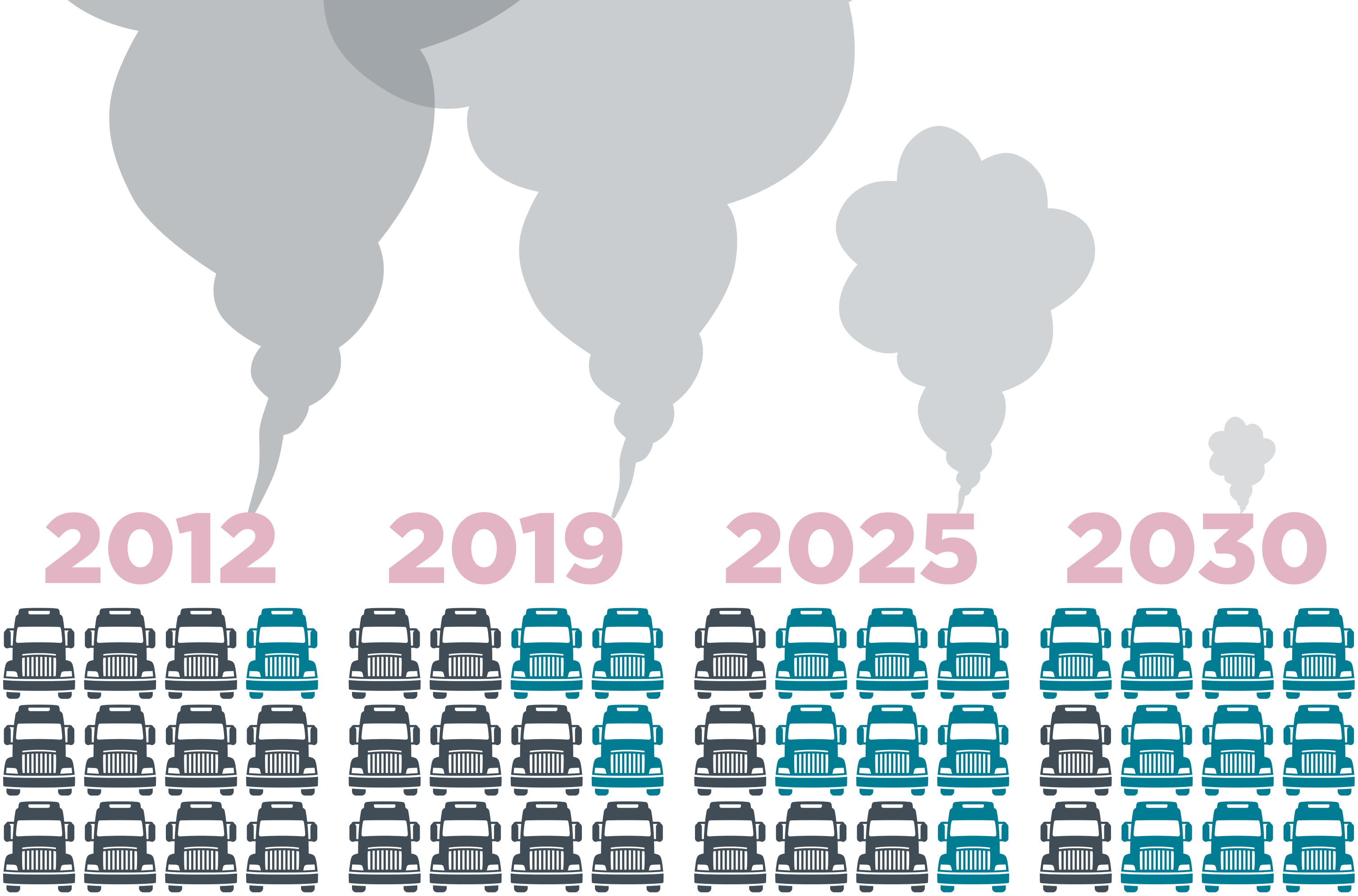
GLOBAL PROGRESS TOWARD SOOT-FREE DIESEL VEHICLES IN 2019

Joshua Miller and Lingzhi Jin



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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

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

ACKNOWLEDGEMENTS

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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.

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.

International Council on Clean Transportation
1500 K Street NW Suite 650
Washington, DC 20005 USA

communications@theicct.org | www.theicct.org | @TheICCT

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EXECUTIVE SUMMARY

This report assesses global progress in 2019 toward reducing black carbon (BC) emissions from diesel on-road light-duty and heavy-duty vehicles. Black carbon—also known as soot—is a component of fine particulate matter that is a byproduct of incomplete combustion. Its major sources include on-road and non-road diesel engines and the burning of coal and biomass for activities such as electricity production, cooking, and heating. The transportation sector accounts for an estimated 25% of global anthropogenic BC emissions (Klimont et al., 2017). The tiny size of a BC particle allows it to carry toxic substances found in vehicle exhaust into sensitive areas of the body. Black carbon is also a potent short-lived climate pollutant (SLCP) that contributes to rapid near-term climate change. The rapid reduction of diesel BC emissions is a key element of a strategy to avoid 0.5°C of warming in 2050 by reducing emissions of SLCPs—BC, methane, and hydrofluorocarbons—from multiple sectors.

Within on-road diesel vehicles, heavy-duty vehicles (HDVs) are the main contributor to exhaust emissions and health impacts: HDVs were responsible for 86% of on-road diesel NO_X emissions in 2015 (Anenberg et al., 2017) and 78% of on-road diesel BC emissions in 2017, despite accounting for less than a quarter of the diesel vehicle fleet (Miller & Jin, 2018). The disproportionate contribution of HDVs is a key reason for their prioritization by the Climate and Clean Air Coalition (CCAC) Heavy Duty Vehicles Initiative (HDVI), which works to catalyze major reductions in BC through adoption of clean fuel and vehicle regulations and supporting policies. The HDVI defines "soot-free" engines as those that achieve a 99% or greater reduction in BC compared with older-technology diesel engines. All diesel or alternative engines that meet Euro 6/VI or equivalent emission levels for particle mass or particle number are considered soot-free. These can include diesel engines with a wall-flow diesel particulate filter, gas-powered engines, and dedicated electric-drive engines.

This report provides an update to a 2018 assessment that evaluated progress toward reducing diesel BC emissions at the global, regional, and national scales (Miller & Jin, 2018). It estimates the projected tons of BC emissions avoided under recently adopted policies and the potential to further reduce BC emissions by accelerating the global implementation of soot-free standards for vehicles, engines and fuels. It also evaluates the implications for global temperature pathways and societal costs that include climate and health damages. The results in this assessment are presented for 195 countries and regions.[1] Results are also provided for groups of countries according to geography and political and economic relationships. In many regions, progress toward soot-free standards can be accelerated through cooperation among countries. Examples of such cooperation are already underway in South America, Southeast Asia, Southern Africa, and Western Africa (Climate & Clean Air Coalition, International Council on Clean Transportation, Asian Institute of Technology, & Regional Resource Centre for Asia and the Pacific, 2018; UN Environment, 2018; Posada, 2019; Posada, Miller, Delgado, & Minjares, 2019).

As of July 2019, 39 countries have implemented soot-free standards for new heavy-duty diesel engines (Figure ES-1); five more have adopted such standards for implementation before 2025: Brazil (2023), China (2021), Colombia (2023), India (2020), and Mexico

1 These countries and regions correspond to ISO alpha-3 codes. See the Supplementary data for definitions.

(2021). A total of 63 countries have on-road diesel fuels available that average less than 15 parts per million (ppm) fuel sulfur content.[2] By 2023, at least six additional countries are planning to complete the transition to ultralow-sulfur diesel: Argentina (2023), Colombia (2023), India (2020), Saudi Arabia (2021), Thailand (2023), and Vietnam (2021).[3] The world regions where further diesel fuel quality improvements are particularly needed are Central and South America; Africa; the Middle East; and Central, South, and Southeast Asia.

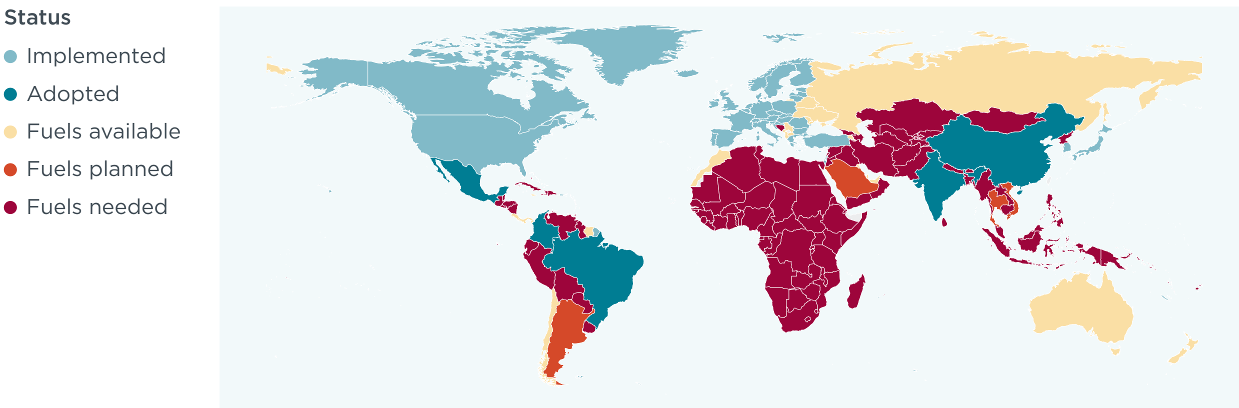

Figure ES-1. Implementation status of soot-free heavy-duty engine standards and ultralow-sulfur diesel by country as of July 2019. Recently adopted standards will take effect between 2020 and 2023, depending on the country. Fuels available or planned means soot-free engine standards are not yet adopted. Fuels needed means fuel sulfur reductions are needed to enable implementation of soot-free engine standards.

Figure ES-2 shows projected global diesel BC emissions for five policy scenarios in comparison with a 75% reduction in global diesel BC emissions from 2010 to 2030, corresponding to the level of BC reduction targeted by the CCAC Scientific Advisory Panel (Shindell et al., 2017).[4] Policies that have been adopted or implemented since 2015 are projected to avoid 2 million tonnes of diesel BC emissions cumulatively from 2015 to 2030, equivalent to a 16% reduction in cumulative emissions compared with a baseline without these policies (Figure ES-2). More than 70% of these BC reductions are attributable to soot-free standards in China and India (Figure ES-3). Nevertheless, currently adopted policies are still insufficient to achieve a 75% reduction in global diesel BC emissions from 2010 to 2030. The 10-year transition and 5-year transition scenarios correspond to the Global Sulfur Strategy and High Ambition scenarios in the 2018 assessment. We have added a leapfrog scenario to show the upper bound for mitigation potential based on what is purely technically feasible and not just politically feasible. As shown, only the 5-year transition and leapfrog scenarios would reduce global diesel BC emissions in line with the Scientific Advisory Panel target. Accordingly, to meet this target, soot-free standards will need to be implemented in virtually all countries between 2020 and 2025.

