GLOBAL PROGRESS TOWARD SOOT-FREE DIESEL VEHICLES IN 2018

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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

CLIMATE & CLEAN AIR COALITION
TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

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ABOUT THE CCAC

The CCAC is a voluntary global partnership of governments, intergovernmental organizations, businesses, scientific institutions, and civil society organizations committed to catalyzing concrete, substantial action to reduce short-lived climate pollutants (SLCPs), including methane, black carbon, and many hydrofluorocarbons. The coalition works through collaborative initiatives to raise awareness, mobilize resources, and lead transformative actions in key emitting sectors. The coalition's Heavy-Duty Vehicles and Fuels Initiative works to catalyze major reductions in black carbon through adoption of clean fuel and vehicle regulations and supporting policies. Efforts focus on diesel engines in all economic sectors.

ABOUT THE ICCT

The ICCT is an independent nonprofit organization founded to provide first-rate, unbiased technical research and scientific analysis to environmental regulators. Our mission is to improve the environmental performance and energy efficiency of road, marine, and air transportation to benefit public health and mitigate climate change.

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EXECUTIVE SUMMARY

This report assesses progress in 2018 toward implementing the Global Strategy to Introduce Low-Sulfur Fuels and Cleaner Diesel Vehicles of the Climate and Clean Air Coalition (CCAC). The rapid reduction of diesel black carbon emissions is one element of a multi-pollutant and multi-sectoral strategy proposed by the CCAC Scientific Advisory Panel (SAP) to reduce near-term climate warming by an average of 0.5°C over 25 years. To achieve this target, emissions of black carbon from all sectors must fall to 75% below 2010 levels by 2030. The Heavy-Duty Vehicles (HDV) Initiative of the CCAC released its global strategy in 2016 with the aim for all countries to implement vehicle emissions and fuel quality requirements equivalent to Euro 4/IV by 2025 and Euro 6/VI by 2030. This study finds that this strategy, if fully implemented, can reduce diesel black carbon emissions to 88% below 2010 levels by 2040 but that higher ambition—equal to Euro 4/IV implementation by 2021 and Euro 6/VI no later than 2025—is necessary to meet the emissions reduction and temperature targets proposed by the SAP.

Diesel on-road engines today move a large share of people and goods, yet this reliance on diesel technology comes with significant environmental and health costs. Worldwide consumption of diesel fuel by on-road vehicles has grown eightfold since 1970, driven by rapid growth of road freight activity and dieselization of light-duty vehicle fleets (IEA, 2017b). Diesel accounts for more than 40% of global on-road energy consumption and is the principal fuel of approximately 90% of all heavy-duty trucks and more than 75% of all buses (IEA, 2017b; IEA, 2017a). The widespread presence of older-technology diesel engines is a global health concern since diesel exhaust is a Class 1 carcinogen for humans, according to the International Agency for Research on Cancer (IARC, 2012). Older diesel engines emit high volumes of black carbon (BC): Researchers estimate that diesel engines accounted for 88% of BC emissions from road transport in 2010 (Klimont et al., 2017). Diesel on-road vehicles are a particularly good target for emissions control given their disproportionate contribution to impacts on climate and health, the existence of clear and cost-effective technology pathways for achieving substantial emissions reductions, and the joint benefits of reductions for climate, health, and agriculture (Shindell et al., 2011).

Rapid technological advances have led to a set of important technology and policy solutions to address diesel exhaust emissions. Since 2007, a growing number of national governments have implemented tailpipe emissions standards that can be met only with the installation of a wall-flow diesel particulate filter (DPF) when applied to diesel engines. These “soot-free” engines—which we define as those equivalent to or better than Euro VI for HDVs, Euro 5b for light-duty vehicles (LDVs), or any policies that explicitly require the installation of a DPF—are capable of reducing exhaust emissions of diesel BC by 99% compared with older-technology engines. Implementation of these limits also requires improvements in diesel fuel quality to no greater than 10–15 parts per million (ppm) of sulfur for soot-free engines to operate most effectively. To understand progress toward reducing diesel BC, we should look closely at the pace of adoption of DPFs and the enabling ultralow-sulfur diesel fuel.

Most of the world’s diesel supply by volume is already adequate to fuel vehicles meeting Euro VI-equivalent emissions standards. As of 2018, more than 70% of the world’s road diesel is ultralow-sulfur. Under policies adopted as of May 2018, this share is projected to grow to more than 80% by 2021 (Figure ES-1). Yet at least 127 countries still have average on-road diesel sulfur levels above 15 ppm. Particularly for heavy-duty diesel trucks and buses, securing cleaner fuels is a critical milestone for achieving deep reductions in BC emissions.

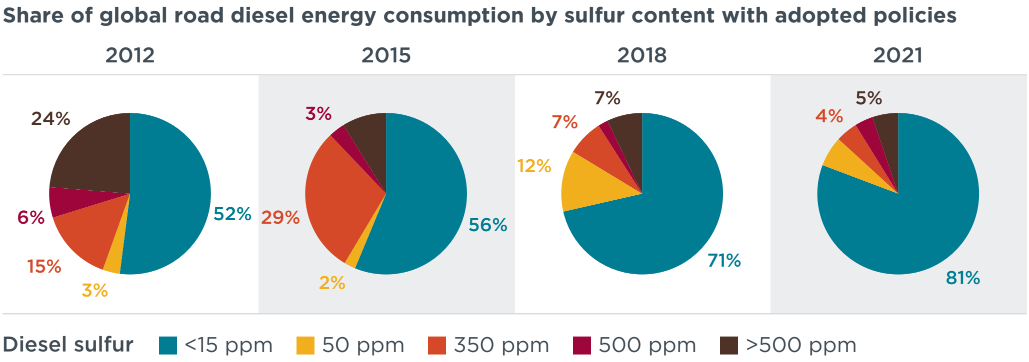

Figure ES-1. Share of global road diesel energy consumption by sulfur content with adopted policies. Adopted policies includes final regulations that have become law as of May 2018.

This study finds that in 2018, 40% of new heavy-duty diesel vehicles (HDDVs) sold worldwide are equipped with DPFs (Figure ES-2). This share is projected to grow to 50% in 2021 after adopted Euro VI-equivalent standards have gone into force in India and Mexico. If China and Brazil introduce Euro VI-equivalent standards, the share of new HDDVs with DPFs would increase to 70%.[1]

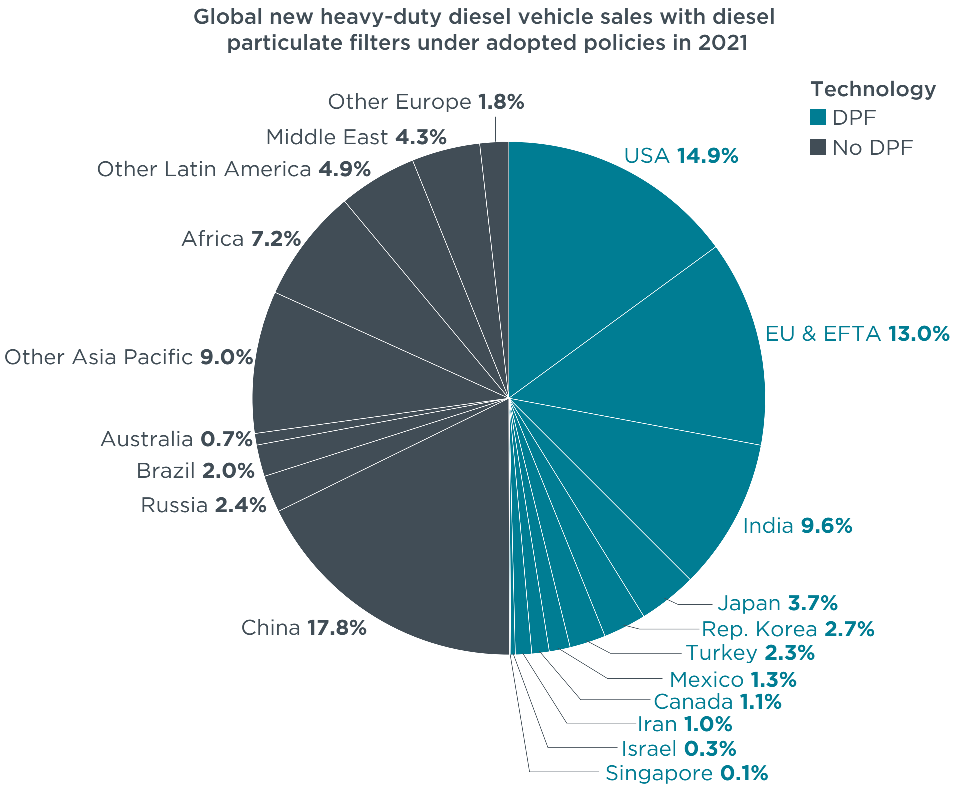

Figure ES-2. Share of global new heavy-duty diesel vehicle sales with diesel particulate filters under adopted policies in 2021. Adopted policies include final regulations as of May 2018.

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[1] As of May 2018, Euro VI-equivalent standards were under consideration in China and Brazil.

While soot-free standards are increasing the share of new vehicles equipped with DPFs, the transition will take substantially longer for the in-use vehicle fleet to turn over and be replaced with cleaner vehicles. In 2012, 5% of in-use HDDVs were equipped with DPFs. This share tripled by 2018 to 15%. Under currently adopted policies, one in five in-use HDDVs worldwide will have a DPF by 2021 (Figure ES-3).

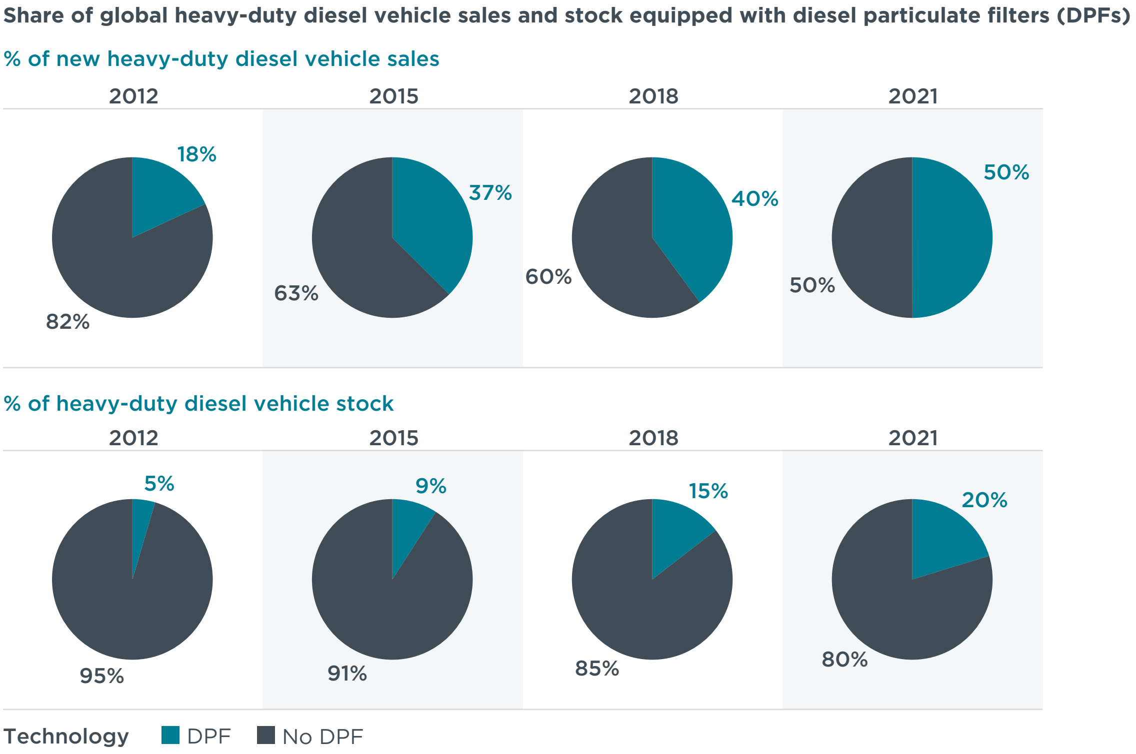


Figure ES-3. Share of global heavy-duty diesel vehicle sales and stock equipped with diesel particulate filters. Projected sales and stock shares include the effects of adopted policies. Adopted policies include final regulations as of May 2018.

Compared with a baseline with 2015 policies, policies adopted as of May 2018 are projected to reduce global BC emissions from diesel road transport by 37% by 2040, equivalent to 40% below 2010 levels (Figure ES-4). As with the baseline scenario, further policies are still needed to counteract the global emissions increase projected to result from activity growth. Implementation of the Global Sulfur Strategy could reduce BC emissions to 88% below 2010 levels in 2040. Under a high ambition scenario, in which all countries implement at least Euro 4/IV by 2021 and Euro 6/VI by 2025, global BC emissions could be reduced to 75% below 2010 levels in the 2030 timeframe and 93% below 2010 levels by 2040. The high ambition scenario would enable diesel road transport to deliver BC reductions in line with the global target for anthropogenic BC emissions proposed by the SAP (Shindell et al., 2017).

In 2011, an assessment by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) identified a set of 16 short-lived climate pollutant (SLCP) mitigation actions in multiple economic sectors that could avoid 0.5°C of additional warming by 2050 (UNEP and WMO, 2011). The SAP subsequently proposed 0.5°C, or 500 millidegrees (thousandths of a degree), as a near-term target to reduce SLCP temperature impacts over the next 25 years. Compared with the baseline scenario, the Global Sulfur Strategy (GSS) and high ambition scenarios would avoid 77 millidegrees (0.077°C) of additional warming in 2050, equivalent to 15.4% of the 500 millidegrees in SLCP mitigation identified in the 2011 UNEP-WMO assessment. The marginal benefits of the high ambition scenario compared with the GSS with respect to climate are evident when considering warming *over the next 25 years*, as opposed to at an endpoint such as mid-century. In 2030, the midpoint between 2018 and 2042, the high ambition scenario would avoid an additional 28 millidegrees of warming from the baseline scenario, compared with 19 millidegrees avoided by the GSS.

Global BC from diesel road transport, 2010–2040 (kt, thousand tonnes)

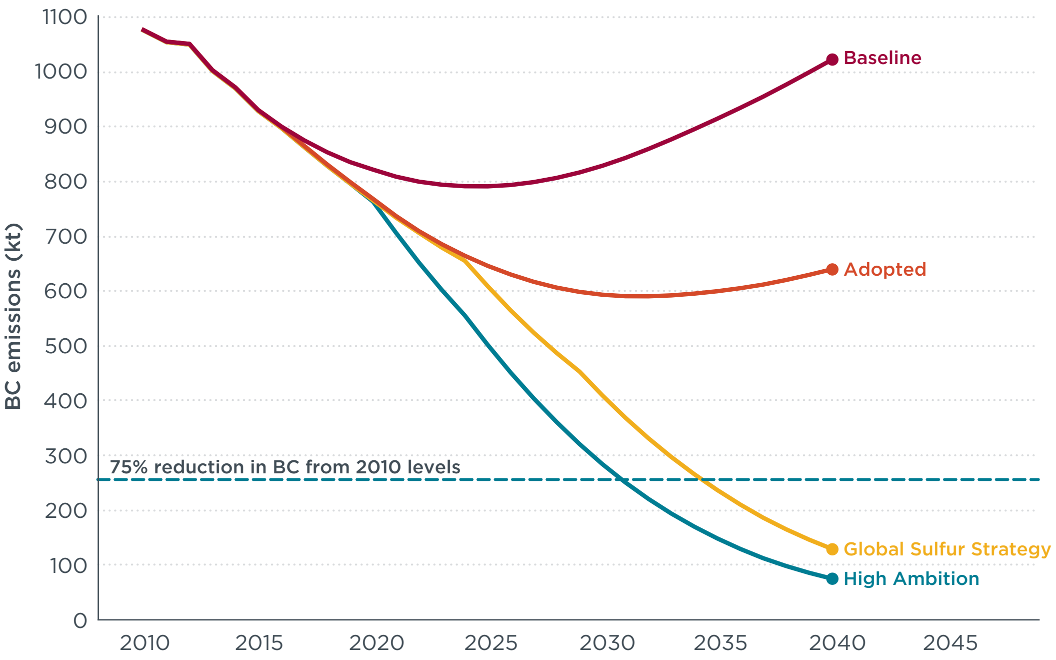
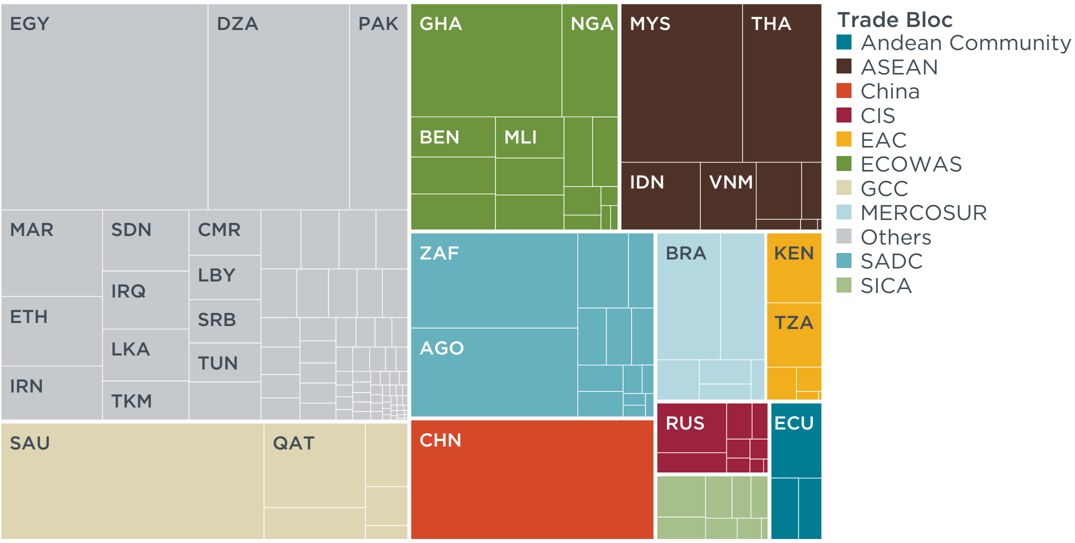


Figure ES-4. Global black carbon emissions from diesel road transport, 2010-2040. *Baseline:* Includes the historical timeline of vehicle emissions and fuel quality standards and assumes no changes in policy implementation after 2015. *Adopted:* Includes final regulations that have been adopted into law as of May 2018 but may have a future implementation date. Comparison of the adopted and baseline scenarios yields the projected benefits of recently adopted policies. *Global Sulfur Strategy*: Evaluates the impacts of implementing the Initiative's global strategy for cleaner diesel vehicles and fuels (Malins et al., 2016); this scenario assumes all countries implement at least Euro 4/IV by 2025 and Euro 6/VI by 2030, and some countries implement these policies sooner. *High Ambition:* In recognition that countries could move more quickly to reduce BC emissions than targeted in the Global Sulfur Strategy, the high ambition scenario assumes that all countries implement at least Euro 4/IV by 2021 and Euro 6/VI by 2025; some markets that are already considering Euro 6/VI are assumed to implement those standards a few years earlier.

