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Fuel efficiency and climate impacts of soot-free heavy-duty diesel engines

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Introduction

Heavy-duty (HD) engine emission standards, supported by fuel quality standards, have driven the technological development of diesel engines over time and have greatly reduced the pollutant emission rates of modern diesel engines. All HD diesel engines that meet European Union Euro VI or United States EPA 2010 emission requirements, which achieve a 99% or greater reduction in black carbon (BC) emissions compared with untreated diesel exhaust, are considered soot-free. Heavy-duty diesel engines certified to these standards employ highly efficient emission control strategies and aftertreatment technologies to greatly reduce emissions of harmful pollutants, as well as the overall toxicity of diesel exhaust.[1] Reducing BC emissions from HD diesel vehicles is also a key component of a multipollutant, multisectoral strategy to avoid 0.5°C of additional warming over the next 25 years.[2]

As of July 2019, 39 countries have implemented soot-free standards for new HD diesel engines; five more have adopted such standards for implementation before 2025: Brazil, China, Colombia, India, and Mexico (see Figure 1). ICCT estimates nearly all countries will need to implement soot-free standards between 2020 and 2025 to meet the target of a 75% reduction in global on-road diesel BC emissions from 2010 to 2030.[3]

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[1] Health Effects Institute, "The Advanced Collaboration Emissions Study (ACES), Executive Summary," (December 2015), https://www.healtheffects.org/publication/executive-summary-advanced-collaborative-emissions-study-aces.

[2] Drew Shindell et al., "A climate policy pathway for near- and long-term benefits," *Science* 356, 6337 (2017): 493–494, https://doi.org/10.1126/science.aak9521.

[3] Joshua Miller, and Lingzhi Jin, *Global progress toward soot-free diesel vehicles in 2019,* (ICCT: Washington, DC, 2019), https://theicct.org/publications/global-progress-toward-soot-free-diesel-vehicles-2019.

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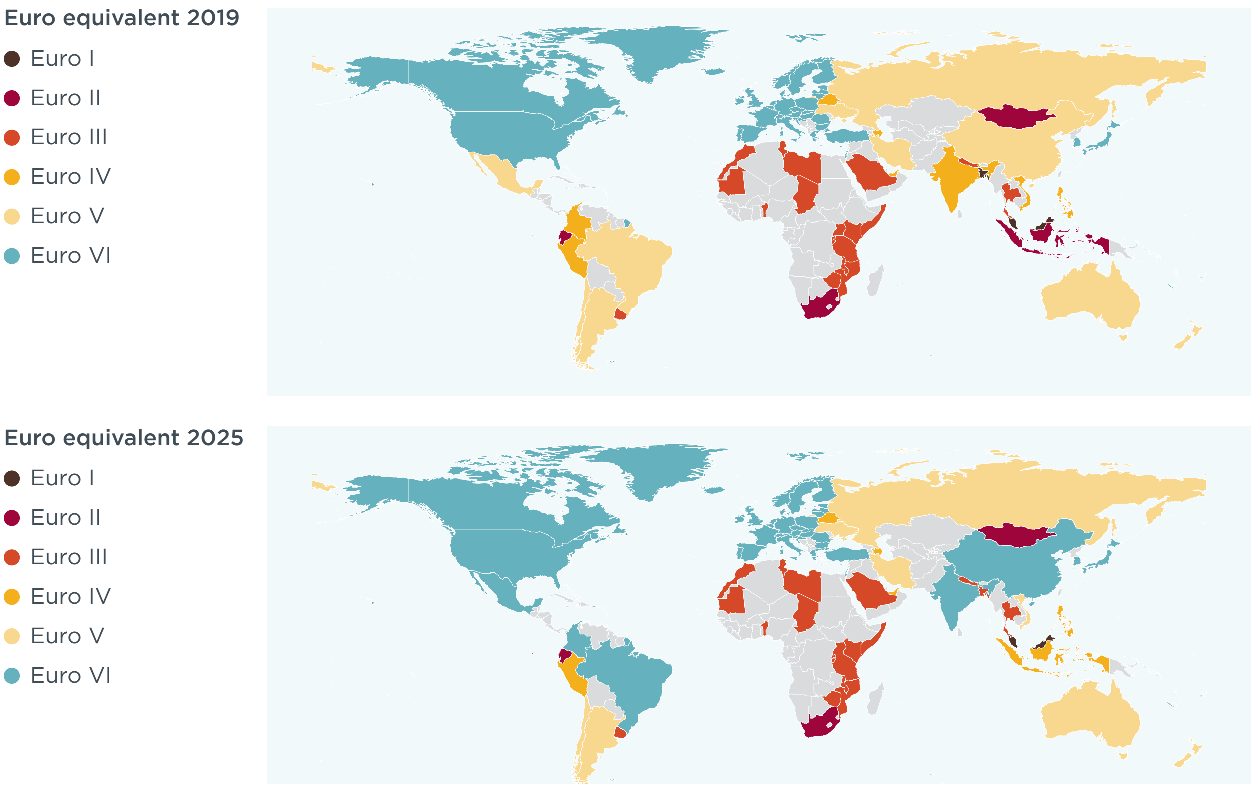

Figure 1. Implementation of heavy-duty diesel emission standards in 2019 and 2025. Source: Joshua Miller, Lingzhi Jin, *Global progress toward soot-free diesel vehicles in 2019*, (ICCT: Washington, DC, 2019).

Historically engine manufacturers have faced trade-offs between more efficient engines and better control of engine-out emissions of harmful pollutants, in particular nitrogen oxides (NO_x). Although modern emission control systems have removed some of this trade-off, the risk of higher fuel consumption may still be seen as a barrier to adopting soot-free standards. Any impacts of soot-free HD diesel engines on fuel consumption will directly influence carbon dioxide (CO_2) emissions. Moreover, aftertreatment technologies used in soot-free diesel engine designs also impact emissions of non-CO_2 climate pollutants, like BC and nitrous oxide (N_2O). As an increasing number of countries across the globe develop and implement HD vehicle efficiency and greenhouse gas (GHG) standards, it is important to understand the interactions between conventional pollutant control in soot-free diesel engines and climate pollutant emissions.

This paper explores the technological development of HD diesel engines used in the United States and the European Union in response to increasingly stringent emission standards, and the impacts of this technological development on fuel efficiency and climate pollutant emissions. The following sections present technology pathways for soot-free HD diesel engine designs; explore the effects of emission control technologies needed to meet soot-free standards on efficiency and climate pollutant emissions; present a comparative assessment of the performance of soot-free HD engines and vehicles; and consider how developments in HD vehicle efficiency and GHG standards and tailpipe emission standards will continue to influence the evolution of HD diesel engine designs.

Technology pathways for soot-free HD diesel engines

This section provides an overview of the progression of HD engine emission and fuel quality standards. It also describes the engine technologies needed to meet emission standards for HD diesel engines and their application in response to increasingly stringent regulatory programs in the United States and the European Union.

Emission standards

The United States and the European Union have promulgated increasingly stringent regulatory programs to control emissions from HD engines. Figure 2 shows the progression of NO_x and particulate matter (PM) emission limits through the various stages of the U.S. and EU programs, along with diesel fuel sulfur content limits. In each region, limits set in the current standards, Euro VI and EPA 2010, are 90%–95% lower than limits that were in place in 2000. Furthermore, the regulatory programs have been strengthened over time through the introduction of more representative certification test cycles, extended durability requirements, in-use test requirements, on-board diagnostic system specifications, and other provisions that have contributed to the improved real-world control of pollutant emissions from soot-free diesel engines. The addition of a particle number (PN) limit in the Euro VI regulation, in addition to PM mass-based limits, was the key driver of diesel particulate filter (DPF) adoption in European heavy-duty vehicle (HDV) engine designs. The emission standards for new engines in the U.S. and EU programs have been a primary driver of the development of diesel engine and aftertreatment technologies over the past 30 years.

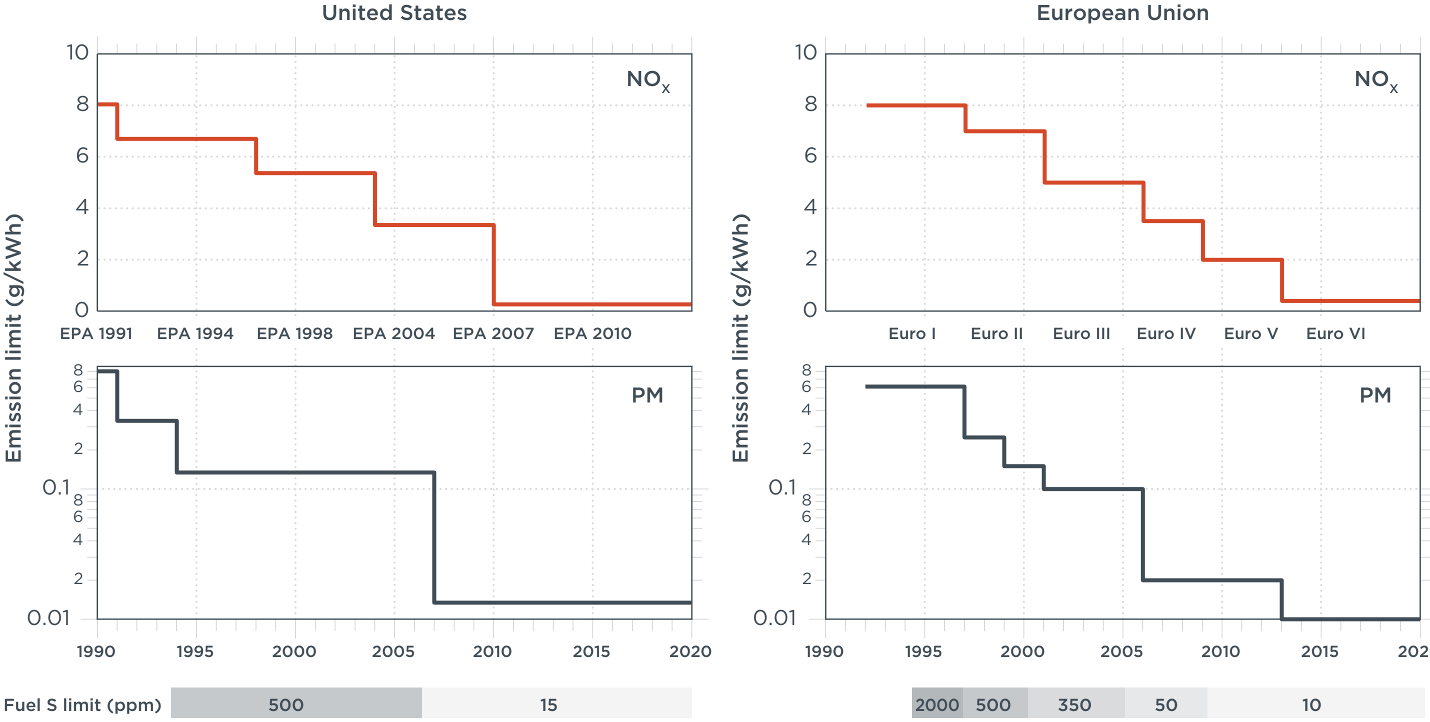

Figure 2. Comparison of on-road HD engine NO_x and PM emission limits and diesel fuel sulfur content limits in the United States and the European Union. Note log scale used for vertical axis in PM emission limit panels.

