



# Low NO<sub>x</sub> Research Update

*Bill Robertson  
Vehicle Program Specialist  
California Air Resources Board*

**NACAA Mobile Sources and Fuels Committee**  
February 22, 2022

# Outline

- **CARB Heavy-Duty Engine Emissions Standards**
- **Technical Feasibility**
- **Costs and Benefits**
- **Conclusion**

# NOx and PM Certification Standards

- **FTP/RMC Test Cycles**

- NOx: 0.20 g/bhp-hr
- PM: 0.01 g/bhp-hr
- Optional NOx:
  - 0.02/ 0.05/ 0.10 g/bhp-hr

- **NOx idling standard**

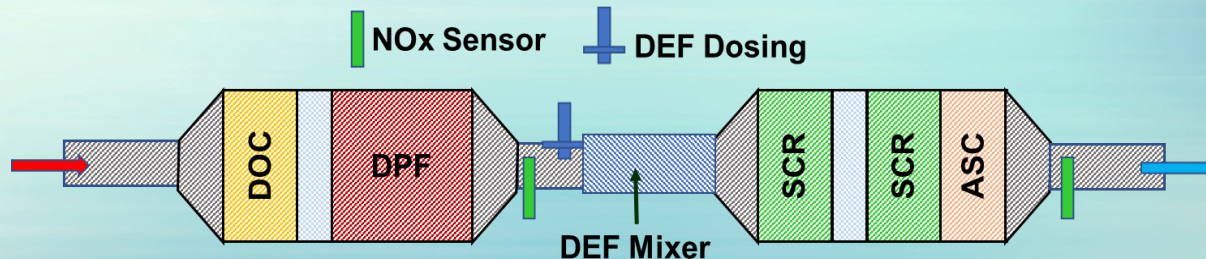
- 30 grams/hour

- **Diesel Engine Technology**

- Diesel Oxidation Catalyst (DOC)
- Diesel particulate filter (DPF)
- Urea or diesel exhaust fluid (DEF) based selective catalytic reduction (SCR)
- Ammonia slip catalyst (ASC)

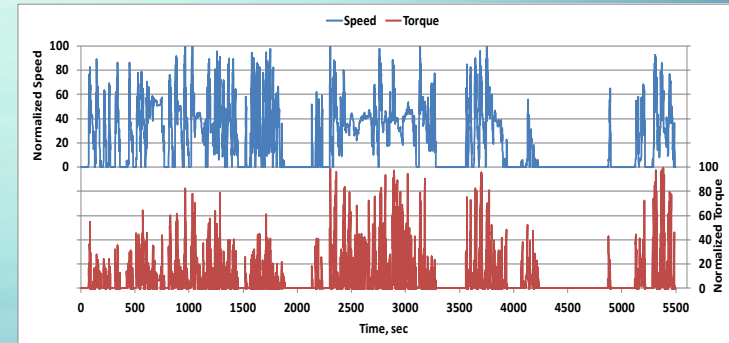
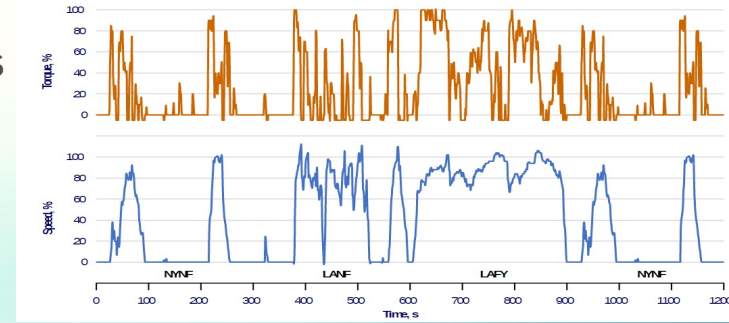
- **Otto-Cycle Engine Technology**

- Three-way Catalyst



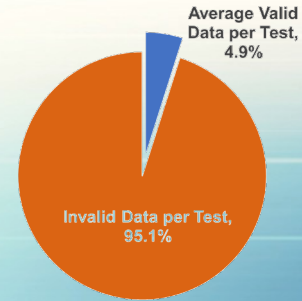
# Current Certification Test Cycles

- **FTP and RMC test cycles**
  - Do not account for sustained low load operations
  - SCR not functional at low exhaust temperatures
- **Low load duty cycles have lower exhaust temperatures**
  - Prevalent in urban stop-and-go operation in communities near congested transportation corridors
- **Need for low load certification cycle (LLC)**
  - Ensure engine/aftertreatment system controls needed for low load operations are functional