These findings highlight both the need and the opportunity for more ambitious actions to support national governments in making the transition to cleaner fuels and vehicles. In 2016, 36 countries accounting for one-third of global new HDDV sales signed the Marrakech Communiqué. Those countries committed to adopt, maintain, and enforce world-class fuel quality and emissions standards for LDVs and HDVs (Climate and Clean Air Coalition, 2016). As of May 2018, 15 of the 36 signatories adopted soot-free standards for new HDDVs. These findings suggest the CCAC should continue to support the remaining 21 countries in adopting Euro VI-equivalent standards while inviting more countries to sign on to the objectives of the communiqué.

With the adoption of soot-free standards forthcoming in the largest vehicle markets, the remaining countries without such standards will account for 30% of new HDDV sales spanning more than 150 national jurisdictions. Harmonization of such policies across trade blocs will remain an important strategy to deliver more rapid progress than if each country were to develop regulations individually (Figure ES-5). Alignment of vehicle emissions standards, fuel quality standards, and used vehicle import policies among countries with strong economic ties could have the added benefit of eliminating or reducing barriers to progress such as competitiveness concerns, cross-border traffic, limited access to cleaner fuels, and limited availability of vehicle models meeting local design specifications. Extending support for tightened standards to a short list of populous countries could also have an outsized impact on the global BC emissions trajectory.



Cumulative BC mitigation potential of diesel road transport from 2018 through 2040 achievable with high ambition scenario, compared with policies adopted as of May 2018

Figure ES-5. Cumulative BC mitigation potential of diesel road transport from 2018 through 2040 achievable with high ambition scenario, compared with policies adopted as of May 2018. Area is proportional to remaining BC emissions mitigation potential after considering the effects of adopted policies. ASEAN, Association of Southeast Asian Nations; CIS, Commonwealth of Independent States; EAC, East African Community; ECOWAS, the Economic Community of West African States; GCC, the Gulf Cooperation Council; MERCOSUR, Southern Common Market (South America); NAFTA, the North American Free Trade Agreement; SADC, Southern African Development Community; SICA, Central American Integration System.

INTRODUCTION

BACKGROUND

About one in eight deaths worldwide in 2012 were associated with exposure to air pollution, and half of those were linked to outdoor air pollution. In 2016, outdoor air pollution resulted in 4.2 million premature deaths worldwide (WHO, 2018). Black carbon (BC) is a major contributor to air pollution and premature deaths globally (Climate and Clean Air Coalition, 2017). BC is a potent short-lived climate pollutant and a major component of fine particulate matter ($PM_{2.5}$) from diesel exhaust, which is classified as a Class 1 carcinogen to humans by the International Agency for Research on Cancer (IARC, 2012). One-fifth of global anthropogenic BC emissions are estimated to originate in the transport sector, and more than 90% comes from diesel vehicles (Minjares, Wagner, and Akbar, 2014).

Diesel accounts for more than 40% of global on-road energy consumption and is the principal fuel of heavy-duty trucks, at about 90% of energy consumption, and buses, at more than 75% (IEA, 2017b; IEA, 2017a). Worldwide consumption of diesel by on-road vehicles has grown eightfold since 1970 (IEA, 2017b), driven by rapid growth in road freight activity worldwide and dieselization of passenger car fleets in markets such as the European Union, India, South Korea, and Turkey. For most of the world's freight operators and consumers, diesel remains relatively inexpensive compared with other conventional fuels. In 2016, diesel cost less than gasoline on a per-liter basis in 180 countries and less on an energy-equivalent basis in 203 countries (German Agency for International Cooperation, 2018).[2] Yet the global reliance of road transport—especially heavy-duty vehicles—on diesel fuel also comes with significant environmental and health costs.

In 2005, an estimated 242,000 premature deaths annually were associated with exposure to ambient particulate matter from surface transportation including on-road, off-road, and rail (Chambliss, Silva, West, Zeinali, & Minjares, 2014). Global exhaust emissions of fine particulate matter from on-road vehicles increased from 2005 to 2010 (Klimont et al., 2017), as did BC emissions. On-road vehicles with diesel engines accounted for 88% of BC emissions from road transport in 2010 (Klimont et al., 2017). In addition to directly emitted PM, nitrogen oxides (NO_X) from diesel vehicles contribute to the formation of secondary $PM_{2.5}$ and ozone.

Starting in 2007, a growing number of national governments have reduced the sulfur content of diesel fuel to 10–15 parts per million (ppm) and implemented stringent tailpipe emissions standards that require installation of a diesel particulate filter (DPF) to meet very low PM emissions limits. We define soot-free standards as those equivalent to or better than Euro VI for heavy-duty diesel vehicles (HDDV) and Euro 5b for light-duty diesel vehicles (LDDV), or any standards that explicitly require the installation of a DPF. Such standards are capable of reducing exhaust emissions of PM and BC up to 99% compared with uncontrolled levels.[3]

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[2] Diesel contains approximately 10.4% more energy per liter of fuel than gasoline (IEA, 2004).

[3] Diesel vehicles that achieve a 99% reduction in tailpipe BC emissions relative to uncontrolled diesel exhaust are also included in the list of technologies that we define as soot-free. Soot-free technologies include any diesel or alternative fuel engines certified to Euro VI or U.S. 2010 emissions levels.

In 2016, more than 120 countries had limited or no access to the low-sulfur diesel fuel necessary for diesel particulate filters to function. To support those countries working to reduce diesel vehicle emissions, the CCAC launched the Heavy-Duty Vehicles Initiative[4] with the objective to "virtually eliminate fine particle and black carbon emissions from new and existing heavy-duty diesel vehicles and engines through the introduction of low sulfur fuels and vehicle emission standards" (CCAC, 2012). In 2016, the co-leads[5] of the initiative released a Global Strategy to Introduce Low-Sulfur Fuels and Cleaner Diesel Vehicles, which was later endorsed by the High Level Assembly of the CCAC in Marrakech (CCAC, 2016). The strategy aims to achieve a 90% reduction in $PM_{2.5}$ and BC emissions from the global on-road diesel fleet with the implementation of Euro 4/IV fuel and vehicle emissions norms by 2025 and Euro 6/VI fuel and vehicle emissions norms no later than 2030.[6] The strategy recommends actions for regions, countries, and cities to make the transition to cleaner fuels and soot-free diesel engines (Malins et al., 2016).

OBJECTIVES AND APPROACH

This report is the first of two annual assessments that aim to monitor progress toward implementing the global strategy of the HDV Initiative.[7] In this assessment we focus on actions to reduce BC emissions from on-road diesel vehicles, particularly HDDVs. We define data-driven metrics for the status and coverage of fuel quality and emissions regulations, their impacts on the uptake of cleaner vehicles and fuels, and the resulting changes and trends in BC emissions. Key metrics for regulations, vehicles, and fuels include:

- Number of countries requiring ultralow-sulfur (10 ppm) and low-sulfur (50 ppm) on-road diesel.
- Number of countries that have implemented soot-free standards for new HDDVs.
- Share of world on-road diesel fuel consumption by sulfur level.
- Share of new HDDV sales equipped with diesel particulate filters.
- Share of in-use HDDV stock equipped with diesel particulate filters.

We then examine the net emissions impact of developments in the sector, estimating the change in global BC emissions from HDDVs that occurred from 2010 to 2015, evaluating the projected emissions benefits of recently adopted policies, and quantifying the potential for further emissions reductions with new policies.

We develop four policy scenarios to evaluate the future trends in emissions from diesel road transport. The **baseline** scenario represents the historical timeline of implemented vehicle emissions and fuel quality standards and includes standards that were already in

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[4] The full name of the Initiative is "Reducing Emissions from Heavy-Duty Vehicles and Fuels Initiative." Before 2018, the full name was "Reducing Black Carbon Emissions from Heavy-Duty Diesel Vehicles and Engines Initiative." In this report, we refer to the initiative in brief as the Heavy-Duty Vehicles initiative.

[5] "The Global Strategy to Introduce Low-Sulfur Fuels and Cleaner Diesel Vehicles has been developed by the five co-leads of the Climate and Clean Air Coalition's (CCAC) Heavy Duty Diesel Initiative (HDDI): the Government of the United States of America, the Government of Canada, the Government of Switzerland, the United Nations Environment Programme (UNEP) and the International Council on Clean Transportation (ICCT)." (Malins et al., 2016)

[6] This timeline corresponds to introducing low-sulfur diesel (maximum 50 ppm) in all countries by 2025 and ultralow-sulfur diesel (maximum 10–15 ppm) in all countries by 2030.

[7] The model developed for this report is capable of evaluating the emissions impacts of fuel standards, vehicle standards, and import restrictions for nearly 200 countries individually, which accounted for 99.8% of the world's population in 2015. The results of this report and the associated model will also facilitate follow-up evaluations of impact indicators for policies adopted or under consideration in CCAC member countries following the "Demonstrating Impacts" framework.

force in 2015. The **adopted** scenario includes final regulations that have been adopted into law as of May 2018, including policies with a future planned implementation date. To quantify the benefits of further policy action, we develop two policy scenarios for a global transition to soot-free diesel vehicles. The **Global Sulfur Strategy** (GSS) scenario is based on the Initiative's strategy and assumes that all countries implement at least Euro 4/IV by 2025 and Euro 6/VI by 2030. The **high ambition** scenario goes further, considering an accelerated timeline that is ambitious but achievable; it assumes that all countries implement at least Euro 4/IV by 2021 and Euro 6/VI by 2025.

STRUCTURE OF THE REPORT

The structure of this report is as follows. After an overview of methods and data sources, we present our findings on the current status of diesel-fueled road transport worldwide. We include data-driven metrics on the status and coverage of soot-free vehicle emissions standards, vehicle technology deployment, and fuel quality across roughly 200 national jurisdictions. Next, we evaluate the projected emissions impacts of four policy scenarios for diesel road transport worldwide, assess the mitigation potential in various countries and trade blocs, and identify potential priority regions for future technical and policy support activities. We then utilize new climate metrics provided by the CCAC Scientific Advisory Panel to evaluate the temperature impacts of emissions from diesel road transport and assess the temperature reduction potential of policies targeting non-CO_2 emissions from the sector. Finally, the technical appendix provides details on the methodology and data sources used to develop and evaluate the metrics presented, as well as to estimate and project the pollutant emissions and temperature impacts of diesel road transport.

METHODS AND DATA

Diesel road transport exhaust emissions are a product of several factors. These include vehicle activity, policy, and other drivers in emissions calculation. Activity drivers we considered include new diesel vehicle sales, used vehicle imports, diesel vehicle stock, retirements, annual vehicle mileage, mileage degradation, vehicle energy efficiency, and energy consumption. Policy drivers include new vehicle emissions standards, used vehicle import restrictions, and diesel sulfur content. Other drivers include fuel-specific emissions factors, particulate matter speciation, sulfur effects, and the impacts of high-emitting vehicles. Methods for calculating fleet emissions based on these drivers are illustrated in Figure 1.

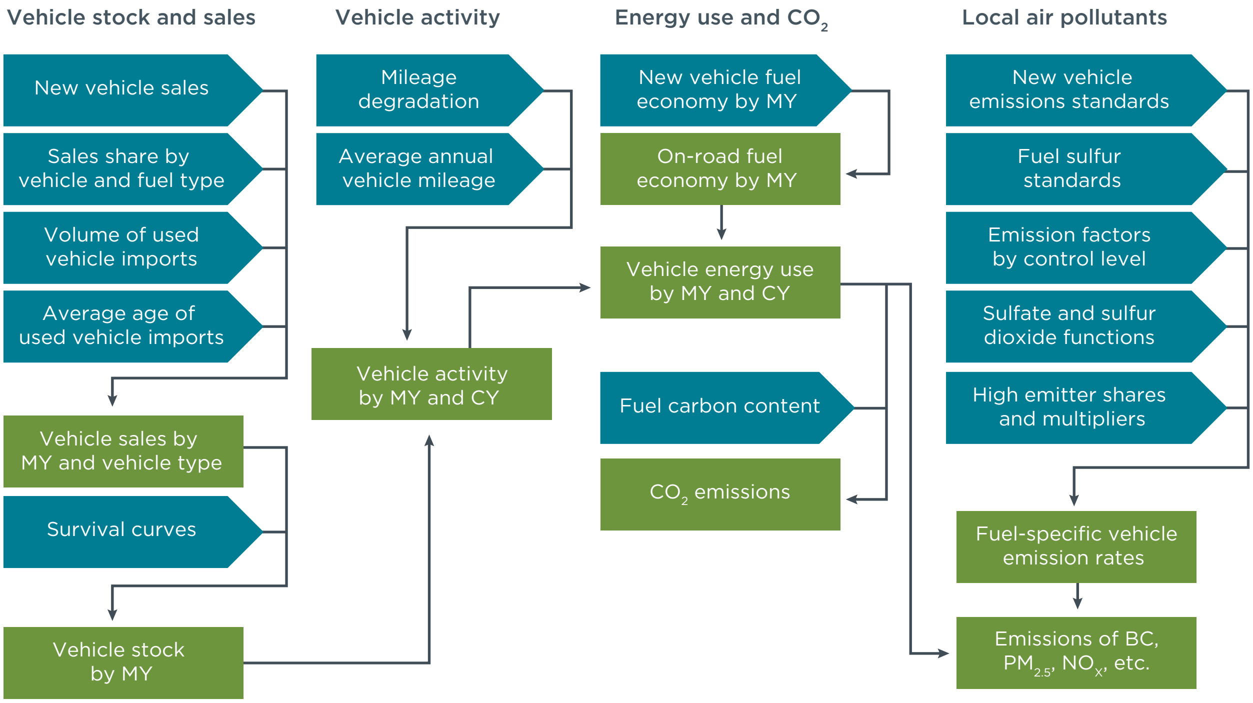


Figure 1. Diagram of diesel road transport fleet emissions model methodology. Blue fill indicates model inputs; green fill indicates calculations. MY, model year; CY, calendar year.

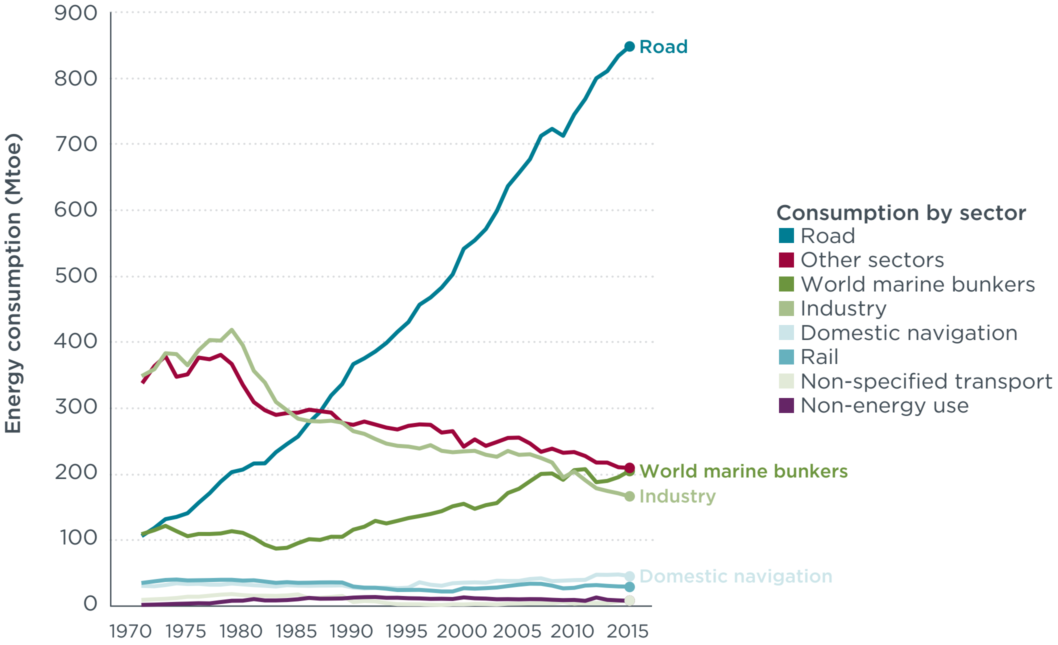
We utilize data from a variety of sources, including international organizations such as the International Energy Agency (IEA) and the United Nations Environment Programme (UNEP); government documents, websites, and contacts; published reports and peer-reviewed articles; and consultants, including Stratas Advisors and CITAC. Details on methods and data sources are given in the technical appendix.

CURRENT STATUS OF DIESEL ROAD TRANSPORT WORLDWIDE

DIESEL VEHICLE SALES, STOCK, AND ENERGY CONSUMPTION

Worldwide diesel fuel consumption in road transport has grown eightfold since 1971 and quadrupled since 1980 (Figure 2). More than 97% of the energy consumed by on-road diesel engines is derived from fossil fuels; the remainder is biodiesel. Road transport is by far the largest source of demand for diesel fuel, consuming more than all other sectors combined.

World diesel fuel consumption, 1970–2015 (Mtoe)



Includes gas/diesel oil and fuel oil. Mtoe, million tonnes of oil equivalent.
Based on IEA data from the World Energy Balances Data Service © OECD/IEA 2017, www.iea.org/statistics.
Licence: www.iea.org/t&c; as modified by ICCT.

Figure 2. World diesel fuel consumption by sector, 1971–2015. Mtoe, million tonnes of oil equivalent. Based on IEA data from the World Energy Balances Data Service © OECD/IEA 2017, www.iea.org/statistics. License: www.iea.org/t&c; as modified by ICCT.

Within diesel road transport, HDDVs are the principal source of energy demand and BC emissions. In 2017, HDDVs accounted for less than 25% of diesel vehicle sales and stock but approximately 75% or more of energy use and BC emissions (Figure 3). LDDVs, in contrast, accounted for about 70% of diesel vehicle sales and stock but less than 25% of energy consumption and less than 20% of BC emissions. The disproportionate contribution of HDDVs to energy consumption and emissions is one of the key reasons the CCAC has focused on this sub-sector of transport.

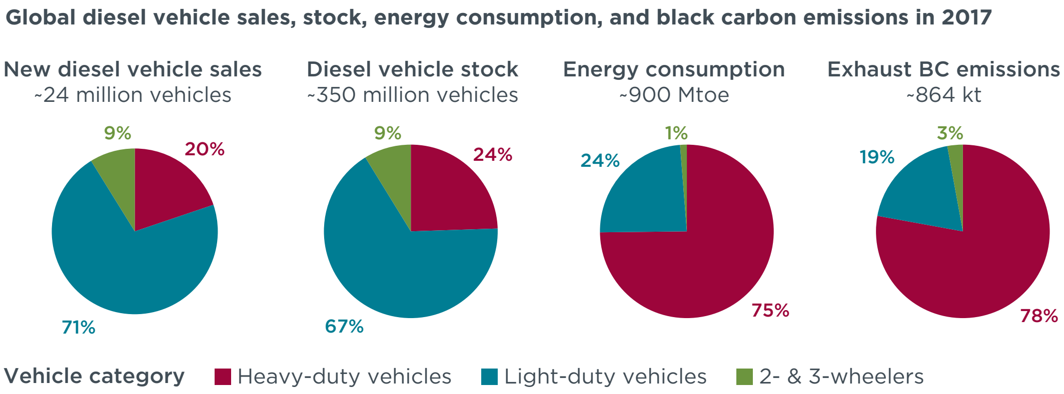


Figure 3. Global on-road diesel vehicle sales, stock, energy consumption and black carbon emissions in 2017.

