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FUTURE HEAVY-DUTY EMISSION STANDARDS

AN OPPORTUNITY FOR INTERNATIONAL HARMONIZATION

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EXECUTIVE SUMMARY

The European Union and the United States have initiated regulatory processes to update heavy-duty vehicle emission standards.

The parallel development of such new standards in the European Union and the United States provides a good opportunity for harmonization. Given the significant overlap between international manufacturers selling heavy-duty vehicles (HDVs) in both regions, an alignment of regulations would enable synergies in technology development and reduce compliance cost. As most countries around the world follow the U.S. and EU requirements, harmonization of new HDV emission standards would have positive international repercussions.

In this report, the ICCT makes recommendations for the regulatory processes in the European Union and the United States, with an emphasis on harmonizing future HDV emission standards.

The recommendations are summarized in the table below.

Table 1. Summary of recommendations for future HDV emission standards

What to regulate	
NO_x	• NO_x limits should be tightened. Commercially available emission controls allow setting lower NO_x limits than those in place in the European Union and the United States. • Focus should be placed on cold-start emissions and low-load operation, tackling the measured gap between regulatory emission limits and real-world emission measurements. • Emission limits should drive the adoption of technologies that simultaneously reduce NO_x and CO_2. Tighter NO_x limits do not necessarily make it more difficult to comply with CO_2 standards.
PM/PN	• Introduce particle number (PN) limits where they do not exist. • Where a PN limit exists, lower the size cutoff for particle counting from 23 nm at least to 10 nm and include volatile and semi-volatile particles. • Include emissions that occur during the regeneration of the aftertreatment (e.g., diesel particulate filter or lean NO_x trap) in on-road ISC tests.
GHGs	• Introduce stringent certification limits for CH_4 and N_2O where they do not exist. • Monitor CH_4 and N_2O emissions during on-road tests.

How to regulate it	
In-use test	• Not-to-exceed (NTE) methodology should be abandoned in the United States, which should harmonize with the EU moving average window (MAW) methodology. • All valid windows in the MAW methodology should be used for compliance evaluation. • Remove the minimum power requirements for the validation of on-road test data. • Urban driving should be prescribed during on-road testing. • Emissions that occur during filter regeneration should be accounted for. • Cold-start should be properly captured in on-road tests. • In-use data should be made publicly available.
Engine certification	• Introduce a low-load cycle for engine certification in addition to the transient and steady-state cycles. The limit should be stringent enough to drive the adoption of technologies targeting low-load and low-speed operation. • Introduce strict idling standards to drive the adoption of technologies for the thermal management of the aftertreatment system and for preventing or reducing idling.

	How to guarantee it
Durability	• Extend the definition of useful life for durability demonstration. • Establish full useful life testing as the only option for durability demonstration.
Warranty and defects	• Set an emissions warranty program with minimum warranty periods aligned with the useful life definition. • Set an emissions defect tracking and reporting program.
On-board diagnostics and monitoring	• Harmonize the on-board diagnostics (OBD) requirements of future emission standards. • OBD systems should be compatible with inspection and maintenance programs. • Investigate the use of on-board particle sensors to detect diesel particulate filter (DPF) failure as part of OBD requirements. • Introduce on-board monitoring of pollutant emissions and fuel consumption.
Market surveillance	• Develop a methodology for fleet screening to identify noncompliant vehicle models. • Develop a remote sensing standard and establish a database of measurements. • Strengthen the anti-tampering provisions.

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POLICY BACKGROUND

Air pollution continues to be a major threat to public health. According to the World Health Organization (WHO),[1] exposure to air pollution can cause or aggravate heart and respiratory ailments, such as heart attacks and asthma, can affect the nervous and reproductive systems, and has been linked to cancer, stroke, diabetes, and Alzheimer's disease.

In 2017, 96% of the European Union's urban population was exposed to ground ozone levels in excess of air quality guidelines (AQGs) from WHO and 77% to levels of particulate matter with diameters of less than 2.5 micrometers ($PM_{2.5}$) above WHO's AQGs.[2] In the United States the picture is similar. An estimated 93% of the U.S. urban population lives in cities with ground-level ozone levels higher than WHO's AQGs, and 38% live in cities exceeding WHO's AQG for $PM_{2.5}$.[3] On-road diesel vehicle emissions were associated with 35,000 premature deaths from $PM_{2.5}$ and ozone in the European Union and 9,150 in the United States in 2015.[4]

Motor vehicle emissions of carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x), and particulates are not only concerning because of the health effects associated with direct exposure to them, but also, and more importantly, because of their role as precursors for the formation of $PM_{2.5}$ and ground-level ozone. Due to the gap between certified and real-world emissions, heavy-duty vehicles (HDVs) continue to be a major source of NO_x despite the regulatory efforts of the past decade. HDVs are responsible for more than 70% of NO_x emissions from on-road transport in California[5] and 40% in the European Union.[6]

Current HDV emission standards date to more than a decade ago in both regions. Euro VI standards[7] were adopted in 2009 and were implemented beginning in 2013. The U.S. standards, EPA 2010,[8] were adopted in 2001, started implementation in 2007, and were fully implemented in 2010. California adopted practically identical standards in October 2001. The details of each regulation are shown in Table 2.

Strict control of pollutant emissions from mobile sources is an indispensable tool in the battle against the public health impacts of air pollution. Lowering U.S. HDV NO_x standards by 90% could avoid 2,100 premature deaths from $PM_{2.5}$ and 700 deaths from ozone exposure in the U.S. annually in 2040. Similarly, tightening the EU NO_x limits for all

1 World Health Organization, *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease*, 2016, http://www.who.int/phe/publications/air-pollution-global-assessment/en/.

2 European Environment Agency, "Exceedance of Air Quality Standards in Urban Areas," July 3, 2019, https://www.eea.europa.eu/data-and-maps/indicators/exceedance-of-air-quality-limit-3/assessment-5.

3 U.S. EPA and Office of Air and Radiation, "Air Quality - Cities and Counties," Data and Tools, US EPA, May 7, 2019, https://www.epa.gov/air-trends/air-quality-cities-and-counties.

4 Susan C. Anenberg, Joshua Miller, Daven K Henze, Ray Minjares, and Pattanun Achakulwisut, "The Global Burden of Transportation Tailpipe Emissions on Air Pollution-Related Mortality in 2010 and 2015," *Environmental Research Letters* 14, no. 9 (September 2019): 094012, https://doi.org/10.1088/1748-9326/ab35fc.

5 California Air Resources Board, "California Air Resources Board Staff Current Assessment of the Technical Feasibility of Lower NOx Standards and Associated Test Procedures for 2022 and Subsequent Model Year Medium-Duty and Heavy-Duty Diesel Engines," Staff White Paper, April 18, 2019, https://www.arb.ca.gov/msprog/hdlownox/white_paper_04182019a.pdf.

6 European Commission, "Impact Assessment. Accompanying the Document Proposal for a Regulation of the European Parliament and of the Council Setting CO_2 Emission Performance Standards for New Heavy Duty Vehicles" (Brussels, May 17, 2018), http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD:2018:185:FIN.

7 European Commission, "Commission Regulation (EU) No 582/2011 of 25 May 2011 Implementing and Amending Regulation (EC) No 595/2009 of the European Parliament and of the Council with Respect to Emissions from Heavy Duty Vehicles (Euro VI) and Amending Annexes I and III to Directive 2007/46/EC of the European Parliament and of the Council Text with EEA Relevance. (Consolidated Version)," *Official Journal of the European Union*, no. L 167 (July 22, 2018): 1–168, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02011R0582-20180722.

8 U.S. EPA, "40 CFR Parts 69, 80, and 86. Control of Air Pollution From New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements; Final Rule," Federal Register / Vol. 66, No. 12, January 18, 2001, https://www.govinfo.gov/content/pkg/FR-2001-01-18/pdf/01-2.pdf.

diesel on-road vehicles could avoid 7,100 premature deaths from $PM_{2.5}$ and 800 deaths from ozone exposure annually in 2040.[9]

The preparatory work for formulating a new round of HDV emission standards in the European Union is underway. The post-Euro VI process informally started in 2018 with two separate stakeholder meetings. In 2019, the European Commission contracted a consortium to explore the different regulatory avenues and created the Advisory Group for Vehicle Emission Standards. A regulatory proposal is expected in 2021.

In the United States, California and the federal government have initiated rulemaking. Since the 2013 introduction of its voluntary low-NO_x standard, the California Air Resources Board (CARB) has been engaged in assessing the technical feasibility of reducing NO_x certification limits. In 2017, CARB approved the establishment of new HDV emission standards and in-use emission requirements. This enabled CARB staff to move forward to the proposal phase and to conduct the technical assessment required for it. CARB's proposal is tentatively scheduled for board consideration in the first quarter of 2020. At the federal level, the U.S. Environmental Protection Agency (EPA) announced in late 2018 the Cleaner Truck Initiative, a future rulemaking to update HDV emission standards. While the EPA's timeline has not yet been finalized, a regulatory proposal can be expected by the end of 2020.

Table 2. Comparison of Euro VI and EPA 2010 emission standards

	Euro VI	EPA 2010
Engine duty cycles	**World Harmonized Stationary Cycle (WHSC):** Steady-state, hot-only. **World Harmonized Transient Cycle (WHTC):** Transient, cold- and hot-start.	**Supplemental Emissions Test (SET):** Steady-state, hot-start only. **Heavy-Duty FTP Transient Cycle (FTP):** Transient, cold- and hot-start.
Idling in cycle	17% of total WHTC time	41% of total FTP time
Mean load of duty cycles	WHSC: 25% (normalized to full load) WHTC: 24% (normalized to full load)	SET: 55% (normalized to full load) FTP: 24% (normalized to full load)
Cold start test	Yes. Weighting is 14% (WHTC only)	Yes. Weighting is 14% (FTP only)
NO_x emissions limit	WHSC: 0.4 g/kWh (~0.29 g/bhp-hr) WHTC: 0.46 g/kWh (~0.34 g/bhp-hr)	SET: 0.2 g/bhp-hr (~0.27 g/kWh) FTP: 0.2 g/bhp-hr (~0.27 g/kWh)
PM emissions limit	WHSC 10 mg/kWh (~7.5 mg/bhp-hr) WHTC: 10 mg/kWh (~7.5 mg/bhp-hr)	SET: 10 mg/bhp-hr (~13 mg/kWh) FTP: 10 mg/bhp-hr (~13 mg/kWh)
PN emissions limit	WHSC: 8.0×10^{11} g/kWh WHTC: 6.0×10^{11} g/kWh	Does not exist
Off-cycle test	Yes. NTE engine dyno test. Limit: 0.6 g/kWh (~0.45 g/bhp-hr)	Yes. NTE engine dyno test. Limit: 0.3 g/bhp-hr (~0.4 g/kWh)
In-use testing program	In-service conformity (ISC). 3 engines per engine family are tested in first 18 months and then every other year.	Manufacturer-Run HD In-Use Testing program (HDIUT). 5 vehicles per engine family per year. Maximum 25% of engine families. EPA notifies manufacturers in advance.
On-road test methodology	PEMS testing with moving average window (MAW) evaluation	PEMS testing with not-to-exceed (NTE) evaluation
Durability requirements	700,000 km (~435,000 miles) for N3 trucks	435,000 miles (~700,000 km) for class 8 trucks
Emissions warranty	Does not exist	5 years or 100,000 miles (~160,000 km)
Defect report program	Does not exist	Reporting required if an emissions defect exists on 25 or more engines
Implementation	2013 new types and 2014 all new vehicles Implementation steps stretch to 2022.	The phase-in was done on a percent-of-sales basis: 50% from 2007 to 2009 and 100% in 2010.

9 Susan C. Anenberg, Joshua Miller, Ray Minjares, Li Du, Daven K. Henze, Forrest Lacey, Christopher S. Malley, et al., "Impacts and Mitigation of Excess Diesel-Related NO_x Emissions in 11 Major Vehicle Markets," *Nature* 545, no. 7655 (May 25, 2017): 467–71, https://doi.org/10.1038/nature22086.

Below are recommendations to consider in the European Union and the United States, with an emphasis on harmonizing future HDV emission standards. The report is divided into three sections. The first section provides recommendations on the pollutants to be regulated and the respective limits. Section two presents proposals for improving the way those emissions are measured and evaluated during certification and in-use testing. The third section makes suggestions on how to ensure low real-world emissions over vehicles' useful life.

WHAT TO REGULATE? POLLUTANTS AND LIMITS

NITROGEN OXIDES

Current emission standards are based on technology feasibility assessments dating back more than a decade. Recent advances in engine and emissions control technologies enable further reductions in NO_x emissions from the levels mandated by present-day regulations.