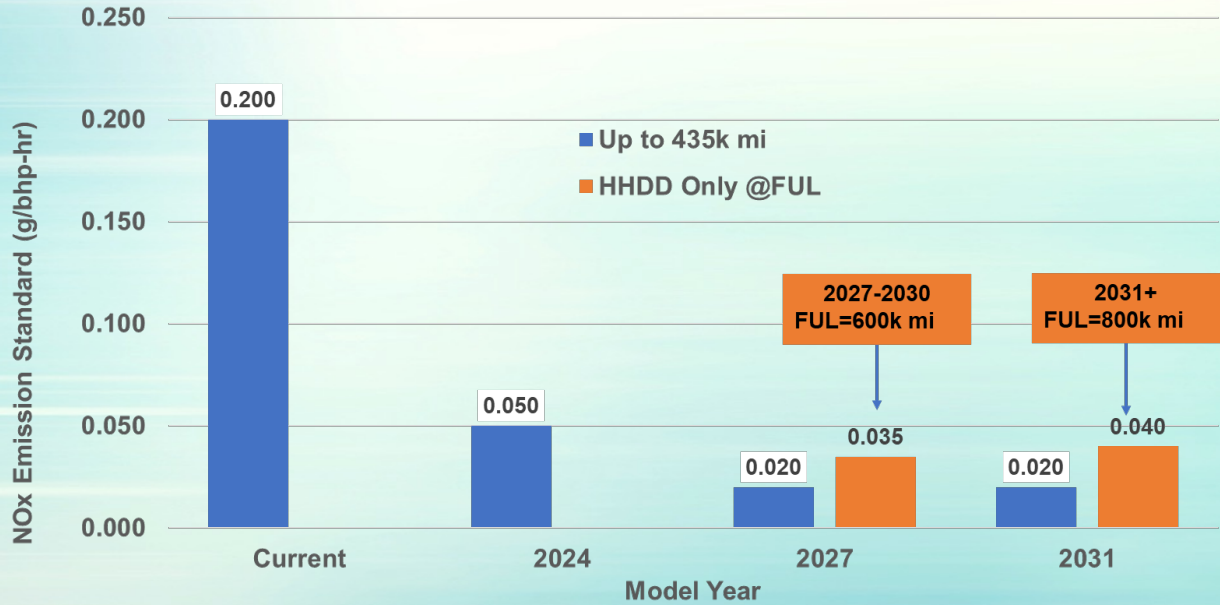
# Current In-Use Requirements

- **Heavy-Duty In-Use Testing (HDIUT) program**
  - Manufacturer self testing
  - Methodology based on the Not-to-Exceed (NTE) method
  - NTE method evaluation captures only a small portion of real-world operation and emissions
  - CARB's testing has identified significant problems, resulting in mandated recalls of hundreds of thousands of heavy-duty trucks
- **Emissions warranty and useful life periods**
  - Current requirements do not reflect the longevity of heavy-duty engines and vehicles



# Heavy-Duty Engine Emissions Standards

# NOx Emission Standard – FTP Cycle (GVWR > 10,000 lbs)

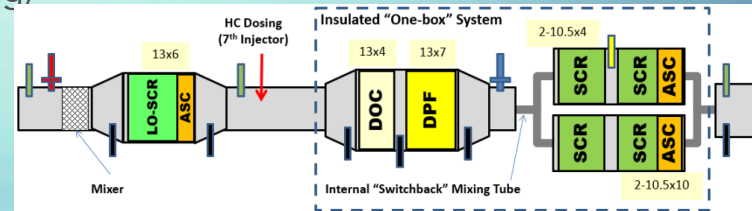
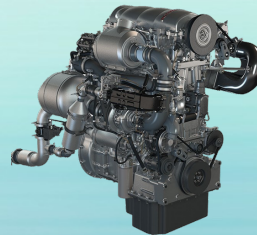
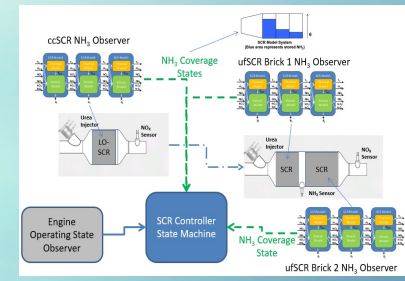
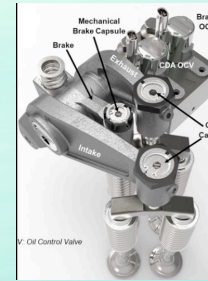
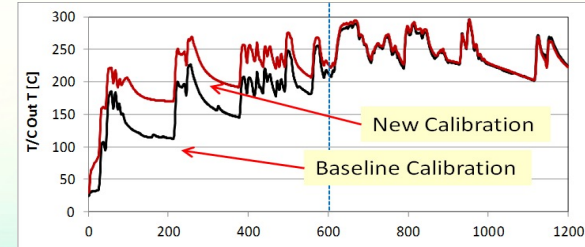