2 Countries that have adopted or implemented soot-free heavy-duty engine standards are labeled adopted or implemented in Figure ES-1.

3 Countries yet to adopt soot-free heavy-duty engine standards are labeled fuels planned in Figure ES-1.

4 To achieve the target to reduce global anthropogenic BC emissions to 75% below 2010 levels by 2030, similar reductions are needed in other transport and non-transport sectors.

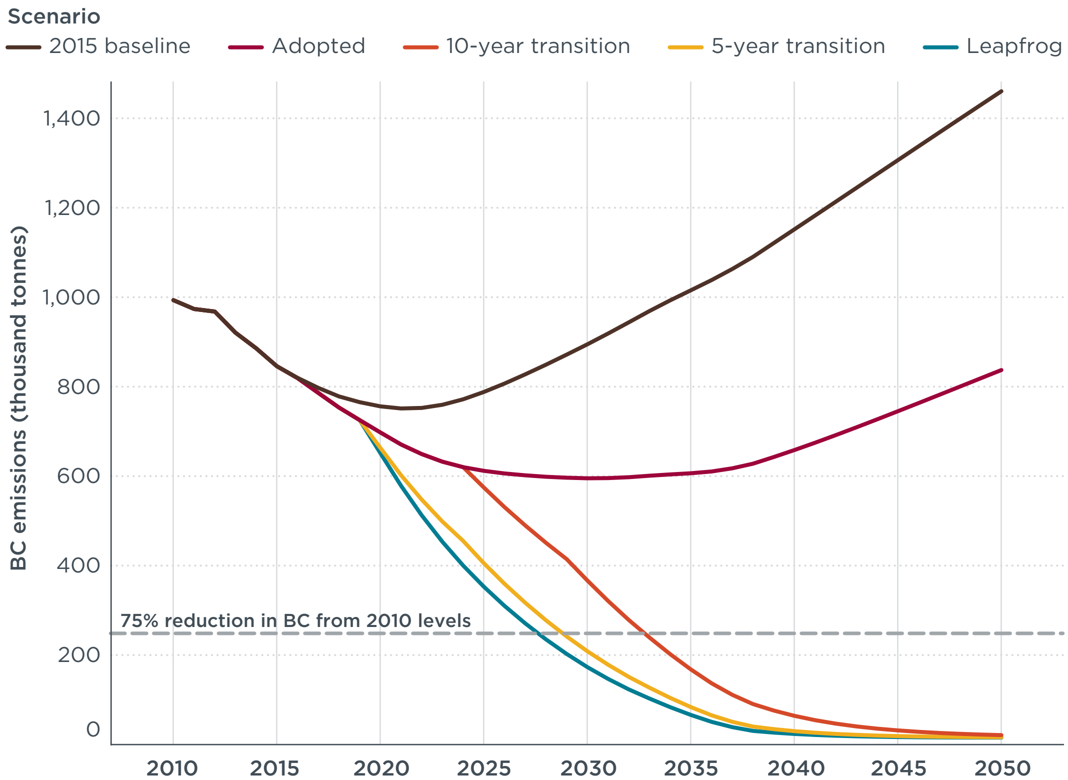

Figure ES-2. Global diesel BC emissions from light-duty and heavy-duty vehicles from 2010 to 2050. The 2015 baseline includes standards already in force in 2015. Adopted includes final regulations as of July 2019, including those with a future implementation date. New policy scenarios assume soot-free standards are implemented for new and secondhand vehicle sales in all countries by 2030 (10-year transition), 2025 (5-year transition), or 2020 (leapfrog).

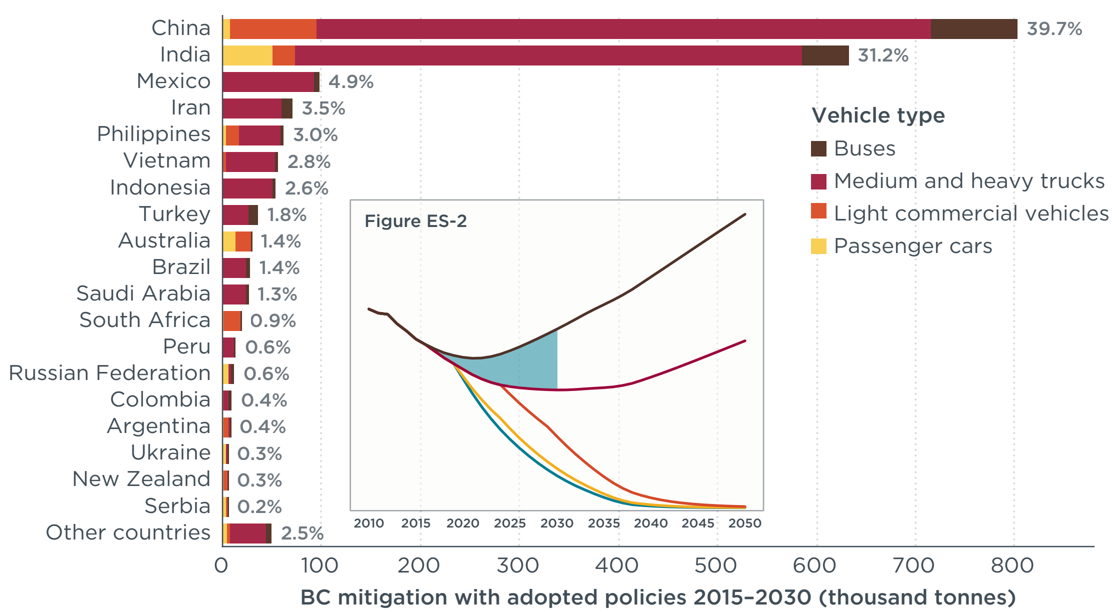

Figure ES-3. Cumulative BC mitigation with adopted policies from 2015 to 2030 compared with a 2015 baseline scenario. The total of this figure corresponds to the shaded area in the subplot (see Figure ES-2). Data labels show the share of BC mitigation with adopted policies in each country/region.

Expanded worldwide adoption of soot-free standards could avoid up to 2.7 million tonnes of BC from 2020 to 2030, equivalent to 40% of cumulative emissions under adopted policies, and up to 15.6 million tonnes of BC from 2020 to 2050, which is equivalent to 76% of cumulative emissions under adopted policies.[5] More than half of the additional diesel BC mitigation potential not captured by currently adopted or implemented policies from 2020 to 2050 is concentrated in three regions (Figure ES-4): the Gulf Cooperation Council (GCC), the Arab Maghreb Union (AMU), and a shortlist of other countries in the Middle East that includes Egypt and Iran. The Association of Southeast Asian Nations (ASEAN) accounts for nearly one-tenth of additional BC mitigation potential. Sub-Saharan Africa accounts for about 16% of additional BC mitigation potential, encompassing the Southern African Development Community (SADC), the Economic Community of West African States (ECOWAS), the East African Community (EAC), the Central African Economic and Monetary Community (CEMAC), and a shortlist of other countries in Africa that includes Ethiopia. Apart from these regions, notable countries with a substantial share of global BC mitigation potential include Pakistan, Russia, Venezuela, and Peru. With some exceptions, most countries with the largest remaining BC mitigation potential will need to transition to ultralow-sulfur fuels in conjunction with soot-free standards (Figure ES-1).

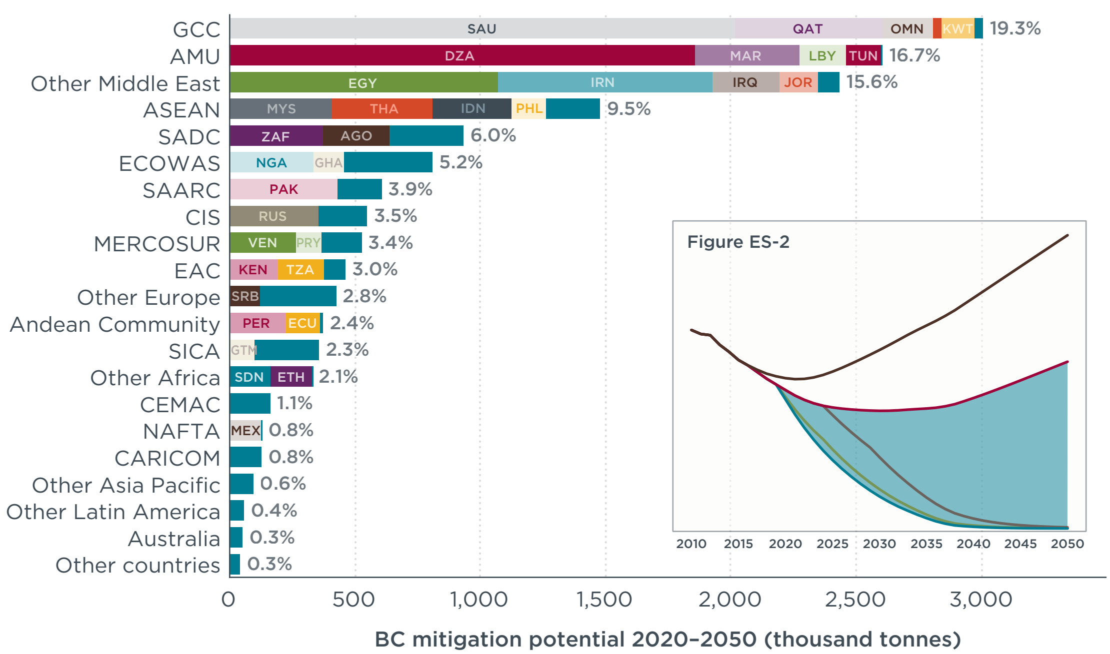

Figure ES-4. Remaining BC mitigation potential from 2020 to 2050 with soot-free standards by 2020 compared with policies adopted or implemented since 2015. The total of this figure corresponds to the shaded area in the subplot. Data labels show the share of BC mitigation potential in each country or region that has not yet adopted Euro 6/VI standards for both light-duty and heavy-duty vehicles. For region definitions, see Appendix.

The amount of additional diesel BC mitigation over the next decade depends on the timing of new policies in regions that have yet to adopt soot-free standards.

5 This corresponds to the difference between the adopted and leapfrog scenarios in Figure ES-2.

If countries wait until 2025 to implement Euro 4/IV equivalent[6] and until 2030 to implement Euro 6/VI (10-year transition), they would leave more than 70% of estimated global BC mitigation potential over the next decade off the table. If countries instead implement Euro 4/IV by 2020 and Euro 6/VI by 2025 (5-year transition), they would reduce roughly three times as much BC over the next decade. For countries that have already implemented Euro 4/IV standards, leapfrogging to Euro 6/VI within the 2020–2025 time frame would yield BC reductions somewhere between the 5-year transition and leapfrog scenarios.

Targeting diesel BC emissions can contribute substantively to SLCP mitigation objectives: Compared with the 2015 baseline, recently adopted policies for diesel vehicles are projected to reduce associated non-CO_2 temperature change by 44% in 2050. This is equivalent to 8% of the 0.5°C of warming in 2050 avoidable through SLCP mitigation in multiple economic sectors (Amann, Klimont, & Kupiainen, 2011). By 2041, non-CO_2 temperature change from diesel vehicles can be eliminated using currently available technology and assuming all countries require soot-free engines from 2025. Compared with the 2015 baseline scenario, new and adopted policies combined could avoid the equivalent of 18% of the 0.5°C of warming avoidable with SLCP mitigation in 2050.