As shown in Figure 1, Euro VI standards set a NO_x limit 0.4 grams per kilowatt-hour (g/kWh), equivalent to around 0.29 grams per brake horsepower-hour (g/bhp-hr), over the WHSC steady-state cycle, and of 0.46 g/kWh (~0.34 g/bhp-hr) over the WHTC transient cycle. The NO_x limit set by EPA 2010 is 0.2 g/bhp-hr (~0.27 g/kWh) for both the transient FTP and the steady-state SET cycles. While the emission limits are not directly comparable because of differences in certification test cycles, the technology pathways followed to meet the standards are very similar: Emissions control systems rely on advanced fuel injection and air induction management strategies, exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) for NO_x control, combined with a diesel particulate filter (DPF) for meeting the particulate emission limits. Still, manufacturers presumably use different calibration strategies reflecting the requirements imposed by on-road in-use testing and by region-specific greenhouse gas (GHG) requirements.

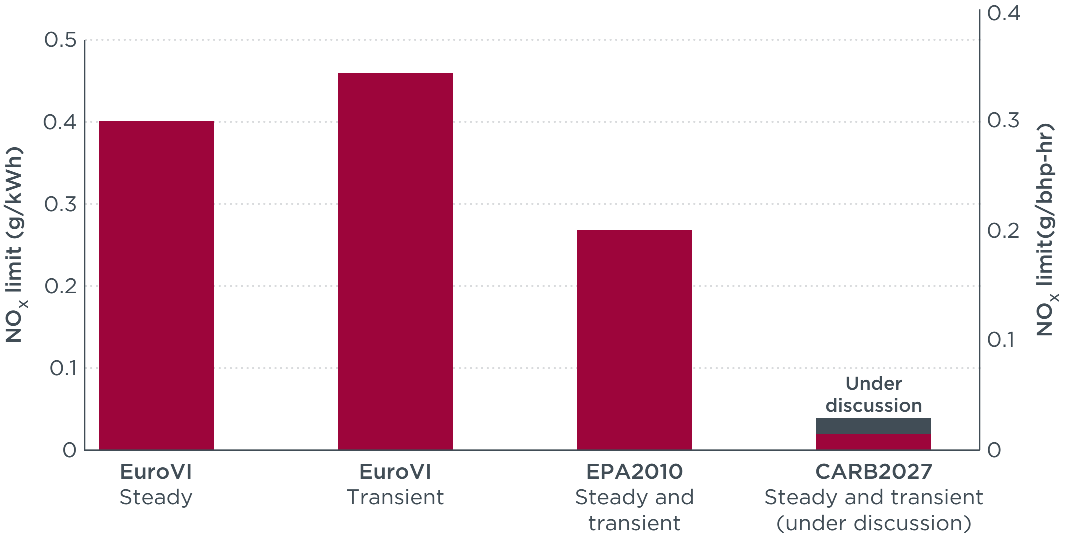

Figure 1. NO_x limits for HDV engine certification in the European Union and the United States. Range under discussion for low-NO_x limits in California is also shown.

While the European Commission, EPA, and CARB have all announced their intentions to update the HDV emission standards, only California has made public the planned regulatory changes and feasibility assessments.[10]

10 California Air Resources Board, "CARB Staff Current Assessment of the Technical Feasibility of Lower NO_x Standards and Associated Test Procedures for 2022 and Subsequent Model Year MD- and HDDEs."

CARB currently envisions a two-step approach. In the first phase, applicable from 2024 to 2026, the FTP certification NO_x limit would be reduced; a low-load cycle (LLC) would be introduced; and idling limits would be made mandatory. The FTP certification limit would drop from 0.2 g/bhp-hr (~0.27 g/kWh) to 0.05 g/bhp-hr (~0.07 g/kWh). The LLC would cover low-load NO_x emissions operation, such as idling or urban driving. The limits over the LLC would be 0.2 g/bhp-hr (~0.27 g/kWh), four times the proposed FTP limit. The idling NO_x emissions limit, currently a voluntary program, would set a mandatory 10 g/hr limit. These requirements are expected to be met without the introduction of any major engine hardware changes, requiring only system calibration and aftertreatment system improvements.[11]

In the second phase, from 2027 onward, CARB plans to introduce more-stringent NO_x limits. CARB's goal is to reduce NO_x emissions from HDVs by 90%,[12] which if met would translate to a certification value between 0.015 and 0.030 g/bhp-hr (~0.02 to 0.04 g/kWh). Complying with these limits is expected to require the introduction of engine hardware upgrades and significant changes to the aftertreatment configuration while still relying on SCR systems as the main emissions control technology.

The technology required to achieve such low levels of NO_x emissions builds upon the architecture of current emissions control systems. Under the right temperature conditions, a well-designed SCR system can convert NO_x with more than 99% efficiency. Low exhaust temperatures, however, like those found during cold-start and extended low-load and idling operation, can significantly reduce the SCR conversion efficiency. As a result, emission rates during urban driving are much higher than in other vehicle operation modes. Thus, technology interventions are necessary to reduce emissions under these conditions. Table 3 summarizes the technologies that would enable meeting future low NO_x limits.

Since HDVs must also make mandatory CO_2 reductions, the impact of the different technologies on CO_2 emissions is qualitatively presented in Table 3. The table also categorizes the different technologies according to their main function. Reducing tailpipe NO_x can be achieved by lowering NO_x concentration at the inlet of the SCR, warming up the SCR as quickly as possible, maintaining the SCR temperature, or increasing SCR conversion efficiency.

11 California Air Resources Board, "Heavy-Duty Low NO_x Program. Proposed Heavy-Duty Engine Standards," in *Public Workshop to Discuss Potential Changes to the Heavy-Duty Engine and Vehicle Emission Standards, Test Procedures, Warranty, and Other Related Heavy-Duty Programs.*, 2019, https://ww2.arb.ca.gov/our-work/programs/heavy-duty-low-nox/heavy-duty-low-nox-meetings-workshops.

12 California Air Resources Board, "Mobile Source Strategy," May 2016, https://ww3.arb.ca.gov/planning/sip/2016sip/2016mobsrc.pdf.

Table 3. Technologies available to meet future low-load cycle and idling NO_x standards

		Short description	Impact on CO_2 / GHG	Low NO_x into SCR	Fast warm-up	Stay warm	High conv. efficiency
ENGINE TECHNOLOGIES	**Air gap insulated manifold**	Insulates the exhaust manifold and reduces heat losses before the SCR inlet during cold-start	→		X		
	Cylinder deactivation	Deactivating cylinders at low loads increases exhaust temperatures of the firing cylinders	↓		X	X	
	Dual urea dosing	Improves NO_x conversion in high load operation and enables the use of closed-coupled SCRs	→				X
	Ducted fuel injection	Eliminates trade-off between soot and NO_x, allowing higher EGR rates and less-frequent DPF regeneration	→	X			
	EGR (backpressure)	Exhaust gases recirculation (EGR) reduces NO_x formation during combustion by diluting the intake air	↑	X			
	EGR pumps	Allows accurate control of EGR rates and eliminates the increase in backpressure to drive the EGR flow	↓	X			
	Coolers bypasses	Bypassing hardware with high thermal inertia reduces heat losses upstream of the SCR during cold-start	→		X		
	Electric boosting	Electric motors built into the turbo improve transient response reducing NO_x peaks. 48V required.	↓		X		
	Fast idle	Accelerates warm-up by increasing the flow of hot exhaust gases in cold-start	↑		X		
	Mild-hybrid (48 Volts)	Increases exhaust temperatures (higher engine load), improves transient NO_x, and enables other measures	↓	X	X	X	
	Post / late injection	Increases the exhaust temperature and reduces engine-out NO_x at the cost of higher fuel consumption	↑	X	X	X	
	Stop/start	Prevents cooling of the SCR during idle by stopping the flow of cool exhaust gases. 48V required.	↓			X	
	Variable valve actuation	Enables temperature management by early exhaust valve opening, intake valve closing modulation	↓		X	X	
AFTERTREATMENT TECHNOLOGIES	**Burner**	Burns additional fuel in the exhaust and increases exhaust temperature at the inlet of the SCR	↑		X	X	
	Closed-coupled SCR	By positioning an SCR unit close to the engine, significantly faster warm-up is possible	→		X		
	Electric catalyst heating	Accelerates warm-up and ensures operating temperature independent of engine load	↑		X	X	
	Heated urea dosing	Enables urea dosing at lower temperatures without formation of deposits in the SCR inlet	↑		X		X
	Improved SCR chemistries	Improved formulations increase the NO_x performance at low temperatures and reduce N_2O formation	↓		X		X
	Larger SCR volume	Larger SCR volumes can increase conversion efficiency but require more thermal management	→				X
	Passive NO_x adsorbers	Trap NO_x during cold-start and release it once the SCR is warm enough. Require periodic regeneration.	↑	X			
	SCR on DPF (SCRF)	Integrating the SCR into the DPF substrate enables faster warm-up as it puts the SCRF closer to the engine	→		X		
	Seventh injector	Injects fuel directly in the exhaust which is oxidized by the DOC increasing the exhaust temperature	↑		X	X	

↓: Better CO_2/GHG performance. →: No impact on CO_2/GHG performance. ↑: Worse CO_2/GHG performance.

The Southwest Research Institute (SwRI), an independent, nonprofit research organization based in San Antonio, Texas, investigated[13] the use of passive NO_x adsorbers to reduce cold-start emissions, fuel burners to achieve a rapid warm-up of the SCR system, and SCR coating of DPF to improve thermal behavior. On a system aged to full useful life, researchers achieved 0.034 g/bhp-hr (~0.046 g/kWh) of NO_x emissions over the composite FTP cycle[14] and 0.036 g/bhp-hr (~0.048 g/kWh) over the composite WHTC.[15] The findings show that even on equipment near its end of life, the technologies can significantly lower NO_x emissions to the levels required to meet the proposed new CARB standards for 2024.

In a subsequent phase of the study currently underway, SwRI is considering several aftertreatment system configurations. The common denominator among them is the use of a closed-coupled, low-temperature formulation SCR catalyst in addition to the larger SCR in the traditional aftertreatment module. Furthermore, the demonstrator engine features cylinder deactivation and EGR bypass for rapid warm-up and strategies for maintaining the temperature of the emissions control system. Recent results by SwRI put the NO_x emissions levels achievable by this configuration at 0.018 g/bhp-hr (~0.024 g/kWh) over the composite FTP cycle.[16] The findings show that the technologies can reduce NO_x emissions to the levels proposed by CARB for 2027. However, the impact of aging has not yet been assessed on this configuration.

The Manufacturers of Emission Controls Association (MECA) tested tailpipe NO_x emissions over the composite FTP cycle of current emissions control systems and modeled the impact of additional technologies to further reduce NO_x emissions.[17] MECA's engine testing demonstrated that commercially available SCR formulations in a traditional aftertreatment system can yield tailpipe NO_x emissions over the hot-start FTP of close to 0.02 g/bhp-hr (~0.03 g/kWh). MECA's modeling work included the effect of in-cylinder thermal management, an advanced cold-start calibration, and advanced ammonia slip catalyst. The modeling results suggest that currently available emissions control systems with the traditional DOC-DPF-SCR architecture with a single urea injector can achieve 0.02 g/bhp-hr (~0.03 g/kWh) over the composite FTP. This would allow a sufficient compliance margin to meet CARB's proposed NO_x limits for 2024 (0.05 g/bhp-hr / ~0.07 g/kWh) over the composite FTP.

13 Christopher Sharp, Cynthia C. Webb, Dr. Cary Henry, Gary Neely, Sankar Rengarajan, Jayant Sarlashkar, Bryan Zavala Bryan Zavala et al., "Achieving Ultra Low NO_x Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine and an Advanced Technology Emissions System," in *SAE WCX 2017*, 2017, https://ww3.arb.ca.gov/research/veh-emissions/low-nox/sae_congress-2017-01-0954-956-958_presentation_sharp.pdf.

14 The cycles are run as both cold- and hot-start tests. The composite results are obtained by using a weighing factor of 1/7 and 6/7 for the cold- and hot-start results, respectively.

15 Ibid.

16 Gary Neely, Christopher Sharp, Matthew S. Pieczko, and James E. McCarthy, "Simultaneous NO_x and CO_2 Reduction for Meeting Future CARB Standards Using a Heavy Duty Diesel CDA-NVH Strategy" (SAE COMVEC, Indianapolis, IN, 2019).

17 MECA, "Technology Feasibility For Model Year 2024 Heavy-Duty Diesel Vehicles In Meeting Lower NO_x Standards" (Manufacturers of Emission Controls Association, June 2019), http://www.meca.org/resources/MECA_MY_2024_HD_Low_NOx_Report_061019.pdf.

Other research organizations such as TNO;[18] engineering service providers such as AVL,[19] FEV,[20] and IAV;[21] and emissions control manufacturers such as Corning,[22] BASF,[23] Johnson Matthey,[24] Umicore,[25] and Tenneco[26] have also identified several possible aftertreatment architectures to meet future low NO_x emission standards.