The historically largest vehicle markets generate about 70% of new HDDV sales worldwide (Figure 4). China accounts for 19% of global new HDDV sales, followed by the United States and the European Union, each of which accounts for about 14% of global sales. Countries in the Middle East, Africa, and Latin America make up a larger share of the world's in-use HDDV stock than indicated by their share of new vehicle sales. Imports of used HDDVs are estimated to contribute a substantial share of the incoming vehicles in these regions.

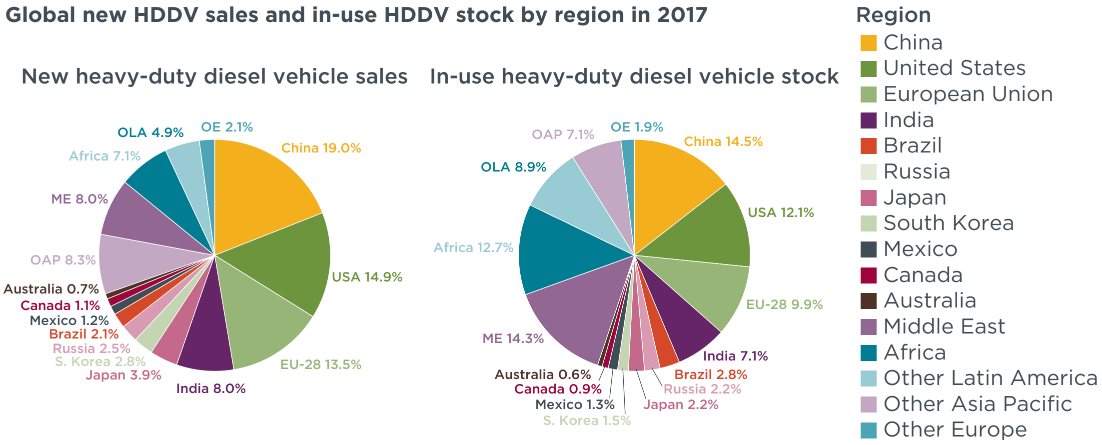


Figure 4. Global new heavy-duty diesel vehicle (HDDV) sales and in-use stock by region in 2017.

DIESEL VEHICLE EMISSIONS STANDARDS

Diesel particulate filters (DPFs) are required starting at Euro VI/U.S. 2007 for HDDVs and Euro 5b/U.S. Tier 2/China 5 for LDDVs. Established emission factor models such as COPERT show that soot-free standards reduce exhaust particulate matter and BC more than 99% compared with uncontrolled levels (Figure 5). As emissions standards become more stringent, PM emissions levels fall across all emission factor models, and variability declines among emission factor estimates.

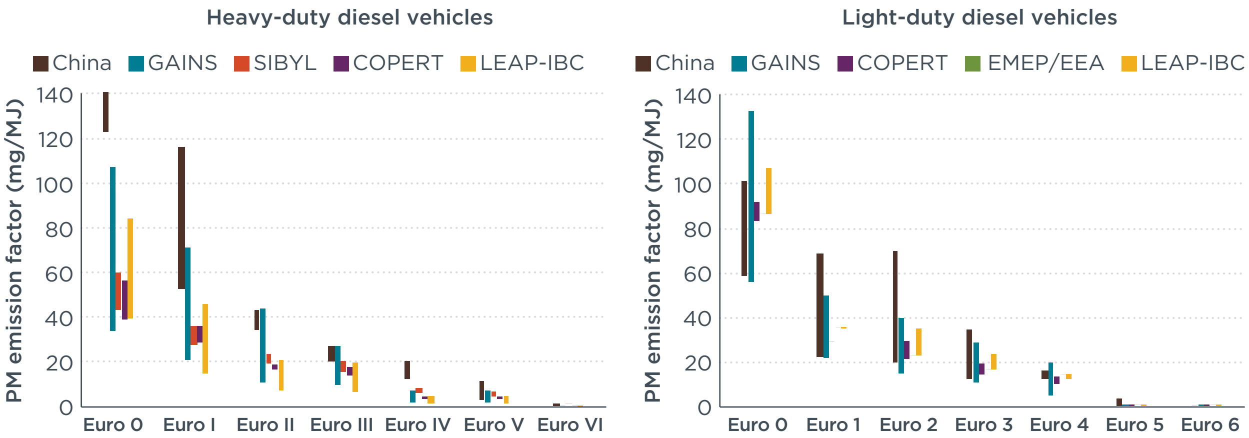


Figure 5. Comparison of PM emission factors of heavy- and light-duty diesel vehicles by Euro-equivalent emissions standard. Units are milligrams per megajoule (mg/MJ). Bars indicate minimum and maximum estimates within each technology category. China data were obtained from Tsinghua University and converted to fuel-specific estimates (maximum of 212 mg/MJ); GAINS estimates are from Klimont et al. (2017); SIBYL from Emisia; COPERT from ICCT analysis of COPERT in Chambliss et al. (2013); LEAP-IBC from SEI; and EMEP/EEA from Ntziachristos & Samaras (2017).

Figure 6 shows that average BC emissions levels of in-use vehicles vary substantially across trade blocs as a result of differing fuel and vehicle standards. Europe has the lowest emissions levels and variability among countries due to harmonization of soot-free standards. Countries in Africa have the highest fleet average emissions levels resulting from nonexistent or outdated vehicle emissions standards, prevalence of high-sulfur fuels, and lax or nonexistent restrictions on used vehicle imports. Yet this region also offers the greatest potential for improvement with new policies in the high ambition scenario. Considering adopted policies only, the difference among regions will widen, with dramatically decreasing emissions levels in regions that have adopted Euro VI-equivalent standards such as India and NAFTA, whereas other regions improve very slowly with existing policies. As illustrated in the high ambition scenario, most regions have a tremendous opportunity to reduce BC and by 2050 achieve the fleet average emissions levels seen in leading regions.

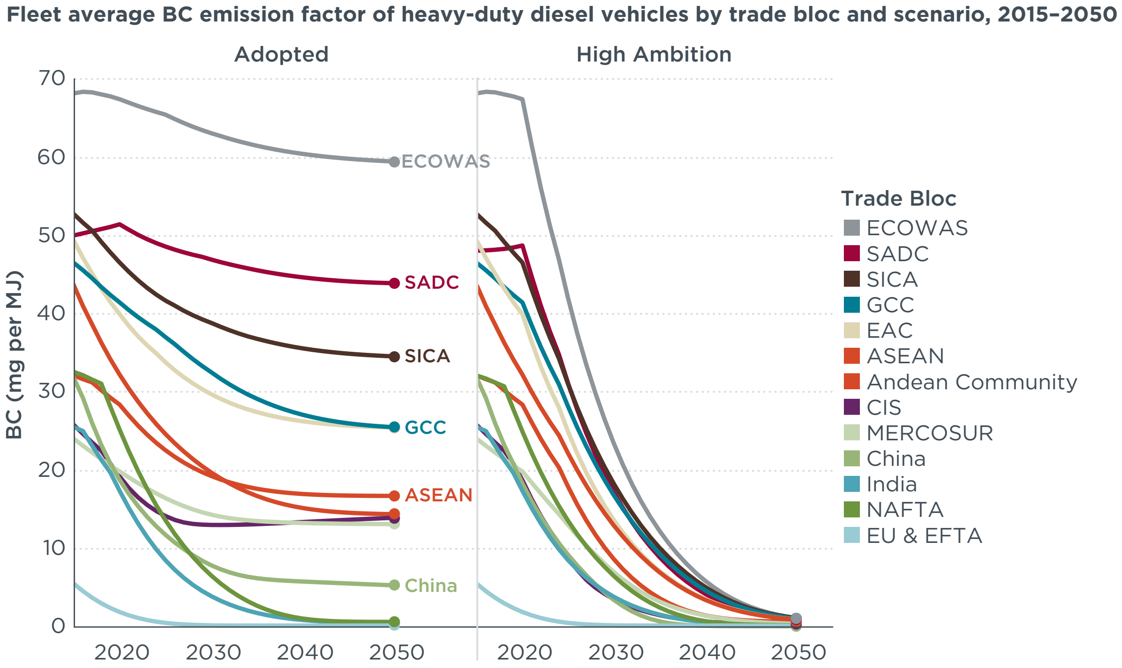


Figure 6. In-use fleet average BC emissions levels for heavy-duty diesel vehicles by trade bloc under adopted policies and high ambition scenarios. Units are milligrams per megajoule (mg/MJ). ASEAN, Association of Southeast Asian Nations; CIS, Commonwealth of Independent States; EAC, East African Community; ECOWAS, the Economic Community of West African States; GCC, the Gulf Cooperation Council; MERCOSUR, Southern Common Market (South America); NAFTA, the North American Free Trade Agreement; SADC, Southern African Development Community; SICA, Central American Integration System.

During the CCAC 8th High Level Assembly in November 2016 in Marrakech, 36 countries signed and adopted the Marrakech Communiqué, which aims to reduce short-lived climate pollutants. These signatories committed to "… adopting, maintaining, and enforcing world-class diesel fuel quality and tailpipe emissions standards for on-road light and heavy-duty vehicles in our markets." (CCAC, 2016). These 36 countries account for approximately one-third of new HDDV sales worldwide. As of May 2018, 15 of the 36 signatories (Figure 7) adopted soot-free standards for new HDDVs. Under adopted policies, 80% of new HDDVs sold among Marrakech signatories will be equipped with DPFs by 2021. The remaining 21 signatories are mostly in Africa, the Asia-Pacific, and Latin America. These findings suggest that the CCAC should continue to support these countries in adopting and enforcing Euro VI-equivalent standards, while inviting more countries to sign on to the objectives of the communiqué.

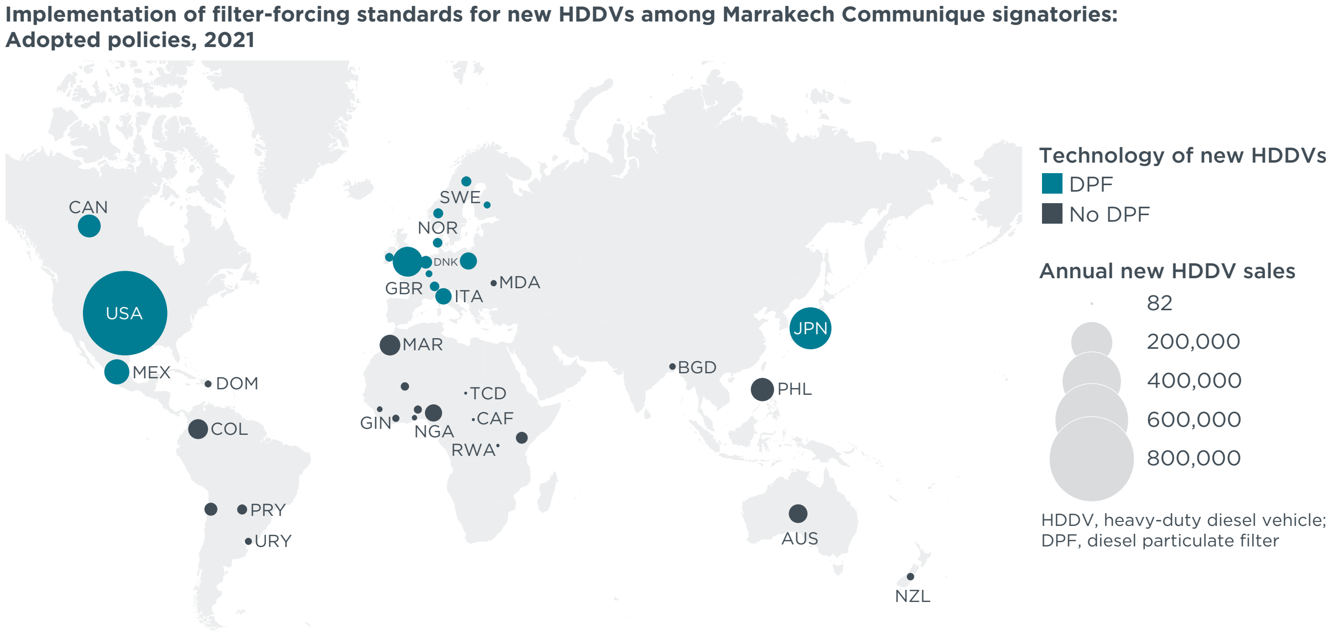

Implementation of filter-forcing standards for new HDDVs among Marrakech Communique signatories: Adopted policies, 2021

Figure 7. Implementation of soot-free standards for new heavy-duty diesel vehicles among Marrakech Communiqué signatories under adopted policies in 2021. Mexico's standards apply in 2021.

The opportunities for soot-free standards are widespread globally. With the exception of Europe, North America, and a handful of markets elsewhere, most vehicle markets have yet to adopt soot-free standards. As of May 2018, a few major markets such as China and Brazil were considering adopting soot-free standards but had yet to finalize the standards and introduction dates.

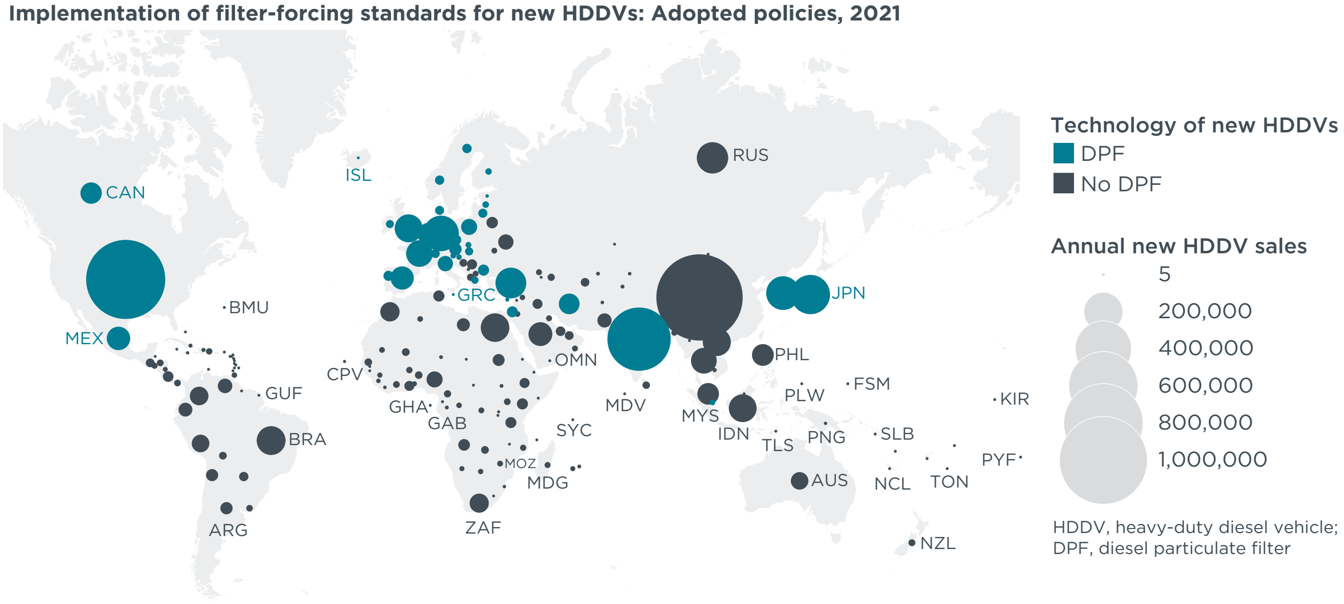

Implementation of filter-forcing standards for new HDDVs: Adopted policies, 2021

Figure 8. Implementation of soot-free standards for new heavy-duty diesel vehicles under adopted policies in 2021. India's and Mexico's standards apply in 2020 and 2021, respectively.

Soot-free standards are increasing the share of new vehicles with DPFs, but the transition takes longer for the in-use vehicle fleet. Under currently adopted policies, the share of new HDDV sales with DPFs will grow from 40% in 2018 to 50% in 2021, whereas the share of HDDV stock with DPFs will reach only 20% in 2021 (Figure 9). Accelerated adoption of soot-free standards and retrofit or fleet renewal programs could speed up the transition to cleaner diesel vehicles (Kubsh, 2017; Wagner and Rutherford, 2013).

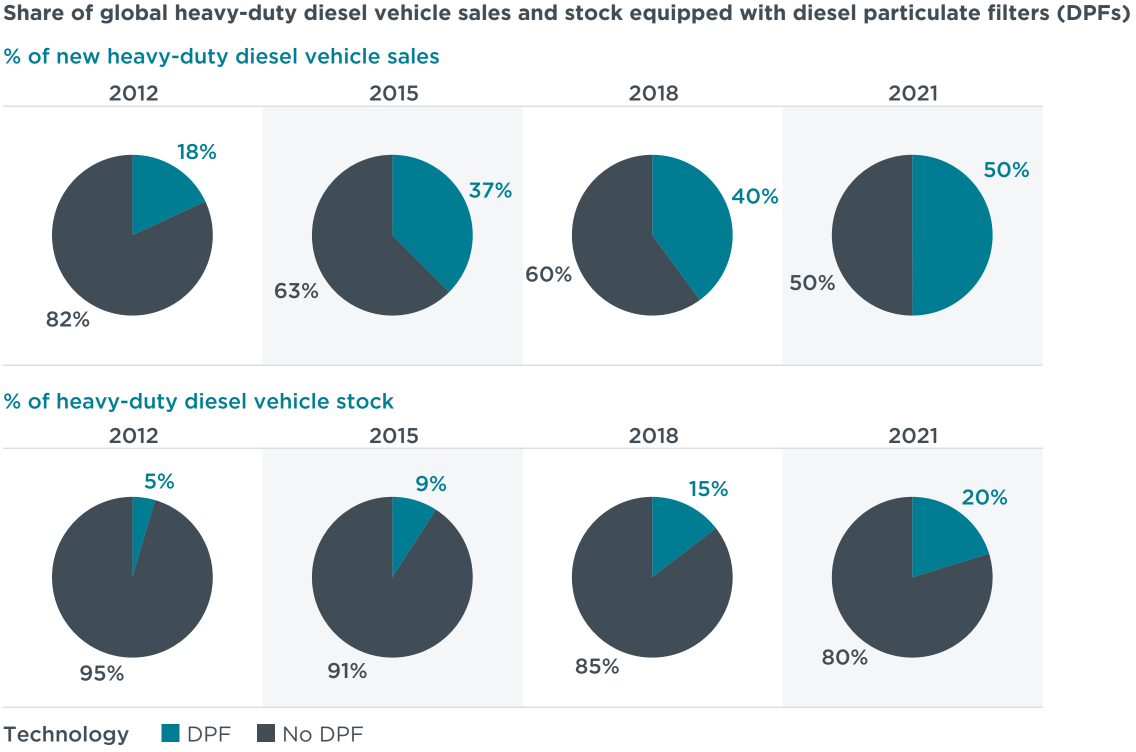


Figure 9. Share of global heavy-duty diesel vehicle sales and stock equipped with diesel particulate filters. Projected sales and stock shares include the effects of adopted policies. Adopted policies include final regulations that have become law as of May 2018.

