Opportunities for Going Beyond Euro Standards: Lessons from U.S. Experience

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Emission Control Technologies 2024

New Delhi, India

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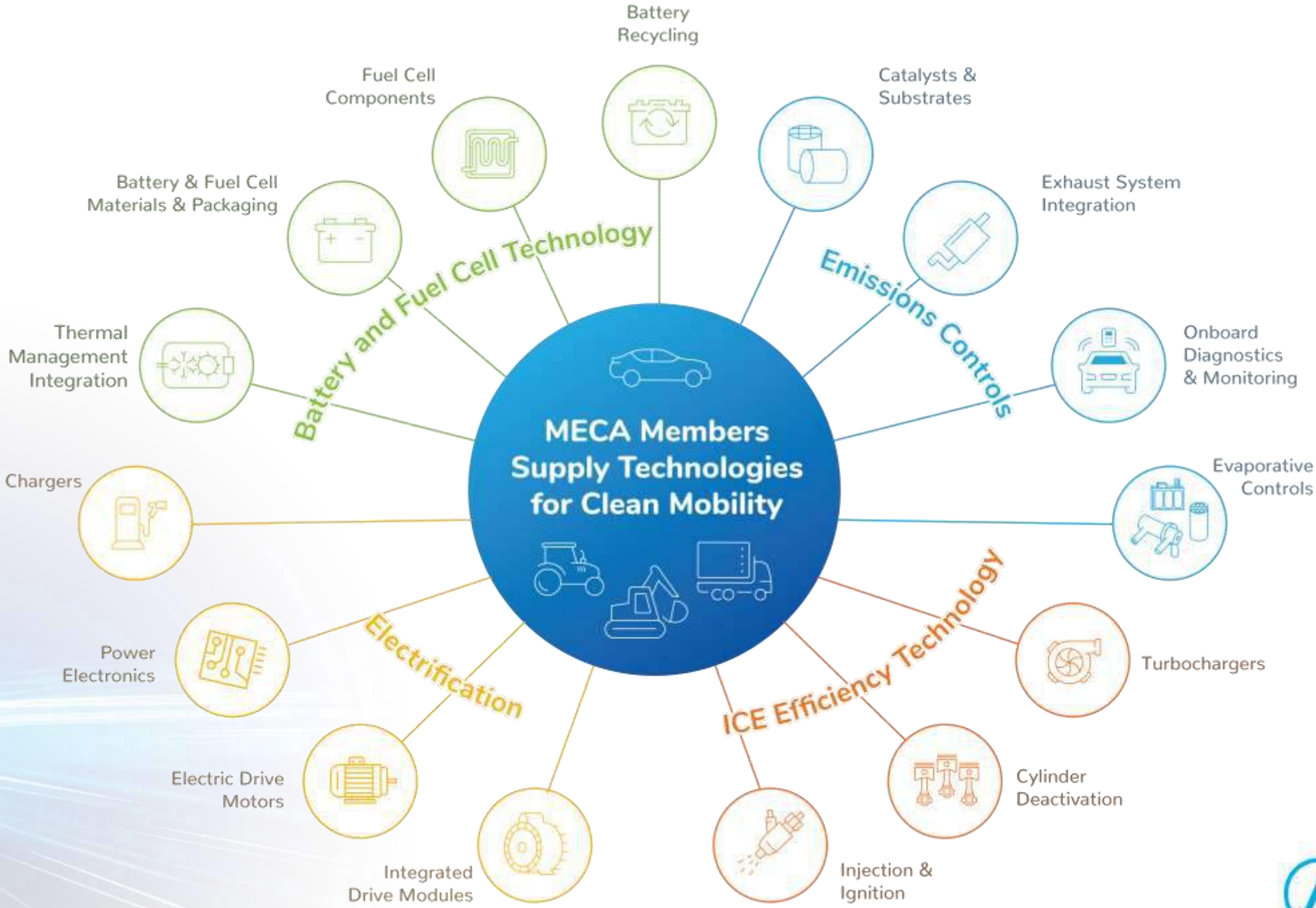

Battery Recycling
Fuel Cell Components
Catalysts & Substrates
Battery & Fuel Cell Materials & Packaging
Exhaust System Integration
Battery and Fuel Cell Technology
Emissions Controls
Thermal Management Integration
Onboard Diagnostics & Monitoring
MECA Members Supply Technologies for Clean Mobility
Chargers
Evaporative Controls
Power Electronics
Electrification
ICE Efficiency Technology
Turbochargers
Electric Drive Motors
Cylinder Deactivation
Integrated Drive Modules
Injection & Ignition

Outline

- Heavy-duty GHG and Pollution Regulations
- Light-duty/Medium-duty GHG and Pollution Regulations
- CARB Nonroad Tier 5 Regulation Proposal

U.S. Heavy-Duty Emission Regulations

CARB and EPA Clean Truck Regulation for Criteria Pollutants

	Useful Life (miles)	Emissions Warranty (miles)	FTP & SET Standards (NOx/PM/HC/CO) at Useful Life (mg/bhp-hr)	Low Load Cycle Standards (NOx/PM/HC/CO) at Useful Life (mg/bhp-hr)	In-Use Moving Average Window NOx Requirements
Heavy-Heavy Diesels	650,000	450,000	NOx: 35 / 50*	NOx: 50 / 65*	Bin 1 (idle): 10 g/hr
Medium-Heavy Diesel	350,000	280,000	PM: 5	PM: 5	Bin 2 (interim):73 mg/bhp-hr
Light-Heavy Diesels	270,000	210,000	HC: 60	HC: 140	
HD Gasoline**	200,00	160,000	CO: 6.0 g/hp-hr	CO: 6.0 g/hp-hr	Bin 2 (final): 58 mg/bhp-hr

*In-use Bin 2 interim NOx compliance allowance applies to MHDE and HHDE

**HD gasoline engine SET CO limit is 14.4 g/hp-hr

PM standard = 5 mg/hp-hr for FTP/RMC/LLC cycles

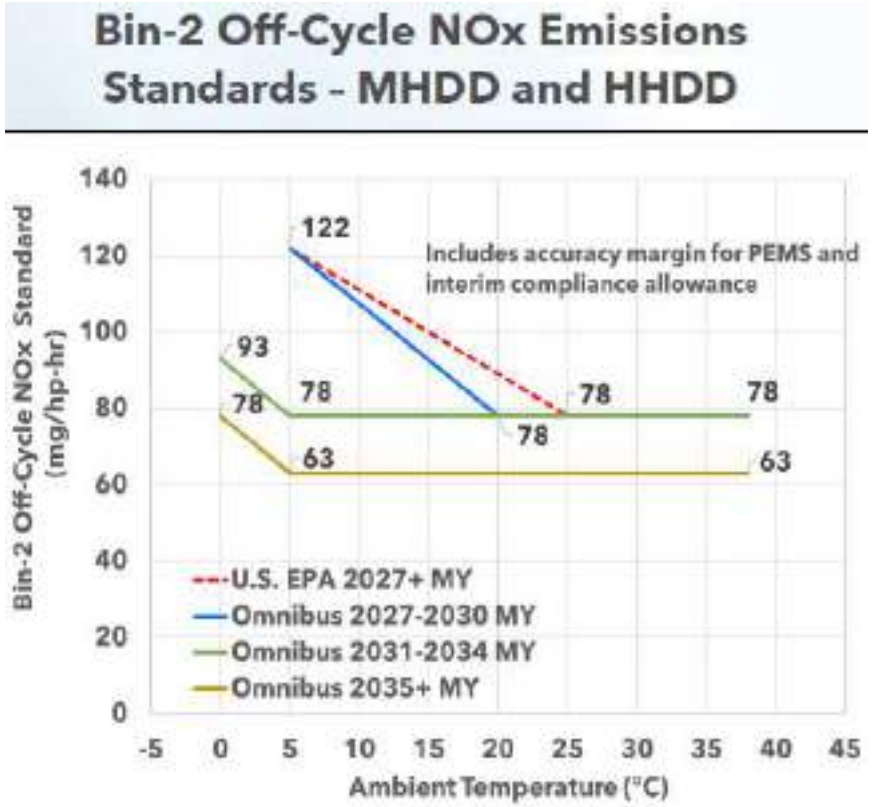
NMHC standard = 60 mg/hp-hr for FTP/RMC/LLC cycles

