Technology Solutions for Meeting Future Heavy-Duty Standards

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MECA Clean Mobility

2022 Emission Control Technology Conference

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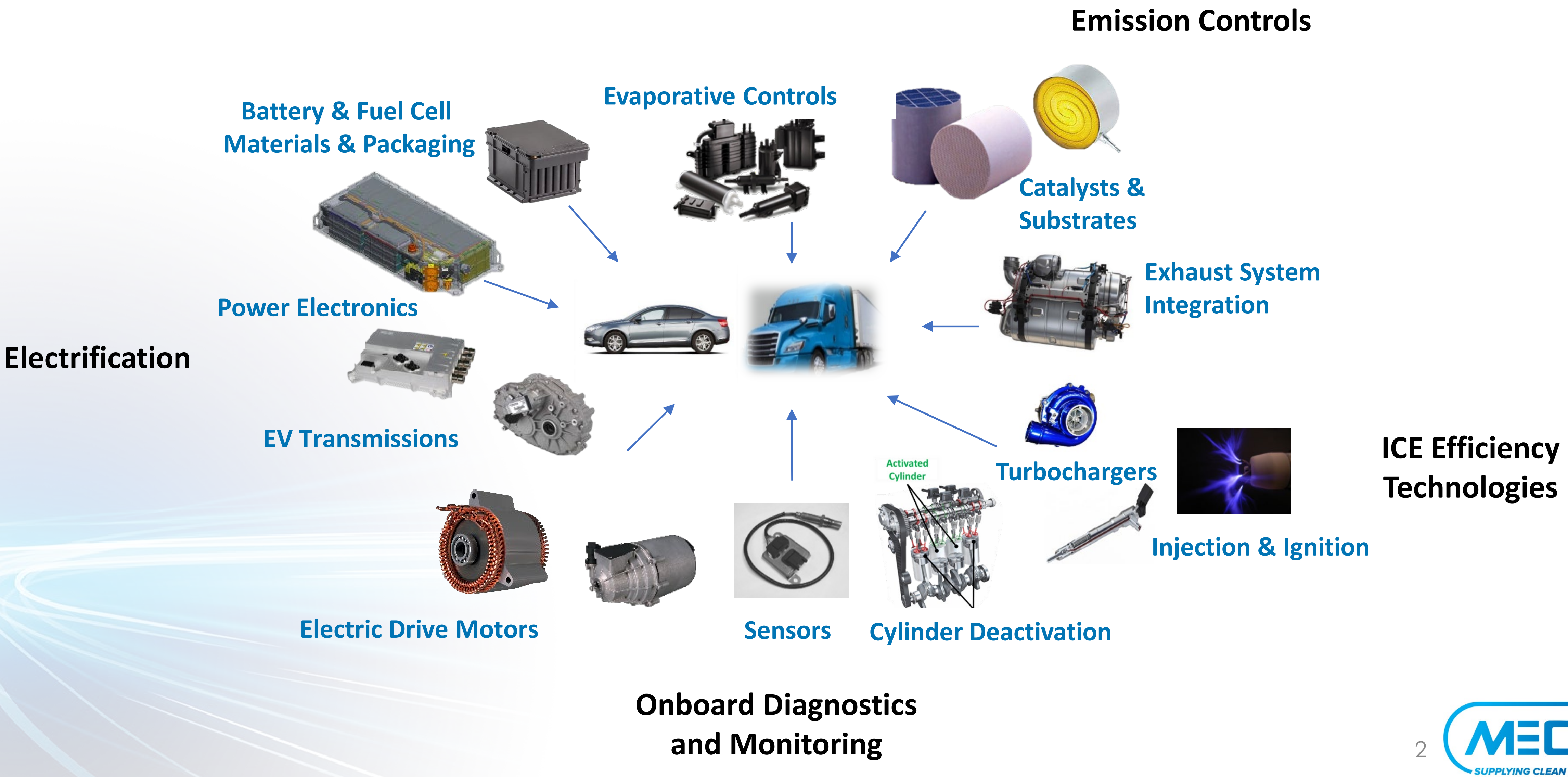
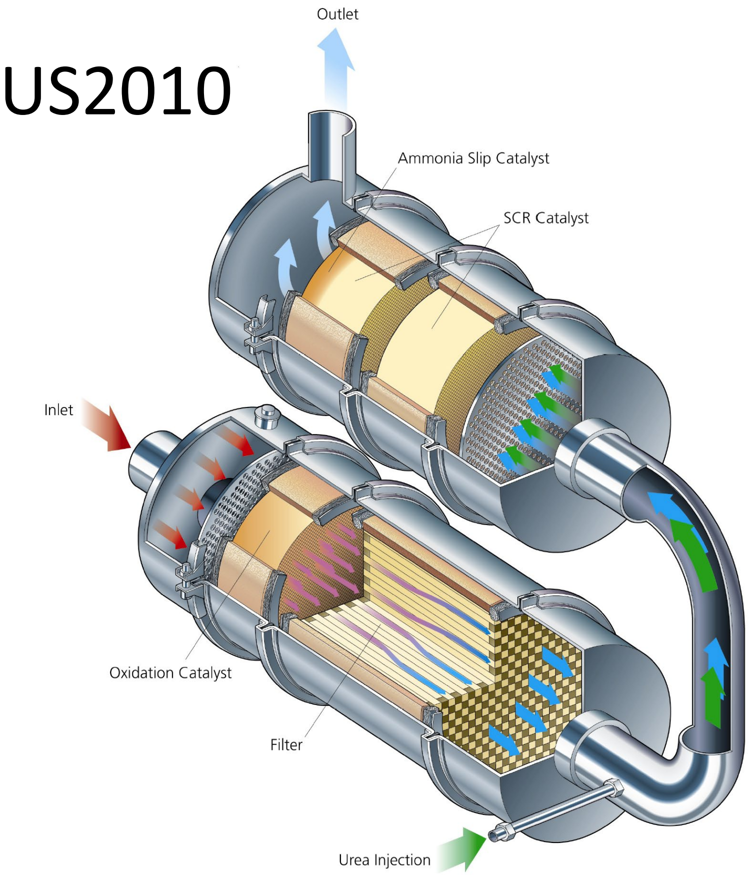
MECA Represents Suppliers of Clean Mobility Technology



Evolution of Heavy-Duty Exhaust Control Technology

US2010



Repackaged

A natural optimization has resulted in 2022 systems being 60% smaller, 40% lighter, and cheaper than 10 years ago.

US2013

Downsized

US2022

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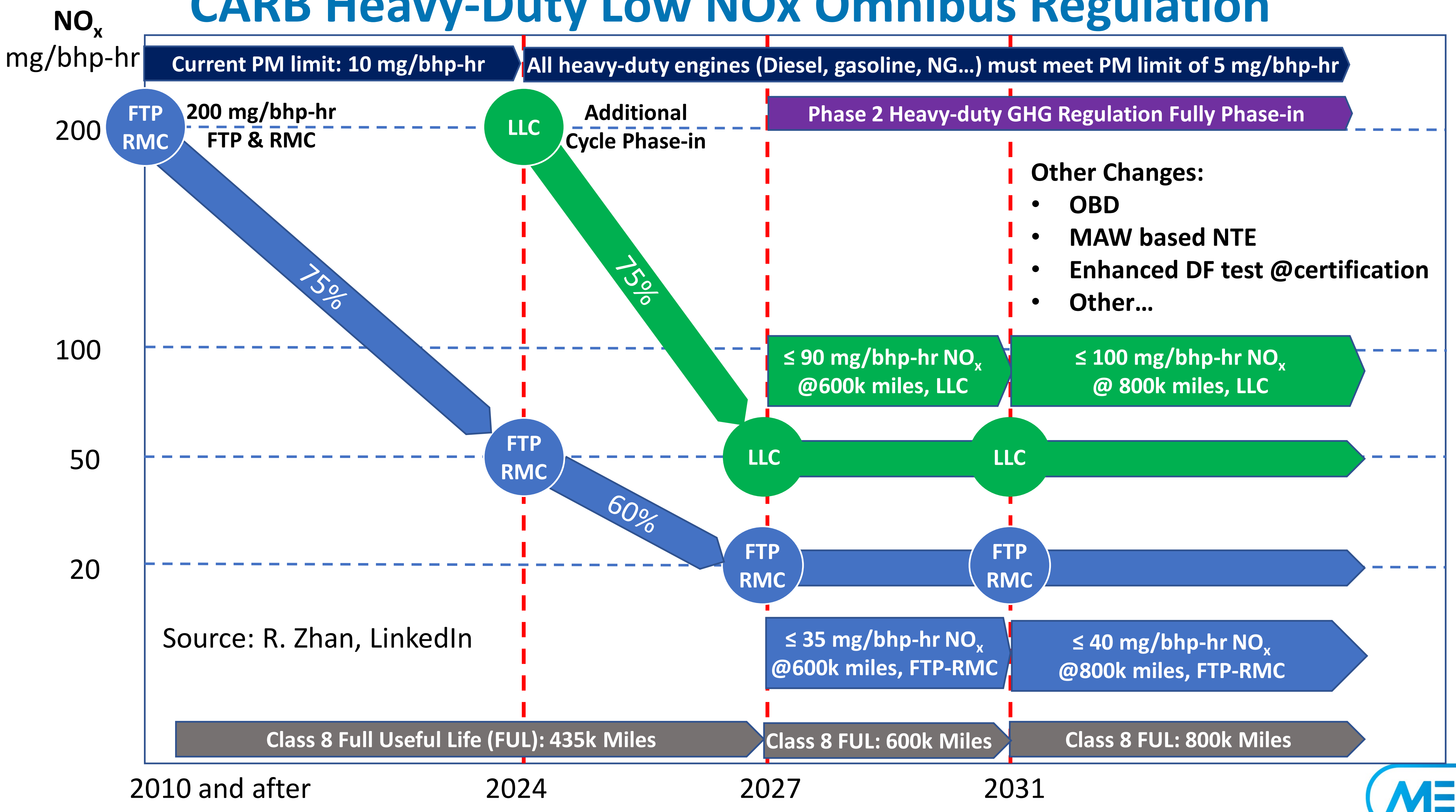
CARB Heavy-Duty Low NOx Omnibus Regulation



CARB/EPA Low NO_X Test Program

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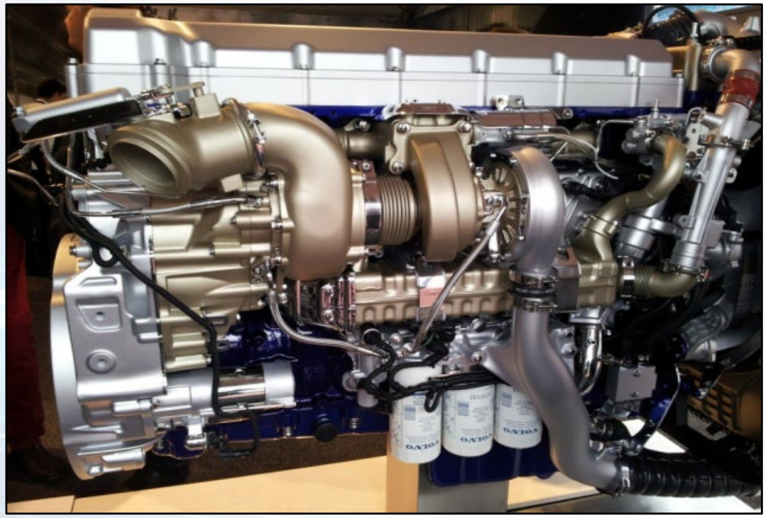
CARB HD Low NOx Test Program Objectives
Contract with Southwest Research Institute