Emission control strategies and technologies

The emission control strategies developed to control air pollutant emissions from HD diesel engines can broadly be subdivided into two groups: in-cylinder approaches and exhaust aftertreatment devices. In-cylinder approaches encompass engine design changes and control strategies that aim to limit pollutant formation during the fuel combustion process. Emission control is achieved primarily through developments and modifications of the fuel injection and air handling systems, although in-cylinder approaches also include changes to engine geometries aimed at promoting better mixing of air and fuel. Engine-out NO_x emissions are reduced through the use of exhaust gas recirculation (EGR). In-cylinder emission control strategies have advanced through the widespread deployment of electronic engine controls, which enable better control over the combustion process.

For in-cylinder emission control approaches, there is often a trade-off between control of NO_x emissions and two other parameters—PM emissions and fuel consumption. Similarly, because of fundamentally different formation mechanisms, PM control strategies often are not effective in reducing NO_x emissions, and in some cases can lead to increased emissions of NO_x.

The adoption of soot-free emission standards in the United States and the European Union has lowered emission limits to a point where in-cylinder strategies are not sufficient to control both NO_x and PM emissions from HD diesel engines. The need for additional emission reductions beyond what is achievable through control of the combustion process alone has led to a need for aftertreatment technologies capable of removing pollutants from the exhaust gas stream. The key aftertreatment technologies applied in modern HD diesel engine designs include DPFs for the control of PM and selective catalytic reduction (SCR) systems for the control of NO_x. Diesel fuel sulfur content can affect both the performance and durability of aftertreatment systems. Sulfur tolerance varies among aftertreatment devices, although modern aftertreatment technologies are most effective when used with ultralow-sulfur diesel fuels of 10 ppm or less.

Table 1 is a brief overview of important technologies and strategies that have been used for the control of emissions from on-road HD diesel engines.

Table 1. Engine design strategies and aftertreatment technologies used for the control of air pollutant emissions from HD diesel engines.[4]

Design strategy/technology	Pollutants targeted	Description
In-cylinder—fuel injection system		
Fuel injection pressure	PM, NO_x, HC, CO[a]	Increased injection pressure allows for more aggressive EGR strategies without increasing PM formation as drastically as with lower pressures.
Rate of fuel injection, multiple injections	Rate shaping: NO_x Multiple injections: NO_x	Fine tuning of fuel injection during a single combustion event by varying rate of injection or using multiple injections. Multiple injection strategies require electronically controlled high-pressure unit injectors or common rail injection systems.
Fuel injection timing	Advanced: PM, CO, HC Delayed: NO_x	Advanced or delayed fuel injection to tune the combustion process. Advanced timing increases combustion pressures and temperatures resulting in improved fuel efficiency, reduced PM emissions, and increased NO_x formation. Delayed fuel injection timing reduces NO_x emissions at the expense of fuel economy and PM emission penalties.
EGR and air-handling technologies		
Exhaust gas circulation (EGR)	NO_x	Portion of exhaust gas mixed with intake air to serve as diluent, lowering peak combustion temperatures and reducing NO_x formation. EGR can be internal (i.e., residual exhaust is retained within the cylinder) or external (i.e., high- and/or low-pressure loops feed exhaust into the intake).
Turbocharger	PM, CO, HC	Turbine design to drive high-pressure or internal EGR. Wastegated, multiple-stage, and variable geometry turbochargers developed to improve turbocharger performance over a broad range of engine operating conditions.
Charge air and EGR coolers	NO_x	Heat exchanger used to lower temperature of gases entering combustion chamber to reduce peak combustion temperatures.
Aftertreatment devices		
Diesel oxidation catalyst (DOC)	PM[b], HC, CO	Flow-through catalytic converter composed of a monolith honeycomb substrate coated with a platinum group metal catalyst.
Diesel particulate filter (DPF)	PM	Wall-flow filtration device. Filters are regenerated using active and/or passive regeneration methods to oxidize and remove collected particles.
Selective catalytic reduction (SCR)	NO_x	Catalytic reduction of NO and nitrogen dioxide (NO_2) to N_2 and H_2O using ammonia as reducing agent. Catalyst types include vanadium, iron-exchanged zeolite, and copper-exchanged zeolite. Catalysts vary in effective temperature ranges, exhaust NO_2/NO_x sensitivity, and sulfur tolerance. Ammonia is generated from the decomposition of a urea solution, which is referred to as diesel exhaust fluid in the United States and by the brand name AdBlue in Europe.
Ammonia slip catalyst (ASC)	NH_3	Oxidation catalyst used for the control of ammonia passing through the SCR system.

[a] Carbon monoxide (CO). [b] DOC treats the soluble organic fraction of exhaust PM only.

Technology pathways

Figure 3 shows key engine technologies used to comply with each stage of U.S. and EU on-road HD engine emission control programs. In general, in-cylinder control strategies were sufficient to meet emissions requirements through the EPA 1998 and Euro III stages of on-road HD engine regulatory programs. To meet these standards, similar technologies were used in the two regions and included turbochargers, electronic engine controls, electronic unit injectors, and variable fuel injection. Succeeding regulatory stages introduced more stringent requirements and led to the development and widespread use of aftertreatment control technologies. Today, engines designed to meet EPA 2010 and Euro VI level emission requirements incorporate similar design elements: high-pressure variable fuel injection, cooled EGR, and an aftertreatment

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[4] Tim Dallmann, and Aparna Menon, *Technology pathways for diesel engines used in non-road vehicles and equipment*, (ICCT: Washington, DC, 2016), https://theicct.org/publications/technology-pathways-diesel-engines-used-non-road-vehicles-and-equipment.

system of DOC, DPF, SCR, and ASC in series.[5] A diagram of typical emission control technology packages used in Euro VI and EPA 2010 compliant on-road HD diesel engines is shown in Figure 4.[6]

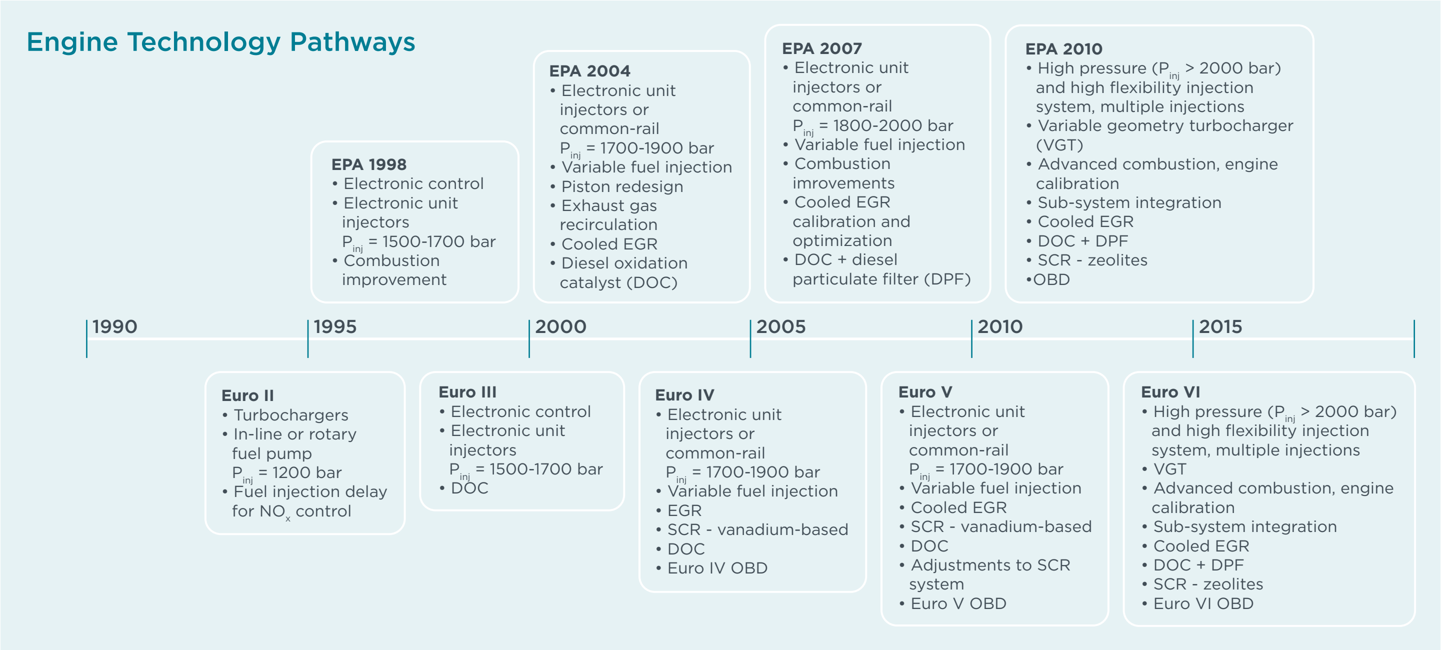

Figure 3. U.S. and EU regulatory compliance technology pathways for on-road HD diesel engines.

