THE INTERNATIONAL COUNCIL
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August 25th, 2020

Clerk of the Board
California Air Resources Board
Sacramento, California

RE: ICCT Comments in Response to California Air Resources Board Heavy-Duty Engine and Vehicle Omnibus Regulation and Associated Amendments
Hearing date: August 27th, 2020

These comments are submitted by the International Council on Clean Transportation (ICCT). The ICCT is an independent nonprofit organization founded to provide unbiased research and technical analysis to environmental regulators. Our mission is to improve the environmental performance and energy efficiency of road, marine, and air transportation, in order to benefit public health and mitigate climate change. We promote best practices and comprehensive solutions to increase vehicle efficiency, increase the sustainability of alternative fuels, reduce pollution from the in-use fleet, and curtail emissions of local air pollutants and greenhouse gases (GHG) from international goods movement.

The ICCT welcomes the opportunity to provide comments on the Air Resource Board proposed Heavy-Duty Engine and Vehicle Omnibus Regulation and Associated Amendments. The ICCT recognizes and applauds the constructive role that ARB has played in building the technical knowledge and public support for this critical rulemaking, and for paving the way for future federal level standards. The comments below offer a number of observations and recommendations for ARB to consider in its continued efforts to strengthen the HDV program and maximize the program's benefits in mitigating the risks associated with a growing HDV fleet that is still reliant on fossil fuels. We focus our comments on emission standards and test procedures, technologies to meet the proposed standards and their costs, in-use testing procedures, and impacts on the heavy-duty greenhouse gas phase 2 compliance.

We would be glad to clarify or elaborate on any points made in the below comments. If there are any questions, ARB staff can feel free to contact Dr. Francisco Posada (francisco@theicct.org).

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ICCT Comments in Response to California Air Resources Board Heavy-Duty Engine and Vehicle Omnibus Regulation and Associated Amendments

The California Air Resources Board Staff is proposing the Heavy-Duty Engine and Vehicle Omnibus Regulation, known as the Heavy-Duty Vehicle (HDV) Low NOx omnibus regulation. The Low NOx omnibus regulation aims to significantly reduce nitrogen oxides (NOx) emissions from new heavy-duty diesel and gasoline engines by 2027 and aims to overhaul the most important components of the current EPA 2010 standard. The proposed amendments cover exhaust emissions standards and test procedures for heavy-duty vehicles and engines Model year 2024 and subsequent, the in-use testing program, emissions warranty period and useful life requirements. The proposed amendments also cover additional reporting requirements for warranties and in-use emissions program. It would provide better alignment with powertrain test procedures for Phase 2 HDV greenhouse gas regulations.

HDV directly increase the environmental and health burden in the state of California. HDVs are significant sources of oxides of nitrogen (NOx) and particulate matter (PM) emissions. HDVs are the biggest source of NOx emissions in the state, contributing to 31 percent of all statewide NOx emissions, as well as 26 percent of total statewide diesel PM emissions.[1] These emissions contribute to exposing more than 12 million of the state's 40 million residents to unhealthy levels of pollutants. The Los Angeles South Coast Air Basin and San Joaquin Valley are the two areas most affected, classified as "extreme" under the national eight-hour ozone standard. [2]

Current HDV emission standards in the U.S., known as EPA 2010, were adopted in 2001, started implementation in 2007 and were fully phased in 2010. The adoption of the EPA 2010 heavy-duty regulations resulted in widespread deployment of advanced particulate matter and NO_x emission control systems with positive vehicle emission reductions.

At the same time, in-use emissions testing has shown that there is still a large gap between real-world NO_x emissions from HDVs and what their laboratory certified levels show. A recent analysis by ICCT of PEMS data for U.S. HDVs reveals that a disproportionate amount of NO_x emissions occurs during urban driving. Urban-driving NO_x emissions form HDVs are five times higher than the engine emissions standard of 0.2 g/bhp-hr. For class 8 trucks the data shows an even larger gap, almost seven times the standard. Average NOx emissions are about two times higher than the standard.

The need to maintain and improve future air quality standards in California as the current fleet continues to grow in size requires that those future HDVs be as clean as possible. Motivated by emission and GHG regulation compliance, manufacturers and their suppliers are continuously investing and developing technologies to ensure that the latest generation of HVDs is cleaner and more efficient than the previous one. As a result, emission control technologies are more efficient at treating harmful pollutants, and are smaller, lighter and cheaper than the first generation that was launched to meet the EPA 2010 standards.

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[1] ARB Notice of Public hearing. Source: https://ww3.arb.ca.gov/regact/2020/hdomnibuslownox/notice.pdf

[2] CARB Heavy-duty low NOx program: Proposed heavy-duty engine standards. Public Workshop presented at the Diamond Bar, CA. Retrieved from https://ww2.arb.ca.gov/our-work/programs/heavy-duty-low-nox/heavy-duty-low-nox-meetings-workshops

Low NOx emissions are needed not just in the laboratory, but also in real world operation. Aggressive standards and long-term signals are needed to fully realize this technology potential. **The ICCT recognizes and applauds the constructive role that California has played in building the technical knowledge and public support for this critical rulemaking, and for moving forward with the decision to consider adopting the next step in HDV emissions control in the State of California**.

ICCT is providing detailed comments in support of the following positions on the issues:

1. Lower emission standards and new test procedures are imperative. Air quality issues and health impacts generated by heavy-duty diesel vehicles are exacerbated in urban areas, where EPA 2010 certified trucks are missing the mark on NOx emission control. A recent study by the ICCT confirms that these diesel trucks emit 5 to 7 times more NOx during urban driving than what the limit allows in a laboratory. Adoption of a supplemental low-load cycle with a corresponding emissions standard is necessary to provide level ground for future development and adoption of emission controls for urban driving and other relevant low load and low speed operation conditions.
2. Technologies to meet future HDV standards that align with California Low NOx rulemaking are available, their effectiveness is proven, and their estimated costs on par with those form previous HDV regulatory efforts.
3. New in-use testing protocols are required. The NTE is designed to only evaluate in-use NOx emissions during highway operation. The in-use compliance evaluation tool that would replace the NTE would have to properly evaluate in-use emissions from HDVs that are designed to meet the new idle, low load cycle and the FTP standard limits. Thus, the ICCT agrees with the 3-bin Moving average approach and recommends that the new in-use testing method independently evaluates each idle, low load conditions, and mid- to high-load conditions. This will ensure the current emissions gap as the emissions results achieved in engine dynamometer tests will also be reflected during in-use, real world operations – and that no data/conditions should be excluded.
4. Tighter HDV NOx limits do not jeopardize compliance with adopted U.S. HDV GHG Phase 2 standards. The compliance requirements to meet GHG engine standards are evaluated under high speed conditions that are far from the envisioned speed and low-load conditions of the proposed NOx rule.

Each item is discussed in detail below:

1. Lower emission standards and new test procedures

The HDV Low NOx Omnibus proposal was born as ARB's response to help attaining national ambient air quality standards (NAAQS) that ensure a healthy living for U.S. citizens. Although the concentration on NOx levels in air have been reduced in the past 40 years due to regulatory efforts to curb NOx emission from multiple sources and industries, the transport sector is still problematic. By ARB's estimates, over 12 million California residents still breathe unhealthy air. The South Coast still has the highest ozone levels in the nation while the San Joaquin Valley has the greatest PM2.5 challenge. The South Coast and San Joaquin Valley are the only two extreme ozone areas in the nation, with an attainment deadline of 2031. The South Coast attainment dates are 2023 for the 80 ppb 8-hour ozone standard, and 2031 for the 75 ppb 8-hour ozone standard.