- Program goal was to demonstrate 90% reduction below current HD NO_X standards
  - 0.02 g/bhp-hr (0.03 g/kWh)
  - Aged parts (Full useful life engine-based accelerated aging)
- What's needed to achieve 0.030 g/kWh from 4 or 5 gram/kWh engine out NOx
  - 95% conversion for cold start
  - 99% conversion for hot start
- Engine calibration in parallel with thermal management and exhaust control development
- Solution must be production ready
- Solution not adversely impact GHG standards (CO_2 , N_2O)

Test Engines

Diesel - 2014 Volvo MD13TC (Euro VI)

- A diesel engine with cooled EGR, DPF and SCR
  - Power 361kW @ 1477 rpm
  - Torque 3050 Nm @ 1050 rpm
- Includes turbo-compound (TC)



2017 Cummins ISX15

- A diesel engine with enhanced EGR, DPF and SCR
  - Power 336kW
  - Torque 2800 Nm
- Non-Turbocompounding

Low NO_X Technology Demonstration Program

- **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*
- **Stage 2** – Heavy-Duty Low Load Emission Control (2017-2019) - ***Complete***
    - Expand previous technology evaluation to low-load and urban operating cycles
- **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

EPA Low NOx Effort – Improvements to system beyond Stage 3 (2020 to present)

- Improved aftertreatment
- 1.3 M mile durability
- In-use compliance on real driving cycles
- PEMS and sensor characterization
- Low temperature testing

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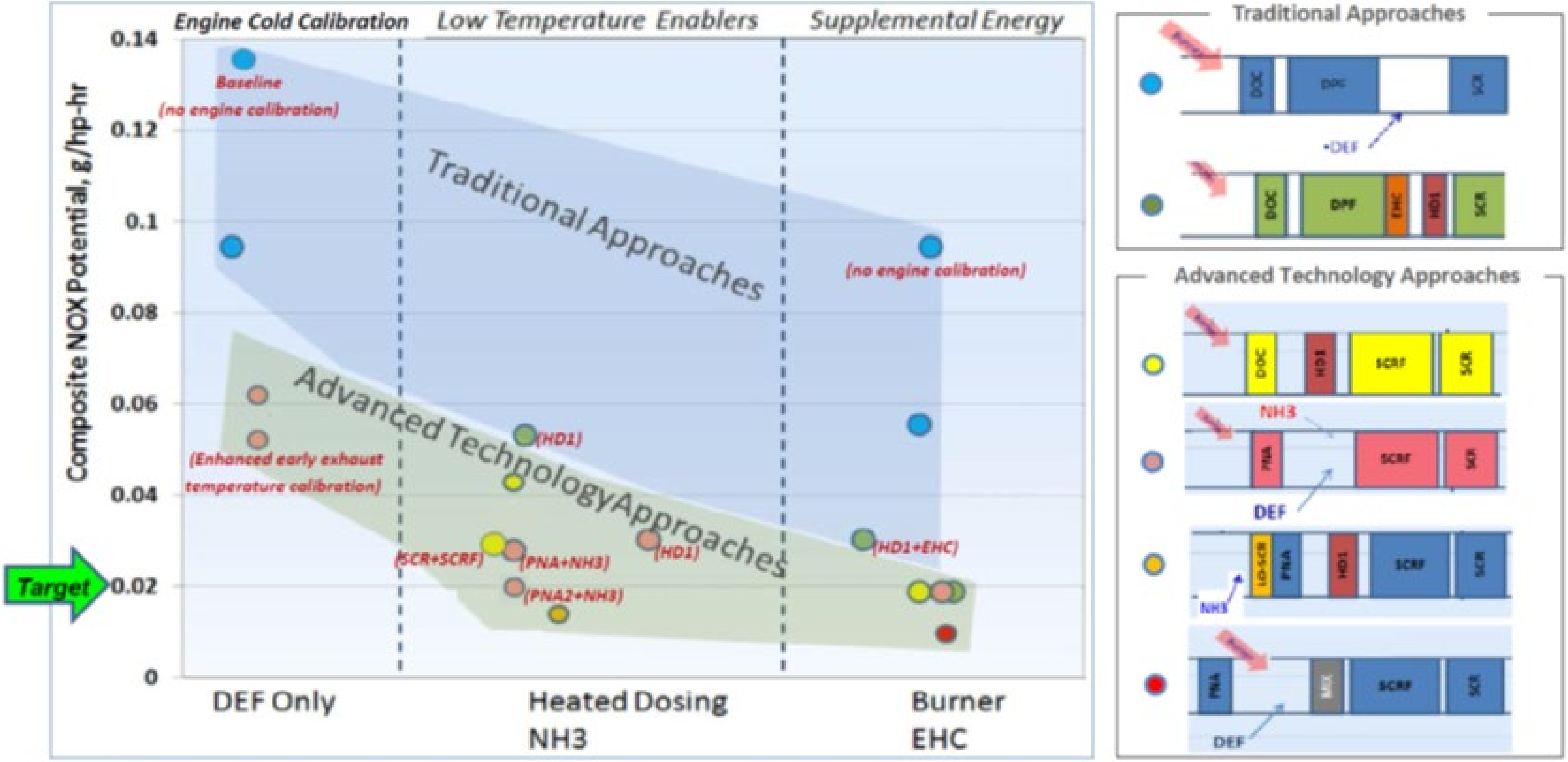
Stage 1 Focused on Screening Technology to achieve NO_X emissions below 0.02 g/bhp-hr



Acronyms

DOC: diesel oxidation catalyst; ***DPF***: diesel particulate filter; ***SCR***: selective catalyst reduction; ***Burner***: 10kw mini-burner; ***EHC***: electrically heated catalyst; ***HD1***: heated DEF dosing; ***SCRF***: SCR catalyst coated DPF; ***PNA***: passive NOx adsorber; ***PNA2***: PNA with altered catalyst formulation; ***NH3***: gaseous ammonia injection; ***LO-SCR***: close-coupled light-off SCR

SwRI

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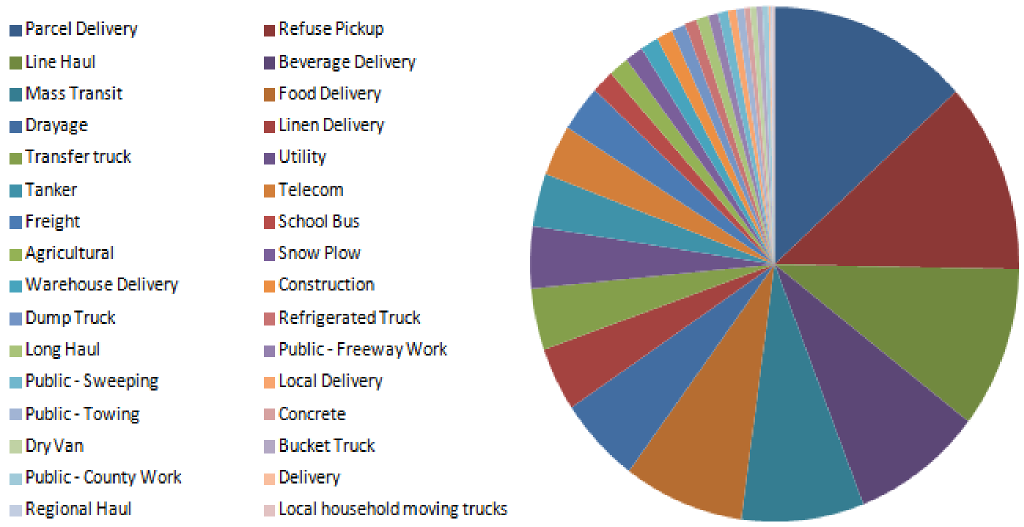
Stage 2: Low Load Cycle (LLC) for Certification

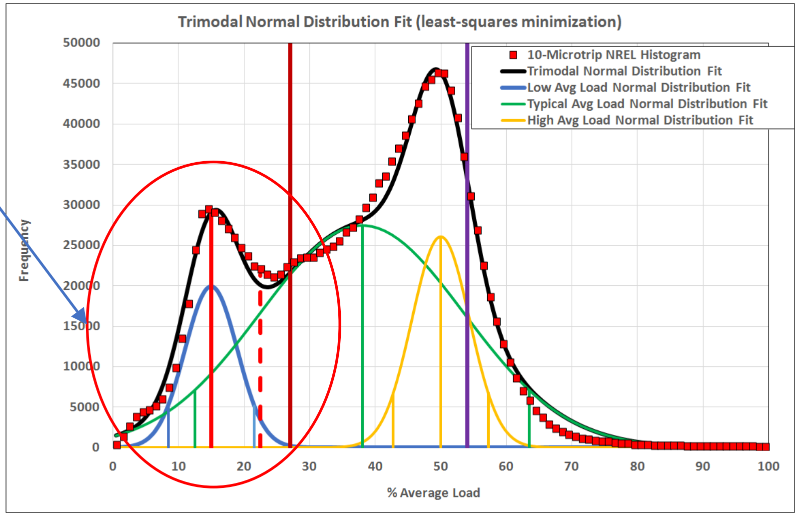


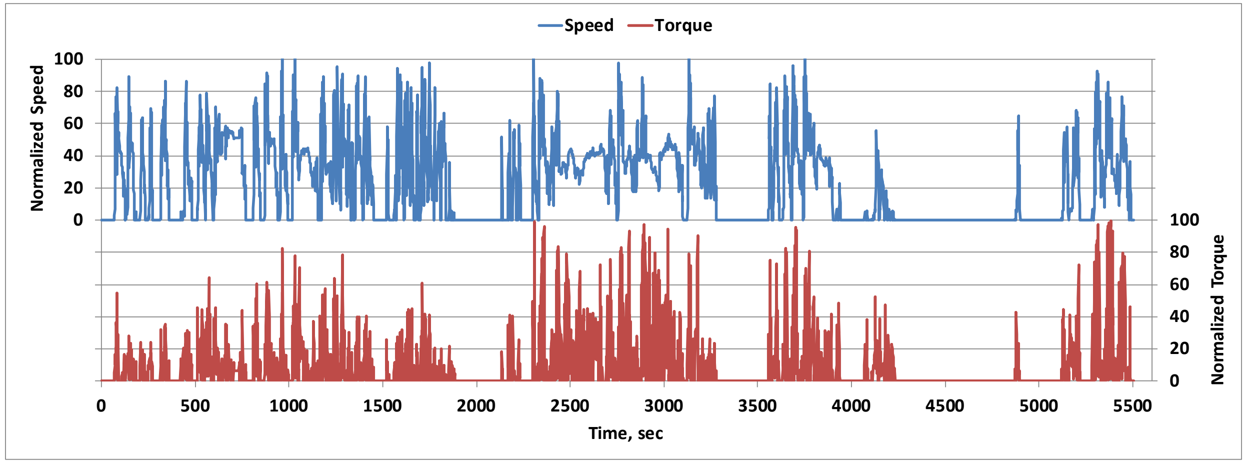
Developed from Real World Data at Low Load

- 751 unique vehicles located across the US~600+ Gb of raw data
- 25 Distinct Locations
- 44 Unique Vocational Designations
- 55 Unique Fleets

