Addressing Carbon Neutrality Exhaust Thermal Management

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Outline

- Emission Regulations
- Introduction
- Proven Configuration
- Multiple Options Investigated
- How Various Options Stack Up
- Summary and Conclusions

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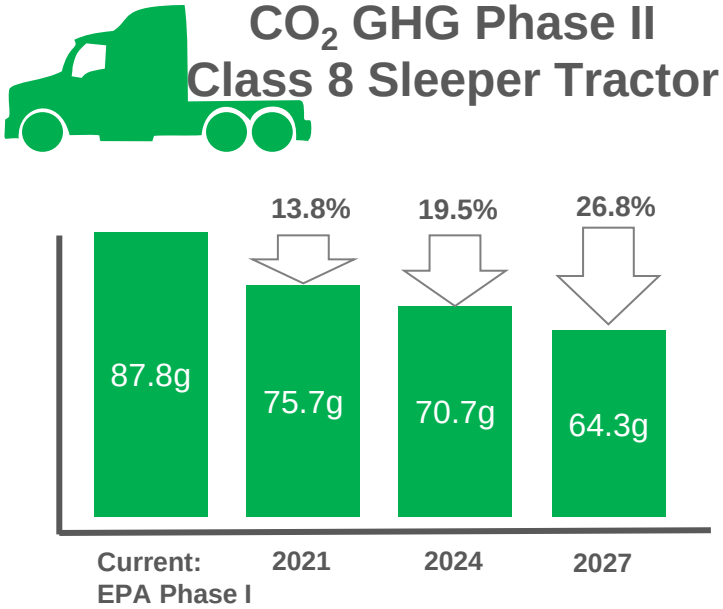
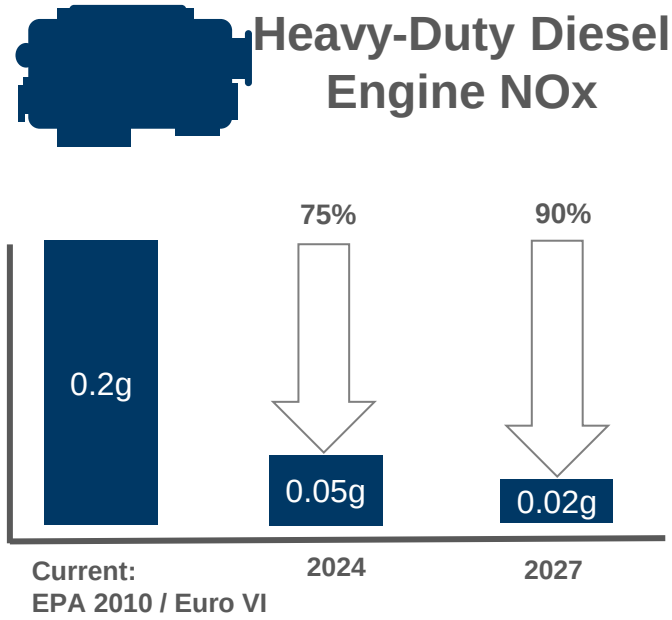
Regulations Driving Change

Simultaneous NOx and CO_2 within 2024-2027 timeframe worldwide



Europe 15% and 30% reduction in 2025 and 2030



Euro VII expected similar to U.S.

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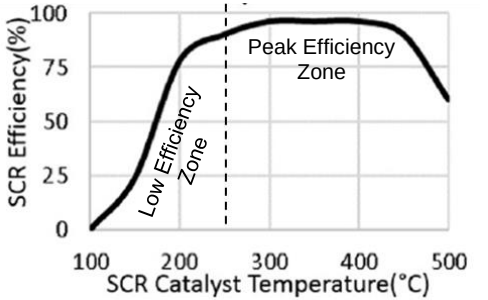
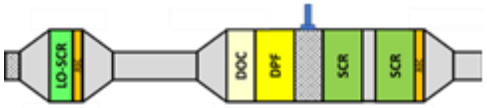
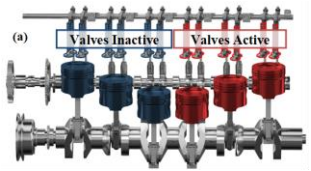
Introduction