The global societal costs associated with emissions of BC, organic carbon, and sulfur dioxides from diesel light-duty and heavy-duty vehicles were assessed using the social cost of atmospheric release (Shindell, 2015). Compared with a 2015 baseline, adopted policies will avoid $1 trillion to $1.4 trillion (U.S.) in cumulative societal costs from 2015 to 2030. Yet under adopted policies, the value of climate and health damages from diesel vehicle emissions is still projected to grow from $300 billion to $380 billion for 2019 emissions to $740 billion for 2050 emissions. Achieving even a 10-year transition to soot-free standards could avoid between $3.2 trillion and $7.2 trillion in projected societal costs from 2020 to 2050 compared with adopted policies. Considering the cumulative societal costs of 2020 to 2030 emissions under adopted policies, the 10-year transition would avoid 15% of societal costs, the 5-year transition would avoid 39%, and the leapfrog scenario would avoid 45%. Complementary policies that accelerate the replacement of older technologies could avoid a greater share of these costs.

6 We subsequently refer to Euro 4/IV and Euro 6/VI equivalent standards as Euro 4/IV and Euro 6/VI.

INTRODUCTION

BACKGROUND

Transportation tailpipe emissions resulted in approximately $1 trillion (U.S.) in health damages globally in 2015 (Anenberg, Miller, Henze, Minjares, & Achakulwisut, 2019). Among transportation subsectors, on-road diesel vehicles were the leading contributor to air pollution and associated disease burdens. Within on-road diesel vehicles, heavy-duty vehicles (HDVs) are the main contributor to exhaust emissions and health impacts: HDVs were responsible for 86% of on-road diesel NO_X emissions in 2015 (Anenberg et al., 2017) and 78% of on-road diesel BC emissions in 2017, despite accounting for less than a quarter of the diesel vehicle fleet in 2017 (Miller & Jin, 2018).

The disproportionate contribution of HDVs is a key reason for their prioritization by the CCAC Heavy Duty Vehicles Initiative (HDVI), which works to catalyze major reductions in BC through adoption of clean fuel and vehicle regulations and supporting policies. The HDVI defines “soot-free” engines as those that achieve a 99% or greater reduction in BC compared with older-technology diesel engines. All diesel or alternative engines that meet Euro 6/VI or equivalent emission levels for particle mass or particle number are considered soot-free. These can include diesel engines with a wall-flow diesel particulate filter (DPF), gas-powered engines, and dedicated electric-drive engines. Fuel desulfurization plays a critical role in enabling the introduction of soot-free diesel engines. Euro 6/VI diesel engines, which include DPFs and advanced systems for NO_X control, are designed to operate with ultralow-sulfur fuel (< 10–15 ppm sulfur).

Recent trends in air pollution and health effects of diesel vehicle exhaust are heterogeneous across regions: from 2010 to 2015, the health burden of diesel vehicle exhaust declined in regions such as the United States, European Union, and Japan that have led the implementation of world-class, soot-free standards for vehicles and fuels (Anenberg et al., 2019). Yet over the same period, diesel vehicle emissions and associated health impacts increased in China, South Asia, Southeast Asia, and many countries in Africa, the Middle East, and Latin America.

In addition to the substantial air pollution and health benefits of diesel vehicle emissions control, reducing fine particulate matter ($PM_{2.5}$) and particularly black carbon (BC) emissions from older-technology diesel engines is an essential component of a multi-pollutant, multi-sectoral strategy to avoid 0.5°C of additional warming over the next 25 years (Shindell et al., 2017). To achieve this strategy, the CCAC Scientific Advisory Panel proposed a target to reduce global anthropogenic BC emissions to 75% below 2010 levels by 2030. The HDVI has been working to reduce diesel BC emissions in line with this target by implementing the Global Strategy to Introduce Low-Sulfur Fuels and Cleaner Diesel Vehicles (Malins et al., 2016). This strategy supports the HDVI’s objective to support actions at all levels of government—global, regional, national, and local—to reduce diesel BC emissions and thereby benefit climate and health (Amann, Klimont, & Kupiainen, 2011; International Agency for Research on Cancer & World Health Organization, 2012; Janssen et al., 2012). This sectoral strategy was endorsed by Ministers representing the CCAC’s State Partners at the CCAC High Level Assembly in Marrakech (Climate and Clean Air Coalition, 2016).

STUDY OBJECTIVES, APPROACH, AND STRUCTURE

This report is the second annual assessment to monitor progress toward implementing a global strategy to reduce black carbon emissions. The first assessment in 2018 established metrics for the status and coverage of fuel quality and vehicle emission standards, evaluated their impacts on the uptake of cleaner vehicles and fuels, projected trends in BC emissions, and assessed further mitigation potential with accelerated uptake of soot-free vehicles and fuels (Miller & Jin, 2018). This assessment provides an update on progress made from June 2018 to July 2019. We provide updates to metrics from the 2018 assessment and list recent updates in specific countries and regions. As in 2018, this assessment covers diesel light-duty and heavy-duty on-road vehicles and engines. Off-road engines (e.g., agricultural and construction equipment), marine engines, and stationary engines, like diesel generators, are important sources of BC; however, these are outside the scope of this assessment.

The paper summarizes the current status and recent developments in diesel fuel quality and vehicle and engine emission standards. It provides updated estimates since the 2018 assessment for the following metrics:

- countries with ultralow-sulfur (10 ppm) and low-sulfur (50 ppm) on-road diesel;
- share of world on-road diesel fuel consumption by sulfur level;
- countries that have adopted or implemented soot-free heavy-duty engine standards;
- share of new heavy-duty engine sales equipped with diesel particulate filters; and
- share of in-use heavy-duty vehicle stock equipped with diesel particulate filters.

Next, we provide updated projections of global diesel BC emissions from light-duty and heavy-duty vehicles. These projections evaluate the effects of recently adopted policies and quantify the additional BC mitigation potential with expanded adoption of soot-free standards. For those countries that have not yet adopted soot-free standards, we assess BC mitigation potential for three new policy scenarios that illustrate the effects of varying implementation timelines. The 10-year transition and 5-year transition scenarios in this assessment correspond to the Global Sulfur Strategy and High Ambition scenarios in the 2018 assessment. We have added a leapfrog scenario to show the upper bound for mitigation potential based on what is purely technically feasible and not just politically feasible. These scenario definitions are as follows.

Scenarios for evaluating the effects of recently adopted policies:

- **2015 baseline:** Counterfactual scenario that includes the historical timeline of vehicle emissions and fuel quality standards that were already in force in 2015.
- **Adopted:** Includes final regulations that have been adopted into law as of July 2019, including those with a future implementation date. The projected BC benefits of recently adopted policies are defined as the difference between the 2015 baseline and adopted policies scenario.

New policy scenarios for assessing additional BC mitigation potential with soot-free standards:

» **10-year transition:** Assumes that all countries implement at least Euro 4/IV by 2025 and Euro 6/VI by 2030. This timeline is consistent with the Global Sulfur Strategy scenario in the 2018 assessment.
» **5-year transition:** Assumes that all countries implement at least Euro 4/IV by 2020 and Euro 6/VI by 2025. This timeline for Euro 6/VI is consistent with the High Ambition scenario in the 2018 assessment.
» **Leapfrog:** Assumes that all countries implement Euro 6/VI by 2020. This timeline represents the earliest technically feasible date that countries could newly transition to soot-free standards. It does not consider political constraints.

Finally, we evaluate the global average temperature pathways and global societal costs of diesel light-duty and heavy-duty vehicle non-CO_2 emissions under each scenario. We conclude with recommendations for policymakers and a discussion of uncertainties and recommendations for future research. The Appendix provides a summary of methodological changes since the 2018 assessment and lists supplementary data that accompanies this report.

CURRENT STATUS OF DIESEL ROAD TRANSPORT

FUEL QUALITY

Countries with ultralow-sulfur and low-sulfur diesel

The number of countries with access to ultralow-sulfur or low-sulfur diesel continues to grow. Figure 1 shows the estimated average sulfur content of on-road diesel in 195 countries under adopted policies in 2019 and 2025.[7] As of 2019, 63 countries have diesel fuel averaging less than 15 parts per million (ppm) sulfur. These countries account for 70% of global on-road diesel consumption. By 2023, at least six additional countries are planning to complete the transition to ultralow-sulfur diesel: Argentina (2023), Colombia (2023), India (2020), Saudi Arabia (2021), Thailand (2023), and Vietnam (2021).[8] Indonesia has committed to transition to low-sulfur diesel by 2025. This list does not include other countries that are planning to transition to lower-sulfur diesel but have not yet finalized their plans or those for which data were unavailable.

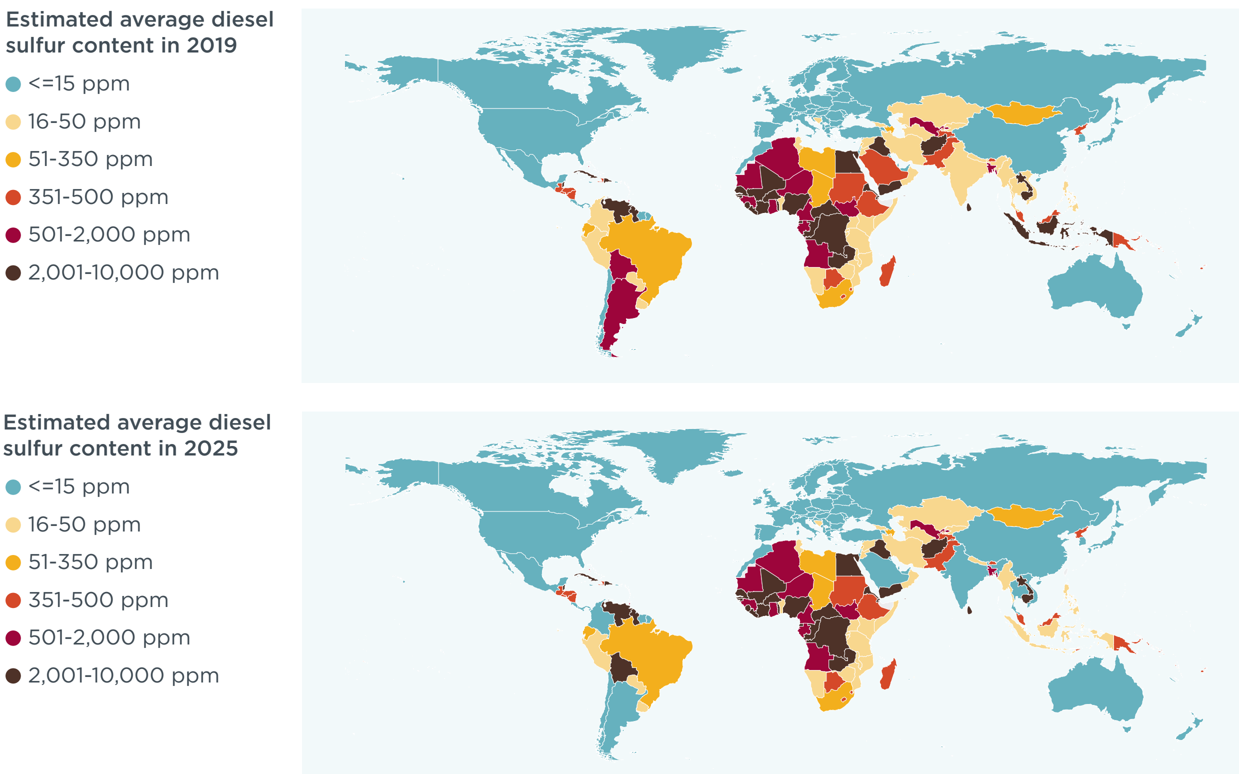

Figure 1. Estimated average diesel sulfur content by country in 2019 and 2025

Share of world on-road diesel fuel consumption by sulfur level

Ultralow-sulfur diesel constitutes a growing share of the world's on-road diesel supply (Figure 2). Between 2019 and 2025, the share of ultralow-sulfur diesel will grow to more than four-fifths of global on-road diesel supply. Under adopted policies, the share of

7 In countries with multiple fuel grades, the estimated average sulfur content of diesel reflects a volume-weighted average of all diesel fuel grades used for road transport. For details, see Appendix.