NOx are precursors to fine particulate matter ($PM_{2.5}$) and ground-level ozone, both of which are known to have adverse effects on human health. Long-term exposure to $PM_{2.5}$ and ozone is associated with increased risk of premature death from cardiovascular, lung, and kidney diseases. In addition, direct NO_2 exposure is associated with asthma incidence among children. Reduction of NOx emissions can lead to substantial public health benefits from improved air quality, including fewer hospitalizations, fewer missed days at work, and lowered risk of premature death from cardiovascular, lung, and kidney diseases. **These benefits are the main drivers for decreasing NOx emissions**.

HDV trucks certified to the EPA 2010 standards are generating more NOx emissions than what was expected with the adoption of the rule. Portable emissions measurement system (PEMS) testing data on post-MY 2010 line-haul and delivery trucks shows that NO_x emissions reach an average of 0.45 g/bhp-hr, or twice the engine certification standard.[3,4,5] Remote sensing data from HDVs in California show that the best performers, at 3.8 g NO_x/kg of fuel, emit about 3.3 times more than the engine certification standard would permit.[6]

Air quality issues and health impacts generated by heavy-duty diesel vehicles are exacerbated in urban areas, where EPA 2010 trucks are excessively missing the mark on NOx emission control. A recent study by the ICCT confirms that trucks certified to the EPA 2010 heavy-duty diesel standard emit 5-7 times more NOx during urban driving than what the limit allows in a laboratory (Figure 1).[7] Other findings of the HDV in-use NOx data reveal:

- A disproportionate amount of NOx emissions from heavy-duty vehicles is emitted during the low-speed operation characteristic of urban driving. Vehicle operation at speeds of less than 25 mph results in NOx emissions of more than five times the certification limit for the average heavy-duty vehicle in the study.
- At mid-speed driving conditions, between 25 and 50 mph and characteristic of suburban driving, average NOx emissions from heavy-duty vehicles (HDVs) are 2.7 times the certification limit. Only at highway speeds, above 50 mph, do HDVs present average NOx emissions at the certification limit and below the in-use NTE emissions limit of 0.3 g/bhp-hr.
- Line-haul trucks, defined as class 8 trucks for long-distance goods transport, have the highest average NOx emissions at less than highway speeds. Their average NOx emissions of 1.41 g/bhp-hr are more than 7 times the engine certification limit in urban

[3] Besch, M. C. (2018). Real-world emissions from heavy-duty in-use testing program. Presented at the 8th Annual PEMS Conference & Workshop

[4] Duncan, A., & Hamady, F. (2019). A comprehensive study of manufacturers in-use testing data collected from heavy-duty diesel engines using portable emissions measurement system (PEMS). CRC Real World Emissions Workshop. U.S. EPA

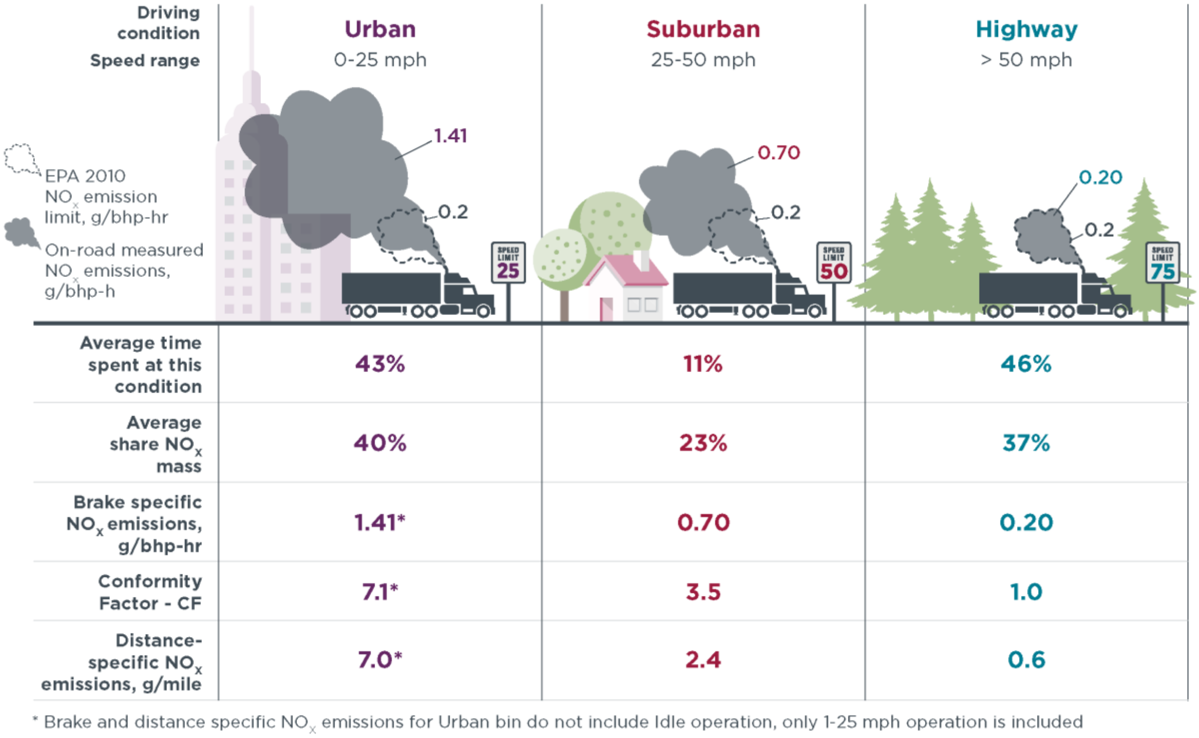
[5] Quiros, D. C., et al.. (2016). Real-world emissions from modern heavy-duty diesel, natural gas, and hybrid diesel trucks operating along major California freight corridors. *Emission Control Science and Technology*, *2*(3), 156–172. https://doi.org/10.1007/s40825-016-0044-0

[6] Bishop, G. A. (2019). Three decades of on-road mobile source emissions reductions in South Los Angeles. Journal of the Air & Waste Management Association, 69(8), 967–976. https://doi.org/10.1080/10962247.2019.1611677

[7] Badshah, Posada & Muncrief. (2019) Current State of NOx Emissions from In-Use Heavy-Duty Diesel Vehicles in the United States. Retrieved from: https://theicct.org/sites/default/files/publications/NOx_Emissions_In_Use_HDV_US_20191125.pdf

driving and more than 3 times the limit in suburban driving. Only during high-speed operation do line-haul trucks emit NOx at engine certification limit levels.

