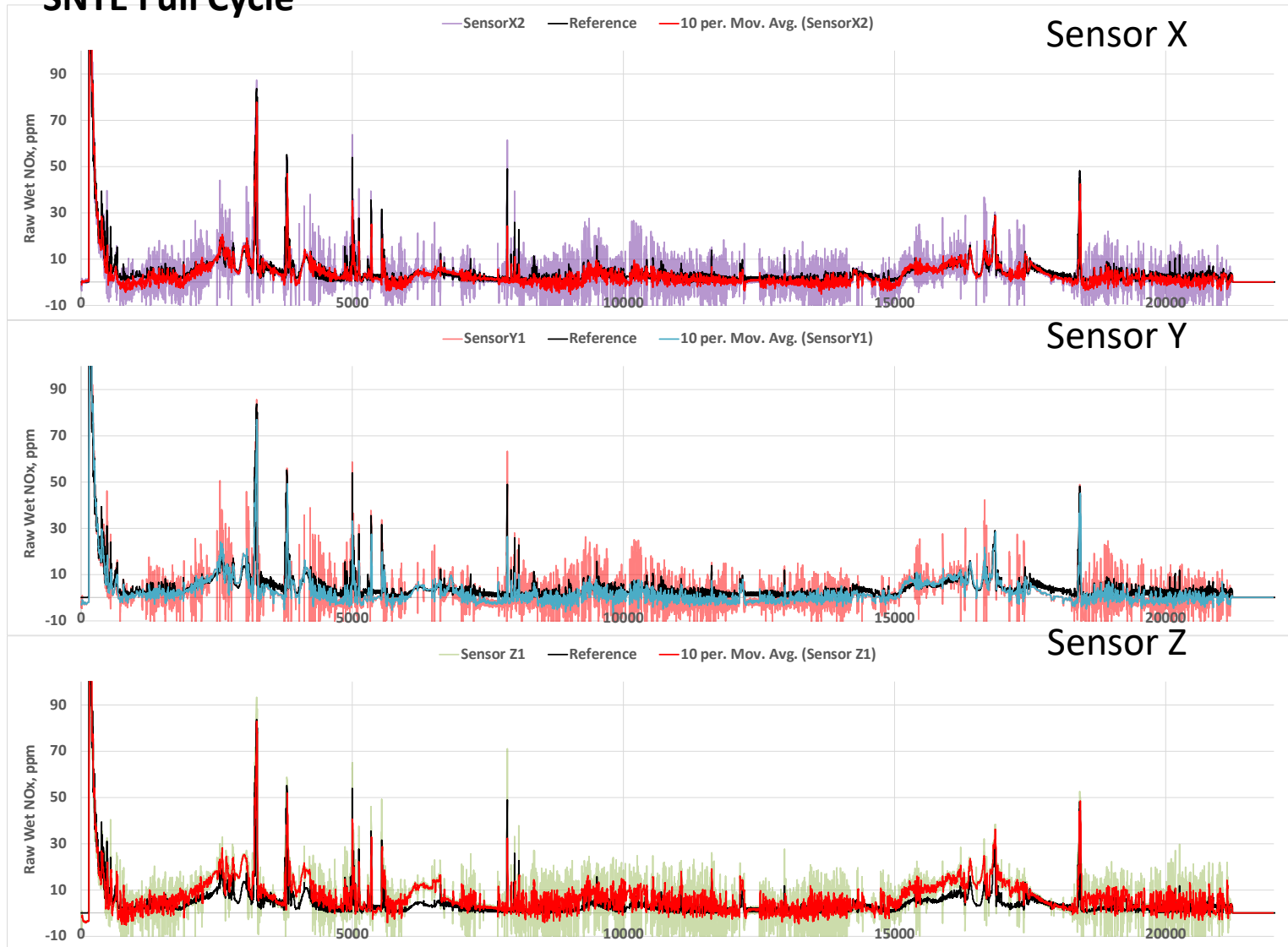
- Data is from same SNTE field cycle as PEMS examples
- Controller is tailpipe NO<sub>x</sub> sensor from test article (~1200 hours)
- Sensor X/Y/Z examples from different suppliers
  - Not Aged Sensors
- Lab Reference is same as for PEMS comparisons
- At this scale data appears to be very “noisy” compared 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 (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