8 Values in parentheses correspond to implementation years for nationwide ultralow-sulfur diesel.

ultralow-sulfur diesel is projected to increase 12 percentage points by 2025, whereas the share of 351–500 ppm sulfur diesel is projected to shrink to about 1% of global demand. As shown in Figure 1, the world regions where further diesel fuel quality improvements are needed are Central and South America; Africa; the Middle East; and Central, South, and Southeast Asia.

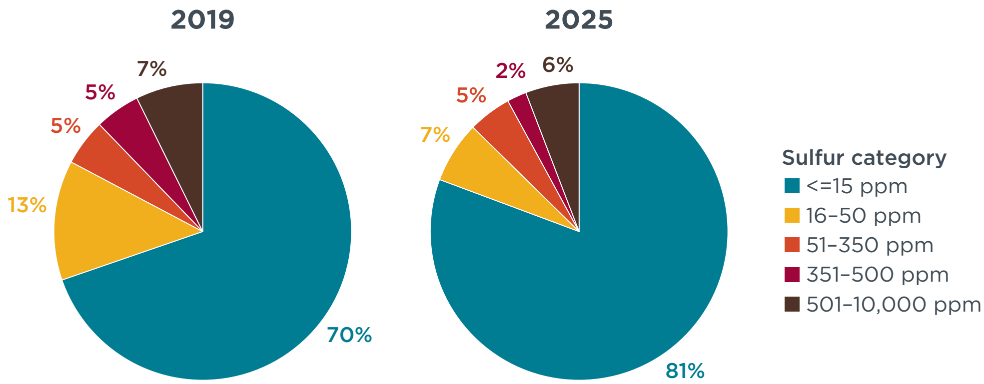

Figure 2. Estimated share of world on-road diesel by sulfur content in 2019 and 2025

Fuel quality improvements in G20 economies

The Group of 20 (G20) economies account for more than four-fifths of global on-road diesel consumption; yet even among the G20, progress on diesel desulfurization has not been uniform. In 2015, 11 G20 economies (including the EU and four member states that are G20 economies individually) had diesel fuel sulfur content averaging less than 15 ppm. Russia, China, and Mexico have since transitioned to ultralow-sulfur diesel. India, Saudi Arabia, and Argentina are planning to complete similar transitions by 2020, 2021, and 2023, respectively (Figure 3). As of July 2019, multiple diesel fuel grades are permitted in Argentina, Brazil, Indonesia, and South Africa (for details, see Appendix):

» Argentina: 16.5% of diesel is 10 ppm, 29% is 500 ppm, and the rest is 1,000 ppm.

» Brazil: An estimated 70% of diesel is 10 ppm, and 30% is 500 ppm.

» Indonesia: Most diesel is 2,500 ppm or 500 ppm; availability of 50 ppm is limited.

» South Africa: 80% of diesel is 50 ppm; 10 ppm is a niche grade; the rest is 500 ppm.

The implications of these fuel quality developments for tightening vehicle emission standards are discussed in the next section.

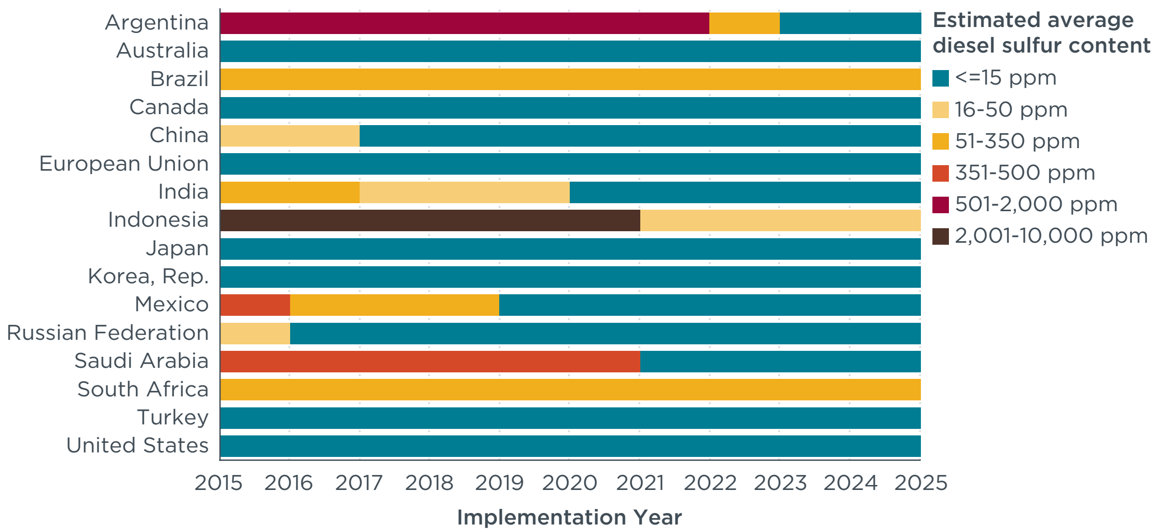

Figure 3. Timeline of average on-road diesel sulfur content in G20 economies

VEHICLE EMISSION STANDARDS

Countries with new heavy-duty engine emission standards

Figure 4 shows the latest standards for new heavy-duty diesel engines in each country under adopted policies in 2019 and 2025. As of July 2019, 39 countries have implemented Euro VI-equivalent standards for new heavy-duty diesel engines. These countries accounted for 40% of new diesel HDV sales worldwide in 2019. Five more countries have adopted such standards for implementation before 2025: Brazil, China, Colombia, India, and Mexico (Table 1). Some notable features of these policies are discussed below:

» Brazil's Euro VI-equivalent standards apply to all new diesel HDV sales and registrations starting in 2023. Cities are allowed to require Euro VI engines earlier than the national timeline (Miller & Posada, 2019).

» As a complement to adopting world-class standards for light-duty and heavy-duty vehicles (He & Yang, 2017; Yang & He, 2018), China has adopted a clean diesel action plan that establishes targets for improving compliance with vehicle emissions and fuel quality standards (He & Yang, 2019). The plan also includes measures to accelerate the retirement of older-technology vehicles.

» Colombia's timeline for Euro VI-equivalent standards matches Brazil's timeline (2023), yet Colombia's law goes further and requires that all in-use HDVs meet these standards by 2035. This provision is expected to increase the benefits of Colombia's transition to soot-free vehicles by accelerating the retirement of older-technology vehicles (Ministry of Health and Social Protection, 2019).

Table 1. Implementation year and projected vehicle sales affected by soot-free standards.

Country	Implementation Year	Projected share of world new diesel HDV sales in 2025
Brazil	2023	3%
China	2021	16%
Colombia	2023	3%
India	2020	11%
Mexico	2021	1%

As of July 2019, soot-free vehicle standards have been proposed or are under development in several additional countries. Because these standards are not yet finalized, they are not included in the adopted policies scenario in this assessment:[9]

- Georgia has developed a draft technical regulation in cooperation with the Ministry of Environmental Protection and Agriculture, the National Steering Committee, the Ministry of Economy and Sustainable Development, and the Ministry of Internal Affairs; however, timelines are still being discussed.
- In Thailand, the Pollution Control Board has proposed measures to introduce ultralow-sulfur fuels and leapfrog to Euro 6/VI-equivalent vehicle standards by 2023.
- In many regions, progress toward soot-free standards can be accelerated through cooperation among countries. Examples of such cooperation are already underway in South America, Southeast Asia, Southern Africa, and Western Africa (Climate & Clean Air Coalition et al., 2018; UN Environment, 2018; Posada, 2019; Posada et al., 2019).

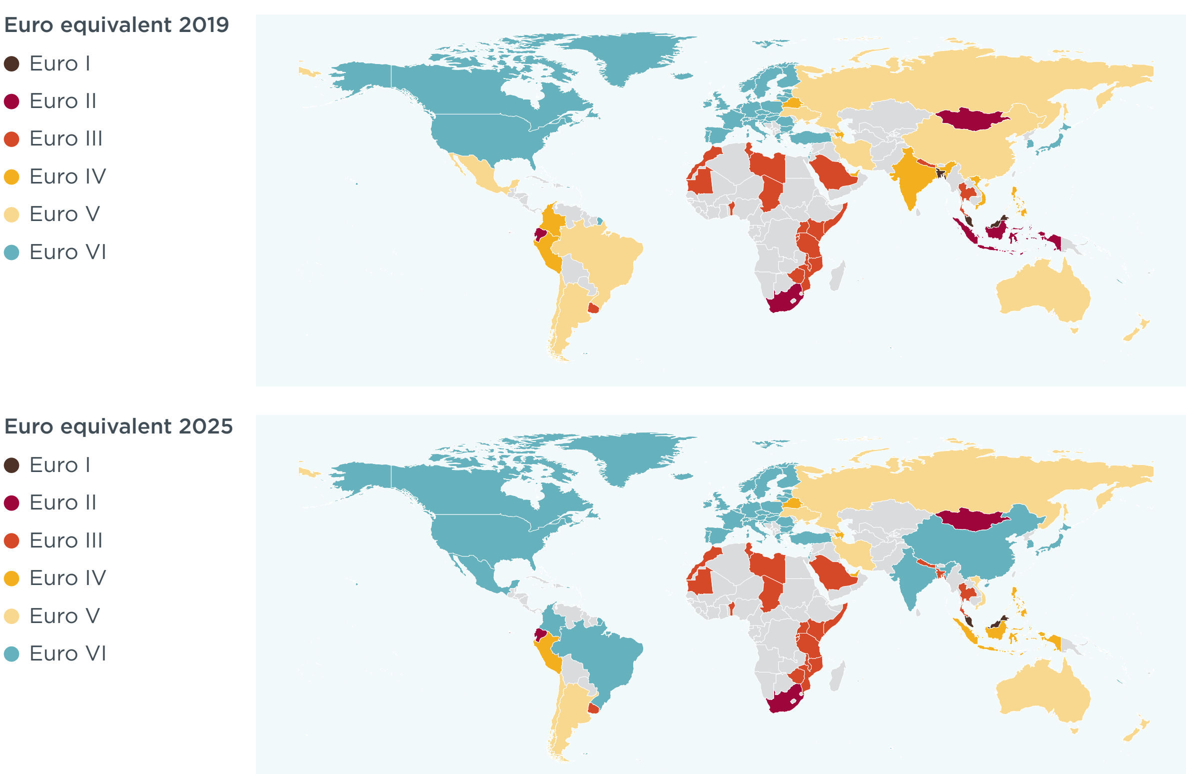

Figure 4. Implementation of heavy-duty diesel engine emission standards in 2019 and 2025

