DIESEL PROGRESS SUMMIT

New on-highway regulatory standards and technologies available to meet emissions requirements

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September 25, 2023

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Agenda

NOX & CO_2 REGULATIONS - 2024 AND BEYOND

TECHNOLOGIES TO LOWER NOX AND CO_2

TESTING A FEW TECHNOLOGIES

HOW TESTING RESULTS STACK UP

SUMMARY

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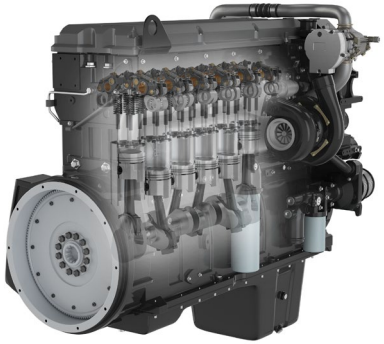
The challenge for on-highway trucks

2027 will have lower emissions and Greenhouse Gas (GHG)



EPA standards are in place

Composite NOx FTP reduction from 0.2 g/hp-hr

- 0.035 g/hp-hr Federally at 650k miles
- Increased useful life from 435k to 650k miles

Added Low Load Cycle (LLC): 0.05 g/hp-hr NOx (>95% reduction)

GHG reductions are already in place

Stricter Phase 3 requirements out to 2032+

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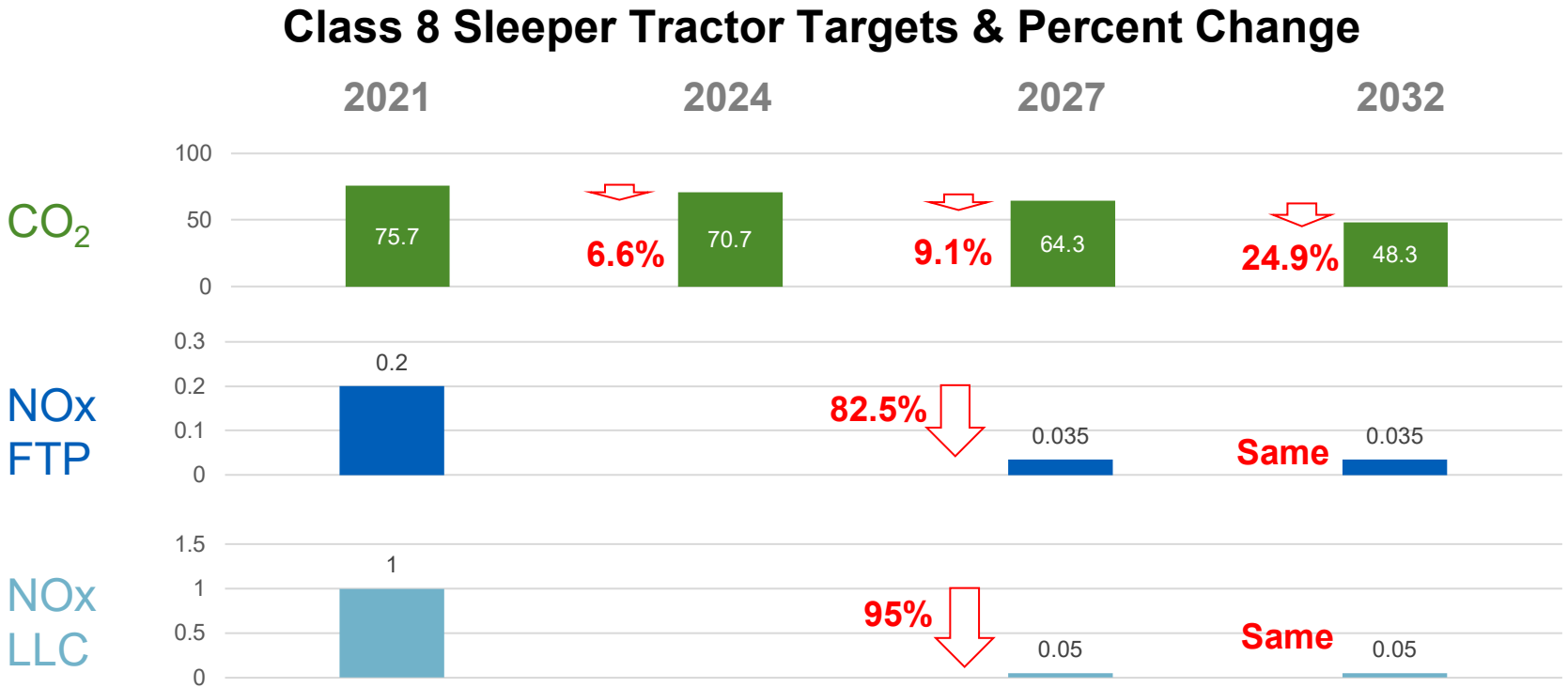
Regulations Driving Change