Two-Bin Moving Average Window – Bin 1 is <6% engine power and Bin 2 is >6% engine power

Interim compliance margin of 15 mg/hp-hr for in-use field or lab compliance testing

PEMS accuracy margin of 5 mg/hp-hr for in-use testing with PEMS

Ambient temperature correction (above figure)



EPA HD GHG Phase 3 Standards Proposed Vs Final Reductions

- Vehicle CO_2 standards are "performance based" to be met by either EVs, hybrids, hydrogen, engine technology or advanced ICE in GEM
- EPA anticipates that a compliant fleet will include a diverse range of ICE and EV technologies.
- BEVs, FCEVs and H2-ICE considered as zero CO_2 emissions

Model Year		2027	2028	2029	2030	2031	2032
LHD Vocational	Final	-17%	-22%	-27%	-32%	-46%	-60%
	Proposal	*-22%*	*-28%*	*-34%*	*-39%*	*-45%*	*-57%*
MHD Vocational	Final	-13%	-16%	-19%	-22%	-31%	-40%
	Proposal	*-19%*	*-21%*	*-24%*	*-26%*	*-30%*	*-35%*
HHD Vocational	Final	0%	0%	-13%	-15%	-23%	-30%
	Proposal	*-16%*	*-18%*	*-19%*	*-30%*	*-33%*	*-40%*
Day Cab Tractors	Final	0%	-8%	-12%	-16%	-28%	-40%
	Proposal	*-10%*	*-14%*	*-15%*	*-20%*	*-30%*	*-34%*
Sleeper Cab Tractors	Final	0%	0%	0%	-6%	-12%	-25%
	Proposal	*0%*	*0%*	*0%*	*-10%*	*-20%*	*-25%*
Heavy Haul Tractors	Final	0%	0%	-1%	-1%	-2.9%	-5%
	Proposal	***0%***	***0%***	***0%***	***-11%***	***-12%***	***-15%***

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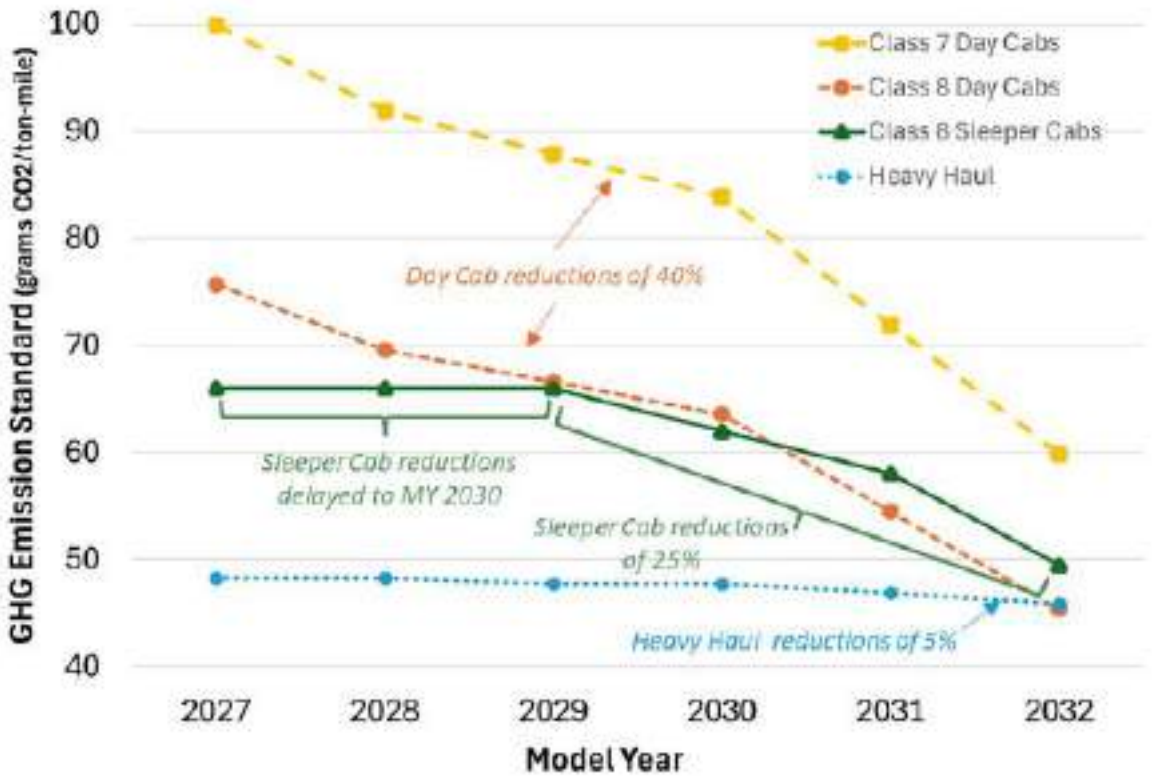
EPA Final HD GHG Phase 3 Standards Finalized April 2024

Final Phase 3 Tractor Standards



Final Phase 3 Vocational Standards (grams/ton-mile)

Model Year	Subcategory	CI Light Heavy	CI Medium Heavy	CI Heavy Heavy	SI Light Heavy	SI Medium Heavy
Phase 2 2027	Urban	367	258	269	413	297
	Multi-Purpose	330	235	230	372	268
	Regional	291	218	189	319	247
2027 Final	Urban	305	224	269	351	263
	Multi-Purpose	274	204	230	316	237
	Regional	242	190	189	270	219
Phase 3 2032+ Final	Urban	147	155	188	193	194
	Multi-Purpose	132	141	161	174	174
	Regional	116	131	132	144	160

ZEV Projections for 2032 Compliance

Vocational			School Bus	Other Bus	Refuse Hauler	Tractors		
LHD	MHD	HHD				Day Cabs	Sleeper	Heavy-Haul
60%	40%	30%	40%	30%	16%	40%	25%	5%