- A single line-haul truck emits the NOx equivalent of 100 cars for each mile driven in urban driving. The data shows that under urban driving conditions, line-haul trucks are emitting on average 7.0 g/mi of NOx, compared with less than 0.07 g/ mi for a gasoline car. The PEMS data shows that these trucks, which are optimized



Driving condition Speed range	Urban 0-25 mph	Suburban 25-50 mph	Highway > 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 1 Comparison of Line haul vehicle NOx emission under urban, suburban and highway driving conditions. Conformity factor is defined as the ratio of measurement to engine dynamometer emission limits.

As a result of this analysis, **it is evident that the current standards and in-use testing protocol are inadequate to ensure low NOx emissions of HDVs needed to meet the desired NAAQS, especially at the low load and low speed conditions**.

The prospect of future NOx standards set over low-load cycle and idle tests, in addition to the traditional federal test procedure, demands the adoption of a different tool for proper in-use compliance. That tool should ensure that in-use compliance is evaluated not only with highway data but also includes low-speed, low-load, and idle data. This would ensure that engine dynamometer emission results obtained in the laboratory translate to real-world benefits

Based on these findings, the ICCT supports the ARB Low NOx Omnibus proposal adoption of more stringent FTP engine certification limits and supplemental dynamometer testing and in-use procedures:

- A 90% more stringent heavy-duty engine NOx emissions standard is justified based on emissions data showing a significant gap between real-world and engine-certified emissions.
- Transport emissions inventory tools (i.e., EMFAC in and MOVES) used by California and other states should be updated to reflect the reality of hundred of thousands of HDVs sold under the EPA 2010 certification. Those vehicles are emitting today much higher amounts of NOx than what was originally intended with the EPA 2010 regulation – which assumed in-use NOx emissions to be below 1.5 times the FTP standard.
- Adoption of a supplemental low-load cycle with a corresponding emissions standard is necessary to provide level ground for future development and adoption of emission controls for urban driving and other relevant low load and low speed operations.
- Adoption of a new in-use testing evaluation protocol that purposely targets the most challenging conditions for NOx control is needed. The current NTE protocol rejects more than 90% of the data captured during in-use tests. The new evaluation tool should focus on evaluating emissions where NOx control is more challenging, such as low vehicle speed and engine load. The adoption of a low-load cycle also calls for an in-use protocol that evaluates data captured under such operating condition.

The reader is invited to review the ICCT documents on current state to HDV NOx emissions by Badshah, Posada and Muncrief (2019) and the policy recommendation document on future of HDV emission standards by Rodriguez and Posada (2020).[8]

2. Technologies to meet future HDV standards that align with California Low NOx rulemaking and their estimated costs

ARB is currently envisioning a two-step approach to reduce HDV NOx emission contributions. In the first phase, applicable from 2024 to 2026, the engine certification NOx limit would be reduced by 75%, from 0.2 g/bhp-hr to 0.05 g/bhp-hr. The low load cycle (LLC) will also be introduced in this timeframe. The LLC compliance NOx limit has been discussed in public regulatory development workshops and is proposed to be around 0.20 g/bhp-hr.

In the second phase, from 2027 onwards, CARB would introduce more stringent NOx emissions standards. CARB's intent of reducing NOx emissions from HDVs by 90% translates to a certification value between 0.02 and 0.04 g/bhp-hr depending on year and useful life compliance. The LLC limit will fall somewhere between 0.05 and 0.10 depending on year and useful life compliance. Meeting these requirements are expected to require the introduction of engine and aftertreatment hardware upgrades.

Table 1 provides a summary of the ARB Low NOx envisioned changes for heavy heavy-duty diesel (HHDE) engines – not all regulatory changes are listed here. Note that Useful life values change for non-HDDEs.

[8] Rodriguez, F. & Posada, F. (2019). Future heavy-duty emission standards: An opportunity for international harmonization. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/ future-hdv-standards-harmonization

Table 1 Summary of ARB key proposed changes to engine emission standards compared to the current EPA 2010 standard. Applies HD diesel-cycle engines (HDDE).

Test cycle	EPA 2010 standard	ARB MY 2024-2026	ARB MY 2027 and beyond
Engine FTP emission limit (g/bhp-hr)	0.2	0.05 (75% reduction) Or optional 50-State: 0.10	MY 2027-2030: 0.020 @435k miles UL, or 0.035 @600k miles UL MY 2031+: 0.020 @435k miles UL, or 0.040 @800k miles UL -
NEW Low load cycle (LLC) emission limit (g/bhp-hr)	-	0.20 Or optional 50-State 0.30	MY 2027-2030: 0.050 @435k miles UL, or 0.090 @600k miles UL MY 2031+: 0.050 @435k miles UL, or 0.100 @800k miles UL -
Idle limit	-	10 g/hr	5 g/hr
Durability HDDE HDV	435,000 miles	435,000 miles	600,000 miles by 2027 800,000 miles by 2031
MDDE HDV	185,000 miles	185,000 miles	360,000 miles by 2027 450,000 miles by 2031

Technology requirements

The technologies required to meet the proposed standards for MY2024-20206 and MY2027 and beyond have been identified and their durability demonstrated by ARB research projects. The technology deployment required to achieve those low levels of NOx emissions builds upon the architecture of current emission control systems. Under the right temperature conditions, a well-designed SCR system can convert NOx with over 99% efficiency. Low exhaust temperatures however, like those found during cold-start and extended low-load operation, can significantly reduce the SCR conversion efficiency and are responsible for the majority of NOx emissions in heavy duty vehicles (HDVs). Keeping the SCR substrate in the right temperature range and accelerating the light-off process are key goals for low load NOx control. Thus, technology interventions in engine-out NOx control and aftertreatment systems are necessary to tackle emissions under these conditions.

Conventional strategies to reduce engine-out emissions focus on improved fuel injection, improved air handling, and exhaust gas recirculation (EGR). A new set of technology that is entering the diesel engine space as a potential solution for emission control and fuel efficiency, and that has been widely used in light-duty gasoline engines, is variable valve actuation and cylinder deactivation (CDA). For the purpose of cost evaluation, we focus on CDA technologies, as well as EGR handling, air-charge cooler, and turbo bypass.

Cylinder deactivation (CDA) encompasses a range of technologies which disable one or more cylinders during engine operation. This effectively creates a smaller displacement engine which cylinders operate at higher loads (Isenstadt, German, & Dorobantu, 2016). CDA is already used in light-duty vehicles, primarily for the improvements in fuel economy due to operating active cylinders in more efficient zones. Likewise, Diesel engines also realize efficiency benefits. Additionally, since CDA increases exhaust gas temperatures it can rapidly warm the aftertreatment system, and maintain that warmth, even under low load (Dorobantu, 2019; Eaton, 2019a; McCarthy, Jr, 2016; Ramesh et al., 2018).

CDA has already proven that it can enable achieving ARB 2027 NOX targets and a reduction in CO2 emissions. According to a recent ongoing study performed by SwRI, CDA realized a 44% reduction in work-specific NOx while simultaneously reducing fuel consumption by 2.8% over the low load cycle on a modern aftertreatment system (Neely, Sharp, Pieczko, & McCarthy, Jr, 2019). The same study shows CDA contributed a 32% reduction in work-specific NOx with a simultaneous 2.5% reduction in CO_2 on the same aftertreatment system over the FTP.