DIESEL FUEL QUALITY

The application of soot-free standards requires diesel fuel of sufficient quality to maintain the efficiency and durability of the emissions control system. Today, most of the world's diesel supply by volume is adequate to fuel vehicles designed to meet Euro VI-equivalent emissions standards (Figure 10). More than two-thirds of the world's road diesel is already ultralow-sulfur (maximum 15 ppm sulfur). This share is projected to grow to more than four-fifths under adopted policies in 2021.

DPF AND 50 PPM SULFUR FUEL AS INTERIM SOLUTION

In March 2017 Iran restricted for the first time the sale and registration of new medium and heavy-duty diesel vehicles to those meeting a maximum particle number limit of 1 x 10^12 and Euro IV emissions limits for other pollutants. This particle limit will require manufacturers to develop a Euro IV+DPF or a Euro V+DPF technology solution at the 50 ppm sulfur fuel level, since cleaner 10 ppm sulfur fuels are not available in the Iranian market. The Euro IV/V+DPF solution opens new possibilities for countries at the 50 ppm sulfur level that are slow to deliver 10 ppm sulfur fuels. At the 50 ppm sulfur level, countries can leapfrog directly to DPF solutions more quickly, effectively eliminating the most toxic components of diesel particulate matter.

But Euro IV/V+DPF technology is relatively untested, with little public demonstration of real-world emissions performance. Manufacturers may be forced to make trade-offs between fuel consumption and emissions performance. The durability of systems may likewise be more limited, reducing the cumulative emissions reductions over the lifetime of the emissions control system. Additionally, maintenance intervals may be more frequent; low ash lubricating oil may be required; and the design of NO_x control systems will most likely be affected. In the absence of conclusive information, the net emissions and health benefits of an accelerated DPF requirement remain uncertain.

Consequently, an accelerated DPF requirement is an interim supplement to Euro IV or Euro V, not an alternative to Euro VI and the necessary investments in 10 ppm sulfur fuels. Euro VI and U.S. 2010 vehicle and fuel standards remain the best-practice approach to diesel emissions control in HDVs. These standards deliver real-world particulate matter and NO_x emissions control, effectively eliminating the excess NO_x emissions commonly generated under Euro IV and Euro V standards. Euro VI engines have stronger durability and warranty requirements up to 700,000 kilometers or seven years and stronger on-board diagnostic requirements including the best available mechanisms to prevent the use of emulators to override NO_x system controls. These engines are widely available in the global marketplace, lowering their cost. When used in combination with 10 ppm sulfur fuels, Euro VI engines deliver the best combination of cost-effective emissions controls and fuel economy for conventional HDDVs.

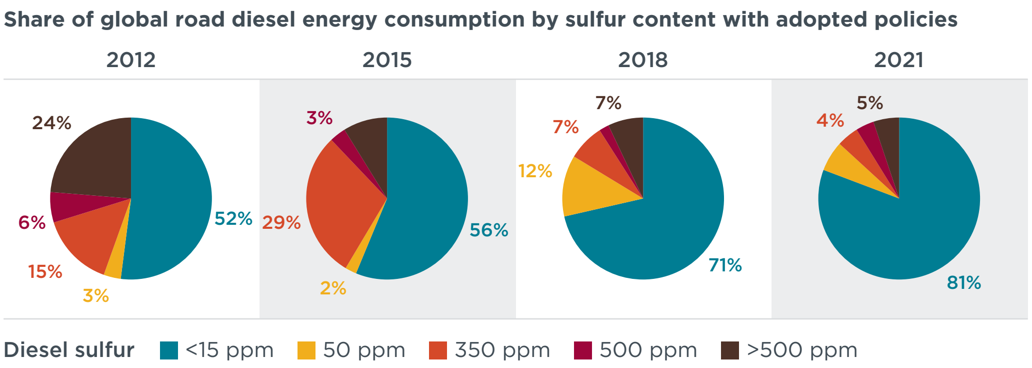


Figure 10. Share of global road diesel energy consumption by sulfur content with adopted policies. Adopted policies includes final regulations that have become law as of May 2018.

The number of countries with ultralow- and low-sulfur diesel has grown substantially since the CCAC initiated work on fuel desulfurization in 2012. Between 2012 and 2018, 17 countries switched to ultralow-sulfur diesel, and another 17 made the transition to low-sulfur diesel (Figure 11). Yet most of the world's countries still have average diesel sulfur levels well above 15 ppm, and there remain opportunities for desulfurization in every region (Figure 12). We estimate that at least 127 countries have average on-road diesel sulfur levels above 15 ppm; most of the countries with the highest sulfur levels of more than 500 ppm are in Africa. In regions that lack access to low- or ultralow-sulfur diesel fuel, importing these fuels or working with relevant government agencies and stakeholders to secure their availability are prerequisites to achieving substantial BC reductions for on-road diesel vehicles (Malins et al., 2016). Specific vehicle categories such as urban buses (Miller, Minjares, Dallmann, and Jin, 2017) or light-duty vehicles may be able to switch to alternative fuels given adequate pricing incentives or regulations. Yet, particularly for heavy-duty diesel trucks and buses, securing cleaner fuels is a critical milestone for achieving BC emissions reductions at scale.

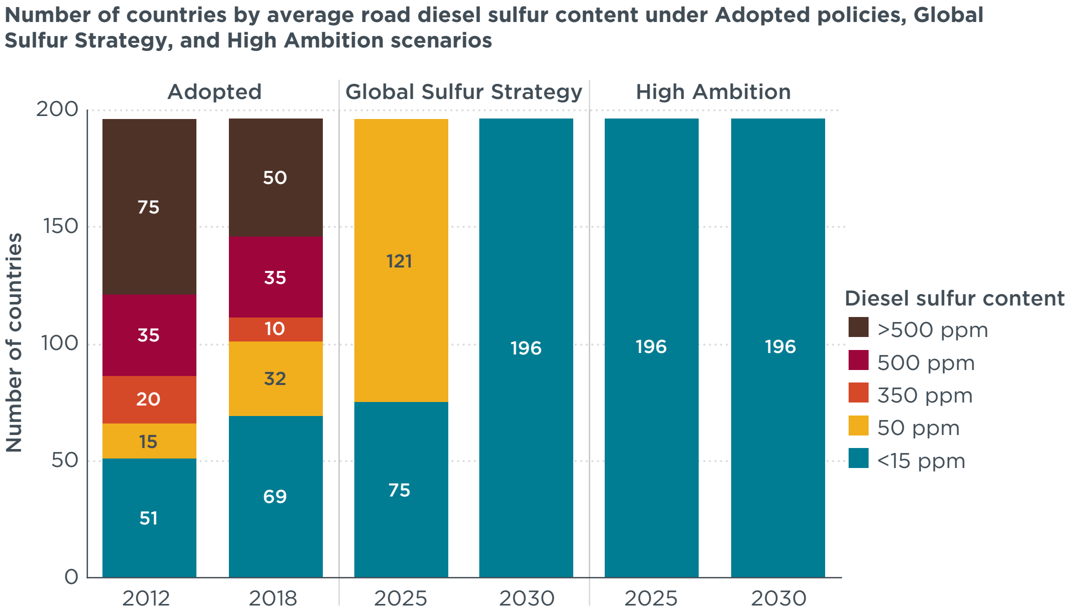
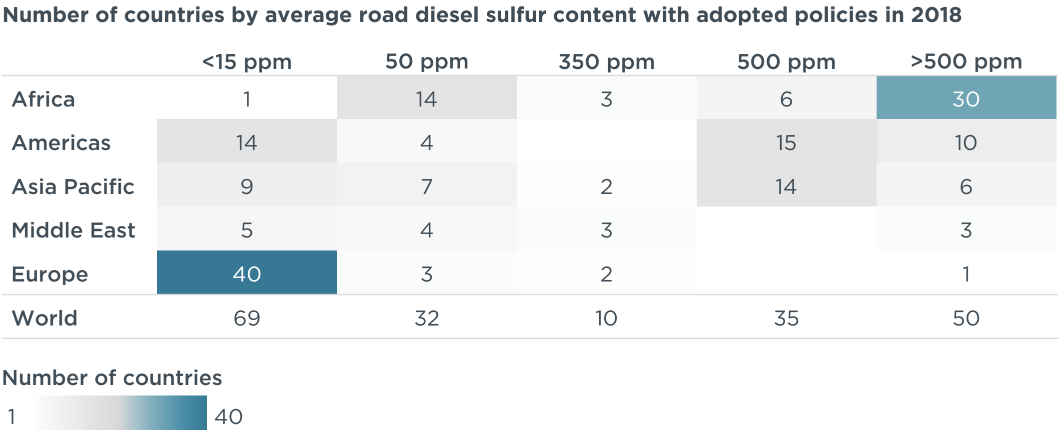


Figure 11. Number of countries by average road diesel sulfur content under adopted policies, global sulfur strategy, and high ambition scenarios. Counts for years 2012 and 2018 are based on adopted

policies; counts for 2025 and 2030 are assumptions of soot-free transition scenarios. Average diesel sulfur content is weighted by the estimated volume of fuel sales by grade in parts per million.

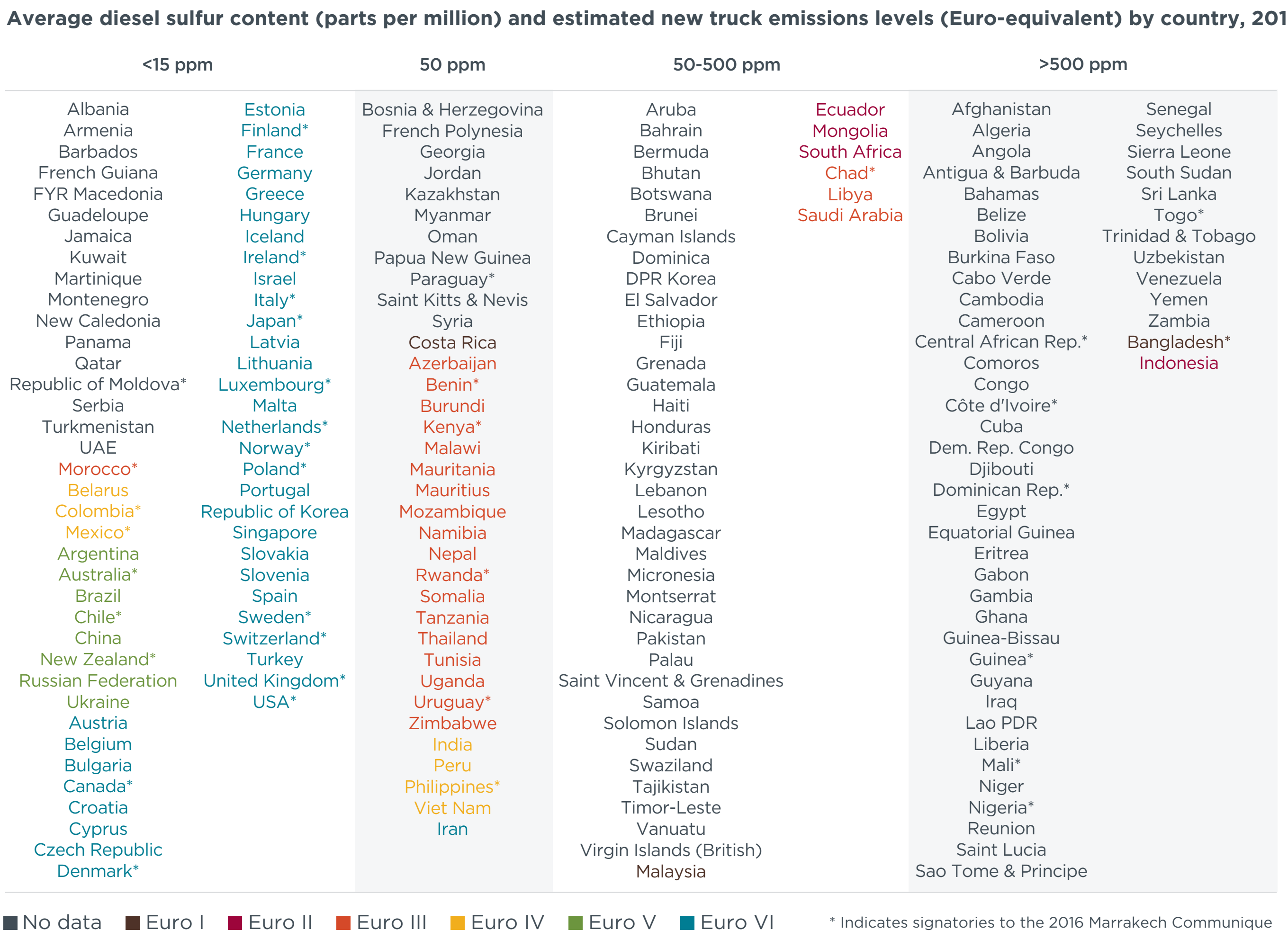


Number of countries by average road diesel sulfur content with adopted policies in 2018

	<15 ppm	50 ppm	350 ppm	500 ppm	>500 ppm
Africa	1	14	3	6	30
Americas	14	4		15	10
Asia Pacific	9	7	2	14	6
Middle East	5	4	3		3
Europe	40	3	2		1
World	69	32	10	35	50

Figure 12. Number of countries by average road diesel sulfur content with adopted policies in 2018, by world region. Average diesel sulfur content is weighted by the estimated volume of fuel sales by grade in parts per million.

Figure 13 lists countries according to their average diesel sulfur content and estimated new heavy-duty diesel truck emissions levels as of 2018. This comparison of fuel quality and new truck emissions levels reveals that many countries have not yet taken full advantage of their available low- or ultralow-sulfur diesel. An estimated 29 countries have access to ultralow-sulfur diesel but have not implemented Euro VI-equivalent standards. Although a handful of these are at Euro V-equivalent standards, such as Brazil, China, and Russia, other countries are at earlier stages of emissions control, such as Morocco. Looking forward, key actions by the CCAC and its partners could include supporting the adoption and enforcement of Euro VI-equivalent standards in Marrakech signatories such as Australia, Chile, New Zealand, Colombia, and Morocco and in G20 economies such as Argentina, Brazil, China, and Saudi Arabia.



Average diesel sulfur content (parts per million) and estimated new truck emissions levels (Euro-equivalent) by country, 2018

<15 ppm

Albania
Armenia
Barbados
French Guiana
FYR Macedonia
Guadeloupe
Jamaica
Kuwait
Martinique
Montenegro
New Caledonia
Panama
Qatar
Republic of Moldova*
Serbia
Turkmenistan
UAE
Morocco*
Belarus
Colombia*
Mexico*
Argentina
Australia*
Brazil
Chile*
China
New Zealand*
Russian Federation
Ukraine
Austria
Belgium
Bulgaria
Canada*
Croatia
Cyprus
Czech Republic
Denmark*
Estonia
Finland*
France
Germany
Greece
Hungary
Iceland
Ireland*
Israel
Italy*
Japan*
Latvia
Lithuania
Luxembourg*
Malta
Netherlands*
Norway*
Poland*
Portugal
Republic of Korea
Singapore
Slovakia
Slovenia
Spain
Sweden*
Switzerland*
Turkey
United Kingdom*
USA*

50 ppm

Bosnia & Herzegovina
French Polynesia
Georgia
Jordan
Kazakhstan
Myanmar
Oman
Papua New Guinea
Paraguay*
Saint Kitts & Nevis
Syria
Costa Rica
Azerbaijan
Benin*
Burundi
Kenya*
Malawi
Mauritania
Mauritius
Mozambique
Namibia
Nepal
Rwanda*
Somalia
Tanzania
Thailand
Tunisia
Uganda
Uruguay*
Zimbabwe
India
Peru
Philippines*
Viet Nam
Iran

50-500 ppm

Aruba
Bahrain
Bermuda
Bhutan
Botswana
Brunei
Cayman Islands
Dominica
DPR Korea
El Salvador
Ethiopia
Fiji
Grenada
Guatemala
Haiti
Honduras
Kiribati
Kyrgyzstan
Lebanon
Lesotho
Madagascar
Maldives
Micronesia
Montserrat
Nicaragua
Pakistan
Palau
Saint Vincent & Grenadines
Samoa
Solomon Islands
Sudan
Swaziland
Tajikistan
Timor-Leste
Vanuatu
Virgin Islands (British)
Malaysia
Ecuador
Mongolia
South Africa
Chad*
Libya
Saudi Arabia

>500 ppm

Afghanistan
Algeria
Angola
Antigua & Barbuda
Bahamas
Belize
Bolivia
Burkina Faso
Cabo Verde
Cambodia
Cameroon
Central African Rep.*
Comoros
Congo
Côte d'Ivoire*
Cuba
Dem. Rep. Congo
Djibouti
Dominican Rep.*
Egypt
Equatorial Guinea
Eritrea
Gabon
Gambia
Ghana
Guinea-Bissau
Guinea*
Guyana
Iraq
Lao PDR
Liberia
Mali*
Niger
Nigeria*
Reunion
Saint Lucia
Sao Tome & Principe
Senegal
Seychelles
Sierra Leone
South Sudan
Sri Lanka
Togo*
Trinidad & Tobago
Uzbekistan
Venezuela
Yemen
Zambia
Bangladesh*
Indonesia

⬛ No data 🟫 Euro I 🟥 Euro II 🟧 Euro III 🟨 Euro IV 🟩 Euro V 🟦 Euro VI

* Indicates signatories to the 2016 Marrakech Communique

Figure 13. Average diesel sulfur content (parts per million) and estimated new truck emissions levels (Euro-equivalent) by country in 2018. Not all countries have adopted mandatory emissions standards for new vehicles. The 36 signatories to the Marrakech Communique have committed to adopt, maintain, and enforce world-class fuel quality and emissions standards for LDVs and HDVs. Iran notably set Euro IV+DPF standards for medium and heavy-duty diesel vehicles that took effect in 2017.

FUTURE IMPACTS OF DIESEL ROAD TRANSPORT WORLDWIDE

We develop four policy scenarios to understand future emissions trends for diesel vehicles and quantify the benefits of further action. These scenarios focus on the impacts of national-level policies that principally affect emissions of BC and other non-CO_2 pollutants. From a CO_2 and energy perspective, these four scenarios are largely identical. They each consider the effects of adopted policies such as vehicle efficiency standards but do not consider the impacts of future policies focused on CO_2 mitigation or energy efficiency.