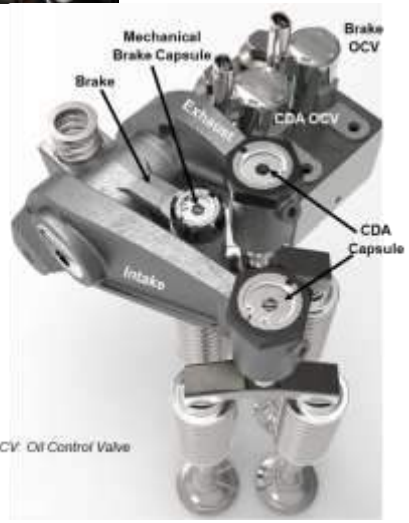
EPA Low NO_X Demonstration Engine

2017 Cummins X15 Engine

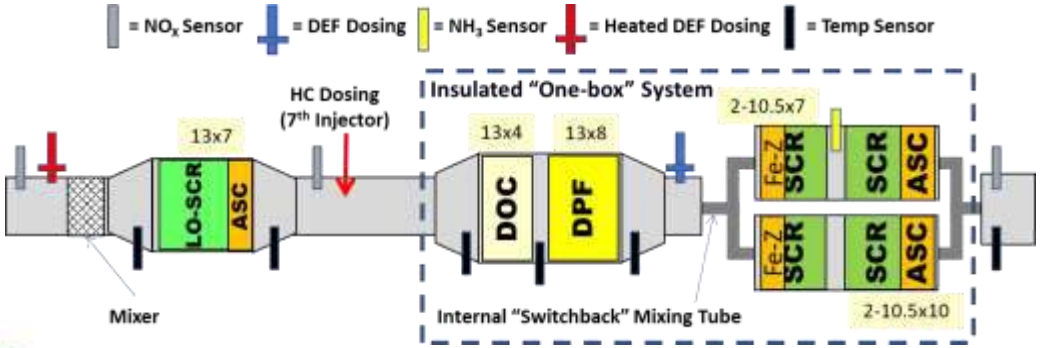
Full System Details
SAE Paper
2021-01-0589

Additional Engine Hardware (Cylinder Deactivation)

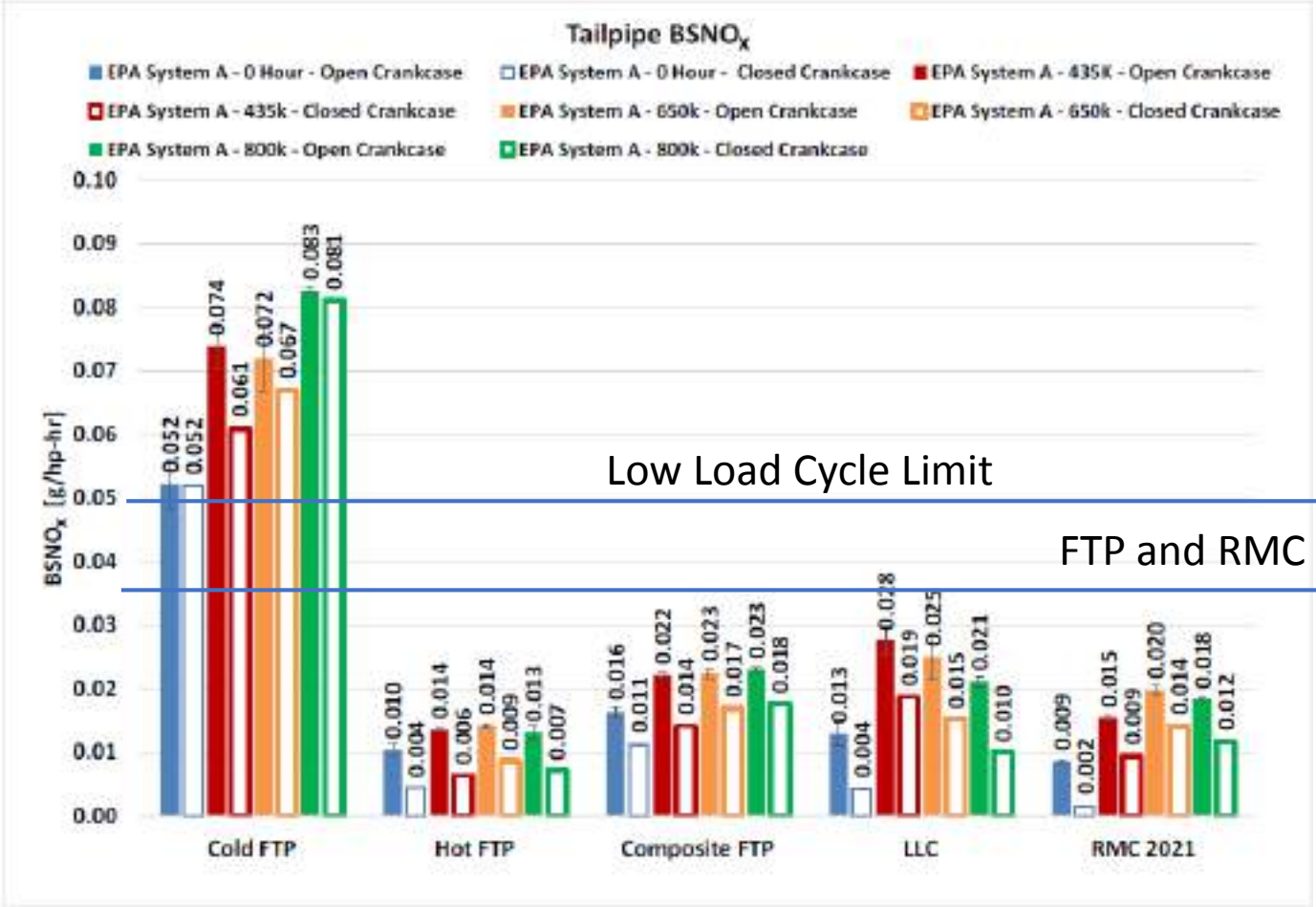
Eaton Cylinder Deactivation Hardware



Advanced Low NO_X Aftertreatment (Dual SCR-Dual Dosing)



Low NOx System after 1,200,000 km aging



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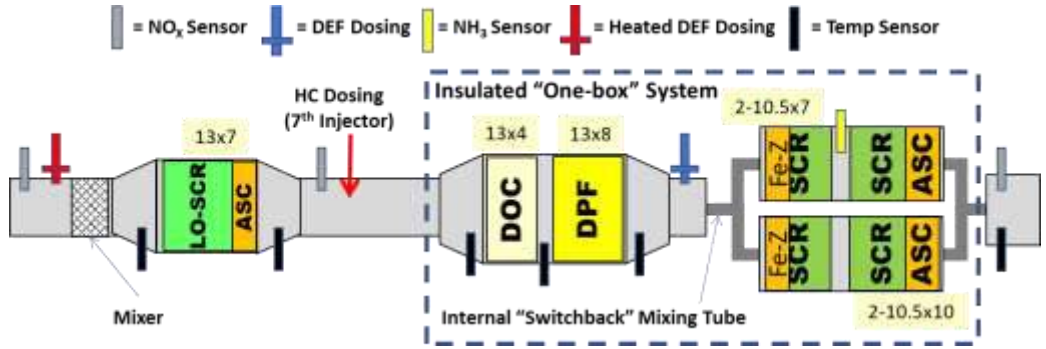