9 This list is not intended to be exhaustive.

Implementation of the Marrakech communiqué

In November 2016, at the CCAC 8th High Level Assembly in Marrakech, 38 countries endorsed the global strategy to adopt, maintain, and enforce world-class diesel fuel quality and tailpipe emission standards for on-road light- and heavy-duty vehicles. They resolved to "develop national implementation plans outlining timelines for the nationwide introduction of such standards, if such standards are not already in place" (Climate and Clean Air Coalition, 2016). Of these 38 signatories, 15 had implemented such standards before signing the communiqué (Figure 5). Mexico and Colombia signed the communiqué and have since adopted world-class standards for heavy-duty diesel engines with implementation years of 2021 and 2023, respectively. As of July 2019, five signatories—Chile, Morocco, Moldova, Australia, and New Zealand—already have ultralow-sulfur diesel but have not yet adopted world-class standards for heavy-duty diesel engines. For the other 16 signatories, fuel quality improvements are needed in addition to updated vehicle and engine standards.

As of July 2019, the CCAC has 65 State Partners, including two Regional Economic Integration Organizations: ECOWAS and the European Commission. Several countries had implemented soot-free standards but were not among the original signatories to the Marrakech communiqué. India, which recently joined the CCAC, will implement soot-free standards in 2020. Three more CCAC State Partners—Panama, Argentina, and Russia—have ultralow-sulfur diesel available but have not yet adopted soot-free vehicle standards. Of those CCAC State Partners that were not original signatories to the Marrakech communiqué, 16 would need fuel-quality improvements and soot-free vehicle standards to deliver on the objectives of the communiqué.

Implementation status
- Implemented before signing
- Not signed but implemented
- Adopted after signing
- Not signed but adopted
- Fuels available
- Not signed but fuels available
- Fuel quality improvements needed
- Not signed and fuels needed
- No data / Not a CCAC State Partner

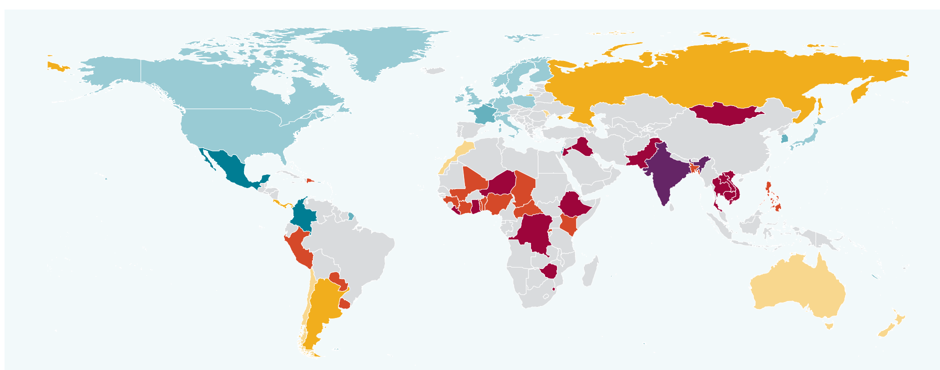

Figure 5. Implementation status of Marrakech communiqué by CCAC State Partners as of July 2019

Heavy-duty engine emission standards in G20 economies

G20 economies collectively account for 80% of global transportation energy demand and an estimated 84% of premature deaths from $PM_{2.5}$ and ozone from transportation tailpipe emissions (Anenberg et al., 2019). As of July 2019, 14 of the G20 economies have implemented or adopted soot-free standards for new heavy-duty diesel engines (Figure 6).[10] Argentina, Australia, and Russia have implemented Euro V-equivalent standards but have not yet adopted a timeline for Euro VI. Saudi Arabia's planned

10 Implementation dates are approximate and reflect the year of application to all sales and registrations of new heavy-duty diesel engines. Some countries have earlier implementation years for new type approvals and/or subnational jurisdictions. In the United States, filter-forcing standards were first introduced in 2007.

transition to ultralow-sulfur diesel provides an opportunity to leapfrog from Euro III to Euro VI. In South Africa, the transition to ultralow-sulfur diesel has been delayed since June 2017; however, current availability of low-sulfur diesel creates an immediate opportunity to transition from Euro II to Euro IV. In Indonesia, revising national fuel quality standards to require Euro 4 and Euro 5 fuels could allow the implementation of Euro IV emission standards by 2021 and Euro 6/VI shortly thereafter (Climate & Clean Air Coalition et al., 2018).

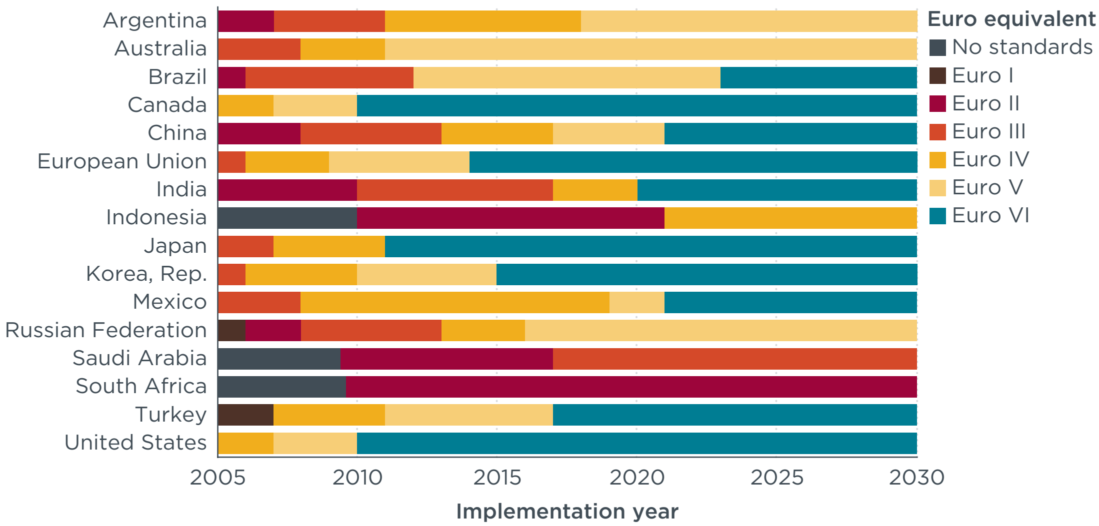

Figure 6. Implementation of heavy-duty diesel engine emission standards in G20 economies

Share of new and in-use diesel vehicles with particulate filters

Figure 7 shows the share of world new diesel vehicle sales and in-use diesel vehicle stock estimated to be equipped with diesel particulate filters (DPFs) under adopted policies in 2015, 2020, and 2025. These sales shares are influenced by the implementation status of soot-free standards and the shares of new diesel vehicle sales and in-use diesel vehicle stock in each country. For buses and medium and heavy trucks, the share of in-use vehicles with DPFs lags the share of new vehicles with DPFs by about 10 years. For example, just under one-third of new diesel bus sales were equipped with DPFs in 2015, but it will likely take until 2025 for the share of the diesel bus stock with DPFs to reach a similar level.

Figure 8 shows the estimated sales shares in Figure 7 broken down for 16 region groups.[11] Over the next five years, the largest changes in global sales shares with DPFs are estimated to be driven by implementation of soot-free standards in China, India, Brazil, Mexico, and Colombia. The effects of these changes on vehicle emissions are discussed in the next section.

11 Countries with a historically small share of global vehicle sales are grouped together to make the figure readable.

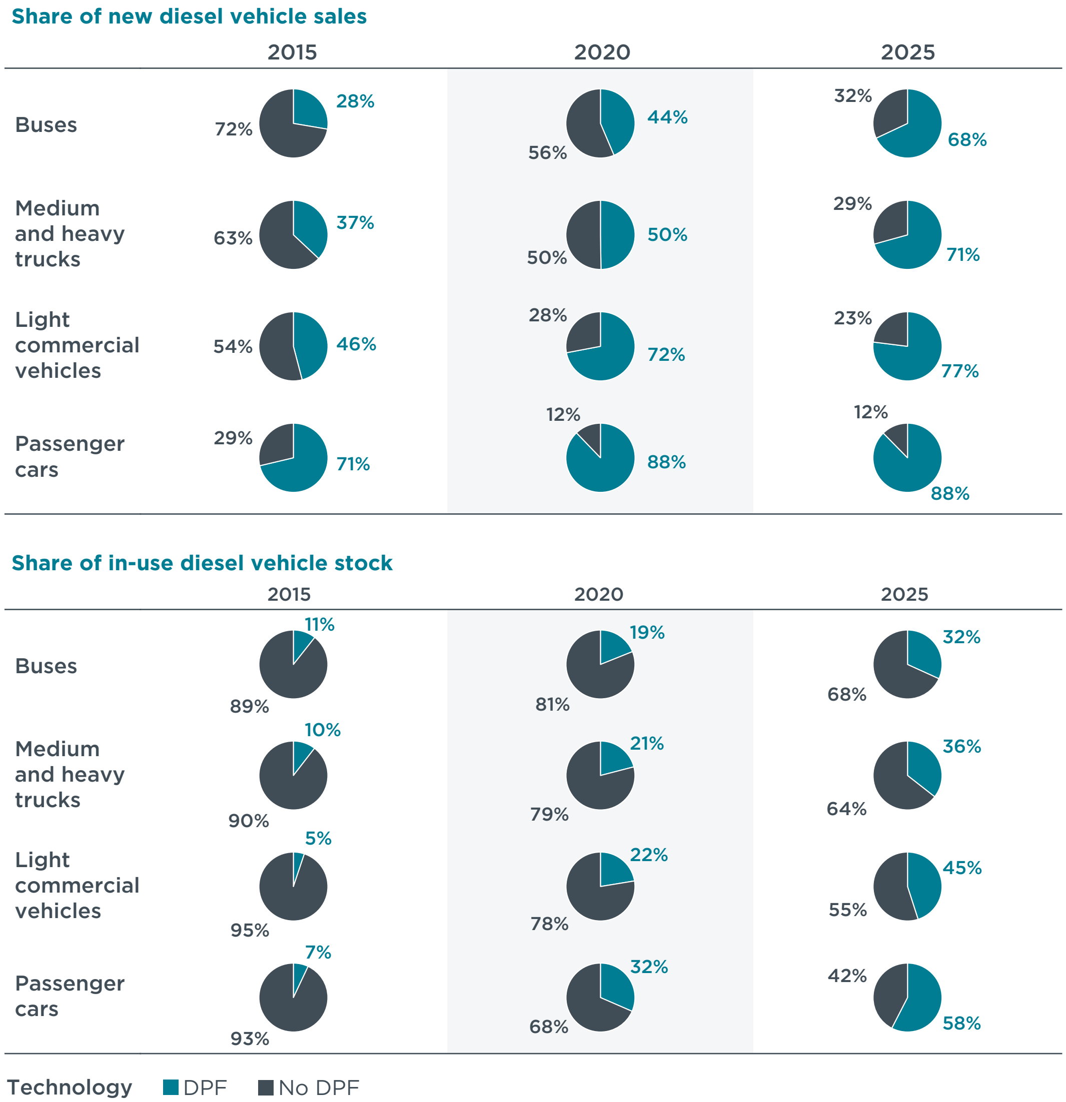

Figure 7. Estimated share of world new diesel vehicle sales and in-use stock equipped with DPFs under adopted policies in 2015, 2020, and 2025.