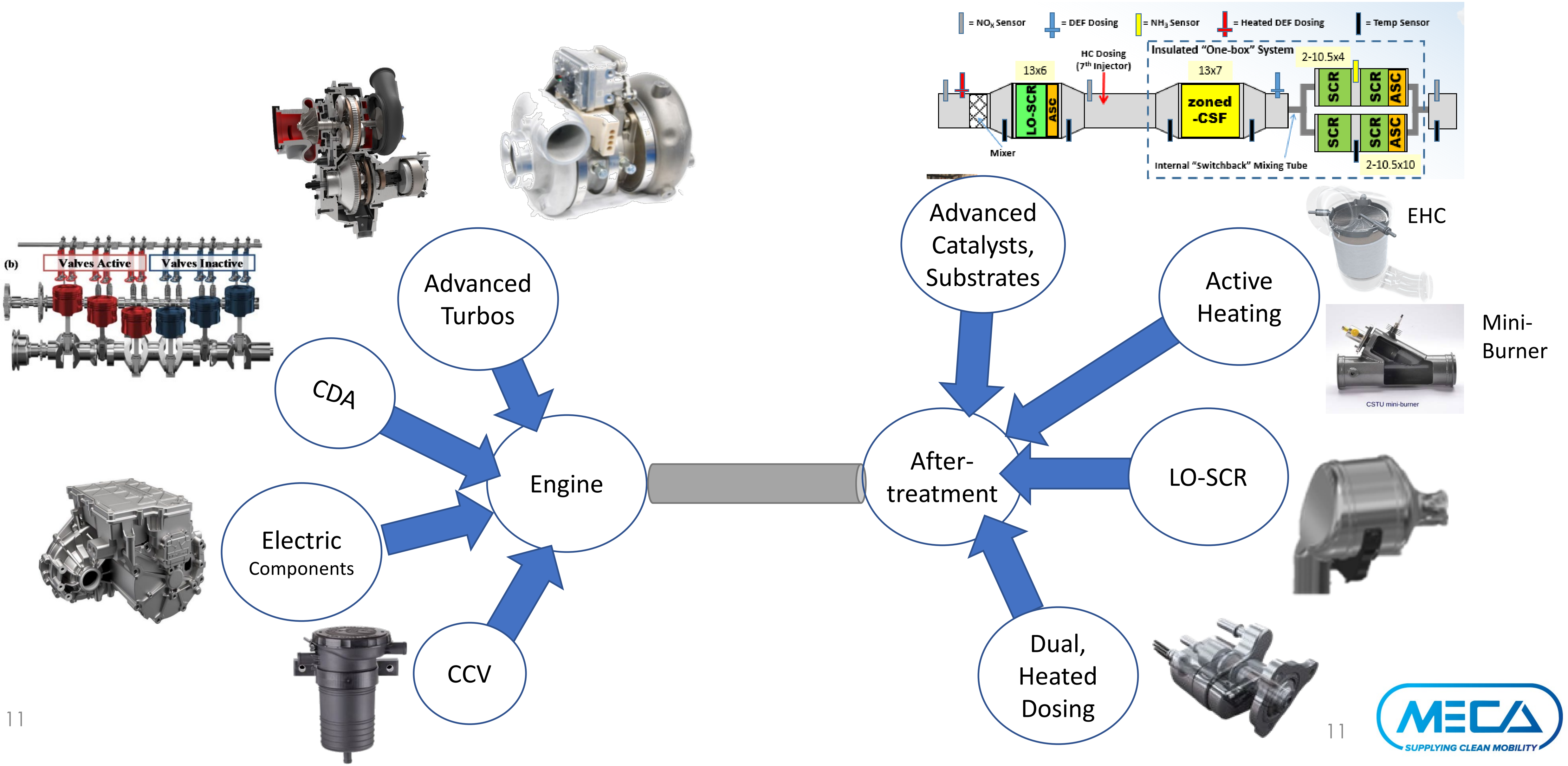
Low Load Cycle (LLC) from field data developed, requires manufacturers to demonstrate control of low load emissions (average cycle load is only 5-7% of maximum power)

Low Load Operations Identified





8-years of Industry Testing has Identified Multiple-Technology Pathways to Reduce NOx and CO_2



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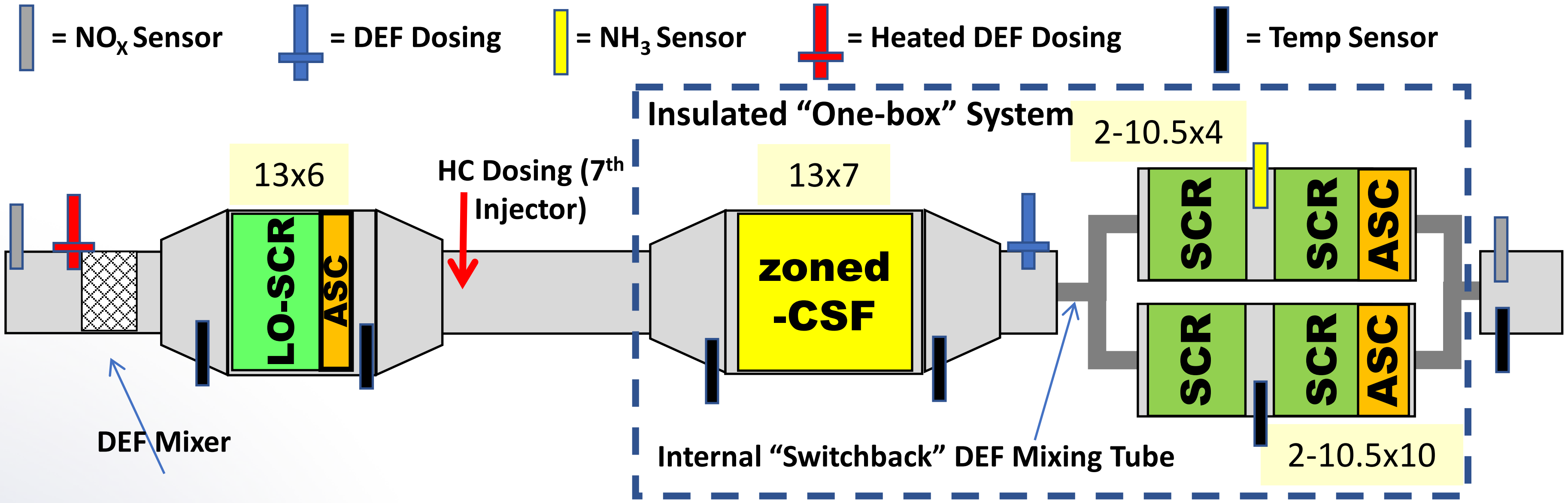
Stage 3 - Final Aftertreatment System Schematic



Zone coated CSF for reduced thermal inertia upstream of SCR

Need 7th injector to avoid HC exposure on LO-SCR

Dual dosing with heated doser for LO-SCR

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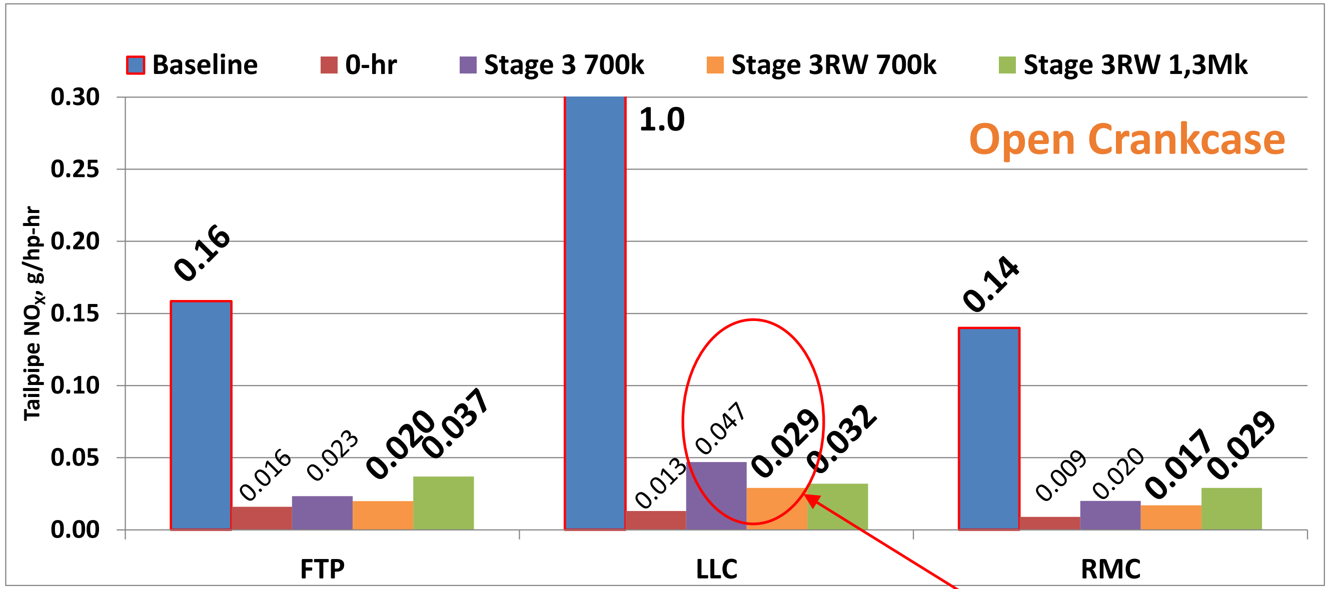
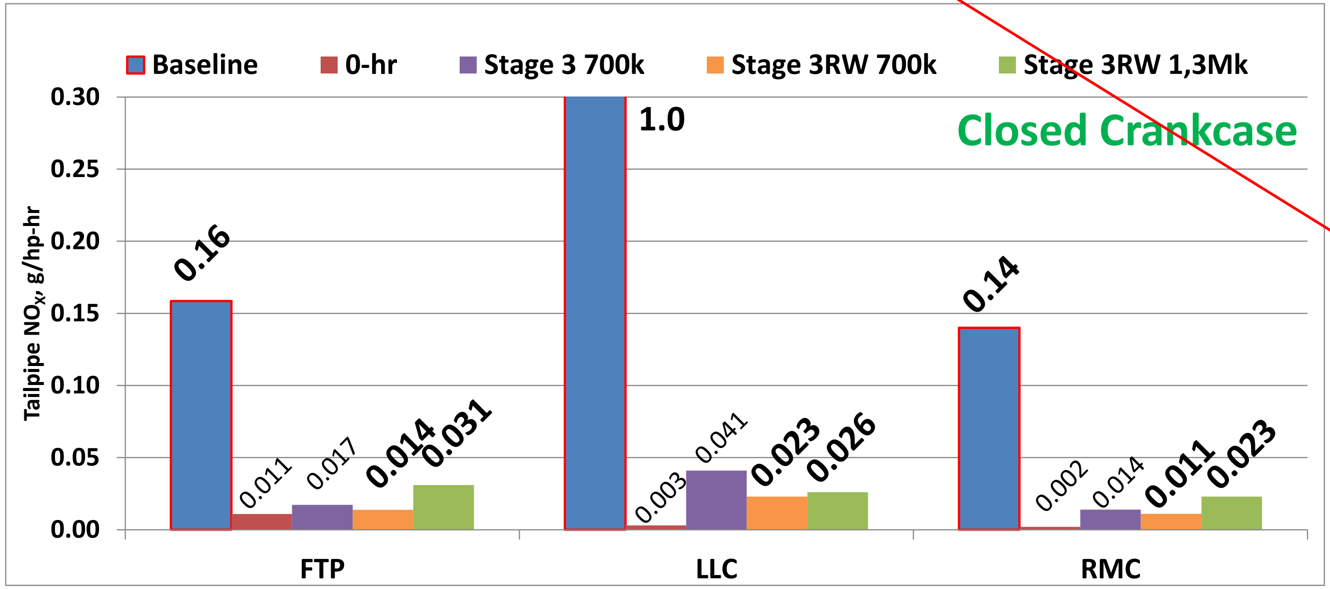
Low NO_X Emissions on U.S. Regulatory Cycles