Cylinder Deactivation Hardware

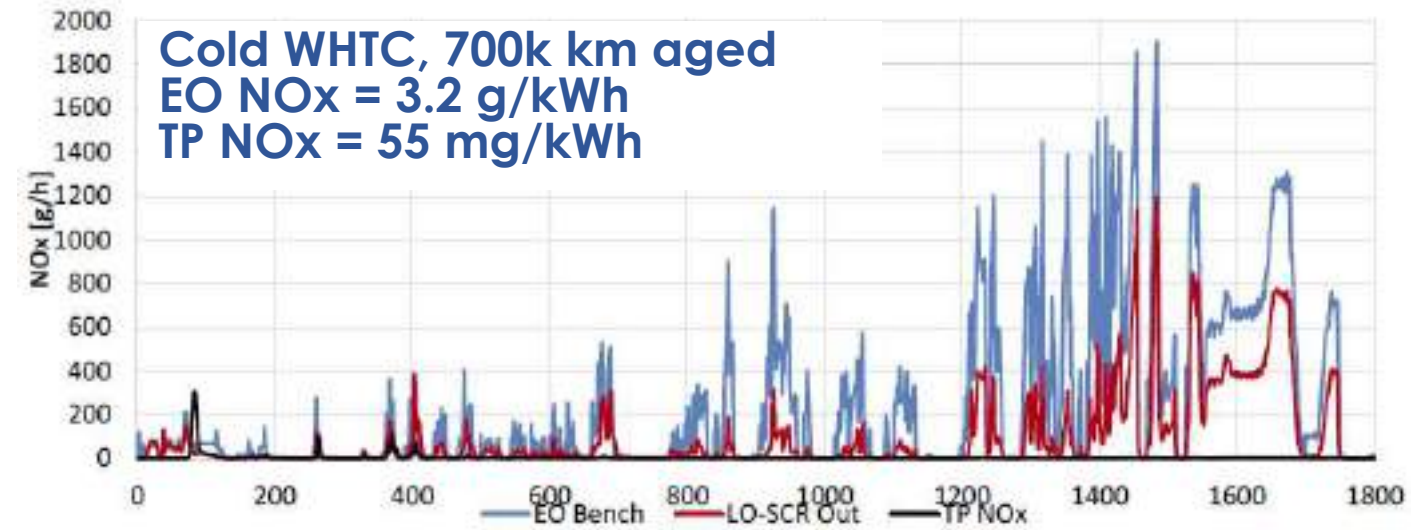
- Sufficient margin below the limits after accelerated aging
- Closing the crankcase provides additional NOx reduction by up to 0.01 g/kWh

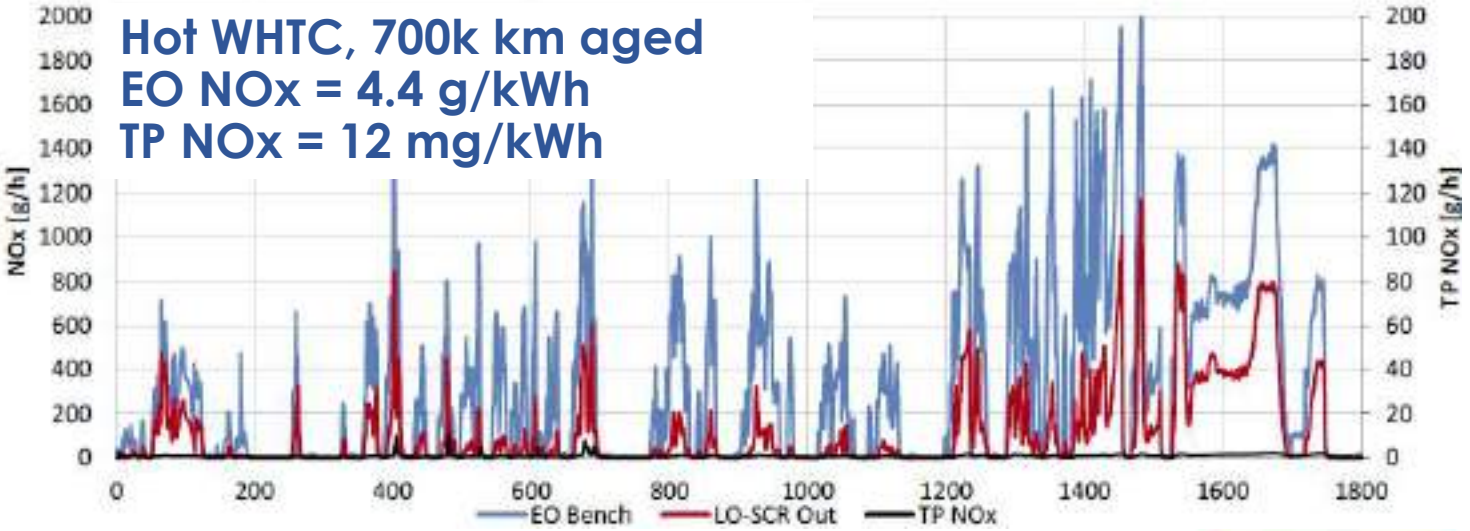
Opportunities: Low-NOx Engine Provides Significant Margin Below Euro 7

Euro 7 WHSC/WHTC standard = 200 mg/kWh

Euro 7 MAW low power threshold was reduced from 10% to 6%, but there is no low-load cycle test requirement to require control below 6% power

- Applications such as drayage or during traffic conditions with stop and go (creep) operation will have high emissions





U.S. Light- and Medium-Duty Emission Regulations

U.S. Approaches to Reducing Passenger Car Emissions: EPA

EPA Set Performance Standards and allow EVs in Fleet Average at 0 g/mile

Model Year	LDV, LDT1, LDT2 NMOG+NOx (mg/mi)	LDT3, LDT4, MDPV NMOG+NOx (mg/mi)		MDV[t] NMOG+NOx (mg/mi)			
				Class 2b		Class 3	
Tier 3 (current)	30	30	30*	178	178*	247	247*
2027	25	30	25*	178	175*	247	175*
2028	23	30	23*	178	160*	247	160*
2029	21	30	21*	178	140*	247	140*
2030	19	15	19*	178	120*	247	120*
2031	17	15	17*	75	100*	75	100*
2032	15	15	15*	75	80*	75	80*
2033+	15	15	15*	75	75*	75	75*

*** Denotes early compliance pathway**

U.S. Bin Structure for Fleet Average

Bin	NMOG+NOx (mg/mile)	Bin	NMOG+NOx (mg/mile)
Bin 170*	170	Bin 45	45
Bin 150*	150	Bin 40	40
Bin 125*	125	Bin 35	35
Bin 100*	100	Bin 30	30
Bin 85*	85	Bin 25	25
Bin 75*	75	Bin 20	20
Bin 70	70	Bin 15	15
Bin 65	65	Bin 10	10
Bin 60	60	Bin 5	5
Bin 55	55	Bin 0	0
Bin 50	50		

*** Bins only available for MDVs**

EPA Proposed Stringent PM standards with Phase In

Test Cycle	Proposed PM Standard (mg/mi)
25°C FTP	0.5
US06	0.5
-7°C FTP	0.5

Model Year	LDV, LDT1/2	100% for others
2027	20%	
2028	40%	
2029	60%	
2030	100%	LDT3/4, MDPV
2031+	100%	MDV

CARB and EPA aligned* on eliminating emissions from off cycle operation

- Same numerical standards on all cycles: 25°C FTP, HFET, US06 and SC03.
- Single NMOG+NOx fleet average -7C FTP standard of 300 mg/mi
- Set limit for high power cold starts over US06 for PHEVs
- Limits for 8 sec and current 20 sec. on FTP
- Partial soak warm engine starts (10 min., 40 min, >180 min)
- Tighter evaporative limits on running loss, sealed tanks and incomplete chassis to cover all gasoline vehicles.
- Battery minimum performance standards based on UNECE