- Baseline: Includes the historical timeline of vehicle emissions and fuel quality standards and assumes no changes in policy implementation after 2015.
- Adopted: Includes final regulations that have been adopted into law as of May 2018 but may have a future implementation date. Comparison of the adopted and baseline scenarios yields the projected benefits of policies that have been adopted or implemented after 2015.
- Global Sulfur Strategy (GSS): Evaluates the impacts of implementing the Global Strategy for Low-Sulfur Fuels and Cleaner Diesel Vehicles (Malins et al., 2016). This scenario assumes that all countries implement at least Euro 4/IV by 2025 and Euro 6/VI by 2030 and that some countries implement these policies sooner.
- High ambition: Assumes that all countries implement at least Euro 4/IV by 2021 and Euro 6/VI by 2025. Some markets that are already considering Euro 6/VI are assumed to implement those standards earlier than under the GSS scenario.

TRENDS IN ON-ROAD DIESEL BC EMISSIONS AND KEY DRIVERS

Under adopted policies, worldwide energy consumption of diesel road transport is likely to continue increasing (Figure 14). Yet, as a result of adopted Euro VI-equivalent emissions standards, BC emissions in major vehicle markets such as the European Union, United States, and India will shrink to a small fraction of global BC emissions. Even as these markets continue to account for a large proportion of global diesel energy consumption, their actions will most likely decouple energy consumption growth from BC emissions. In contrast, BC emissions in Africa, the Asia-Pacific, the Middle East, and Latin America are projected to increase in the absence of new soot-free standards.

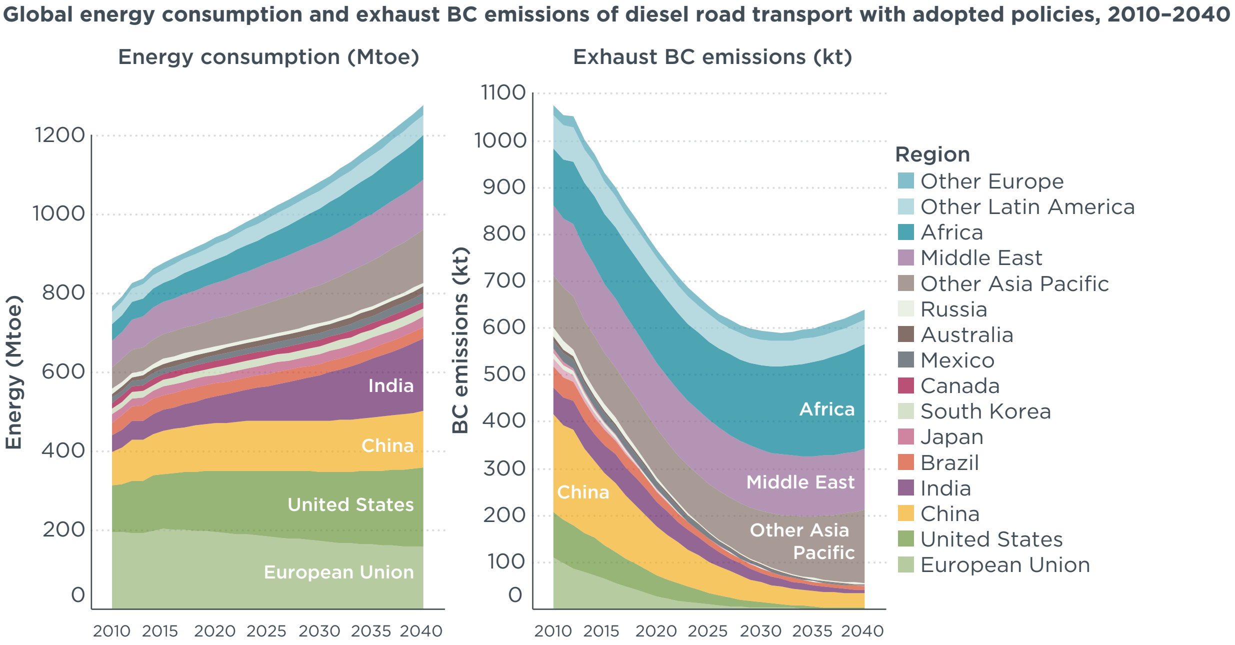


Figure 14. Global energy consumption and exhaust BC emissions of diesel road transport with adopted policies, 2010-2040. Mtoe, million tonnes of oil equivalent; kt, thousand tonnes.

Under adopted policies, countries in Africa, the Asia-Pacific, the Middle East, and Latin America could account for as much as 88% of global diesel BC by 2040 despite accounting for only a third of diesel energy consumption (Figure 14). Further policy development in these regions will be needed to stabilize and then substantially reduce BC emissions.

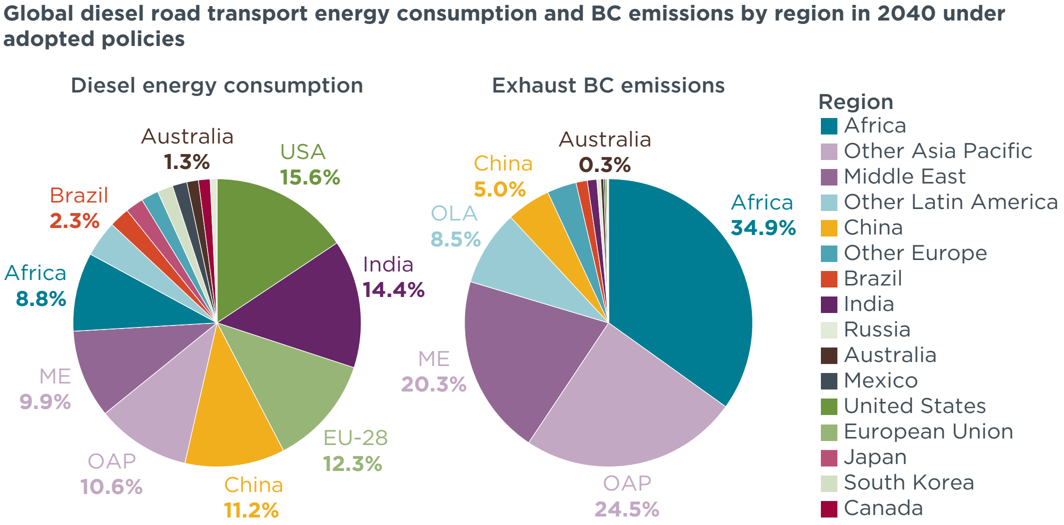


Figure 15. Global diesel road transport energy consumption and BC emissions by region in 2040 under adopted policies. Full names of regional abbreviations are given in the legend.

The GSS and high ambition scenarios reflect ambitious timelines for a global transition to soot-free diesel vehicles (Figure 16). In the high ambition scenario, 84% of the world's HDDV fleet would be equipped with DPFs by 2040. The GSS scenario would equip 74%

of the fleet with DPFs by 2040. Each of these scenarios is in stark contrast with the adopted policies scenario, in which 37% of the world's HDDVs would be equipped with DPFs by 2040.

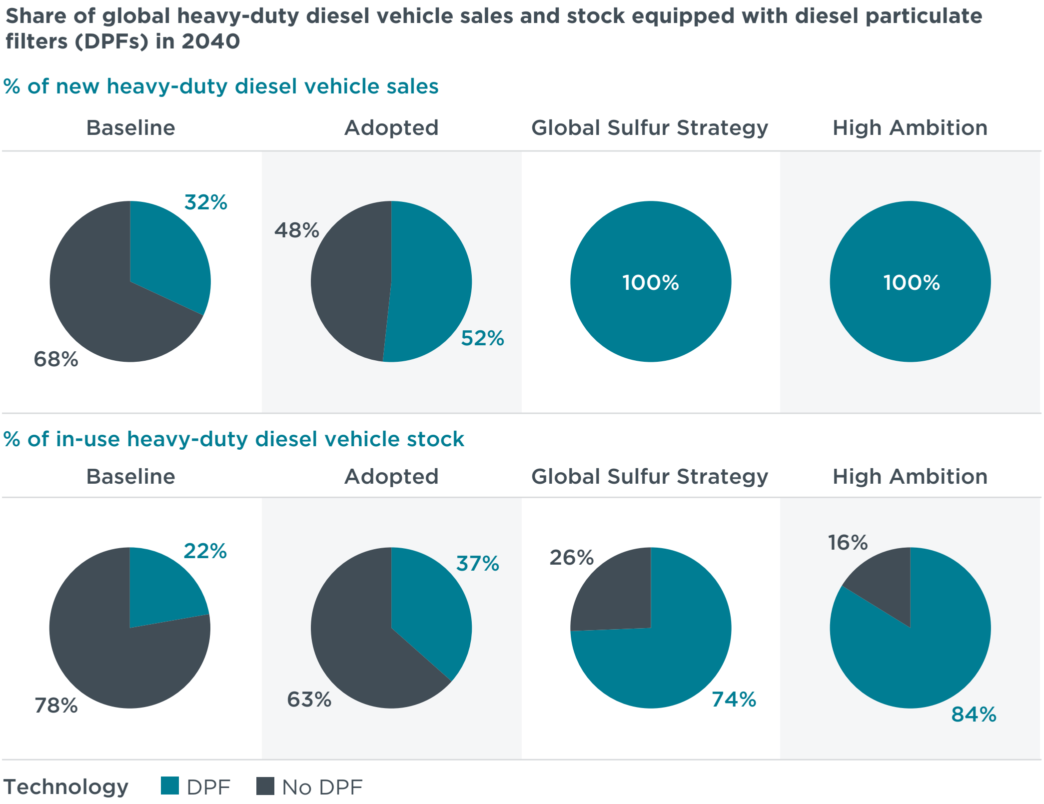
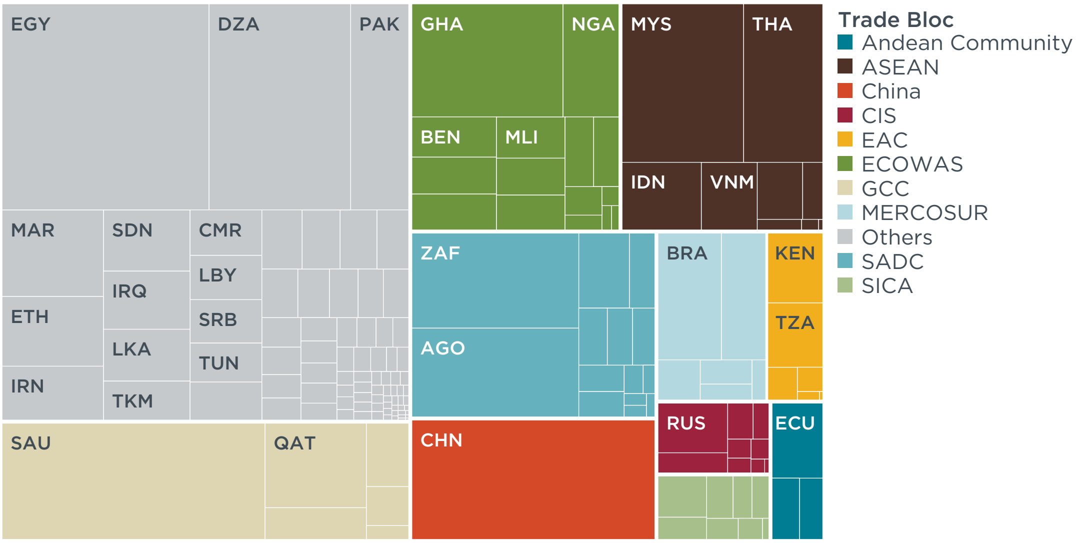


Figure 16. Share of global heavy-duty diesel vehicle sales and stock equipped with diesel particulate filters (DPFs) under four policy scenarios in 2040.

Trade blocs and a handful of populous countries are important targets for near-term introduction of soot-free standards (Figure 17). Coordinated actions to harmonize technical regulations in trade blocs such as ASEAN and ECOWAS could enable groups of countries to progress faster than if each country were to develop technical regulations individually. Alignment of vehicle emissions standards, fuel quality standards, and used vehicle import policies among countries with strong economic ties could have the added benefit of eliminating or reducing barriers to progress such as competitiveness concerns, cross-border traffic, limited access to cleaner fuels, and limited availability of vehicle models meeting local design specifications (Miller et al., 2017). Extending support for tightened standards to a short list of populous countries such as Egypt and Saudi Arabia could also have an outsized impact on the global BC emissions trajectory.



Cumulative BC mitigation potential of diesel road transport from 2018 through 2040 achievable with high ambition scenario, compared with policies adopted as of May 2018

Figure 17. Cumulative BC mitigation potential of diesel road transport from 2018 through 2040 achievable with high ambition scenario, compared with policies adopted as of May 2018. Area is proportional to remaining BC emissions mitigation potential after considering the effects of adopted policies. ASEAN, Association of Southeast Asian Nations; CIS, Commonwealth of Independent States; EAC, East African Community; ECOWAS, the Economic Community of West African States; GCC, the Gulf Cooperation Council; MERCOSUR, Southern Common Market (South America); NAFTA, the North American Free Trade Agreement; SADC, Southern African Development Community; SICA, Central American Integration System. The list of countries in each trade bloc is provided on page 48.

As shown in Figure 18, soot-free standards would make the difference between increasing BC emissions versus dramatic emissions reductions in several trade blocs. In EAC, ECOWAS, SADC, and ASEAN, BC emissions could increase by 60% for EAC to more than 100% for ECOWAS and SADC without new policies. Implementing the recommendations of the GSS could reduce global BC emissions to 86% below 2015 levels in 2040, compared with 31% below 2015 levels with adopted policies. The high ambition scenario would achieve greater BC emissions reductions in 2040 compared with the GSS due to the accelerated timeline for implementation of soot-free standards. The marginal benefits of the high ambition scenario are particularly salient for regions with projected BC emissions increases under adopted policies.

Percent change in annual BC emissions by trade bloc and scenario from 2015 to 2040

		Baseline	Adopted	Global Sulfur Strategy	High Ambition
Africa	EAC	59%	59%	-60%	-77%
	ECOWAS	160%	126%	-55%	-76%
	SADC	104%	103%	-62%	-80%
	Other Africa	8%	8%	-84%	-92%
Americas	NAFTA	-71%	-97%	-98%	-98%
	MERCOSUR	-46%	-52%	-90%	-94%
	Andean Community	-31%	-38%	-77%	-85%
	SICA	7%	2%	-72%	-83%
	Other Latin America	-10%	-10%	-76%	-87%
Asia Pacific	Australia	-61%	-61%	-98%	-98%
	Japan	-97%	-97%	-98%	-98%
	South Korea	-98%	-98%	-99%	-99%
	China	-24%	-79%	-99%	-99%
	India	185%	-89%	-91%	-91%
	ASEAN	80%	9%	-79%	-90%
	Other Asia Pacific	107%	97%	-76%	-91%
Europe	EU & EFTA	-99%	-99%	-99%	-99%
	CIS	-42%	-48%	-93%	-97%
	Other Europe	34%	19%	-81%	-91%
Middle East	GCC	9%	-7%	-73%	-84%
	Other Middle East	16%	-15%	-78%	-87%
World		10%	-31%	-86%	-92%

% change in BC

-99% ▨ 185%

Figure 18. Percent change in annual BC emissions by trade bloc and scenario from 2015 to 2040. ASEAN, Association of Southeast Asian Nations; CIS, Commonwealth of Independent States; EAC, East African Community; ECOWAS, the Economic Community of West African States; GCC, the Gulf Cooperation Council; MERCOSUR, Southern Common Market (South America); NAFTA, the North American Free Trade Agreement; SADC, Southern African Development Community; SICA, Central American Integration System. The list of countries in each trade bloc is provided on page 48.

TEMPERATURE IMPACTS OF ON-ROAD DIESEL BC EMISSIONS

In 2011, an assessment by UNEP and WMO identified a set of 16 short-lived climate pollutant (SLCP) mitigation actions in multiple economic sectors that could avoid 0.5°C of additional warming in 2050 (UNEP and WMO, 2011). In May 2017, members of the CCAC Scientific Advisory Panel (SAP) co-wrote an article in *Science* calling for reductions in CO_2 and SLCPs to meet global climate and sustainable development goals. The authors argue that "without reductions in both CO_2 and SLCPs, temperature increases are likely to exceed 1.5°C during the 2030s and exceed 2°C by mid-century" (Shindell et al., 2017). Their recommendations include two proposed targets that are relevant to this assessment. The first adapts the mitigation potential identified in the 2011 UNEP-WMO assessment as a near-term climate goal: to reduce SLCP emissions from all sectors by enough to avoid an average 0.5°C of warming over the next 25 years.

The second target is to reduce global anthropogenic BC emissions to 75% below 2010 levels by 2030 (Shindell et al., 2017).

We compare these targets against what we project is achievable under each of the four scenarios evaluated. Figure 19 shows the projected change in BC emissions from diesel road transport under each scenario. These trajectories are compared against the 75% BC reduction target, assuming diesel road transport contributes the same level of BC reduction as other emissions sources. The high ambition scenario could achieve a 75% reduction for diesel road transport in the 2030 timeframe, approximately five years faster than under the GSS. Additional fleet retrofit or renewal programs could further accelerate these emissions reductions. The results also illustrate that implementation of adopted policies with no further policy action is insufficient to reach a 75% reduction from 2010 levels. As with the baseline scenario, further policies are still needed to counteract the global emissions increase projected to result from activity growth.

Global BC from diesel road transport, 2010–2040 (kt, thousand tonnes)

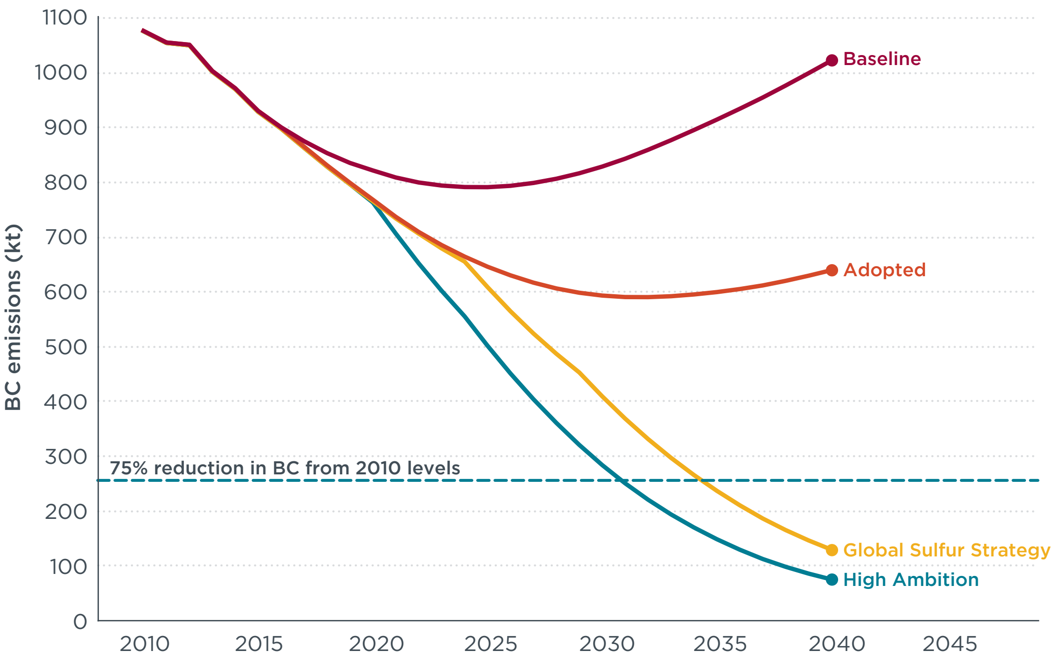


Figure 19. Global black carbon emissions from diesel road transport, 2010–2040. *Baseline:* Includes the historical timeline of vehicle emissions and fuel quality standards and assumes no changes in policy implementation after 2015. *Adopted:* Includes final regulations that have been adopted into law as of May 2018 but may have a future implementation date. Comparison of the adopted and baseline scenarios yields the projected benefits of recently adopted policies. *Global Sulfur Strategy*: Evaluates the impacts of implementing the initiative's global strategy for cleaner diesel vehicles and fuels (Malins et al., 2016); this scenario assumes that all countries implement at least Euro 4/IV by 2025 and Euro 6/VI by 2030 and that some countries implement these policies sooner. *High Ambition:* In recognition that countries could move more quickly to reduce BC emissions than targeted in the Global Sulfur Strategy, the high ambition scenario assumes that all countries implement at least Euro 4/IV by 2021 and Euro 6/VI by 2025; some markets that are already considering Euro 6/VI are assumed to implement those standards a few years earlier.