Recommendations

Commercially available emission controls allow setting lower NO_x limits than those in place in the European Union and the United States. Emission limits should force the adoption of technologies that control NO_x emissions under all driving conditions with a focus on cold-start emissions and low-load operation. Since technologies that simultaneously reduce NO_x and CO_2 are commercially available, tighter limits do not jeopardize compliance with CO_2 standards. We offer the following recommendations:

» **Tighten NO_x limits:** Future NO_x limits should force the adoption of technologies currently available and accelerate the commercialization of those under development. Emission levels of no more than 0.036 g/bhp-hr (~0.048 g/kWh) over the composite WHTC and FTP cycles have already been demonstrated in the United States using off-the-shelf technologies. The impact of additional engine technologies and aftertreatment configurations is currently being studied in detail. Preliminary results indicate that NO_x emission levels below 0.02 g/bhp-hr (~0.03 g/kWh) over the composite FTP can be achieved.

» **Focus should be placed on cold-start emissions and low-load operation:** Future NO_x standards should tackle the measured gap between regulatory emission limits and real-world emission measurements. Those technologies would address the most challenging operational conditions for real-world NO_x control: cold-start emissions, low-load operation, and improving the thermal management of the aftertreatment system

» **Emission limits should drive the adoption of technologies that simultaneously reduce NO_x and CO_2:** Opposition to the introduction of more-stringent NO_x limits is often presented in the form of a false dichotomy: Lower NO_x means higher CO_2. The discussion above shows that many technologies exist that can simultaneously reduce NO_x and CO_2 emissions, and many more can reduce NO_x without increasing CO_2. Moreover, the applications of rapid warm-up and stay-warm strategies are limited to cold-start and low-load operation. Under highway conditions—like those used for CO_2 certification of most HDVs in both markets—exhaust temperatures are higher, and no additional technologies are needed to achieve low NO_x emissions. Therefore, future low NO_x limits will have little negative impact on the ability of

18 Xander Seykens, Frank Kupper, Paul Mentink, and Sudarshan Ramesh, "Towards Ultra-Low NO_x Emissions within GHG Phase 2 Constraints: Main Challenges and Technology Directions," in *SAE Technical Paper*, 2018, 2018-01-0331, https://doi.org/10.4271/2018-01-0331.

19 Mario de Monte, "SCR Control Strategies With Multiple Reduction Devices For Lowest NO_x Emissions," in *SAE 2018 Heavy-Duty Diesel Emissions Control Symposium*, 2018.

20 Mufaddel Dahodwala, Satyum Joshi, Erik W. Koehler, Michael Franke, and Dean Tomazic, "Strategies for Meeting Phase 2 GHG and Ultra-Low NO_x Emission Standards for Heavy-Duty Diesel Engines," *SAE International Journal of Engines* 11, no. 6 (April 3, 2018): 1109–22, https://doi.org/10.4271/2018-01-1429.

21 Vadim Strots and Reza Rezaei, "Technology Approaches for Meeting Future Emission Requirements for Commercial Vehicles," in *SAE 2018 Heavy-Duty Diesel Emissions Control Symposium*, 2018.

22 Timothy Johnson, "HD Regulations, Engine, and Exhaust After-Treatment Technology Trends," in *SAE 2018 Heavy-Duty Diesel Emissions Control Symposium*, 2018.

23 Ansgar Wille and Martin Kalwei, "Meeting Future Heavy Duty On-Road Emission Legislations – Catalyst Component And System Development," in *SAE 2018 Heavy-Duty Diesel Emissions Control Symposium*, 2018.

24 Andrew Newman, "High Performance Heavy Duty Catalysts For Global Challenges Beyond 2020," in *SAE 2018 Heavy-Duty Diesel Emissions Control Symposium*, 2018.

25 Andreas Geisselmann and Andrea De Toni, "Improvements in Low Temperature $DeNO_x$ of HDD Systems," in *SAE 2018 Heavy-Duty Diesel Emissions Control Symposium*, 2018.

26 Thomas Miller Harris, Kristoffer Mc Pherson, Reza Rezaei, David Kovacs, Hendrik Rauch, and Yinyan Huang, "Modeling of Close-Coupled SCR Concepts to Meet Future Cold Start Requirements for Heavy-Duty Engines," in *SAE Technical Paper*, 2019, https://doi.org/10.4271/2019-01-0984.

manufacturers to meet mandatory CO_2 reductions. Furthermore, future low NO_x standards can incentivize the adoption of technologies that simultaneously reduce NO_x and CO_2 emissions, creating synergies between both regulations.

ULTRAFINE PARTICLES

Exposure to primary ultrafine particles are of particular concern because they are most likely to be deposited within the human body. They also have a large surface-to-volume ratio, which appears to be correlated with the biological activity of particles within the body.[27] Particles smaller than 100 nm—such as those produced during combustion—are much more likely to be captured within the human body,[28] where they can cause damage. Particle deposition efficiency rapidly increases as the particles become smaller and smaller, as shown in Figure 2.[29]

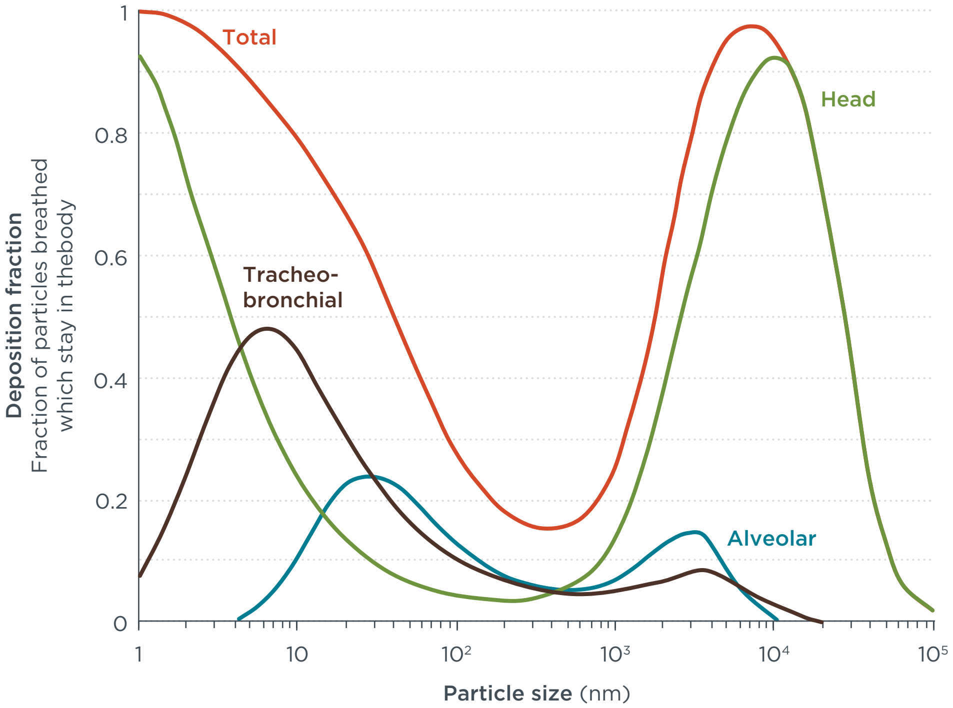

Figure 2. Mathematical model of particle deposition via nasal breathing in the whole lung (total), nose, pharynx and larynx (head), tracheobronchial airways, and alveolar region in healthy adults. Note: Adapted from U.S. EPA (2014).

The particulate emission limits of current standards in the European Union and the United States are intended to force the use of the best available technology for reducing particulate mass (PM) and particulate number (PN) emissions from diesel engines: Wall-flow particulate filters.

Euro VI standards set a PM limit of 10 mg/kWh (~7.5 mg/bhp-hr) applicable to both the stationary and transient cycles. This represents a 50% reduction relative to the previous standard, Euro V, which did not effectively force DPFs into the HDV market. To ensure

27 Richard W. Baldauf, Robert B. Devlin, Peter Gehr, Robert Giannelli, Beth Hassett-Sipple Heejung Jung,Giorgio Martini et al., "Ultrafine Particle Metrics and Research Considerations: Review of the 2015 UFP Workshop," *International Journal of Environmental Research and Public Health* 13, no. 11 (November 2016), https://doi.org/10.3390/ijerph13111054.

28 Coarse particles, generally larger than 2.5 micrometers (µm), readily deposit in the head's nasal, pharyngeal, and laryngeal passages through impaction. Fine particles, 100 nm to 2.5 µm, are primarily deposited by sedimentation in bronchioles and alveoli. Ultrafine particles, smaller than 100 nm, are deposited by sedimentation and diffusion in the head and lung airways.

29 U.S. EPA, "Particle Pollution Exposure," Collections and Lists, September 15, 2014, https://www.epa.gov/pmcourse/particle-pollution-exposure.

that DPFs are used in emission control systems, Euro VI standards also include a particle number (PN) limit of 8.0×10^{11} #/kWh over the WHSC cycle and of 6.0×10^{11} #/kWh over the WHTC. EPA 2010 standards set a PM limit of 10 mg/bhp-hr (~13 mg/kWh) over both the stationary and transient cycles, but do not set any PN requirements.

In its latest assessment, CARB considers lowering the PM standard to 5 mg/bhp-hr (~6.5 mg/kWh) to maintain the reductions achieved in PM emissions and to prevent DPFs with higher porosity and lower backpressure but with lower filtration efficiency from becoming mainstream.[30]

While current standards already force the application of DPFs, the following paragraphs present support for the introduction of stringent PN standards as part of any future HD emission standards.

During the development of the Particle Measurement Programme of the United Nations Economic Commission for Europe, the European Commission's Joint Research Centre carried out assessments to understand the correlation between the PM and PN emissions of HDV engines. The results are shown in Figure 3.

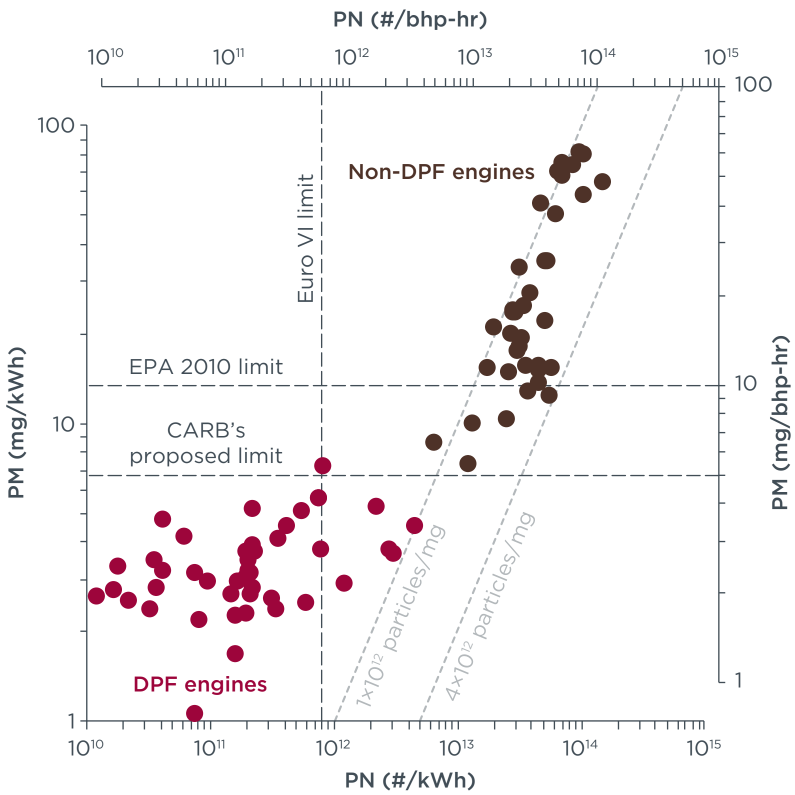

Figure 3. Comparison of solid PN (larger than 23 nm) and PM emissions for different vehicle technologies. The dotted lines show the legislation limits for the European Union and the United States. Dashed lines represent the approximate correlation between PN and PM for non-DPF engines. Adapted from Giechaskiel et al. (2010) and Giechaskiel et al. (2012).

30 California Air Resources Board, "CARB Staff Current Assessment of the Technical Feasibility of Lower NO_x Standards and Associated Test Procedures for 2022 and Subsequent Model Year MD- and HDDEs."

As the figure shows, there is a relatively strong correlation between PM and PN emissions of non-DPF engines.[31] However, the correlation is lost for engines equipped with DPFs. Compliance with the Euro VI PN limit would ensure compliance with the EPA 2010 PM limit, but the converse does not hold. While EPA 2010 PM standards allow the use of DPFs with higher porosities, the PN limit of Euro VI standards requires high filtration efficiencies across a wider range of particle sizes and does not provide such flexibility.