*** CARB currently proposing amendments to potentially align further with EPA**

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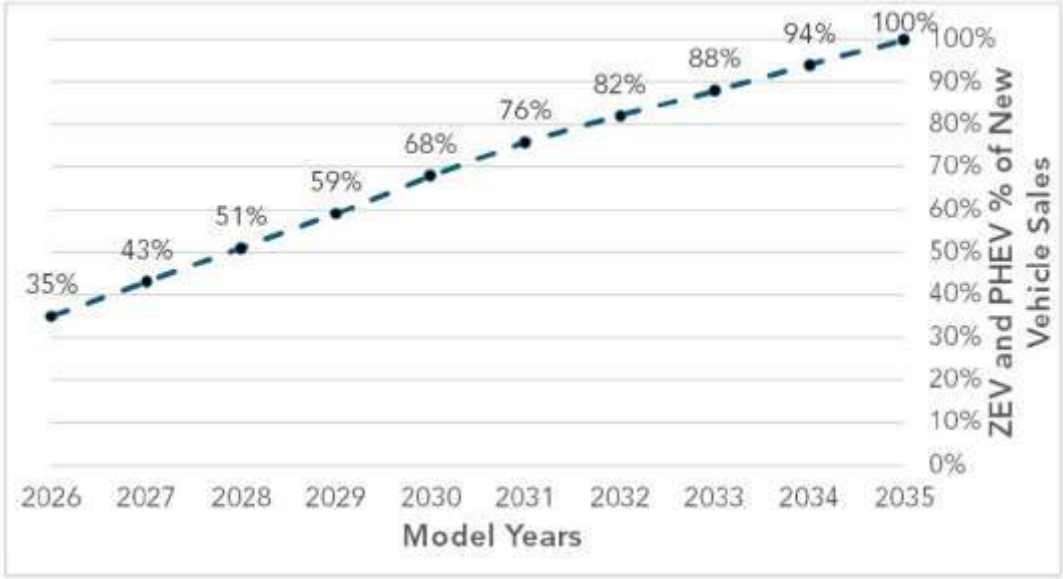
U.S. Approaches to Reducing Passenger Car Emissions: California

California ZEV Sales Requirements



CARB Phasing out ZEVs from Criteria Standards

Model Year	NMOG + NOx Fleet Average	% of ZEVs Allowed in average
Pre-2025	30 mg/mile	100
2026	30 mg/mile	60
2027	30 mg/mile	30
2028	30 mg/mile	15
2029	30 mg/mile	0

California ZEV Minimum Technical Requirements

Requirement	Current through MY2025	MY2026+
Minimum Range	50 miles over UDDS	200 miles over 2-cycle
Level 2 J1772 (or adapter)	Required	Required
On Board Charger	≥ 3.3 kW	≥ 5.76 kW
DC Fast Charge Capability and Connector	Not Required	SAE J1772 Combined Charging Standard (or adapter)
Convenience Cord	Not Required	Required (Level 1 and 2 capable)
ZEV Assurance Measures	Not Required	Required

PHEVs can count as ZEVs for up to 20% of an OEMs obligation:

- > 50 miles all electric range for full credit
- US06 all electric operation
- SULEV30 certified
- 8 year/100,000 mile battery warranty above 70%/75% SOH for 2026-2030/2031+
- 5.76 kW on-board charger and convenience cord (same as BEVs)

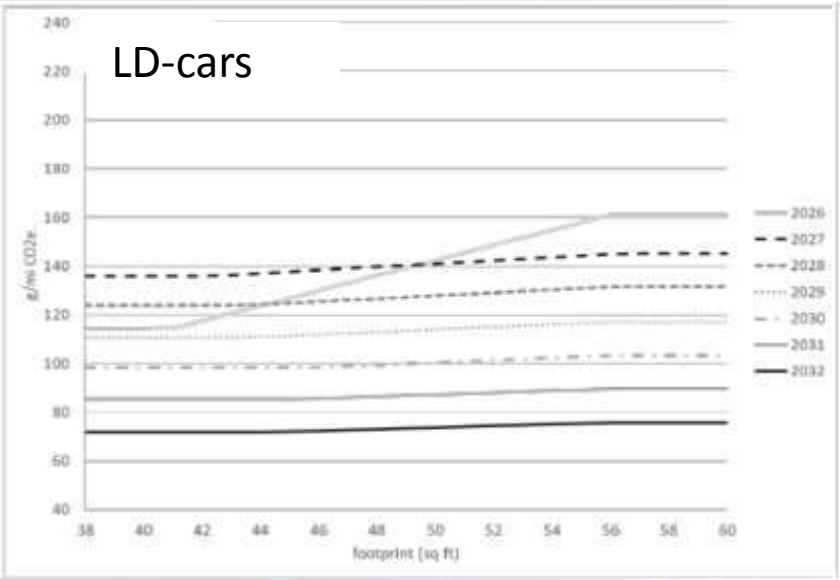
EPA's Multipollutant LD/MD standards include GHG standards - CO_2 limits

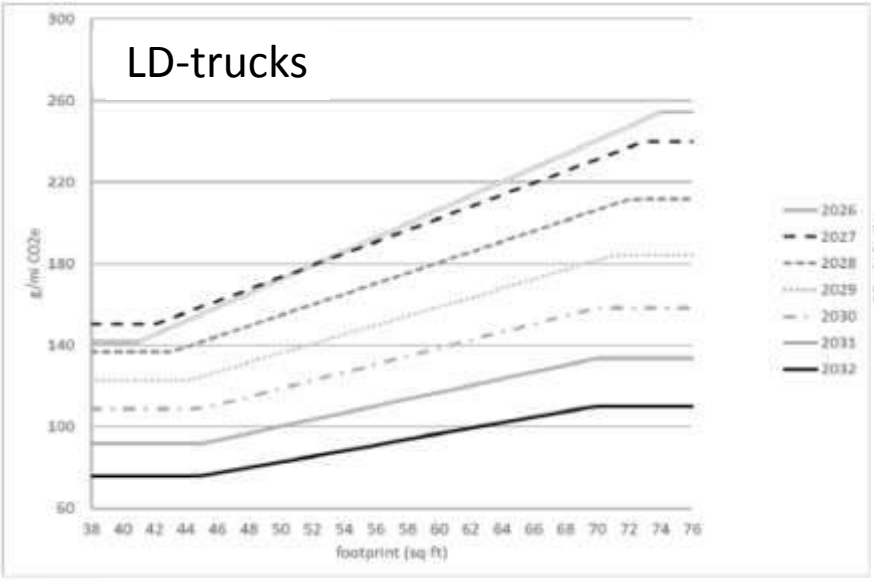
EPA's Performance Based CO2 Fleet Average standards remain footprint based