Low NO_X Tailpipe emissions are 90%+ below Baseline

- 1.3M km still 85% below un-aged baseline system
- Low Load emissions (LLC) are 25X lower and comparable to high load

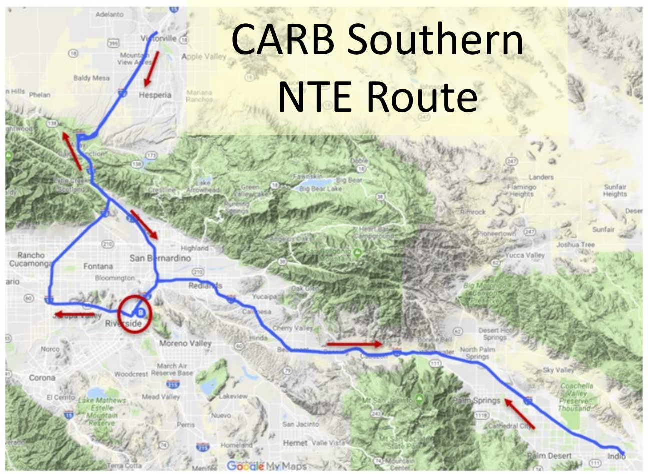
Catalyst Aging is visible, but tailpipe NO_X levels are still low at end of life

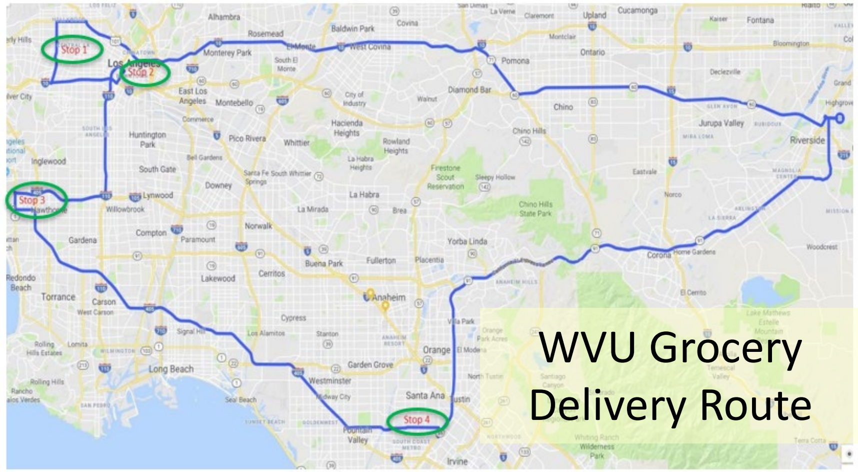
Moved to Closed Crankcase Ventilation System

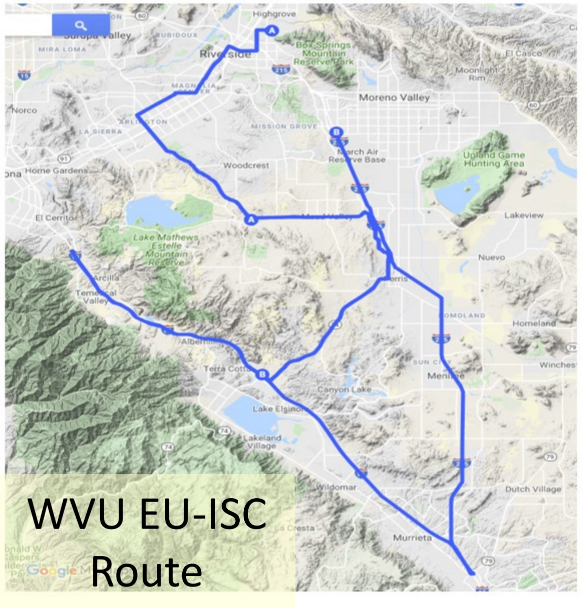
- Reduced all emission levels by additional ~ 0.01 g/kWh (30-50%)

Real World Road Cycle Testing

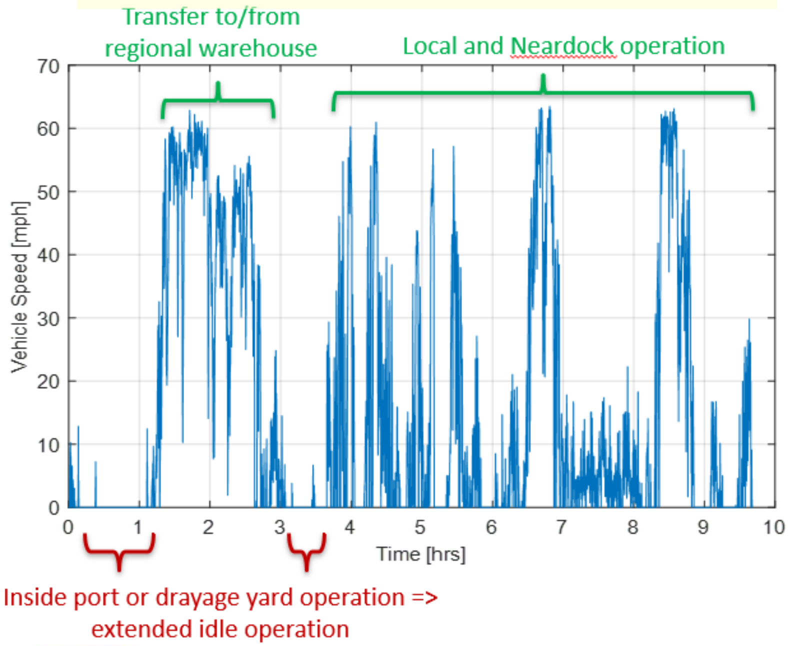
Real-World Duty Cycles







WVU Drayage Route



Real working routes driven with multiple Class 7 and Class 8 trucks

Cycles represented a wide variety of different kinds of vehicle operations over a full day

Recorded Vehicle Data used to develop speed/load profiles for laboratory use and replayed on dynamometer

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Proposed Euro VII[1] In-Service Conformity (WBW)

Euro VII emphasizes in-use testing

No data exclusion, including cold-start, no minimum window average power

Complete duty-cycle using Euro VI Work-Based Window (WBW) methodology

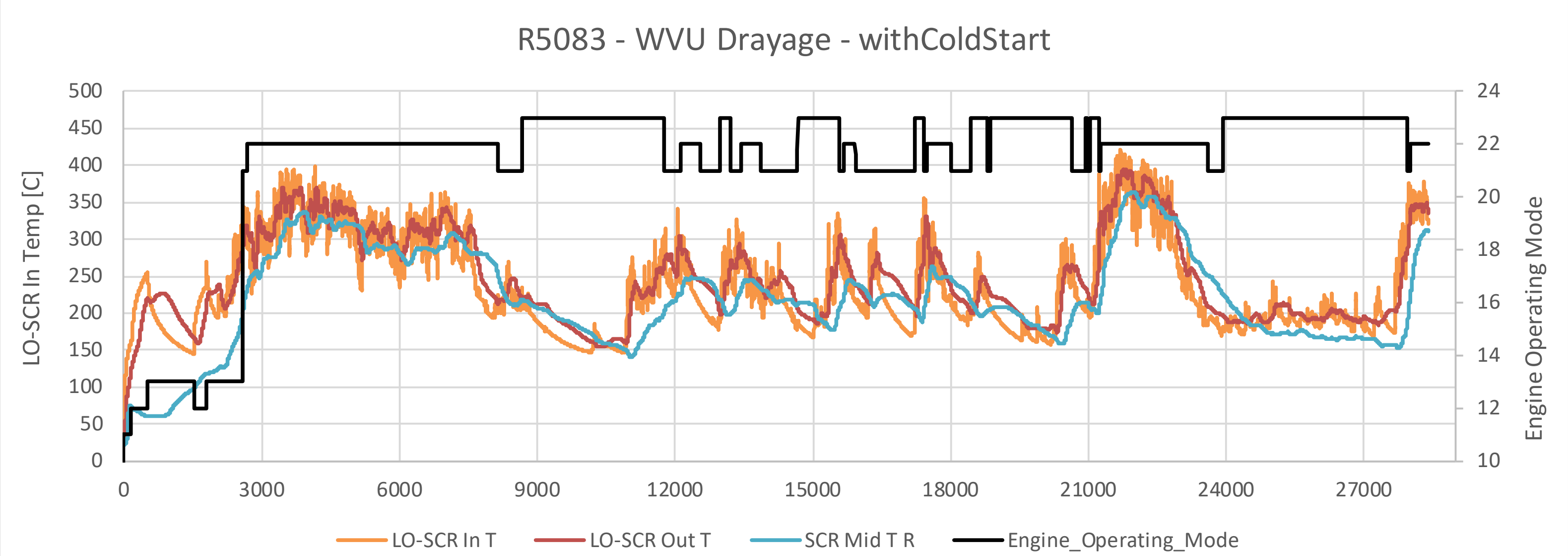
- Window size still based on WHTC

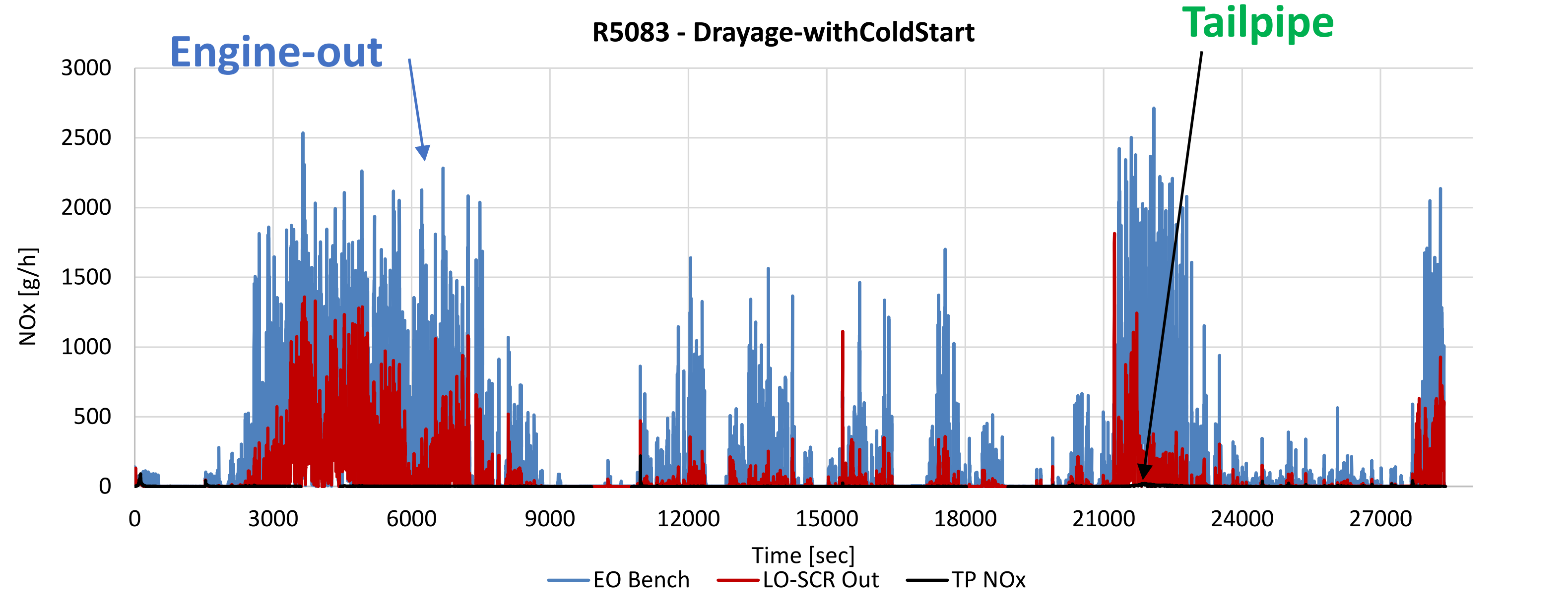
WBW Issues at very low loads (<5% average work)