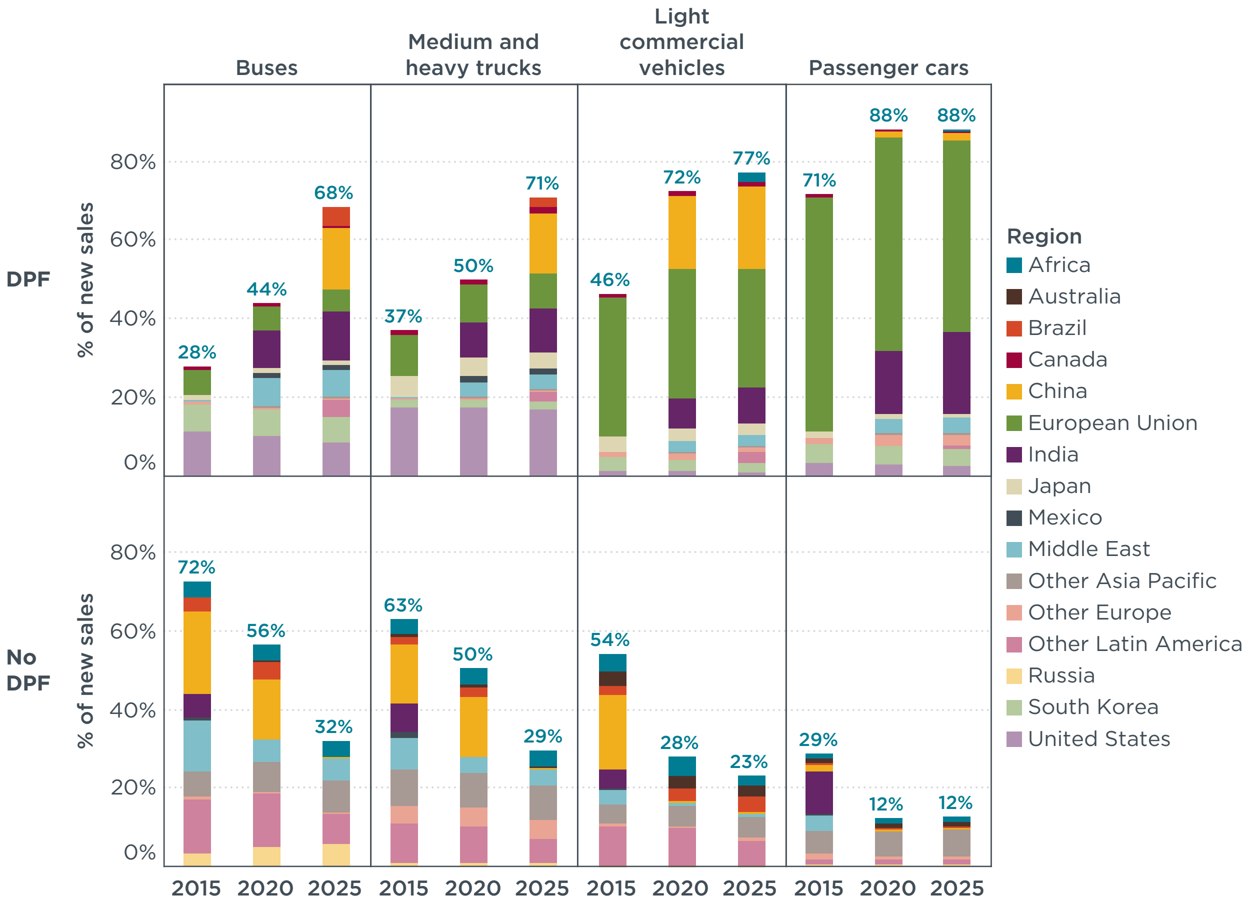

Figure 8. Estimated share of world new diesel vehicle sales with and without DPFs under adopted policies in 2015, 2020, and 2025. Results are shown for 16 region groups.

FUTURE IMPACTS OF DIESEL ROAD TRANSPORT

PROJECTED BC EMISSIONS BY SCENARIO

Figure 9 shows projected global diesel BC emissions from light-duty and heavy-duty vehicles for each policy scenario. Compared with the 2018 assessment, this 2019 assessment is more pessimistic about the baseline due to lowered expectations of the presence and performance of emission controls on secondhand imported vehicles. The projected differences between adopted policies and the 2015 baseline are greater than in the previous assessment due to recent policy developments discussed in the previous section. These projected BC benefits of recently adopted policies are broken down by region and vehicle type in the next section.

Projected BC emissions under new policy scenarios are shown in comparison with a 75% reduction from 2010 levels. This reduction is consistent with the Scientific Advisory Panel target to reduce global anthropogenic BC emissions 75% from 2010 to 2030; however, the target will only be met with similar reductions in other sectors (Shindell et al., 2017).[12] Consistent with the finding of the 2018 assessment, a 75% reduction in diesel BC emissions from 2010 levels is achievable by 2030, but only if soot-free standards are implemented in virtually all countries by 2025, reflecting the 5-year transition scenario.

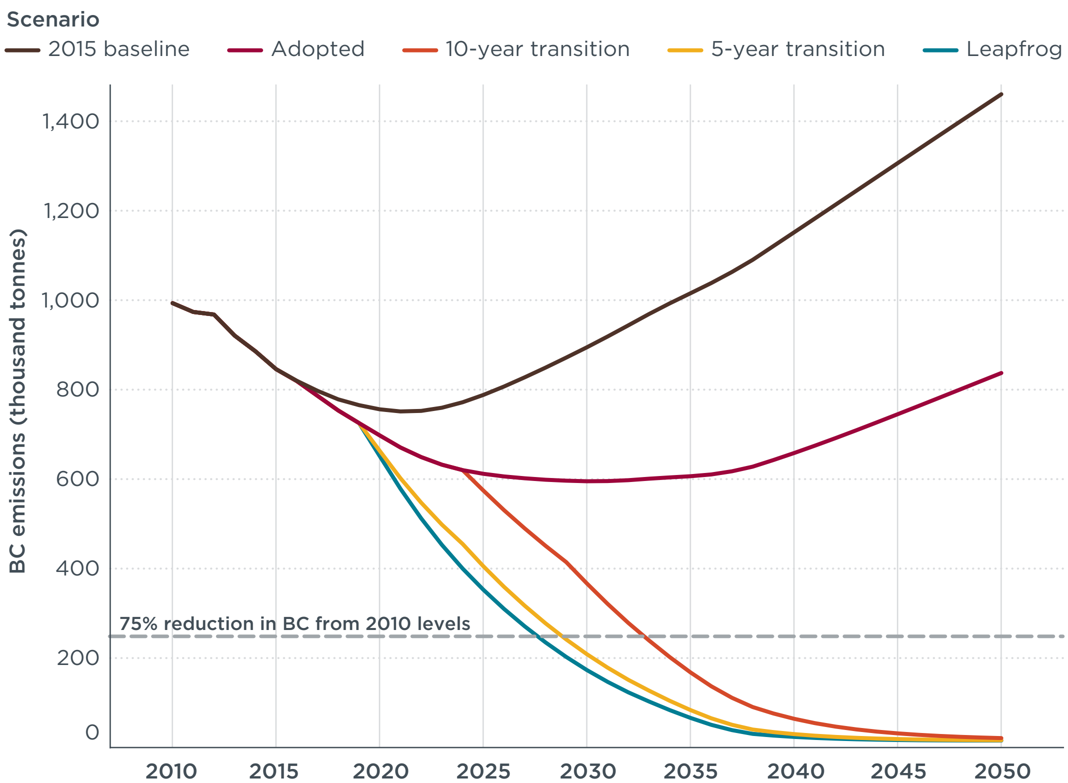

Figure 9. Global diesel BC emissions from light-duty and heavy-duty vehicles from 2010 to 2050. For scenario definitions, see Introduction.

12 For a brief discussion of non-road diesel engines and non-transportation sources, see Appendix.

PROJECTED BC BENEFITS OF RECENTLY ADOPTED POLICIES

Policies that have been adopted or implemented since 2015 are projected to avoid 2 million tonnes of diesel BC emissions from 2015 to 2030. More than 70% of these estimated BC benefits are attributable to soot-free standards in China and India. About three-quarters of these estimated BC reductions globally are from medium and heavy trucks, followed by buses (9%), light commercial vehicles (9%), and passenger cars (5%). The share of BC reductions attributable to buses is expected to be substantially higher in cities that implement soot-free bus fleet transitions ahead of national timelines.

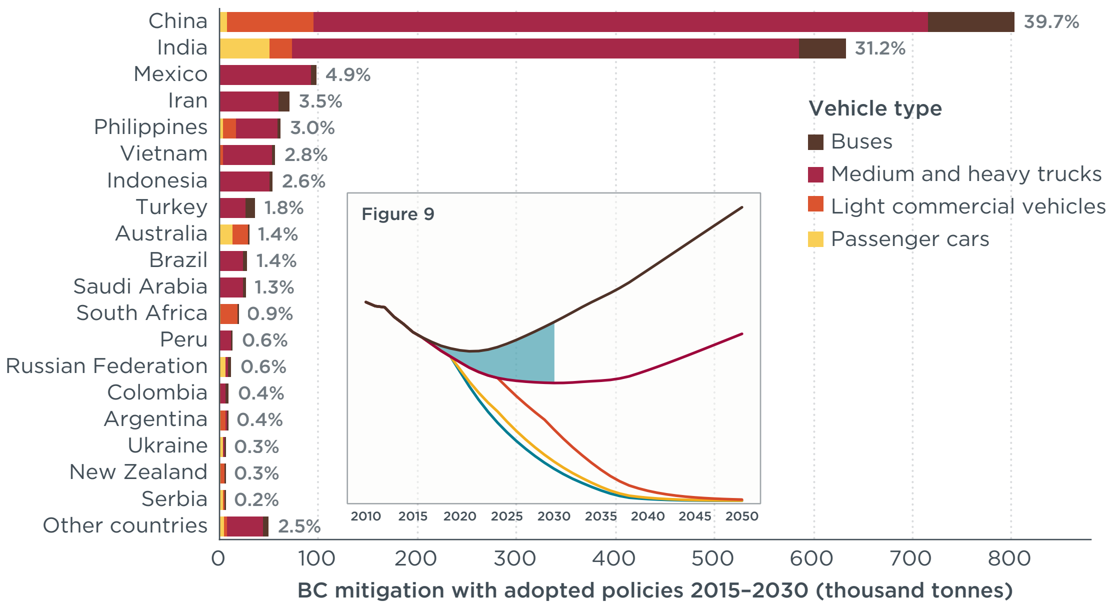

Figure 10. Cumulative BC mitigation with adopted policies from 2015 to 2030 compared with a 2015 baseline scenario. The total of this figure corresponds to the shaded area in the subplot (see Figure 9). Data labels show the share of BC mitigation with adopted policies in each country/region.