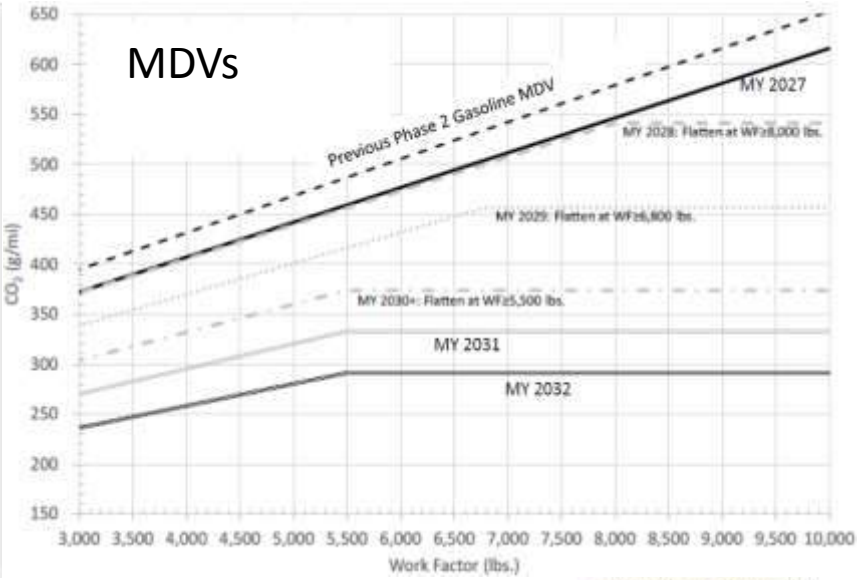
	Light-Duty Vehicles (CO_2, g/mile)			Medium-Duty Vehicles (CO_2, g/mile)		
Model Year	Cars	Trucks	Fleet	Vans	Pickups	Combined
2027	139	184	170	392	497	461
2028	125	165	153	391	486	453
2029	112	146	136	355	437	408
2030	99	128	119	317	371	353
2031	86	109	102	281	331	314
2032+	73	90	85	245	290	274

U.S. EPA EV Compliance Scenario

	2027	2028	2029	2030	2031	2032
Sedans	40%	47%	58%	66%	69%	75%
SUVs	31%	35%	43%	49%	59%	66%
Pickups	27%	31%	45%	55%	63%	67%
Total	32%	37%	46%	53%	61%	68%
Vans	3%	4%	24%	44%	64%	76%
Pickups	3%	4%	8%	17%	15%	26%
Total	3%	4%	14%	27%	32%	43%







Opportunities: Evaporative Emissions

Emission Standard	India BS6	Europe Euro7	USA Tier 3	Brazil PL7	China 6b
Evaporative (hot soak + diurnal)	1-day 2.0 g/day	2-day 1.5 g/test ~0.63 g/day	2-day & 3-day 0.30 g/day	2-day 0.50 g/day	2-day 0.70 g/day
On-Board Refueling Control	None (Stage II)	None (Stage II)	0.20 g/gal (~0.05 g/L)	0.05 g/L	0.05 g/L

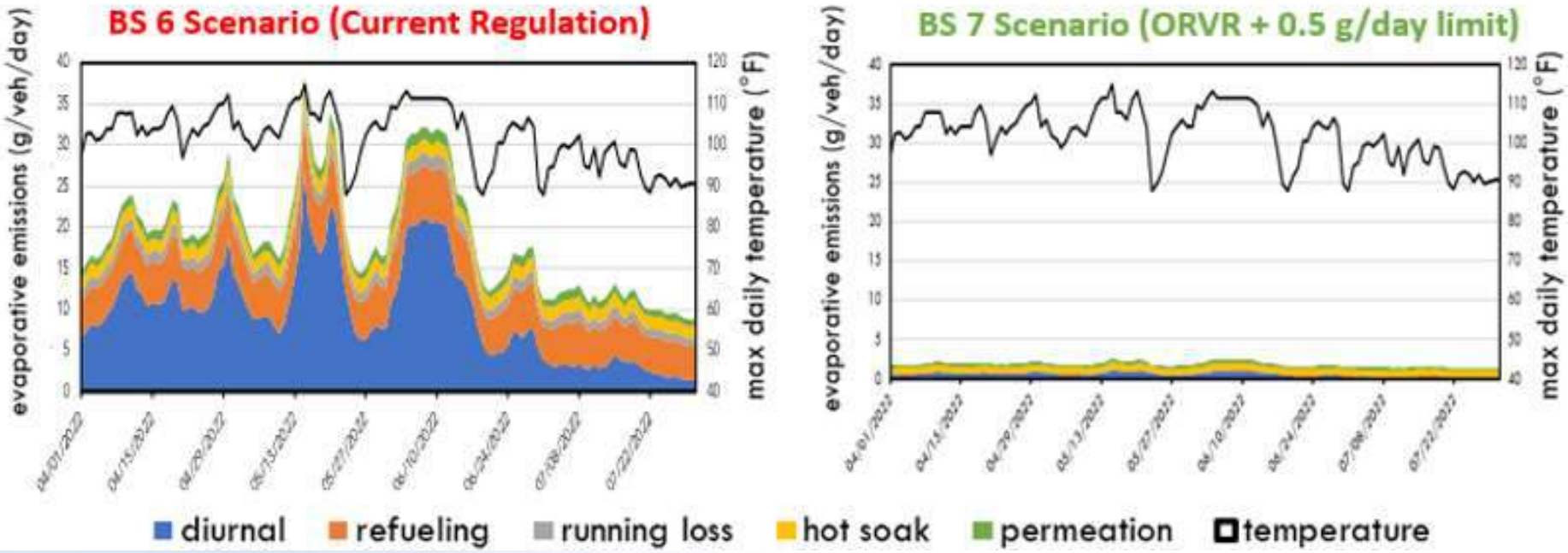
Petrol cars represent 3.26 million per year – > 65% of new sales

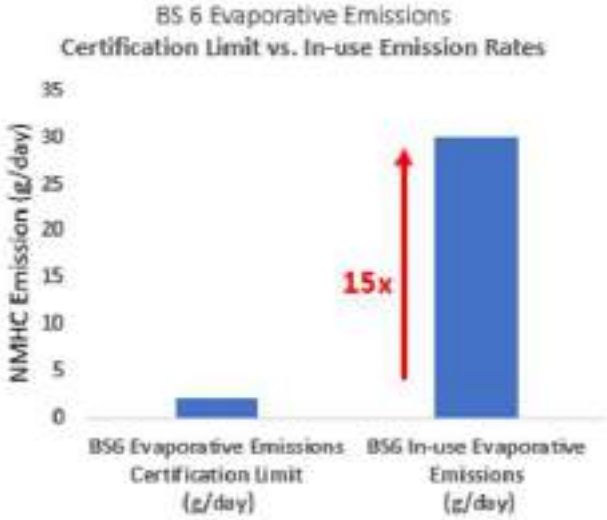
Ethanol blending increasing to E20 – up to 70 kPa vapor pressure

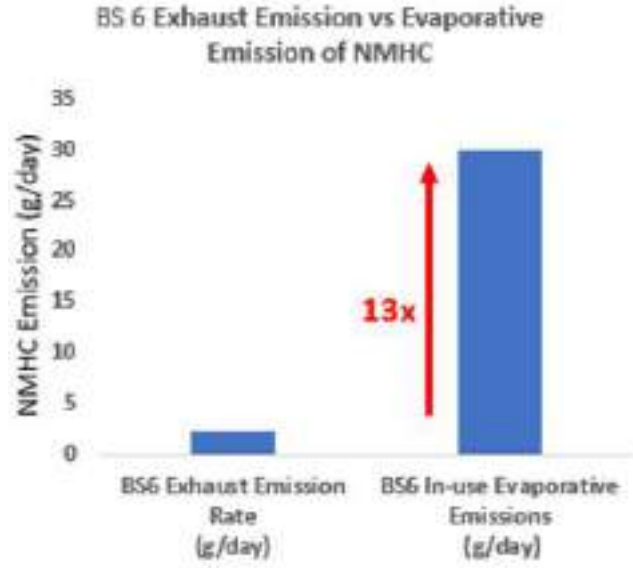
- Current certification fuel is 60-65 kPa

