Continuing Progress Towards 2027 Low NO_X Targets
Update on Demonstration Efforts at SwRI
2021 CLEERS Virtual Workshop

SOUTHWEST RESEARCH INSTITUTE®

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CLEERS Cross-Cut Lean Exhaust Emissions Reduction Simulations

POWERTRAIN ENGINEERING

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Low NO_X Programs at SwRI

- ***CARB Stage 1*** *– Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles (2014-2017)* - ***COMPLETE***
  - *Initial Technology Evaluation – Diesel and CNG*
  - *Primary focus on Regulatory Cycles*
- ***CARB Stage 1b*** *– Repeat Aging and Evaluation of Stage 1 Hardware (2018-2019)* - ***COMPLETE***
  - *Answer questions from Stage 1 and provide robust parts for Stage 2*
- ***CARB Stage 2*** *– Heavy-Duty Low Load Emission Control (2017-2019)* - ***COMPLETE***
  - *Expand previous technology evaluation to low-load and urban operating cycles*
- **CARB Stage 3** – Further Evaluation and Development of Low NO_X Technologies on 2017 (non-Turbocompound) Engine Platform (2018-2020) – ***COMPLETE***
  - Focus on both Low Load (Real world) and Regulatory cycles
  - ***Stage 3b – Engine Hardware Technology Effort organized by SwRI to augment Stage 3***
- ***EPA Continued Low NO_X Efforts on Stage 3 Engine (2020-2022) – In Progress***
- Nonroad Stage 1 - Baseline Testing and Modeling (2019-2020) – ***Completed***
- Nonroad Stage 2 - Technology Demonstration (2020-2022) – ***In Progress***

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Continued EPA Low NO_X Efforts

- Aftertreatment Updates
  - Stage 3 Re-worked (Stage3RW) System – improvements to Stage 3 hardware for increased durability and performance
  - EPA Aftertreatment System A
    - Updated architecture similar to Stage 3, but further improved
    - Updated formulations – improved and more durable low temperature performance
    - Slightly larger catalyst sizing in some areas
    - Incorporate lessons learned in Stage 3 work for further improved durability and performance
  - EPA Aftertreatment System B
    - Underfloor-only configuration
- Longer aging times – both systems to be tested at 600,000 miles and 800,000 miles equivalent (DAAAC aging including chemical and thermal components)
- Examination of real-world duty cycle performance (shared effort with EMA)
- Examination of PEMS measurement capability at Low NO_X (shared effort with EMA)

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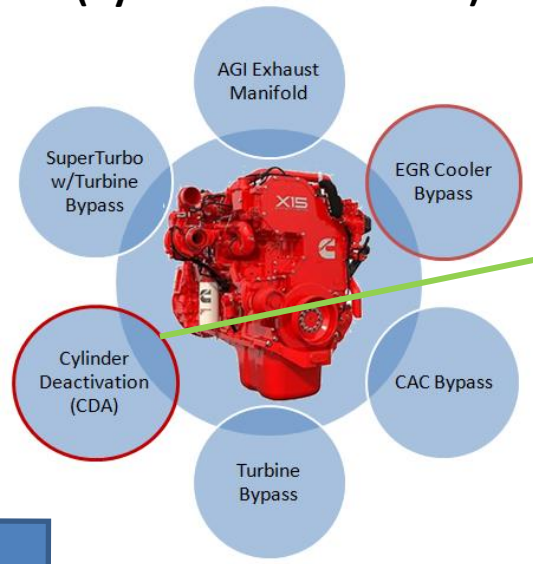
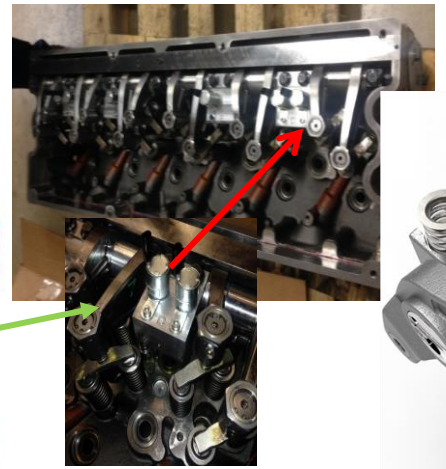
CARB Stage 3 Low NO_X Demonstration Program

2017 Cummins X15 Engine

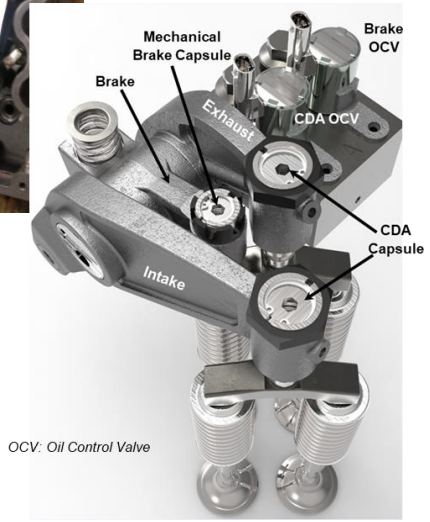
SAE Paper
2021-01-0589

Additional Engine Hardware (Cylinder Deactivation)

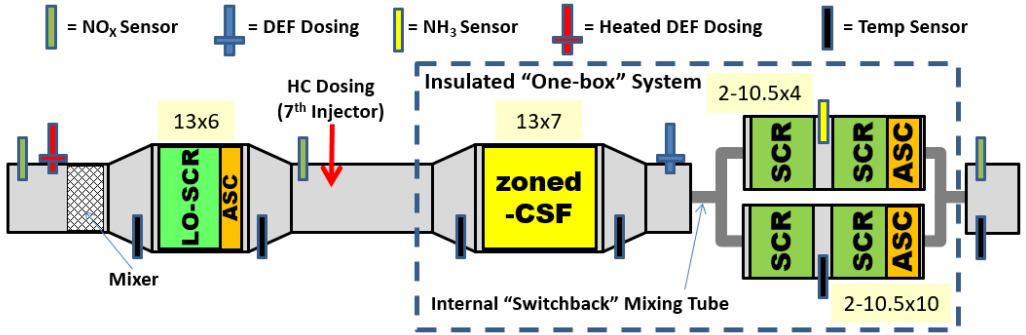




Eaton CDA Hardware



Advanced Low Aftertreatment (Dual SCR-Dual Dosing)



Targets:

- **FTP/RMC NO_X 0.02 g/hp-hr**
- **Lowest feasible LLC and in-use NO_X**
- **No adverse GHG impact**

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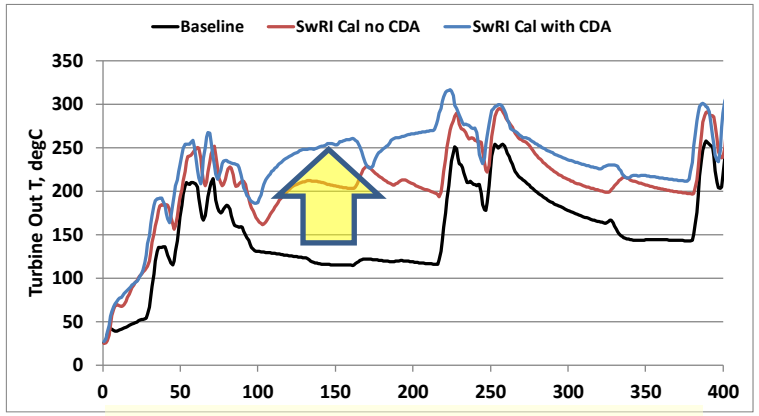
Stage 3 Engine and Aftertreatment Controls

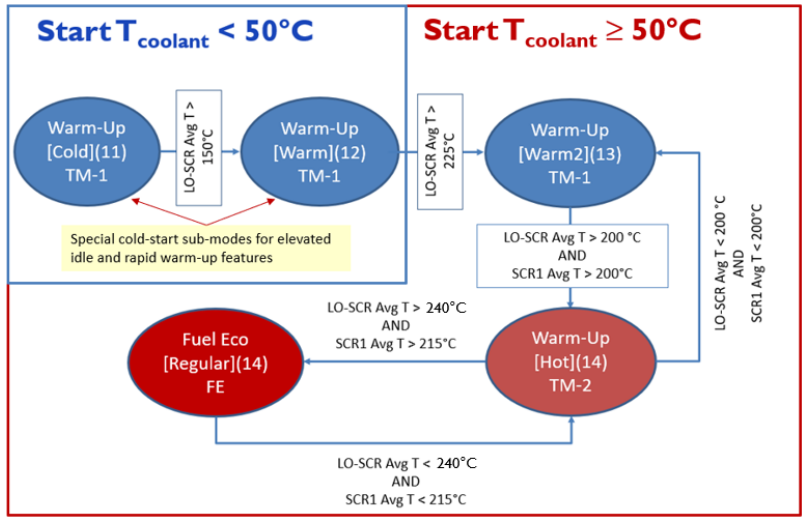
Engine Controls



50-125°C Higher Temperature in early Cold-Start

- Modified Engine Calibration and Hardware
  - CDA, modifications to EGR, VGT, injection, multiple injections, cold-start elevated idle, etc.
- Increased Temperature and Reduced NO_X when Aftertreatment is Cold
- Minimize Impact in CO_2 over Cycles

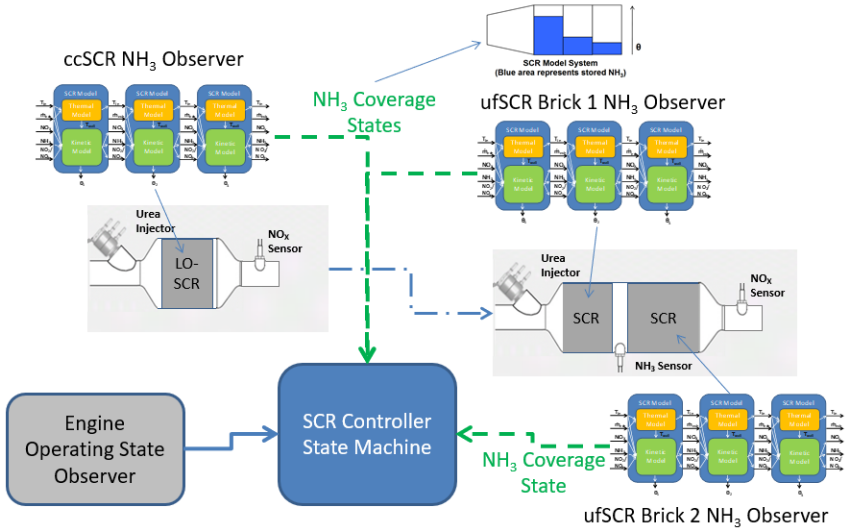
Thermal Management/Strategy



FE = Fuel Economy Mode (Highest EO NO_X)
TM-1 = Aggressive Thermal Management (Lowest EO NO_X)
TM-2 = Low Thermal Management (Moderate EO NO_X)