To reach ARB's envisioned low NOx levels—below 0.02 g/bhp-hr— aftertreatment improvements are needed. These improvements focus on cold start and high conversion efficiencies for the entire FTP test and supplemental low load cycle are needed. These requirements imply reducing the time to achieve SCR light-off and maintaining adequate temperatures for the whole cycles. Three main strategies are anticipated to be used to meet this 90% reduction in NOx limits:

- First, adding heat to quickly warmup SCR catalysts without increasing fuel consumption. Heated urea dosing reduces the need to heat up the exhaust gases enabling low load fuel efficiency gains; 48V electrical system enables electric catalyst or heated urea dosing. The energy supply for this heating could in part come from recuperated braking energy, which reduces real-world fuel consumption from fast light-off.
- Adding SCR volume and positioning some of the additional volume close to the engine exposes such close-coupled SCR (ccSCR) to higher temperatures, thereby enabling faster light-off of the ccSCR.

At the request of ARB, SwRI studied the potential of meeting the envisioned standards through a combination of those strategies. Those strategies have been materialized for experimental work in a series of aftertreatment configurations and engine calibration and hardware changes. In this section we summarize those architectures that have achieved the most promising results for emission control under the different test cycles.

1) The simplest improvement to meet future ARB 2027 standards adds a closed coupled SCR (ccSCR) located next to the turbocharger outlet. This system includes a urea doser and SCR/ASC upstream of the DOC for fast light off. In these configurations, one (heated) urea injector is located in front of the ccSCR (composed of SCR/ASC), which comes before the filter, while the second injector remains in front of the downstream SCR. The two injectors better control the desired ammonia and also manage NO_2 slip for passive soot regeneration of the DPF (A. Joshi, 2019). Based on actual engine testing, this system can meet future ARB 2027 NOx limits over the composite FTP and LLC (Neely et al., 2019; Sharp, 2019).
2) Further modifying the previous configuration by combining the separate DOC and DPF into one catalyzed soot filter (CSF). CSF are characterized by performing the DOC function in the front section of the filter substrate. The CSF was selected as it promises lower thermal inertia ahead of the downstream SCR, which helps achieving low NOx

emissions over the low load cycle. In addition, CSF provides lower backpressure than the DOC+DPF combination, reducing CO_2 penalties according to recent modeling by SwRI (Sharp, 2019).

It should be noted that all of these technologies are commercially available today. Cylinder deactivation is used by 12% of new light-duty vehicles sold in the U.S. in 2018 – General Motors alone applies CDA in 42% of their LDVs, mainly in SUVs and light-trucks.[9] Closed coupled SCR systems have already been deployed commercially in diesel vehicles. Compliance with the most stringent NOx real world emission standard in Europe (Euro 6d) drove Volkswagen to adopt *Twin SCR systems* for one of their most popular diesel passenger cars, the Passat 2.0 TDI and will be adopted in the new Golf.[10]

Table 2 summarizes technology solutions proven in the engine certification tests to meet the ARB envisioned low NOx standards in 2024 and 2027. For engine out control we are considering EGR cooler bypass, charge air cooler bypass, and CDA as part of the overall solution. For aftertreatment technologies we cover the SwRI technologies best suited to meet both future FTP limits and the LLC requirements. We only estimate the costs for these potential architectures in the next sections.

Table 2 Current and potential future technology options to meet ARB-proposed low NOx standards in 2024 & 2027

Technologies	EPA 2010 technology	CARB 2024	CARB 2027
Engine-out			
Fuel injection	Common rail fuel injection (P>2,200 bar)	Common rail fuel injection (P>2,200 bar)	Common rail fuel injection (P>2,200 bar)
Air induction	Turbochargers (waste gate, VGT and two-stage)	Turbochargers (waste gate, VGT and two-stage)	Turbochargers (waste gate, VGT and two-stage)
NO_x control	EGR high pressure	EGR high pressure	EGR high pressure and EGR cooler bypass
Cold start and low load NO_x control	-	-	Cylinder deactivation (CDA) – Provides strong fuel consumption benefits
Aftertreatment			
Oxidation catalyst	DOC	DOC	DOC or CSF
Particulate matter filtration	DPF	DPF	DPF, CSF or SCRF
NO_x reduction and ammonia slip control	SCR and ASC	SCR and ASC	Increased volume SCR (or SCRF) and ASC

[9] The 2018 EPA Automotive Trends Report. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100W5C2.PDF?Dockey=P100W5C2.PDF

[10] Volkswagen announces innovative twin dosing systems. https://www.volkswagen-newsroom.com/en/press-releases/innovative-twin-dosing-reduces-nox-emissions-by-approx-80-percent-5281

Cold start and low-load NO_x control	-	Heated urea injection (HUI) for downstream SCR	Close-coupled SCR/ASC with HUI
Aftertreatment configurations	DOC+DPF+SCR/ASC	Configuration 1: DOC+DPF+SCR/ASC Configuration 2: SCR/ASC+ DOC+DPF+SCR/ASC	Configuration 1: ccSCR/ASC+ DOC+DPF+SCR/ASC Configuration 2: ccSCR/ASC+ DOC+SCRF+SCR/ASC Configuration 3: ccSCR/ASC+ CSF+SCR/ASC

Notes: Diesel oxidation catalyst (DOC); Diesel particulate filter (DPF); Catalyzed particulate filter (CSF); ASC Ammonia slip catalyst.

There are additional technologies that have not been tested and costed here that have equal or higher potential to enter the market and enable meeting the 2027 NOx targets and fuel efficiency requirements. Technologies such as 48 V mild hybrid technologies can reduce fuel consumption and GHG emissions by taking over engine accessories loads and enabling electric turbochargers, electric EGR systems, electrically heated catalyst and urea injectors, These enabled technologies contribute to lowering engine-out NOx emissions and improving aftertreatment thermal load management (SCR light off and keep-warm actions). Thus, many other technology pathways exist that would help achieve the targets in a cost-effective manner.

The ARB proposal is adopting powertrain testing amendments to facilitate chassis testing that can accommodate 48 V mild hybrid and full hybrid technologies for certification testing of heavy-duty vehicles. The powertrain testing procedures would align with corresponding federal procedures for powertrain testing and would be based on the U.S. EPA Phase 2 GHG technical amendments for powertrain testing.

Incremental costs to meet envisioned ARB 2027 standards

The cost of the technology required to meet CARB's envisioned regulatory changes in 2024 and 2027 was investigated by ICCT researchers and published in May 2020.[11] The cost-estimation methodology follows the steps outlined in previous ICCT work for light-duty vehicles, heavy-duty vehicles, and nonroad engines. Each technology involved in emissions control, in-cylinder, and aftertreatment components, is studied independently. In-cylinder technology cost is presented as a single value. Aftertreatment cost values are dissected for each of the main system components and parts. The cost information for each item comes from bottom-up assessments, available literature, trade publications, suppliers, and expert reviews. Indirect cost values are determined from methodologies developed by the EPA and added to the detailed manufacturing costs. The effect of time and production learning are also accounted for in 2024 and 2027. The impact of increased useful life requirements is also estimated. However, the effect of changes in

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[11] Posada et al. (2020). Estimated cost of diesel emissions-control technology to meet the future California low NOx standards in 2024 and 2027. https://theicct.org/publications/cost-emissions-control-ca-standards

warranty requirements is out of the scope of this report. The main output of this analysis is the incremental cost of meeting future requirements in 2024 and 2027 compared with a baseline EPA 2010 technology case.