In-use verification of emissions performance is a fundamental element of standards. In the United States, the heavy-duty in-use test program sets limits for PM emissions over the not-to-exceed (NTE) protocol (see section *On-road test protocol and data evaluation*). In the European Union, with the future implementation of Euro VI-Step E in 2021, PN emissions will be subject to on-road in-service conformity (ISC) testing.

Portable emissions measurement system (PEMS) for PM and PN on-road tests have already been developed and validated for regulatory purposes.[32] Still, on-road measurement of PN emissions is orders of magnitude more sensitive than PM and enables a better assessment of absolute DPF filtration efficiency. Consequently, DPF durability issues can be identified more accurately.

Research carried out in the United States[33] and the European Union[34] shows that the solid PN emissions of unfiltered natural gas engines are five to 50 times higher than those of diesel engines equipped with DPFs, depending on the duty cycle. PN limits are a useful tool to drive exhaust filters on gasoline and natural gas engines that emit copious amounts of ultrafine particles but have no trouble complying with PM limits because of the small size and mass of those particles. Euro VI-Step E, with its PN ISC requirements, is expected to force exhaust filters on natural gas HDV engines.

Recommendations

PN is a better suited metric for regulating particulate emissions. Current PN regulations leave a significant fraction of PN emissions unregulated and have significant room for improvement. EU standards exclude all volatile and semi-volatile particles, solid particles smaller than 23 nm, and particles emitted during the regeneration of particulate filters. These unregulated particles can have detrimental health effects due to the biological interactions of primary[35] and secondary particles when inhaled. We offer the following recommendations:

» **Introduce PN limits where they do not exist:** A stringent PN standard should form part of future HDV emission standards in the United States. Particle filters

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31 Barouch Giechaskiel, Martin Cresnoverh, Herwig Jörgl, and Alexander Bergmann, "Measurement of Automotive Nonvolatile Particle Number Emissions within the European Legislative Framework: A Review," *Aerosol Science and Technology* 46, no. 7 (July 1, 2012): 719–49, https://doi.org/10.1080/02786826.2012.661103; Barouch Giechaskiel et al., "Calibration and Accuracy of a Particle Number Measurement System," *Measurement Science and Technology* 21, no. 4 (April 1, 2010): 045102, https://doi.org/10.1088/0957-0233/21/4/045102.

32 Barouch Giechaskiel, Tero Lahde, Ricardo Suarez-Bertoa, Michael Clairotte, Theodoros Grigoratos, Alessandro Zardini, Adolfo Perujo, and Giorgio Martini, "Particle Number Measurements in the European Legislation and Future JRC Activities," *Combustion Engines*, December 2018, https://doi.org/10.19206/CE-2018-301.

33 Tianyang Wang, David C. Quiros, Arvind Thiruvengadam, Saroj Pradhan, Shaohua Hu, Tao Huai, Eon S. Lee, and Yifang Zhu, "Total Particle Number Emissions from Modern Diesel, Natural Gas, and Hybrid Heavy-Duty Vehicles During On-Road Operation," *Environmental Science & Technology* 51, no. 12 (June 20, 2017): 6990–98, http://doi.org/10.1021/acs.est.6b06464.
Imad A. Khalek, Huzeifa Badshah, Vinay Premnath, and Rasto Brezny, "Solid Particle Number and Ash Emissions from Heavy-Duty Natural Gas and Diesel w/SCRF Engines," in *SAE Technical Paper*, 2018, https://doi.org/10.4271/2018-01-0362.

34 Barouch Giechaskiel, "Solid Particle Number Emission Factors of Euro VI Heavy-Duty Vehicles on the Road and in the Laboratory," *International Journal of Environmental Research and Public Health* 15, no. 2 (February 9, 2018): 304, https://doi.org/10.3390/ijerph15020304.

35 Primary particles are those emitted directly by vehicles. Secondary particles are those formed from primary particles and other gaseous pollutants through complex atmospheric processes.

that reduce PN emissions in a wide size spectrum are available; there is no technology barrier to meeting PN emission limits with the DPF technology currently. Measurement protocols for PN already exist and have been validated. A PN requirement provides several advantages over PM standards alone: (1) They safeguard against increases in particle emissions from higher porosity filters, (2) allow the early identification in on-road tests of filter durability issues, and (3) drive the adoption of filters on engines with low PM emissions but whose emissions are still hazardous because of the small size of the particles.

» **Lower the size cutoff for particle counting from 23 nm at least to 10 nm and include volatile and semi-volatile particles, if a PN limit already exists:** Lowering the size threshold from 23 nm to 10 nm for solid particles is possible without large investment costs or significant modifications to existing measurement systems. As particle counting techniques continue to evolve, measuring in the sub-10 nm range is likely to be feasible. On the other hand, the current particle counting methodologies do not allow a robust and repeatable measurement of nonsolid particles. Future standards can enable the inclusion of volatile and semi-volatile particles by developing the right regulatory framework and forcing the development of a suitable methodology.

» **Include emissions that occur during the regeneration of the aftertreatment in on-road ISC tests:** Emissions that occur during periodic aftertreatment regeneration such as in DPFs or lean NO_x traps are currently excluded from on-road in-service conformity tests in the European Union. U.S. provisions set requirements that allow the inclusion of regeneration events during in-use testing. In practice, however, those requirements are rarely met (see the *On-road test protocol and data evaluation* section below). Regeneration events can be a significant source of particle and other pollutant emissions. Such events and their frequency of occurrence should be properly captured during on-road in-use tests.

GREENHOUSE GASES

Methane (CH_4) and nitrous oxide (N_2O) are powerful greenhouse gases (GHGs) that can be found in significant quantities in the exhaust of motor vehicles. The 20-year global warming potentials (GWPs) of these two species, reflecting how much more heat is trapped by them compared to carbon dioxide (CO_2) in a 20-year time horizon, are 86 for CH_4 and 268 for N_2O. Because of the relatively short atmospheric lifetime of CH_4 (~12 years) but the long atmospheric lifetime of N_2O (~120 years), the 100-year GWP of CH_4 decreases to 34, but the GWP for N_2O is higher at 298.

CH_4 emissions are a result of incomplete combustion in HDV natural gas engines; diesel engines produce negligible CH_4 emissions. Because CH_4 is a relatively stable molecule, catalytic converters are less effective at oxidizing CH_4 than other longer-chained hydrocarbons.

N_2O, on the other hand, is formed inside the emission control systems of both natural gas and diesel HDV engines. During the catalytic reduction of NO_x to nitrogen, N_2O forms as an intermediate, unwanted product.

Diesel and lean natural gas engines equipped SCR systems can produce N_2O at temperatures around 250°C through the decomposition of ammonium nitrates. At temperatures above 500°C, the primary mechanism for N_2O formation is NH_3 oxidation in the ammonia slip catalysts (ASC). Innovative SCR formulations can reduce N_2O formation at low temperatures. At high temperatures, improved dosing strategies and model-based SCR control can reduce excess ammonia being oxidized in the ASC.[36]

36 MECA, "Technology Feasibility For Model Year 2024 Heavy-Duty Diesel Vehicles In Meeting Lower NO_x Standards."

N_2O is also formed in the three-way catalysts (TWC) of stoichiometric natural gas and gasoline engines. At high-enough temperatures, the TWC is effective in reducing NO directly to nitrogen. However, at lower temperatures, an alternative reaction pathway takes place forming N_2O as an intermediate product. The composition of the TWC—the loading of rhodium, platinum, and palladium—can be adjusted to reduce N_2O formation.

In the United States, the EPA introduced limits for CH_4 and N_2O emissions of HDVs in 2011 as part of the first phase of GHG standards. While the EPA initially considered an N_2O limit of 0.05 g/bhp-hr (~0.07 g/kWh), the final standards were set at 0.10 g/bhp-hr (~0.134 g/kWh) measured over the composite heavy-duty FTP cycle.[37] The limit for CH_4 was set at the same level of 0.1 g/bhp-hr (~0.134 g/kWh). These limits were left in place for the second phase of the regulation adopted in 2016.

The current European provisions cover CH_4 emissions only from natural gas engines with a limit of 0.5 g/kWh (~0.37 g/bhp-hr). No limit exists for N_2O.

Real-world emissions of N_2O from a Euro V HDVs shows N_2O emissions from 0.063 to 0.139 g/kWh.[38] PEMS tests on Euro VI HDVs show N_2O emission values between 0.05 and 0.07 g/kWh.[39] Tests performed by the Institute of Transport Economics (TØI) and the VTT Technical Research Centre of Finland found high emissions of N_2O in some Euro VI vehicles. In a specific case, N_2O emissions between 0.6 and 0.9 g/km were measured, equivalent to approximately 30% of the direct CO_2 emissions, reflecting its high GWP.[40]

Recommendations

CH_4 and N_2O emissions can both be found in non-negligible amounts in the exhaust of HDVs. Because both species have a strong global warming potential, their contribution to the climate impact of HDVs should receive closer examination. We offer the following recommendations:

» **Introduce stringent certification limits for CH_4 and N_2O, if they do not exist:** Future HDV emission standards should include stringent limits for CH_4 and N_2O. While in the United States these limits are set by the GHG regulation, the regulatory process in the European Union should allow the tightening of the current CH_4 limit and the introduction of an N_2O limit, at least at the level adopted in the United States.

» **Monitor CH_4 and N_2O emissions during on-road tests:** Tighter in-use NO_x limits of future emission standards can lead to increased in-use emissions of N_2O from diesel engines and CH_4 from natural gas engines. Pilot tests[41] using portable systems show that CH_4 and N_2O measurements can be performed in on-road tests. Future standards should enable the inclusion of these GHGs in the in-use test protocols and force the development of a robust measurement methodology.

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37 U.S. EPA and U.S. DOT, "Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles," Federal Register / Vol. 76, No. 179 (Environmental Protection Agency and Department of Transportation, September 15, 2011), https://www.gpo.gov/fdsys/pkg/FR-2011-09-15/pdf/2011-20740.pdf.

38 Ricardo Suarez-Bertoa, Pablo Mendoza-Villafuerte, Pierre Bonnel, Velizara Lilova, Leslie Hill, Adolfo Perujo and Covadonga Astorga, "On-Road Measurement of NH_3 and N_2O Emissions from a Euro V Heavy-Duty Vehicle," *Atmospheric Environment* 139 (August 2016): 167–75, https://doi.org/10.1016/j.atmosenv.2016.04.035.

39 Pablo Mendoza-Villafuerte, Ricardo Suarez-Bertoa, Barouch Giechaskiel, Francesco Riccobono, Claudia Bulgheroni, Covadonga Astorga, and Adolfo Perujo, "NO_x, NH_3, N_2O and PN Real Driving Emissions from a Euro VI Heavy-Duty Vehicle. Impact of Regulatory on-Road Test Conditions on Emissions," *Science of The Total Environment* 609 (December 31, 2017): 546–55, https://doi.org/10.1016/j.scitotenv.2017.07.168.

40 Rolf Hagman and Astrid Helene Amundsen, "Emissions from Vehicles with Euro 6/VI Technology - Test Phase 2," December 2013, https://www.toi.no/publications/emissions-from-vehicles-with-euro-6-vi-technology-test-phase-2-article32442-29.html.

41 See footnotes 38 and 39.

HOW TO REGULATE IT?
TESTS PROTOCOLS AND DATA EVALUATION

ON-ROAD TEST PROTOCOL AND DATA EVALUATION

In-use testing using PEMS is a central element of the emission standards in the European Union and the United States. Yet, there are fundamental differences in the testing requirements, boundary conditions, test protocols, and data evaluation methodologies used in EU and U.S. programs. Table 4 present a summary of the key elements of the HD in-use programs in the European Union and the United States.