- Production oriented multi-mode thermal strategy
- Based on coolant and AT system temperatures
- Balance AT system temperature and fuel consumption

Aftertreatment Controls



- Model-Based Aftertreatment Controls
  - Flexible single calibration for wide variety of real-world conditions
- High Precision
  - Feedback via NH_3 sensor
  - Long-term trim via NO_X sensors

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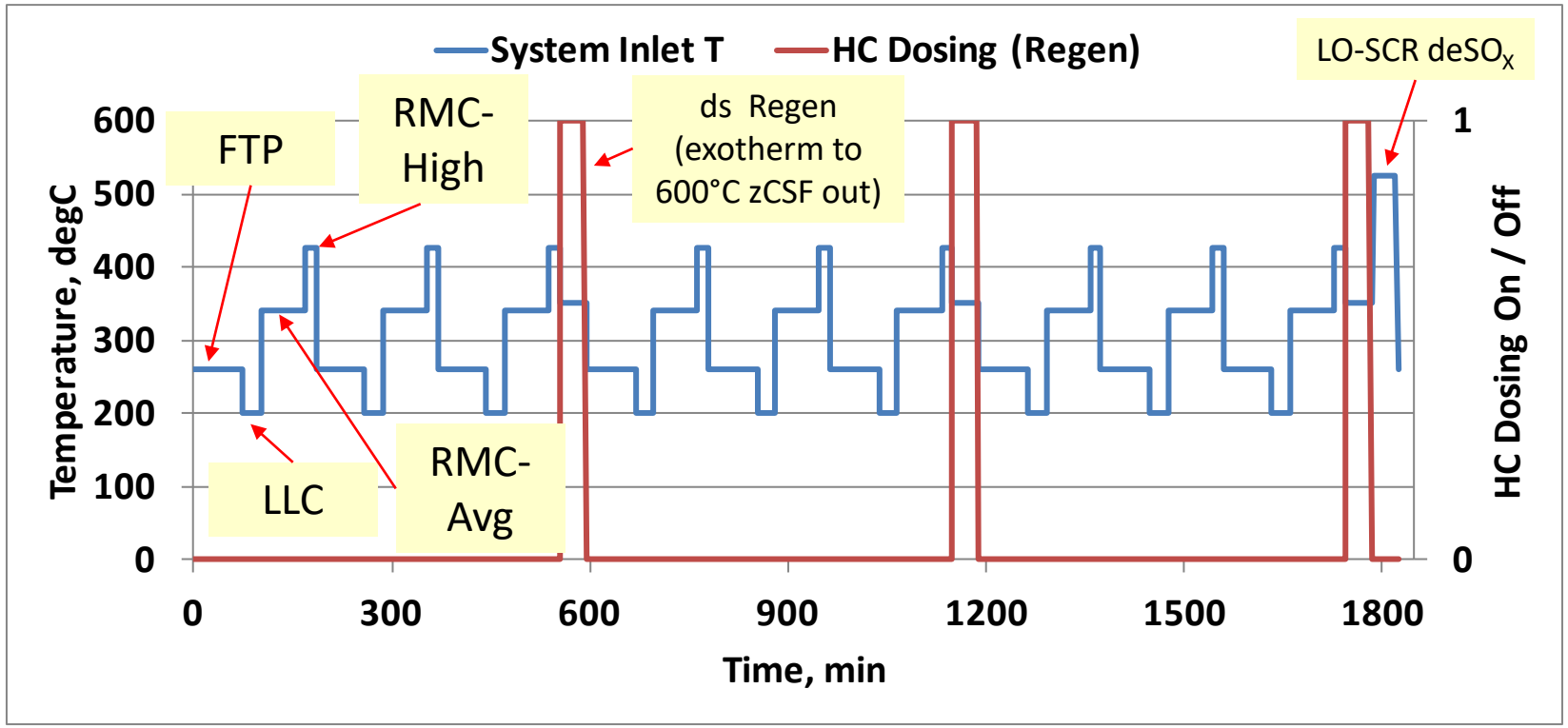
Stage 3 DAAAC-Based Accelerated Aging Cycle



1,000 Hours DAAAC Aging

=

10,000 Hours Field Aging (435,000 miles)

- Regeneration 30 min every 100 hours at 600°C zCSF Outlet Temperature
  - Regeneration using actual exotherm via 7th injection fuel injection in front of zCSF
- LO-SCR long-term $deSO_X$ 30 min every 300 hours at 525°C LO-SCR Inlet T (later modified to 550°C)
- Oil exposure at 10X (combination of modified engine and fuel doping)
- Sulfur exposure at 10X (extra sulfur doped in fuel ~ 2.5ppm SO_2 in exhaust)
- Chemical exposure – 138 kg oil, 183 g/L sulfur on LO-SCR – peak filter ash load 35 g/L reached every 500 hours

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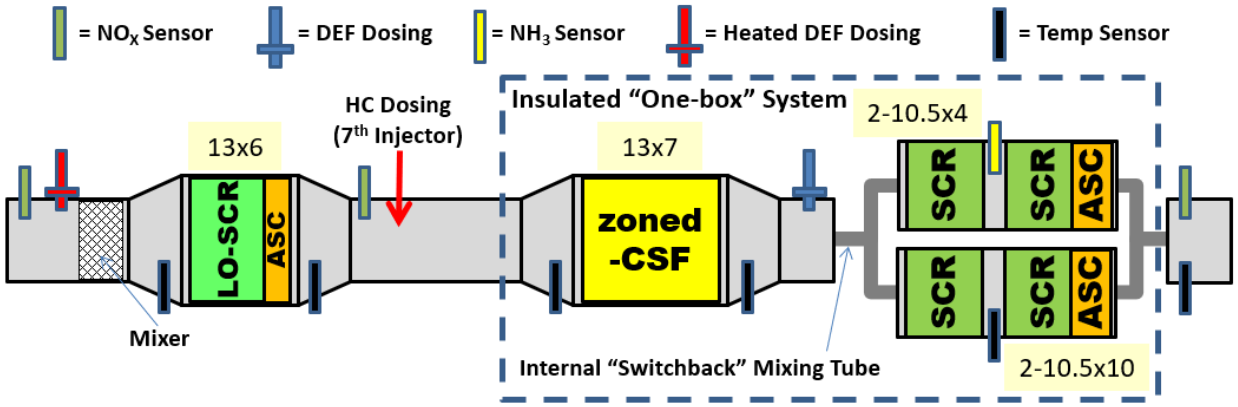
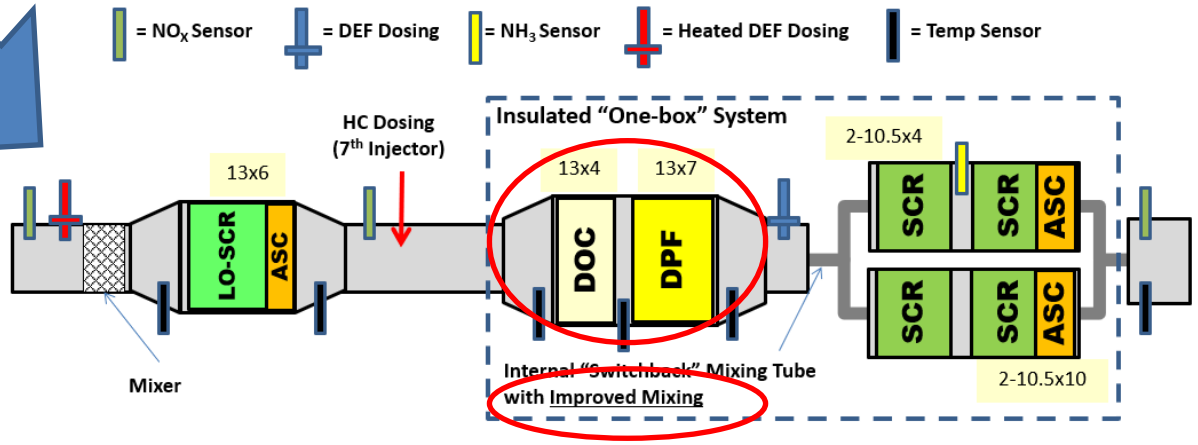
EPA Low NO_X R&D - Further Aftertreatment System Refinement

Stage 3



- Replaced zCSF with DOC+DPF
  - DAAAC-aged to 435,000 miles under identical conditions
- Same SCR catalyst assemblies
- Further improved downstream mixing (added mixing hardware)

EPA Stage 3 Rework



- Further planned efforts
  - Aging to 600,000 and 800,000 miles
  - Additional AT system tests with further updated system designs