The costs of meeting EPA 2010 standards in 2019 have declined significantly compared with previous cost estimates. Costs of aftertreatment technology needed to meet the EPA 2010 standard have dropped by about 30%. Total direct and indirect aftertreatment manufacturing costs in 2019 are estimated in this analysis to be $2,800 for a class 6–7 HDV with a 7.0 liter engine and $4,400 for a class 8 HDV with a 13.0 liter engine.

The technology pathways to meet the proposed standards, and studied in detail for cost analysis, were based on the extensive research commissioned by ARB and performed by Southwest Research Institute.

Meeting the envisioned CARB 2024 targets would require very modest increases in technology complexity and costs. Technology changes are expected to occur in the urea dosing system of current aftertreatment system architectures. The cost of achieving a 75% reduction in NO_x emissions under the FTP and meeting new LLC standards is estimated to range between $100 and $1,000 for a class 6–7 vehicle with a 7.0 liter engine and between $100 and $1,100 for a 13.0 L class 8 HDV (Table 3).

Table 3 Incremental total cost of the proposed 2024 CARB standards, as compared with EPA 2010 standards in 2024 (in 2019 U.S. dollars

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 CARB 2024	$2,675 – $3,575	$4,102 – $5,090
Incremental costs to meet CARB 2024	**$105 – $1,005**	**$105 – $1,093**

Meeting the envisioned CARB 2027 targets would require significant changes in current technology and costs, driven by 90% lower FTP NO_x targets, low-load cycle requirements, and longer useful life mandates. The technology changes are focused on improving thermal management and increasing the aftertreatment system NO_x reduction efficiency and durability. To achieve that, cylinder deactivation and EGR bypass would be added to future engines. Aftertreatment changes would include the addition of a close-coupled SCR and changes to the urea dosing system. Higher useful life would be addressed with changes to catalyst volume and wash coat formulations, and sensor replacement. For class 6–7 HDVs with 7.0 L engines, this would result in additional $1,800 – $2,600 of total emission control costs compared with systems meeting the EPA 2010 standards in 2027. For class 8 HDVs with 13.0 L engines we estimate an increment in total cost ranging from $2,200 to $3,200 compared with systems meeting the EPA 2010 standards in 2027 (Table 4).

Table 4 Incremental cost of the proposed 2027 CARB standards, as compared with EPA 2010 standards in 2027 (in 2019 U.S. dollars).

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 CARB 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 CARB 2027	**$1,803–$1,877**	**$2,514–$2,585**	**$2,170–$2,282**	**$3,115–$3,239**

New useful life values
California is planning on extending diesel useful life requirements for class 8 HDVs to 800,000 miles (from 435k) and warranties to 600,000 miles (from 400,000 miles from 350k). ICCT supports the adoption of regulatory changes that can prevent the loss of aftertreatment function at higher mileages. Manufacturers will have plenty of lead time to select the most effective ways to extend useful life and minimize cost. Moreover, the association that represents manufacturers of emission control technologies (MECA) has expressed the capacity of supplier companies to deliver diesel and gasoline aftertreatment technologies that meet those requirements.

3. In-use emission standards

The ARB Low NOx Omnibus proposal acknowledges the limitations of a U.S. heavy-duty in-use testing program (HDIUT) that follows the not-to-exceed (NTE) protocol for compliance evaluation. Under the NTE evaluation protocol more than 90% of the data collected is rejected. This has opened a large gap in HDV NOx compliance evaluation in the U.S. The ARB Low NOx Omnibus ISOR recognizes that risk and has introduced the 3-bin MAW method for in-use compliance evaluation starting MY2024.

The drawbacks of the NTE: evaluating compliance with less than 10% of available data.

The PEMS data validity requirements of the NTE methodology are numerous and set narrow constraints for compliance evaluation. The exclusions mandated by the NTE methodology significantly reduce the portion of the test data used for compliance evaluation. An in-depth analysis[12] of HDIUT data made publicly available by the EPA from 160 PEMS test on HDVs show that on average, the total amount of time spent in valid NTE events was approximately 9% of the total test time. As a consequence, the average NOx emissions over valid NTE events of 0.18 g/bhp-hr (~0.24 g/kWh) were approximately 60% lower than the emissions over the

[12] Huzeifa Badshah, Francisco Posada, and Rachel Muncrief, Current State of NOx Emissions from In-Use Heavy Duty Diesel Vehicles in the U.S., (ICCT: Washington, DC, 2019), www.theicct.org/publications/nox-emissionsus-hd-diesel-vehicles

complete tests including idle, which averaged across all data sets amounted to 0.42 g/bhp-hr (~0.56 g/kWh)

The drawbacks of the NTE method become even clearer when looking at urban NOx emissions, defined as those occurring at less than 25 mph (40 km/h). The application of the NTE boundary conditions for compliance evaluation typically eliminates all data obtained under urban driving. Consequently, the NTE methodology provides virtually no regulatory oversight of urban emissions. The analysis of the HDIUT data made public by the EPA shows that average urban NOx emissions, defined as those occurring at speeds less than 25 mph (40 km/h), range approximately from 0.95 to 1.18 g/bhp-hr across all datasets (95% confidence interval). Regulatory limits for engine certification of 0.20 g/ bhp-hr and for in-use NTE of 0.30 g/bhp-hr are also included for reference. Figure 2 shows the average NOx emissions across all data sets for different speed regimes for the complete in-use tests and for the complete tests excluding idle

Average NOx emissions in different speed bins were further analyzed by vehicle types: line haul, delivery, and other vehicles. Line-haul trucks exhibited almost twice the average brake specific NOx emissions as delivery or other vehicle types during low speed (1–25 mph) urban driving conditions (Figure 2). Their average NOx emissions of 1.41 g/bhp-hr are more than 7 times the engine certification limit in urban driving and more than 3 times the limit in suburban driving. At highway speeds, NOx emissions seemed very similar across vehicle types. The total route average showed almost no differences among the vehicles studied.

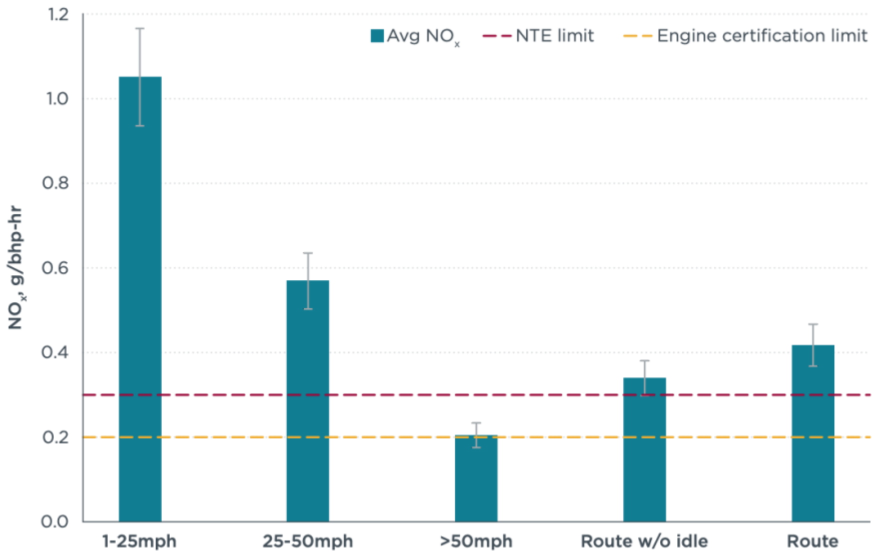

Figure 2 Average U.S. HDV NOx emissions differentiated by vehicle speed. Error bars represent the 95% confidence interval. Adapted from Badshah, Posada and Muncrief. (2019).