- Torque measurement is not very good at light loads (requires extra hardware)
- Window size gets very long at very light loads (overweighting of light load emissions)
- For these reasons CARB/EPA chose fixed-time (300 sec.) windows

[1] *Euro VII methodology proposed by AGVES April 2021, "CLOVE AGVES-HDV_Exhaust Pres 040821.pdf" and "AGVES-2021-04-27-HDV_Exhaust-v6b.pdf"*

Port Operation Route and Transfer to Warehouse





30-minute idle after cold-start

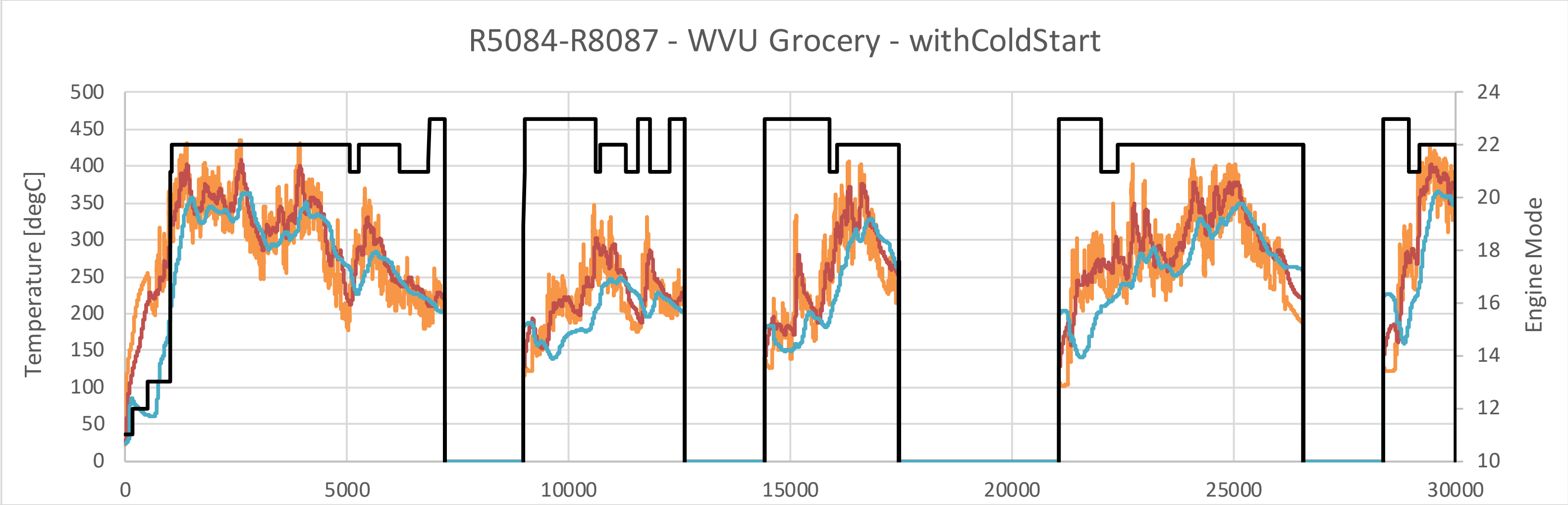
- worst-case idle

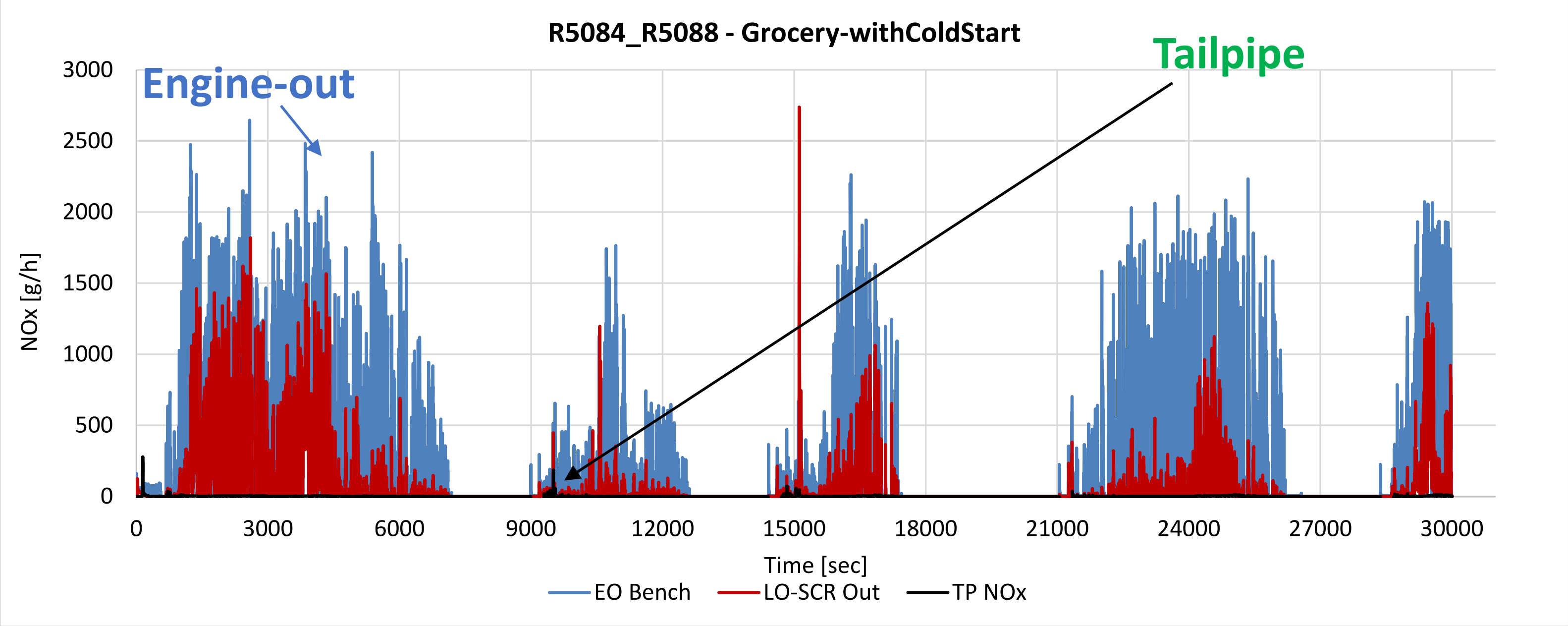
Sustained periods of low speed and low load

- Moving containers inside port

Lowest overall cycle load

Grocery Delivery Route



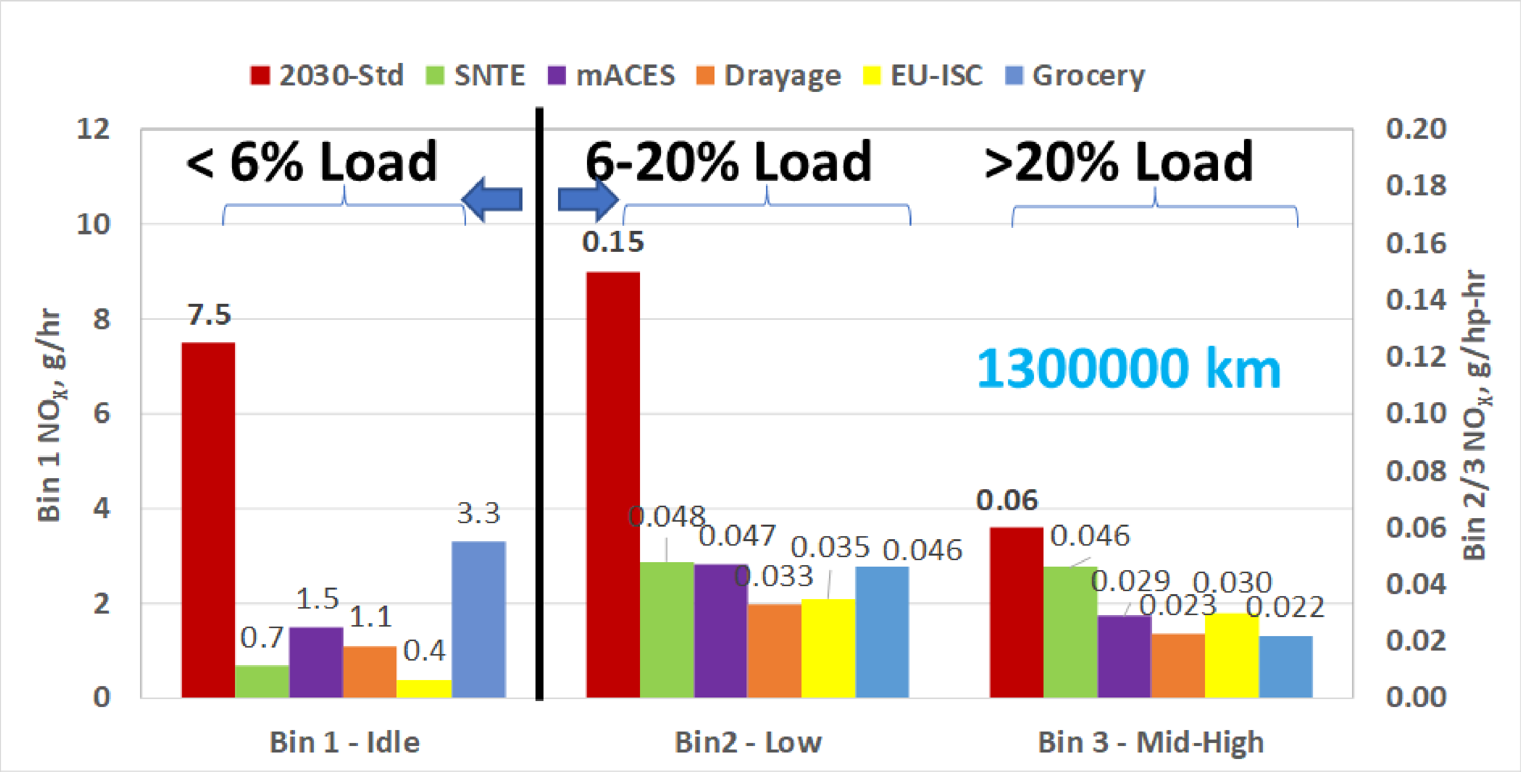


Multiple engine shutdowns between 30 and 60-min duration

Driving between store route at low to mid loads

Rapid system recovery after various cool to warm starts

Field Duty Cycle Results after 1,300,000 km



- Emissions evaluated using new CARB / EPA 3-bin Moving Average Windows method (no Exclusions)
- Low Load emission problem is eliminated with Low NO_X technology
- Emission controls are durable to 1.3 million km
- **For closed-crankcase, Bin 2 and Bin 3 results would be lower by ~ 0.008 g/kWh**