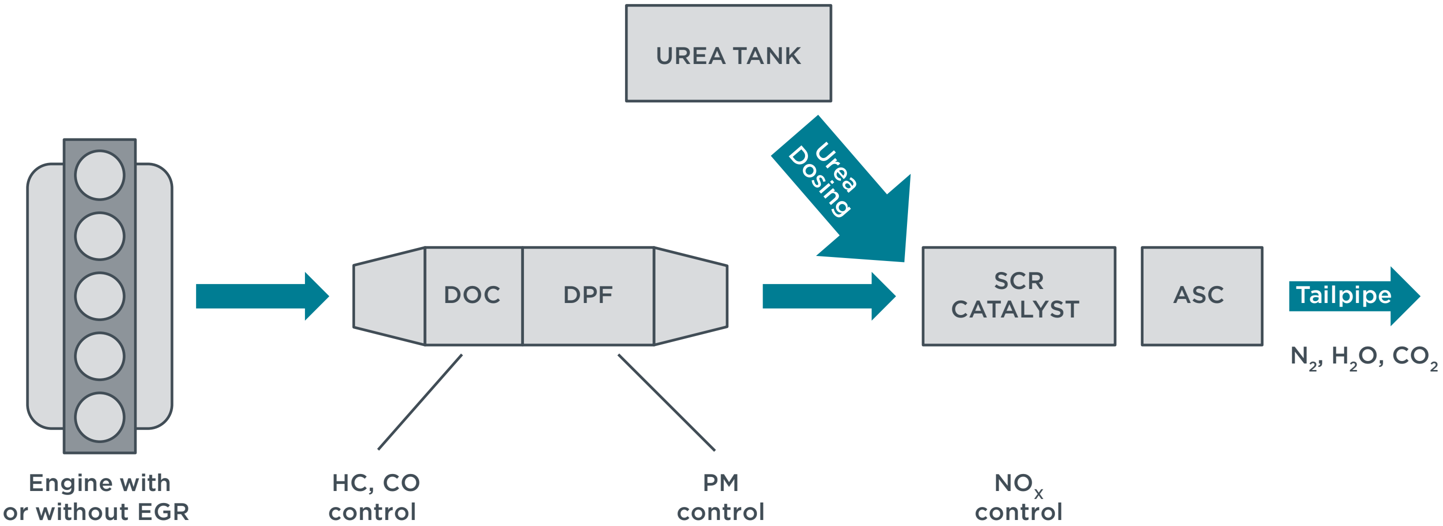

Figure 4. Diagram of typical emission control technology packages used in Euro VI and EPA 2010 compliant on-road HD diesel engines. Figure adapted from Ben Sharpe, and Oscar Delgado, *Engine technology pathways for heavy-duty vehicles in India*, (ICCT: Washington, DC, 2016).

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[5] Owing in part to a slightly higher NO_x emission limit in the Euro VI standards compared to the EPA 2010 NO_x limit, as well as higher diesel fuel prices in Europe, some manufacturers, such as Iveco and Scania, have developed Euro VI HD diesel engines that omit EGR and achieve NO_x control with SCR systems only.

[6] For further discussion of technology pathways of on-road HD diesel engines, please see Francisco Posada, Sarah Chambliss, and Kate Blumberg's *Costs of emission reduction technologies for heavy-duty diesel vehicles* (https://theicct.org/publications/costs-emission-reduction-technologies-heavy-duty-diesel-vehicles) and Ben Sharpe and Oscar Delgado's *Engine technology pathways for heavy-duty vehicles in India* (https://theicct.org/publications/engine-technology-pathways-heavy-duty-vehicles-india).

In other countries that have adopted but not yet implemented soot-free standards, such as China, India, and Brazil, engine designs and aftertreatment technology packages are expected to be similar to those developed for the U.S. and EU markets. In each of these regions, soot-free standards will largely follow the Euro VI regulation, including comparable emission limits and certification test cycles, although China has developed slightly more stringent in-use test and on-board diagnostic requirements.[7] At a minimum, soot-free standards will drive the adoption of DPF and SCR technologies for new HD diesel engines sold in these regions. As was the case in the European market, OEMs will likely have some flexibility in the design of NO_x control systems and whether to incorporate EGR. These decisions will likely be influenced by the relative prices of fuel and urea in each region, and engine and aftertreatment designs will be tailored to provide the lowest total cost of ownership for customers. These regions will benefit from the development and maturation of aftertreatment technologies in the U.S. and EU markets.

Some examples of the direction of soot-free HD diesel engine designs outside of the U.S. and EU have emerged in India, where Bharat Stage VI (BS VI) standards for HD engines came online starting April 2020. Following the adoption of the BS VI standards in 2016, researchers investigated various technology packages available to OEMs to meet the more stringent requirements introduced in the regulation. They found that aftertreatment systems consisting of cooled EGR, DOC, DPF, and SCR were most likely to be used in the Indian market given current fuel and urea pricing.[8] Subsequent announcements from major manufacturers of HD diesel engines for the Indian market have confirmed this technology package. Ashok Leyland has developed a technology package to comply with BS VI standards that includes EGR, DOC, DPF, SCR and ASC.[9] Similarly, Cummins highlighted the introduction of DPF and SCR aftertreatment systems in new engines that have successfully completed BS VI certification testing.[10]

Effects of emission control on engine fuel efficiency and climate pollutant emissions

This section reviews potential impacts on engine efficiency and fuel consumption, as well as emissions of non-CO_2 climate forcing species, resulting from the application of soot-free diesel engine emission control technologies and exhaust aftertreatment systems.

Fuel efficiency and CO_2 emissions

Exhaust gas recirculation

Exhaust gas recirculation technology has been applied widely to control engine-out NO_x emissions from HD on-road diesel engines since the early 2000s. In the United States, engine manufacturers introduced cooled EGR systems to achieve compliance with

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[7] Tim Dallmann, and Anup Bandivadekar, *India Bharat Stage VI emission standards,* (ICCT: Washington, DC, 2016), https://theicct.org/publications/india-bharat-stage-vi-emission-standards; Joshua Miller, Francisco Posada, *Brazil PROCONVE P-8 emission standards,* (ICCT: Washington, DC, 2019), https://theicct.org/publications/brazil-proconve-p-8-emission-standards; Liuhanzi Yang, Hui He, *China's Stage VI emissions standard for heavy-duty vehicles (final rule)* (ICCT: Washington, DC, 2018), https://theicct.org/publications/china%E2%80%99s-stage-vi-emissions-standard-heavy-duty-vehicles-final-rule.

[8] Peter Heuser et al., "Bharat Stage VI Solutions for Commercial Engines for the India Market," SAE Technical Paper 2017-26-0043 (2017), https://www.doi.org/10.4271/2017-26-0043.

[9] Georg Hüthwohl, and Krishnan Sadagopan, "The new developed Ashok Leyland BSVI aftertreatment system," ECT Conference 2019, http://www.ecmaindia.in/uploads/files/Dr.%20Georg%20Huthwohl%20(Albonair).pdf.

[10] "Cummins India successively completes BS-VI compliance tests with the ARAI," First Post, September 16, 2019, https://www.firstpost.com/tech/news-analysis/cummins-india-successfully-completes-bs-vi-compliance-tests-with-the-arai-7349111.html.

the 2.0 g/bhp-hr (2.7 g/kWh) NO_x limit adopted in EPA 2004 emission standards.[11] To comply with the tightened NO_x limit of 0.2 g/bhp-hr (0.27 g/kWh) introduced in EPA 2010 standards, manufacturers have continued to use EGR in combination with SCR systems. In Europe, EGR was first introduced at the Euro IV stage in 2005, although the predominant NO_x compliance strategy at the time relied on SCR rather than EGR. This design strategy continued through the Euro V stage of European HD engine emission standards, and EGR was used only by a few manufacturers to supplement SCR systems.[12] Most engines designed to comply with the Euro VI 0.4 g/kWh NO_x limit employ both EGR and SCR for NO_x control. However, two engine manufacturers, Iveco and Scania, have developed Euro VI-compliant engines that omit EGR and rely solely on high-efficiency SCR systems for NO_x control.

Exhaust gas recirculation can affect engine efficiency and fuel consumption in several ways. Work is required to pump exhaust from the exhaust manifold to the intake manifold of the engine, resulting in pumping losses and decreased engine efficiency. Further, in high-pressure cooled EGR loops, exhaust energy that can normally be recovered across the turbine of the turbocharger, is lost to engine coolant.[13] The magnitude of the fuel consumption penalty associated with EGR systems depends on a number of factors, including the system design and EGR rate, and is generally less than penalties incurred through the application of alternative in-cylinder NO_x control strategies such as delayed fuel injection timing.[14]

Diesel particulate filters

Diesel particulate filters are currently the best available PM control technology for diesel engines, making them a critical component of soot-free HD diesel engine designs. In the U.S. market, DPFs achieved near-universal application in on-road HD diesel engines with the implementation of EPA 2007 emission standards, which established a 0.01 g/bhp-hr (0.013 g/kWh) PM emission limit, representing a 90% reduction from the previous standard. In the European Union, the widespread use of DPFs in HD diesel engine designs came about somewhat later. Diesel particulate filters were not required to meet PM limits set through the Euro V stage of European emission standards for HD diesel engines, and market penetration remained relatively low, at less than 10%, from about 2005 until 2013.[15] This changed with the tightening of the PM limit and introduction of a particle number limit in the Euro VI regulation, which forced DPFs into all new HD diesel engine designs beginning in 2013.

Like EGR systems, the integration of DPFs into HD diesel engine designs can affect fuel consumption and, therefore, CO_2 emissions in a number of ways. The presence

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[11] Manufacturers could, alternatively, certify engines to a combined non-methane hydrocarbon (NMHC) + NO_x limit of 2.4 g/hp-hr (3.2 g/kWh).

[12] Hannu Jääskeläinen, and Magdi K. Khair, "Exhaust Gas Recirculation," *Dieselnet*, https://www.dieselnet.com/tech/engine_egr.php (accessed December 20, 2019); Francisco Posada, Sarah Chambliss, Kate Blumberg, *Costs of emission reduction technologies for heavy-duty diesel vehicles,* (ICCT: Washington, DC, 2016), https://theicct.org/publications/costs-emission-reduction-technologies-heavy-duty-diesel-vehicles.

[13] U.S. Environmental Protection Agency, "Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements" (2000), https://nepis.epa.gov/Exe/ZyPDF.cgi/P100K576.PDF?Dockey=P100K576.PDF; U.S. Department of Transportation National Highway Traffic Safety Administration, "Commercial Medium- and Heavy-Duty Truck Fuel Efficiency Technology Study – Report #1" (2015), https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/812146-commercialmdhd-truckfuelefficiencytechstudy-v2.pdf.

[14] Magdi K. Khair, and Hannu Jääskeläinen, "Effect of EGR on Emissions and Engine Performance," *Dieselnet*, https://www.dieselnet.com/tech/engine_egr_emissions.php (accessed December 20, 2019).

[15] Felipe Rodríguez, Rachel Muncrief, Oscar Delgado, and Chelsea Baldino, *Market penetration of fuel-efficiency technologies for heavy-duty vehicles in the European Union, the United States, and China,* (ICCT: Washington, DC, 2017), https://theicct.org/publications/market-penetration-fuel-efficiency-technologies-heavy-duty-vehicles-european-union.

of a DPF increases exhaust backpressure, which leads to increased pumping losses and a fuel consumption penalty. This penalty increases with increased soot and ash accumulation on the filter. To limit this impact and maintain efficient performance, filters must be regenerated, whereby trapped carbonaceous PM is oxidized to CO_2 and removed from the filter. Filter regeneration can be done actively or passively. In active regeneration systems, oxygen is used to oxidize trapped PM, a process that requires temperatures over 550°C. Because such temperatures are seldom reached during normal vehicle operation, the exhaust temperature must be actively raised through other means. A common approach is to inject fuel upstream of the oxidation catalyst, where the exothermic oxidation of unburned hydrocarbons provides the high temperatures needed for PM oxidation.[16] In active regeneration systems, the use of fuel in the filter regeneration process leads to a fuel consumption penalty. In passive regeneration systems, NO_2 produced from the oxidation of engine-out NO over the DOC is used to oxidize trapped PM at comparatively lower temperatures, about 250°C, than during active regeneration. Because extra fuel is not used in the regeneration process, passive systems have fuel economy benefits when compared to active systems.