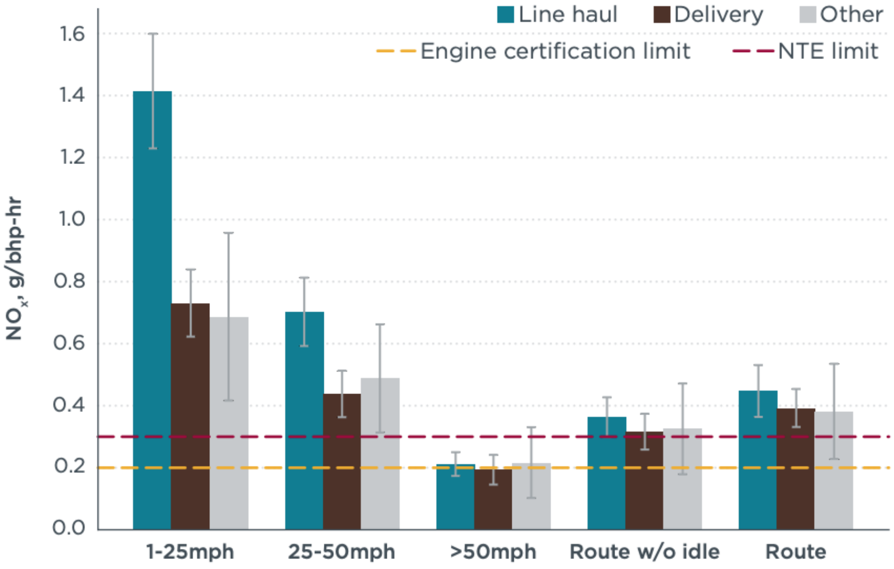

Figure 3 U.S. HDV NOx emissions by vehicle type in speed bins. Whiskers represent the 95% confidence interval of the mean. Adapted from Badshah, Posada and Muncrief. (2019)

In light of the limitations of the NTE methodology, ARB has announced its intention of abandoning the NTE protocol and moving towards a moving average window (MAW) data evaluation method.

The first MAW method deployed for HDV in-use evaluation was the European MAW approach used for their In-Service Conformity program (equivalent to HDIUT) under the Euro VI program. The Euro VI's MAW approach does not have the numerous exclusions of the NTE method, enabling evaluation of a much greater proportion of in-use data, especially at low-load and idling conditions.

To better understand the impact of the regulatory design (NTE and MAW) on the emission levels from HDVs in both regions, the ICCT compared real-world NOx emission from HDVs certified under U.S. EPA 2010 and Euro VI emission programs. NOx emission values from 11 HDVs designed to meet the EPA 2010 NOx standard were compared with five European trucks designed to meet the Euro VI NOx standard. Those vehicles had similar characteristics. NOx emission data come from test done with portable emission measurement systems (PEMS). Second-by-second data were analyzed for both groups by vehicle speed and power demands.

We found that European HDVs are better designed than U.S. trucks to control NOx emissions under low-speed, low-load, and idle conditions (Figure 4). The U.S. HDVs studied emit on average 1.4 times more NOx per unit work than the European vehicles. During urban driving conditions, work-specific NOx emissions of U.S. HDVs almost quadruple in magnitude compared to their total route emissions. European HDVs tend to exhibit a more consistent performance across the speed range, with urban driving emissions being twice as much as their total route emission values. This supported the hypothesis that a MAW approach was better suited for HDV in-use compliance evaluation.

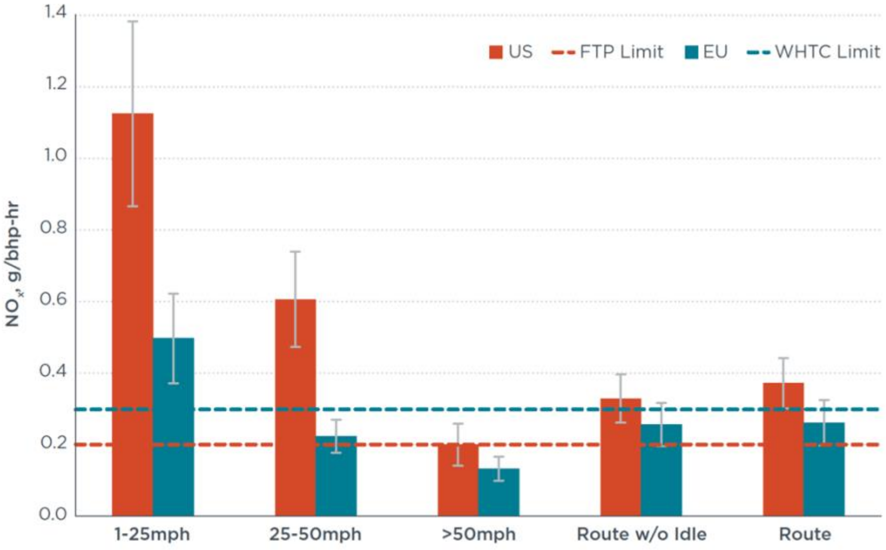

Figure 4 NOx emissions by speed bin for European and U.S. HDVs. Dotted lines represent engine emission NOx limits for U.S. and European HDVs. Error bars show confidence intervals at 95%.

The ICCT also studied the regulatory tools used in each program for analyzing PEMS data and determining in-use emissions compliance. PEMS data from five HDVs, two from Europe and three from the United States, were analyzed following the current regulatory in-use evaluation protocols as defined by the U.S. Not-to-Exceed (NTE) and the European moving average window (MAW) protocols.

Changes to the current regulations were studied in order to provide recommendations for the current regulatory updates for HDV emission control in the United States and Europe. The analysis of the in-use compliance tools, NTE and MAW, indicates that excluding data from the regulatory evaluation directly impacts NOx emission values.

Impact of changes to the NTE protocol

The NTE evaluation protocol excludes the vast majority of the data collected during a PEMS test. This section discusses the impacts of modifications to the NTE conditions, aimed at significantly increasing the share of data considered for evaluation and to induce NTE work-specific values that better evaluate all driving conditions, not only highway driving. The studied NTE alternatives cover multiple parameters changed concurrently and listed in Table 5. Alternative 1 in particular is based on a 2018 proposal by the Engine Manufacturers Association (EMA) on potential NTE-improvements.

Table 5. 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 (IMT)	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.

The reduction of data exclusion conditions generates a large positive impact on the amount of data and type of data that are considered for an NTE event and used for regulatory compliance evaluation. Figure 5 shows the impact of the changes on the NTE baseline conditions on data inclusion for each of the alternatives studied. Alternative 1, which yields an expansion of data validity by a small reduction on thresholds for power, torque, exhaust temperature and IMT conditions results in an increase from 11% to 26% of data included in NTE events. Alternatives 2 and 3 present further positive results: an increase in NTE event data validity of more than 4 times the baseline.