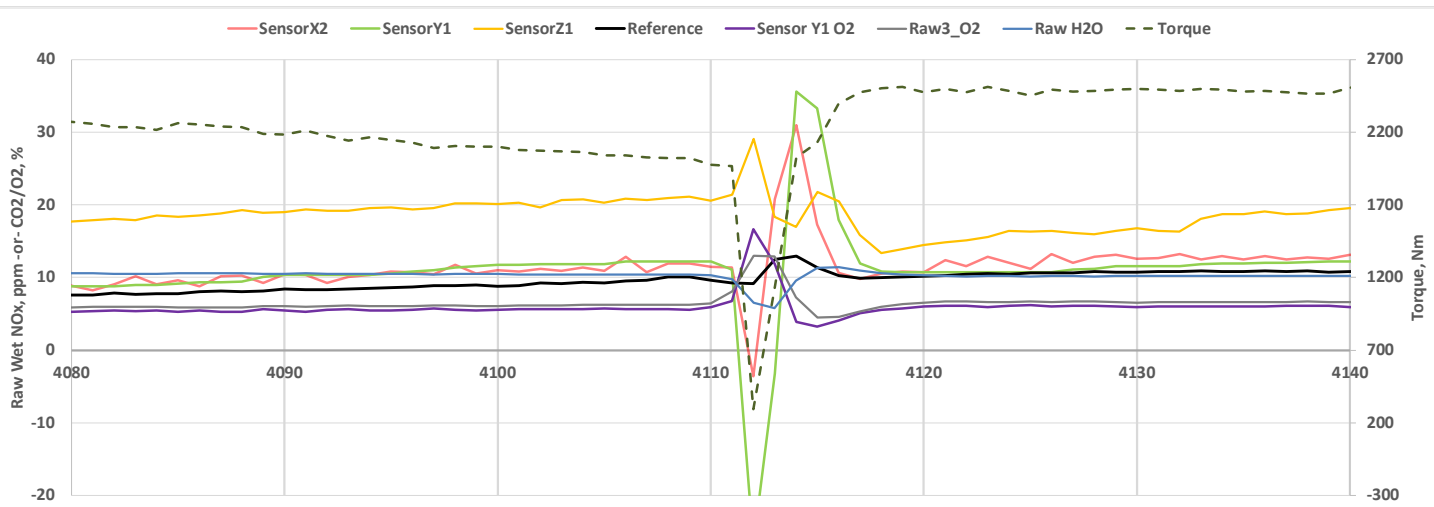
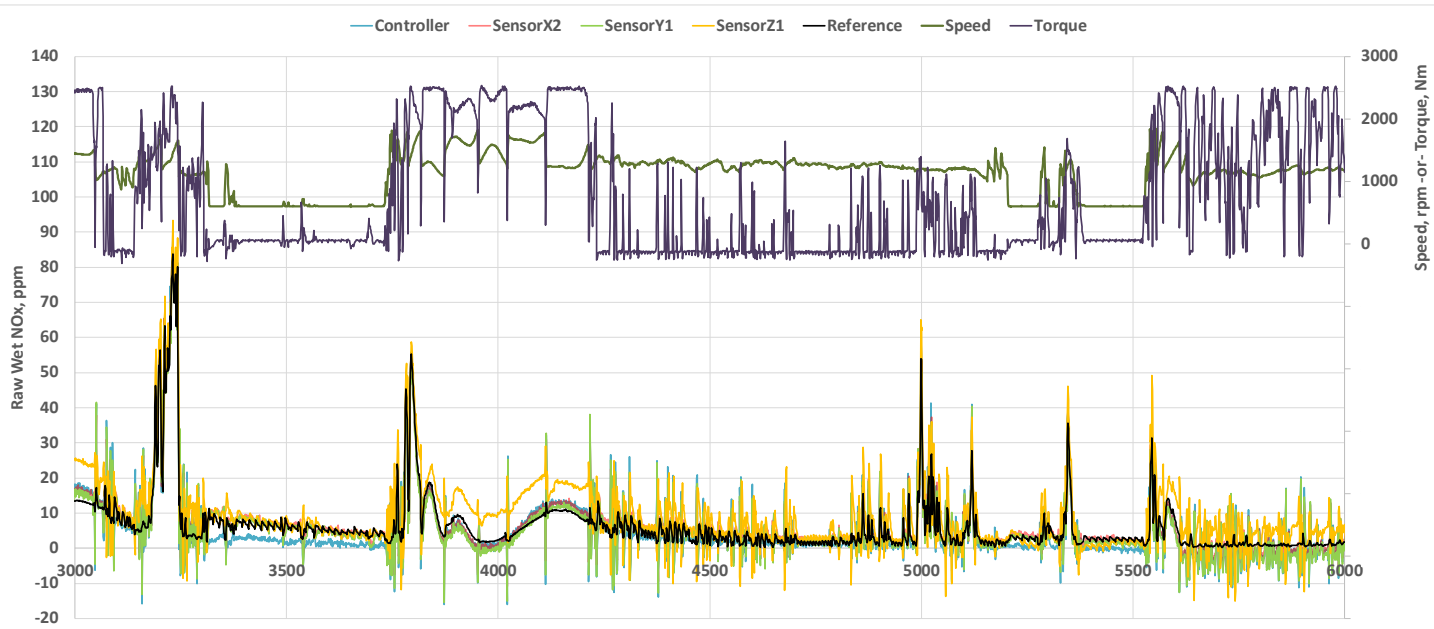
# Filtered Sensor Data Comparisons and Impact on Results