# Technical Feasibility



# Strategies to Meet Standards

- Multiple strategies and technology paths available to improve thermal management during cold starts and sustained low load operations
- **Engine Controls**
  - Elevated idle, EGR rates, combustion phasing
  - Bypasses for EGR cooler/turbocharger/charge air cooler
  - CDA / VVA
  - advanced turbo (SuperTurbo, E-Turbo.)
  - mild hybrids/ 48 V system electrification
- **Aftertreatment strategies**
  - Advanced catalyst substrates – DOC, SCR, ASC
  - Advanced aftertreatment configurations (dual SCR-dual dosing)
  - Heated DEF dosing
  - DEF management controls
- **Opposed piston engine**



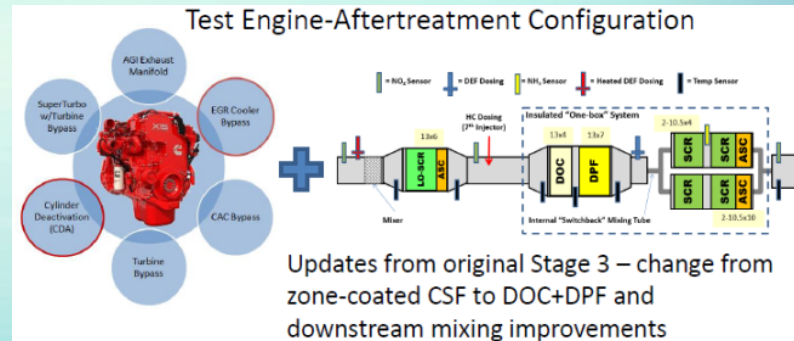
# Standards are Technically Feasible

- Extensive CARB-sponsored demonstration at SwRI
  - Supported by federal / local air agencies and industry
- SwRI testing results of Stage 3-RW system
  - Stage 3-RW: Dual Dosing-Dual SCR with cc Light-Off SCR
  - DAAAC aging (thermal and chemical)



NOx (g/bhp-hr) <sup>1/</sup> Standard		
Test Cycle	@435k mi	@600k mi
FTP	0.020/ 0.020	0.029/ 0.035
LLC	0.029/ 0.050	0.027/ 0.090
RMC	0.017/0.020	0.033/0.035

Results are CO2 neutral



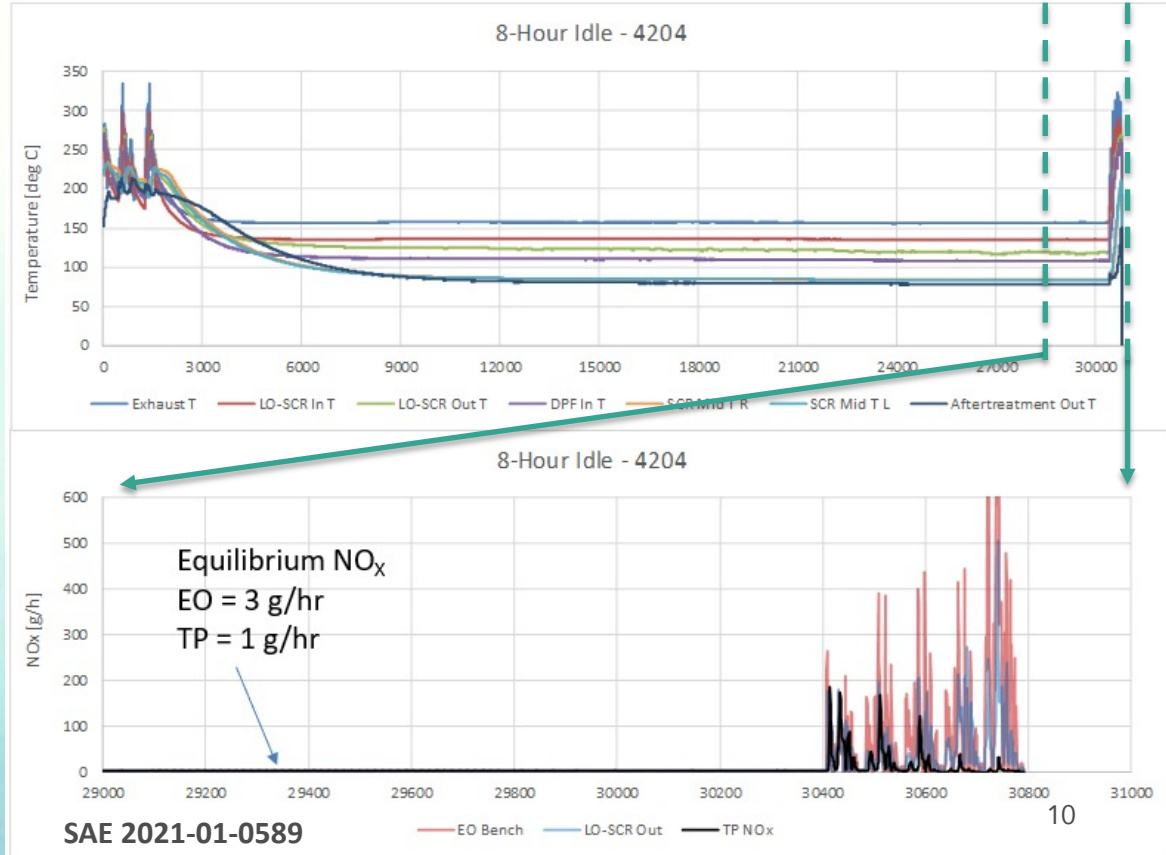
Updates from original Stage 3 – change from zone-coated CSF to DOC+DPF and downstream mixing improvements