Figure 5 also shows that reducing the power and torque requirements to a minimum of 10% of the rated values increases the share of suburban and urban valid data. On average, the suburban data grows from 2% to 14% and the urban portion grows from near zero to 4%.

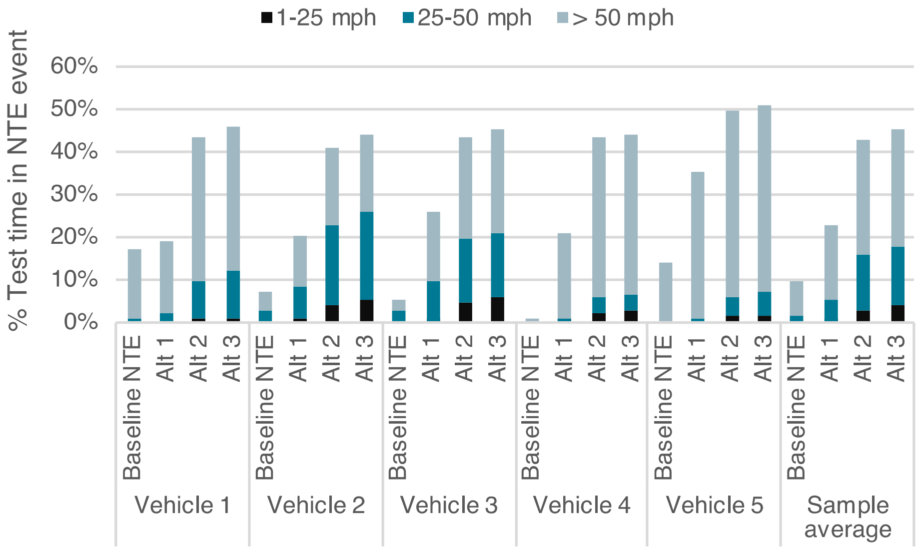

Figure 5. Impact of NTE protocol changes on NTE event data validity. NTE alternatives (Alt 1, Alt 2, Alt 3) are explained in Table 8.

Expanding data inclusion results in higher NTE NO_x values for most vehicles studied. Figure 6 shows the effect of the NTE parametric changes on NO_x emissions. Alternative 1 resulted in a small average increase, 11% in NTE NO_x values. However, alternative 1 induced reductions in NTE NO_x values for vehicles 2 and 4. This may be explained by the large incremental share of highway valid data which typically present lower NO_x emission values. Alternatives 2 and 3 consistently resulted in higher NTE NO_x values, reaching 0.17 g/bhp-hr, almost twice the NTE NO_x obtained under the baseline case (0.09 g/bhp-hr). This increase in NO_x values comes as a result of increasing the amount of data from low-load and low-power operation from urban and suburban driving conditions that is rejected under the existing NTE protocol, as illustrated in Figure 5.

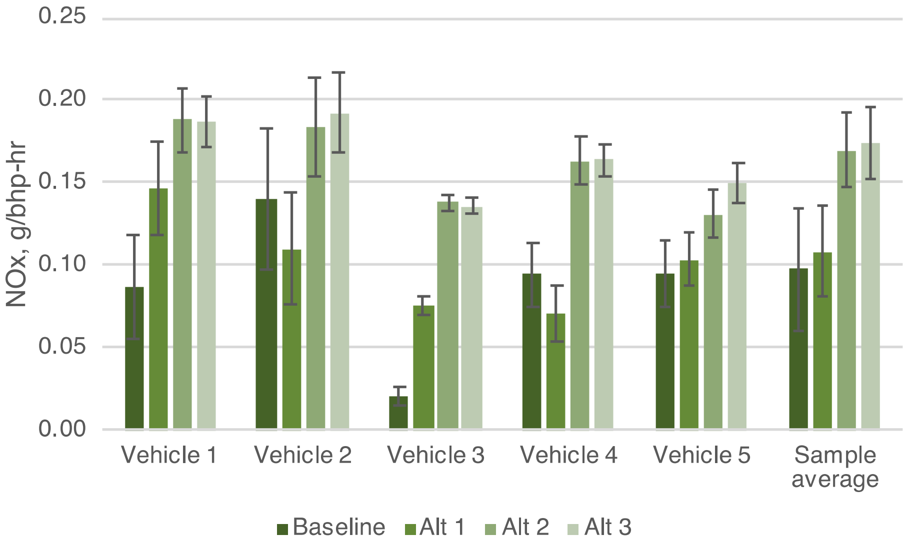

Figure 6. Impact of NTE protocol changes on average NTE event work-specific NO_x values. Whiskers show confidence intervals at 95%.

This result indicates that removing the NTE data evaluation conditions would necessarily converge toward the most basic of PEMS data evaluations: total route emissions (total NOx/total work). Figure 7 shows a per-vehicle comparison of NO_x emissions for urban, suburban, and highway driving conditions and the total route to the NO_x values from the current NTE protocol and Alternative 3. The time-weighted NO_x average values for the sample of vehicles tested is shown on the right. Alternative 3 NO_x values are very close to total route values. For the vehicles that exhibit the wider range of variability in emission values by driving condition (vehicles 2, 4, and 5) the most data-inclusive NTE alternative 3 is still unable to properly evaluate the vehicles performing in the critical conditions (urban) that emit the most NO_x per work unit.

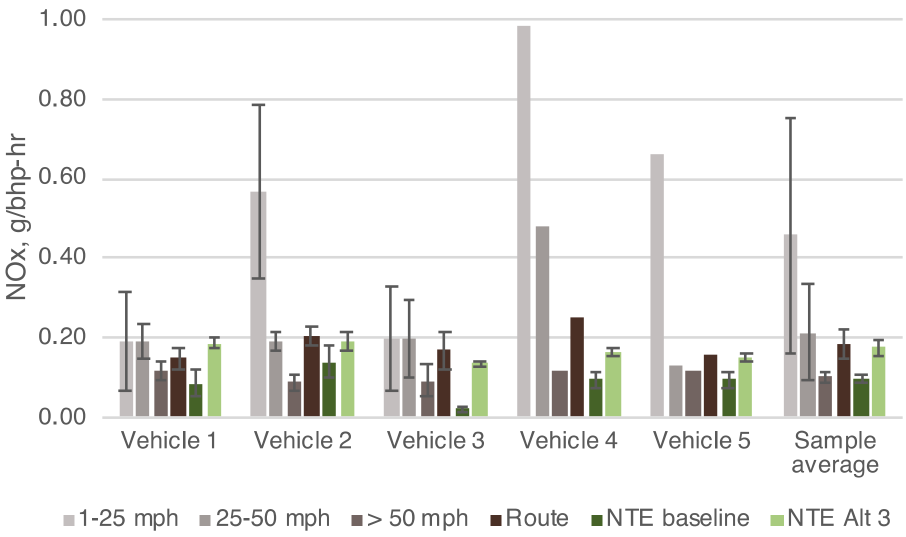

Figure 7. Average work-specific NO_x emissions under urban, suburban, and highway driving conditions compared to the average baseline NTE (as per CFR) and alternative 3 NTE (with fewer data exclusion conditions). Whiskers show confidence intervals at 95%.