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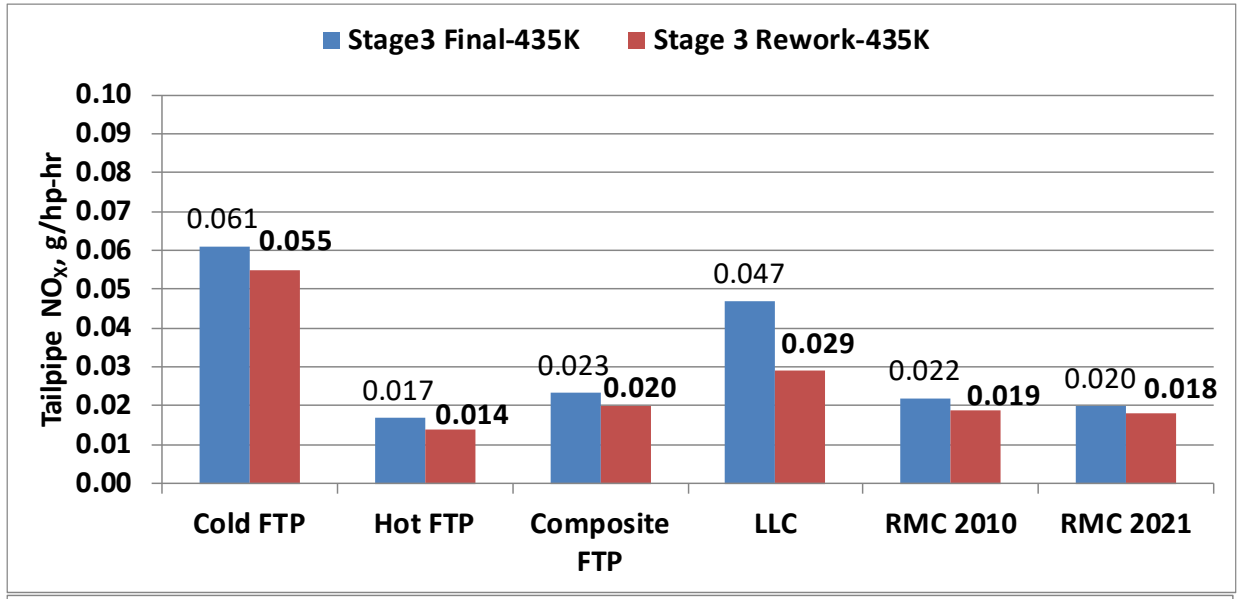
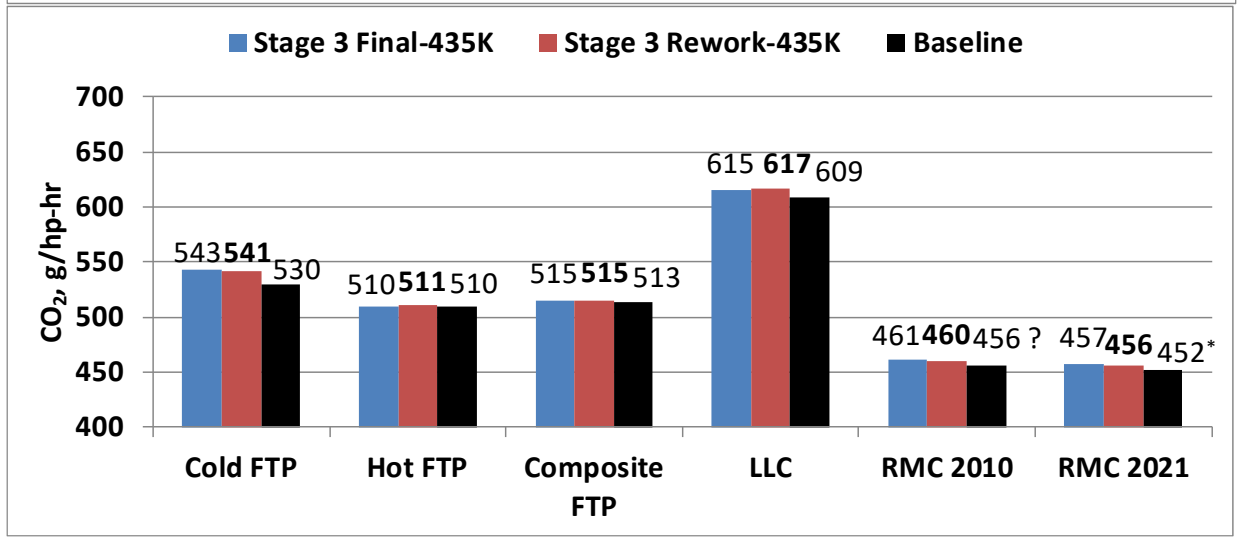
Final Cycle Results on Stage 3 RW – 435,000 miles





- Results are average of triplicate tests
- Tailpipe emissions with DOC+DPF instead of zCSF show improvement
- Better NO-NO_2 oxidation improved downstream system performance at lower temperatures
- Better mixing on downstream system at high load
- CO_2 still generally neutral except LLC which is + 1% to +1.3%

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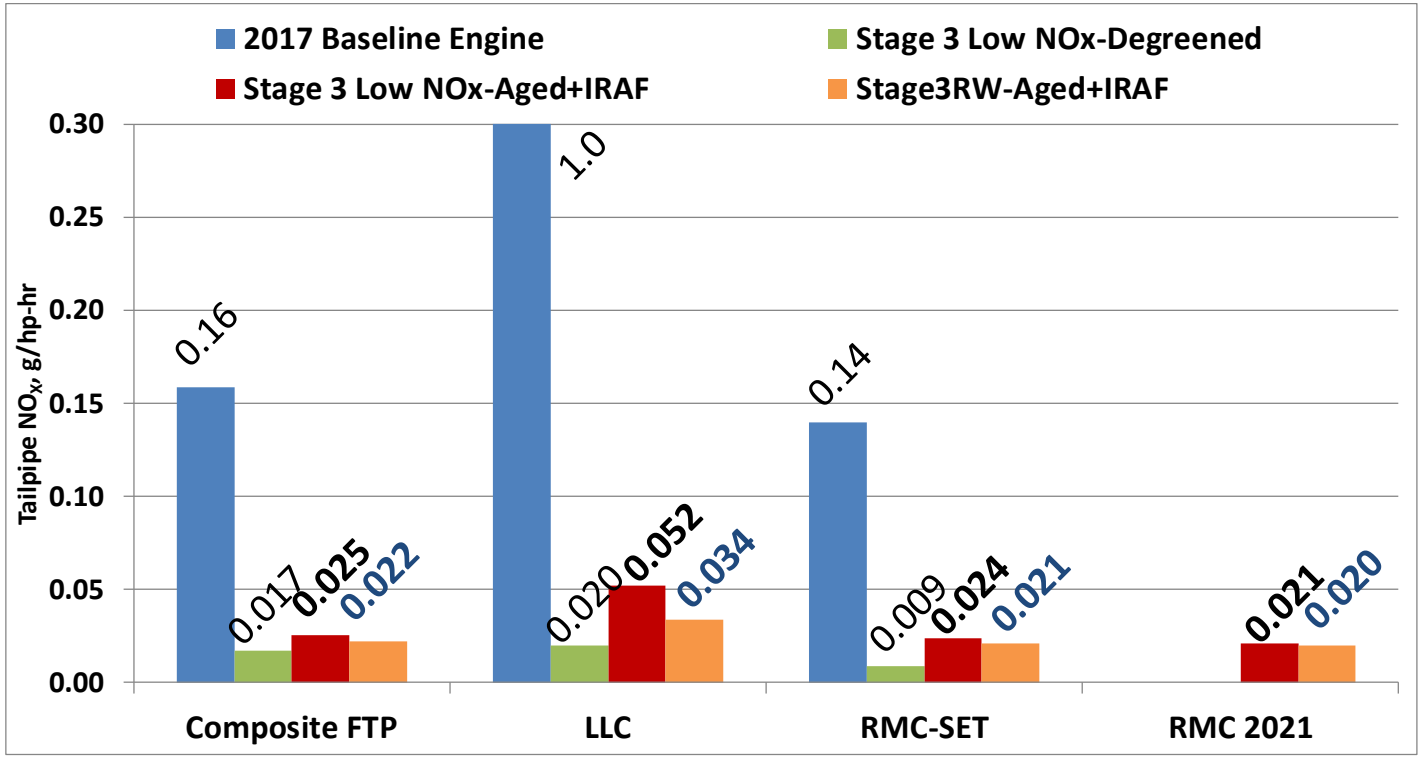
NO_x "Compliance" Results with IRAF – Stage 3 vs Stage 3RW



Baseline result is degreened only

Baseline and Stage 3 Degreened do not include IRAF adjustments

- Final Aged values reflect addition of UAF – same values for both systems
- Stage 3RW improvement in NO-NO_2 not enough to substantially improve FTP UAF
- UAF for RMC not impacted because always good passive regeneration
- UAF for LLC not impacted because never good passive regeneration

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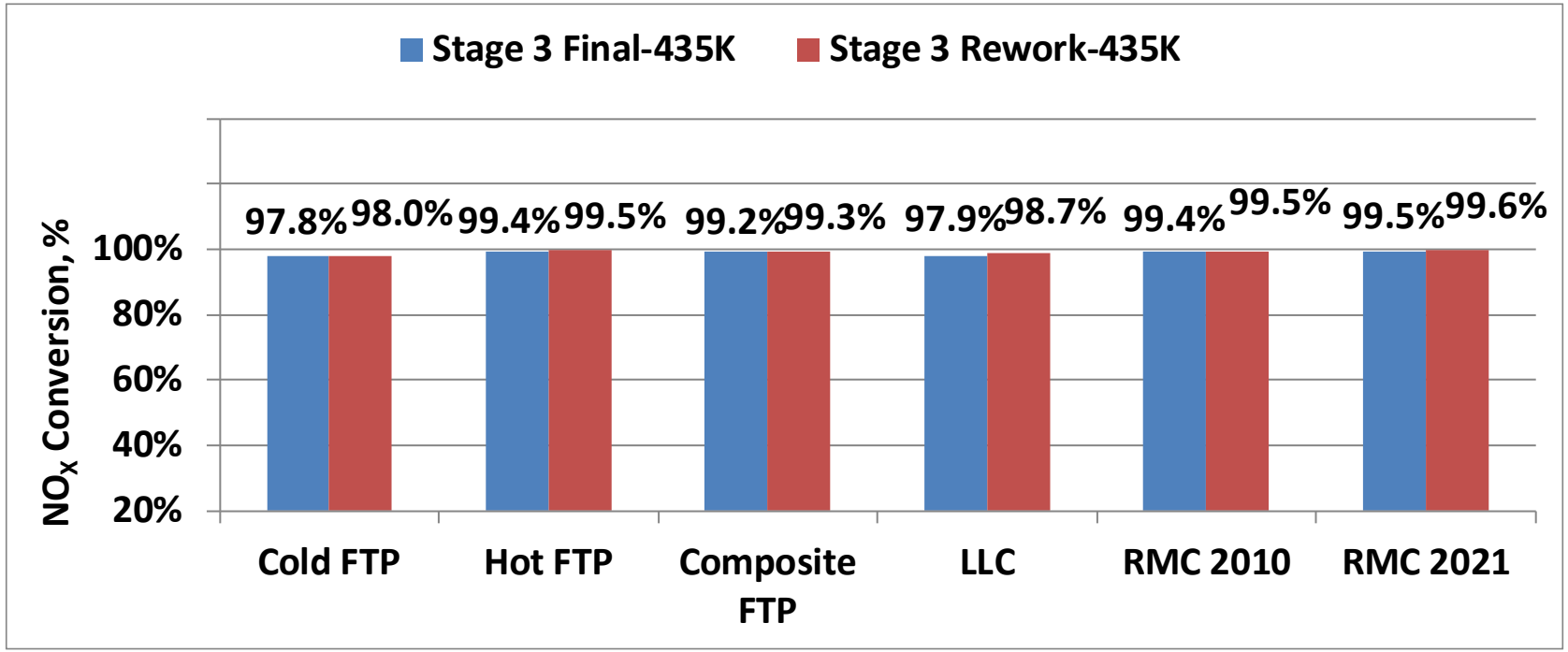
NO_X Conversion Comparison – Stage 3RW versus Stage 3