Opportunities: Evaporative Emissions

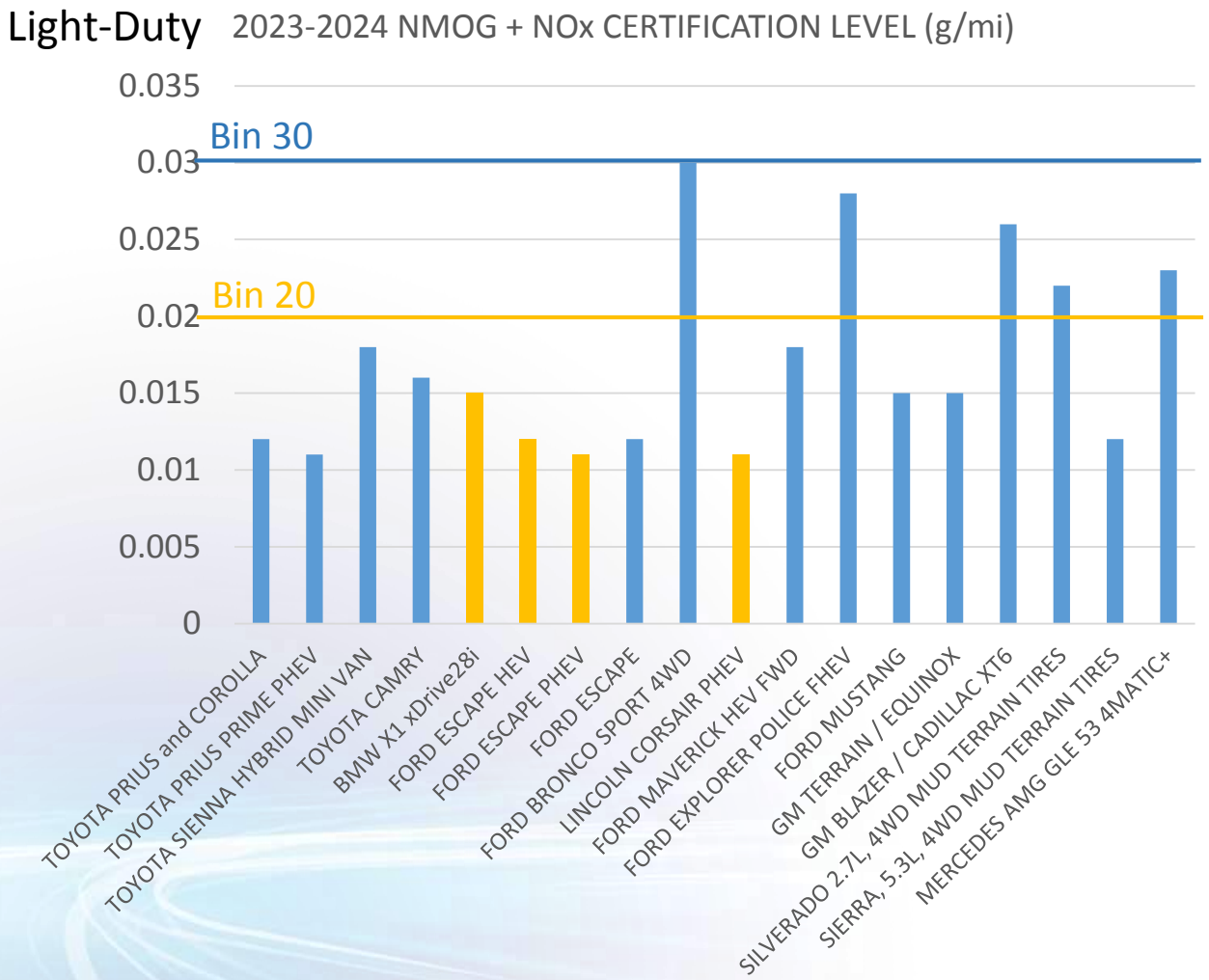
Modeled Daily Evaporative Emissions for Delhi (grams/vehicle/day)







Opportunities: Light/Medium Duty Exhaust Emissions



89 Engine Families Representing 232 Models Certified to Bin 30 or Bin 20

Medium-Duty	MY 2024 CERTIFIED LEVEL (mg/mile) NMOG+NOx			
	Gasoline		Diesel	
Class 2B	FTP Cert Levels	US06 Cert Levels	FTP Cert Levels	US06 Cert Levels
AVERAGE	94	167	111	76
BEST IN CLASS	**22**	**21**	**113**	**10**
WORST IN CLASS	216	586	180	142
Class 3	FTP Cert Levels	LA92 Cert Levels	FTP Cert Levels	LA92 Cert Levels
AVERAGE	124	27	131	Not enough data
BEST IN CLASS	**73**	**20**	**53**	
WORST IN CLASS	216	35	190	

Best in class vehicles for nearly all cycles already achieving 2033 standard (75 mg/mile)

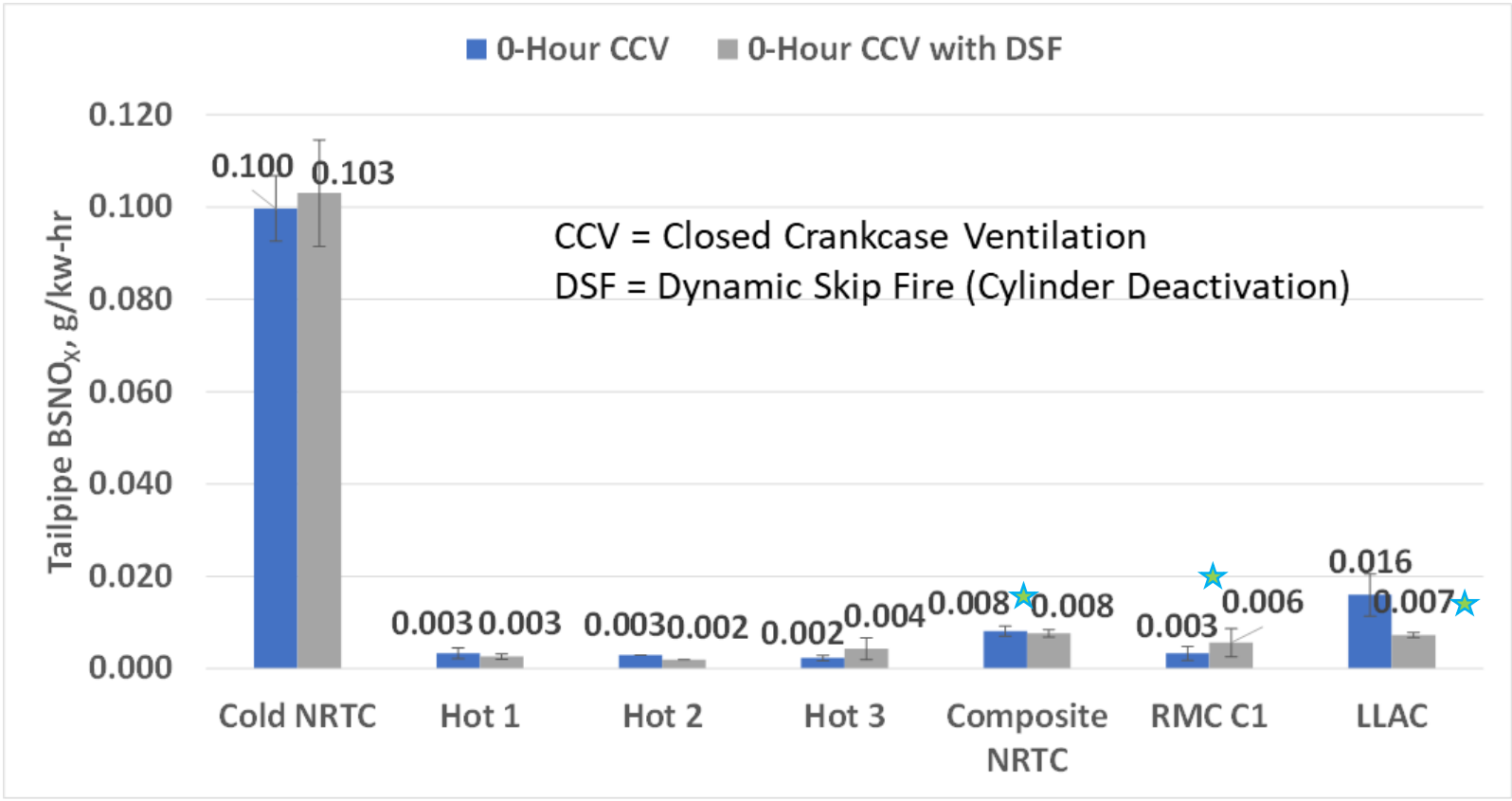
Hybridization could provide further improvements