Other in-use compliance evaluation options

MAW alternatives are much better suited for HDV in-use compliance evaluation. Figure 8 compares work-specific NOx values by vehicle speed condition and total route with NTE and MAW evaluation results. The NTE and MAW values are shown as currently specified in the regulations (baseline) and as improved options. The NTE alternative 3 (labeled as NTE Alt 3) removes all NTE zone conditions except power and torque, which are reduced to 10% of maximum power, and reduces the NTE event minimum duration to 10 seconds. The MAW alternative removes the minimum power requirement and increases the selection of the ranked average window NOx value from the 90th to the 95th percentile.

Figure 8 shows that NOx values from improved NTE tend to be below the values from the current and improved MAW protocol by a significant margin. On average, the NTE values from significantly revised exclusion criteria are still 45% lower than the MAW generated values. Only vehicle 1, with the best NOx emission performance overall, shows little variation in response to the PEMS evaluation redesign except for NTE values. For the rest of the vehicles, the adoption of an improved MAW protocol would result in evaluation values that closely align with the high values obtained under urban driving conditions.

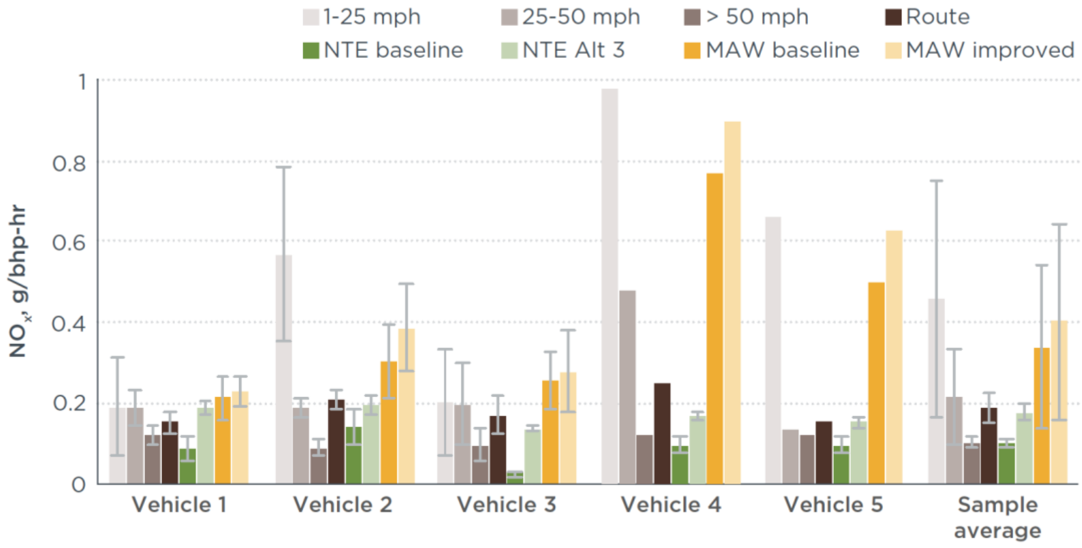

Figure 8 Work-specific NOx emissions under urban, suburban and highway driving conditions compared to NTE results (baseline and improved, in green) and MAW results (baseline and improved, in yellow).

The comparison between the regulatory protocols of U.S. and European HDVs and their impact on emissions allows us to drive the following conclusions:

- High urban NOx emission values found in U.S certified HDVs potentially can be attributed to the current NTE design. The U.S. NTE protocol evaluates in-use NOx data only under a narrow band of vehicle operating conditions, exclusively during highway driving. The rejection of data under all other conditions is caused primarily by engine power, torque, and exhaust temperature data validity requirements set by the NTE protocol.

- **Modifying the NTE will not improve the in-use compliance evaluation.** Reducing or removing the majority of the NTE data validity conditions would not be sufficient to incentivize significant urban NOx control. Any expansion of the current NTE zone conditions would result in an NTE evaluation value between what is obtained with the current NTE and a total route evaluation (total mass of NOx divided by total work).
- The tool that would replace the NTE would have to properly evaluate in-use emissions from HDVs that are designed to meet the idle, LLC, and FTP engine standard limits.
- The European MAW method for in-use compliance evaluation is better suited than the NTE for in-use compliance evaluation. The European MAW captures NOx emissions at the most challenging conditions, which is to say low-speed and low power demands that are characteristic of urban driving. Improvements could be made to the MAW protocol to further incentivize urban NOx reductions. These include expanding window validity to all power conditions and evaluating compliance at the 95th percentile. These changes would better evaluate future HDVs designed to meet currently proposed low-load cycle requirements.
- The 3-bin MAW approach introduced by the ARB Low NOx Omnibus document suggests that it better aligns with the design principles of the MAW approach. It would average and evaluate data by power conditions, and it will include most data collected, including cold starts.
- Thus, the ICCT recommends the adoption of the 3-Bin approach as the new in-use testing method. The 3-bin approach independently evaluates all, idle, low load conditions and mid- to high-load conditions, as a way to ensure that the emissions results achieved in the engine dynamometer are also reflected during in-use real world operations. No data should be excluded. The ICCT is preparing a technical analysis in support of this position.

4. Potential impact on GHG HDV Phase 2

One of the design principles of the ARB Low Nox Omnibus proposal is that it will not undermine the industry’s plans to meet the CO_2 and fuel consumption requirements of the Heavy-Duty Phase 2 program. We agree with ARB and show here that the compliance requirements to meet GHG engine standards are evaluated under vehicle speed conditions that are far from the envisioned low-load certification requirements of the proposed rule.

Future emission standards should incentivize the adoption of technologies that control NOx emissions under all driving conditions, with a focus on cold-start emissions and urban operation. The challenge in these operating conditions is to quickly warm-up the emissions control system and to keep it warm, even under low-load and low-speed operation.

The technological challenge in these operating conditions is to quickly warm-up the SCR system and to keep it above 200°C, even under low-load and low-speed operation. It has been argued that such thermal management strategies have a significant fuel consumption penalty, which would be in conflict with adopted GHG standards

To assess the validity of this claim, the ICCT used vehicle and engine simulation to model a worst-case scenario for the active thermal management of the SCR system, in which the SCR temperature is increased only through late- and post-combustion injection strategies in the low-load and low-speed areas of the engine map, without introducing additional engine technologies. The simulations show that, even in this worst-case thermal management strategy, the fuel consumption impact is limited. Achieving a 25°C increase in the average exhaust temperature the proposed Low Load Cycle—deemed sufficient to achieve a faster light-off of the SCR system—increases the fuel consumption is around 0.9%, over the combined cycles used in U.S. EPA's GHG Phase 2 standards.

There are several technologies are commercially available to simultaneously reduce NOx and CO_2 emissions, or to at least eliminate the small fuel consumption penalty from thermal management. Such technologies include cylinder deactivation, closed-coupled SCR systems, heated urea injectors, and mild hybridization. Therefore, we conclude that **tighter NOx emission limits do not jeopardize compliance with adopted U.S. HDV GHG Phase 2 standards**