The magnitude of the fuel consumption penalty associated with DPFs depends on a number of factors, including the filter regeneration strategy, PM loading rate, regeneration frequency, duty cycle, and DPF design factors such as substrate wall thickness, average pore size, and porosity. Research into the effects of various PM loading and DPF regeneration strategies on the fuel consumption of a diesel engine found the fuel penalty associated with the DPF ranges from 2% to 8%.[17] For most engine-out PM levels, the fuel penalty associated with regeneration exceeded the penalty due to backpressure, indicating strategies to promote passive filter regeneration should be prioritized to reduce the impact of DPFs on fuel consumption. In the rulemaking documents for the EPA 2007 and EPA 2010 HD engine standards, the EPA anticipated that the additional pumping work associated with DPFs would lead to a 1% fuel economy penalty; however, EPA expected this penalty to be offset by optimization of the engine and aftertreatment systems.[18] A more recent assessment conducted in support of the development of HDV efficiency and GHG standards estimated a fuel consumption penalty of 1.5% to 2% for DPFs used in engines designed to comply with EPA 2007 standards.[19] The authors anticipated that this penalty would decrease to significantly less than 0.5% in EPA 2010 engine designs because of the low engine-out PM engine calibrations enabled through the application of SCR aftertreatment systems.

Selective catalytic reduction

Selective catalytic reduction systems to control NO_x emissions from on-road HD diesel engines were first widely used in Europe in response to the implementation of Euro IV emission standards beginning in 2005. SCR-based NO_x control was the primary compliance strategy to meet the 3.5 g/kWh Euro IV NO_x limit, although some manufacturers employed EGR-based NO_x control strategies. With the further tightening of the NO_x limit to 2.0 g/kWh in the Euro V standards, SCR systems achieved full

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[16] Ibid.

[17] Navtej Singh et al., "Investigation into Different DPF Regeneration Strategies Based on Fuel Economy Using Integrated System Simulation," SAE Technical Paper 2009-01-1275 (2009), https://doi.org/10.4271/2009-01-1275.

[18] U.S. Environmental Protection Agency, "Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements" (2000), https://nepis.epa.gov/Exe/ZyPDF.cgi/P100K576.PDF?Dockey=P100K576.PDF.

[19] Matthew A. Kromer, Wendy W. Bockholt, and Michael D. Jackson, *Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles*, (TIAX: Cupertino, CA, 2009).

market penetration in on-road HD diesel engines.[20] Relative to the European market, widespread use of SCR systems in HD diesel engine designs was delayed by about five years in the United States. Prior to the full implementation of the EPA 2010 NO_x limit of 0.2 g/bhp-hr, manufacturers of engines for the U.S. market were able to achieve compliance with NO_x control requirements using EGR and in-cylinder control strategies. However, the more stringent NO_x limit introduced in EPA 2010 has driven the near universal application of SCR in the United States.

Unlike EGR and DPFs, the application of SCR systems in HD diesel engine designs is not associated with a fuel consumption penalty. In fact, SCR systems promote fuel efficiency improvements by moving NO_x control to the exhaust aftertreatment system, thereby reducing the need for in-cylinder NO_x control. Because of the trade-off between in-cylinder control of NO_x emissions and fuel consumption, the use of SCR allows engine designers to reduce EGR rates and calibrate engines for higher efficiency. These calibrations also tend to lower engine-out PM emissions and, consequently, PM loading in the DPF for soot-free engine designs. This tends to reduce the engine backpressure originating from the DPF, as well as the need for active filter regeneration, both of which support improved engine efficiency. An assessment of fuel economy technologies for medium- and heavy-duty vehicles estimated that the introduction of SCR aftertreatment in EPA 2010 engine designs would improve fuel consumption by 3% relative to EPA 2007 engines employing EGR as the primary NO_x control method.[21]

System integration

Previous sections discussed the impacts on engine efficiency and fuel consumption of individual emission control technologies. These technologies are not applied in isolation, and the degree to which their application will impact fuel consumption will depend on how they are integrated into the complete engine design. Furthermore, additional developments that have improved the performance of diesel engines, such as electronic engine controls and better fuel injection systems, have worked to offset fuel consumption penalties introduced by modern emission control systems.

When assessing the impacts of soot-free diesel engines on efficiency and CO_2 emissions, it is also important to note the influence of different implementation pathways in the U.S. and EU on efficiency and emissions trends. In the EU, SCR systems were integrated into HD diesel engine designs prior to DPFs, which gained widespread use only with the introduction of Euro VI emission standards. In contrast, DPFs—required for compliance with EPA 2007 PM limits—preceded SCR systems in U.S. HD diesel engines. Countries like India that are following the European regulatory pathway for HD engines but have leapfrogged emission standard stages to accelerate the introduction of soot-free engines will have unique technology pathways that avoid the staged implementation of aftertreatment control technologies.

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[20] Felipe Rodríguez, Rachel Muncrief, Oscar Delgado, and Chelsea Baldino, *Market penetration of fuel-efficiency technologies for heavy-duty vehicles in the European Union, the United States, and China*, (ICCT: Washington, DC, 2017), https://theicct.org/publications/market-penetration-fuel-efficiency-technologies-heavy-duty-vehicles-european-union.

[21] Matthew A. Kromer, Wendy W. Bockholt, and Michael D. Jackson, *Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles*, (TIAX: Cupertino, CA, 2009).

Nitrous oxide emissions

Nitrous oxide is a potent greenhouse gas, with a climate warming impact 265 times that of CO_2 when compared over a 100-year time period.[22] Emissions of N_2O from diesel engines without aftertreatment systems are very low; the predominant nitrogenous exhaust species are NO and NO_2. The addition of catalytic emission control equipment to soot-free diesel engine designs in the form of diesel oxidation catalysts, selective catalytic reduction systems, and ammonia slip catalysts can affect the ratio of NO_2/NO in the exhaust stream and lead to the formation of additional nitrogen-containing species like N_2O and ammonia (NH_3). With respect to N_2O, there are a number of formation pathways within the emission control systems applied in soot-free diesel engine designs. At low temperatures of around 250°C, decomposition of ammonium nitrate formed over the SCR catalyst is the predominant N_2O formation mechanism, whereas at higher temperatures, above 500°C, the primary mechanism is ammonia oxidation. Parameters that influence N_2O formation include exhaust temperature, NO_2-to-NO_x ratio, ammonia-to-NO_x ratio, SCR catalyst formulation, and the temperature of the catalyst. [23]

Because of the high warming potential of N_2O, it is important that emissions of this species are minimized in soot-free diesel engine designs. Otherwise, there is a risk that the benefits of reductions in the emissions of other climate pollutants, such as BC, may be partially offset by increased N_2O emissions. In the United States, a N_2O emission limit of 0.10 g/bhp-hr (0.134 g/kWh) was introduced in 2014 for HD diesel engines in the GHG and fuel efficiency standards for medium- and heavy-duty engines and vehicles developed by the U.S. Environmental Protection Agency and Department of Transportation.[24] In contrast, the European Union currently does not regulate N_2O emissions from HD diesel engines.

Black carbon emissions

Black carbon contributes 3200 times as much climate warming as CO_2 over a 20-year time horizon and 900 times as much over a 100-year time horizon. Control of BC emissions from HD diesel engines is key to limiting the near-term warming impacts of short-lived climate pollutants. Soot-free HD diesel engines employ DPFs to control emissions of BC, and the application of this control technology has greatly reduced emissions of this species from modern diesel engines.

Figure 5 shows estimates of BC emission factors by emission standard for three HD vehicle types. When expressed on a per-kilometer basis, BC emissions from soot-free (Euro VI) HD vehicles are 99% lower than those from HD vehicles equipped with diesel engines not subject to Euro standards (Euro 0). The application of DPFs in Euro VI HD vehicles results in significant reductions in BC emissions relative to Euro V vehicles—ranging from 92% to 96% depending on vehicle type. When BC emission factors are

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[22] Like N_2O, methane is an important GHG, and emissions of methane to the atmosphere have a considerable near-term warming impact. We do not include methane in our assessment of the climate impacts of soot-free diesel engines because emissions of methane from these engines, as well as older technology diesel engines, are very low. Methane emissions are of greater concern for HD vehicles equipped with engines fueled by compressed or liquified natural gas.

[23] Manufacturers of Emission Controls Association, "Technology feasibility for model year 2024 heavy-duty diesel vehicles in meeting lower NOx standards," (June 2019), http://www.meca.org/resources/MECA_MY_2024_HD_Low_NOx_Report_061019.pdf.

[24] 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.

converted to a CO_2-equivalent basis using the 20-year (100-yr) global warming potential value of 3200 (900), this translates to reductions in emissions of 787–1204 gCO_2e/km (221–340 gCO_2e/km) for Euro VI vehicles compared to Euro 0 vehicles and 58–129 gCO_2e/km (16–36 gCO_2e/km) for Euro VI vehicles compared to Euro V vehicles using SCR technologies.

