NOx Emissions from Heavy-Duty Vehicles in Urban Areas

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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Current policy windows

ARB Low NOx

EPA CTI

ARB Low NOx proposal summary

Limits	EPA 2010	CARB MY 2024-2026	CARB MY 2027 +
Engine FTP emission limit	0.2	California only 0.05 g/bhp-hr or Voluntary Nationwide 0.1 g/bhp-hr	0.02 g/bhp-hr (90% reduction)
NEW Low load cycle (LLC)	-	0.2 g/bhp-hr (or 0.3 g/bhp-hr VN)	0.05 g/bhp-hr
NEW Idle standard	-	10 g/hr	5 g/hr
Useful life Class 8 HDV	435,000 miles	435,000 miles	600,000 miles by 2027 800,000 miles by 2031
Class 6-7 HDV	185,000 miles	185,000 miles	360,000 miles by 2027 450,000 miles by 2031
In-use testing and compliance evaluation	HDIUT+ NTE	HDIUT + 3-Bin MAW	HDIUT + 3-Bin MAW + On-board monitoring (OBM)

https://ww3.arb.ca.gov/regact/2020/hdomnibuslownox/isor.pdf

EPA CTI Summary

- What is clear today (ANPRM):
  - Timeline: Apply from MY2027, not before
- What they are looking at now (tech and costs)
  - FTP standards reductions
  - Potential for LLC adoption
  - Potential for Idle standard (maybe covered by LLC)
  - Increased UL and Warranties
  - Replacing NTE with 3-Bin MAW (as ARB)
  - HDV chassis certification for advanced powertrains (48V, Hybrids, …)
  - Gasoline HDV standards
- What is uncertain
  - Obvious: levels of every single item listed
  - Harmonization with ARB
  - Trump 2.0 or Biden admin

ARB and EPA Calendar

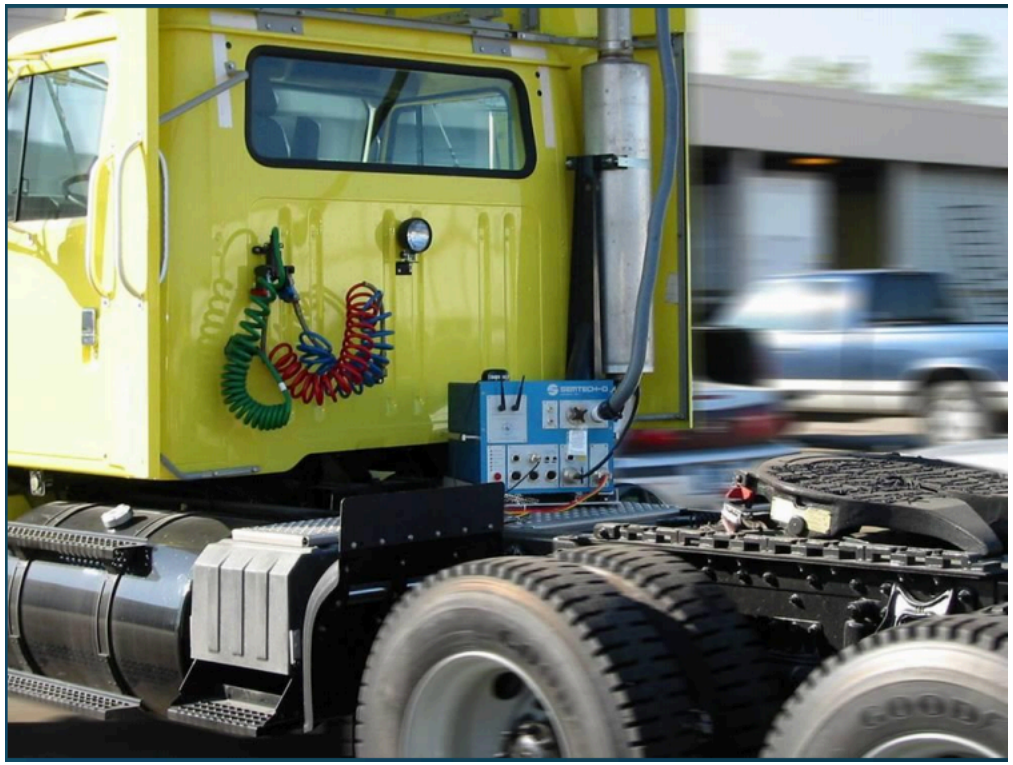
- ARB
  - ISOR: June 23, 2020 (ready) https://ww2.arb.ca.gov/rulemaking/2020/hdomnibuslownox
  - Board meeting: Aug 26, 2020
- EPA
  - NPRM: ~~Fall 2020 (unofficial)~~ - Delayed

ICCT work

1. U.S. HDV NOx baseline
2. U.S. vs EU HDVs
3. Cost to meet ARB Low NOx

Data sources:
EPA's Heavy Duty in Use Test (HDIUT) database

- EPA mandates in-use HDV tests on selected trucks
  - PEMS tests
- Used for compliance evaluation following Not-to-Exceed protocol
- Up to 25% of engine families per year
- Data is made publicly available (with some key parameters removed)



1. Second by second data
2. NTE evaluation results

Source: EPA

NTE vs total route NOx emissions

- Average NTE NOx: 0.18 g/bhp-hr,
- Average route NOx emissions:
  - w/o idle: 0.34 g/bhp-hr (1.9 x NTE NOx value)
  - all: 0.42 g/bhp-hr (2.3 x NTE NOx valua)