ADDITIONAL BC MITIGATION POTENTIAL OF NEW SOOT-FREE STANDARDS

Expanded worldwide adoption of soot-free standards could avoid an additional 2.7 million tonnes of diesel BC emissions from 2020 to 2030 (Figure 12) and a total of 15.6 million tonnes of diesel BC emissions from 2020 to 2050 (Figure 11). More than half of the additional BC mitigation potential from 2020 to 2050 is concentrated in three regions: the Gulf Cooperation Council (GCC), the Arab Maghreb Union (AMU), and a shortlist of other countries in the Middle East that includes Egypt and Iran (Figure 11). The Association of Southeast Asian Nations (ASEAN) accounts for nearly one-tenth of additional BC mitigation potential. Sub-Saharan Africa accounts for about 16% of additional BC mitigation potential and encompasses the Southern African Development Community (SADC), the Economic Community of West African States (ECOWAS), the East African Community (EAC), the Central African Economic and Monetary Community (CEMAC), and a shortlist of other countries in Africa that includes Ethiopia.[13] Apart from

13 Sudan is included in the "Other Africa" region but is not in the UN classification of Sub-Saharan Africa.

these groups of countries, notable individual countries with a substantial share of global BC mitigation potential include Pakistan, Russia, Venezuela, and Peru.

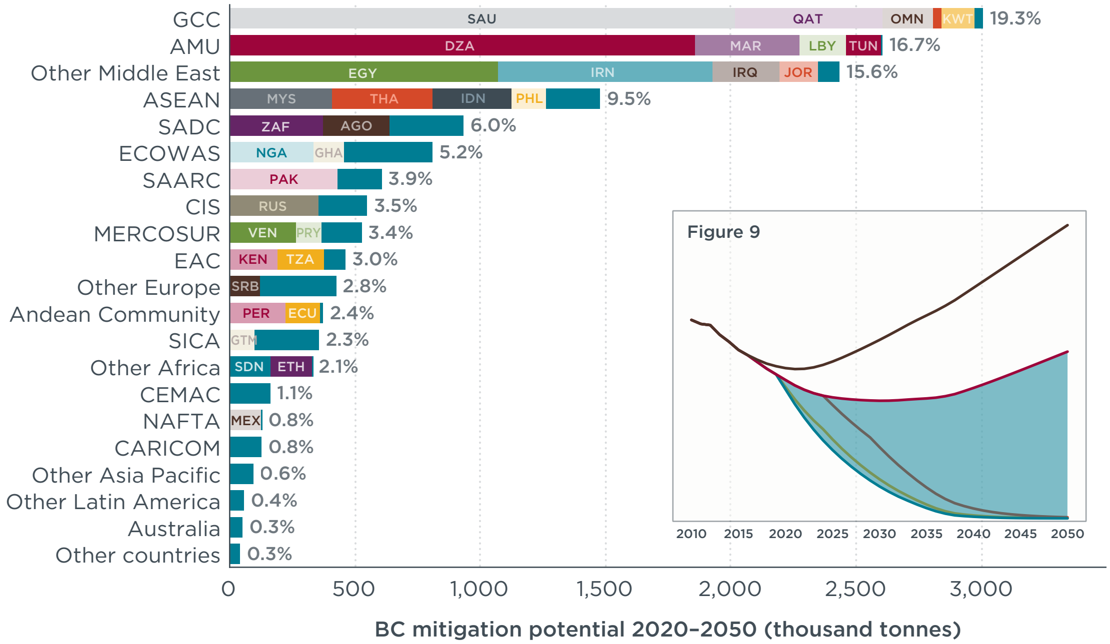

Figure 11. Remaining BC mitigation potential from 2020 to 2050 with Euro 6/VI standards by 2020 compared with adopted policies. The total of this figure corresponds to the shaded area in the subplot (see Figure 9). Data labels show the share of BC mitigation potential in each country that has not yet adopted Euro 6/VI standards for both light-duty and heavy-duty vehicles. For region definitions, see Appendix.

Near-term BC mitigation is not only important for near-term climate benefits, but also for meeting the 2030 Sustainable Development Goals related to air pollution and cleaner fossil-fuel technologies (United Nations, n.d.).[14] As shown in Figure 12, the amount of additional diesel BC mitigation over the next decade (2020–2030) depends on the timing of new policies in regions that have yet to adopt soot-free standards. If most countries wait until 2025 to implement Euro 4/IV and until 2030 to implement Euro 6/VI, which is the 10-year transition scenario, they would leave more than 70% of estimated global BC mitigation potential from 2020 to 2030 off the table. If most countries instead implement Euro 4/IV by 2020 and Euro 6/VI by 2025, which is the 5-year transition scenario, they would reduce roughly three times as much BC over the next 10 years. Leapfrogging directly to Euro 6/VI in 2020 would increase BC mitigation from 2020 to 2030 by an additional 19% compared with the 5-year transition scenario.

14 Sustainable Development Goals related to BC mitigation include: Target 3.2: Reducing infant mortality from exposure to ambient PM2.5; Target 3.9: Reducing premature deaths from air pollution; Target 7.a: Expanding access to advanced and cleaner fossil-fuel technology; and Target 11.6: Reducing adverse per capita impacts on air pollution in cities.

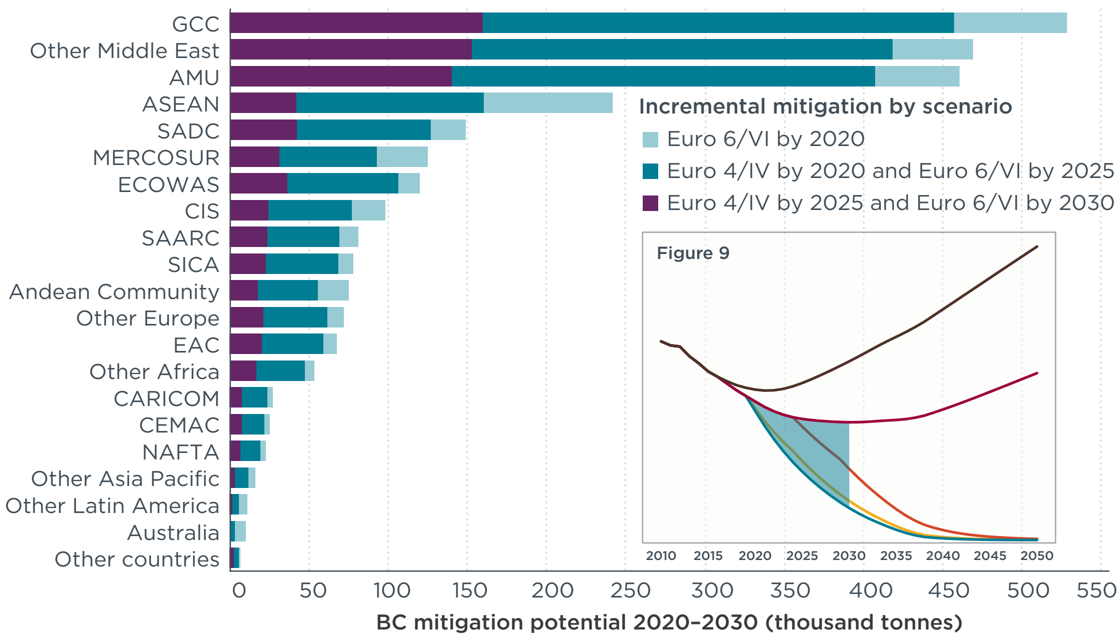

Figure 12. Incremental BC mitigation potential from 2020 to 2030 compared with adopted policies. The total of this figure corresponds to the shaded area in the subplot (see Figure 9).

GLOBAL AVERAGE TEMPERATURE PATHWAYS

The global average temperature pathways associated with non-CO_2 emissions in each policy scenario were estimated using the absolute global temperature change potential metrics provided by the CCAC Scientific Advisory Panel. Figure 13 isolates the temperature pathways associated with post-2015 non-CO_2 emissions from diesel light-duty and heavy-duty vehicles and compares these under each of the five policy scenarios. In all scenarios, BC is the pollutant with the largest contribution to non-CO_2 warming, followed by NO_x, which has the second largest contribution until around 2030.

Compared with the 2015 baseline scenario, adopted policies for diesel light-duty and heavy-duty vehicles are projected to reduce non-CO_2 associated temperature change by 44% in 2050. This reduction in temperature change is equivalent to 8% of the 0.5°C of additional warming in 2050 avoidable with SLCP mitigation in multiple economic sectors (Amann et al., 2011).

Each of the new policy scenarios could effectively eliminate warming from non-CO_2 emissions from diesel light-duty and heavy-duty vehicles; the timing of this ranges from 2041 for the leapfrog and 5-year transition scenarios to 2045 for the 10-year transition scenario. In other words, non-CO_2 temperature change from diesel vehicles can be eliminated by 2041 with currently available technology and assuming all countries require soot-free engines from 2025. Compared with the 2015 baseline scenario, new and adopted policies combined could avoid the equivalent of 18% of the 0.5°C of warming avoidable with SLCP mitigation in 2050.