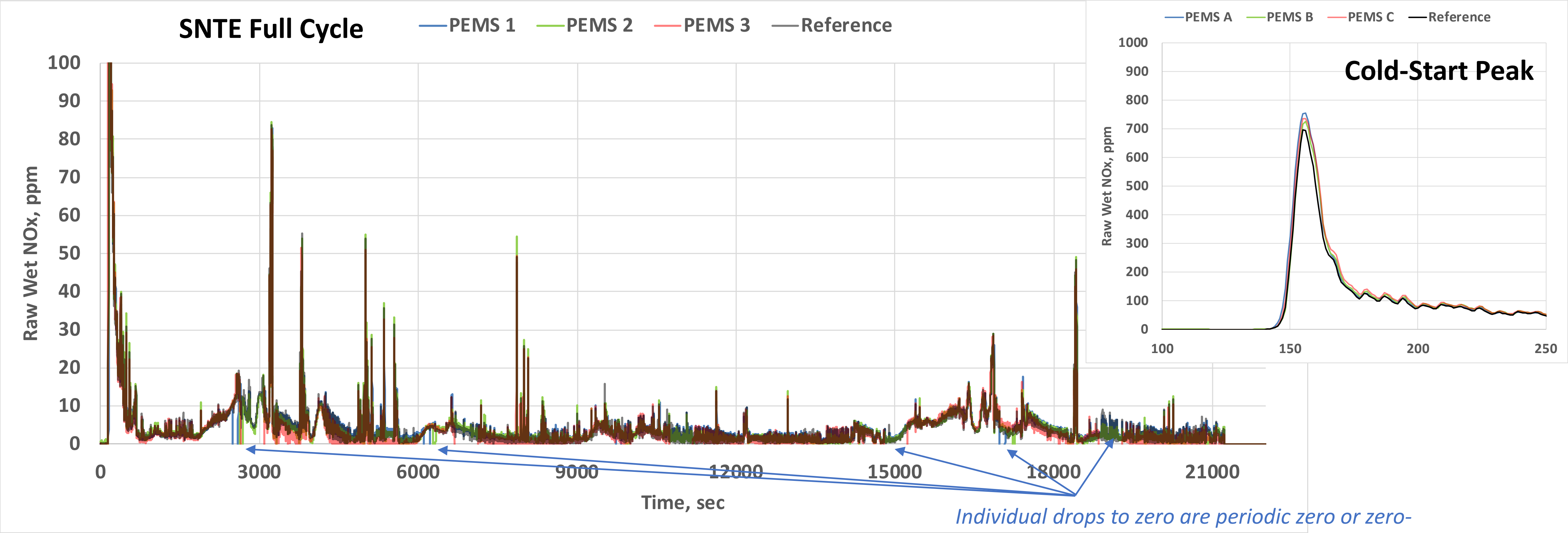
Euro VII Analysis Result – Using Proposed WBW Methodology[1]

	Duty Cycle					Euro VII HD3 Limit Values
	CARB Southern	Drayage	EU-ISC	5m-ACES	Grocery	
	BSNO$_X$ Level, mg/kw-hr					
50th percentile	32	25	25	41	27	n/a
90th percentile	**83**	**58**	**61**	**84**	**51**	**90**
100th percent	**143**	**106**	**88**	**94**	**79**	**175**
3xWHTC "budget"	**56**	**35**	**55**	**48**	**37**	**100**

- Results on all real-world duty cycles are still below stringent HD3 scenario proposed by CLOVE for Euro-VII

[1] *Euro VII methodology proposed by AGVES April 2021, "CLOVE AGVES-HDV_Exhaust Pres 040821.pdf" and "AGVES-2021-04-27-HDV_Exhaust-v6b.pdf"*

PEMS vs Lab Analyzer – NO_X results



Individual drops to zero are periodic zero or zero-span events on a given PEMS

Overall PEMS NO_X behavior very similar to Lab Reference over 6.5 hours

Reference is average of 3 separate Lab emission benches

Conclusions

Control of emissions to near zero levels from all powertrains will be needed as we transition transportation to achieve air quality goals

Technology is evolving at a rapid pace creating opportunities for control and monitoring to ensure real world reductions.

Available sensors and telematics is providing new approaches for compliance and enforcement

On-road experience can benefit nonroad equipment, technology demonstration is ongoing at Southwest Research Institute with funding from CARB and MECA.

Thank You

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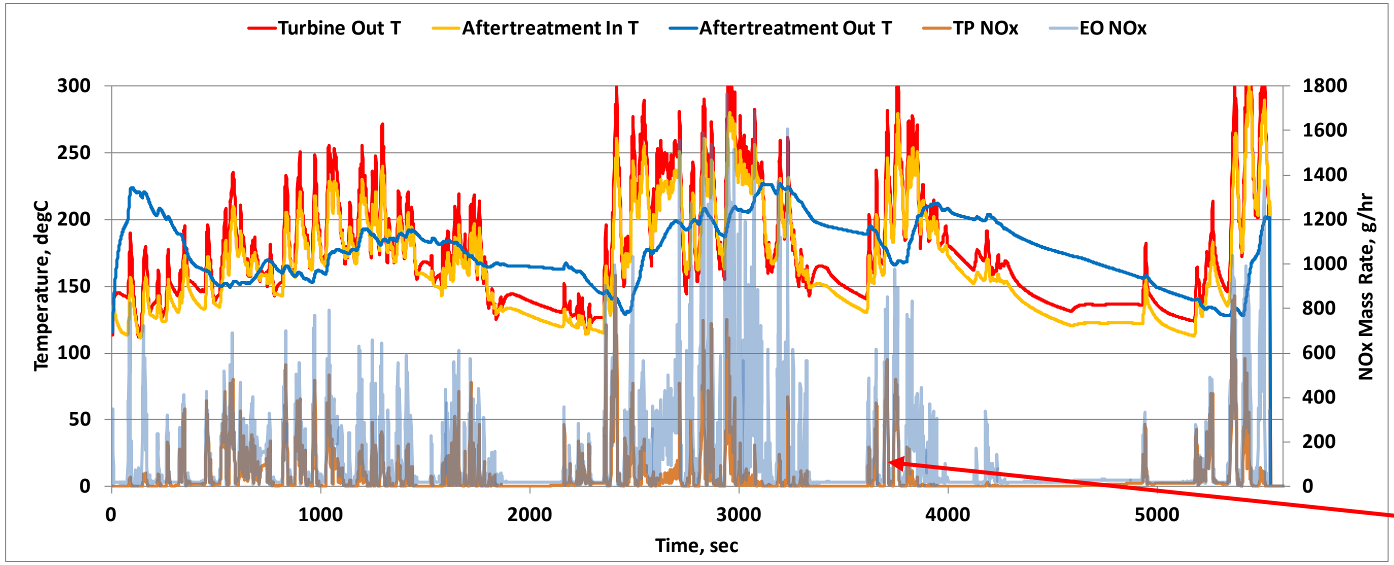
Supplemental Slides

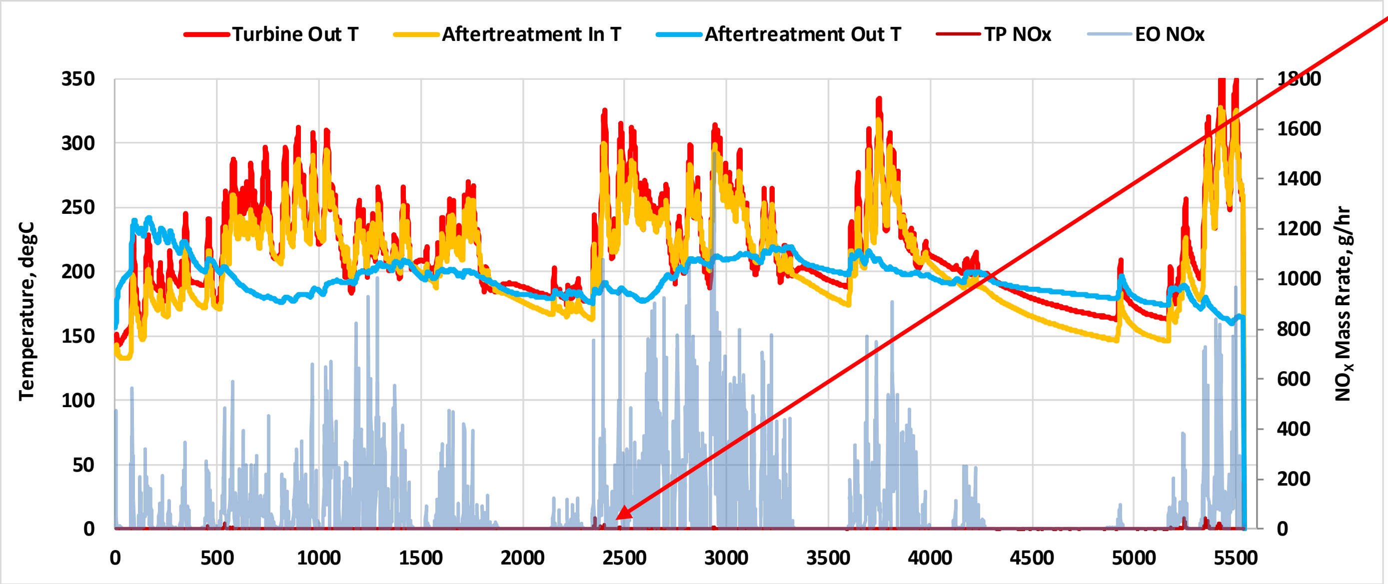
LLC Comparison – Base Engine vs Low NO_X Engine



Base Engine Example

- Overall 64% conversion
- EO NO_X (g/hp-hr) = 2.9
- TP NO_X (g/hp-hr) = 1.0

Tailpipe NO_X



Stage 3RW Low NO_X Engine

- Overall 98.6% conversion
- EO NO_X (g/hp-hr) = 2.3
- TP NO_X (g/hp-hr) = 0.03

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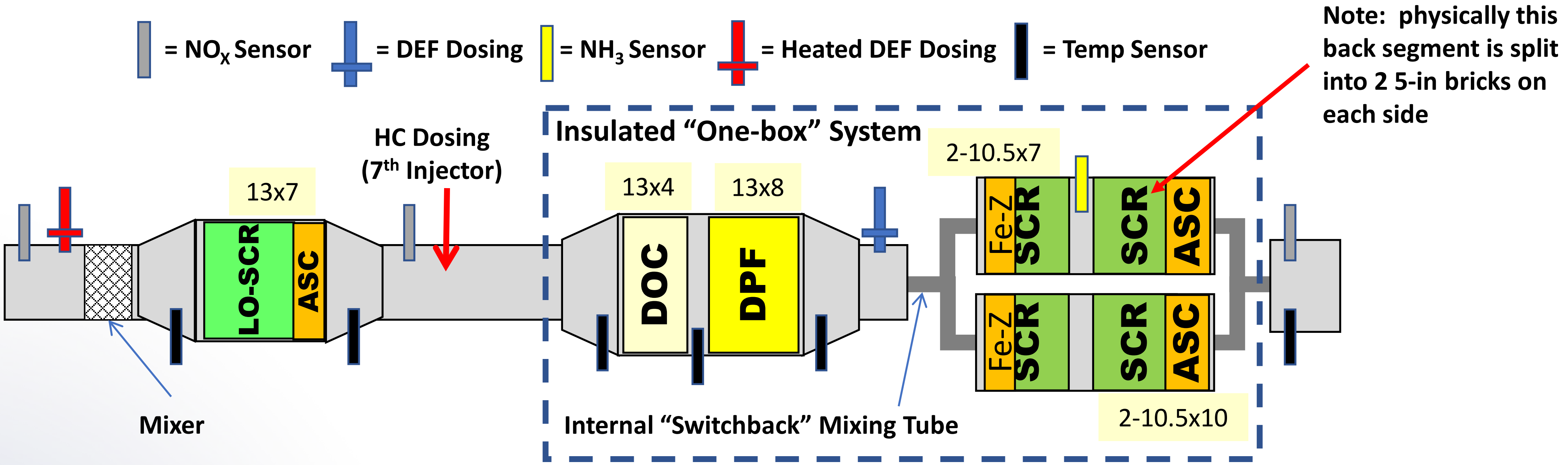
EPA Improved Aftertreatment System for low N_2O