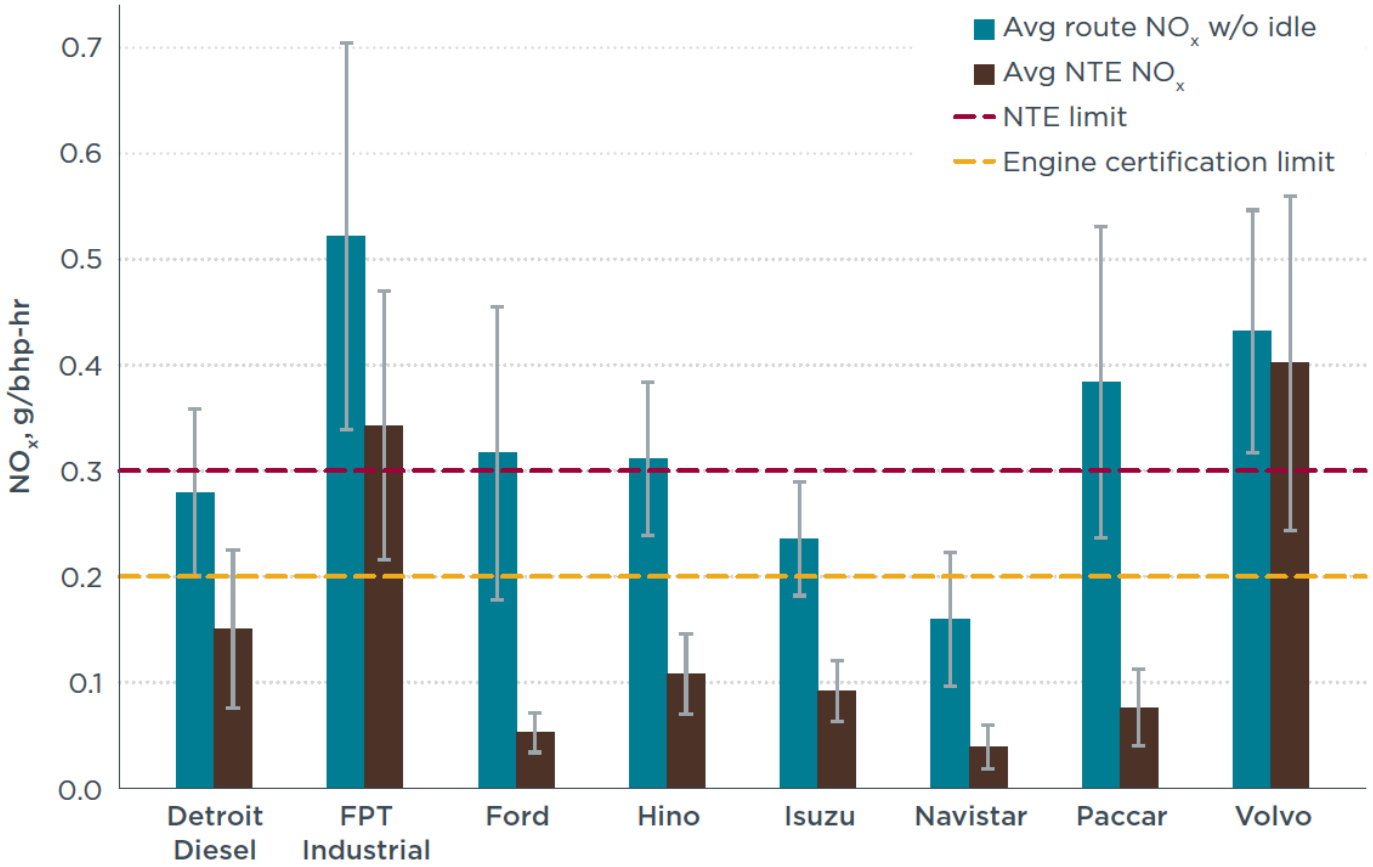


Figure 4 Comparison of Route NO_x to NTE NO_x by manufacturer. Whiskers represent the 95% confidence interval of the mean.

HDV NOx emissions by vehicle speed

- All data from HDIUT non-credit engines
- **Average route BSNOx**
  - 0.42 g/bhp-hr, all data
  - 0.34 g/bhp-hr w.o idle
- **Low speed – Urban driving**
  - 5.2 x FTP standard
- Urban driving characteristics:
  - Average exhaust temp: 213˚C
  - Urban average power range typically < 30% of maximum rated power

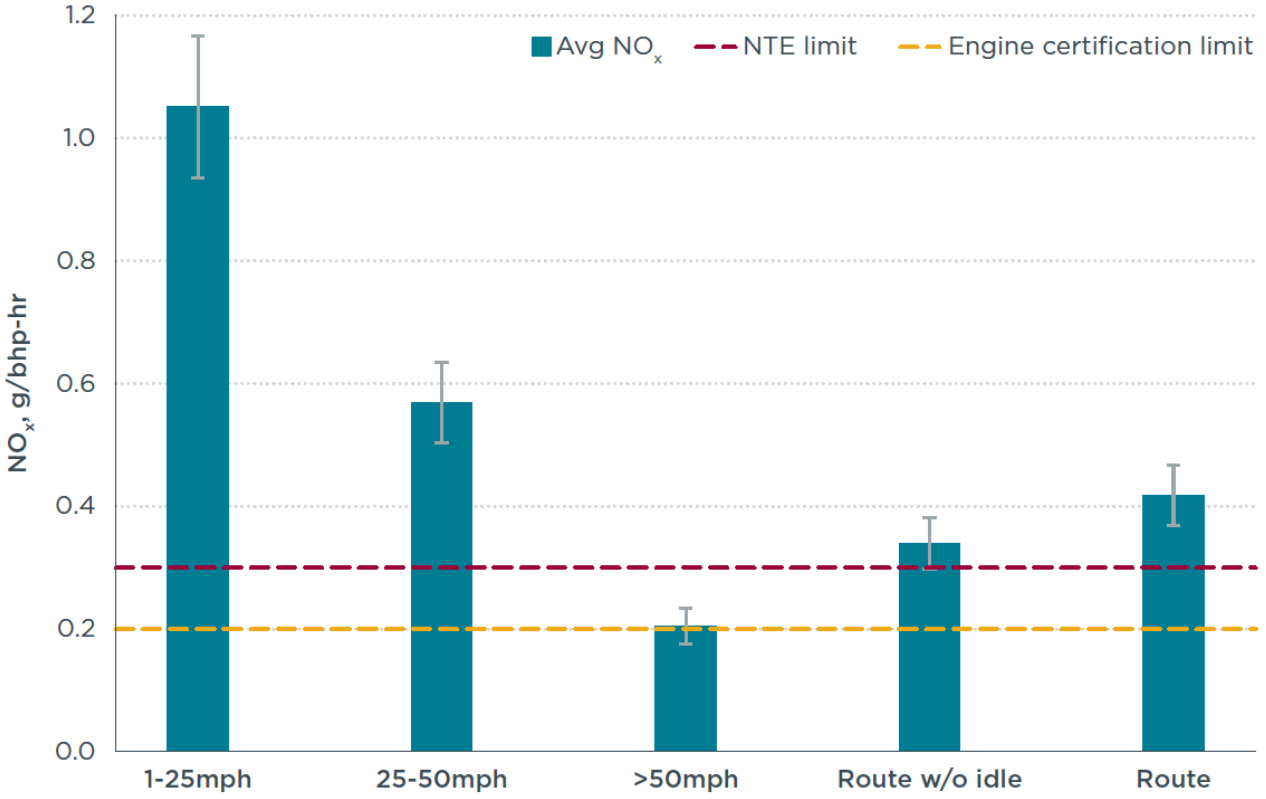
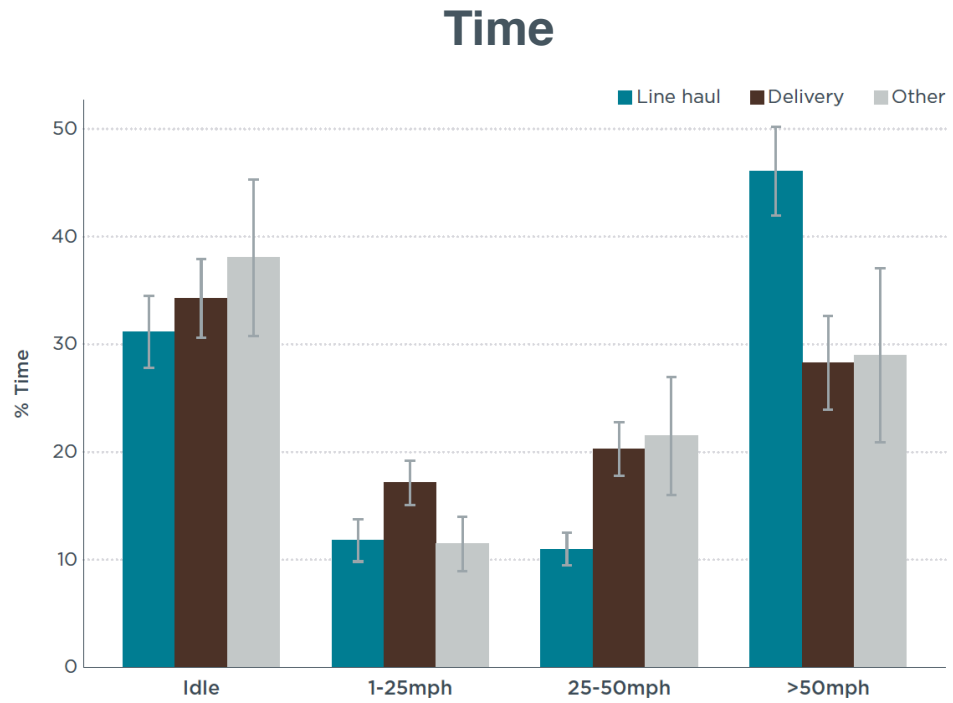