Figure 20 illustrates the global average temperature change from 2015 to 2050 associated with emissions from diesel road transport from 2015 through 2050.

Temperature change is estimated using the absolute global temperature change potential metrics provided by the SAP. In all four scenarios for diesel road transport, BC is the pollutant with the largest contribution to temperature change until at least 2030, and NO_X has the second-largest contribution until around 2025. Under currently adopted policies, future temperature change associated with BC emissions from diesel road transport remains substantial and increases further at mid-century.

Temperature pathways of 2015–2050 emissions from global diesel road transport by pollutant

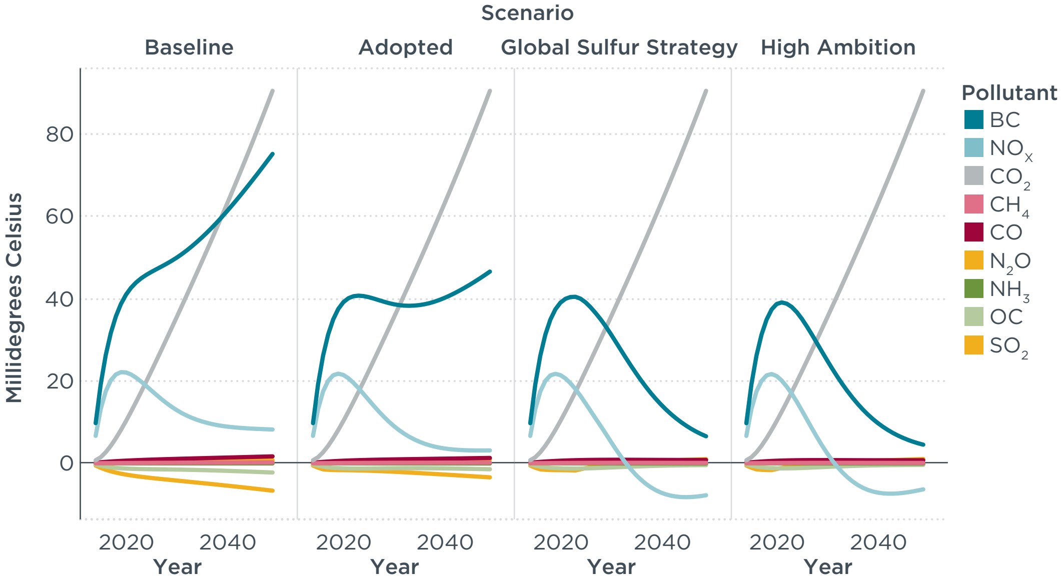


Figure 20. Temperature pathways of 2015–2050 global diesel road transport emissions by pollutant. One millidegree is equal to one thousandth of a degree Celsius. The cooling effects of certain pollutants such as OC and SO_2 are small compared with the warming impacts of BC. Absolute global temperature change potential metrics were not available for SO_4.

Figure 21 shows these same results but aggregates the impacts of non-CO_2 emissions. Under a baseline scenario, the aggregate temperature change associated with post-2015 non-CO_2 diesel road transport emissions would have rivaled the impacts of CO_2 at mid-century (77 versus 91 millidegrees).[8] Under adopted policies, the temperature change associated with non-CO_2 diesel road transport emissions is projected to peak in the 2020–2025 timeframe but increase again starting in the late 2030s. Only the GSS and high ambition scenarios would reduce the temperature change associated with non-CO_2 diesel road transport emissions to net zero by mid-century.

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[8] Additional CO_2 mitigation actions could reduce CO_2-related impacts but are outside the scope of this study.

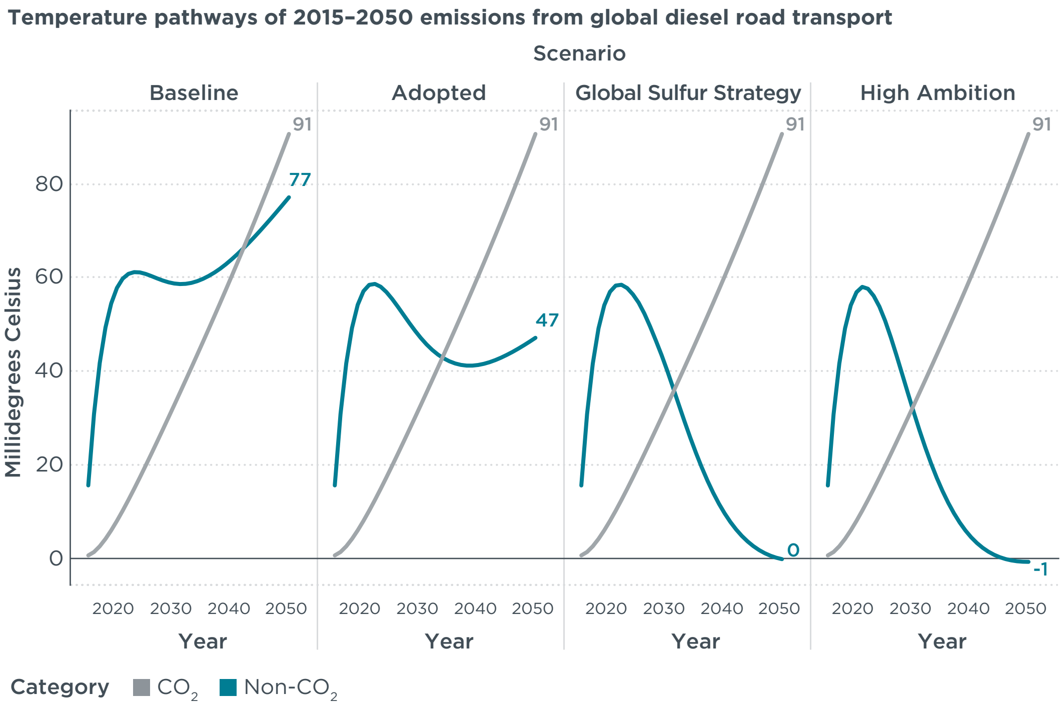

Figure 21. Temperature pathways of 2015–2050 global diesel road transport emissions. HFCs and SO_4 are not included. One millidegree is equal to one thousandth of a degree Celsius.

Figure 22 isolates the temperature pathways associated with post-2015 non-CO_2 emissions and compares these under each of the four policy scenarios. Adopted policies introduced after 2015 would reduce the temperature change associated with post-2015 non-CO_2 emissions by 40% in 2050 compared with the baseline scenario. Both the GSS and high ambition scenarios could effectively eliminate the temperature change associated with post-2015 non-CO_2 diesel road transport emissions by 2050. Compared with the baseline scenario, the GSS and high ambition scenarios would avoid 77 millidegrees of additional warming in 2050, equivalent to 15.4% of the 500 millidegrees in SLCP mitigation identified in the 2011 UNEP-WMO assessment.[9] The marginal benefits of the high ambition scenario compared with the GSS with respect to climate are evident when considering warming *over the next 25 years*, as opposed to at an end point such as mid-century. In 2030, the midpoint between 2018 and 2042, the high ambition scenario would avoid an additional 28 millidegrees of warming from the baseline scenario, compared with 19 millidegrees avoided by the GSS.

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[9] This assessment evaluates only the end-point temperature target. It does not evaluate the complementary target to reduce "average temperature impact over 25 years" proposed in Shindell et al. (2017). Evaluating the latter target would require estimates of historical emissions well before 2015, which are outside the scope of this assessment.

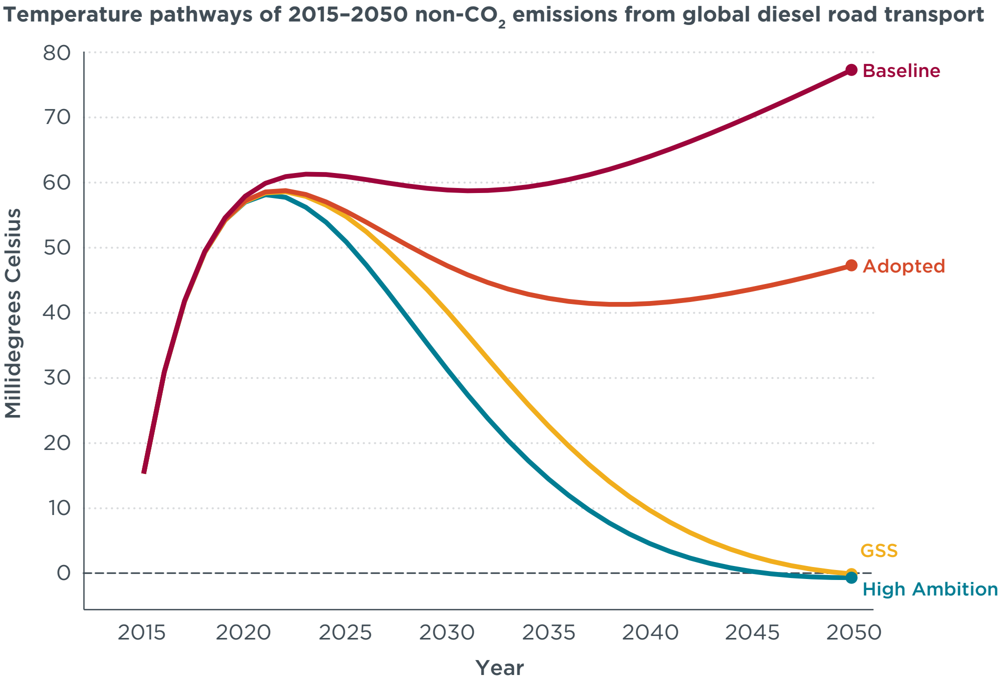

Figure 22. Temperature pathways of 2015–2050 non-CO_2 global diesel road transport emissions. HFCs and SO_4 are not included. One millidegree is equal to one thousandth of a degree Celsius.

TECHNICAL APPENDIX

This appendix describes the methods and data sources used to estimate and project the global air pollutant emissions and climate impacts of diesel-fueled road transport. The results cover nearly 200 countries and 99.8% of the world's population in 2015.

Diesel road transport exhaust emissions are a product of several factors. These include activity drivers such as vehicle sales, survival curves, and annual mileage; policy drivers such as new vehicle emissions standards, fuel quality standards, and used vehicle import policies; and other drivers such as the relationship between fuel sulfur content and the emissions factors of specific vehicle technologies. The methods for calculating fleet emissions based on these drivers are illustrated in Figure 23.

The number of new vehicles and used imported vehicles added to the fleet each year are based on sales data and projections, estimated used import volumes, and approximations of the average age of used imports. These are then combined with survival curves to estimate the number of vehicles remaining in the fleet over time.

The total level of vehicle activity, measured in vehicle-km traveled, is the product of the number of vehicles in the fleet in a given year and the average annual mileage of those vehicles. Mileage adjustments are then made to account for the trend that newer vehicles tend to accumulate mileage faster than older vehicles.

Energy consumption is the product of vehicle activity and vehicle efficiency. CO_2 emissions are the product of energy consumption and fuel carbon content. SO_2 emissions are based on energy consumption and fuel sulfur content.

Vehicle emissions rates of other air pollutants such as $PM_{2.5}$, BC, and NO_X depend on the presence and functioning of emissions control technologies such as diesel particulate filters (DPFs), selective catalytic reduction (SCR), etc. The extent to which new vehicles are equipped with these technologies depends on the applicable emissions standards at the time of type approval and registration. Whether these technologies continue to function properly is influenced by regulatory provisions such as durability, on-board diagnostic systems, and in-service conformity testing; additional compliance and enforcement activities; complementary programs such as inspection and maintenance; and vehicle operating characteristics such as fuel quality, maintenance, or tampering.

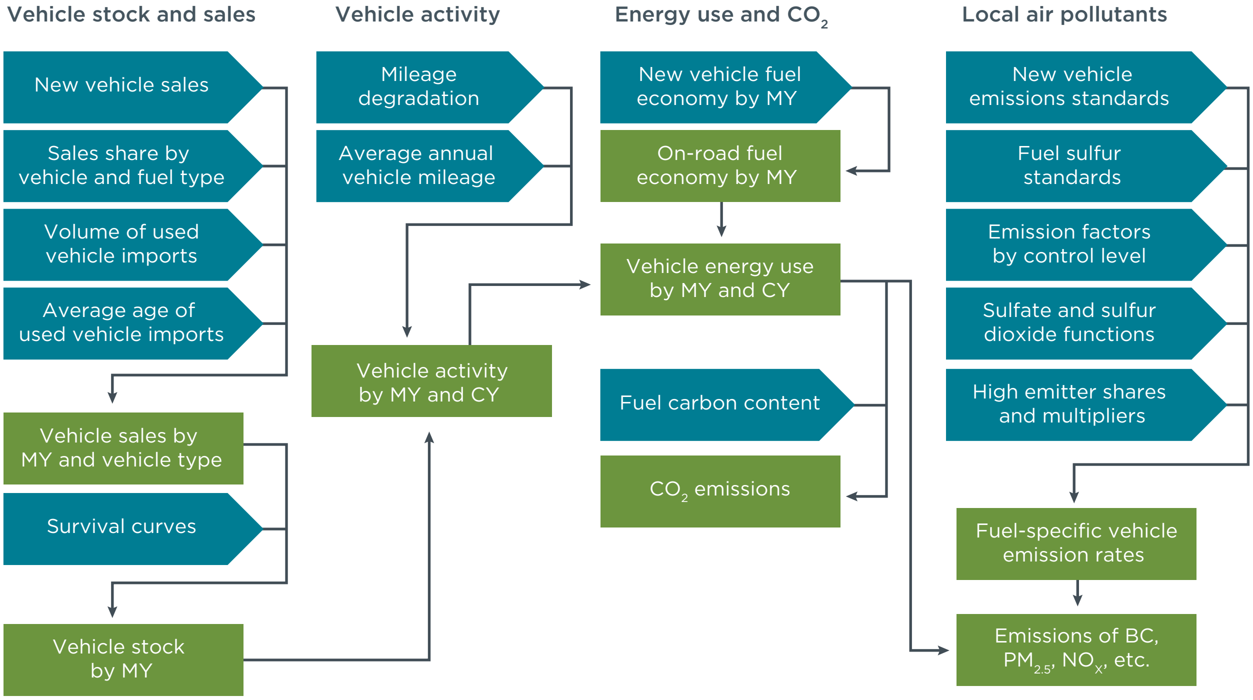

Figure 23. Diagram of diesel road transport fleet emissions model methodology. Blue fill indicates model inputs; green fill indicates calculations. MY, model year; CY, calendar year.

ACTIVITY DRIVERS

The growing global demand for passenger and freight services is an important driver of growth in diesel vehicle sales, energy consumption, emissions, and associated health and climate impacts. Yet rising incomes and increased trade activity also create opportunities to increase the global deployment of emissions control technologies and cleaner fuels that can decouple air pollutant emissions trends from diesel road transport activity. The following sections describe the key data sources and methods for estimating and projecting the activity drivers of diesel road transport emissions.

Vehicle definitions

Within diesel road transport, we consider three vehicle categories and six vehicle types (Table 1). Passenger cars and light commercial vehicles generally correspond to M1 and N1 vehicles in alignment with the EU's regulatory definitions. Medium- and heavy-duty trucks cover N2 and N3 vehicles and trailers, where applicable. Buses and minibuses cover M2 and M3 vehicles. Motorcycles and tricycles cover the small share of vehicles that are powered by diesel and are concentrated in a few countries.

Table 1. Diesel vehicle definitions. t, tonnes gross vehicle weight.

Vehicle Category	Vehicle Type	Definition
LDV (light-duty vehicles)	PC	cars and light trucks used primarily for passenger transport
	LCV	light commercial vehicles used primarily for freight (< 3.5 t)
HDV (heavy-duty vehicles)	MDT	medium-duty trucks (3.5 to 15 t)
	HDT	heavy-duty trucks (> 15 t)
	Bus	buses and minibuses
MC (2- & 3-wheelers)	MC	motorcycles and tricycles used for passengers or freight

New diesel vehicle sales

Historical estimates of new diesel vehicle sales by vehicle type are based on the IEA's Mobility Model database (IEA, 2017a). These estimates, which cover a mix of 42 countries and aggregate regions, were then allocated to individual countries using each country's share of the region's energy balance for on-road diesel and biodiesel combined (IEA, 2017b).[10] Projections of new diesel vehicle sales by region and vehicle type apply the annualized sales growth rates from IEA's Reference Technology Scenario for the period 2015 to 2050 (IEA, 2017a).

Estimates of global commercial vehicle sales by the International Organization of Motor Vehicle Manufacturers (OICA) include light commercial vehicles and non-diesel fueled vehicles. Thus, a direct comparison to IEA estimates of diesel vehicle sales is not possible. Nevertheless, OICA's global sales estimates confirm an important trend, that total commercial vehicle sales were relatively stable from 2011 to 2017 with the exception of North America[11] (International Organization of Motor Vehicle Manufacturers, 2017). This global trend is also present in IEA's estimates of new HDDV sales. There is, however, substantial uncertainty about actual sales volumes of diesel vehicles by country because sales statistics do not reliably differentiate among fuel types and vehicle types. It is possible that actual sales volumes for individual countries differ substantially from the volumes estimated and projected in this analysis. As will be discussed later, a key advantage of calibrating to match energy balances is that it ensures reasonable estimates of energy consumption and emissions, even if vehicle sales or other data inputs are uncertain. A second advantage of the modeling framework developed for this analysis is that it allows the refinement of data inputs and policy assumptions for individual countries as additional information becomes available. Subsequent versions of the global progress report will incorporate the refinements that result from such country-specific analyses.

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[10] Most of the biodiesel for road transport is blended into diesel fuels. We therefore consider both biodiesel and diesel when estimating the energy consumption and emissions of diesel road transport.

[11] Light commercial vehicles in the United States are most likely a large portion of the increase in North American sales.