- Generally, we have seen improvement of 0.1% to 0.15% NO_X Conversion with Stage 3RW
  - 0.2% better on cold-start
  - LLC was ~ 1% better
- Original Stage 3 was 0.3% to 0.4% conversion loss on FTP-RMC and 1.5% on LLC
  - this result significant improvement…but still not enough on FTP and RMC to stay below 0.02 g/hp-hr

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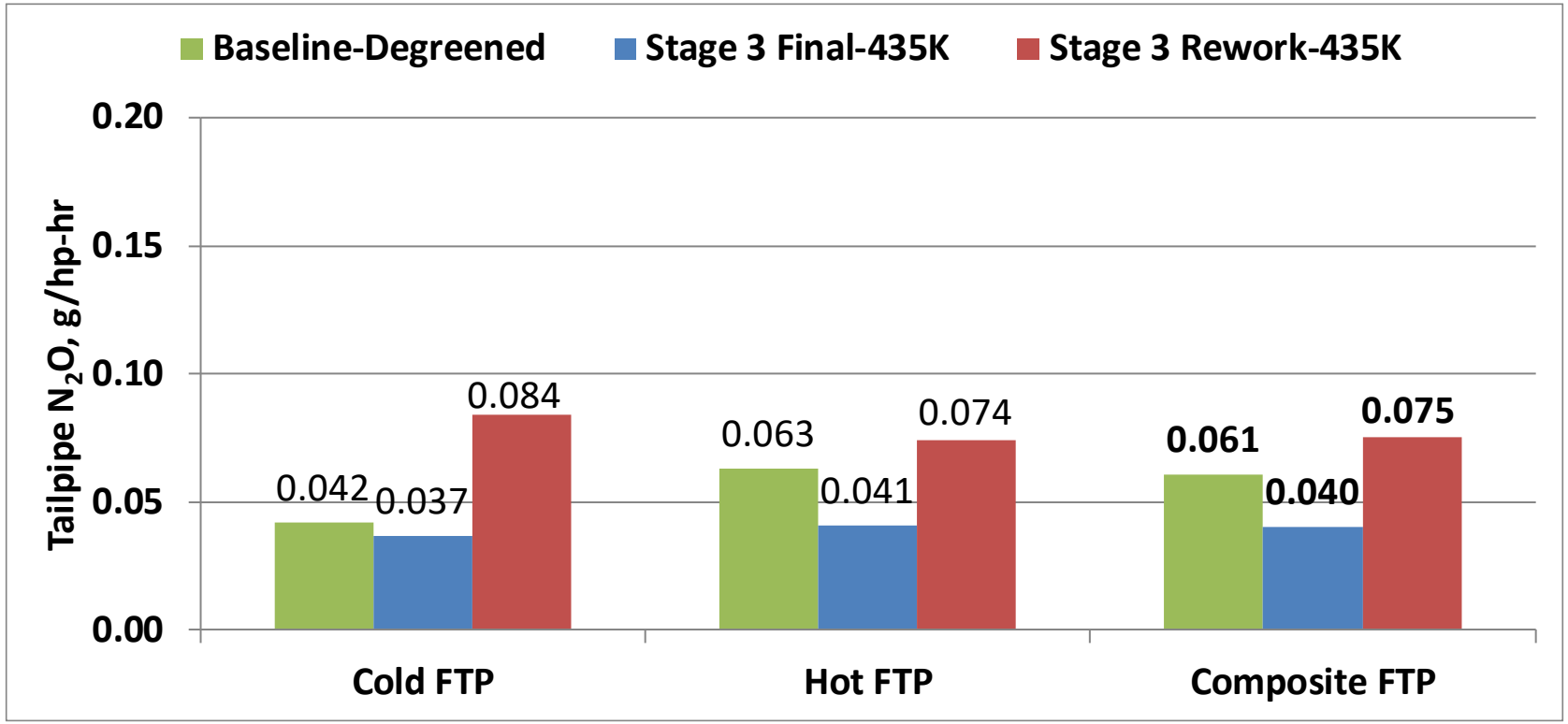
N_2O Emissions – Stage 3RW versus Stage 3



- Stage 3 435,000-mile system had lower N_2O than Baseline due to LO-SCR
- N_2O is higher with Stage 3RW 435,000-mile system higher due to increased NO-NO_2 oxidation on DOC compared to zCSF
  - Above baseline but still good margin to standard of 0.1 g/hp-hr (FTP-only standard)

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Real-World Routes to Cycles

- Engine dynamometer cycles representative of real-world operation
  - CARB Southern Route Cycle
    - *Dominantly highway operation with elevation changes*
  - Grocery Delivery Truck Cycle
    - *Representing goods delivery from regional warehouses to downtown and suburban supermarkets*
    - *Extended engine-off events characteristic of unloading events at supermarkets*
  - Drayage Truck Cycle
    - *Dominantly Neardock and Local operation of drayage trucks*
    - *Extended idle and creep operation while waiting in line at the ports*
    - *Lower speed dynamic operation between ports and local warehouses and rail yards*
  - Euro-VI ISC Cycle
    - *Modeled after Euro VI ISC route requirements*
    - *Mix of 30% urban, 25% rural and 45% highway operation*
  - ACES 4hr Cycle
    - *5 mode cycle developed as part of ACES program*
    - *4 test modes are derived from chassis dynamometer cycle plus FTP*

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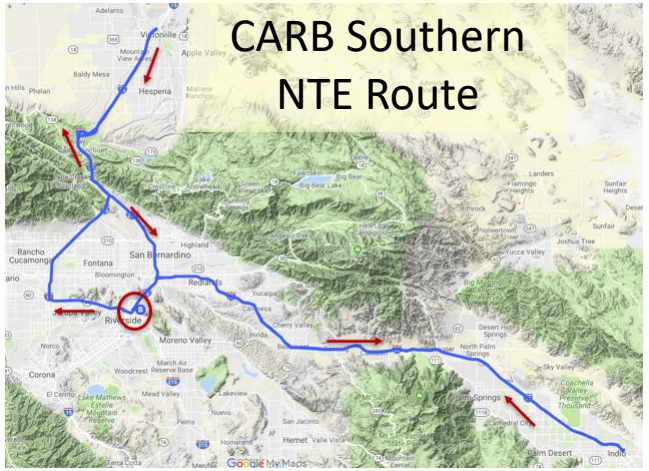
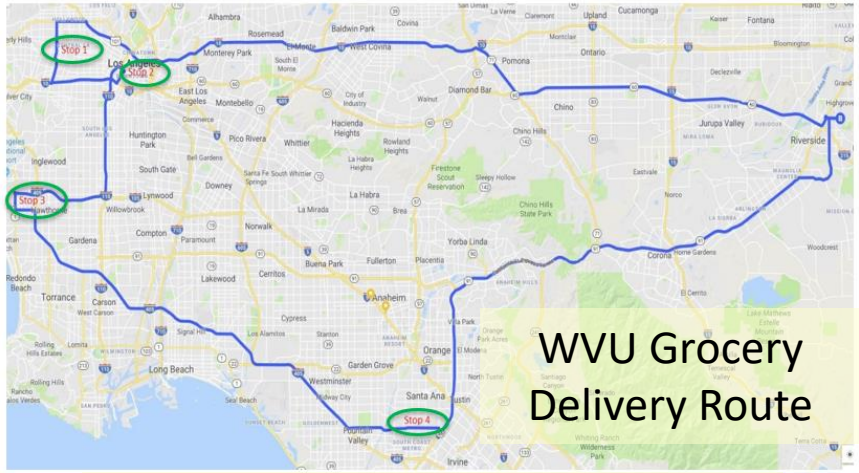
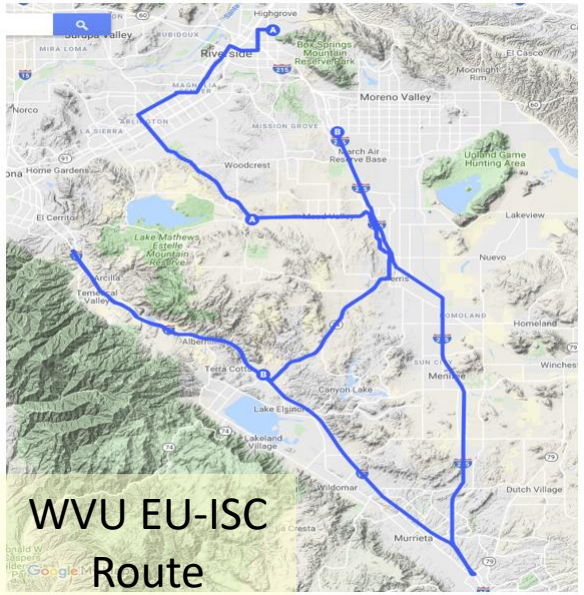
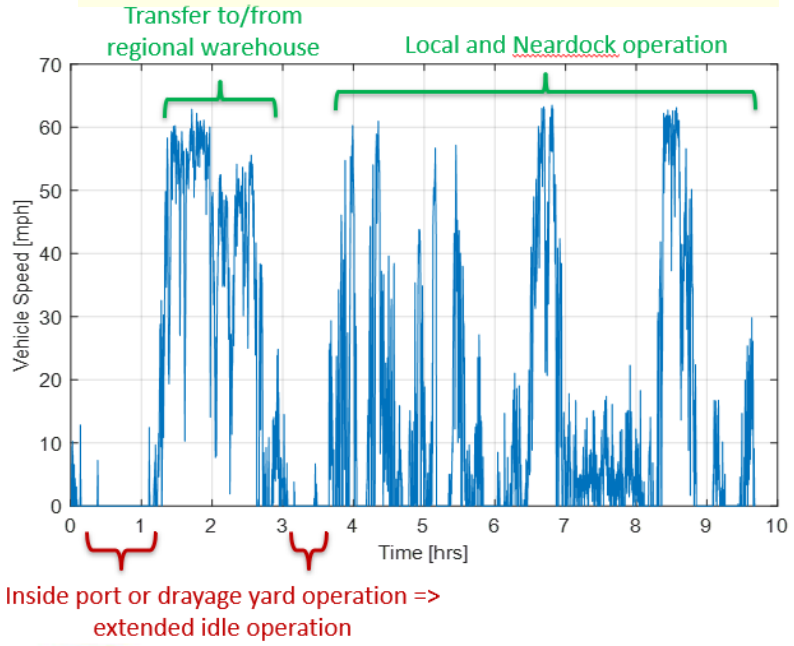
Real-World Duty Cycles