Figure 6 Average NO_x emissions in g/bhp-hr differentiated by vehicle speed. Whiskers represent the 95% confidence interval of the mean.

Time and mass share by speed condition



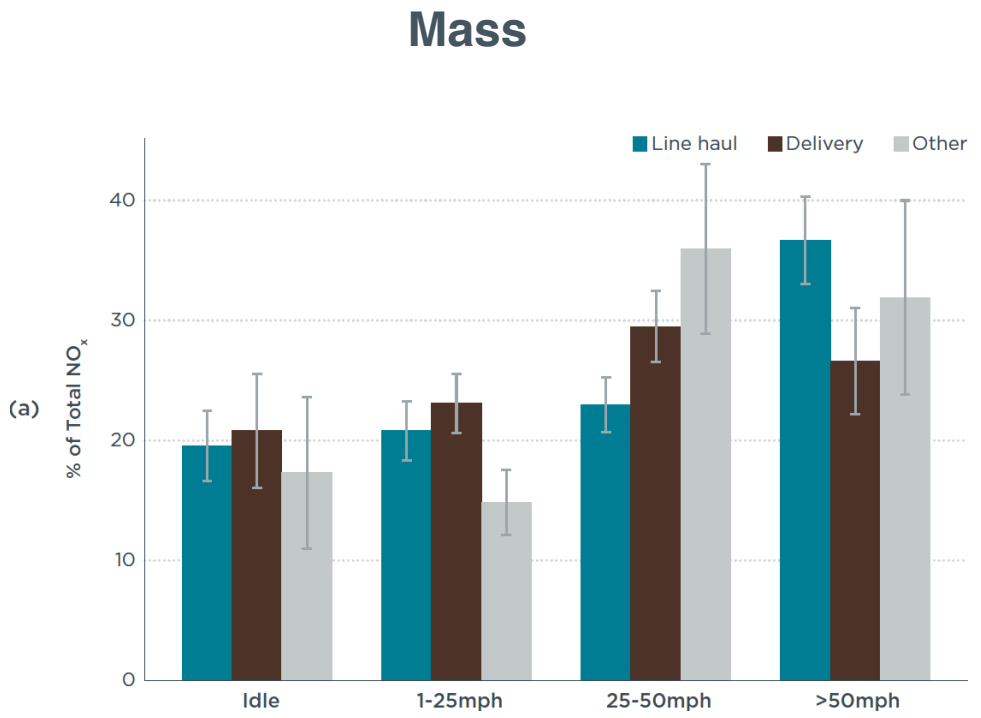


Figure 10 Percentage of time spent at each speed condition by vehicle type. Whiskers represent the 95% confidence interval of the mean.

- All vehicle types: 30-40% of time idling
- Urban driving (idle+ low speed): 41-55% of operational time

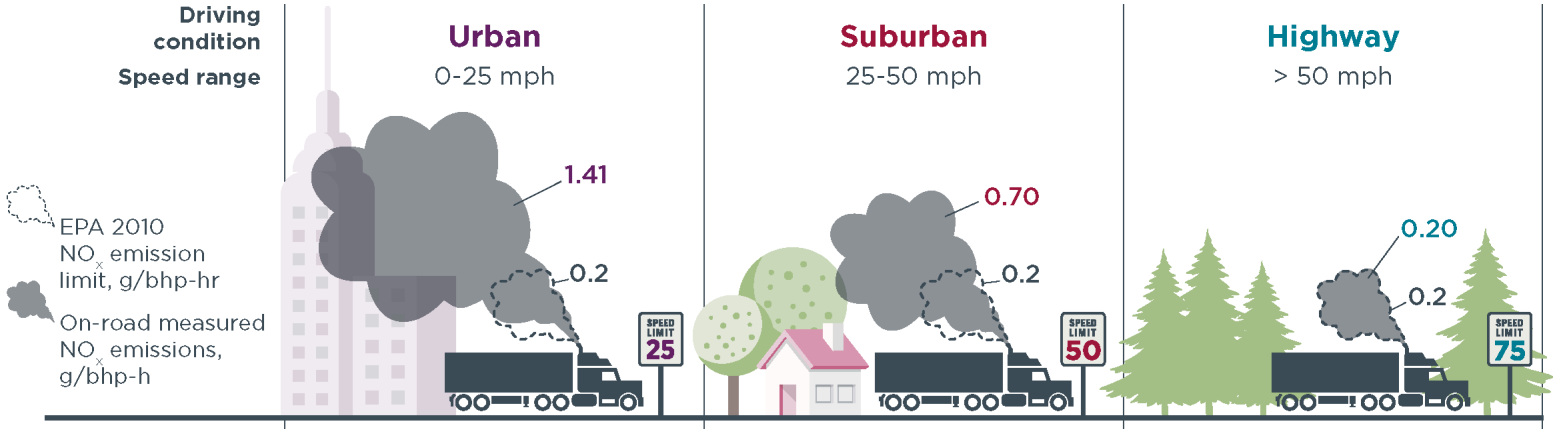
- Idling: ~20% of total mass of NOx
- Idling + low speed (urban driving) : 40-44% total mass of NOx

Note: Idle is defined here as vehicle speed < 1 mph.

https://theicct.org/sites/default/files/publications/NOx_Emissions_In_Use_HDV_US_20191125.pdf

U.S. HDVs exhibit excessive NOx emissions under urban driving

- Data from 160 PEMS test on 30 engine families 2013-2017
- Near engine out levels below 25 mph and below 20% rated power
- NTE values provide a much rosier picture, below the FTP standard



Driving condition	Urban	Suburban	Highway
Speed range	0-25 mph	25-50 mph	> 50 mph
Average time spent at this condition	43%	11%	46%
Average share NO_x mass	40%	23%	37%
Brake specific NO_x emissions, g/bhp-hr	1.41*	0.70	0.20
Conformity Factor - CF	7.1*	3.5	1.0
Distance-specific NO_x emissions, g/mile	7.0*	2.4	0.6

* Brake and distance specific NO_x emissions for Urban bin do not include Idle operation, only 1-25 mph operation is included

Figure ES-1 Comparison of line-haul vehicle NO_x emissions under urban, suburban, and highway driving conditions. Conformity factor is defined as ratio of measurement to engine dynamometer emission limits.