- 2027 will have lower emissions & improved fuel economy
  - CARB standard issued / EPA NPRM proposals have similarities
  - Composite FTP: 0.02 g/hp-hr NOx (90% reduction)
  - Added Low Load Cycle (LLC): 0.05 g/hp-hr NOx (90%+ reduction)
- NOx aftertreatment systems are temperature sensitive
  - High NOx conversion occurs around 250 C
  - Exhaust thermal management required at low load
- Enabling Tools and Pairings
  - Cylinder Deactivation (CDA) for fuel efficiency and AT heating
  - Dual SCR: Close Coupled SCR + Primary Downstream SCR
  - E-heater at various locations
  - Fuel Burner upstream of DPF and SCR







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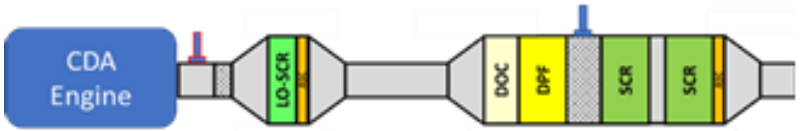
Repeatable Composite FTP Over 4 Years

- Proven configuration with CDA, LO-SCR and Primary Aftertreatment system

+ CDA



- Catalysts were hydrothermally aged to end-of-life (435,000+ miles)
- System results were repeatable over 4 years showing up to 30% margin from CARB 2027 NOx

Year Tested	Composite FTP, g/hp-hr			Year Published	Publication
	EO NOx	TP NOx	CO_2		
2019	3.2	0.020	506	2020	SAE Intl. Journal Engines
2020	3.1	0.015	515	2021	SAE 2021-01-0211
2020	3.0	0.015	515	2020	GAMC 2020
2021	2.9	0.014	521	2022	Frontiers in Mech. Eng.
2022	3.0	0.014	517	2022	GAMC 2022

30% NOx Margin

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GHG benefits with CDA

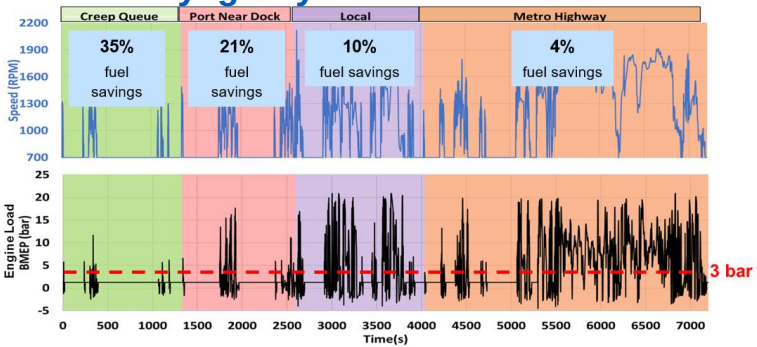
Driven by CDA and Less Time in Engine Thermal Management Mode

Significant GHG Benefit: Real-World Driving with CDA

- LLC: 6% (14% NO_X reduction)
- OCTA: 3% (86% NO_X reduction)
- NYBC: 8% (33% NO_X Reduction)
- Beverage: 5% (67% NO_X Reduction)

Data from testing of a CDA equipped 15L engine with production EATS
Int. J. Powertrains, Vol. 9, No. 4, pp. 315–344 (2020)