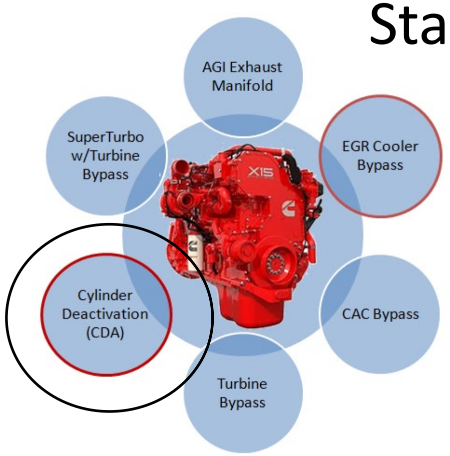
Improved formulation including Fe-zeolite layer at front of downstream SCR

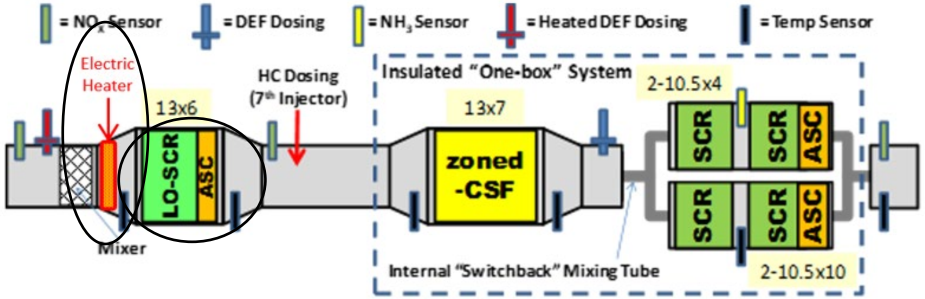
- Reduced N_2O formation with new system at below half of EPA standard (0.13 g/kWh)

Further improved low temperature durability

Synergy with Mild Electrification

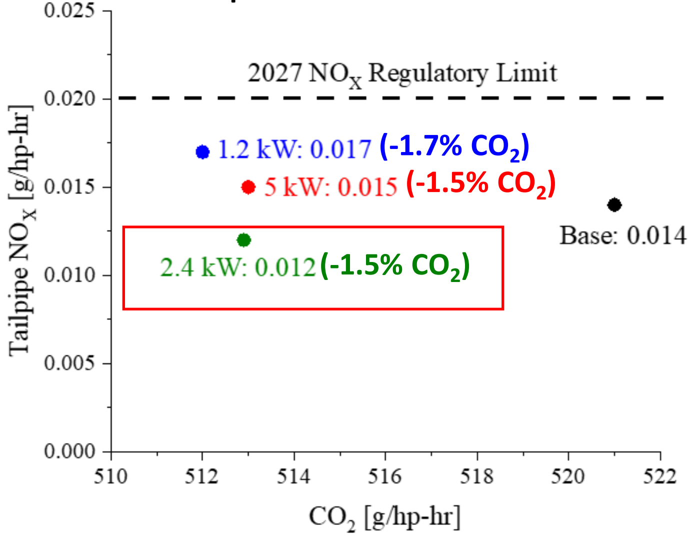
Stage 3 + e-Heater



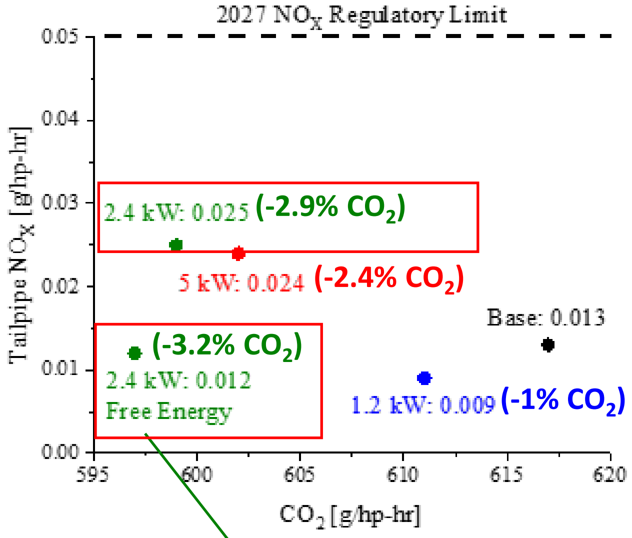


- **e-Heater can be used on this configuration even at lower power to enhance NO_X margin <u>and</u> improve overall system CO_2**
- **Best combined improvement in NO_X and CO_2 at moderate power (2.4kw)**
  - CO_2 improvement from reduced need for engine-based thermal management modes

Composite FTP Result



LLC Result



("Free Energy" = heater power taken from battery storage from Hybrid Regen Braking)

Reference: "Fast Diesel Aftertreatment Heat-up Using CDA and an Electrical Heater between 1.2 and 5.0 kW," Frontiers in Mechanical Engineering, 7/25/2022.

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Vehicle CO_2 Analysis with GEM – Impact of Low NO_X Engine

Vehicle ID	GEM Run Vehicle Parameters used for 2027 "Stringency Vehicles"															GEM Results		
Vehicle ID		Drive Axle	Drive Axle	Aerodyna	Steer Axle	Drive Axle	Drive Axle	Drive Axle	Technology Improvement	Technolog	Technolog	Technolog	Technolog	Technolog	Technolog	Baseline Engine	Low NOx Engine	Low NOx Engine
	Regulatory S	Configura	Ratio	Aerodyna	Rolling Re	Rolling Re	Rolling Re	Loaded Ti	Weight Reduction	Neutral-Id	Start-Stop	Automati	Accessory	Tire Press	Other	GEM CO2 Emissions	GEM CO2 Emissions	Percent
	(e.g. HHD_R)	(e.g. 6x4)	#	m^2	kg/t	kg/t	kg/t	rev/mi	lbs	Y/N	Y/N	Y/N	%	%	%	g CO2/ton-mile	g CO2/ton-mile	
Vocational Vehicles																		
7hrAMTtiresweight	HHD_R	6X4	3.76	0	6.2	6.9	6.9	496	125	N	N	N	0	0	0	213.3	210.5	**-1.3%**
7hraxle	HHD_R	6X4D	3.76	0	6.2	6.9	6.9	496	125	N	N	N	0	0	0	210.9	208.0	**-1.4%**
7hrNI	HHD_R	6X4	3.76	0	7.7	7.7	7.7	496	0	Y	N	N	0	0	0	220.5	217.6	**-1.3%**
7hrSS	HHD_R	6X4	3.76	0	7.7	7.7	7.7	496	0	N	Y	N	0	0	0	219.3	216.6	**-1.2%**
7hmAMT350	HHD_M	6X4	4.33	0	6.2	6.9	6.9	496	125	N	N	N	0	0	0	264.1	253.9	**-3.8%**
7hrengineonly	HHD_R	6X4	3.76	0	7.7	7.7	7.7	496	0	N	N	N	0	0	0	224.7	221.9	**-1.3%**
7hrMTtireswt	HHD_R	6X4	3.76	0	6.2	6.9	6.9	496	125	N	N	N	0	0	0	217.4	214.5	**-1.3%**
7hrAES	HHD_R	6X4	3.76	0	7.7	7.7	7.7	496	0	N	N	Y	0	0	0	217.8	216.7	**-0.5%**
7hmMT455	HHD_M	6X4	4.33	0	6.2	6.9	6.9	496	125	N	N	N	0	0	0	268.8	258.5	**-3.8%**
7hmMT455	HHD_U	6X4	4.33	0	6.2	6.9	6.9	496	125	N	N	N	0	0	0	301.7	287.1	**-4.9%**
7hmMT455	HHD_U	6X4	4.33	0	6.2	6.9	6.9	496	125	Y	N	N	0	0	0	301.7	287.1	**-4.9%**
HD Tractors																		
2027_TRAC1	C8_SC_HR	6X4	3.16	5.26	5.6	5.8	5.8	512	0	N	0.8	0.5	3	1.1	5.5	71.5	71.0	**-0.7%**
2027_TRAC2	C8_SC_MR	6X4	3.16	6.21	5.8	6.2	6.2	512	0	N	0.8	0.5	3	1.1	5.5	75.8	75.4	**-0.5%**
2027_TRAC3	C8_SC_LR	6X4	3.16	5.08	5.8	6.2	6.2	512	0	N	0.8	0.5	3	1.1	5.5	69.7	69.3	**-0.7%**
2027_TRAC4	C8_DC_HR	6X4	3.21	5.67	5.6	5.8	5.8	512	0	N	0.8	0.5	0	1.1	5.7	82.8	82.1	**-0.8%**
2027_TRAC5	C8_DC_M	6X4	3.21	6.21	5.8	6.2	6.2	512	0	N	0.8	0.5	0	1.1	5.7	83.9	83.3	**-0.7%**
2027_TRAC6	C8_DC_LR	6X4	3.21	5.12	5.8	6.2	6.2	512	0	N	0.8	0.5	0	1.1	5.7	78.9	78.2	**-0.8%**
2027_TRAC7	C7_DC_HR	4X2	3.21	5.67	5.6	5.8	NA	512	0	N	0.8	0.5	0	1.1	5.1	107.9	107.2	**-0.7%**
2027_TRAC8	C7_DC_M	4X2	3.21	6.21	5.8	6.2	NA	512	0	N	0.8	0.5	0	1.1	5.1	109.4	108.6	**-0.7%**
2027_TRAC9	C7_DC_LR	4X2	3.21	5.12	5.8	6.2	NA	512	0	N	0.8	0.5	0	1.1	5.1	101.6	100.8	**-0.7%**
2027_TRAC10	C8_HH	6X4	3.7	NA	5.8	6.2	6.2	512	0	N	0.8	0.5	0	1.1	9.5	47.4	47.1	**-0.8%**

Lower CO_2 on a wide variety of vehicle configurations

While reaching Low NO_X levels in all cases

Category	CO2 % Change
HD Vocational - Rural	**-1.2%**
HD Vocational - Mixed Use	**-3.8%**
HD Vocational - Urban	**-4.9%**
HD Tractor	**-0.8%**

Vehicles are configurations used by EPA to set stringency of Phase 2 Standards in 2027

- Same vehicles run with both Baseline Engine fuel maps and Low NO_X Engine fuel maps

Results are generated with GEM using Steady-State map (closest GEM comparison to VECTO approach)

Even at Low NO_X levels, use of CDA results in net CO_2 reduction in all vehicle categories (no penalty)