<sup>1</sup>Sharp, C. "Characterization of In Use Performance and Measurement Instrumentation Capability at Low NOx Levels for 2027 and Beyond" 2022 CRC MSAT Workshop, February 10, 2022

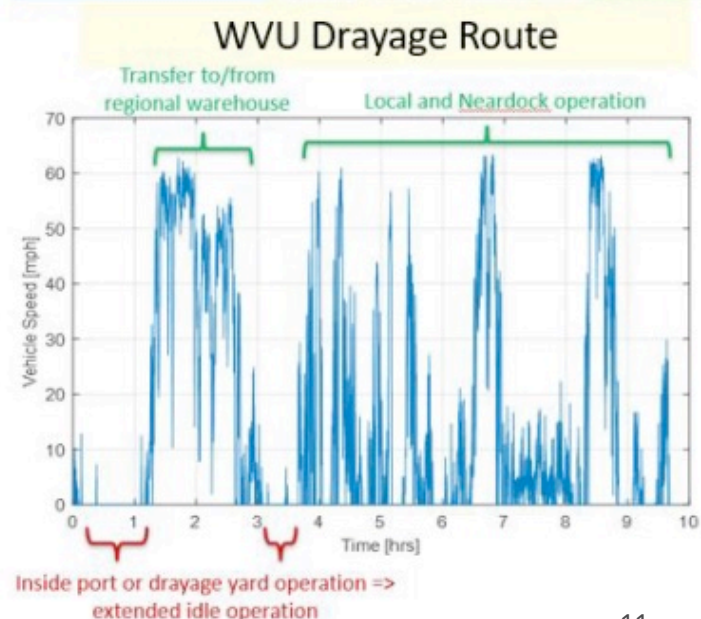
# Extended Idle Test Performance

- Idle Standard:
  - 2024: 10 g/hour
  - 2027+: 5 g/hour
- Stage 3 Results:
  - 1 g/hour



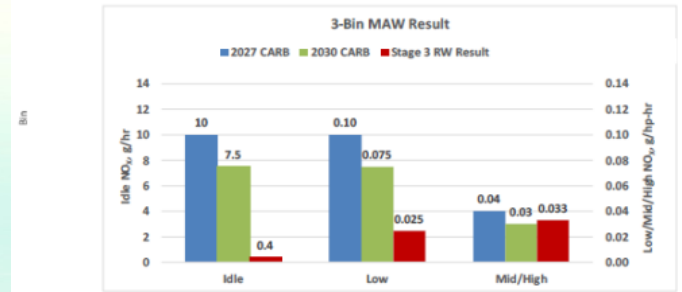
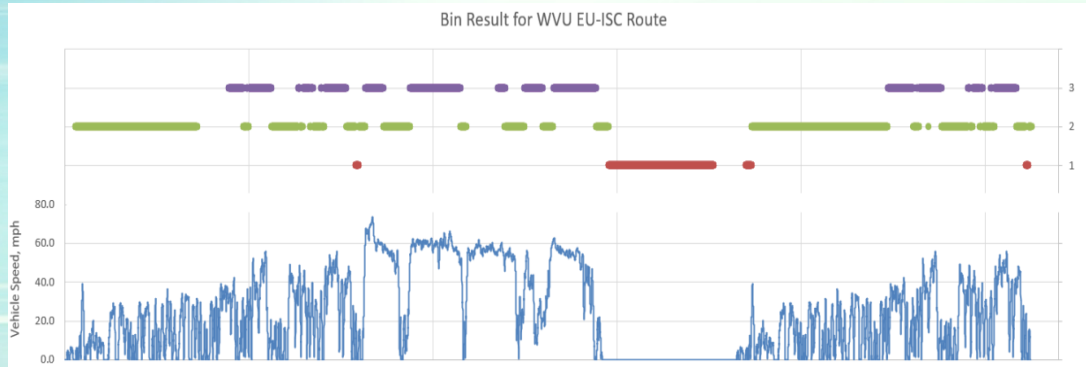
# 3B-MAW – Real World Duty Cycles