Table 4. Comparison of HD in-use programs in the European Union and the United States

	Euro VI	EPA 2010
In-use program	In-service conformity program (**ISC**). Manufacturers perform the testing according to ISC provisions.	Manufacturer-run in-use testing program for heavy-duty diesel engines (**HDIUT**). Manufacturers perform the testing.
Testing requirements	**3 engines per engine family are tested.** First test at 18 months with minimum of 25,000 km and then every two years. Testing allowed up to useful life.	**5 vehicles per engine family per year.** Maximum 25% of engine families. No mandated frequency. Testing allowed up to useful life.
Compliance evaluation	Moving average window (**MAW**). **90% of valid windows** below the in-use limits. Invalid test if less than 50% of windows are valid or if no urban-only window is left after deleting the 10% worst NO_x windows.	Not-to-exceed (**NTE**) evaluation. **90% of valid NTE events** (see Table 5) below the in-use limits.
In-use limits	$CO/HC/CH_4/NO_x$ = **1.5 × WHTC** PN = **1.63 × WHTC**	$HC/NO_x/PM$ = **1.5 × FTP** + PEMS margin CO = **1.25 × FTP** + PEMS margin
Payload	**10% to 100% for ISC.** 50-60% for type-approval demonstration.	"Normal loads" as they pertain to the actual usage of the vehicle
Trip requirements	**30%/25%/45% (Urban/Rural/Motorway) for HDVs over 12 tonnes (N3).** Urban, rural, and motorway definition agreed with approval authority prior to testing.	Not specified. "Normal driving" without any predetermined speed or time distribution rules.
Test length	Long enough to complete 4 to 8 times the work performed during the WHTC	Not specified
Cold-start inclusion	**Partially**. Evaluation in Euro VI-Step E starts at $T_{coolant}$ = 30°C. No cold soak.	No.
Ambient conditions	**Temperature:** -7 to 38°C (-19 to 100°F) **Pressure:** < 82.5kPa (~5,577 ft elevation)	**Temperature:** < 100°F (~ < 38°C) **Elevation:** < 5,500 ft (~83 kPa of pressure)
Treatment of DPF regen.	If regeneration occurs during testing, the manufacturer can request the trip to be voided.	Regeneration data can be included under very strict conditions. In practice, data during regeneration is excluded.

The U.S. heavy-duty in-use testing program (HDIUT) follows the not-to-exceed (NTE) protocol for compliance evaluation. Under the NTE test protocol, HDVs are driven under normal operating conditions and the emissions are continuously measured. A vehicle is deemed compliant if the average emissions of at least 90% of all valid NTE events are below the NTE limit, determined by calculating the average emissions of valid NTE events that occurred during testing. A valid NTE event takes place when a set of several boundary conditions, shown in Table 5, are met for at least 30 consecutive seconds.

The EU in-service conformity (ISC) program follows the moving average window (MAW) evaluation method. Under the MAW method, mass emissions are calculated for subsets of a complete data set, called windows. The window size is defined by the work, or CO_2 emissions, over the window, which must be equal to the WHTC work, or CO_2. A vehicle is deemed compliant if the average emissions of at least 90% of all valid windows are below the ISC limit. The conditions for valid windows are shown in Table 5.

Table 5. Comparison of boundary conditions for valid windows (EU) and NTE events (U.S.)

Euro VI: Valid window	EPA 2010: Valid NTE event
The following condition must be met for a valid window to be valid: • **Average engine power** of the window must be greater than or equal to **10%** of the rated engine power (as of 2018, with Step D) • **Coolant temperature** must be greater than **30°C (86°F)** (as of 2020, with Step E) • **Regeneration events** (e.g., of the DPF) invalidate tests and the associated windows.	The following conditions must be met **for at least 30 consecutive seconds**, for a valid NTE event: • **Engine speed** must be greater than a given engine speed (called n_{15}) defined from the engine full load curve **(~850 to 950 rpm)** • **Engine torque** must be greater than or equal to **30%** of the peak torque • **Engine power** must be greater than or equal to **30%** of the rated engine power • **Intake temperature** must be greater than a function of intake pressure **(~38°C / 100°F)** • **Coolant temperature** must be greater than a function of intake pressure **(~60°C / 140°F)** • Exhaust gas **temperature** has to be above **250°C** (measured 1.0 feet from SCR outlet) • If a **regeneration event** takes place, the NTE event duration requirement increases significantly from the 30 seconds required in the absence of regeneration.

As shown in the table above, the validity requirements of the U.S. NTE methodology are more numerous and set narrower constraints than in the EU MAW method. The exclusions mandated by the NTE methodology significantly reduce the portion of the test data used for compliance evaluation. An in-depth analysis[42] of HDIUT data made publicly available by the EPA is shown in Figure 4.

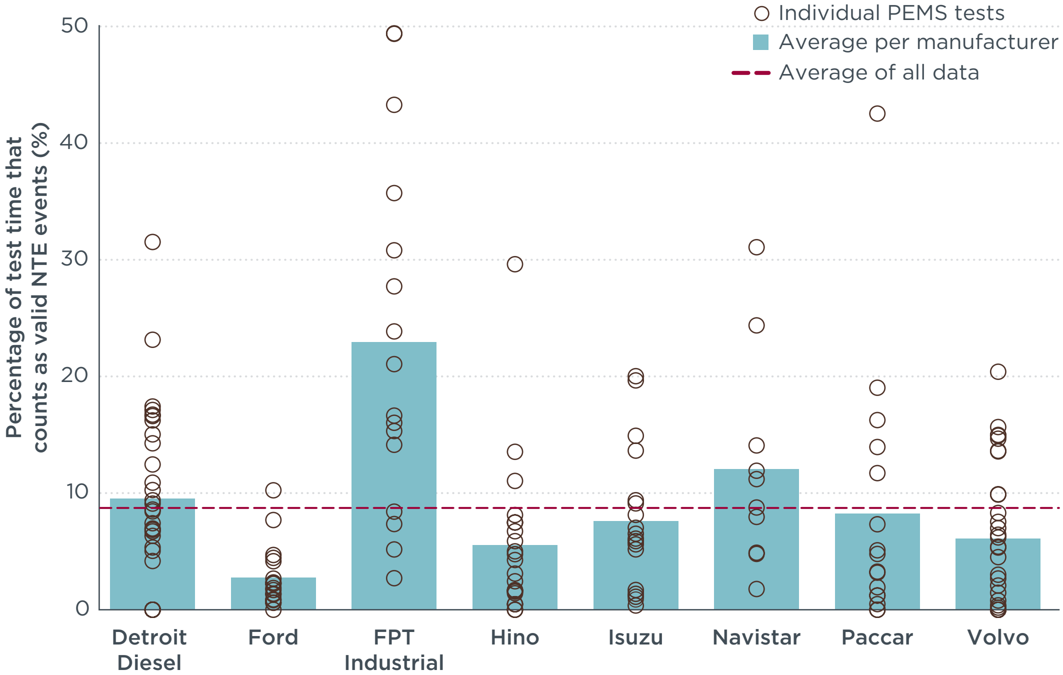

Figure 4. Fraction of PEMS test duration constituting valid NTE events for 160 PEMS tests. Each dot represents a single PEMS test that includes at least one NTE event. Bars represent the average time spent in NTE events by manufacturer. The red dashed line is the average time spent in NTE events of all 160 PEMS tests. Adapted from Badshah et al. (2019).

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

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 NO_x emissions over valid NTE events of 0.18 g/bhp-hr (~0.24 g/kWh) were approximately 60% lower than the emissions over the 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 NO_x emissions, defined as those occurring at less than 25 mph (40 km/h). The application of the NTE boundary conditions for compliance evaluation (see Table 5) 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 NO_x emissions, defined as those occurring at speeds less than 25 mph (40 km/h), range approximately from 1 to 1.2 g/bhp-hr (~1.3 to 1.6 g/kWh) across all datasets (95% confidence interval). Figure 5 shows the average NO_x emissions across all data sets for different speed regimes for the complete in-use tests and for the complete tests excluding idle.

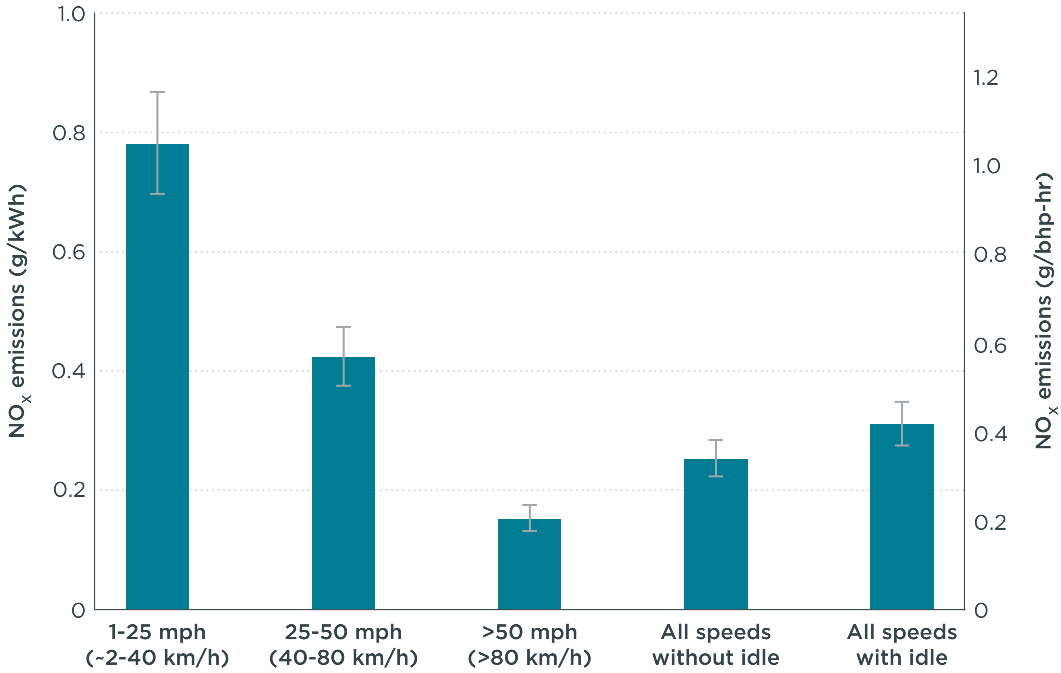

Figure 5. Average NO_x emissions differentiated by vehicle speed. Error bars represent the 95% confidence interval. Adapted from Badshah et al. (2019).

In light of the limitations of the NTE methodology, California has announced its intention of abandoning the NTE protocol and moving toward the MAW method. 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. CARB's current assessment[43] includes the use of Euro VI-Step D[44] methodology, that is without the inclusion of cold-start emissions, for the period 2024–2026, and power threshold window validity of 10% minimum.

43 California Air Resources Board, "CARB Staff Current Assessment of the Technical Feasibility of Lower NO_x Standards and Associated Test Procedures for 2022 and Subsequent Model Year MD- and HDDEs."

44 Euro VI standards were implemented in five steps. Step A implemented for new types in 2013, step B in 2014, step C in 2016, step D in 2018, and step E in 2021. The implementation steps differ in the OBD requirements (full phase-in from step C onward), the power threshold for validating windows in the ISC test (20% for steps A, B and C, and 10% for steps D and E), and the inclusion of cold-start (step E).

From 2027 onward, CARB plans to include cold-start emissions, remove the 10% power threshold requirement (see Table 5) to allow windows with any average power to become valid,[45] and tighten the criteria to pass the in-use test by requiring a higher percentage of windows to be below the in-use limit.[46]

CARB will not introduce trip requirements, as done in the European Union, and will maintain its requirements on the number and frequency of in-use tests (see Table 4). For the 2024-and-beyond requirements, PEMS trips are expected to generate three hours of valid data as the minimum to be considered valid trips.

Recommendations

The alignment of in-use test protocols creates a big opportunity for the harmonization of calibration and emissions control technology deployment.

The NTE methodology has several limitations that render it an inadequate method for the evaluation of in-use tests. The MAW methodology used in the European Union results in a more representative evaluation of in-use emissions and should be adopted in the United States as well. Still, a small number of modifications to the Euro VI MAW method are needed. We offer the following recommendations:

» **100% of valid windows should be used for compliance evaluation:** The Euro VI MAW methodology establishes that only 90% of the windows must be below the in-use limit to be in compliance. Given that the size of each window is comparable to the WHTC, it is justifiable to include all windows in the evaluation.

» **Remove the minimum power requirements for window validity:** Urban operation is characterized by low load and low speed. Setting minimum power requirements for valid windows disincentivizes the development of technologies aimed at reducing NO_x emissions in urban conditions. The data evaluation should go down to idle.

» **Urban driving should be prescribed during on-road testing:** While in-use testing should occur under the normal driving route of the test vehicle and should not be constrained to speed or time distribution rules, a minimum distance of urban driving should be mandated as part of in-use testing requirements. Urban driving represents a sizable portion of HDV operation and emissions. As has been demonstrated with PEMS data from a wide range of U.S. and EU HDVs, urban NO_x emissions are much higher than the average values over the complete trip. Thus, low-speed urban driving, typically at less than 25 mph (40 km/h), should be better reflected in the determination of in-use compliance. The U.S. in-use program does not have any low-speed trip requirements.

» **Account for emissions that occur during filter regeneration:** The contribution of emissions during DPF regeneration can be significant. Under the current in-service conformity provisions in the European Union, the manufacturer can request that the test be invalidated if an active regeneration takes place. While the U.S. provisions allow for the inclusion of regeneration events, the NTE conditions must be continuously satisfied from the start of one regeneration event to the start of the next regeneration event. This effectively removes DPF regeneration events from the data evaluation, given that DPFs are regenerated only every few hundred kilometers.