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https://theicct.org/sites/default/files/publications/NOx_Emissions_In_Use_HDV_US_20191125.pdf

Euro VI trucks have more relaxed engine standards but in real world emit 50% less NOx than U.S. EPA 2010 trucks– Similar engine sizes (N3 vs C8)

- EU trucks are consistently cleaner across the operating envelope
- U.S. NTE only evaluates NOx during highway
- Euro VI MAW does include low load data
- NTE must be replaced

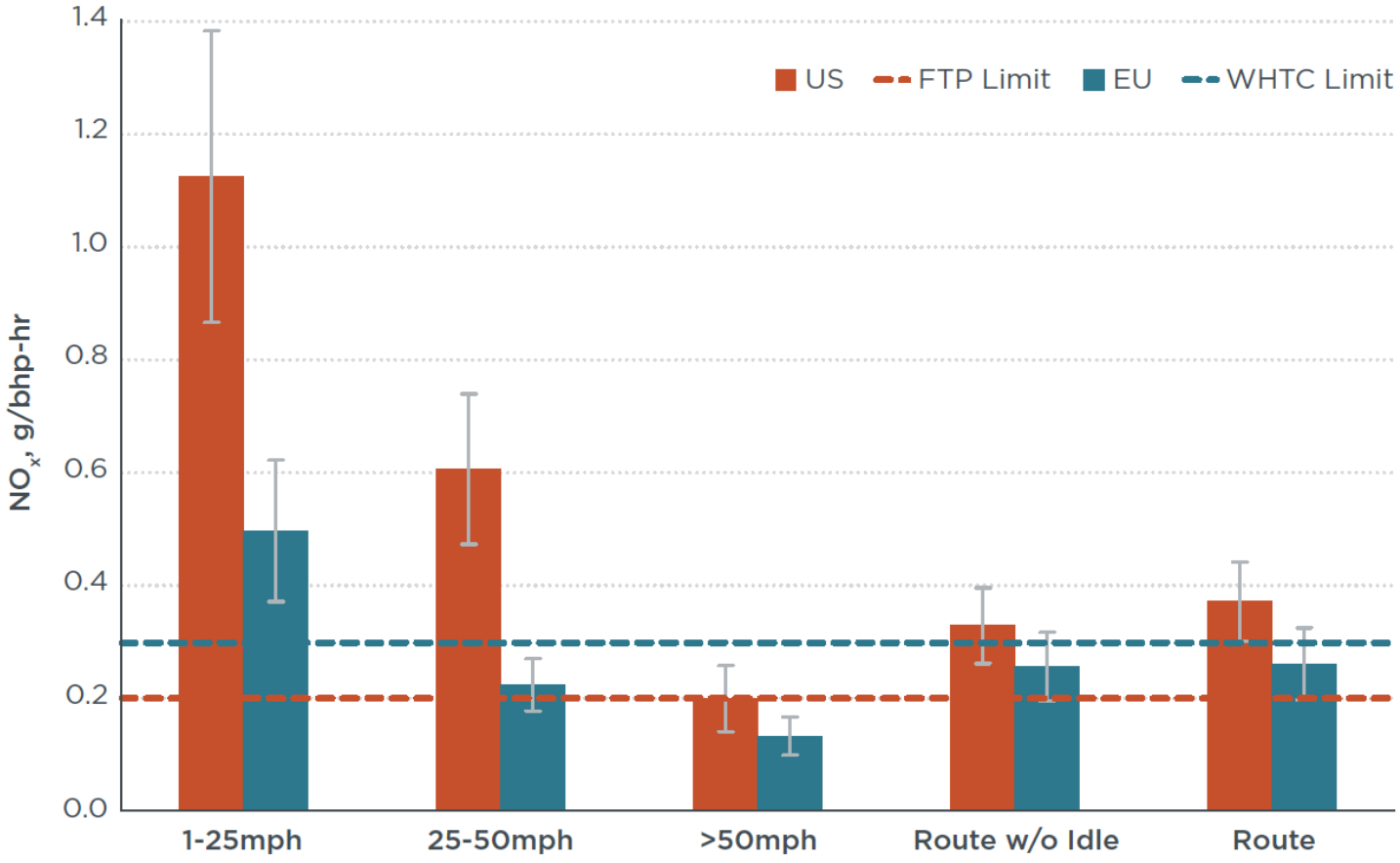

Figure ES-1. NO_x emissions by speed bin for European and U.S. HDVs. Dotted lines represent engine emission NO_x limits for U.S. and European HDVs. Error bars show confidence intervals at 95%.