Port Drayage Cycle

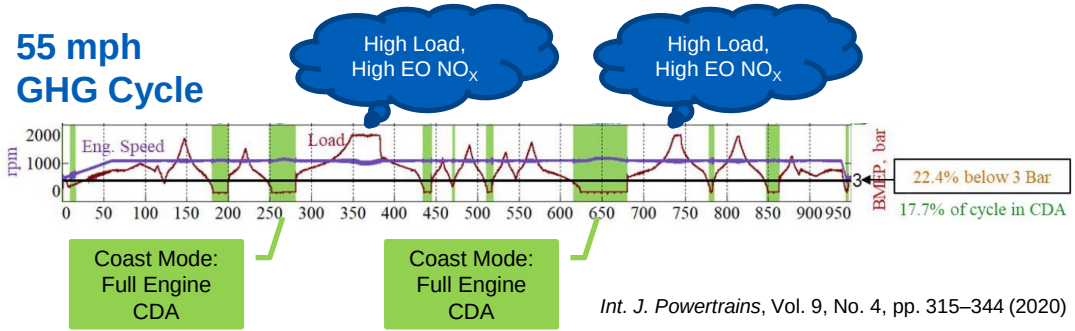


Data from simulation of a CDA equipped 6.7L engine with production EATS
SAE 2018-01-0880, 4/3/2018

Upside Potential for Reduced CO_2: GHG Certification Cycle with CDA

- ARB: 1% (45% NO_X Reduction)
- 55-mph: 1% (65% NO_X Reduction)

55 mph GHG Cycle



Int. J. Powertrains, Vol. 9, No. 4, pp. 315–344 (2020)

Coasting with full engine CDA

- Eliminates emissions during coast
- Keeps EATS hot
- Reduces need to heat EATS back up when load resumes

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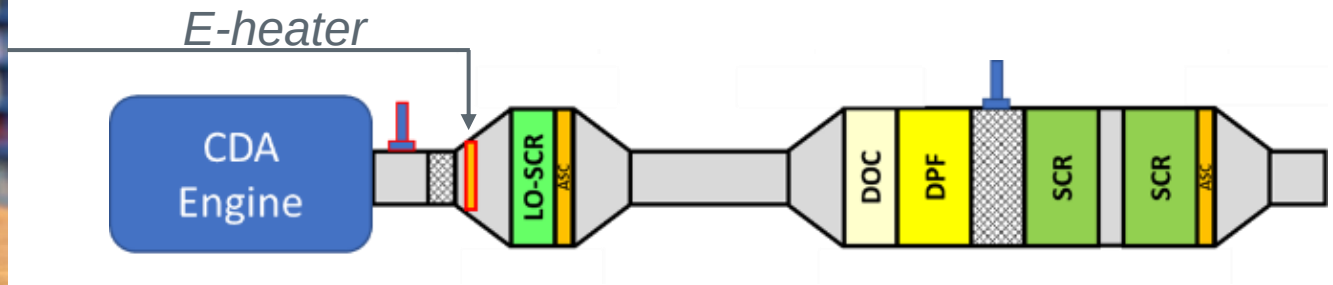
Added an Upstream Electric Heater

- An electric heater was added upstream of the LO-SCR.



Initial work found 5 kW maximum to be useful

	Composite FTP, g/hp-hr			
	EO NOx	TP NOx	CO_2	CO_2 Savings
Proven Configuration	3.14	0.015	515	
+ E-heater	3.22	0.016	511	0.8%

Reference: "Fast Diesel Aftertreatment Heat-up Using CDA and an Electrical Heater," SAE Technical Paper 2021-01-0211.

Optimization yielded 2.4 kW maximum as ideal

Power Level	TP NO_X [g/hp-hr]	$BSCO_2$ [g/hp-hr]	CO_2 Savings
No Heater	0.014	521	--
1.2 kW	0.017	512	1.7%
2.4 kW	0.012	513	1.5%
5 kW	0.015	513	1.5%

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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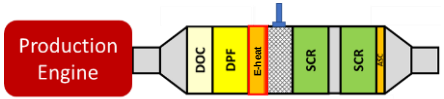
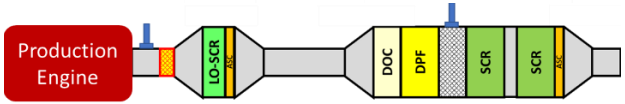
More Configurations Tested