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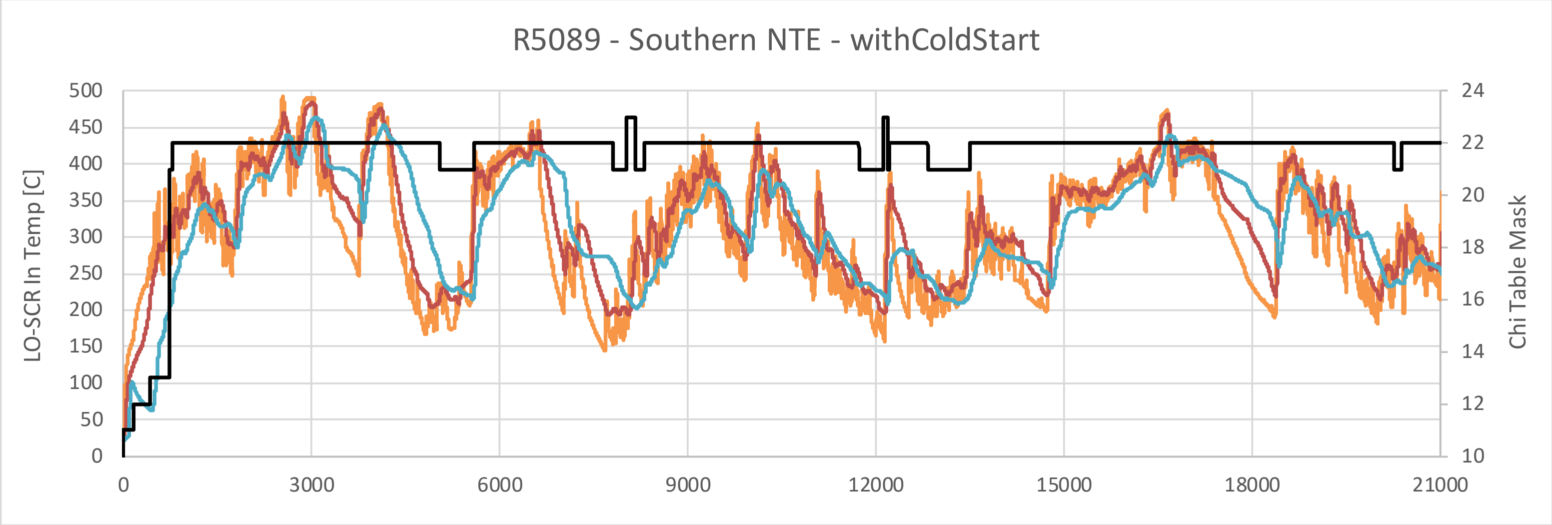
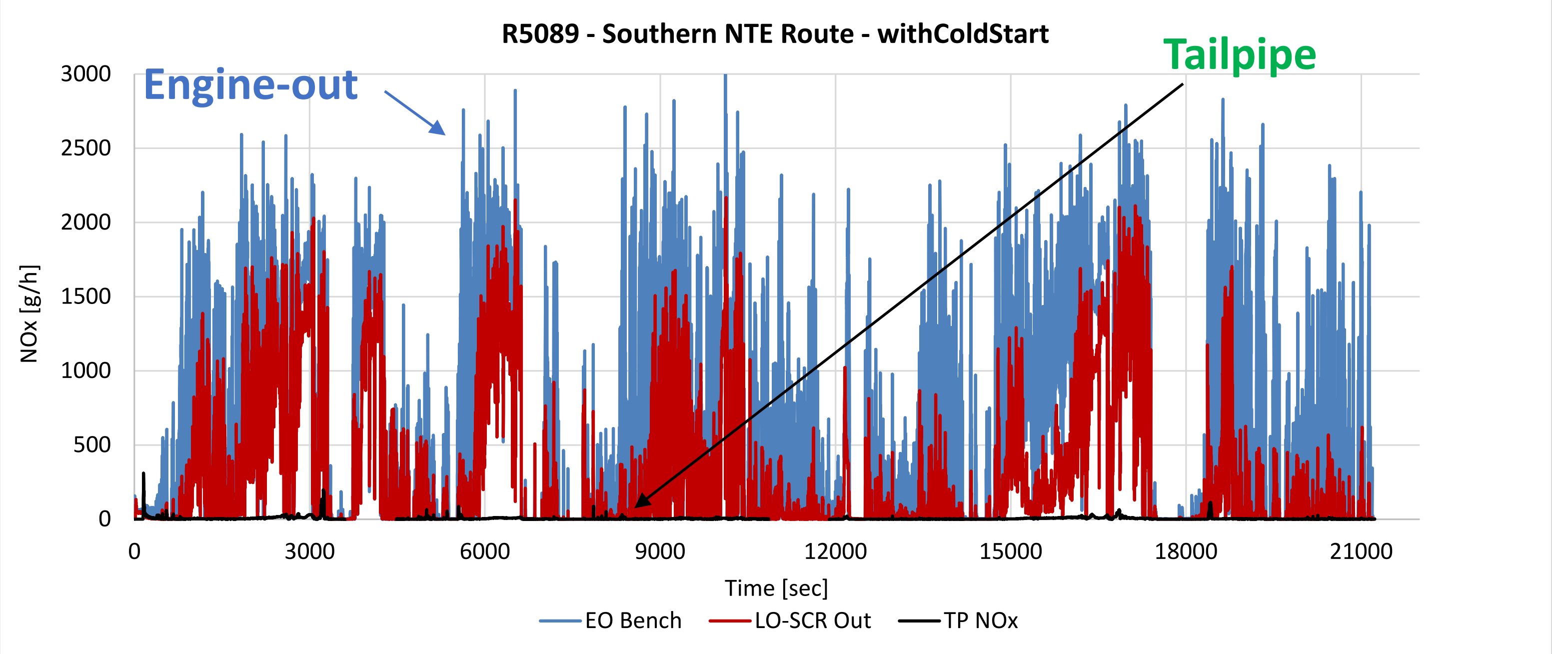
CARB In-Service Compliance (SNTE) Route for Long-haul Truck





6 minutes of idle after cold-start

Includes both Urban and Highway operation with large downhill sections

Multiple examples of different low-to-high load transitions at different rates

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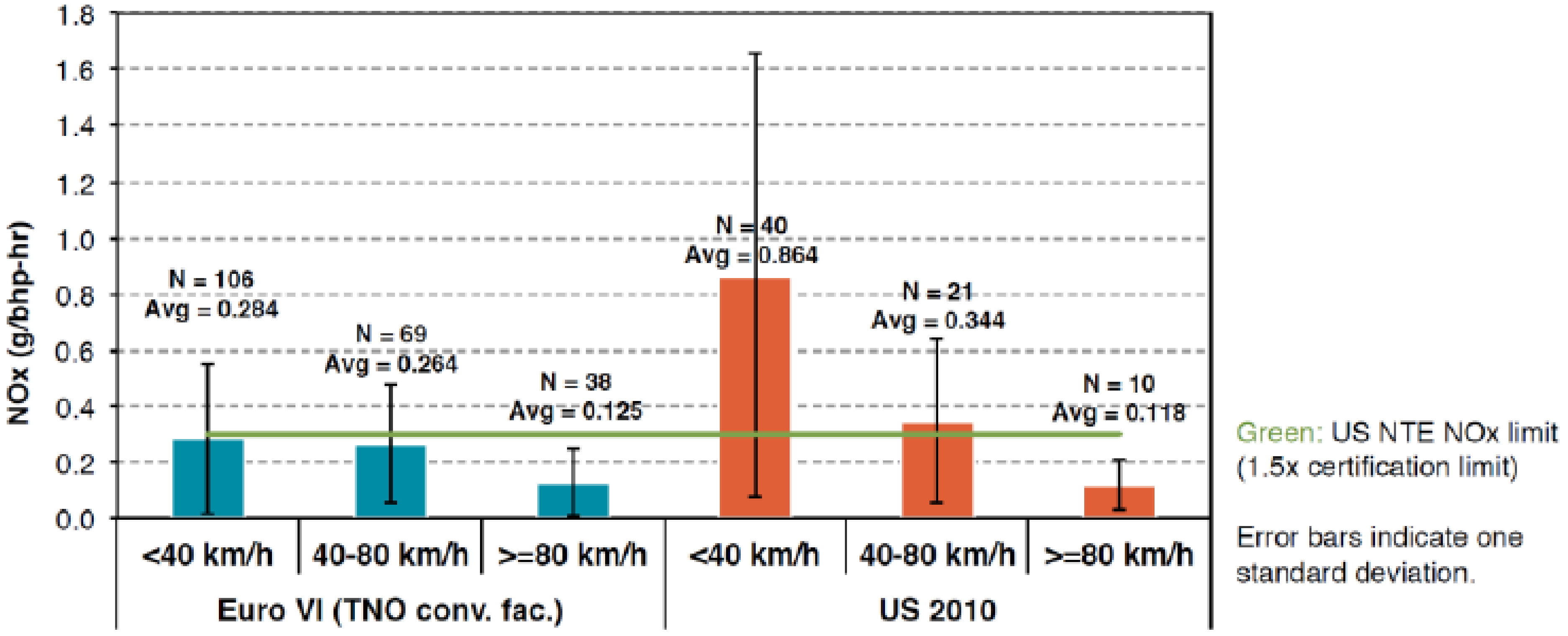
Heavy-Duty In-Use Testing: Not-to-Exceed (US) Versus Moving Average Windows (EU)



Source: ICCT, Integer 2017 Emissions Summit

Non-Road Test Program

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Nonroad Low NO_X Demonstration Program

Overall goal of Nonroad Low NO_X effort is to demonstrate production feasible technologies to reduce emissions:

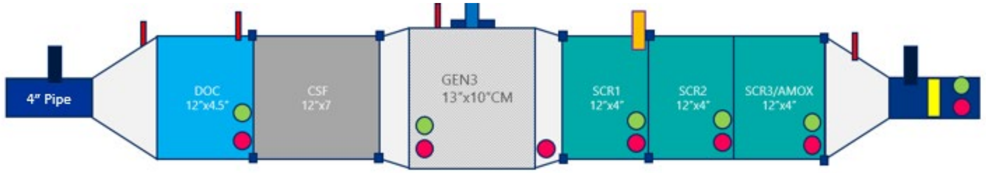
- NO_X by 90% (nominal target of 0.04 g/kw-hr)
- PM by 75% (nominal target of 0.005 g/kw-hr)
- Extended Useful Life target at 12,000 hours (test at 8,000 hours)

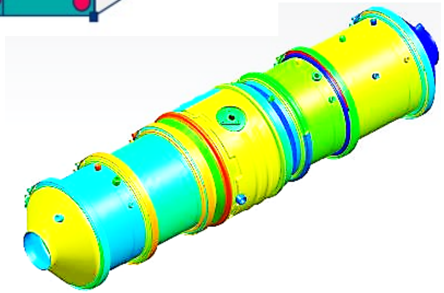
John Deere 6068 (6.8L) Tier 4f Engine

Demonstration Plan is for two technology packages…

- Package 1 = Meet NO_X Target at GHG neutral
- Package 2 = Meet NO_X Target with GHG reduction of 5-8.6%
  - Will require additional engine hardware levers to enable success

Preliminary Results with 12k hour hydrothermally aged parts





Cycle	EO NO_X, g/kw-hr	TP NO_X, g/kw-hr	NO_X Efficiency, %	CO_2, g/kw-hr	Baseline CO_2, g/kw-hr
Cold NRTC	2.3	0.138	93.9	763	761
Hot NRTC	2.4	0.004	99.8	741	747
Composite NRTC	**2.4**	**0.011**	**99.5**	**745**	**748**
RMC C1	**2.7**	**0.009**	**99.7**	**689**	**697**
LLAC	**4.1**	**0.011**	**99.7**	**832**	**836**

SUPPLYING CLEAN MOBILITY