- Challenging grades
- Local/Regional Delivery
- Stop&Go Port service
- EU-type in-use assessment
- Combination of cert & chassis dyno cycles



# 3B-MAW – In-Use Testing Performance

- EU ISC Route (Stage 3RW - 435k mi System)



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

Sharp, C. "Characterization of In Use Performance and Measurement Instrumentation Capability at Low NOx Levels for 2027 and Beyond," 2022 CRC MSAT Workshop, February 10, 2022

# 3B-MAW - Real World Duty Cycles Results

- EPA Stage 3-RW Platform (435,000 miles Aging)
- Real world routes -

2027-Std

2030-Std

CARB Southern NTE Route (SNTE)

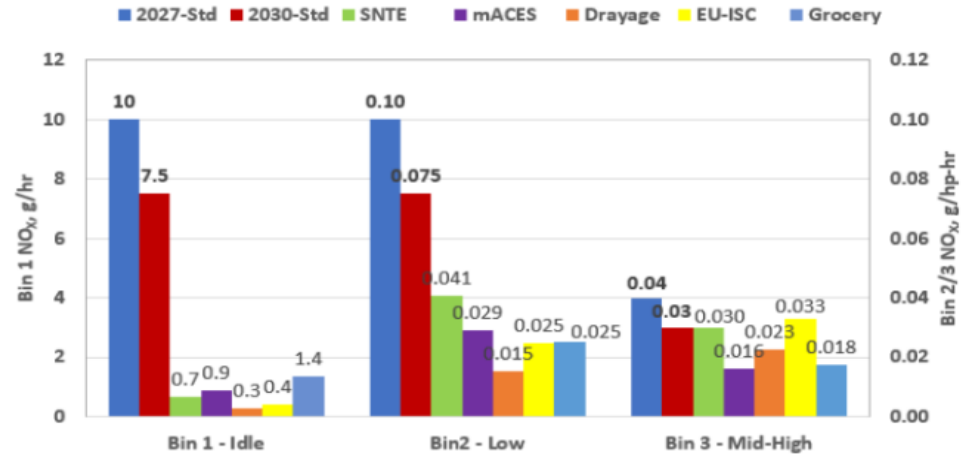
CARB 5 mode (modified ACES cycle)

WVU Drayage Route

WVU EU ISC Route

WVU Grocery Route

3-bin MAW\* In-Use Method Results

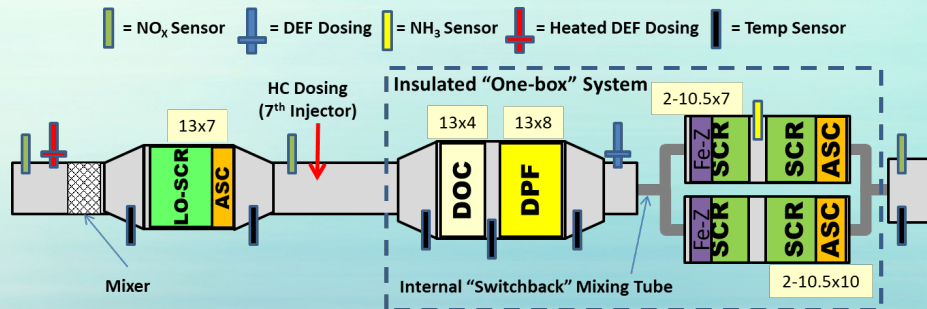


- Regulatory Cycle performance (with LLC) does translate to real-world performance for this system
- Bin 1 / 2 – below 2030 thresholds with margin
- Bin 3 – some duty cycles in but some were at or above 2030 thresholds, below 2027 but little margin

\* 3-bin MAW is the new in-use testing protocol (EPA/CARB), considers all operation including cold-start, 5-min averaging window results sorted into three "load" bins

# SwRI Technology Demonstration Continues

- SwRI Stage 3-RW - NO<sub>x</sub> at full useful life of 800k miles - testing in progress
- Additional testing to evaluate performance of a new aftertreatment system – testing in progress
  - Dual SCR-Dual Dosing System with upstream close-coupled light-off SCR and a downstream Iron/Copper Zeolite SCR formulation



Powering Business. Worldwide.