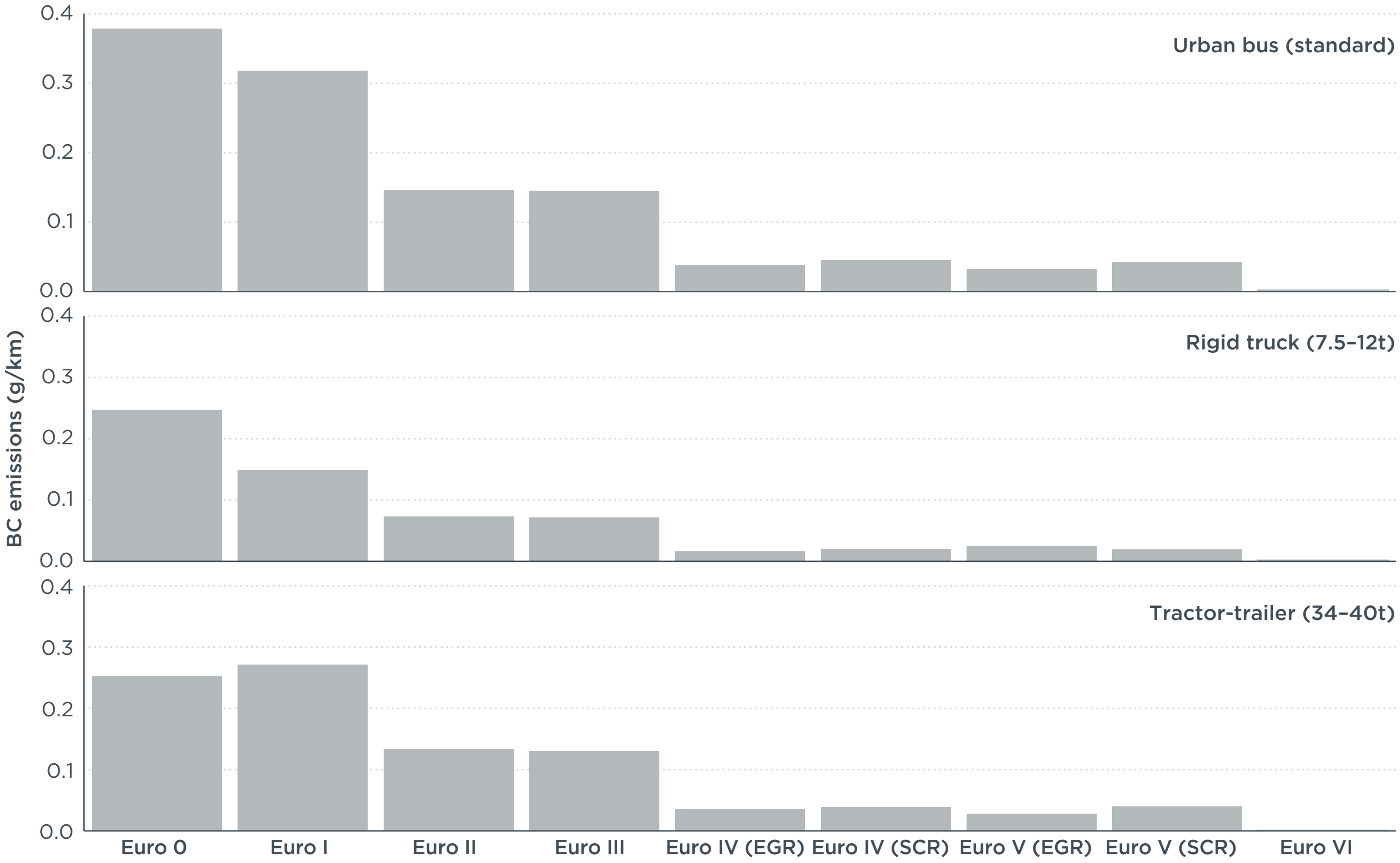

Figure 5. Black carbon emission factors by emission control level for three HD vehicle types. Emission factors are sourced from Handbook Emission Factors for Road Transport, (HBEFA version 4.1), https://hbefa.net/e/index.html.

Comparative assessment of fuel consumption and emissions of soot-free diesel engines

The previous section reviews the impacts the application of emission control technologies typical of soot-free HD diesel engine designs may have on engine efficiency and emissions of CO_2 and non-CO_2 climate pollutants. Here we investigate the fuel consumption and emissions of current soot-free HD diesel engines and vehicles compared to diesel engines and vehicles certified to prior emission standards. Our aim is to identify and analyze data sources where these groups of diesel engines and vehicles are tested under similar conditions and using similar methodologies. These data sources include laboratory chassis and engine dynamometer emissions testing; national, fleetwide surveys and estimates; and on-road testing.

U.S. EPA HD engine certification database

The U.S. EPA's HD engine certification database compiles data submitted by engine manufacturers during the certificate of conformity application process.[25] These data include engine dynamometer certification emissions testing results. For this analysis, we extracted PM, NO_x, and CO_2 data for HD diesel engines tested on the U.S. EPA Federal Test Procedure (FTP) cycle and for engines with model years ranging from 1998 to 2019 and power ranging from 110 to 630 hp. Database entries with no PM or NO_x results were excluded from the analysis. Figure 6 shows a comparison of CO_2 and NO_x certification testing results, with indications of the emission control system employed for each engine.[26] Figure 7 shows a similar comparison of BC and CO_2 emissions.[27]

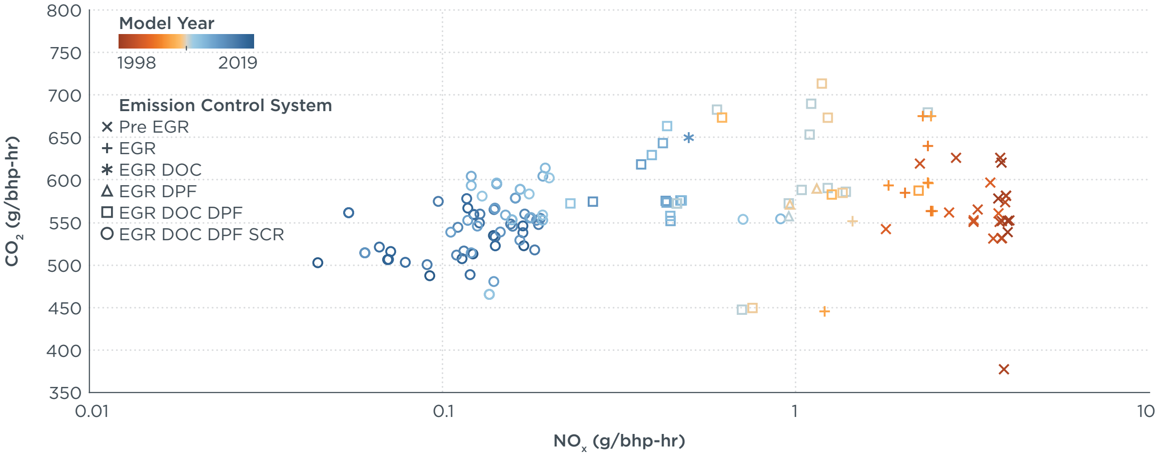

Figure 6. U.S. EPA heavy-duty diesel engines certification levels comparing NO_x and CO_2. Note log scale used for horizontal axis.

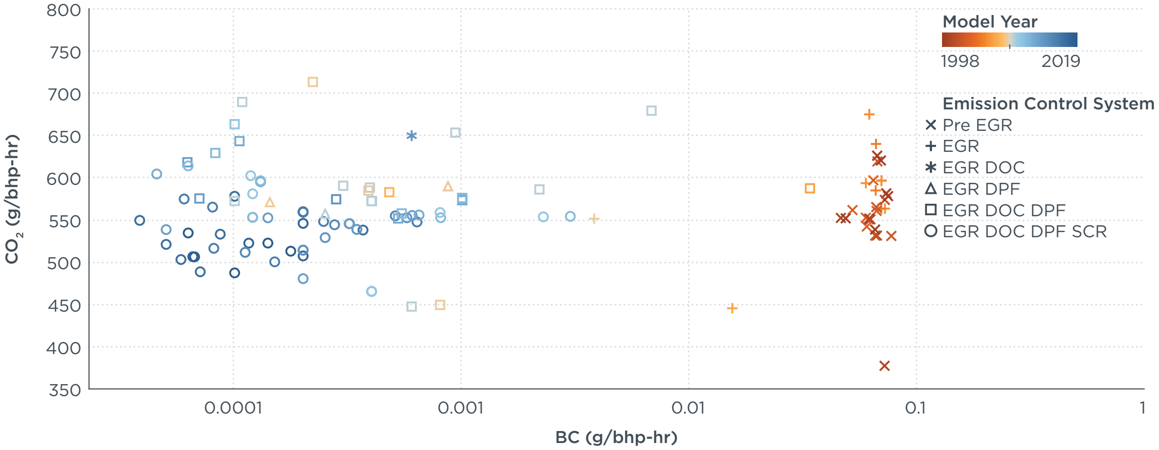

Figure 7. U.S. EPA heavy-duty diesel engines certification levels comparing BC and CO_2. BC emission rates are calculated using reported PM certification levels along with assumed BC to PM mass emission ratios reported in the EPA MOVES model. Note log scale used for horizontal axis.

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[25] "Annual Certification Data for Vehicles, Engines, and Equipment: Heavy-Duty Highway Gasoline and Diesel Certification Data," U.S. Environmental Protection Agency, accessed June 2019, https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-data-vehicles-engines-and-equipment.

[26] Entries with no PM or NO_x readings are excluded. Emission control systems are not identified for data after 2015, but most engines in years just prior to that have a combination of EGR, DOC, DPF, and SCR, thus we assume the same for the years after 2015.

[27] BC data are derived from PM test results based on speciation from EPA's MOtor Vehicle Emission Simulator (MOVES): 0.1 on or after 2017 and 0.77 before 2017.

One key observation illustrated in each of the two figures is the dramatic reduction in NO_x and BC emissions that has occurred over the past 20 years. The application of advanced emission control strategies and technologies has resulted in certification emission levels for modern, soot-free diesel engines that are more than an order of magnitude lower than those of engines that do not employ these technologies. At the same time, manufacturers have been able to achieve these low emission levels while generally maintaining engine efficiency, as evidenced by the relative flat CO_2 emission trends. Although there appears to be some increase in CO_2 emissions when EGR is introduced, the spread in CO_2 emission levels for engines employing similar emission control systems is greater than differences across engines with different control systems. Modern, soot-free engines equipped with SCR aftertreatment have among the lowest CO_2 emissions over the FTP cycle of any engines included in the database, with evidence of the impacts of the U.S. HD engine GHG and efficiency standards apparent in data from the most recent years.[28]

IEA AMF commercial vehicle test program

The second data source considered in this comparative assessment is an extensive investigation of fuel and technology alternatives for commercial vehicles carried out by the International Energy Agency Technology Collaboration Programme on Advanced Motor Fuels (IEA AMF).[29] The study included chassis dynamometer testing of 35 different commercial vehicles over common test cycles, covering a broad matrix of engine technology and fuel options, including diesel medium- and heavy-duty trucks and semi-trailer tractors certified to Euro IV, V, and VI emission standards. Testing on common test cycles allows for direct comparison of the performance and emissions of soot-free Euro VI HD vehicles with those of vehicles certified to prior emission standards.