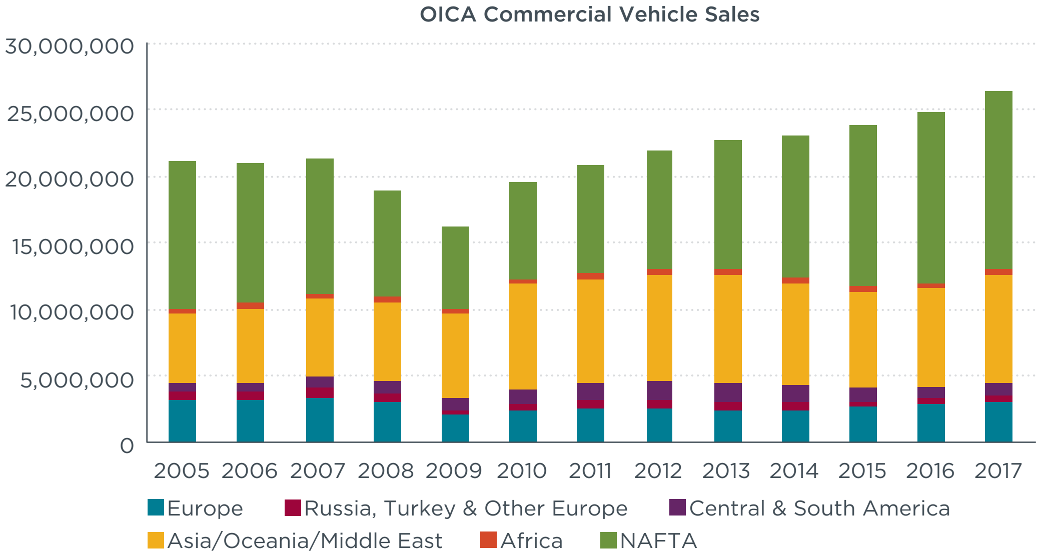

Figure 24. OICA world commercial vehicle sales estimates, 2005–2017.

Volume of used vehicle imports

In comparison with new vehicle sales, international data on the volume and characteristics of used vehicles is relatively scarce. Most studies have focused on the trade flows of used passenger cars and light trucks (Coffin, Horowitz, Nesmith, and Semanik, 2016; UN Environment, 2017). Much less is known about the trade flows of used commercial vehicles such as diesel trucks and buses. The IEA's Mobility Model (MoMo) database includes rough estimates of the volume of used vehicle imports in certain regions derived using a stock balance approach. That is, by estimating the volume of used vehicles that would need to be added to a region's vehicle fleet so that the total vehicle stock is in line with estimates of energy consumption, annual vehicle mileage, and retirement rates (IEA, 2017a). These estimates are used as a starting point for the volume of used vehicle imports by vehicle type in Africa, the Middle East, Latin America, Asia-Pacific, and Russia. Within these regions, countries that are known to ban outright the import of used cars, trucks, and/or buses are credited as effectively enforcing those bans.[12] This approach results in a conservatively low estimate of diesel road transport emissions, since factoring in extralegal used vehicle trade would probably increase emissions estimates. Projections of used vehicle imports for those regions without outright bans apply the same annualized growth rates as for new vehicle sales. This assumption effectively holds the share of used vehicle imports constant as a percentage of total sales to avoid assuming that the relative importance of used vehicle imports will increase or decrease when the directionality is not known.

Vehicle survival curves

The share of vehicles remaining in operation at a given vehicle age varies substantially across countries, vehicle types, and fleets. Although vehicle scrappage rates vary from year to year in response to economic factors, data on stock and sales over several decades can be used to approximate the average share of vehicles remaining in operation at a given vehicle age. Vehicle survival curves for each region are

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[12] See section on used vehicle import restrictions.

approximated using a Weibull distribution function as applied by Hao, Wang, Ouyang, and Cheng (2011):

$$SR_{i,m}(t) = \frac{SP_{i,m}(t)}{RP_{i,m}} = exp\left(-\left(\frac{t}{T_{i,m}}\right)^{k_{i,m}}\right),$$

> where $SR_{i,m}(t)$ is the survival ratio of vehicles (type *m*, registered in year *i*) at the vehicle age of *t*; $SP_{i,m}(t)$ is the number of not-scrapped vehicles (type *m*, registered in year *i*) at the vehicle age of *t*; $RP_{i,m}$ is the total number of vehicles of type *m* registered in year *i*; and $T_{i,m}$ and $k_{i,m}$ are the characteristic parameters.

Assuming a default value of 5 for *k*, vehicle survival curves were calibrated for each region and vehicle type by adjusting for T_m such that cumulative new vehicle sales and imports match IEA's stock estimates after accounting for vehicle retirements. The resulting T_m values are an approximation of the average vehicle retirement age. Survival curves were calibrated to match 2015 stock levels. Unless otherwise specified (e.g. to model the effects of a scrappage program), these survival curves are applied for all years of the analysis. In cases where the survival curve could not be fit, we assume a default T_m of 30. In practice, the default value is applied in fewer than 5% of the calibrated survival curves. Figure 25 shows the average, maximum, and minimum values of the results of the survival curve calibration for 42 regions. The average estimated retirement age across regions is approximately 16 years.

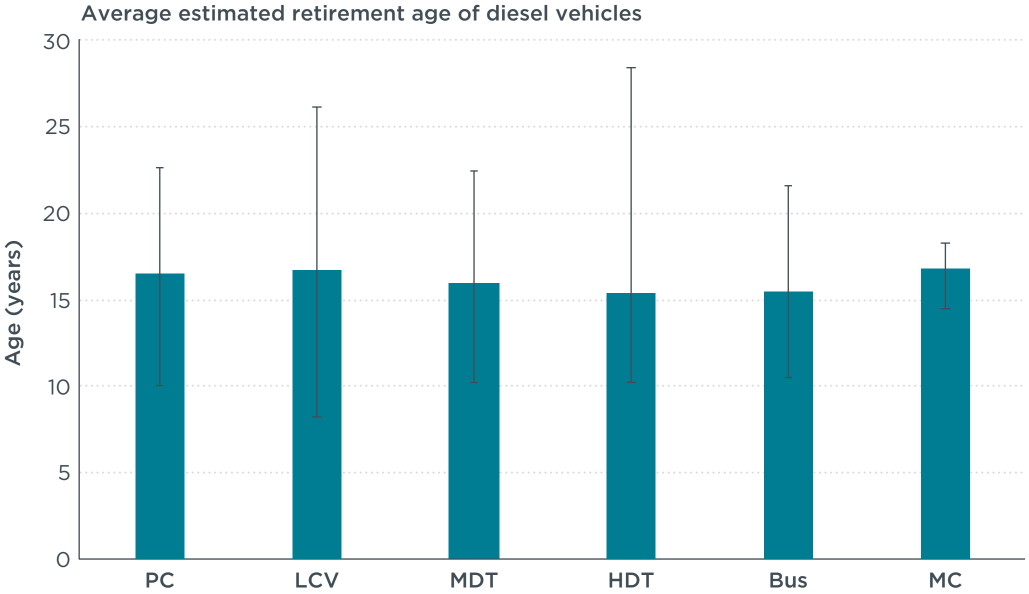

Figure 25. Average estimated retirement age of diesel vehicles based on calibration of survival curves to align stock and sales data. Vehicle definitions are given in Table 1. Error bars indicate maximum and minimum values among MoMo regions. Averages reflect a simple average across MoMo regions.

Diesel vehicle stock

New vehicle sales and used vehicle imports are taken as inputs and combined with the parameterized survival curves to estimate the stock of vehicles in each year. With respect to fleet turnover, used vehicle imports are treated as "age zero" when they are added to a country's vehicle fleet, such that the percentage of vehicles remaining in the fleet after a given time period is not dependent on whether those vehicles were added to the fleet as brand new sales or used imports. This assumption is designed to prevent underestimation of the emissions of used vehicles, which would occur if these were assumed to exit the fleet after only a couple of years as an artificial result of their high import age.

Annual vehicle mileage

Historical estimates of the average annual mileage by vehicle type and region are based on the IEA's MoMo database (IEA, 2017a). Because actual annual vehicle mileage varies from year to year in response to economic drivers, these estimates were then adjusted for historical years from 2000 to 2015 to align energy consumption estimates for each country with the applicable energy balances. Annual vehicle mileages for subsequent years are based on the calibrated 2015 estimates.

Mileage degradation

Studies in the United States, the European Union, and China have found that annual mileage accumulation tends to decline as vehicles age (Caserini, Pastorello, Gaifami, and Ntziachristos, 2013; Huo, Zhang, He, Yao, and Wang, 2012; Kolli, Dupont-Kieffer, and Hivert, 2010). These "mileage degradation" effects are an important consideration for emissions inventory modeling, since otherwise the share of vehicle activity by older vehicles and hence emissions may be overestimated. Since international information on mileage accumulation by vehicle age is limited, except where otherwise specified, we apply a set of default mileage degradation curves originally developed for the ICCT's India emissions model. These curves are applied to vehicles that were brand new when they entered the fleet and to used vehicle imports according to the time since they entered the importing country's vehicle fleet. As for vehicle retirements, this approach is designed to account for mileage degradation effects without assigning an artificially low mileage to used vehicle imports based on their high import age.

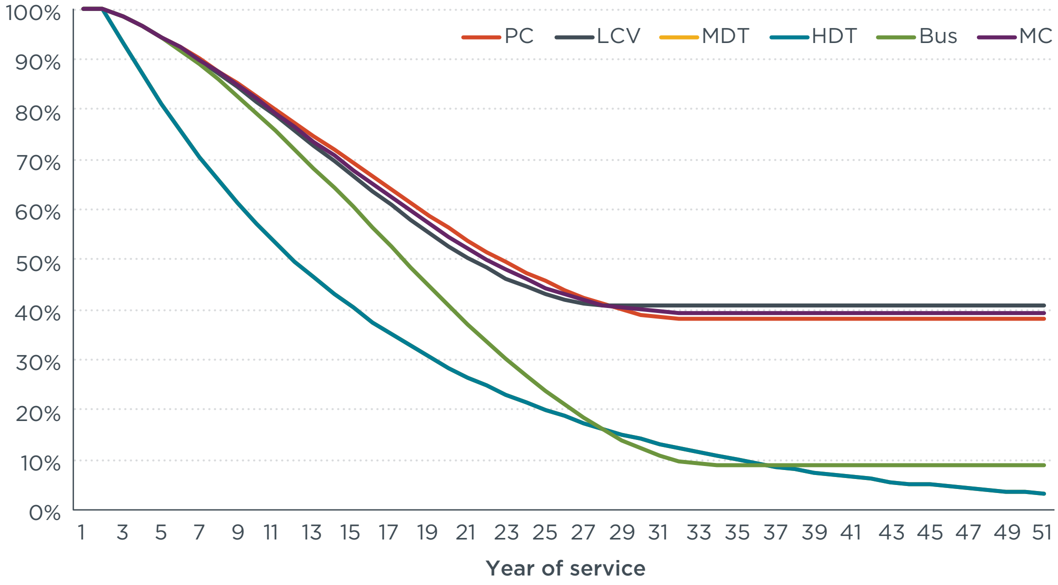

Figure 26. Default mileage degradation curves. Vehicle definitions are given in Table 1. 100% corresponds to vehicle mileage at age zero.

Vehicle energy efficiency

The fuel economy of new vehicles is affected by the existence and stringency of applicable fuel economy, CO_2, or greenhouse gas standards. Estimates of historical vehicle energy efficiency by model year are based on the MoMo database to maintain consistency with stock and mileage estimates (IEA, 2017a). These on-road fuel efficiency estimates for new vehicles account for differences between test cycle fuel economy and the performance of vehicles operating in real-world driving conditions. For those countries that have adopted mandatory vehicle efficiency standards for light-duty vehicles or heavy-duty vehicles, the fuel efficiency of new vehicles is assumed to follow the percentage improvement in targets implied by those standards.

Energy consumption

Energy consumption estimates are the product of mileage, stock, and energy efficiency for each vehicle type. Historical energy consumption estimates for diesel road transport are calibrated to match the IEA's energy balances. The advantage of this approach is that it offers a consistent starting point for evaluating diesel road transport emissions by country and tracking changes from year to year, since emissions are determined from energy consumption, the technology mix of the vehicle fleet, and technology-specific emissions factors. Calibrating the fleet model to match energy balances also allows for a consistent comparison of road transport estimates with other sectors of the economy. One potential downside is that the energy balances may not fully capture the actual energy consumption for road transport in specific countries.[13] Another limitation is that detailed, sector-specific energy balances are not available for all countries.

The 2017 edition of the IEA's world energy balances includes energy consumption estimates for diesel-fueled road transport in 138 countries; an additional 60 countries are covered within aggregate regions (IEA, 2017b). Those 138 countries with individual balances accounted for 99% of world road diesel energy consumption in 2015. To facilitate the aggregation of any combination of countries in our model, such as by trade blocs, we downscaled the IEA estimates for aggregate regions to their constituent countries using each country's share of the regional population. This yielded a data set of 199 countries covering 99.5% of world road diesel energy consumption in 2015. We then screened these estimates for apparent inconsistencies, such as a country with a substantial, unexplained drop in diesel consumption, and made adjustments for 58 countries. The additional data sets that we used to adjust the IEA estimates are from CITAC as reported in Naré and Kamakaté (2017) and the Joint Organisations Data Initiative (JODI, 2016). In the case that only total diesel consumption was given, we applied the share of road transport diesel consumption by region from the IEA (IEA, 2017b). Energy consumption is scaled based on population for historical years with missing energy inputs. The final data inputs to the fleet model cover 199 countries and 99.8% of world population in 2015.

POLICY DRIVERS

The following sections describe the methods and data sources for evaluating three key policy drivers of diesel road transport emissions: new vehicle emissions standards, used vehicle import restrictions, and fuel sulfur standards.

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[13] For example, the energy balances for road transport diesel consumption in Nigeria show a decline from 3.1 million tonnes of oil equivalent in 2004 to 537,000 in 2015, equivalent to a drop of more than 80% in a decade.

New vehicle emissions standards

The vast majority of new vehicles originate in countries with mandatory national emissions performance standards. Details on the stringency and implementation dates of adopted emissions regulations for new light- and heavy-duty vehicles were compiled from a combination of sources, including TransportPolicy.net, the Partnership for Clean Vehicles and Fuels, and other government, industry, and non-governmental sources. Details on adopted regulations in select countries were validated by regional experts at UN Environment and government contacts in CCAC member countries. This information will be updated in subsequent reports as countries adopt additional policies.

Whereas most major vehicle markets have introduced vehicle emissions regulations concurrently with improvements in fuel quality, vehicle emissions regulations do not necessarily take full advantage of available fuel quality. The potential mismatch is particularly salient for countries that have secured availability of ultralow-sulfur diesel (less than 10–15 parts per million sulfur) but have vehicle standards in force that are less stringent than Euro 6/VI. This is necessarily the case for all countries with Euro 5/V standards in force, since Euro 5/V vehicles use the same fuel as Euro 6/VI. Other examples of not fully leveraging available fuel quality include countries that have 50 ppm diesel available yet do not require new vehicles or incoming used vehicle imports to meet Euro 4/IV specifications. For countries either lacking mandatory emission standards or for which information is not available, emissions levels of new vehicles are estimated using expert judgment, considering vehicle flows, the vehicle emissions characteristics of the region, and diesel sulfur content. For example, countries in the EAC have access to 50 ppm diesel, but incoming vehicles are unlikely to perform better than Euro 3/III since those countries have not yet implemented Euro 4/IV-equivalent standards.

Used vehicle import restrictions

Countries permit the import of used vehicles to varying degrees. Some countries ban used vehicle imports entirely, whereas others restrict imports based on vehicle age or—less commonly—emissions certification level. Available information on historical and current used vehicle import restrictions was compiled for each country, with particular attention to whether the restrictions apply to cars, trucks, and/or buses (Coffin et al., 2016; Davis and Kahn, 2008; Fuse, Kosaka, and Kashima, 2009; Edwards, 2017; UN Environment, 2017; United States Department of Commerce, 2015).

Several simplifying assumptions are made to assess the emissions impacts of used vehicle import policies. First, countries that ban used imports of a given vehicle category are assumed to have negligible used imports for that category. While this assumption gives credit to countries that have banned used vehicle imports, it does not account for potential illegal or parallel market flows of used vehicles.

Provided that the model year or age of a used vehicle import and its country of origin are known, the original emissions certification level of that vehicle can be approximated based on the timeline of new vehicle emissions standards in the originating country. This approach yields an approximation rather than a definitive emissions control level, since in practice, vehicle importing countries tend to source their vehicles from multiple export markets. The top vehicle exporting trade partner for each country, vehicle category, and calendar year was identified using the value of imports obtained from the Observatory of Economic Complexity (Simoes, n.d.). In countries that set a maximum age for used vehicle imports, that age is taken to be the limiting factor for determining the minimum emissions control level of used vehicle imports based on the timeline of emissions standards in the top vehicle exporting country.[14]

In countries for which no information on used vehicle import restrictions is available, used cars are assumed to be a maximum of 15 years old upon entry, and used trucks and buses are assumed to be a maximum of 20 years old upon entry. As in countries with age restrictions, the level of emissions performance is estimated using information on the largest vehicle exporting trade partner and the timeline of new vehicle emissions standards in the exporting country. The inferred emissions control levels are then adjusted subject to fuel quality constraints as described further below.

In those countries that set a minimum emissions performance requirement for used vehicle imports, that level of emissions performance is assumed initially to apply to all used vehicle imports of a given vehicle category. In future years, the more stringent of the inferred control level based on vehicle age and country of origin and the minimum emissions requirement are assumed.

In countries where the sulfur content of diesel is higher than the design specifications of incoming used vehicle imports, the emissions control level of these imports is adjusted to reflect the removal or malfunction of emissions control technologies. For example, if Euro 4 cars are brought into a country with 5,000 ppm diesel, those cars are assumed to emit at uncontrolled levels for the remainder of their useful life. Although subsequent improvements in fuel quality are assumed to reduce fleetwide SO_2 and SO_4 emissions as a result of reduced sulfur content, those improvements are not assumed to fix any of the emissions control problems of vehicles that have been imported.

Taken together, these assumptions reflect several expectations of the evolving nature of the global used vehicle trade:

- The fleet of used vehicles exported from countries with advanced emissions standards is likely to become cleaner over time as countries continue to adopt progressively stringent new vehicle emissions requirements, including enhanced durability and OBD provisions.
- Countries with high-sulfur diesel are likely to miss out on the benefits of used vehicle imports with advanced emissions controls, since these controls are liable to either malfunction or be removed upon import.
- Used vehicle-importing countries with 10 ppm diesel may be able to reach soot-free emissions performance by simply requiring used imports to demonstrate Euro 6/VI-equivalent certification.