California Nonroad Technology Demonstration and Standards Development

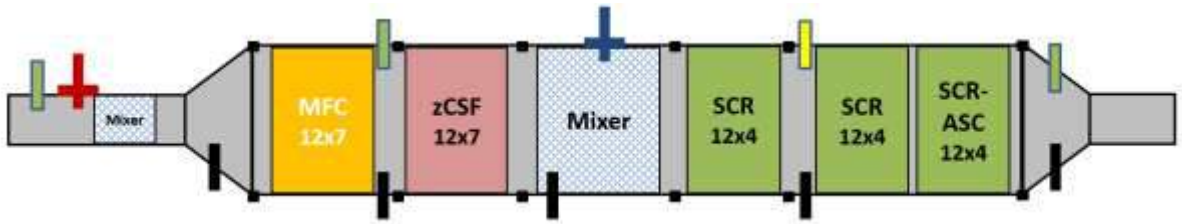
Nonroad Low NO_X Demonstration Program

John Deere 6068 (6.8L) Tier 4f Engine

Cycle	Improvement in CO2, %	
	Pkg 2 without CDA	Pkg 2 with CDA
Cold NRTC	4.7%	5.7%
Hot NRTC	5.6%	6.3%
Composite NRTC	**5.6%**	**6.3%**
RMC C1	3.3%	4.4%
LLAC	5.5%	10.9%



Cylinder Deactivation



CARB Proposed Nonroad Low NO_x Standards

- No GHG standards proposed; plan to address GHGs through a zero-emission equipment requirement – Phased Advanced Clean Equipment Regulation (PACE)

Power Category	Implementation Period	NO_x Interim	NO_x Final	PM Interim	PM Final	NMHC* Final	CO
< 8 kW (< 11 HP)	2031-2033	6.0*	-	0.3	-	-	8.0
	2034 +	-	5.0*	-	0.2		
8 ≤ kW < 19 (11 ≤ HP < 25)	2031-2033	5.5*	-	0.2	-	-	6.6
	2034 +	-	4.0*	-	0.1		
19 ≤ kW < 56 (25 ≤ HP < 75)	2031-2033	3.7	-	0.015	-	0.19	5.0
	2034 +	-	2.5	-	0.008		
56 ≤ kW < 130 (75 ≤ HP < 175)	2031-2033	0.22	-	0.005		0.080[1]	5.0
	2034 +	-	0.040	0.005			
130 ≤ kW ≤ 560 (175 ≤ HP ≤ 750)	2029-2032	0.22	-	0.005		0.080[1]	3.5
	2033 +	-	0.040	0.005			
> 560 kW (Gen Sets) (> 750 HP)	2030-2033	0.50	-	0.015	-	0.080[1]	3.5
	2034 +	-	0.35	-	0.008		
> 560 kW (Mobile) (> 750 HP)	2030-2033	3.5	-	0.040		0.19	3.5
	2034 +	-	3.0				

Proposed LLC and Idle Standards

Power Category	Implementation Period	NO_x Final Standard (g/kW-hr)	PM Final Standard (g/kW-hr)	NMHC Final Standard (g/kW-hr)	NO_x Idle Standard (g/hr)*
< 8 kW (< 11 HP)	-	-	-	-	-
8 ≤ kW < 19 (11 ≤ HP < 25)	-	-	-	-	-
19 ≤ kW < 56 (25 ≤ HP < 75)	-	-	-	-	10.0 – 30.0
56 ≤ kW < 130 (75 ≤ HP < 175)	2034+	0.060	0.005	0.19	5.0 - 10.0**
130 ≤ kW ≤ 560 (175 ≤ HP ≤ 750)	2033+	0.060	0.005	0.19	10.0 - 15.8**
> 560 kW (Gen Sets) (> 750 HP)	-	-	-	-	-
> 560 kW (Mobile Machines) (> 750 HP)	-	-	-	-	50.0

Useful Life and Warranty Requirements

Power (kW)	Constant Speed		Variable Speed
<19	UL: 3k hrs / 5 yrs → **8 yrs** W: 1.5k hrs / 2 years → **3 yrs**		
19 to <37	RPM≥ 3,000 UL: 3k hrs / 5 yrs → **8 yrs** W: 1.5k hrs / 2 years → **3 yrs**	RPM , 3,000 UL: 5k hrs / 7 yrs → **11 yrs** W: 3k hrs / 5 yrs → **8 yrs**	UL: 5k hrs / 7 yrs → **11 yrs** W: 3k hrs / 5 yrs → **8 yrs**
≥ 37	UL: 8k hrs / 10 yrs → **15 yrs** W: 3k hrs / 5 yrs → **8 yrs**		

Conclusions

- Control of emissions to near zero levels from all powertrains will be needed as we transition transportation to achieve air quality goals
- Technology continues to rapidly evolve, creating new opportunities for system-based solutions including engines, aftertreatment and fuels
- US standards for evaporative emissions and light- and medium-duty diesel vehicles would likely yield significant emission benefits if adopted in India
- Nonroad engines and equipment will benefit from on-road experience: technology demonstration nearly complete at Southwest Research Institute with funding from CARB and MECA

Thank You

mgeller@meca.org

Supplemental

CARB Advanced Clean Trucks ZEV Mandate

Model Year (MY)	Class 2b-3	Class 4-8	Class 7-8 Tractors
2024	5%	9%	5%
2025	7%	11%	7%
2026	10%	13%	10%
2027	15%	20%	15%
2028	20%	30%	20%
2029	25%	40%	25%
2030	30%	50%	30%
2031	35%	55%	35%
2032	40%	60%	40%
2033	45%	65%	40%
2034	50%	70%	40%
2035+	55%	75%	40%