Figure 8 shows the measured specific energy consumption of diesel trucks included in the test program as a function of test weight. These results support one of the key findings reported by the authors of the study—Euro VI diesel trucks show no fuel consumption penalty when compared to vehicles compliant with previous regulations. The specific energy consumption of Euro V and Euro VI diesel trucks tested in the study was similar and both are somewhat lower than that of Euro IV diesel trucks, in particular at lower vehicle weights. Although not shown here, the study also confirmed significant reductions in regulated tailpipe pollutant emissions for Euro VI vehicles relative to vehicles and engines certified to prior standards. Citing evidence that manufacturers were able to develop solutions to comply with Euro VI emission standards while maintaining the fuel efficiency of HD diesel vehicles, the study's authors conclude that "...countries with less stringent emission legislation in place, when considering tightening requirements, should not go for Euro IV or Euro V, but rather leapfrog to Euro VI, on the condition that high quality fuel is available."[30]

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[28] Ben Sharpe, *U.S. greenhouse gas emissions and fuel efficiency standards for medium- and heavy-duty engines and vehicles*, (ICCT: Washington, DC, 2011), https://theicct.org/publications/us-heavy-duty-vehicle-standards; Nic Lutsey, Rachel Muncrief, Ben Sharpe, Oscar Delgado, *U.S. efficiency and greenhouse gas emission regulations for MY 2018–2027 heavy-duty vehicles, engines, and trailers*, (ICCT: Washington, DC, 2015), https://theicct.org/publications/us-efficiency-and-greenhouse-gas-emission-regulations-my-2018%E2%80%932027-heavy-duty-vehicles.

[29] IEA Alternative Motor Fuels Technology Collaboration Programme, "Fuel and Technology Alternatives for Commercial Vehicles," Annex 49 (October 2016), https://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_49.pdf.

[30] Ibid., 3.

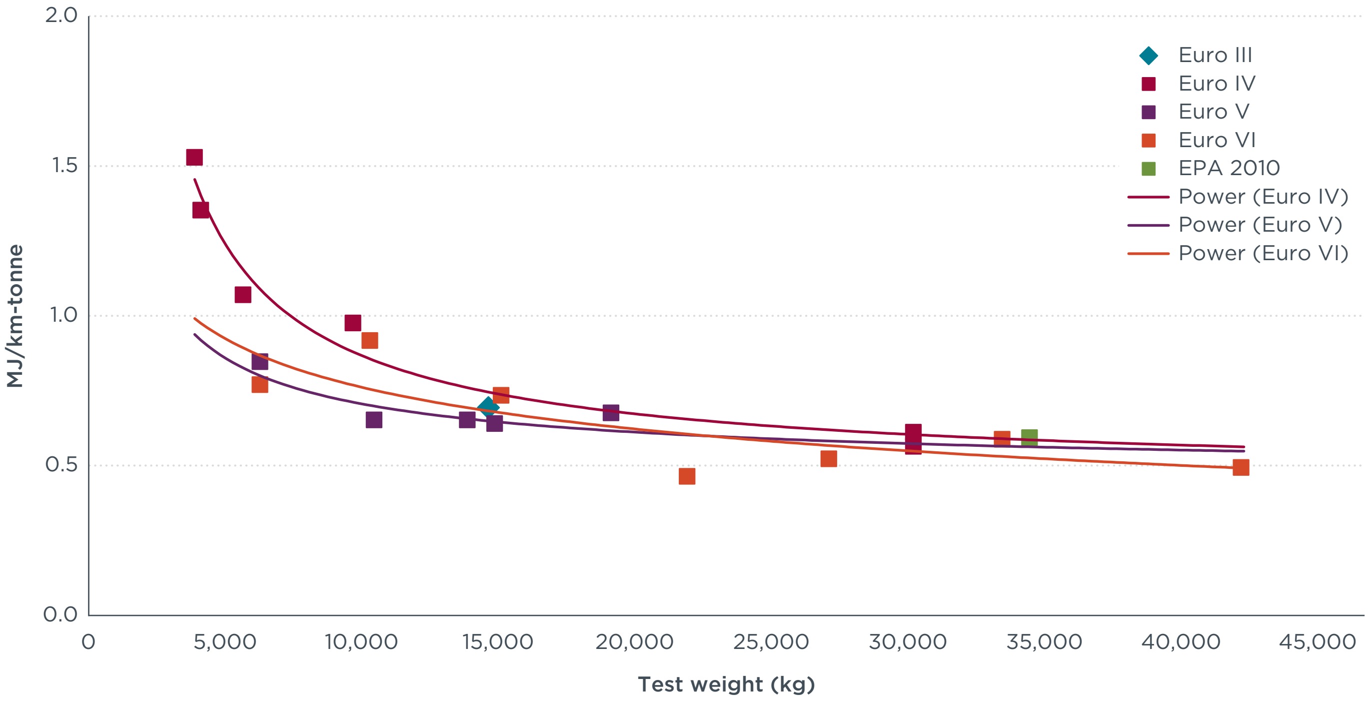

Figure 8. Specific energy consumption by emission class for diesel medium- and heavy-duty trucks and semi-trailer tractors tested over the Worldwide Harmonized Vehicle Cycle. Adapted from IEA Alternative Motor Fuels Technology Collaboration Programme, "Fuel and Technology Alternatives for Commercial Vehicles," Annex 49 (October 2016).

*Trans Aktuell/*Fehrenkötter long-term test program

Turning from laboratory dynamometer testing to on-road evaluation, the next data source we consider is long-term performance monitoring of Euro V and VI diesel trucks sponsored by the German magazine *Trans Aktuell* and Fehrenkötter, a transport and logistics company. As part of a technology comparison evaluation, seven Euro V diesel trucks from leading European manufacturers operating in the Feherenkötter fleet were tracked over a period of nearly three years, from 2007 to 2010. Detailed information regarding fuel and urea consumption, operating and maintenance costs, and other parameters relevant to total cost of ownership assessment was collected for each truck and published at the conclusion of the evaluation period.[31] A similar evaluation of Euro VI diesel trucks from the same manufacturers was carried out between 2014 and 2016.[32] Information on the vehicles tested during these evaluations is listed in Table 2.

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[31] "Am Ziel [At the Finish]," Trans Acktuell, September 2010, https://www.fehrenkoetter.de/fileadmin/user_upload/Dokumente/Medienberichte/F_Test_Am_Ziel_ta2010.pdf

[32] Markus Braun, "Sieben Kandidaten ziehen Bilanz [Seven candidates take stock], Trans Acktuell, September, 2016, https://www.volvotrucks.de/content/dam/volvo/volvo-trucks/markets/germany/trucks/testberichte/pdf/2016/2016-09-trans-aktuell-volvo-fh-gewinnt-fehrenkoetter-test.pdf

Table 2. Description of vehicles included in the *Trans Aktuell*/Fehrenkötter long-term test program.

Euro standard	Manufacturer	Model
Euro V	DAF	XF105.410
Euro VI	DAF	XF 460
Euro V	Iveco	Stralis AS 260 S 42
Euro VI	Iveco	Stralis 460
Euro V	MAN	TGA 24.400
Euro VI	MAN	TGX 24.440
Euro V	Mercedes	Actros 2541
Euro VI	Mercedes	Actros 2545
Euro V	Renault	Premium 410.25
Euro VI	Renault	T440
Euro V	Scania	R 420
Euro VI	Scania	R 450
Euro V	Volvo	FH 400
Euro VI	Volvo	FH 460

Although the sample size of trucks tested in the evaluations is small, the long-term nature of the monitoring program (each truck was tracked for 320,000–420,000 km), the similarities in vehicle characteristics, and the common fleet make this a unique dataset for comparing Euro V and Euro VI truck performance. Figure 9 shows fuel consumption for each truck averaged over the 3-year monitoring period, along with engine specifications. The data show that almost all manufacturers tested have improved fuel consumption over the years during the transition from Euro V to Euro VI. The one exception was Renault, where the Euro VI truck included in the evaluation had slightly higher fuel consumption than the Euro V truck. The engine power and capacity are similar for tested models with the same manufacturer, although both engine characteristics tended to be slightly greater in the Euro VI engines. In general, most manufacturers were able to improve fuel economy and increase engine power, even as emission standards tightened from Euro V to Euro VI.

Because of the limited number of vehicles tested as part of this study, some caution should be exercised in interpreting these results as reflective of broader trends across the industry. However, these data are consistent with IEA AMF chassis dynamometer test results and add further support to the argument that the transition from Euro V to Euro VI did not result in a fuel consumption penalty for HD diesel trucks.

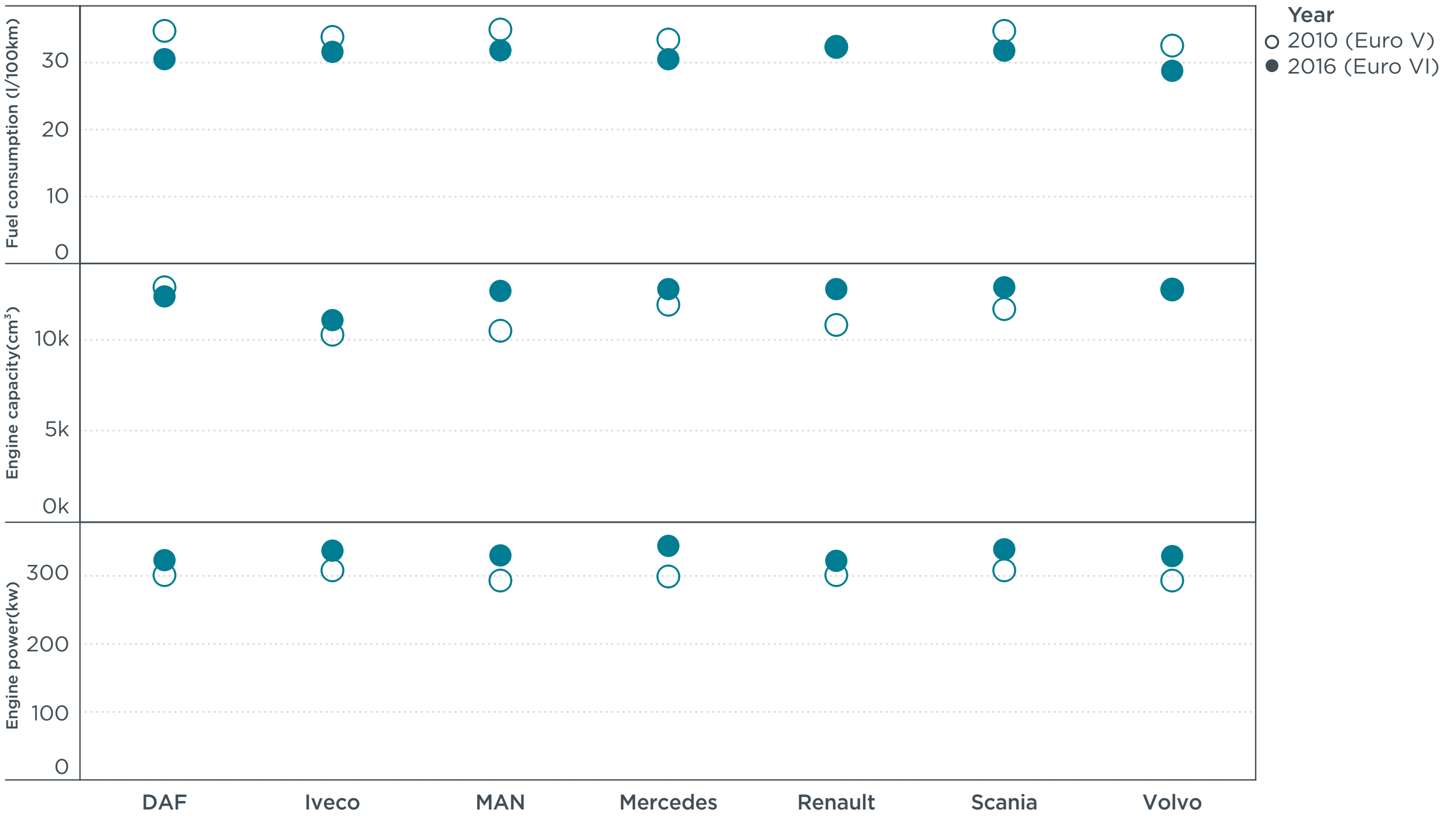

Figure 9. *Trans Aktuell*/Fehrenkötter long-term testing results for Euro V and Euro VI vehicles.