National Renewable Energy Laboratory



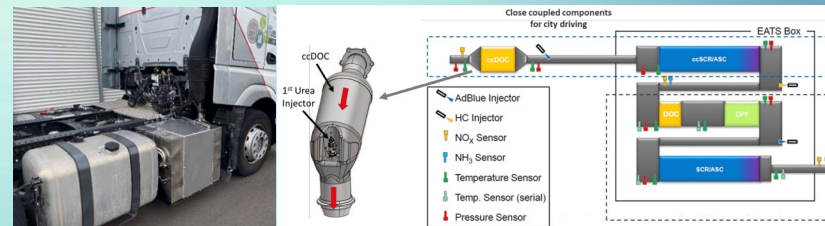
# On-Road Technology Demonstrations

- **Achates Power Low NOx Opposed-Piston Engine<sup>1</sup> (demo'ing in semi tractor at Walmart)**
  - Testing/analysis demonstrated capability to meet the 2027 NOx and CO2 standards with conventional aftertreatment system



**Achates Power 10.6L 2-stroke Diesel Engine**

- **AECC/FEV/IPA (with chassis on road and dyno test demonstration)<sup>2</sup>**
  - Significant improvement for urban emissions including cold-start and
  - Significantly low emissions under warm operation



**Vehicle Integrated Low NOx Aftertreatment**

<sup>1</sup><https://achatespower.com/resources/>

<sup>2</sup><https://www.aecc.eu/wp-content/uploads/2021/12/211208-AECC-presentation-IMechE-conference.pdf>



# Technologies Already Commercialized

Examples:

- Scania/Navistar 13 & 16L engine platforms with Cummins **dual dosing DEF** system
- Faurecia **dual dosing DEF** system, & **heated dosing**
- Vitesco **dual dosing DEF** system, **heated dosing/electrically heated catalysts**
- Jacobs **valve deactivation hardware** already in **series production** in China
- Cummins acquisition of Jacobs CDA (Eaton competitor)
- Cummins production contract with US Army for 1000hp opposed piston engines

DEF Mixers



DEF Mixers  
• Gen3 Compact Mixer Technology  
• Flex Mixer Technology

Electrically Heated Catalyst



Exhaust Gas Heater  
• On demand additional heat  
• 6-8kW

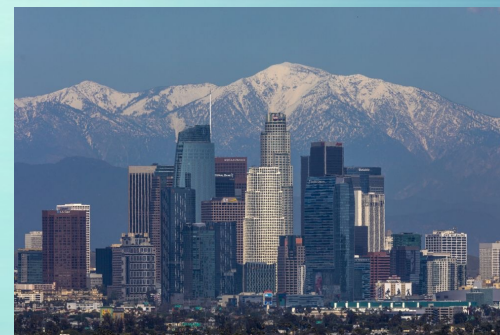
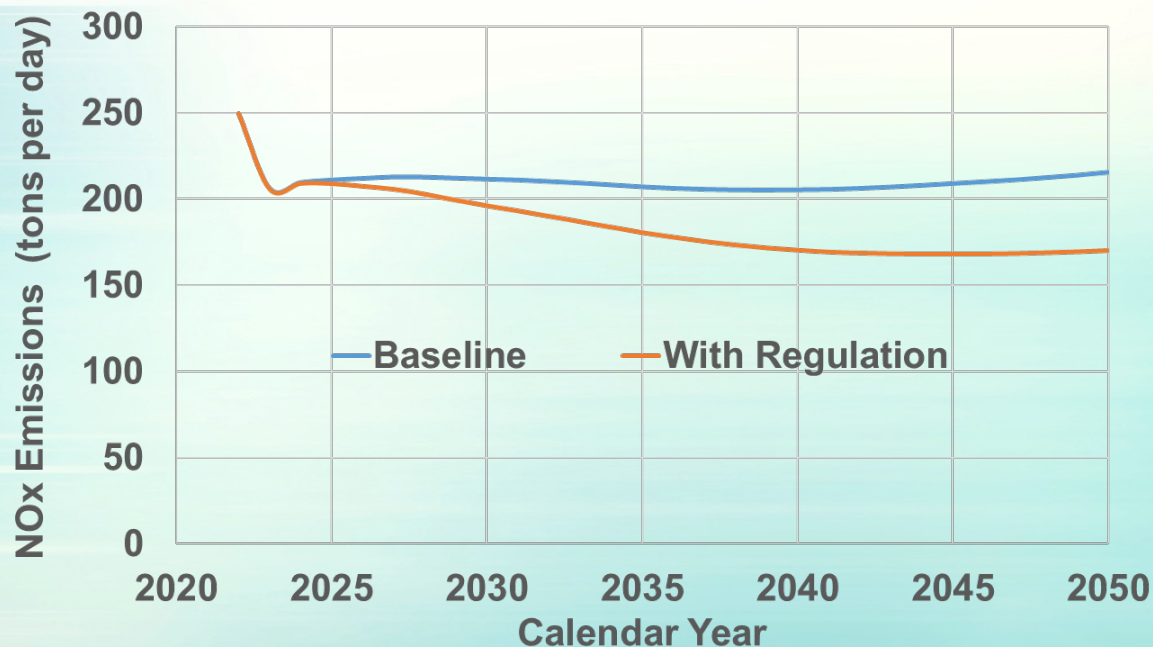
Heated Dosing System