## 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<sub>x</sub> Sensor Behavior versus Engine Operation

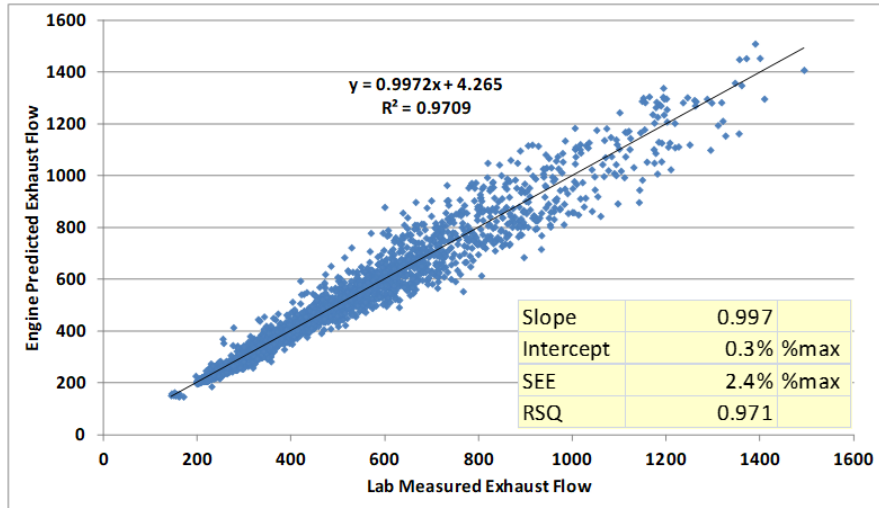


- A variety of different behaviors are seen for different kinds of engine operation
- Rapid changes in speed and/or torque result in significant “noise”
- Sensor behavior impacted by rapid rates of change in load
  - this event show a large but momentary load drop (but not quite a fuel cut event)
- Large swings in O<sub>2</sub> and/or H<sub>2</sub>O appear to cause disturbance in NO<sub>x</sub> sensor reading
  - this can cause positive or negative errors