Diesel sulfur content

High sulfur content of diesel is a key factor in limiting the introduction and proper functioning of advanced emissions control technologies while low sulfur content is key to enabling such technologies. Nationwide fuel quality standards are a key driver of reductions in diesel sulfur content. In countries with domestic refining capacity, a transition to lower sulfur fuels may be accompanied by direct investments in refineries to produce low sulfur fuel, fuel price reforms to encourage those investments by private

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[14] For example, if Mexico limits the age of used vehicle imports to 10 years and its largest vehicle exporting trade partner is the United States, used trucks exported from the United States to Mexico in 2017 are assumed to have an emissions control level equivalent to U.S. EPA 2007 standards.

entities, or limiting the uses of higher sulfur diesel to non-road applications such as marine.[15] In countries that import refined diesel for on-road applications, a transition to 10 ppm sulfur diesel may be accomplished by tightening the standard on fuel imports. In countries with multiple fuel grades, a switch to cleaner fuels can be encouraged through pricing or taxation policies.

Data on diesel sulfur content in 165 countries was obtained from Stratas Advisors. The data set differentiates on-road diesel from diesel for other applications, lists the characteristics of multiple on-road diesel fuel grades where applicable, and differentiates regulatory specifications from estimates of actual sulfur content. These specifications were cross-checked and supplemented with fuel quality measurements from Infineum's winter diesel fuel quality survey, as well as regulatory information from TransportPolicy.net, the Partnership for Clean Vehicles and Fuels, and the CCAC global sulfur strategy. In most cases, the actual reported diesel sulfur levels are at or below the regulatory limit. In other cases, substantially higher actual diesel sulfur levels may indicate that regulatory targets such as the introduction date of 50 ppm diesel were not met.

For the fleet emissions modeling, we prioritized data on actual fuel sulfur levels where such data are available. In countries with multiple fuel grades or varying actual fuel sulfur levels, we used the sales-weighted average fuel sulfur level as the main indicator of fuel quality. For select countries that have 10 ppm or 50 ppm fuels available but still allow the sale of higher sulfur fuels under a separate fuel grade, we assume newer vehicles that require cleaner fuels use the appropriate fuel grade. For example, we assume Euro V vehicles in Brazil and Argentina use 10 ppm diesel, Euro IV vehicles in India use 50 ppm diesel, and DPF-equipped HDVs in Iran use 50 ppm diesel.

EMISSIONS CALCULATIONS

Non-CO_2 pollutant emissions are calculated as the product of technology-specific emission factors, such as milligrams of pollutant per megajoule of energy consumption, and fuel consumption by vehicle type and technology.

Fuel-specific emission factors

Emission factors (EFs) for U.S. standards are derived from the EPA's Motor Vehicle Emission Simulator (MOVES), version 2014a (U.S. EPA, 2016b). These EFs are specific to each U.S. emissions standard and reflect the exhaust emissions for each pollutant species averaged over the applicable vehicle types (Table 2), driving conditions, and model years for vehicles certified to that standard.

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[15] Even the most stringent fuel sulfur limit for international marine vessels operating within emissions control areas is 0.1% (1,000 ppm), which is 100 times higher than the most stringent sulfur limit for on-road diesel fuels. There may thus still be a viable market for higher sulfur fuels if they are diverted from on-road applications to marine vessels.

Table 2. Classification of MOVES source types.

Vehicle	MOVES Source Type Name
PC	Passenger Car
PC	Passenger Truck
LCV	Light Commercial Truck
MDT	Motor Home
MDT	Refuse Truck
MDT	Single Unit Long-haul Truck
MDT	Single Unit Short-haul Truck
HDT	Combination Long-haul Truck
HDT	Combination Short-haul Truck
Bus	Intercity Bus
Bus	School Bus
Bus	Transit Bus
MC	Motorcycle

EFs for European HDV standards were extracted from Emisia SA's Sibyl model. Sibyl estimates emissions for EU member states based on the COPERT methodology, which is part of the EMEP/EEA air pollutant emission inventory guidebook (Gkatzoflias, Kouridis, Ntziachristos, and Samaras, 2012). Fuel-specific EFs for HDVs reflect the energy consumption-weighted average of MDTs and HDTs, respectively. $PM_{2.5}$ EFs for EU LDV standards are sourced directly from the EMEP/EEA guidebook. NO_x EFs for EU LDV standards are sourced from real-world NO_x EF estimates in Anenberg et al. (2017) and converted to fuel-specific EFs using LDV energy efficiency data obtained from Sibyl. These EFs take into account the expected NO_x reductions with the EU's RDE program for Euro 6 LDVs.

EFs for China were derived from ICCT analysis of data from COPERT, Tsinghua University, and the Vehicle Emissions Control Center. These EFs take into account the expected emissions reductions with China's latest China 6a and 6b standards for LDVs (ICCT, 2017).

Particulate matter speciation

Primary particulate matter (PM) emissions consist of several size classes:

$$\textit{Total suspended particulates (TSP)} = \textit{fine } (PM_{2.5}) + \textit{coarse } (PM_{10}) + \textit{large } (PM{\geq}_{10})$$

Exhaust emissions of PM from on-road vehicles consist mostly of $PM_{2.5}$, whereas non-exhaust emissions (brake, tire, road abrasion) consist mostly of PM_{10}. Exhaust emissions of $PM_{2.5}$ are composed of several species: black carbon (BC), organic mass (OM), sulfates, nitrates, metals and elements, and others:

$$PM_{2.5} = BC + OM + SO_4 + NH_3 + NO_3 + \textit{metals and elements} + \textit{other pollutants}$$

The first three categories—BC, OM, and sulfates—account for 90–98% of exhaust $PM_{2.5}$ mass from diesel engines. BC is also referred to as elemental carbon (U.S. EPA, 2012). For air quality modeling, OM is often split into organic carbon (OC) and non-carbon organic mass.

For this analysis, $PM_{2.5}$ emissions for diesel vehicles are speciated using the MOVES methodology (U.S. EPA, 2015). The resulting shares of $PM_{2.5}$ attributed to BC and OC are similar to the shares reported in Table 3.88 of the EMEP/EEA guidebook (Ntziachristos and Samaras, 2017). We apply a ratio of 1.2 for OM to OC following the EPA's methods (U.S. EPA, 2015), which is similar to the ratio of 1.3 applied in Klimont et al. (2017). Although outside the scope of this analysis, exhaust emissions of PM_{10} could be approximated from these exhaust $PM_{2.5}$ estimates using a multiplier of 1.087 for diesel engines (U.S. EPA, 2015).

Sulfates and sulfur dioxide

We calculate sulfate (SO_4) and sulfur dioxide (SO_2) emissions following the methodology in the U.S. EPA's MOVES (U.S. EPA, 2016a). SO_2 emissions are calculated as the product of fuel consumption, fuel-sulfur level, the ratio of molecular weight of SO_2 to sulfur, and the fraction of fuel sulfur that is assumed to be converted to gaseous SO_2 emissions as opposed to SO_4. The SO_2 EF is specific to each source.

SO_4 emissions are calculated using the reference non-elemental carbon $PM_{2.5}$ emission rate, the sulfate reference fraction, the user-supplied fuel sulfur level, the reference fuel sulfur level, and the percentage of sulfate originating from the fuel sulfur in the reference case. These parameters vary by vehicle type and model year. Details on the equations and MOVES inputs used to calculate SO_2 and SO_4 emissions can be found in the MOVES technical documentation.[16]

High emitters

We estimate the PM impacts of high-emitting vehicles largely following the approach applied by Klimont et al. (2017). We define high emitters as vehicles whose emissions control systems are malfunctioning—either as a result of poor maintenance, tampering, or failure—and which as a result produce PM emissions that are substantially higher than regulatory certification limits. We then make assumptions about the share of vehicles affected in each region and apply PM emissions multipliers to the EFs of the affected vehicles as shown in Table 3.

Table 3. PM multipliers applied to high-emitting vehicles

Vehicle category	Euro equivalent emission standard	PM multiplier for high-emitting diesel vehicles
LDV	Euro 0	3
LDV	Euro 1	3
LDV	Euro 2	5
LDV	Euro 3	5
LDV	Euro 4	5
LDV	Euro 5	20*
LDV	Euro 6	20*
HDV	Euro 0	3
HDV	Euro 1	3
HDV	Euro 2	5
HDV	Euro 3	5
HDV	Euro 4	5
HDV	Euro 5	5*
HDV	Euro 6	20*

* Indicates different assumptions from those of Klimont et al. (2017). We assume a relatively high multiplier of 20 for high-emitting vehicles with a malfunctioning diesel particulate filter (DPF), since a properly functioning DPF would otherwise nearly eliminate direct PM emissions. The result is that high-emitting DPF-equipped vehicles are assumed to emit roughly the same as Euro 4/IV vehicles.

We assume that high emitters in the European Union, the United States, and Canada are already largely reflected in the average results of EF models from which our EFs are derived. To the extent that these EF models, for example MOVES and COPERT, do not

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[16] See Equations 9.1 and 9.3 in U.S. EPA. (2016).

account for the full incidence of high emitters in these regions, actual PM emissions could be even higher than those estimated here. For other regions, we assume that 3% to 5% of vehicles are high emitters in Japan and Korea, 4% to 8% in Australia, 10% in European countries outside the European Union, 12% to 15% of vehicles in China, 15% in India, and 20% of vehicles in other emerging markets and developing economies. Where ranges are given, the higher number generally applies to the incidence of high emitters for older technologies up to Euro 3, and the lower number applies to modern technologies starting at Euro 4. The only exception is China, where we assume a 15% incidence for Euro IV and Euro V equivalent HDVs to account for anecdotal reports that a slightly higher share of these vehicles produce high PM emissions than other emissions control stages.

The same assumptions for high emitters are applied to all policy scenarios to isolate the impacts of changes in regulations for vehicles and fuels. There are, however, additional actions which are outside the scope of this study but which could yield further emissions reductions. Such actions could include fleet renewal or retrofit programs, enhanced inspection and maintenance (I&M), roadside monitoring linked to I&M, pollution charges or registration taxes based on vehicle age or emissions control level, or low emissions zones.

Emissions validation

Klimont et al. (2017) evaluate global anthropogenic PM and BC emissions by sector from 1990 to 2010 using the integrated assessment model GAINS. The resulting emissions inventory, ECLIPSE version 5a, includes BC emissions for diesel road transport in 25 geographic regions. Comparison of our estimates of global BC emissions for diesel road transport in 2000, 2005, and 2010 with ECLIPSE shows good agreement at the global level and by region (Figure 27). These emissions inventories are particularly well aligned considering the uncertainties in multiple determinants of black carbon emissions.

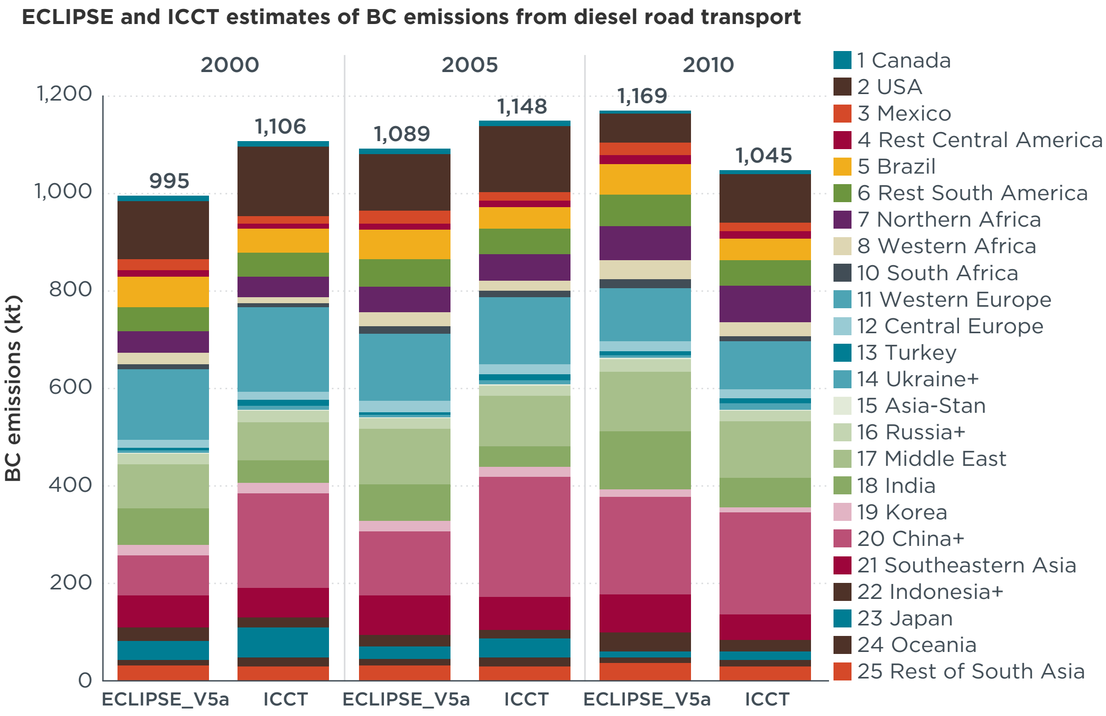

Figure 27. ECLIPSE and ICCT estimates of black carbon emissions from diesel road transport.

TRADE BLOC DEFINITIONS

Table 4 spells out the names of the trade blocs that are considered in this analysis. The lists of countries in each trade bloc are given in Table 5.

Table 4. Trade bloc definitions.

Acronym	Definition
ASEAN	Association of Southeast Asian Nations
CIS	Commonwealth of Independent States
EAC	East African Community
ECOWAS	Economic Community of West African States
GCC	Gulf Cooperation Council
MERCOSUR	Southern Common Market (South America)
NAFTA	North American Free Trade Agreement
SADC	Southern African Development Community
SICA	Central American Integration System

Table 5. List of countries in each trade bloc. Asterisk denotes countries that have signed onto the Marrakech Communiqué.

Region	Trade Bloc	Country	ISO
Africa	EAC	Burundi	BDI
Africa	EAC	Kenya*	KEN
Africa	EAC	Rwanda*	RWA
Africa	EAC	South Sudan	SSD
Africa	EAC	Tanzania	TZA
Africa	EAC	Uganda	UGA
Africa	ECOWAS	Benin*	BEN
Africa	ECOWAS	Burkina Faso	BFA
Africa	ECOWAS	Cabo Verde	CPV
Africa	ECOWAS	Côte d'Ivoire*	CIV
Africa	ECOWAS	Gambia	GMB
Africa	ECOWAS	Ghana	GHA
Africa	ECOWAS	Guinea-Bissau	GNB
Africa	ECOWAS	Guinea*	GIN
Africa	ECOWAS	Liberia	LBR
Africa	ECOWAS	Mali*	MLI
Africa	ECOWAS	Niger	NER
Africa	ECOWAS	Nigeria*	NGA
Africa	ECOWAS	Senegal	SEN
Africa	ECOWAS	Sierra Leone	SLE
Africa	ECOWAS	Togo*	TGO
Africa	SADC	Angola	AGO
Africa	SADC	Botswana	BWA
Africa	SADC	Dem. Rep. Congo	COD
Africa	SADC	Lesotho	LSO
Africa	SADC	Madagascar	MDG
Africa	SADC	Malawi	MWI

Region	Trade Bloc	Country	ISO
Africa	SADC	Mauritius	MUS
Africa	SADC	Mozambique	MOZ
Africa	SADC	Namibia	NAM
Africa	SADC	Seychelles	SYC
Africa	SADC	South Africa	ZAF
Africa	SADC	Swaziland	SWZ
Africa	SADC	Zambia	ZMB
Africa	SADC	Zimbabwe	ZWE
Americas	Andean Community	Colombia*	COL
Americas	Andean Community	Ecuador	ECU
Americas	Andean Community	Peru	PER
Americas	MERCOSUR	Argentina	ARG
Americas	MERCOSUR	Bolivia	BOL
Americas	MERCOSUR	Brazil	BRA
Americas	MERCOSUR	Paraguay*	PRY
Americas	MERCOSUR	Uruguay*	URY
Americas	MERCOSUR	Venezuela	VEN
Americas	NAFTA	Canada*	CAN
Americas	NAFTA	Mexico*	MEX
Americas	NAFTA	USA*	USA
Americas	SICA	Belize	BLZ
Americas	SICA	Costa Rica	CRI
Americas	SICA	Dominican Rep.*	DOM
Americas	SICA	El Salvador	SLV
Americas	SICA	Guatemala	GTM
Americas	SICA	Honduras	HND
Americas	SICA	Nicaragua	NIC
Americas	SICA	Panama	PAN
Asia Pacific	ASEAN	Brunei	BRN
Asia Pacific	ASEAN	Cambodia	KHM
Asia Pacific	ASEAN	Indonesia	IDN
Asia Pacific	ASEAN	Lao PDR	LAO
Asia Pacific	ASEAN	Malaysia	MYS
Asia Pacific	ASEAN	Myanmar	MMR
Asia Pacific	ASEAN	Philippines*	PHL
Asia Pacific	ASEAN	Singapore	SGP
Asia Pacific	ASEAN	Thailand	THA
Asia Pacific	ASEAN	Viet Nam	VNM
Europe	CIS	Armenia	ARM
Europe	CIS	Azerbaijan	AZE
Europe	CIS	Belarus	BLR
Europe	CIS	Kazakhstan	KAZ
Europe	CIS	Kyrgyzstan	KGZ
Europe	CIS	Republic of Moldova*	MDA
Europe	CIS	Russian Federation	RUS
Europe	CIS	Tajikistan	TJK

Region	Trade Bloc	Country	ISO
Europe	CIS	Uzbekistan	UZB
Europe	EU & EFTA	Austria	AUT
Europe	EU & EFTA	Belgium	BEL
Europe	EU & EFTA	Bulgaria	BGR
Europe	EU & EFTA	Croatia	HRV
Europe	EU & EFTA	Cyprus	CYP
Europe	EU & EFTA	Czech Republic	CZE
Europe	EU & EFTA	Denmark*	DNK
Europe	EU & EFTA	Estonia	EST
Europe	EU & EFTA	Finland*	FIN
Europe	EU & EFTA	France	FRA
Europe	EU & EFTA	Germany	DEU
Europe	EU & EFTA	Greece	GRC
Europe	EU & EFTA	Hungary	HUN
Europe	EU & EFTA	Iceland	ISL
Europe	EU & EFTA	Ireland*	IRL
Europe	EU & EFTA	Italy*	ITA
Europe	EU & EFTA	Latvia	LVA
Europe	EU & EFTA	Lithuania	LTU
Europe	EU & EFTA	Luxembourg*	LUX
Europe	EU & EFTA	Malta	MLT
Europe	EU & EFTA	Netherlands*	NLD
Europe	EU & EFTA	Norway*	NOR
Europe	EU & EFTA	Poland*	POL
Europe	EU & EFTA	Portugal	PRT
Europe	EU & EFTA	Slovakia	SVK
Europe	EU & EFTA	Slovenia	SVN
Europe	EU & EFTA	Spain	ESP
Europe	EU & EFTA	Sweden*	SWE
Europe	EU & EFTA	Switzerland*	CHE
Europe	EU & EFTA	United Kingdom*	GBR
Middle East	GCC	Bahrain	BHR
Middle East	GCC	Kuwait	KWT
Middle East	GCC	Oman	OMN
Middle East	GCC	Qatar	QAT
Middle East	GCC	Saudi Arabia	SAU
Middle East	GCC	UAE	ARE

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