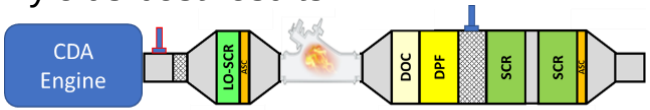
- Positioned a Single Electric Heater Between the DPF and SCR
  - Meet LLC NOx
  - CO_2 was high for both FTP and LLC

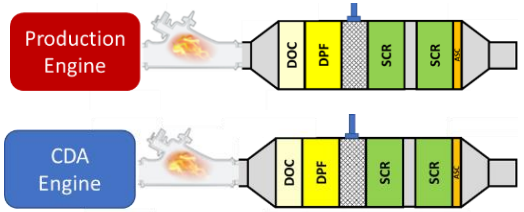


- Removed Heated DEF Dosing in Front of the LO-SCR
  - Meet 2027 NOx for FTP (little margin)
  - Safely within LLC NOx
  - CO_2 was high for both FTP and LLC



- Added a Fuel Burner
  - Burner + CDA + LO-SCR yields best results





Opportunity for Adding Technology to Reduce CO_2 and Lower NOx

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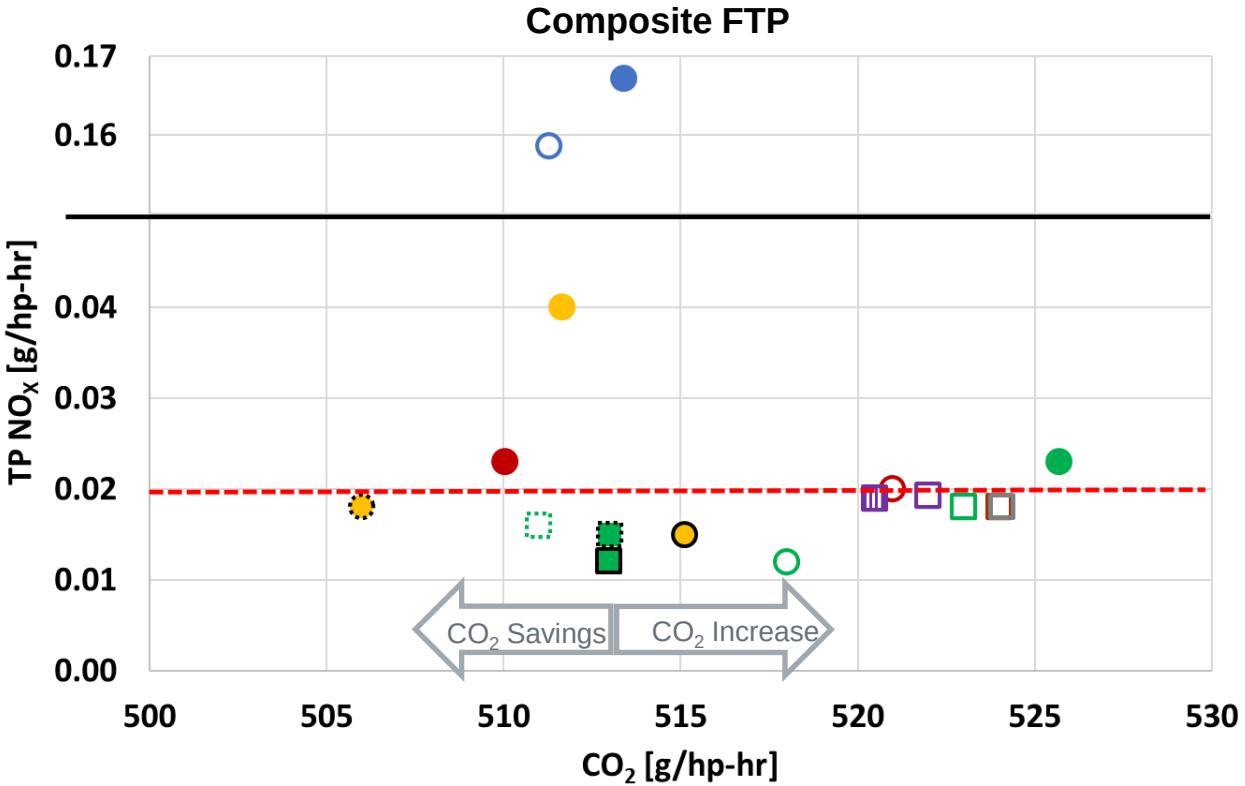
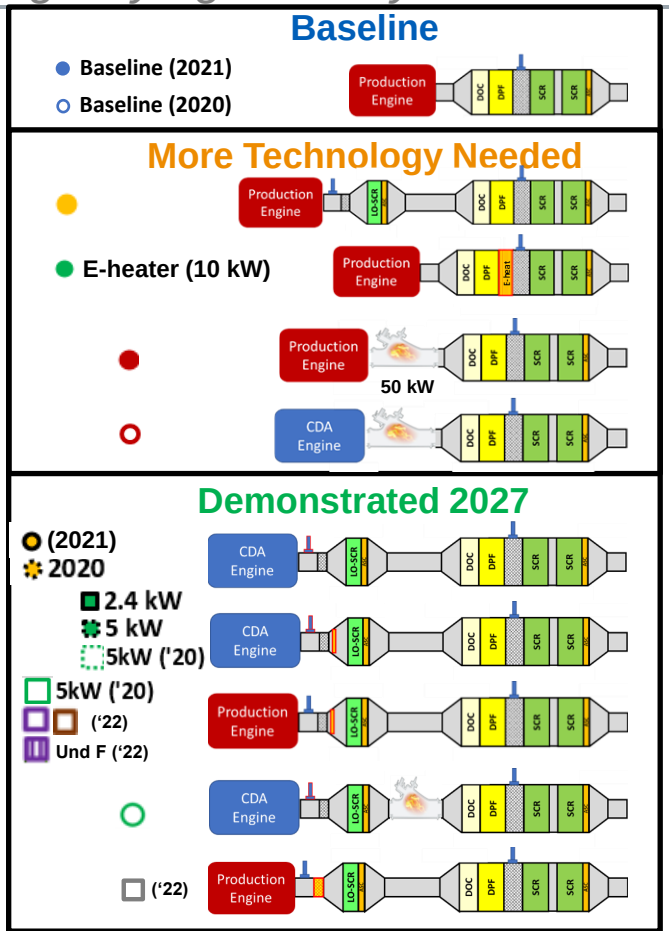
How the various options stack-up