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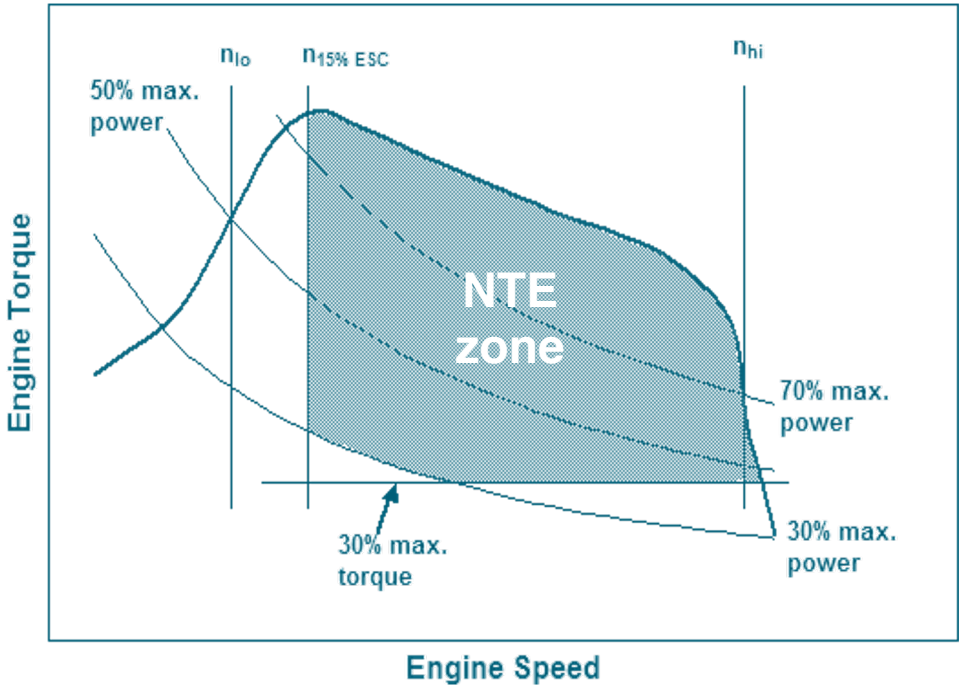
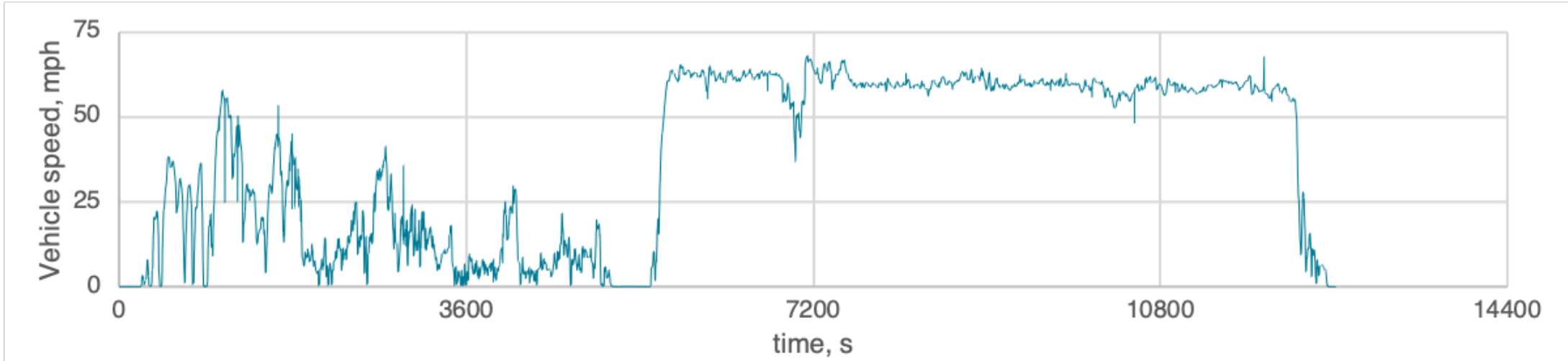
https://theicct.org/publications/inuse-nox-hdvs-us-eu

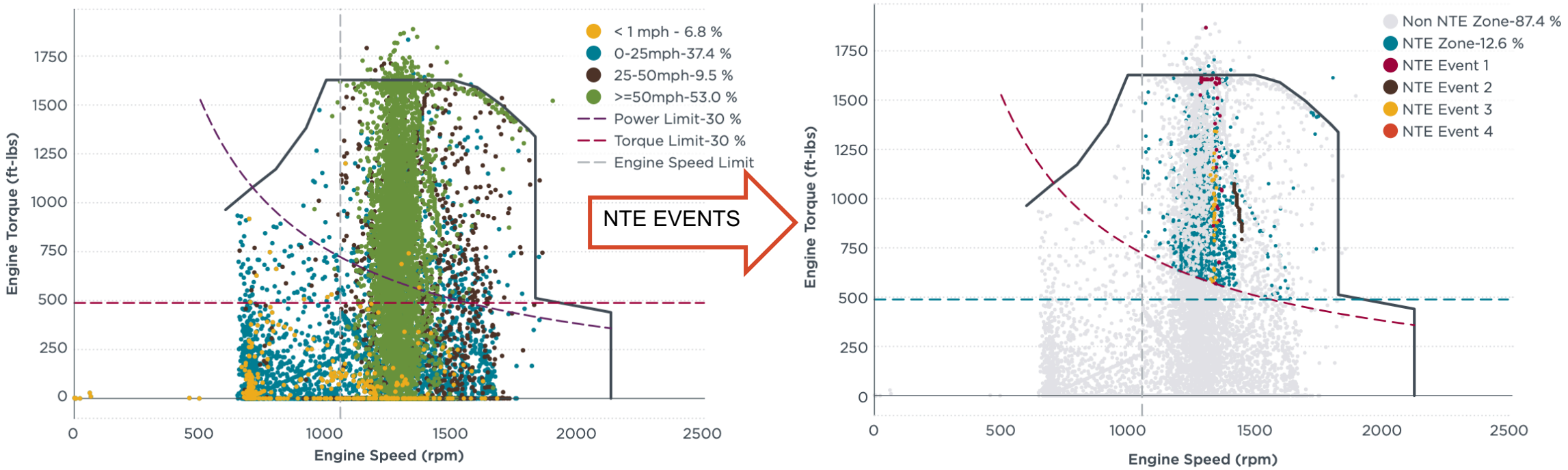
Regulatory evaluation impacts



PARAMETER	KEY	CONDITION
Engine speed (rpm)	RPM	RPM > n_{15}, where $n_{15} = n_{lo} + 0.15*(n_{hi} - n_{lo})$
Torque (ft-lb)	Torque	Torque > 30% peak torque
Power (hp)	Power	Power > 30% rated engine power
Exhaust gas temperature (F)	T_exh	T_exh > 250 C
Intake manifold temperature (F)	IMT	IMT_{limit} = (IMP+7.75)/0.0875, where IMP is in bars
NTE event		All the conditions above within NTE zone and met by at least 30 consecutive seconds



An example of how the NTE rejects PEMS data



VEHICLE	SHARE OF DATA IN NTE ZONE	NUMBER OF NTE EVENTS	SHARE OF DATA IN NTE EVENTS	AVERAGE NTE EVENT VEHICLE SPEED [MPH]	AVERAGE NTE EVENT VEHICLE POWER
Vehicle 1	28.7%	55	17.9%	54	50%
Vehicle 2	18.5%	71	9.0%	46	56%
Vehicle 3	12.1%	22	6.7%	48	81%
Vehicle 4	12.8%	4	1.1%	63	55%
Vehicle 5	31.9%	25	15.0%	56	59%
Average	**20.6%**	**-**	**10.6%**	**50**	**60%**