» **Improve cold-start requirements:** In Euro VI-Step E, the data evaluation starts only after the coolant has reached 30°C. However, in tests at low ambient temperatures, by the time the coolant temperature reaches 30°C, the emissions control system will

45 In CARB's current assessment, a test could be invalidated if more than 50% of windows are below 10% of engine peak power.

46 From 2027 onward, the percentile for warm-start window evaluation would increase from 90% to a higher value that has not yet been determined. The percentile for cold-start window evaluation would be 100%.

have warmed significantly. To align the cold-start definition with existing regulations, it is necessary to extend the cold-start temperature requirements to also include the emissions control system. The cold-start provisions for engine dynamometer testing establish that the lubricant, coolant, and aftertreatment systems must be between 20°C and 30°C at the start of the test. The cold-start definition for in-use testing should be aligned with the one used in engine dynamometer testing by setting a maximum temperature of 30°C for the aftertreatment system at the start of data evaluation.

» **In-use data should be made publicly available:** In the United States, the in-use second-by-second PEMS data and HDIUT compliance evaluation results are publicly available, enabling third parties to analyze the data. In the European Union, ISC data is not made public, creating a knowledge gap for future regulatory development.

LOW-LOAD CYCLE ON ENGINE DYNAMOMETER

Emissions of HDVs are significant at low-speed, low-load operations (see Figure 5), reflecting the ineffectiveness of SCR systems at low exhaust temperatures. CARB estimates suggest that low-speed, low-load emissions will represent half of all NO_x emissions of the HDV fleet by 2030, while representing less than 10% of the distance.[47]

CARB has proposed adding a new low-load cycle (LLC) to the existing set of engine dynamometer tests to capture more accurately the range of real-world activity of HDVs. An LLC candidate developed by SwRI is shown in Figure 6.[48] The test represents real-world vehicle operations, characterized by low engine loads and low vehicle speeds. At approximately 1.5 hours of test duration, and with several transitions between high and low load, incorporating the test would force the deployment of technologies for the active thermal management of the engine and the emissions control system, as summarized in Table 3.

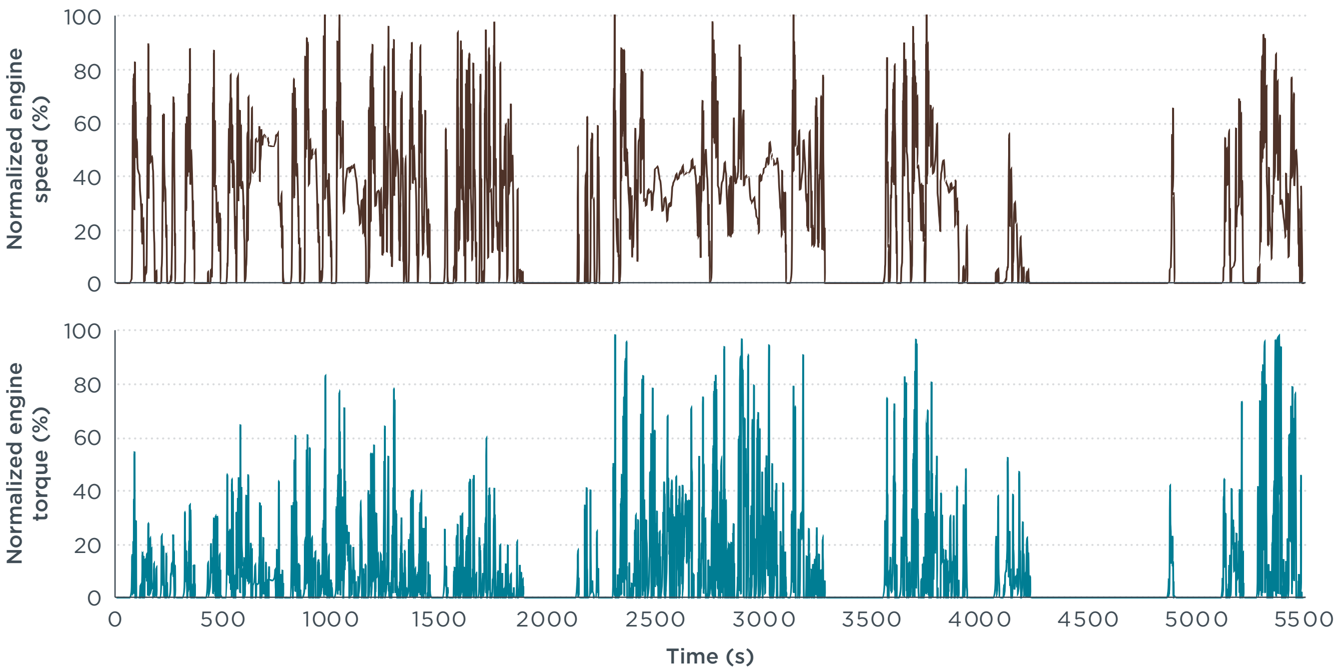

Figure 6. Low-load cycle candidate for future low NO_x emission standards in California

47 California Air Resources Board, “CARB Staff Current Assessment of the Technical Feasibility of Lower NO_x Standards and Associated Test Procedures for 2022 and Subsequent Model Year MD- and HDDEs.”

48 California Air Resources Board, “Heavy-Duty Low NO_x Program. Low Load Cycle,” in *Public Workshop to Discuss Potential Changes to the Heavy-Duty Engine and Vehicle Emission Standards, Test Procedures, Warranty, and Other Related Heavy-Duty Programs.*, 2019, https://ww2.arb.ca.gov/our-work/programs/heavy-duty-low-nox/heavy-duty-low-nox-meetings-workshops.

The candidate cycle shown in Figure 6 has an average engine load of 15% (excluding idling periods) and spends 40% of the time in idle. The cycle represents a vehicle with an average driving speed of around 27 km/h, excluding stops. The LLC targets the three types of operation in urban driving: Sustained low-load, high- to low-load transition, and low- to high-load transition. Examples of these types of operation are shown in Figure 7 using the candidate cycle and are described below.

1. **Sustained low-load operation:** This type of operation is typical of urban driving, where short transients are separated by idling events. Adequate thermal management would be required to maintain the aftertreatment system at operating temperature.

2. **High- to low-load transition:** This type of operation occurs as vehicles arrive at their destinations, transition from highways into urban centers, or stop momentarily for resting or refueling. The test aims to assess how long the aftertreatment system can maintain its temperature and performance during prolonged cool-off.

3. **Low- to high-load transition:** This type of operation takes place as vehicles switch from long idling or low-load urban operation to highway operation or after prolonged periods of downhill operation on the highway. The test aims to assess whether the aftertreatment system is able to handle abrupt increases in engine-out emissions.

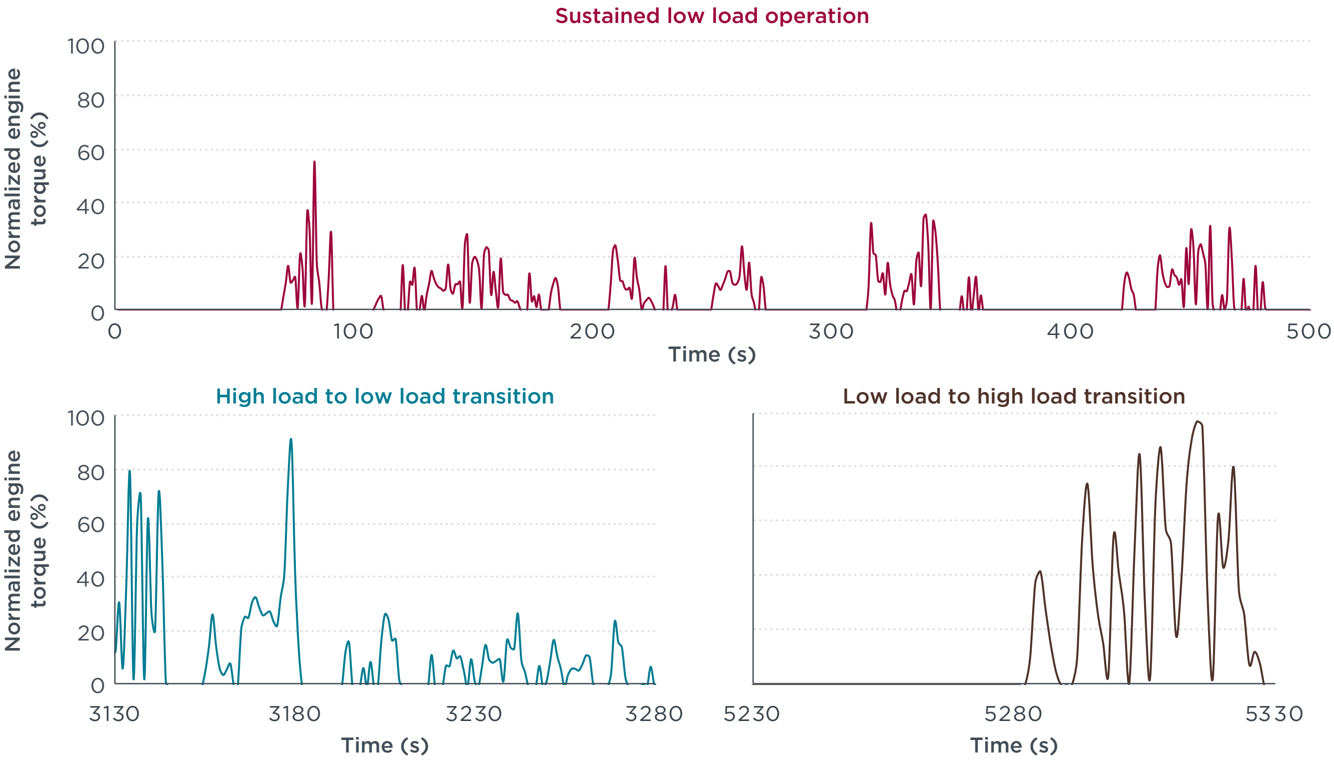

Figure 7. Examples of the three types of operation targeted by the low-load cycle candidate.

Recommendations

The introduction of a low-load cycle for engine certification, or type approval, would create a regulatory push to drive the adoption of technologies for the active thermal management of emission control systems, improving the emissions performance of HDVs and decreasing their impact on the air quality of urban centers. We offer the following recommendations:

» **Introduce a low-load cycle for engine certification:** In addition to the current transient and steady-state cycles, future HDV emission standards should introduce engine dynamometer tests that target low-load and low-speed operation. Such tests gain even more relevance in cases when in-use test protocols, as those in the United States and the European Union, exclude operating conditions at low engine power.

» **Set a stringent limit over the LLC to drive the adoption of technologies targeting low-load and low-speed operation:** The LLC standard could be aligned with CARB's proposal of 0.2 g/bhp-hr (~0.27 g/kWh) for the 2024–2026 timeframe, reduced to one to three times the FTP limit, or between 0.06 and 0.12 g/bhp-hr (~0.08 to 0.16 g/kWh), for 2027 and beyond. The gap between LLC values and real-world NO_x emissions can be controlled with in-use compliance evaluation that eliminates power requirements for the validity of windows and requires 100% of the windows to be below the in-use standard.

IDLING LIMITS

Idling represents a large portion of vehicle operation and is a significant source of NO_x emissions. ICCT's analysis[49] of the EPA's HDIUT database shows that HDVs spend 30% to 40% of their time idling.[50] While this is consistent with the real-world operation of urban trucks, it is higher than the 15% share observed in the operation of long-haul trucks.[51] This discrepancy is a result of changes in the operation of long-haul trucks during on-road testing, as trucks must come back to the testing facility within the same day.

As shown in Figure 8, idling NO_x emissions represent about 20% of total NO_x emissions. On average over the dataset analyzed, long-haul trucks produced the highest idling NO_x emissions rates at 23.6 g/h, while delivery trucks produced less than half the NO_x idling emissions at 9.1 g/h.