- Engine Configurations
  - Production Engine (PE) & Full Authority Cylinder Deactivation (CDA)
- With and Without
  - LO-SCR
  - Electric Heaters
  - Fuel Burners
  - Heated DEF Dosing on the LO-SCR
- Test Cycles
  - HD FTP
  - Low Load Cycle (LLC)

Multiple Paths to Achieve 2027 Targets

Composite FTP achieves 0.02 g/hp-hr with margin using fully aged catalysts





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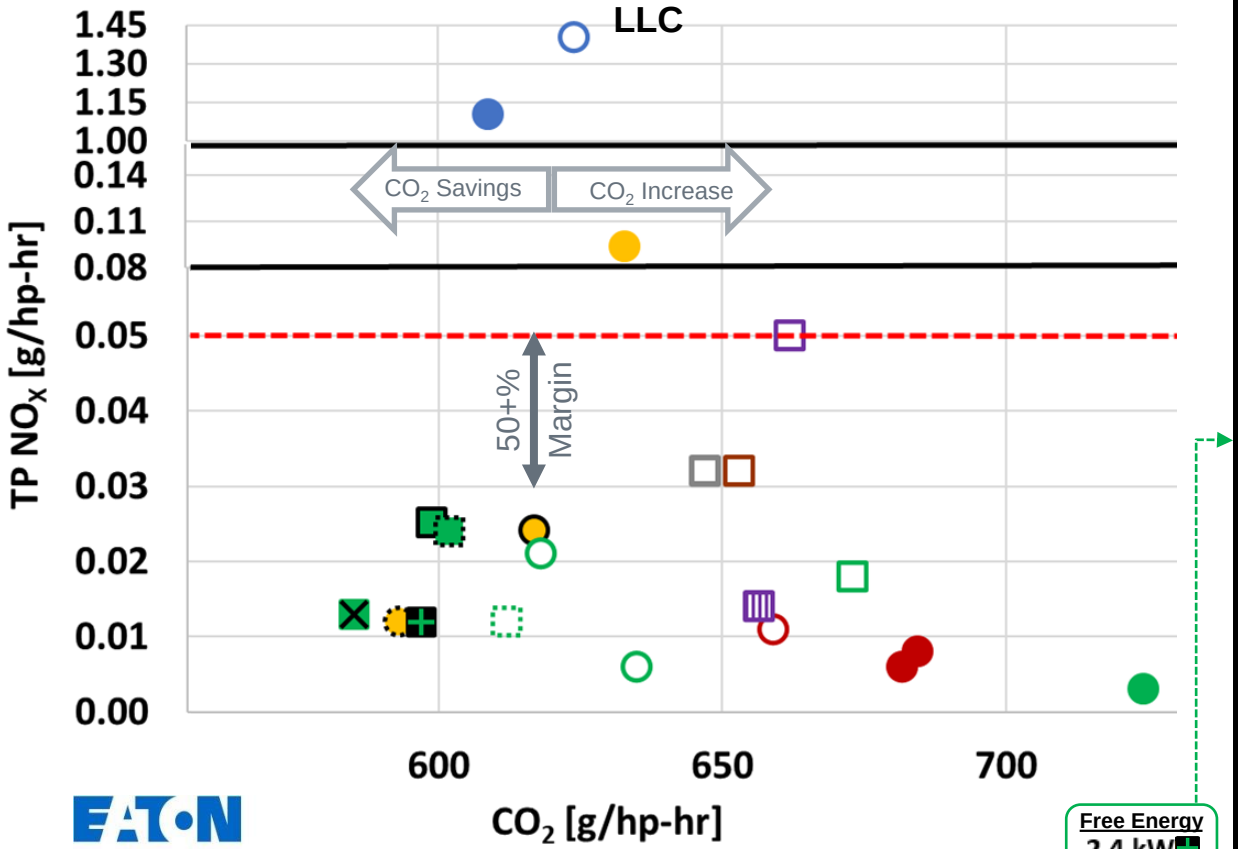
Multiple Paths to Achieve 2027 Targets

LLC achieves 0.05 g/hp-hr with >50% margin using fully aged catalysts



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Free Energy
2.4 kW
5 kW

Baseline

- Baseline (2021)
- Baseline (2020)

Production Engine

More Technology Needed

Production Engine

Demonstrated 0.05g

- (2021)
- 2020
- 2.4 kW
- 5 kW
- 5kW ('20)
- 5kW ('20)
- ('22)
- Und F ('22)
- ('22)
- E-heater (10 kW)

CDA Engine / Production Engine

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Summary and Conclusions

- Multiple options for meeting 2027 emissions have been demonstrated
- Meeting NOx & Remaining CO_2 neutral or better is key for moving forward
- CDA + LO-SCR + Primary Aftertreatment repeatable over 4 years
  - The addition of an e-heater (2.4 kW) can achieve the same excellent NO_X emissions while saving CO_2/fuel
  - The addition of a fuel burner can achieve the same excellent NO_X emissions while remaining CO_2 neutral
- Meeting 0.02 g/hp-hr composite NOx on the FTP and 0.05 g/hp-hr NOx on the LLC has been demonstrated more than 5 years in advance of the CARB 2027 mandate

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