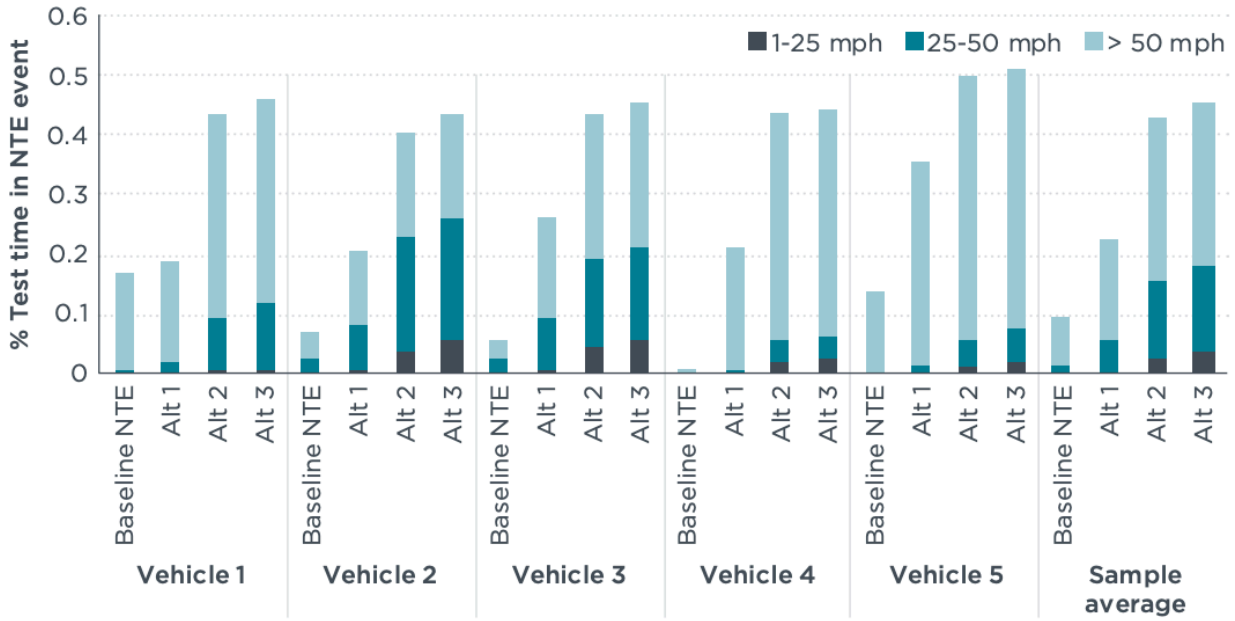
Note: HDIUT dataset reports 9% average of data in NTE events

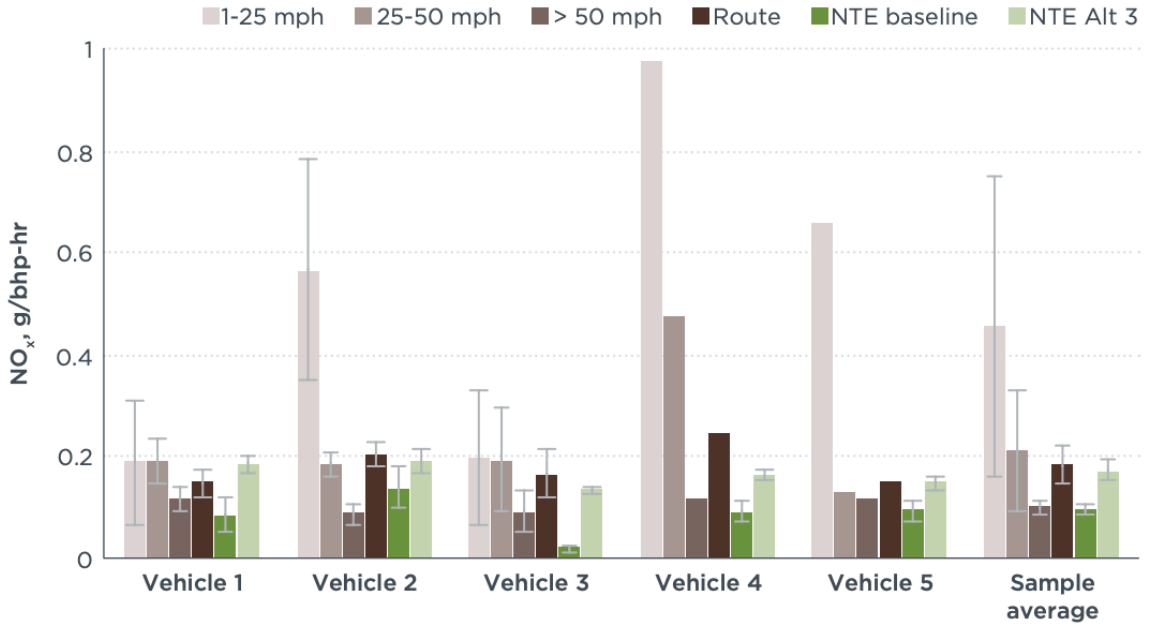
Is updating the NTE enough? **Answer: NO!**

Table 8. Description of alternative changes to current NTE parameters

Parameter	Baseline NTE	Alternative 1	Alternative 2	Alternative 3
Power threshold	30% of maximum	20% of maximum	10% of maximum	10% of maximum
Torque threshold	30% of maximum	20% of maximum	10% of maximum	10% of maximum
Engine speed threshold	Per CFR	Per CFR	Per CFR	No condition
Engine exhaust temperature	T_{exh} > 250°C	T_{exh} > 200°C	No condition	No condition
Intake manifold temperature	Per CFR	Per CFR minus 20°C	No condition	No condition
NTE event minimum duration	30 seconds	20 seconds	10 seconds	10 seconds

Notes: "Per CFR" means that the equation used to calculate the condition applies according to what is written in the Code of Federal Regulations that govern the NTE protocol. "No condition" means that the parameter is not used as a criterion to exclude data.





Any relaxation of NTE conditions, allowing more data to be evaluated, **would result in an NTE value between the current NTE and total route** (total mass NOx / total work)

A new in-use compliance evaluation tool is needed

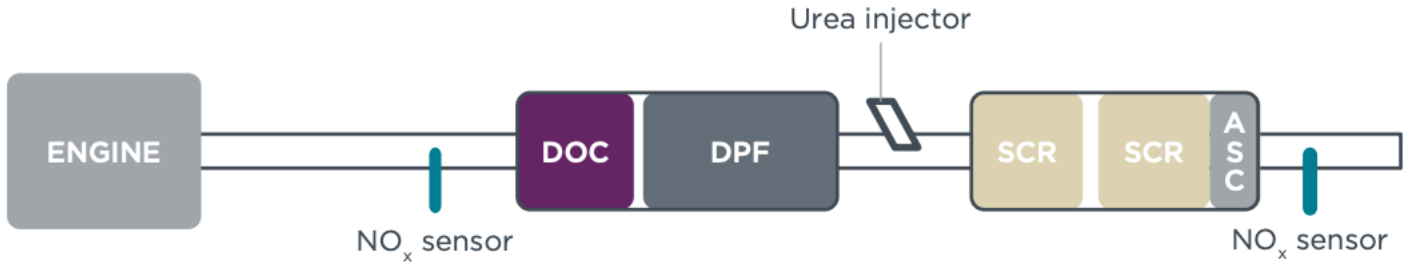
- There are new Low Load Cycle and Idle Standards.
  - We need to evaluate proper low load performance under low load conditions in the real world.
- Modifying the NTE would now address low load conditions performance
- Moving average windows (MAW) proven reliable in Europe (much better performance than U.S. models)
- Newly proposed 3-Bin MAW method looks promising