Heated Dosing System  
• Reduced deposit risk  
• Ability to inject at lower Temp

# Costs and Benefits

# Statewide NOx Emission Inventory



# Lifetime Health Benefits

Outcome	Avoided Incidents (2024-2050)
Premature Mortality	2,484
Cardiovascular Hospitalizations	392
Acute Respiratory Hospitalizations	468
Emergency Room Visits	1,150

- **Omnibus benefits value (2018\$): \$23.4 billion**

# Cost of the Regulation (2018\$)

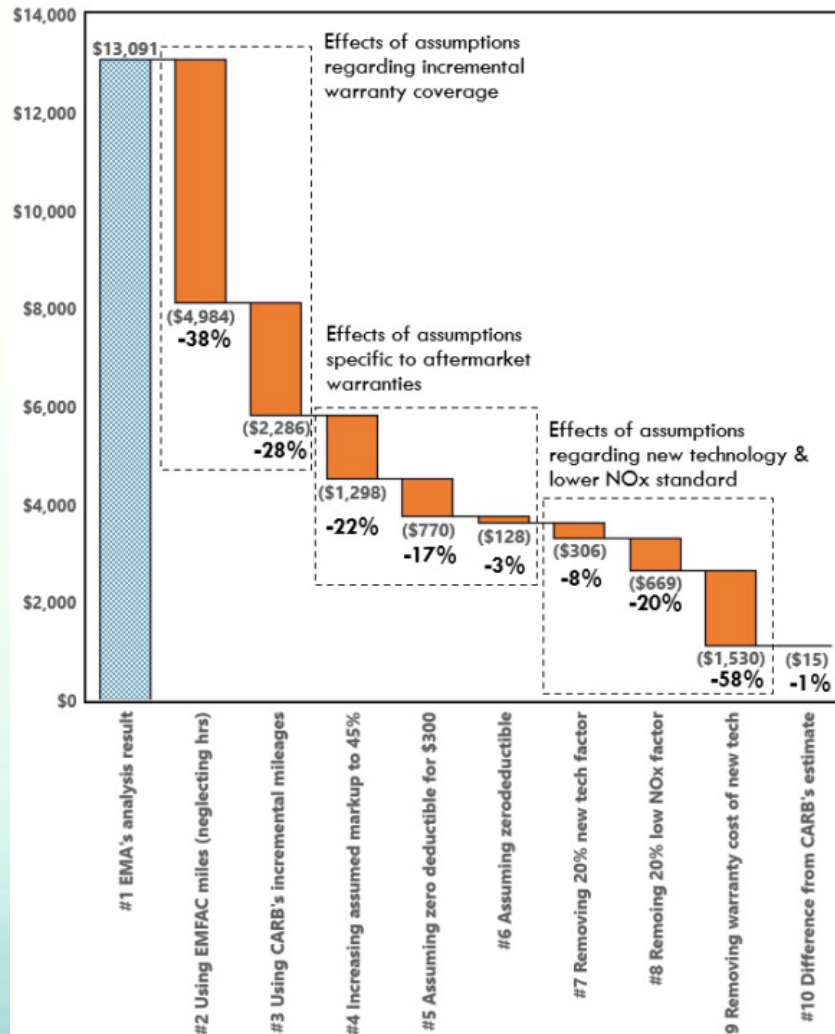
- **Average Incremental Cost /Engine: \$5,495**
- **Cost-effectiveness: \$4.51 per lb of NOx**
  - (Within range of previous CARB measures)
- **Regulation estimated to cost \$2.39 Billion**
  - (2024 through 2050)
- **Expected benefits of \$23.4 billion are about ten times above expected costs**

# Further analysis of cost

CARB directed staff to study “warranty costs” post-adoption with industry, suppliers, and EPA. After 16 meetings over 9 months, staff concluded:

- Methodology & conclusions appropriate
- **If higher warranty costs** had been included, benefits **still justify action** taken
- Engineering **durable parts not a warranty cost**
- New CARB survey of dealers & purchasers:  
Shows longer warranties valued in secondary marketplace—usefulness of **remaining warranty does add value** to used vehicles

Several other warranty cost estimating studies use **scenarios larger than adopted CARB program**



Report:  
[https://ww2.arb.ca.gov/sites/default/files/2022-01/warranty\\_cost\\_study\\_final\\_report.pdf](https://ww2.arb.ca.gov/sites/default/files/2022-01/warranty_cost_study_final_report.pdf)