WVU Drayage Route



- Each of these cycles is a real working route that was driven with multiple actual Class 7 and Class 8 trucks
- 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

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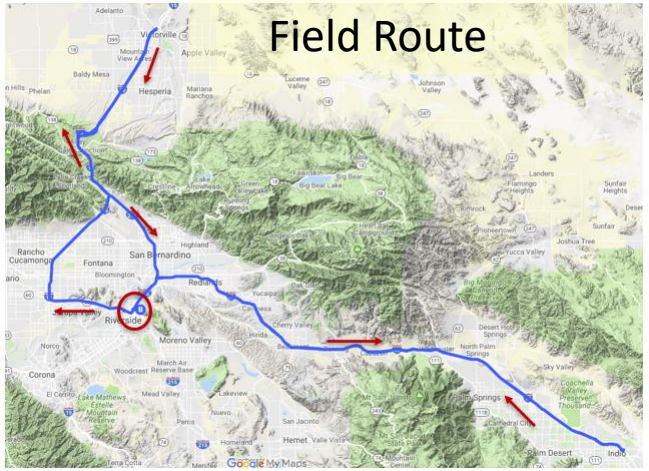
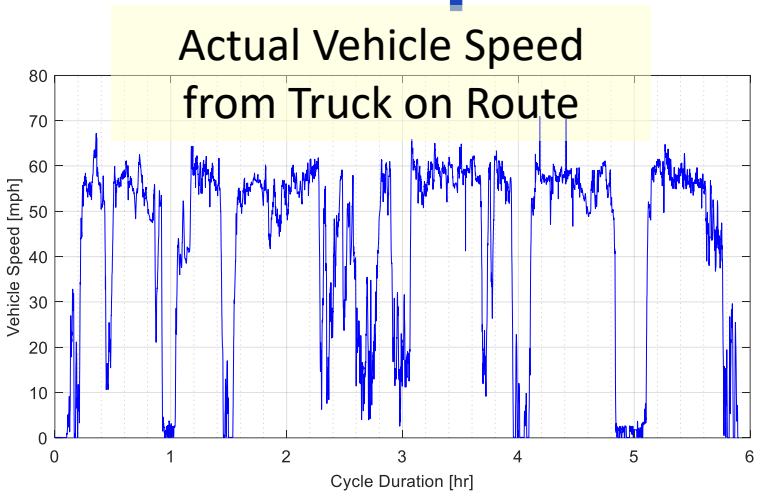
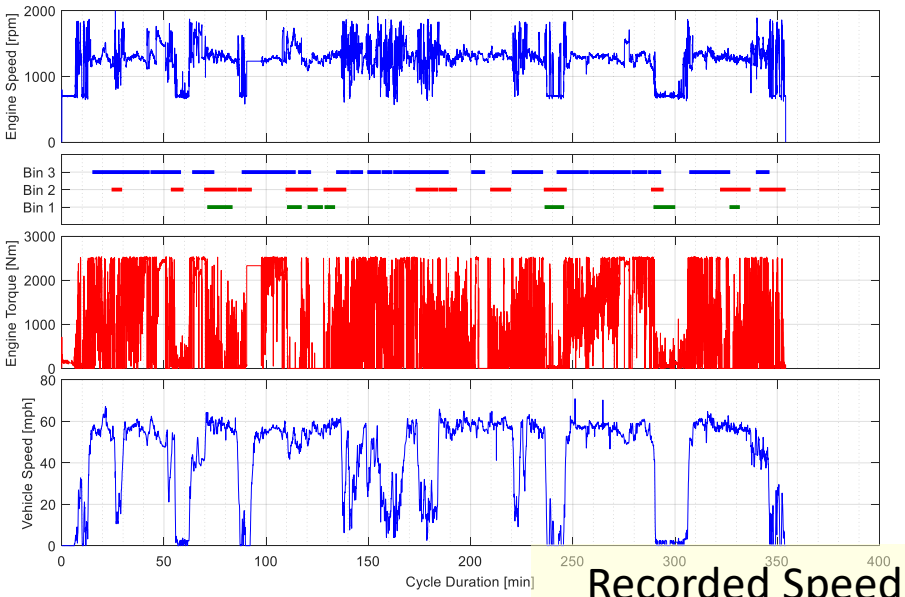
Cycle Translation Process Example – Southern NTE Route

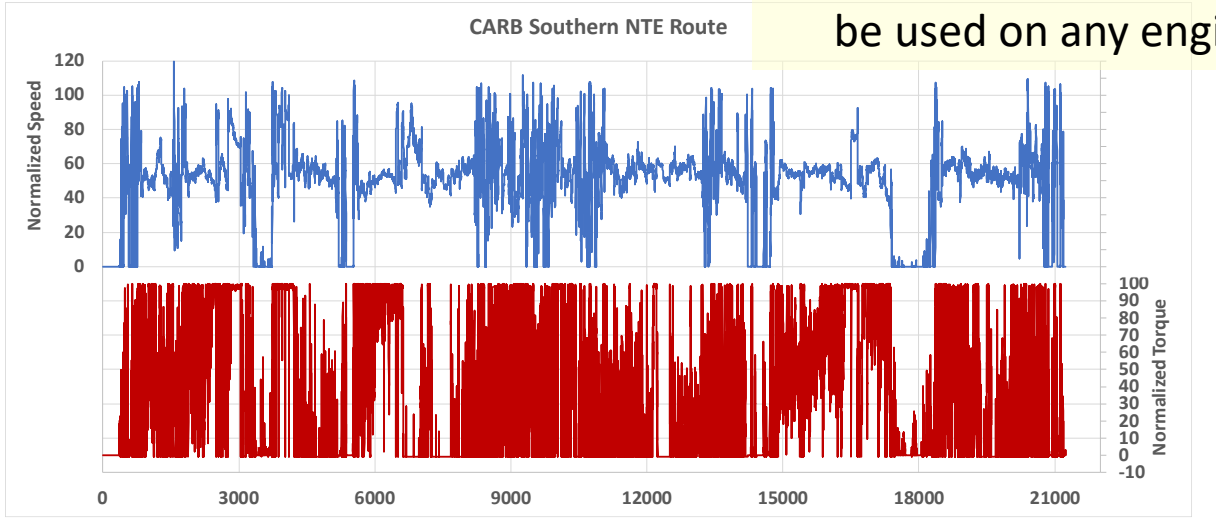




- WVU drove trucks on real-world routes
- Recorded vehicle data used along with engine torque curve information to generate Normalized engine-dyno replay cycle for Lab use



Recorded Speed/Load Data from Drive



Normalized Engine Cycle (can be used on any engine)

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New In-Use Approach – 3-bin Moving Average Window (3B-MAW)

Binning of windows by load (normalized CO_2)

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

	Bin	Engine Type	Normalized Average Window CO2 Rate
Bin 1	Idle	Diesel Cycle	$CO2_{normalized}$ ≤6%
Bin 2	Low	Diesel Cycle	6% < $CO2_{normalized}$ ≤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