LastAuto Omnibus real-world fuel consumption testing

On-road evaluations of European HD truck performance are also regularly performed by a second German trucking magazine, *LastAuto Omnibus*. The magazine performs extensive real-world fuel consumption testing annually on a select group of HD vehicles over a set of different duty cycles. These data have been compiled and reviewed in previous ICCT publications.[33] Figure 10 shows fuel consumption results for tractor-trailers tested between 2002 and 2016 by engine manufacturer. Results are shown for tractor-trailers with engines in the 300 kW to 400 kW power range, which represents approximately 85%–90% of new tractor-trailer sales in Europe. Furthermore, results are shown for testing on the "overall/average" cycle, which represents a duty cycle weighting consistent with typical usage of tractor-trailers for long haul applications.

As can be seen in Figure 10, the *LastAuto Omnibus* testing data indicate that there was little change in the fuel consumption of tractor-trailers in the EU between 2002 and 2016. As with previous data presented in this section, this is another piece of evidence supporting the conclusion that the transition to soot-free Euro VI emission standards did not result in a fuel consumption penalty. These data show manufacturers were able to maintain fuel efficiency of tractor-trailers in the EU while greatly reducing emissions of PM and NO_x from these vehicles. However, the stagnation in fuel consumption

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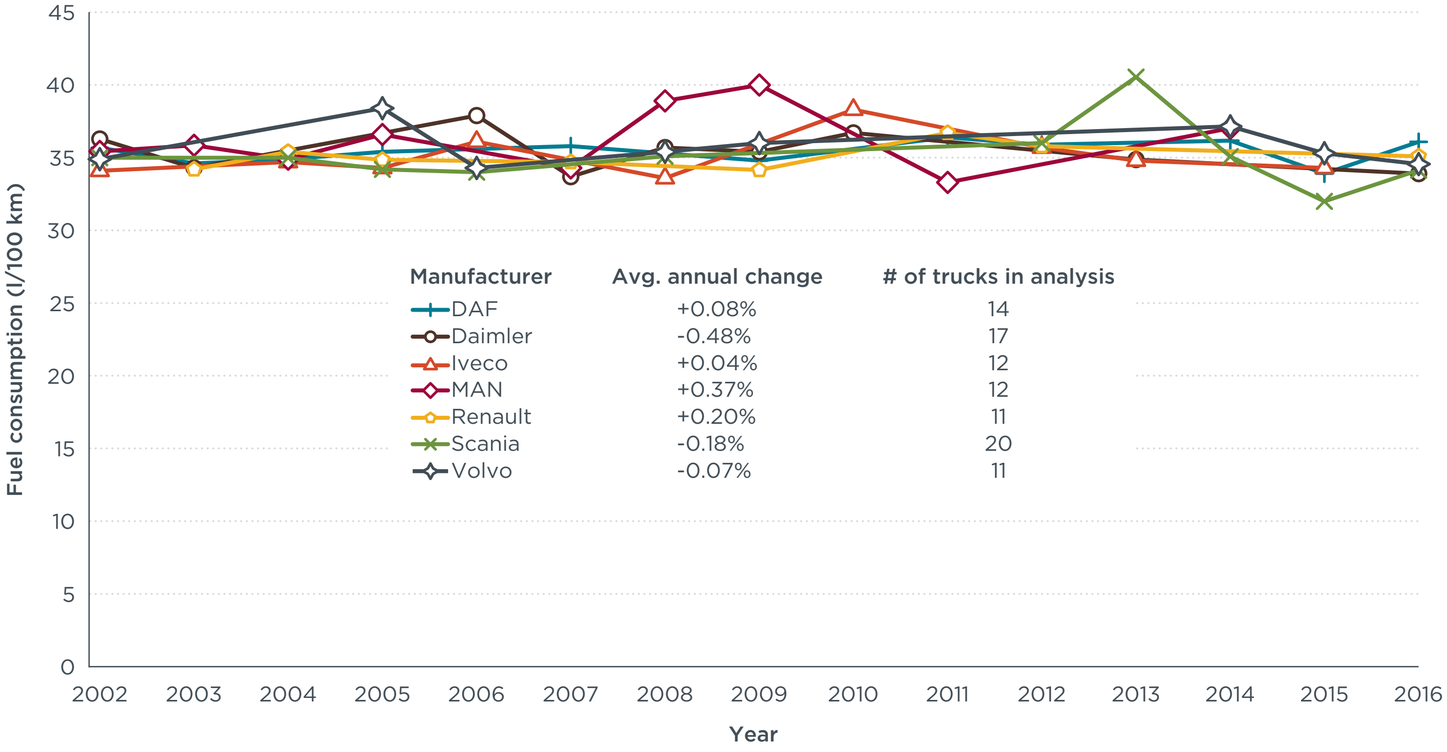
[33] Ben Sharpe, and Rachel Muncrief, *Literature review: Real-world fuel consumption of heavy-duty vehicles in the United States, China, and the European Union*, (ICCT: Washington, DC, 2015), https://theicct.org/publications/literature-review-real-world-fuel-consumption-heavy-duty-vehicles-united-states-china; Rachel Muncrief, Ben Sharpe, *Overview of the heavy-duty vehicle market and CO2 emissions in the European Union*, (ICCT: Washington, DC, 2015), https://theicct.org/sites/default/files/publications/ICCT_EU-HDV_mkt-analysis_201512.pdf.

trends observed in these data is also an indication that reductions in tailpipe emissions were not accompanied by significant improvements in efficiency or reductions in CO_2 emissions. The adoption of CO_2 emission standards for heavy-duty vehicles will drive future improvements in fuel consumption for tractor-trailers in the EU.[34]



Manufacturer	Avg. annual change	# of trucks in analysis
DAF	+0.08%	14
Daimler	-0.48%	17
Iveco	+0.04%	12
MAN	+0.37%	12
Renault	+0.20%	11
Scania	-0.18%	20
Volvo	-0.07%	11

Figure 10. Fuel consumption trends for tractor-trailers in the EU. Source: Rachel Muncrief, “Shell game? Debating real-world fuel consumption trends for heavy-duty vehicles in Europe,” ICCT staff blog, April 24, 2017,, https://theicct.org/blogs/staff/debating-EU-HDV-real-world-fuel-consumption-trends.

FHWA Highway Statistics

Information on the long-term trends in the fuel consumption of HD trucks operating in the United States can be found in the Federal Highway Administration’s (FHWA) Highway Statistics Series.[35] Each year, the FHWA publishes estimates of fleet-average fuel consumption for several HD vehicle types. Because these are fleet-average estimates, they are representative of the fleet of vehicles on the road in a given year. The fleet-average fuel consumption estimates of HD combination trucks (i.e., tractor-trailers) for the years 1993 to 2017 are shown in Figure 11. These data show fleet-average fuel consumption for these vehicles has not changed much, despite the tightening of emission standards.[36] Fleet-average fuel consumption for combination trucks was 40.4 l/100km in 1993 and 39.9 l/100km in 2017. These data show further

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[34] Felipe Rodríguez, *CO_2 standards for heavy-duty vehicles in the European Union*, (ICCT: Washington, DC, 2019), https://theicct.org/publications/co2-stds-hdv-eu-20190416.

[35] Federal Highway Administration, U.S. Department of Transportation (Annual Vehicle Distance Traveled in Miles and Related Data—By Highway Category and Vehicle Type, Table VM-1, accessed June 2019), https://www.fhwa.dot.gov/policyinformation/statistics.cfm.

[36] FHWA’s estimation procedure for heavy-duty vehicles involves using the Census of Transportation Vehicle Inventory and Use Survey (VIUS), and a new survey was used in 1999 and 2003, resulting in inconsistencies in the estimates. This issue does not exist for passenger vehicles. After 2006, FHWA uses a new methodology and results in more consistent estimates. We use the change rate in fuel economy for all motor vehicles to adjust data between 1999 and 2006 that are inconsistent with neighboring years due to the method change.

evidence that manufacturers were able to maintain the fuel efficiency of HD combination trucks sold in the United States during a period when tailpipe pollutant emissions were greatly reduced.