# Conclusions

- **CARB certification standards are technically feasible**
  - Margins will continue to improve with commercial development
  - Low Load and Idle performance already excellent
- **3B-MAW in-use methodology is technically feasible**
- **Progress in technology development continues worldwide**



# NOx Emissions Standards 2024 – 2026 MY

MYs	DIESEL				OTTO
	FTP (g/bhp-hr)	RMC (g/bhp-hr)	LLC (g/bhp-hr)	Idling (g/hr)	FTP (g/bhp-hr)
Current	0.20	0.20	---	30	0.20
<b>2024 - 2026</b>	<b>0.050</b>	<b>0.050</b>	<b>0.200</b>	<b>10</b>	<b>0.050</b>

- **PM standard: 0.005 g/bhp-hr** applies to all 2024 and subsequent MY engines
- FTP/RMC: **75% below current standard**

# NOx Emissions Standards 2027 and Subsequent

	DIESEL ENGINES $\leq$ 33,000 lbs GVWR			OTTO
MYs	FTP/RMC (g/bhp-hr)	LLC (g/bhp-hr)	Idling (g/hr)	FTP (g/bhp-hr)
<b>2027 and later</b>	<b>0.020</b>	<b>0.050</b>	<b>5</b>	<b>0.020</b>

- FTP/RMC: 90% below current standard

# NOx Emissions Standards 2027 and Subsequent

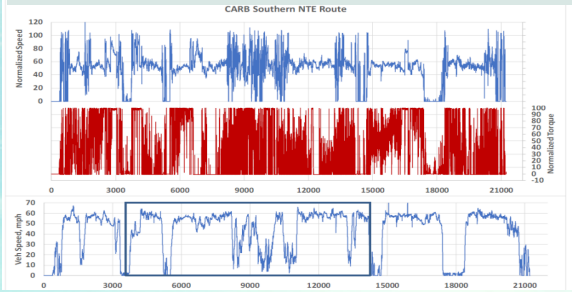
- **FTP/RMC: Intermediate standards 90% below current**
- **New standard at longer useful life**

HEAVY-DUTY DIESELS (>33,000 lbs GVWR)					
MY		2027-2030		2031 and subsequent	
Mileage	(miles)	@435,000	@600,000*	@435,000	@800,000*
FTP/RMC	(g/bhp-hr)	0.020	0.035	0.020	0.040
LLC	(g/bhp-hr)	0.050	0.090	0.050	0.100
Idling	(g/hr)	5	5	5	5

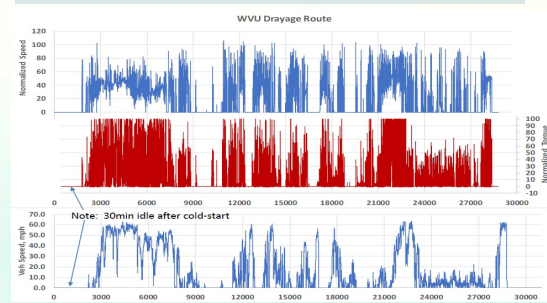
**\*Full useful life**

# 3B-MAW – Real World Duty Cycles

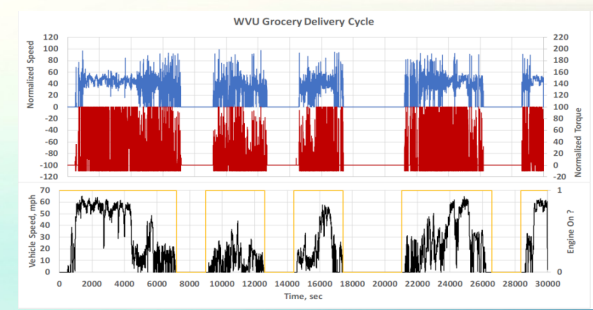
## CARB Southern NTE Route



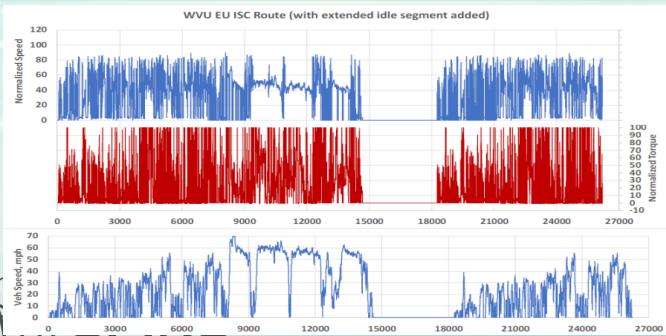
## WVU Drayage Route



## WVU Grocery Delivery Route



## WVU EU ISC Route (with extended idle)



## CARB 5 mode (modified ACES cycle)