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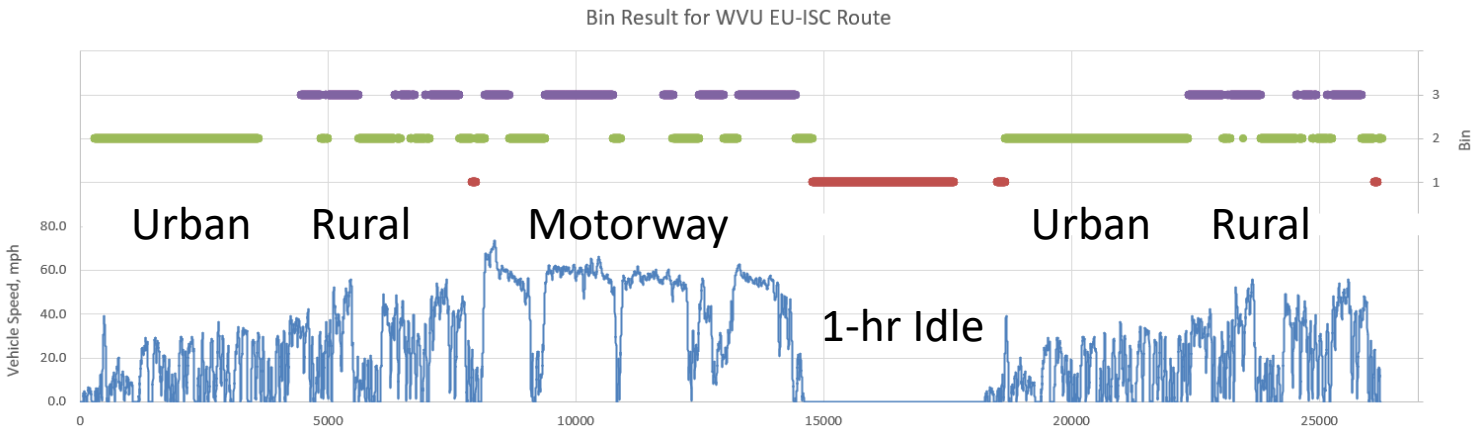
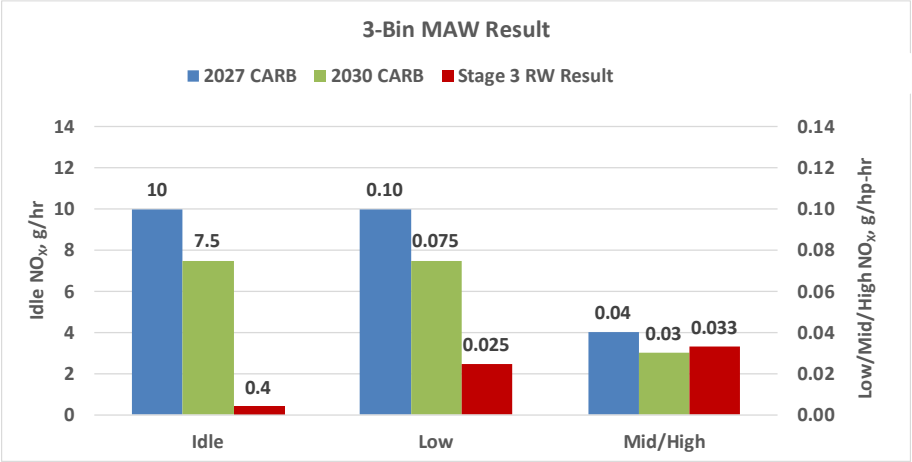
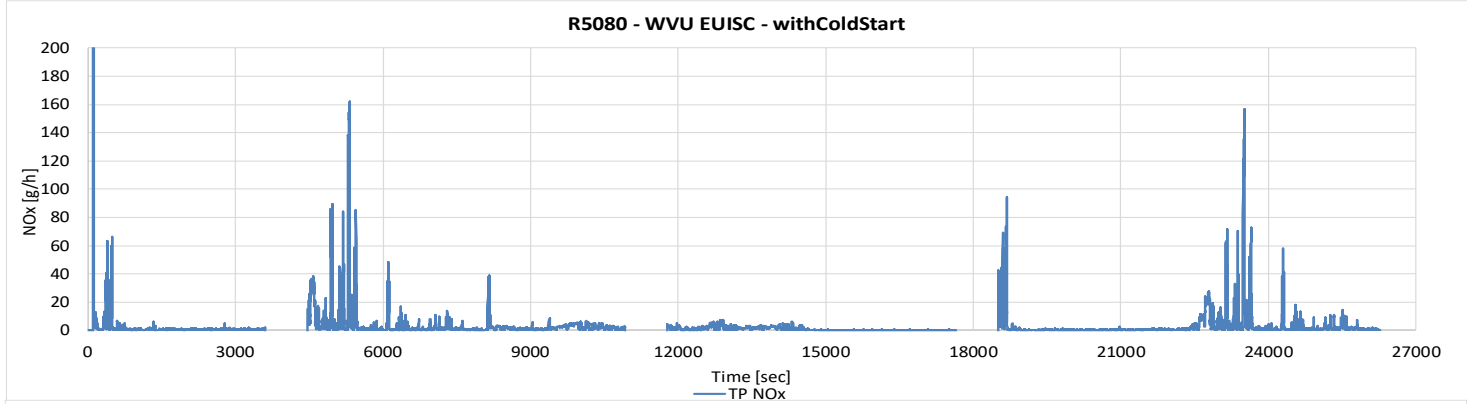
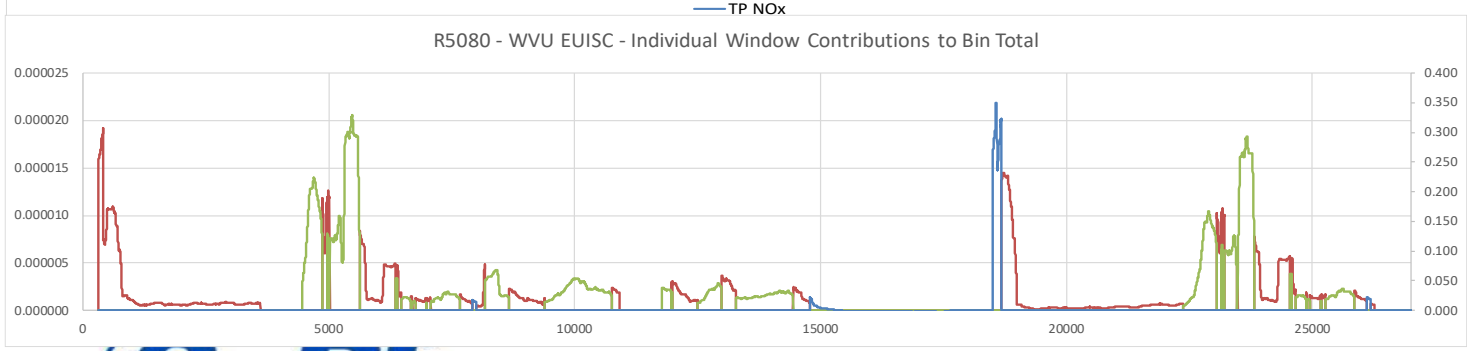
Example of Binning and Emissions – EU ISC Route









Bin	2027	2030	Result		Windows	
			g/hp-hr	g/hr	%	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

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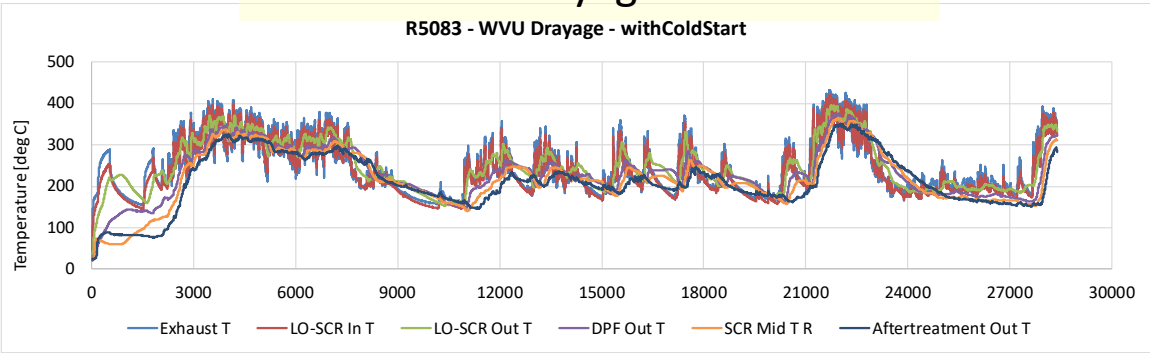
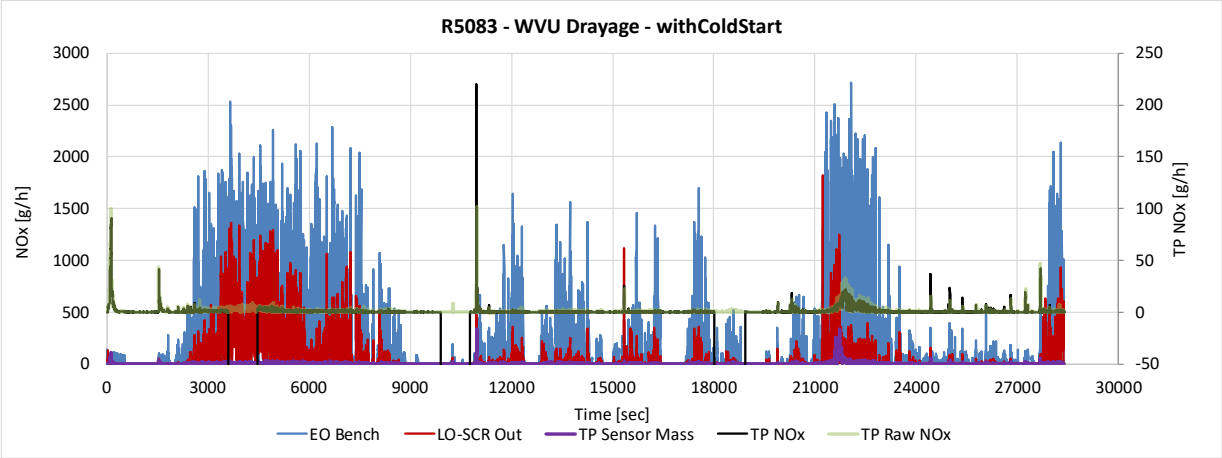
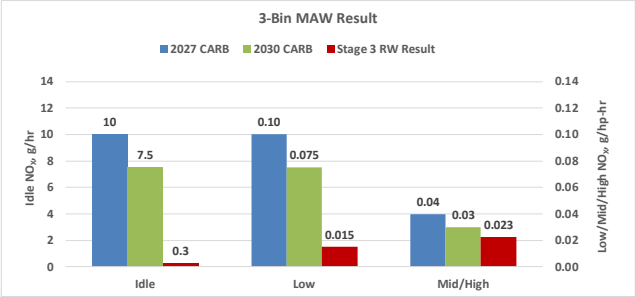
Lower Load Field Cycles – Stage 3RW Engine at 435k