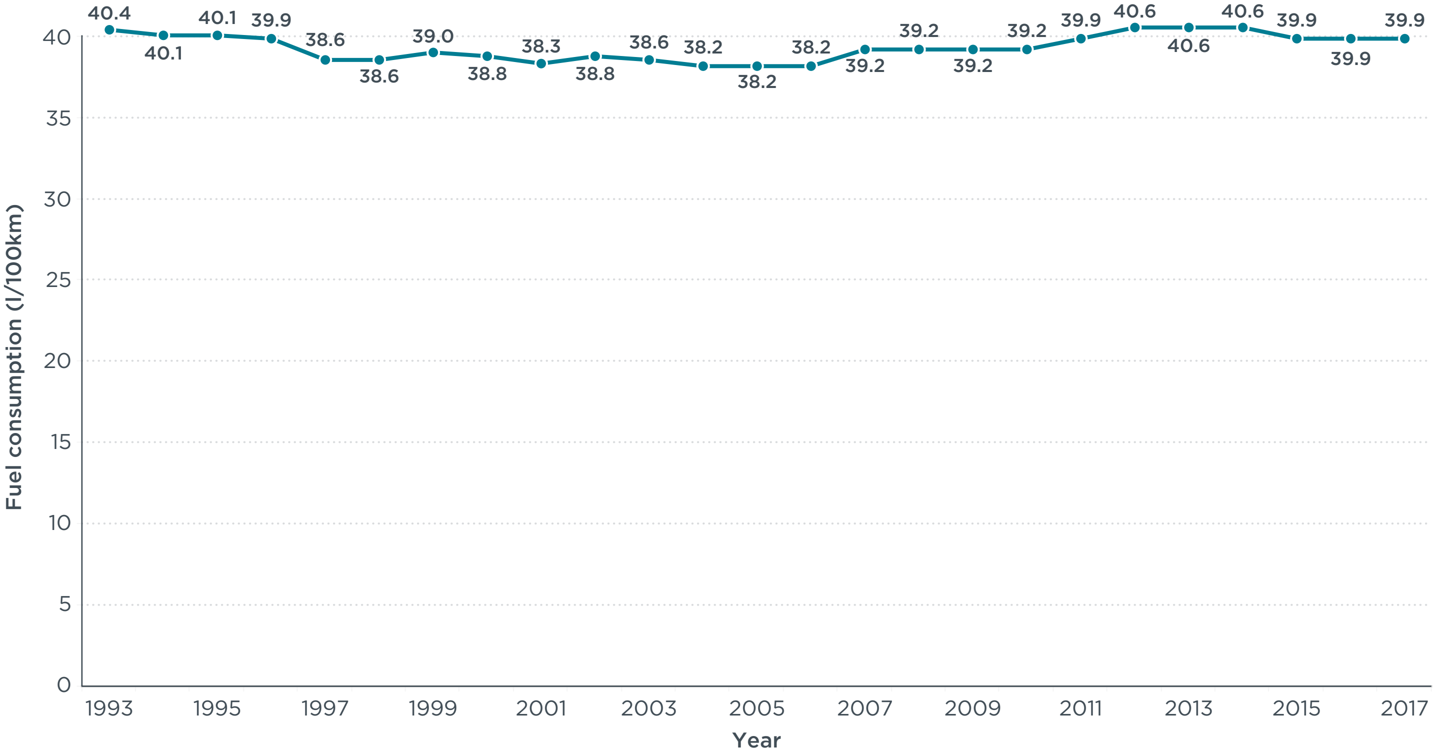

Figure 11. FHWA fleet-average fuel consumption for U.S. combination trucks, 1993 to 2017.

In-use vehicle emissions studies

Whereas the previous examples focused primarily on fuel consumption, we turn now to data sources that report emissions of CO_2 as well as non-CO_2 climate pollutants in order to provide insight regarding the impacts of soot-free diesel engines on emissions of climate-forcing pollutants. The first such source is a recent study of the emissions from in-use trucks operating in Oakland, California.[37] A plume capture method was used to measure the emissions of thousands of trucks at two sampling locations. The sample included trucks certified to EPA 2010 emission standards equipped with SCR and DPF aftertreatment, as well as older trucks without these technologies. The authors found that the average real-world NO_x and BC emissions of EPA 2010 trucks were 71% and 94% lower, respectively, than those of EPA 2004 certified trucks without aftertreatment control equipment. However, the N_2O emissions of trucks equipped with SCR were found to be greater than non-SCR trucks, with emissions increasing from near-zero levels to an average of 0.7 g/kg fuel. On average, estimated N_2O emissions from SCR-equipped trucks contributed 6% of CO_2e emissions when weighted by 100-yr global warming potential (GWP). The authors found that the increase in N_2O emissions was offset by decreased emissions of BC, and that replacing a modern truck without a DPF or SCR with a newer truck equipped with DPF and SCR results in a net decrease in climate-forcing pollutant emissions.

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[37] Chelsea V. Preble, Robert A. Harley, and Thomas W. Kirchstetter, "Control Technology-Driven Changes to In-Use Heavy-Duty Diesel Truck Emissions of Nitrogenous Species and Related Environmental Impacts," *Environ. Sci. Technol. 53*, 24 (2019): 14568–14576, https://doi.org/10.1021/acs.est.9b04763.

Emissions of unregulated pollutants, including N_2O, were also the focus of a real-world emissions testing study of diesel HD trucks in Hong Kong.[38] The study used a portable emissions measurement system (PEMS) to evaluate the in-use emissions from 22 trucks certified to Euro IV, V, and VI emission standards. N_2O emissions were measured from three trucks equipped with SCR systems, one certified to each emission standard. The Euro VI truck had the lowest measured N_2O emissions—72.1 mg/km on average. In this case, N_2O contributed just 2.3% of total GHG emissions when weighted by 100-year GWP. Per kilometer N_2O emission rates of the Euro IV and V trucks were greater compared to the Euro VI truck and accounted for a greater percentage of total GHG emissions—11% for the Euro IV truck and 14% for the Euro V truck. The lower N_2O emissions of the Euro VI truck were attributed to improvements in SCR technology. In all cases, catalyst type and SCR calibration were cited as key factors influencing the magnitude of N_2O emissions.

The role of HDV efficiency standards

Previous sections present evidence that supports the finding that improvements in HD vehicle emission control did not come at the detriment of fuel consumption or efficiency, and that overall decreases in non-CO_2 climate pollutant emissions, in particular BC, have improved the overall climate emissions performance of modern HD diesel engines compared to older, higher emitting diesel engine technologies. However, long-term fuel consumption trends for HD vehicles in Europe and the United States also indicate that the real-world fuel consumption per unit distance traveled of commercial fleets has been relatively stagnant over time. This observation, along with the prominence of HD vehicles as a source of GHG emissions, has driven the development of GHG emission and efficiency standards in many of the largest HD vehicle markets. Figure 12 shows the implementation timeline for these standards in each region. The introduction of HD vehicle and engine GHG and efficiency standards in many global regions will continue to spur technology advances in diesel engine design. For countries moving toward adoption and implementation of soot-free emission standards, complementary efficiency and GHG standards should also be considered in order to reduce CO_2 emissions.

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[38] Christos Keramydas et al., “Characterization of Real-World Pollutant Emissions and Fuel Consumption of Heavy-Duty Diesel Trucks with Latest Emission Control,” *Atmosphere* 10, 0535 (2019), https://www.doi.org/10.3390/atmos10090535.

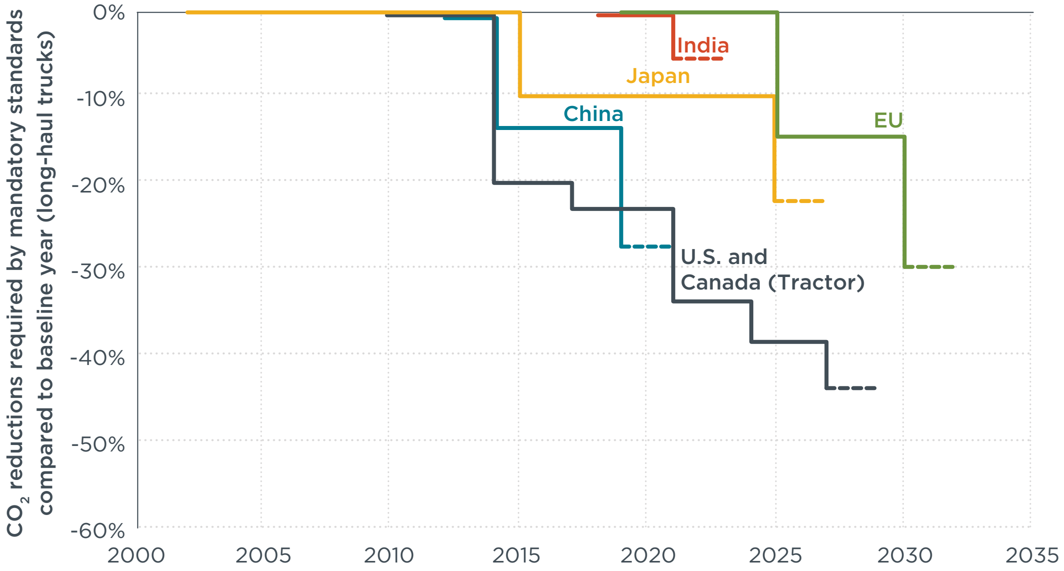

Figure 12. Tractor-truck standards around the world relative to the baseline in the first phase of the standards.[39]

Conclusions

Heavy-duty diesel vehicles are a significant source of pollutant emissions that negatively impact human health and the climate. Increasingly stringent regulatory programs developed in the United States and the European Union designed to control these emissions have spurred technological improvements in HD diesel engines. Today, diesel engines certified to soot-free emission standards—EPA 2010 and Euro VI—employ highly efficient emission control strategies and aftertreatment technologies to greatly reduce emissions of harmful pollutants, as well as the overall toxicity of diesel exhaust. Although much progress has been made in the global uptake of soot-free HD engine emission standards—44 countries have implemented or adopted such standards as of July 2019—more countries will need to follow suit in order to meet the target of a 75% global reduction in BC emissions from 2010 to 2030. Because the application of advanced emission control technologies may impact engine efficiency, the potential for fuel consumption penalties may still be seen as a barrier to adoption of soot-free standards in countries where they have not yet been established.

This paper analyzed the technological development of HD diesel engines used in the United States and the European Union in response to increasingly stringent emission standards and the impacts of this technological development on fuel efficiency and climate pollutant emissions. Despite following somewhat different technological pathways, HD diesel engine designs in the United States and the European Union have converged on a similar package of design elements in order to meet EPA 2010 and Euro VI emission standards—high-pressure variable fuel injection, cooled EGR, and an aftertreatment system of DOC, DPF, SCR, and ASC in series. In isolation, some of these technologies, specifically EGR and DPF systems, can negatively impact engine efficiency, resulting in a fuel consumption penalty. On the other hand, the introduction of SCR systems to soot-free engine designs has allowed designers to calibrate engines

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[39] Felipe Rodríguez, *CO_2 standards for heavy-duty vehicles in the European Union*, (ICCT: Washington, DC, 2019), https://theicct.org/publications/co2-stds-hdv-eu-20190416.

for more efficient operations and thereby offset some of the penalties associated with other control technologies. Furthermore, electronic engine controls, better fuel injection systems, and other engine developments fully offset any fuel consumption penalties introduced by modern emission control systems.

Comparisons of soot-free HD diesel engines and vehicles with engines and vehicles certified to prior emission standards indicate that improvements in emission control did not come at the detriment of fuel consumption. Furthermore, overall decreases in non-CO_2 climate pollutant emissions, in particular BC, have improved the overall climate emissions performance of modern HD diesel engines compared to older diesel engines. However, long-term fuel consumption trends for HD vehicles in Europe and the United States also indicate that the real-world fuel efficiency of commercial fleets has been relatively stagnant over time. These trends indicate that complementary efficiency and GHG emission standards will likely need to be developed in order to meaningfully reduce CO_2 emission from HD diesel vehicles.