ICCT Diesel Emission Cost Study - Scope

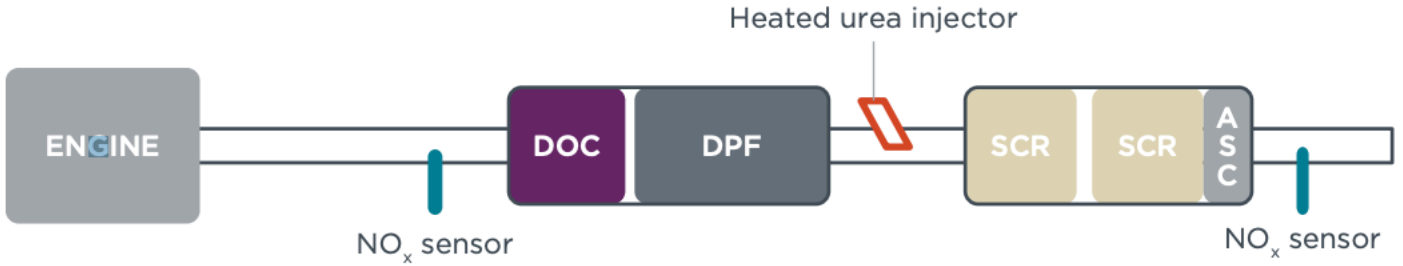
- Diesel only
- Technologies to meet proposed ARB MY2024 and 2027 standards due to changes in:
  - FTP standards
  - New LLC
  - Useful life requirements
- Two engine sizes, 7.0 L and 13.0 L, representing the average of Class 6-7 and Class 8 HDVs, respectively.
- We assess per-vehicle direct manufacturing costs and indirect costs
- The study does not cover
  - Warranty costs
  - Market size considerations (California only vs. Section 177 States, vs. Federal)