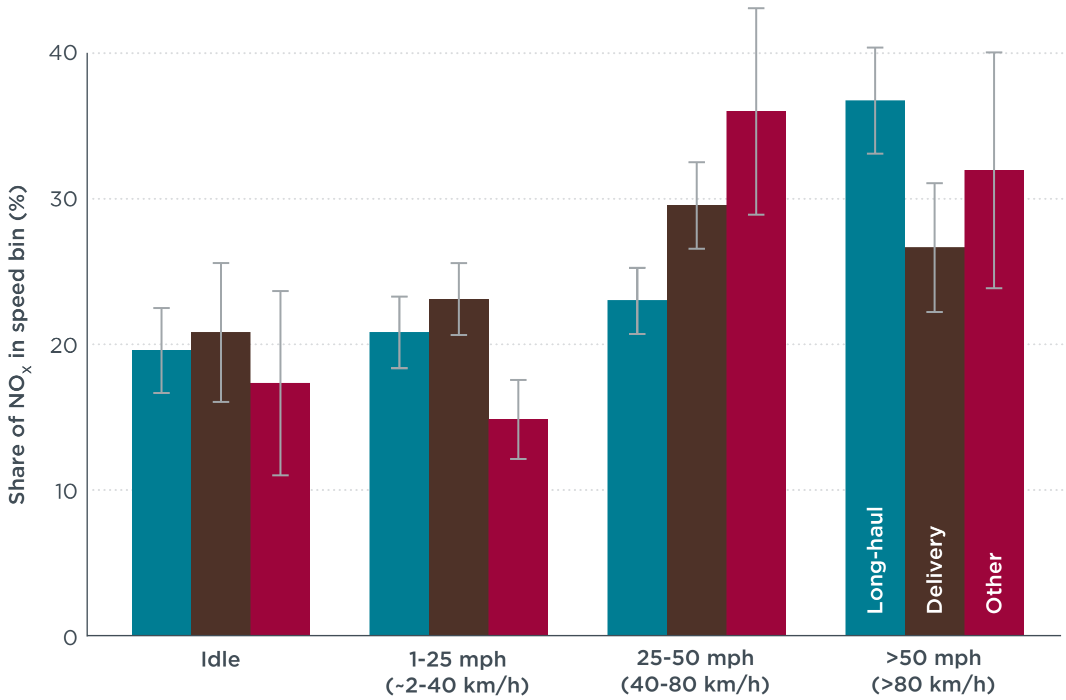

Figure 8. Percentage of NO_x emissions emitted by different vehicle types over the speed segments assessed. Adapted from Badshah et al. (2019).

49 Badshah, Posada, and Muncrief, *Current State of NO_x Emissions from In-Use Heavy Duty Diesel Vehicles in the U.S.*

50 Since engine speed is not available in the EPA data, idling is assumed to take place when the vehicle speed is less than 1 mph.

51 Andrew Kotz and Kenneth J. Kelly, "MOVES Activity Updates Using Fleet DNA Data: Interim Report" (National Renewable Energy Laboratory, 2019), https://www.nrel.gov/docs/fy19osti/70671.pdf.

Currently, California has optional idling NO_x standards in place, limiting idling emissions to 30 g/h. CARB's idle limit is optional in the sense that it can also be fulfilled by equipping the vehicle with a system that automatically turns off the engine after 300 seconds of continuous idling. In CARB's current assessment for future emission standards, the NO_x idling limit will tightened to 10 g/h in the 2024–2026 timeframe. The 2027 NO_x idling limit would be based primarily on the technology assessment being carried out by SwRI.

Recommendation

Reflecting the high contribution of idling NO_x emissions during the operation of HDVs, future emissions regulations should introduce strict idling standards. We offer the following recommendation:

» **Introduce strict idling NO_x standards:** An idling NO_x limit well below 10 g/h can drive the adoption of technologies that prevent idling, such as automatic shutdown systems and stop/start, and of technologies that make idling unnecessary, such as battery-driven auxiliary power units and off-board power capabilities.

DURABILITY DEMONSTRATION

The deterioration of emission control systems can have a significant impact on the in-use emissions of on-road vehicles. Demonstration of durability of emissions control systems during certification helps to ensure adequate emissions performance over the useful life of HDVs. The effectiveness of durability demonstration programs depends on two elements: (1) the definition of useful life, and (2) the procedure for the determination of deterioration factors.

The distance definition of useful life for heavy trucks[52] is the same in the European Union and the United States at 700,000 km (435,000 mi). However, the United States defines the useful-life age limit at 10 years, while EU regulations do so at seven years. As shown in Figure 9,[53] available HDV activity data from the European Union[54] and the United States[55] suggests that the current definitions of useful life are not representative of the vehicle fleet and must be roughly doubled.

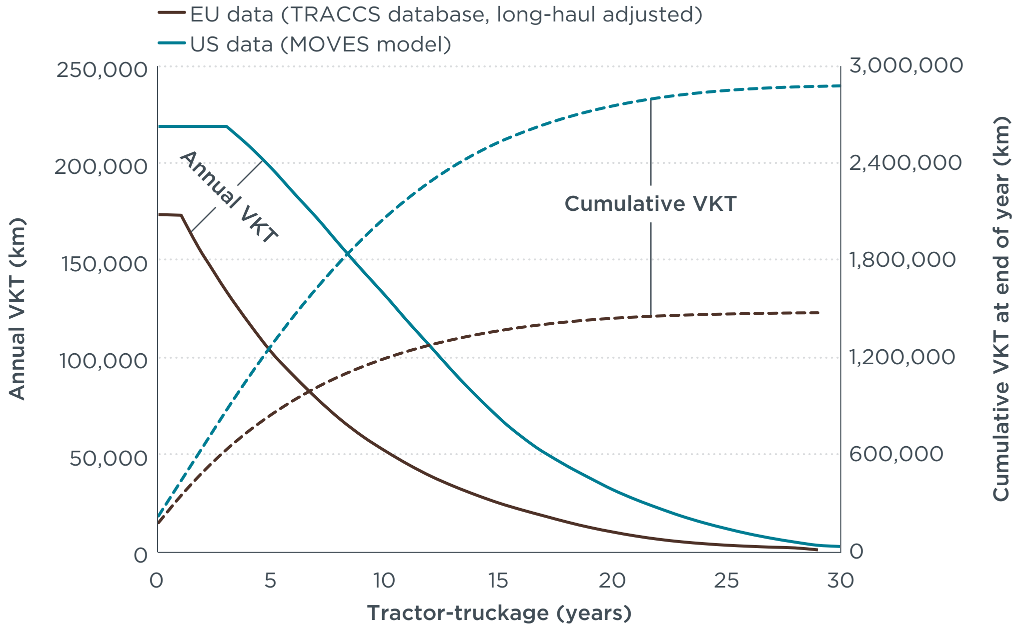

Figure 9. Survival-weighted vehicle-kilometers-traveled (VKT) for long-haul trucks in the European Union and the United States. Adapted from Meszler et al. (2018).

52 Heavy trucks refer to vehicles with a gross vehicle weight above 16 tonnes (35,274 pounds) in the European Union—called N3 vehicles—and above 33,000 lbs. (14.97 tonnes) in the United States—called heavy-heavy-duty vehicles.

53 Dan Meszler Oscar Delgado, Felipe Rodríguez, and Rachel Muncrief, *European Heavy-Duty Vehicles – Cost Effectiveness of Fuel Efficiency Technologies for Long-haul Tractor-trailers in the 2025–2030 Timeframe* (ICCT: Washington, DC, January 2018), http://theicct.org/publications/cost-effectiveness-of-fuel-efficiency-tech-tractor-trailers.

54 European Commission, "TRACCS Database," 2014, https://www.eea.europa.eu/data-and-maps/data/external/traccs.

55 U.S. EPA, "MOVES and Related Models: Where Does EPA Obtain Default Vehicle Miles Traveled (VMT)?" 2014, https://www.epa.gov/moves/where-does-epa-obtain-default-vehicle-miles-traveled-vmt.

According to the latest information from November 2019, CARB intends to lengthen the definition of useful life to 600,000 miles (~965,000 km) or 11 years, whichever comes first, from 2027, and expand it to 800,000 miles (~1.3 million km) or 12 years from 2031 onwards.[56] A previous proposal from September 2019 had suggested a useful life definition of 850,000 miles (~1.4 million km) or 18 years from 2027 onward.[57]

Durability demonstration procedures and methodology for calculating deterioration factors are also similar in both markets. The aging of the engine and aftertreatment system is performed on the engine dynamometer over a duration shorter than the definition of useful life. In the European Union, heavy truck engines must be aged for a minimum of 233,000 km (~145,000 mi). In the United States, there are no specific provisions for the aging cycles or the respective duration and aging is typically done to represent 35%–50% of useful life.[58] The full useful life emissions performance is estimated by linear extrapolation of the test results and is quantified through additive or multiplicative deterioration factors. To overcome the limitations of the current durability demonstration procedure and better capture the real-world deterioration of emission control systems and failures in their components, CARB intends to require that manufacturers perform durability testing representing full useful life.

Recommendations

The current useful life definition for HDVs in the European Union and the United States does not match the retirement ages and lifetime activity of HDV fleets. Furthermore, the durability demonstration provisions are not suitable for capturing nonlinear deterioration or failure of components during the second half of useful life. We offer the following recommendations:

» **Extend the definition of useful life for durability demonstration:** The current definition of useful life is not representative of the EU and U.S. fleets. The useful life definition should be more than doubled from today's values.

» **Establish full useful life testing as the only option for durability demonstration:** The use of generic deterioration factors should not be allowed, as is currently the case under Euro VI, and the emission control systems should be aged for the full useful life to determine compliance with emission standards.

WARRANTY AND DEFECT REPORTING

Certification tests, including durability demonstration, aim to ensure that the design of a vehicle and its emissions control system is capable of meeting emission standards before sale of a new vehicle is authorized. In-use compliance programs aim to ensure production vehicles are calibrated as certified, identify emissions deterioration in properly operating vehicles, and help to ensure that vehicles continue to meet emission standards throughout their life. However, it is also important to identify malfunctions in emission-related parts, which can increase in-use emissions by orders of magnitude. Thus, in addition to in-use testing (see section above), emissions warranty and defect reporting programs are also fundamental elements to ensure that emission-related part failures and defects are identified and repaired.

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56 California Air Resources Board, "Heavy-Duty Low NO_x program. Proposed Heavy-Duty Useful Life and Step 2 Warranty Amendments," External Workgroup, November 2019.

57 California Air Resources Board, "Heavy-Duty Low NO_x Program. Proposed Heavy-Duty Useful Life and Step 2 Warranty Amendments," in Public Workshop to Discuss Potential Changes to the Heavy-Duty Engine and Vehicle Emission Standards, Test Procedures, Warranty, and Other Related Heavy-Duty Programs., September 2019, https://ww2.arb.ca.gov/our-work/programs/heavy-duty-low-nox/heavy-duty-low-nox-meetings-workshops.

58 California Air Resources Board, "CARB Staff Current Assessment of the Technical Feasibility of Lower NO_x Standards and Associated Test Procedures for 2022 and Subsequent Model Year MD- and HDDEs."

Emissions warranty programs encourage vehicle owners to report and repair emission-related issues at no additional cost to the owner, while incentivizing manufacturers to build more-robust emission control systems. Emissions defect reporting programs provide information on the frequency of part failures in the emissions control system and allow the identification of emission-related parts with abnormally high failure rates.

In the United States, the warranty period for key components of heavy trucks is set at 100,000 mi (160,000 km) or five years, whichever occurs first. The warranty covers all components whose failure would increase a vehicle's emissions. In June 2018, CARB adopted amendments to lengthen the distance warranty to 350,000 mi (~560,000 km), or five years, applicable from 2022 onward. Despite these amendments, CARB's staff considers that the warranty period falls short of the real-world longevity of modern HDVs and proposes to further lengthen the warranty period from 2027 onward. CARB's latest proposal suggests extending the warranty period to 450,000 miles (~724,000 km) or 7 years by 2027 and expand it to 600,000 miles (~965,000 km) from 2031 onwards.[59]

Under the U.S. defect reporting program, manufacturers are required to identify faulty emission-related components by tracking component failures identified through the warranty program or other sources, to conduct detailed investigations of possible defects, to report the defective components with failure rates above well-defined thresholds, and to correct defects as soon as possible for future production.

Emissions warranty and defect reporting programs do not currently exist in the European Union. Manufacturers are not required to provide a warranty for vehicle emission controls or to regularly report emission-related warranty and repair claims or any other emission defects. In the absence of emissions warranty and defect reporting programs, vehicle owners have to bear the financial burden associated with repairing faulty or nondurable emission controls, and regulators do not have access to the information required to timely identify emission-related issues and enforce the corresponding corrective actions.

Recommendations

Emissions warranty and defect reporting programs are fundamental elements to ensure in-use emissions compliance of HDVs and should form part of, or be a complement to, any future HDV emissions standard. We offer the following recommendations:

» **Set an emissions warranty program with minimum warranty periods aligned with useful life definition:** An emissions warranty program encourages vehicle owners to report and repair emission-related issues at no cost to the owner and incentivizes manufacturers to build robust emissions control systems. The warranty period should be aligned with useful life definition to prevent emission levels above the regulatory limits in HDVs with mileages within applicable useful-life periods but beyond their warranty periods.

» **Establish an emissions defect tracking and reporting program:** An emissions defect reporting program is a useful tool for collecting information on the frequency of emissions control part failures, identify emission parts with abnormally high failure rates, and take corrective actions. An effective program should require automatic interventions by manufacturers, such as recalls or extended warranties, whenever the failure rate exceeds a specific threshold. A transparent defect reporting program should be based on the number of warranty claims and limit the ability of manufacturers to choose their own methodologies to track failure rates.