Simultaneous CO_2 and NOx reductions starting in 2024-2032



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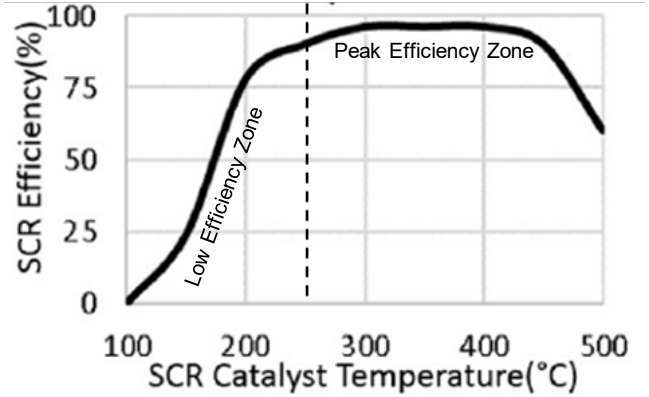
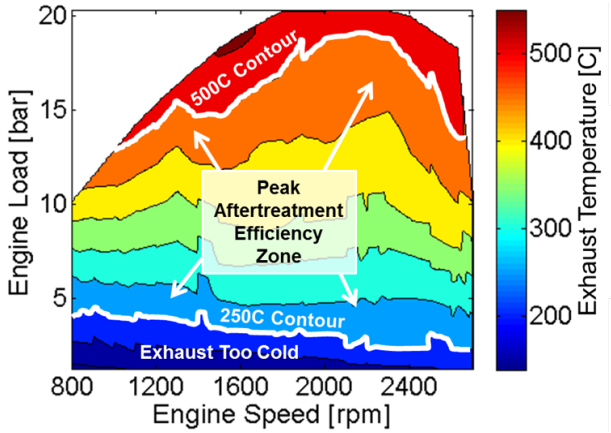
Aftertreatment systems are critical to NOx reduction

- NOx aftertreatment systems are temperature sensitive
  - High NOx conversion occurs around 250 C
- Aftertreatment temperature management is key for Low Load
  - Focus on “low engine load” and “cold” operation





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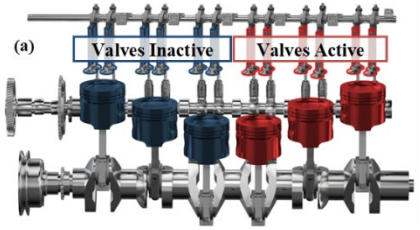
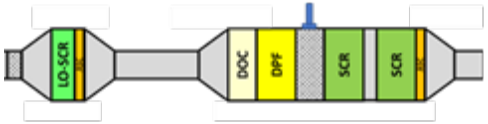
Enabling tools and pairings

- Cylinder Deactivation (CDA) for fuel efficiency and aftertreatment heating
- Dual SCR
  - Light-Off SCR (LO-SCR) + Primary Downstream SCR
- Electric heater at various locations in aftertreatment system
- Fuel Burner upstream of DPF and SCR
- Hybridization





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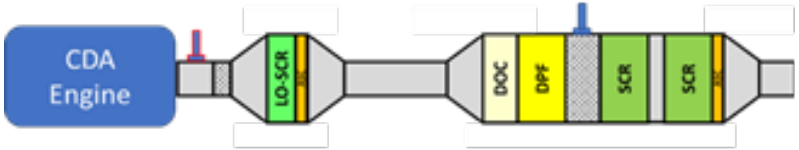
Proven Composite FTP Results Over 4 Years

- CDA, LO-SCR and Primary Aftertreatment meets upcoming regulations

+ CDA



- Catalysts hydrothermally aged to 435,000+ miles (previous end of life target)
- Repeated over 4 years: 60% margin for EPA 2027