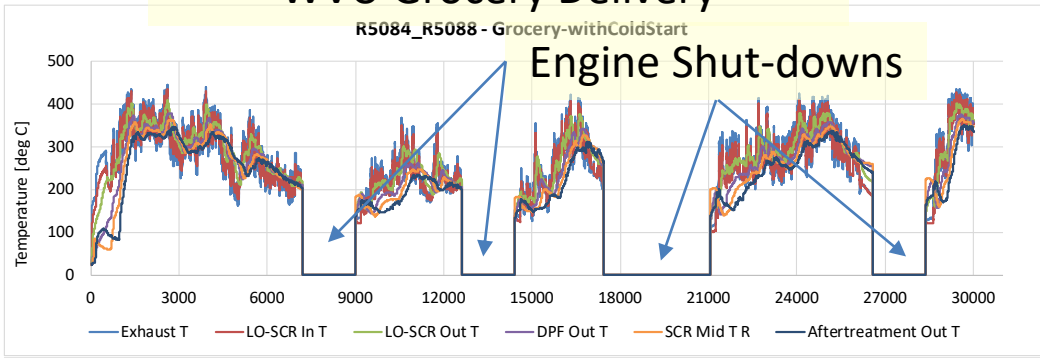
WVU Drayage Route

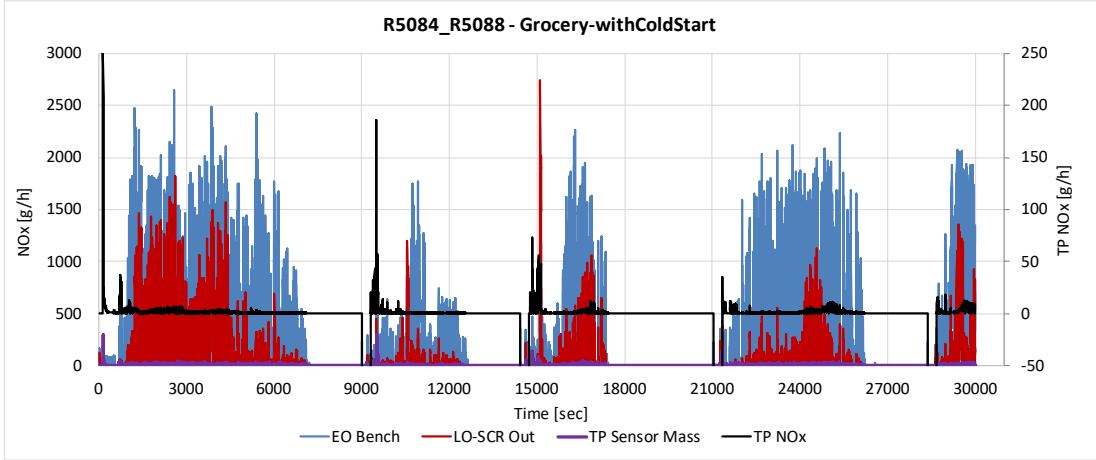


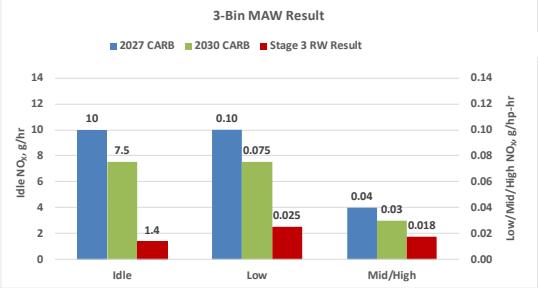




WVU Grocery Delivery







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Real-world Result Summary for Stage 3RW at 435k Miles

		NOx Thresholds - CARB					
				NOx		Windows	
	Bin	2027	2030	g/hp-hr	g/hr	%	Number
SNTE	Idle (< 6%)	10	7.5	0.040	**0.7**	14.5%	2762
	Low (6%-20%)	0.10	0.075	**0.041**	2.6	30.3%	5749
	Mid-High (> 20%)	0.04	0.03	**0.030**	6.6	55.2%	10490
	Total Cycle			0.028			19001
				NOx		Windows	
	Bin	2027	2030	g/hp-hr	g/hr	%	Number
5-Mode mACES	Idle (< 6%)	10	7.5	0.062	**0.9**	26.3%	6845
	Low (6%-20%)	0.10	0.075	**0.029**	1.7	36.2%	9419
	Mid-High (> 20%)	0.04	0.03	**0.016**	2.8	37.5%	9778
	Total Cycle			0.019			26042
				NOx		Windows	
	Bin	2027	2030	g/hp-hr	g/hr	%	Number
WVU Drayage	Idle (< 6%)	10	7.5	0.018	**0.3**	46.4%	11830
	Low (6%-20%)	0.10	0.075	**0.015**	0.9	37.9%	9654
	Mid-High (> 20%)	0.04	0.03	**0.023**	3.2	15.6%	3985
	Total Cycle			0.019			25469
				NOx		Windows	
	Bin	2027	2030	g/hp-hr	g/hr	%	Number
WVU EUISC	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%	12299
	Mid-High (> 20%)	0.04	0.03	**0.033**	5.1	33.8%	7908
	Total Cycle			0.027			23387
				NOx		Windows	
	Bin	2027	2030	g/hp-hr	g/hr	%	Number
WVU Grocery	Idle (< 6%)	10	7.5	0.057	**1.0**	20.1%	4163
	Low (6%-20%)	0.10	0.075	**0.025**	1.4	50.3%	10412
	Mid-High (> 20%)	0.04	0.03	**0.018**	2.5	29.6%	6128
	Total Cycle			0.024			20703

- Bin 1 has very large compliance margins
  - 1 g/hr or less on all duty cycles
- Bin 2 has good compliance margins
  - 50% of threshold or less on all duty cycles
- Bin 3 is ok in 2027 but not ok in 2030 on some duty cycles
  - Most duty cycles are compliant but not all and more compliance margin would be preferred
- Regulatory cycle performance is translating to real-world cycle performance

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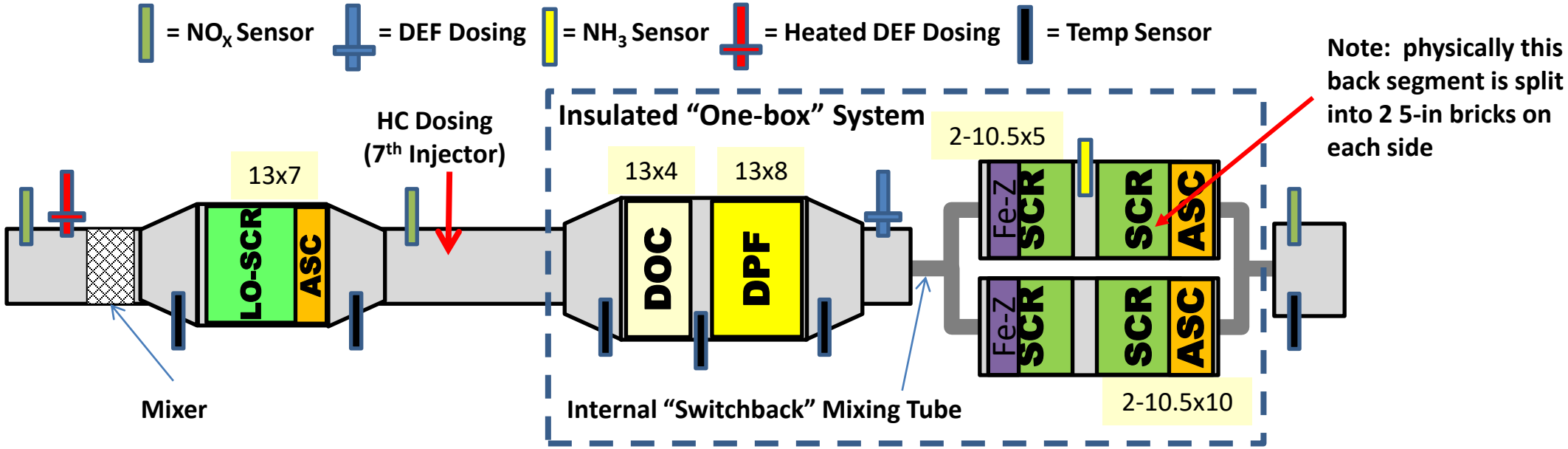
EPA System A Aftertreatment System



- Volume increase on LO-SCR and first brick of downstream SCR
- Formulation change in ds-SCR first brick to Fe-Z / Cu-Z mix
- Other coating updates on rest of system
- Targets are improved performance and durability, mitigation of N_2O concerns
- Plan is for full 800,000-mile DAAAC aged evaluation
  - tests at 435k, 600k, 800k
  - system is degreened and ready for initial calibration and 0-hr testing

Component	Dimensions [in]	cpsi / wall thickness	Notes
LO-SCR	13 x 7	400 / 3.5	With ASC Zone Coated
DOC	13 x 4	400 / 3.5	
DPF	13 x 8	300 / 7 ACT	
SCR	2 – 10.5 x 5	600 / 4.5	Dual Parallel Paths (2in Fe-Z / 3in Cu-Z)
SCR	2 – 10.5 x 5	600 / 4.5	Dual Parallel Paths (Cu-Z)
SCR-ASC	2 – 10.5 x 5	600 / 4.5	Dual Parallel Paths (Cu-Z), with ASC Zone Coated (2.5in)

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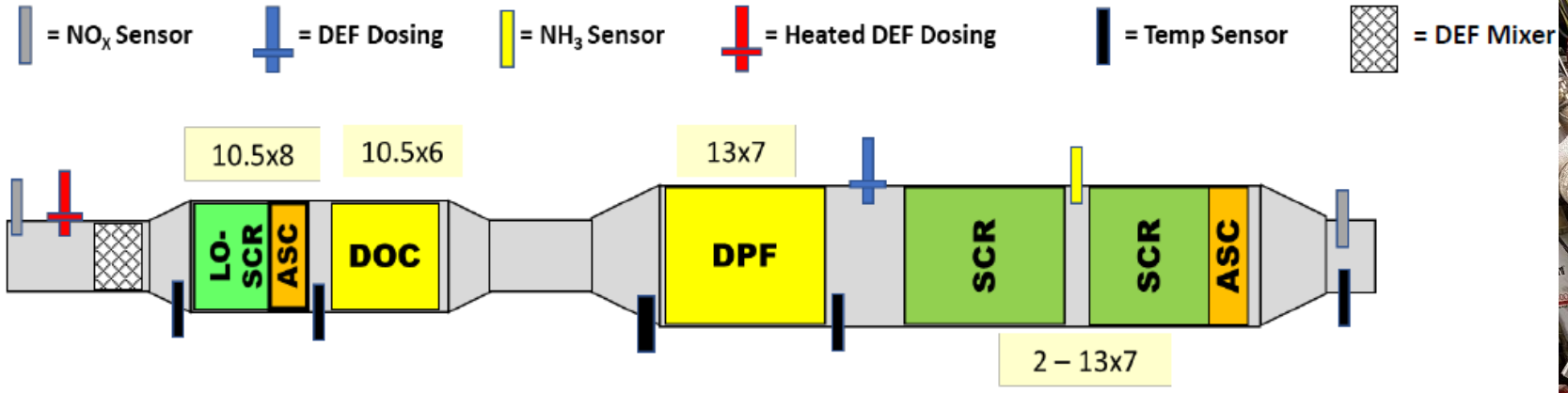
EPA Team B Aftertreatment System