59 California Air Resources Board, "Heavy-Duty Low NOx program. Proposed Heavy-Duty Useful Life and Step 2 Warranty Amendments". External Workgroup. November 2019.

ON-BOARD DIAGNOSTICS AND MONITORING

On-board diagnostics (OBD) systems are a fundamental element of emission control systems. Since the OBD system can pinpoint malfunctioning components, it is a useful complementary tool for a number of emission standards programs, such as warranty, defect reporting, and inspection and maintenance.

The effectiveness of OBD systems in diagnosing emission controls depends on which components and pollutants are monitored, the frequency of the monitoring, the definitions of what constitutes a malfunction—such as the OBD threshold limits (OTL)—how identified malfunctions are stored in the vehicle's memory, and the actions taken once a fault is identified—such as lighting the malfunction indicator lamp (MIL) or limiting the vehicle's performance, also called *inducement*.

Table 6 shows a brief comparison of the HDV OBD requirements in the European Union and California. Since the EPA accepts CARB's OBD as compliant, virtually every new HDV engine certified in the United States meets CARB's requirements.[60]

Table 6. Selected HDV OBD monitor requirements in the European Union and the United States

	Euro VI OBD	CARB's HDV OBD 2010
NO_x and PM OTLs	NO_x: 1.2 g/kWh (2.6 × WHTC limit) PM: 25 mg/kWh (2.6 × WHTC limit)	NO_x: 0.54 g/kWh (2.0 × WHTC limit) PM: 40 mg/kWh (3.0 × WHTC limit)
Oxidation catalyst	Conversion efficiency for hydrocarbons	NMHC catalyst conversion, and DPF heating
SCR	Conversion efficiency; NO_x OTL monitor; urea solution delivery (quantity, quality, consumption) Performance degradation: Torque is reduced by 25% (general action), speed is limited to 20 km/h (severe action)	Conversion efficiency; NO_x OTL monitor; urea solution delivery (quantity, quality, consumption), response of control system Performance degradation: Torque is reduced by 25% percent (general action), speed is limited to 5 mph without idling being possible (severe action)
DPF	Filtering performance; PM OTL monitor; major failure (removal; electrical failure of sensors; clogged filter); regeneration	Filtering performance; PM OTL monitor; pressure differential; regeneration (frequency, completion), missing substrate; active regeneration (fuel delivery); response of control system
Fuel delivery	Pressure, quantity, timing, control	OTL monitor, pressure, quantity, timing, response of control system
Air boost	OTL monitoring, flow rate, response, cooler operation, control.	OTL monitor, flow rate, response, cooler operation, response of control system
Variable valve timing	Variable valve timing target and response	PM, NMHC, and CO OTL monitor; variable valve timing target and response
Engine cooling	Thermostat and total failure	Thermostat, engine coolant temperature, circuit malfunction
Sensors and actuators	Proper operation; voltage, circuit integrity, monitoring capacity	OTL monitoring for exhaust gas sensors; performance (voltage, current); circuit continuity, feedback control, monitoring capacity

Under the U.S. regulation, if a malfunction is present, the diagnostic trouble codes (DTCs) must be permanently stored in the vehicle's control unit, and the MIL should be illuminated. This is in contrast to the European program that requires MIL illumination only for DTCs with emission impacts and does not require permanent fault code storage.[61]

60 Francisco Posada and Anup Bandivadekar, *Global Overview of On-Board Diagnostic (OBD) Systems for Heavy-Duty Vehicles*, (ICCT: Washington, DC, February 9, 2015), https://theicct.org/publications/global-overview-board-diagnostic-obd-systems-heavy-duty-vehicles.

61 Mikael Lundström, "Heavy Duty OBD Around the World" (SAE On-Board Diagnostics Symposium, Stuttgart, 2019).

Compared with the European OBD program, the U.S. program includes more comprehensive and more stringent monitoring requirements—including a larger number of DTCs—and more clearly defined provisions for such requirements, minimizing the room for misinterpretation of the regulation.

California is conducting a rulemaking process[62] to amend the HDV OBD regulation. The amendments include an increase in the minimum in-use monitor performance ratio[63] requirements from 0.1 to 0.3 for most monitors, revisions to the crankcase ventilation system monitoring requirements, additional monitoring requirements for hybrid vehicles, and revising the fines applicable to deficiencies in the OBD system, among others.

California[64] has also adopted an on-board emissions monitoring (OBM) regulation, called Real Emissions Assessment Logging (REAL), requiring the HD OBD systems to collect and store NO_x emissions and fuel consumption data from the vehicle's sensors. These data can be used by regulatory agencies for improving in-use compliance and the effectiveness of inspection and maintenance programs. The data could be accessed during inspection and maintenance procedures or as part of fleet self-monitoring programs. The European Union has also recently mandated the introduction of on-board monitoring for HDV fuel consumption as part of the CO_2 standards. The data is to be transmitted[65] to the European Commission to be used in tracking the gap between certified and in-use CO_2 values, in-service conformity, and CO_2 standard compliance, among other things. The EU framework, however, is limited to CO_2 and fuel consumption and does not contemplate the monitoring of other pollutants, such as NO_x. China's stage VI emission standards, largely based on Euro VI, include requirements for vehicles to be equipped with a remote on-board terminal (remote OBD) for monitoring key emission-related parameters.[66]

Recommendations

A robust and unambiguous OBD and OBM regulation would be instrumental in improving the durability and performance of emission control systems and could be a useful compliance and enforcement tool to ensure that the reductions mandated by the standards translate into lower in-use emissions. The current OBD program in Europe leaves the requirements for monitoring several emission control systems open to interpretation and can fail to identify malfunctions that can lead to high emissions. We offer the following recommendations:

» **Harmonize the OBD requirements of future emission standards:** California's OBD program includes the largest set of monitored components and systems as well as stringent and unambiguous guidelines for all OBD requirements. It can serve as the starting point for a global program that facilitates its implementation and reduces development costs for manufacturers.

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62 At the time of writing, California had not adopted the new amendments. https://ww2.arb.ca.gov/resources/documents/heavy-duty-obd-regulations-and-rulemaking

63 To accommodate for the computing power required to perform monitoring routines, the OBD monitors do not run constantly but only at certain points of during vehicle operation. OBD systems have to count, for every monitored system, how often the boundary conditions to start the monitoring routine are met and how often the OBD monitoring was actually initiated. The ratio between these two results is called the in-use monitor performance ratio.

64 California Air Resources Board, "CARB Gets 'REAL' to Further Cut Pollution from Diesel and Gas Vehicles | California Air Resources Board," November 15, 2018, https://ww2.arb.ca.gov/news/carb-gets-real-further-cut-pollution-diesel-and-gas-vehicles.

65 Jan Dornoff, "One Goal, Multiple Pathways: A Review of Approaches for Transferring on-Board Fuel Consumption Meter Data to the European Commission," White Paper (The International Council on Clean Transportation, October 22, 2019), https://theicct.org/publications/transferring_obfcm_fuel_data_ec.

66 Liuhanzi Yang and Hui He, *China's Stage VI Emission Standard for Heavy-Duty Vehicles (Final Rule),* (ICCT: Washington, DC, July 20, 2018), https://www.theicct.org/publications/china%E2%80%99s-stage-vi-emissions-standard-heavy-duty-vehicles-final-rule.

» **OBD systems should be compatible with inspection and maintenance (I/M) programs:** Adoption of OBD for I/M programs can complement—but not replace—inspection measurements, as the OBD system directly monitors the systems that affect vehicle emissions. To achieve this, the OBD data stream requirements should be extended to include all emissions-relevant vehicle signals—like exhaust and aftertreatment temperatures, EGR valve position and EGR rate, DPF pressure drop, NO_x sensor readings, air flow rate, and air-fuel ratio, among others—through the OBD port in a standardized way.

» **Investigate the use of on-board particle sensors to detect DPF failure as part of OBD requirements:** PM and PN can both be detected using real-time sensing technology. Such sensors can enable the development of tighter OTLs for PM and the introduction of OTLs for PN.

» **Introduce on-board monitoring of pollutant emissions and fuel consumption:** Requiring vehicles to collect and store the pollutant emission measurements and estimates from the vehicle's own sensors and models would enable regulators to identify durability issues faster, help ensure that vehicles maintain low emissions throughout their full lives, and permit demand-based periodic technical inspections. OBM can also be a valuable tool for assessing the limitations of the emission certification procedures, address emissions tampering, and possibly help to establish compliance of in-use vehicles. Furthermore, OBM can enable evaluating compliance with GHG regulations and monitoring fuel consumption progress in the in-use fleet.

MARKET SURVEILLANCE AND ENFORCEMENT

Whereas some deviations between certified and real-world emissions of vehicles are unavoidable, excessive in-use emissions and a persistent disparity between certified and real-world emissions erodes public trust in vehicle manufacturers and the institutions regulating them. Thus, market surveillance and robust compliance and enforcement programs are indispensable elements of emission regulations.

Market surveillance refers to the independent verification, testing, and inspection of vehicles by regulatory agencies. Robust enforcement provisions include punitive elements such as type-approval revocations, recalls, fiscal penalties, consumer compensation, and legal prosecution.

The U.S. compliance and enforcement program is the oldest and most comprehensive in the world, with a strong focus on in-use testing and a solid record of recalls and other corrective enforcement actions. The program has a strong technical expertise and fosters an environment in which the cost of noncompliance is an effective deterrent.

The EU type-approval framework was overhauled in 2018.[67] Under the new framework the European Commission has the authority to carry out its own market surveillance testing, initiate and monitor vehicle recalls, and impose fines on manufacturers. EU member states are also empowered to take measures against noncompliant vehicles sold in their national markets. Regardless of where the vehicles were type-approved, member states can restrict or prohibit the use of affected vehicles and require corrective actions by manufacturers. Member states are required to establish market surveillance authorities independent of type-approval authorities, which must conduct a minimum number of vehicle compliance tests per year. In the new framework, the financial

67 Parliament and Council of the European Union, "Regulation (EU) 2018/858 of the European Parliament and of the Council of 30 May 2018 on the Approval and Market Surveillance of Motor Vehicles and Their Trailers, and of Systems, Components and Separate Technical Units Intended for Such Vehicles, Amending Regulations (EC) No 715/2007 and (EC) No 595/2009 and Repealing Directive 2007/46/EC (Text with EEA Relevance.)," *Official Journal of the European Union* L 151 (June 14, 2018), http://data.europa.eu/eli/reg/2018/858/oj.

relationship between manufacturers and technical services continues to exist. Technical services, which perform certification testing and inspection, are paid directly by manufacturers. This leads to conflicts of interest and casts a shadow on the impartiality of the certification activities.

Recommendations

Based on existing practices, establishing an ideal, one-size-fits-all market surveillance program for all regions is a challenge. Nevertheless, such programs should set up a clear legal authority, avoid conflicts of interest between regulating agencies and regulated parties, conduct reliable testing, implement mandatory recalls and fiscal penalties, and prioritize data and information transparency.[68]

We offer the following specific recommendations to address high emissions associated with the improper design and calibration of emission control systems, component failures, durability issues, and tampering with aftertreatment systems:

» **Develop a standardized methodology for fleet screening to identify potentially noncompliant vehicles:** Emissions warranty and defect reports, inspection and maintenance data, OBD system records, and remote sensing are viable screening methods to identify potentially high-emitting in-use vehicles. Market surveillance programs should leverage multiple data sources to monitor as large a sample of the in-use fleet as possible.

» **Develop a remote sensing standard and establish a database of remote sensing records:** Remote sensing is a very effective technology for identifying high emitters, enabling robust and targeted market surveillance, particularly if the remote sensing records are consolidated and shared across market surveillance authorities. The development of a remote sensing standard would enable consistent application in different regions.

» **Strengthen anti-tampering provisions:** To prevent the use of SCR emulators, the removal of aftertreatment components, the obstruction of exhaust gas recirculation valves, or the reprogramming of the engine control unit, the regulation must mandate and support the development of tamper-proof systems. The scope and design of future regulations should include a stronger focus on inhibiting tampering attempts, placing the burden on manufacturers and forcing the development of tamper-proof communication protocols between sensors, actuators, and control units.

68 Zifei Yang, Rachel Muncrief, and Anup Bandivadekar, *Global Baseline Assessment of Compliance and Enforcement Programs for Vehicle Emissions and Energy Efficiency*, (ICCT: Washington, DC, November 2017), https://www.theicct.org/publications/compliance-and-enforcement-global-baseline.

FINAL REMARKS

The ICCT commends the commitment of regulators in the European Union and the United States to continuing to address on-road emissions of heavy-duty vehicles through a new phase of pollutant emission standards. With this report, the ICCT seeks to bring attention to important issues that would enhance the environmental benefits of future standards while at the same time providing a workable window for harmonization that could reduce the development and compliance expenditures of manufacturers in both markets.