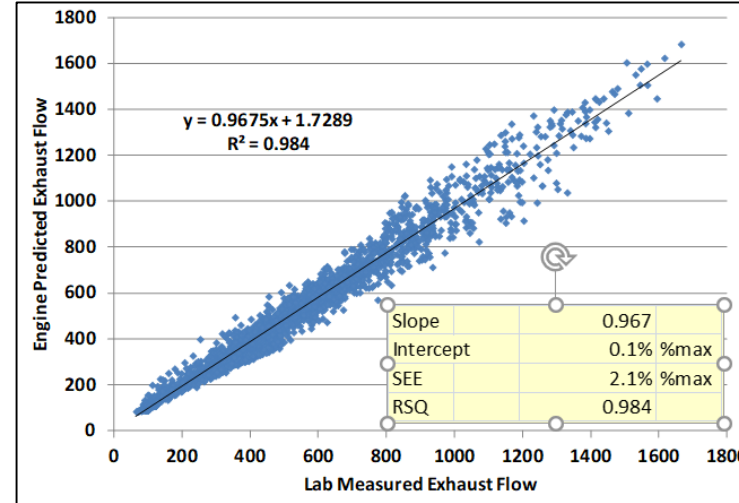


# Engine ECM Exhaust Flow – CAN J1939 versus Lab

## Engine 1



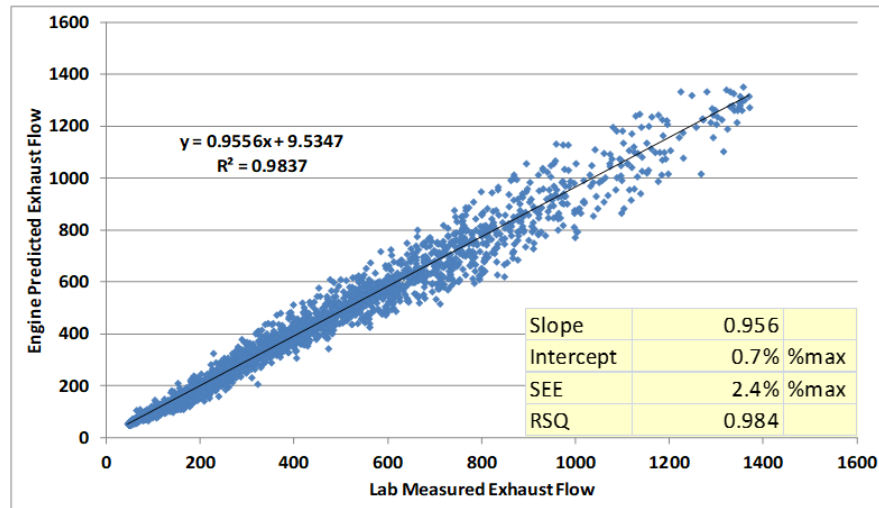
## Engine 2



Data from CARB Stage 2  
Low NO<sub>x</sub> Program

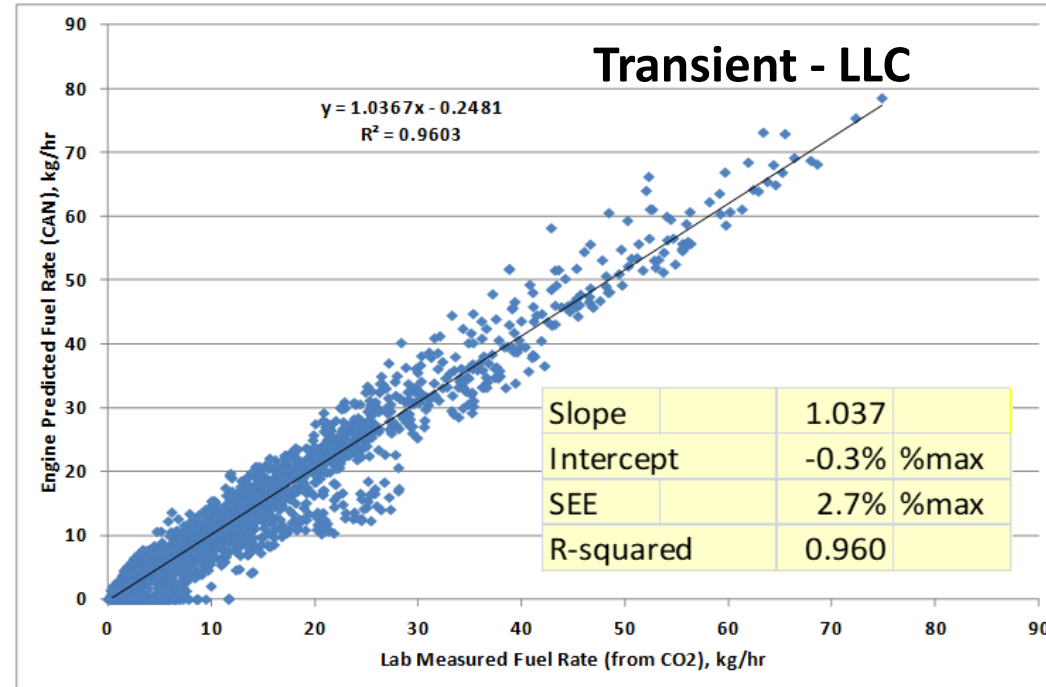
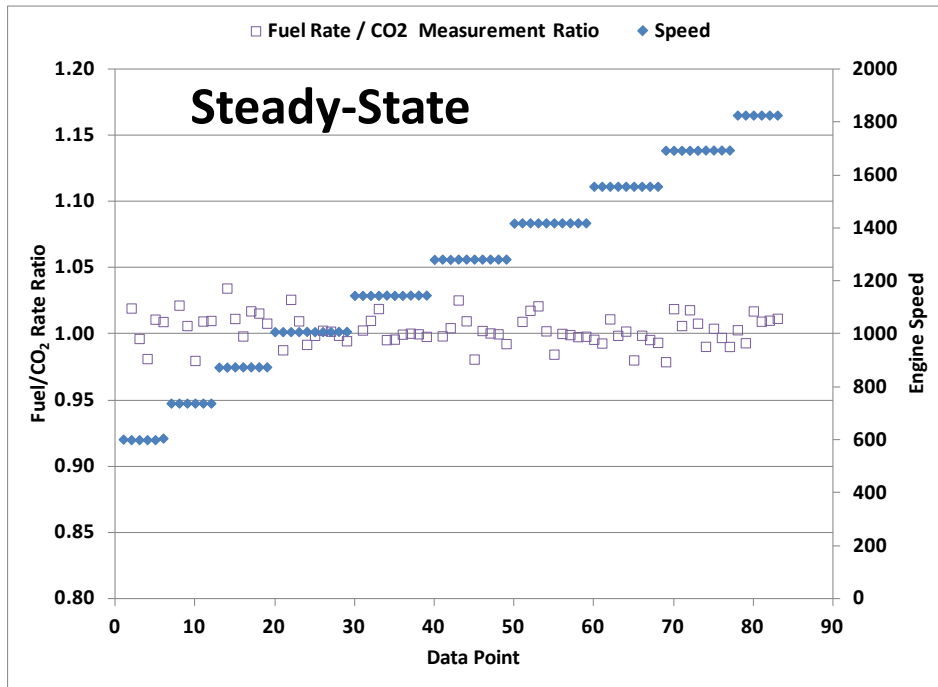
Multiple Production 2018  
Heavy-Duty Engines

## 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 0.85 l kg/L)
- Compared to Lab Reference
  - Measure Intake Air Flow (LFE) + I065 Chemical Balance
- Standard Error ~ 2-3%, Span Errors < 5%

# CO<sub>2</sub> from Engine ECM Fuel Rate – J1939 versus Lab



- ECM Fuel Rate (J1939 EngFuelRate)
- CO<sub>2</sub> 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<sub>x</sub> 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<sub>x</sub> Sensors

- Work yet to be done for “compliance level” measurements at Low NO<sub>x</sub> 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<sub>2</sub> from Fuel Rate)

- Relatively close, maybe good enough to support compliance measurements if NO<sub>x</sub> can be improved