- Designed for minimal packaging impact on existing EPA Class 8 day-cab chassis (with Cummins X15 engine)
- LO-SCR is part of two-can under-floor assembly
- Heated doser and in-pipe mixer would still be located under hood
- Also designed for regeneration via post-injection
- Note original design for 450hp / 1650lb-ft rating
  - tested on Stage 3 engine (500hp / 1850lb-ft rating)

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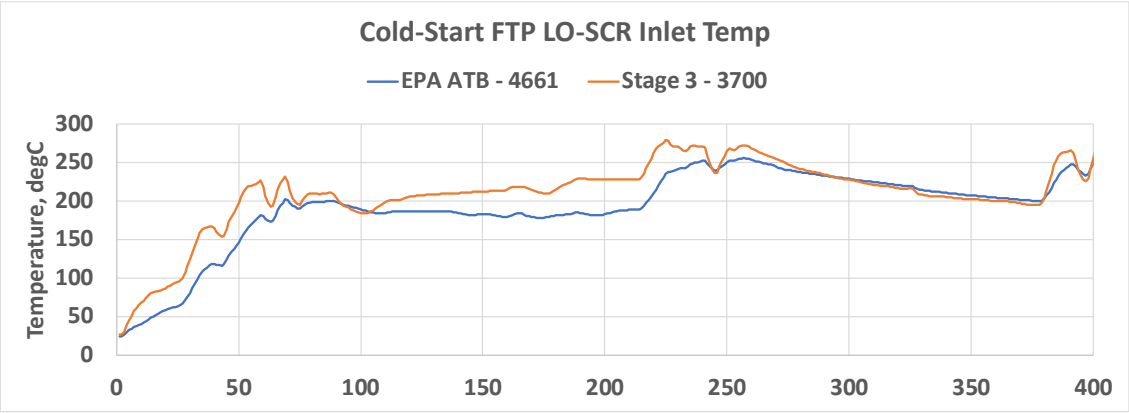
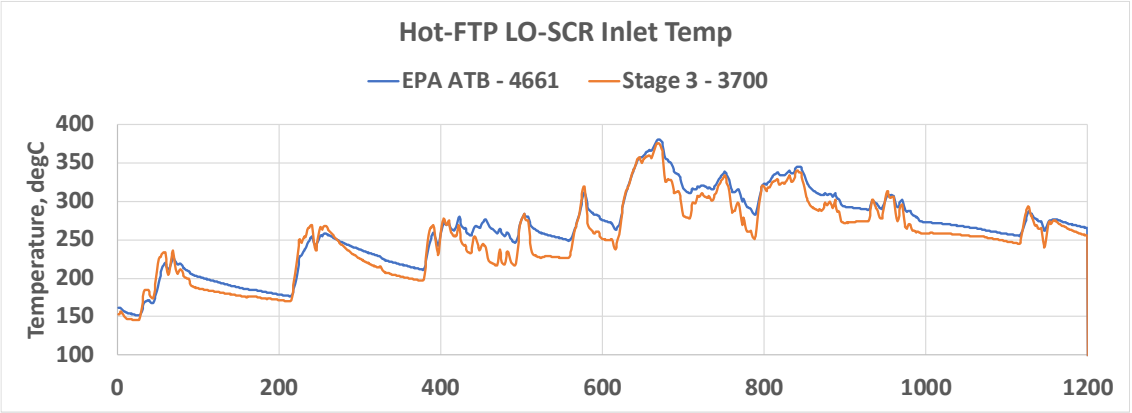
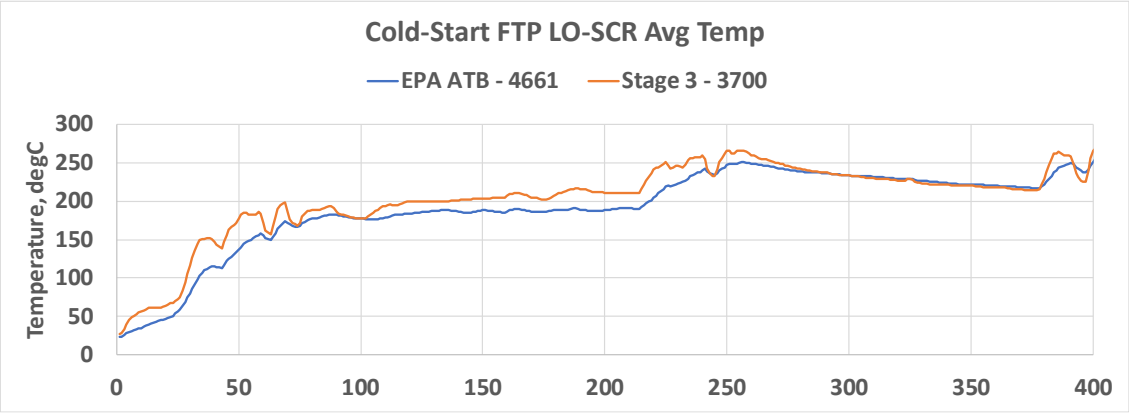
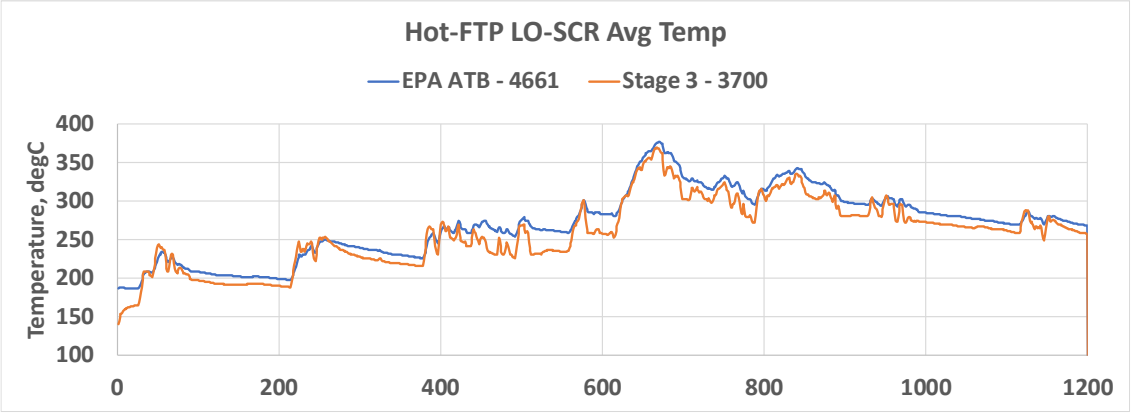
LO-SCR Temperature Comparisons









- Some loss of cold-start temperature with LO-SCR further downstream but better LT catalyst formulation
  - Cold FTP was 0.049 g/hp-hr with ATB and 0.054 g/hp-hr with Stage 3
- Hot-start had better temperatures (but increased backpressure…)

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EPA AT Team B – Degreened Result

Cycle	NO_X, g/hp-hr		NO_X Conversion	CO_2	
	EO	TP		g/hp-hr	Δ from base
Cold-FTP	2.6	0.049	98.3%	541	+2.1%
Hot-FTP	3.1	0.008	99.7%	513	+0.6%
Composite FTP	**3.0**	**0.013**	**99.6%**	**517**	**+0.8%**
RMC-2021	**3.5**	**0.009**	**99.7%**	**463**	**~ +1.5%[1]**
LLC	**2.4**	**0.013**	**99.5%**	**621**	**+2.0%**
RMC-2010	*3.5*	*0.015*	*99.6%*	*467*	*~ +1.5%[2]*

[1] RMC 2021 not run Baseline engine, assumed to be ~ 1% better than 2010 at 455
[2] RMC 2010 Baseline ~ 460

- Data is average of triplicate runs (except RMC-2010…)
- Note that hot start tuning indicates 0.012 g/hp-hr at CO_2 507 g/hp-hr (- 1%) possible, but final tuned values chosen above to provide durability margin on tailpipe NO_X

- System backpressure was 40kpa versus 28kpa with Stage 3 system
- Significant impact noted on RMC CO_2
- Turbomachinery and air-handling limits (and PCP limits) prevent much re-tuning to recover high load CO_2 impact, even at higher NO_X levels
- Did not proceed due to CO_2 impact…

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Next Steps

- Testing of Stage 3RW system at 600,000 miles and 800,000 miles
- Calibration and testing of EPA Team B system
  - Aging to 435k, 600k, 800k miles
- Low Ambient Temperature and Wind testing (EMA funded)
- Short-term fuels impact testing

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More Information on Stage 3 Low NO_X

- Stage 3 SAE Publications
  - Sharp, C., Neely, G., Zavala, B., and Rao, S., "*CARB Low NOX Stage 3 Program - Final Results and Summary*," SAE Technical Paper 2021-01-0589, 2021, https://doi.org/10.4271/2021-01-0589.
  - Rao, S., Sarlashkar, J., Rengarajan, S., Sharp, C. et al., "*A Controls Overview on Achieving Ultra-Low NOx*," SAE Technical Paper 2020-01-1404, 2020, https://doi.org/10.4271/2020-01-1404.
  - Zavala, B., Sharp, C., Neely, G., and Rao, S., "*CARB Low NO_X Stage 3 Program - Aftertreatment Evaluation and Down Selection*," SAE Technical Paper 2020-01-1402, 2020, https://doi.org/10.4271/2020-01-1402
  - Neely, G., Sharp, C., and Rao, S., "CARB Low NOx Stage 3 Program - *Modified Engine Calibration and Hardware Evaluations*," SAE Technical Paper 2020-01-0318, 2020, https://doi.org/10.4271/2020-01-0318
  - Neely, G., Sharp, C., Pieczko, M., and McCarthy, J., "*Simultaneous NO_X and CO_2 Reduction for Meeting Future CARB Standards Using a Heavy-Duty Diesel CDA-NVH Strategy*," SAE Int. J. Engines 13(2):2020, doi:10.4271/03-13-02-0014
- Stage 3 Final Report
  - https://www.arb.ca.gov/lists/com-attach/79-hdomnibus2020-Uj4AaQB2Aj8FbAhw.pdf
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