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

2027 Regulations
60% EPA margin
Must extend to 650k miles and meet 0.035

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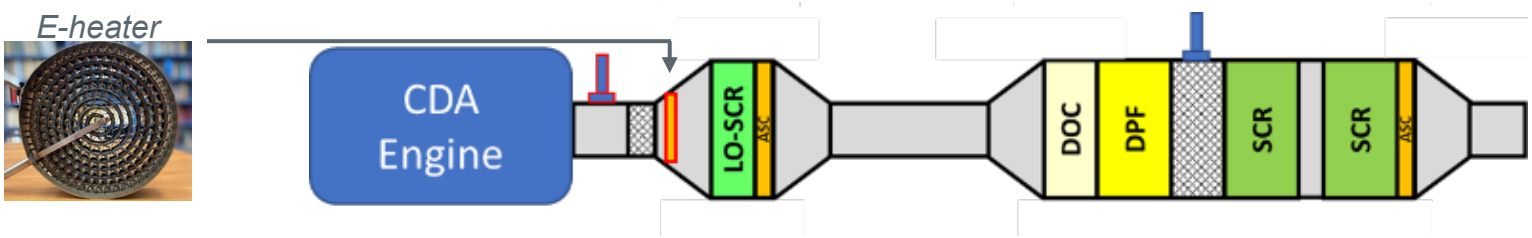
Adding an Upstream Electric Heater



- Optimization shows 2.4 kW had the best trade-off in NOx and CO_2
  - Dropped NOx from 0.014 to 0.012 g/hp-hr (66% EPA margin)
  - Increased CO_2 savings by 1.5%

Power level	TP NOx [g/hp-hr]	$BSCO_2$ [g/hp-hr]	CO_2 savings
No e-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.

With CDA, small e-heater works well (under 5 kW)
Without CDA, ~10 kW e-heater is needed

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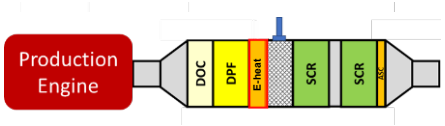
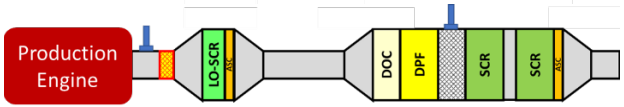
More Configurations Tested

- Adding Technology to understand NOx/CO_2 trade-offs

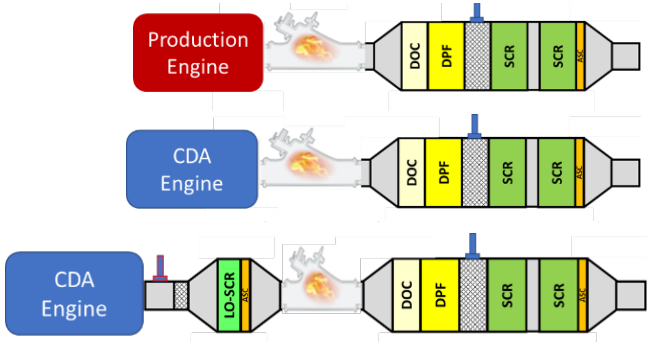
Electric Heater between DPF and SCR



Removed Heated DEF for LO-SCR



Added a Fuel Burner to Various Configurations



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How the various configurations stacked up

- Variables Tested
  - Engine Configurations
    - Production Engine and Full Authority CDA
  - With and Without Comparison
    - LO-SCR
    - Electric Heaters
    - Fuel Burner
    - With and Without Heated DEF on LO-SCR
  - Test Cycles
    - HD FTP
    - Low Load Cycle (LLC)

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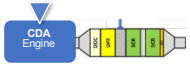
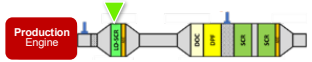
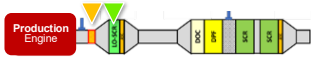
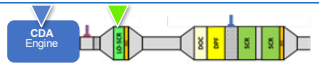
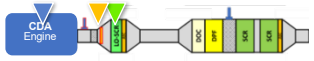
Composite FTP Results: (Both NOx and CO_2 are regulated)