Aftertreatment control

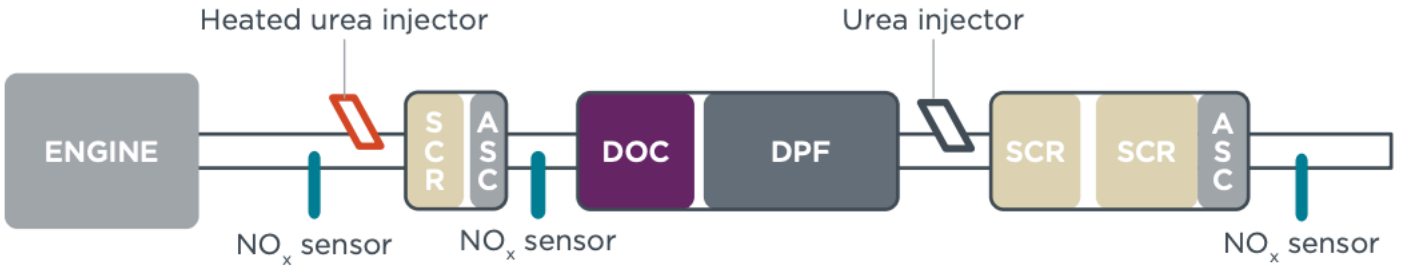
Baseline: EPA 2010 standard in 2019



ARB 2024 – Option 1

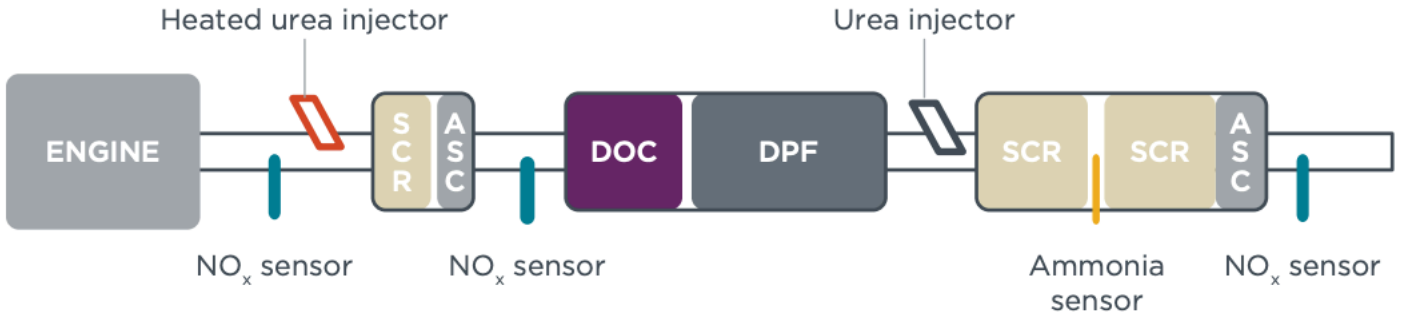


ARB 2024 – Option 2

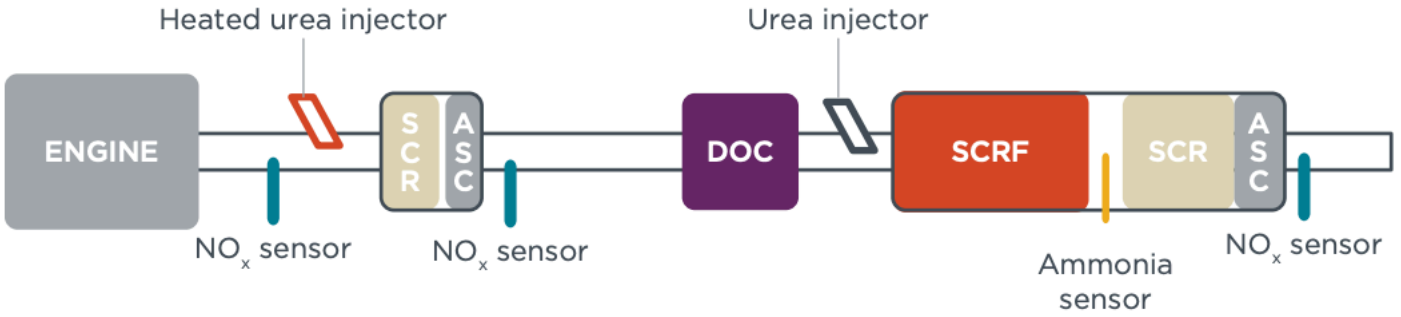


ARB proposal MY2027 and beyond

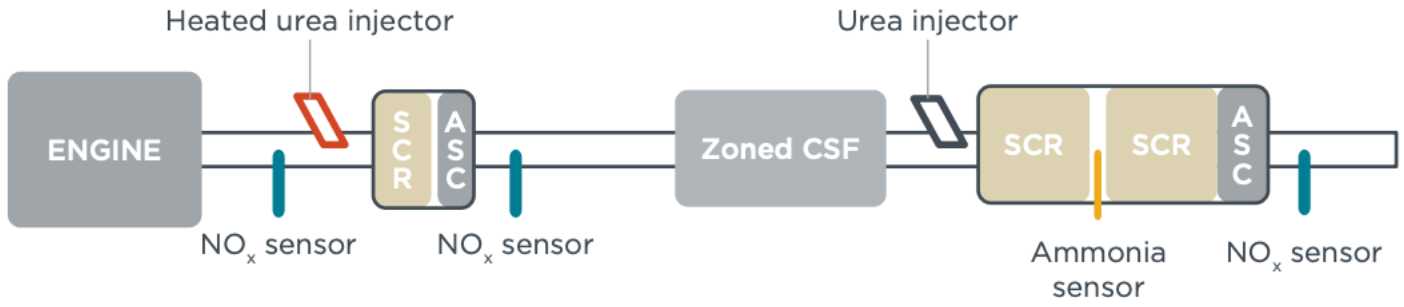
ARB 2027: Configuration 1



ARB 2027: Configuration 2



ARB 2027: Configuration 3

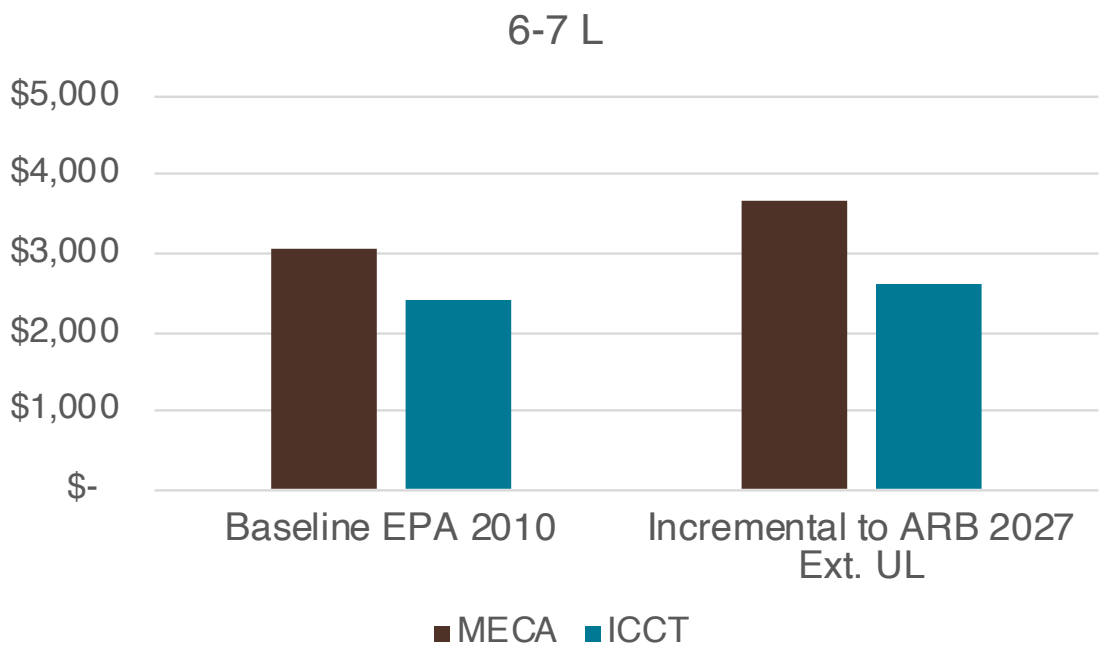


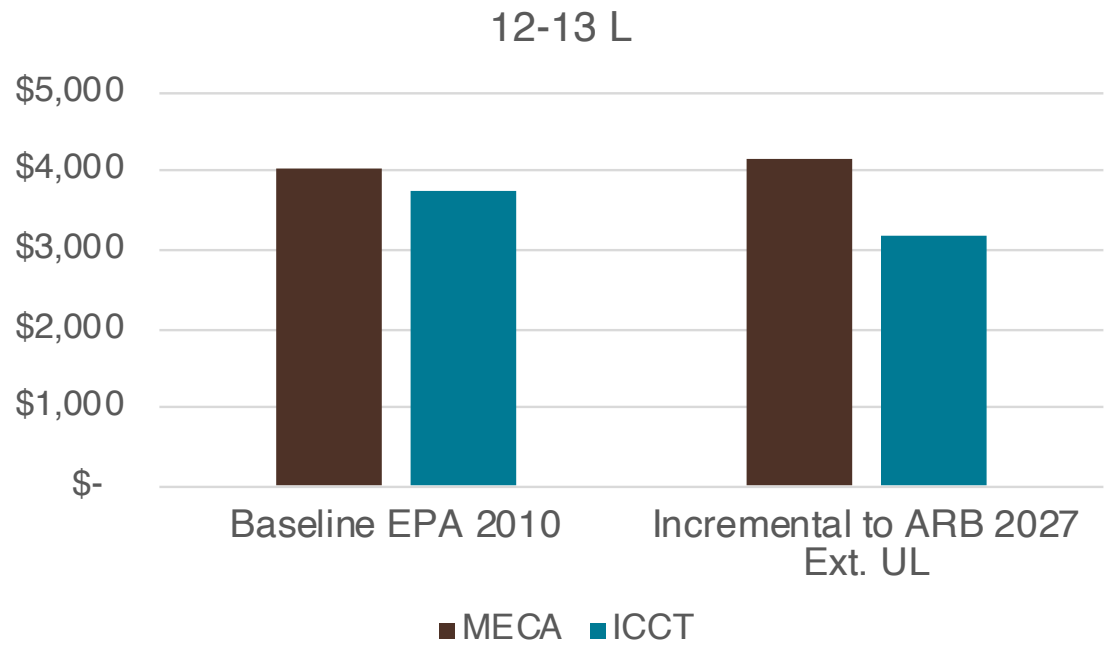
The cost to meet ARB Low NOx standards

Regulatory step	HDV class 6-7 7.0 l engine	HDV class 8 13.0 l engine
Baseline technology costs EPA 2010 in 2024	$2,570	$3,997
Total costs to meet ARB 2024	$2,675 - $3,575	$4,102 - $5,090
Incremental costs to meet ARB 2024	**$105-$1005**	**$105-$1,093**

Regulatory step	HDV class 6-7 7.0 l engine		HDV class 8 13.0 l engine	
Baseline technology costs EPA 2010 in 2027	$2,431		$3,769	
Total costs to meet ARB 2027	Low cost durability case	High cost durability case	Low cost durability case	High cost durability case
	$4,214-$4,288	$4,925-$4,996	$5,919-$6,031	$6,864-$6,988
Incremental costs EPA 2010 to ARB 2027	**$1,803-$1,877**	**$2,514-$2,585**	**$2,170-$2,282**	**$3,115-$3,239**

Comparisons to other cost data





- Average values
- MECA numbers cover UL at 1 million miles, ICCT is set at 800k
- MECA baseline is 2019; ICCT baseline is 2027. ICCT Incremental is also defined as 2027
- Warranty values not included in ICCT analysis

What is next?

Open questions on NOx inventories

Additional open questions

- HDV NOx emissions factors for MOVES and SIPs
  - MOVES public version has not been updated yet – still used with non-corrected NOx EFs
  - PM emission factors will change (better in-use values than anticipated)
  - This is key for C&B analysis – make it or break it

Thank you

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