Adding Technology Levers to Baseline Engine and Aftertreatment

	Technology Lever				Engine & Aftertreatment	Rating	NOx Base (0.16): 0.2→0.035→0.02 g/hp-hr	CO_2 Base: 513 g/hp-hr
	CDA	LO-SCR	eHeater	Burner				
1 Lever	X					----	*0.056 (projected)*	495 *(-3.6%)*
		X				----	0.040 to 0.060	512 *(neutral)*
			X 10 kW			----	0.023	526 *(+2.4%)*
				X 50 kW		----	0.023	510 *(-0.7%)*
2 Levers		X	X 7 kW			★	0.018 to 0.019	521 to 524 *(+1.4 to 2.1%)*
	X			X 50/20 kW		★	0.020	521 *(+1.5%)*
	X	X				★★	0.018→0.015/0.014	506 to 515 *(-1.5% to neutral)*
3 Levers	X	X	X 2.4 kW			★★	0.012	505 *(-1.5%)*
	X	X		X 50/20 kW		★★	0.012	518 *(+0.9%)*

Aftertreatment Aged to 435k+ miles

0.050 0.035 0.020 0.005 Target

3% Cost Neutral 3% Saving

2027 requires 650k useful life

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LLC Results: (NOx is now regulated!)

Adding Technology Levers to Baseline Engine and Aftertreatment

	Technology Lever				Engine & Aftertreatment	Rating	NOx Base (1.1 to 1.5): Unregulated ➔ 0.05	CO_2 Base: 617 g/hp-hr
	CDA	LO-SCR	eHeater	Burner				
1 Lever	X				CDA Engine	----	*0.50 (projected)*	578 *(-6.2%)*
		X			Production Engine	----	0.09	633 *(+2.7%)*
			X 10 kW		Production Engine	★	0.003	717 *(+16%)*
				X 50 kW	Production Engine	★	0.008	685 *(+11%)*
2 Levers		X	X 7 kW		Production Engine	★	0.014 to 0.050	647 to 662 *(+5 to 7.4%)*
	X			X 50/20 kW	CDA Engine	★	0.011	659 *(+6.9%)*
	X	X			CDA Engine	★★	0.012 to 0.024	593 to 617 *(-3.8% to neutral)*
3 Levers	X	X	X 2.4 kW		CDA Engine	★★	0.012 to 0.025	585 to 599 *(-5.1 to -2.8%)*
	X	X		X 50/20 kW	CDA Engine	★★	0.006 to 0.021	635 to 618 *(+3% to 0.2%)*

Aftertreatment Aged to 435k+ miles

0.10 | 0.050 | 0.010 | 0.00 — Target

5% Cost | Neutral | 5% Saving

2027 requires 650k useful life

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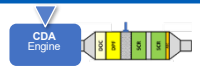
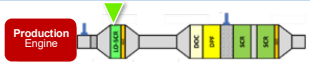
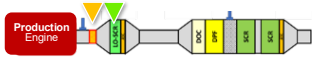
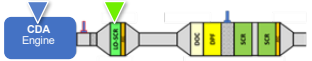
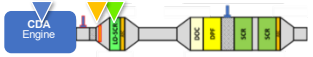
Summary

Adding Technology Levers to Baseline Engine and Aftertreatment

	Technology Lever				Engine & Aftertreatment	Composite FTP		LLC	
	CDA	LO-SCR	eHeater	Burner		NOx	CO_2	NOx	CO_2
1 Lever	X					0.056	-3.6%	0.50	-6.2%
		X				0.04 to 0.06	Neutral	0.09	+2.7%
			X 10 kW			0.023	+2.4%	0.003	+16%
				X 50 kW		0.023	-0.7%	0.008	+11%
2 Levers		X	X 7 kW			0.018/0.019	+2.1%	0.014	+5%
	X			X 50/20 kW		0.020	+1.5%	0.011	+6.9%
	X	X				0.014	Neutral	0.012	-3.8%
3 Levers	X	X	X 2.4 kW			0.012	-1.5%	0.013	-5.1%
	X	X		X 50/20 kW		0.012	+0.9%	0.021	Neutral

Aftertreatment Aged to 435k+ miles

2027 requires 650k useful life

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Summary

- Multiple paths for meeting 2027 NOx and CO_2
  - Aftertreatment, Engine + Aftertreatment or Combination with Hybridization
- Aftertreatment Only
  - Need high source of thermal management (fuel burner or large e-heater), either with or without LO-SCR
- Engine & Aftertreatment
  - Need lower source of thermal management of engine + aftertreatment
    - Engine helps with thermal management and also deals with CO_2
    - Lighter thermal management of Aftertreatment lowers CO_2 increase
- Hybridization (Engine + Electric Powertrain)
  - Significant fuel savings (with engine off)
  - Use multiple methods to keep the Aftertreatment system hot

Thank you

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