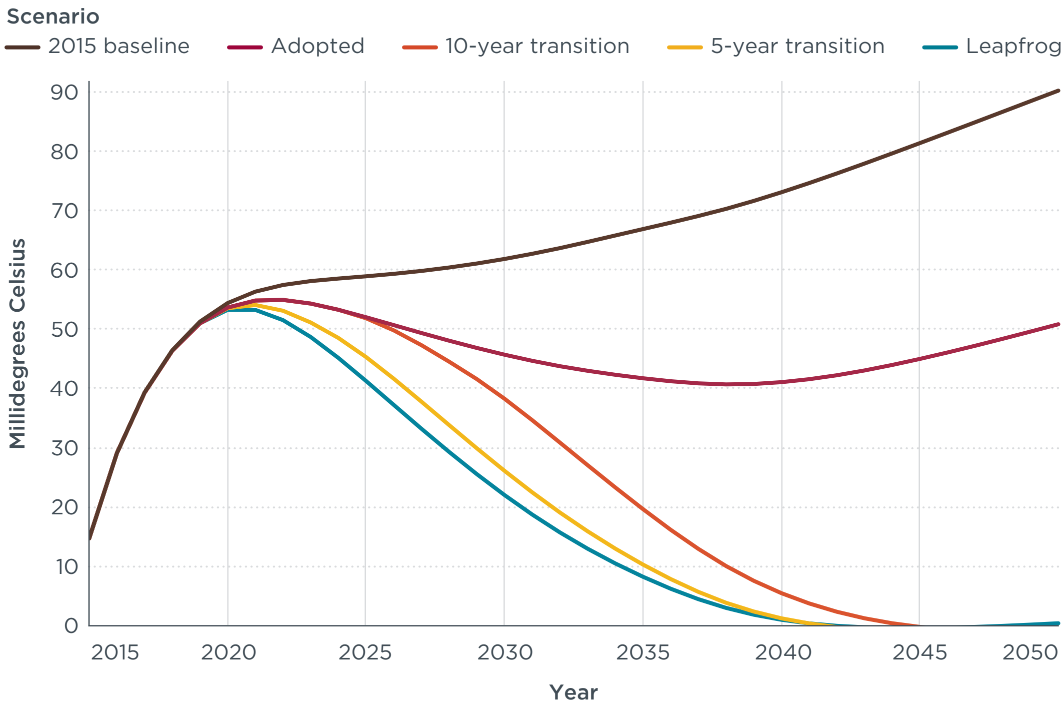

Figure 13. Global average temperature pathways of 2015 to 2050 non-CO_2 emissions from diesel light-duty and heavy-duty vehicles. HFCs and SO_4 are not included. One millidegree is equal to one-thousandth of a degree Celsius.

GLOBAL SOCIETAL COSTS OF EMISSIONS

The global societal costs of diesel light-duty and heavy-duty vehicle emissions for each policy scenario were evaluated according to their social cost of atmospheric release (Shindell, 2015). This methodology considers the damages associated with pollutant emissions, including their direct climate and health impacts, climate-related health damages, and impacts of ozone on reduced agricultural productivity. We calculate the global societal costs of diesel vehicle emissions as the product of cost-per-tonne damage values for each pollutant and year, their emissions, and a corresponding discount factor (Miller, 2019a). For consistency with the way these cost-per-tonne values were calculated, we apply the same social discount rates as in Shindell (2015) to convert climate, health, and agricultural damages to present value terms.

Figure 14 shows estimated global societal costs of BC, organic carbon (OC), and sulfur dioxide (SO_2) emissions from diesel light-duty and heavy-duty vehicles for each policy scenario. These results are subsequently discounted using rates of 1.4% and 5% to illustrate the sensitivity of the valuation to the choice of social discount rate. For each discount rate, the central, low, and high estimates correspond to the median, 5%, and 95% confidence levels from the uncertainty analysis in Shindell (2015).[15]

The global societal costs incurred by diesel light-duty and heavy-duty BC, OC, SO_2 emissions in 2019 are estimated to be $300 billion to $380 billion (central estimates with 1.4% and 5% discounting). About 69% of these costs are attributable to medium

15 The cost-per-tonne values in Table S2 in Shindell's report were converted from 2007 dollars to 2019 dollars using a factor of 1.24. Year-specific values were interpolated linearly using the 2010, 2030, and 2050 estimates. Low and high estimates for all years were calculated using the ratio of the values in Table S4 to their corresponding central estimates for 2010.

and heavy trucks, 13% to buses, 9% to light commercial vehicles, and 9% to passenger cars. Under adopted policies, these costs could rise to about $740 billion for emissions in 2050.[16] Yet without recent policies, the situation would have been substantially worse: Compared with a 2015 baseline, adopted policies are projected to avoid $1 trillion to $1.4 trillion in cumulative societal costs from 2015 to 2030 and $3.6 trillion to $7.3 trillion costs from 2015 to 2050 (central estimates with 1.4% and 5% discounting).

Achieving a 10-year transition to soot-free standards could avoid $3.2 trillion to $7.2 trillion in societal costs from 2020 to 2050 compared with the adopted policies scenario (central estimates with 1.4% and 5% discounting). In other words, policies implemented or adopted since 2015 have secured less than half of the potential benefits of soot-free standards. The value of future policies is greater with faster action: Considering the cumulative societal costs of emissions released from 2020 to 2030 under adopted policies, the 10-year transition scenario would avoid 15% of societal costs; the 5-year transition scenario would avoid 39%; and the leapfrog scenario would avoid 45%. Complementary policies that accelerate the replacement of older technologies could avoid an even greater share of these costs.

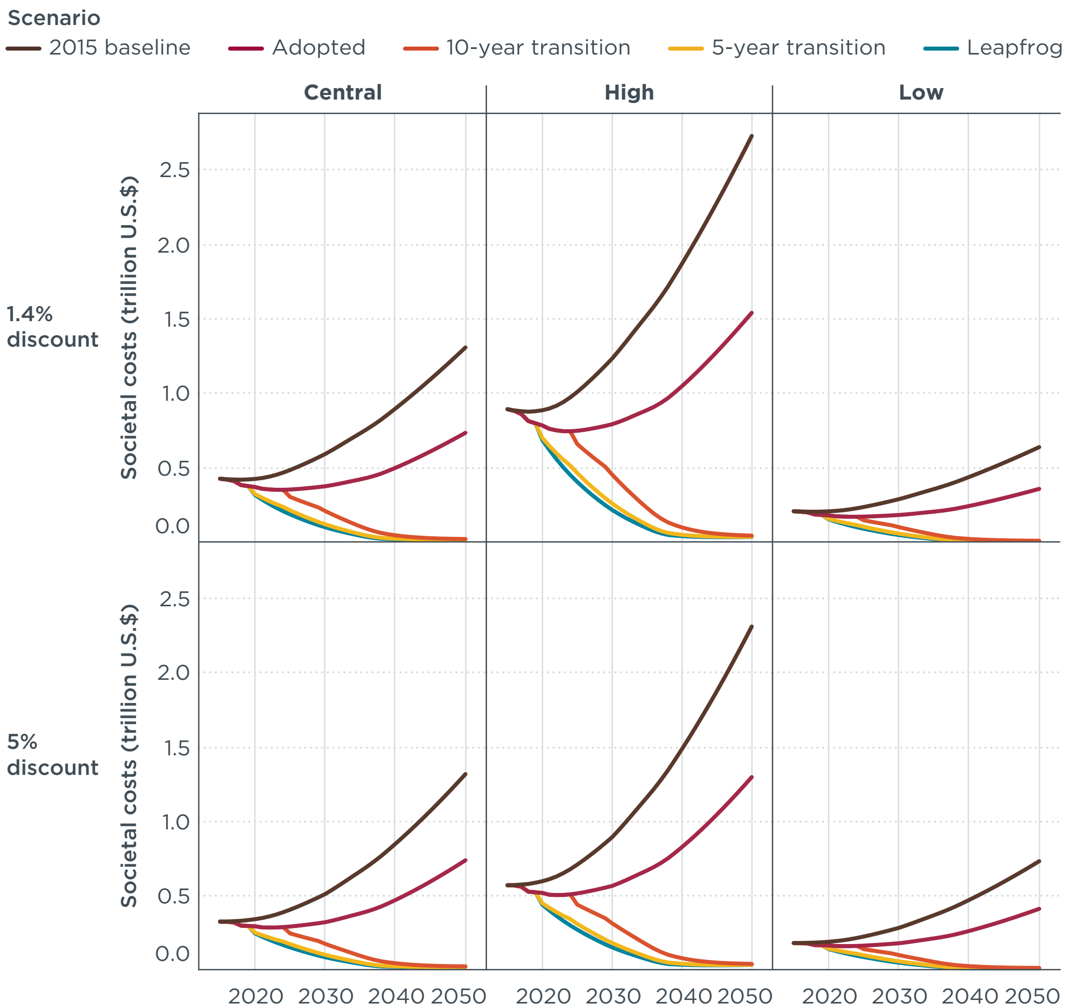

Figure 14. Global societal costs, in trillion U.S. 2019 dollars, of black carbon, organic carbon, and sulfur dioxide emissions from diesel light-duty and heavy-duty vehicles by scenario.

16 The uncertainty results yield a range of +110%/-51% and +76%/-44% for 1.4% and 5% discount rates.

CONCLUSION

This report assesses global progress in 2019 toward soot-free diesel light-duty and heavy-duty vehicles. We find that policies that have been adopted or implemented since 2015 will avoid 2 million tonnes of BC by 2030—equivalent to two years' worth of emissions at 2010 levels. Currently adopted policies are projected to reduce global diesel BC emissions to 40% below 2010 levels by 2030; yet these policies are still insufficient to achieve the 75% reduction in global BC emissions targeted by the CCAC Scientific Advisory Panel. This target is achievable only if new soot-free standards are implemented in virtually all countries in the 2020 to 2025 time frame. While political constraints vary among countries, our analysis shows that leapfrogging to Euro 6/VI equivalent standards would increase the likelihood of achieving the Scientific Advisory Panel target and avoid trillions of U.S. dollars in societal costs (i.e., climate, health, and agricultural damages) associated with diesel vehicle exhaust emissions.

There remains substantial heterogeneity in progress toward soot-free vehicles and fuels among G20 economies, CCAC State Partners, and Marrakech Communiqué signatories. In countries that have recently adopted soot-free standards, the main challenges are to ensure effective compliance and avoid delays in implementation. Supporting activities include fuel quality and vehicle emissions monitoring, in-use conformity testing, and strengthening the legal authority of regulatory agencies to enforce penalties and recalls in cases of non-compliance (Yang, Muncrief, & Bandivadekar, 2017). In countries that have ultralow-sulfur diesel available, we recommend adopting soot-free vehicle and engine standards and scheduling their implementation as soon as possible. The experiences of some CCAC State Partners, such as India, demonstrate the feasibility and greater net benefits of leapfrogging to Euro 6/VI equivalent standards as opposed to making incremental advances (Bansal & Bandivadekar, 2013; Dallmann, 2016). In countries with higher-sulfur diesel, securing ultralow-sulfur diesel should be prioritized as a means of enabling the introduction of soot-free vehicle and engine standards. In countries with multiple fuel grades, ensuring nationwide availability of an ultralow-sulfur diesel grade can enable the introduction of soot-free vehicle and engine standards several years ahead of the transition for all fuels nationwide; in such cases, differential taxes can provide a financial incentive for refiners, importers, and consumers to transition to ultralow-sulfur fuels (Miller, 2019b).

Previous studies have demonstrated that the local benefits of soot-free standards far exceed their costs—often by an order of magnitude—and that this finding is consistent among low-, middle-, and high-income countries (Cui et al., 2018; Miller, 2019a; Miller, Blumberg, & Sharpe, 2014; Miller & Façanha, 2016). Fast implementation of soot-free standards is justified by their substantial local health benefits and will contribute to meeting multiple Sustainable Development Goals. This study also demonstrates the importance of soot-free standards for meeting global BC reduction targets; including soot-free standards in Nationally Determined Contributions under the Paris Climate Accords could enable governments to increase their ambition while delivering local health benefits (Minjares, 2018).

In many regions, progress toward soot-free standards can be accelerated through cooperation among countries. Examples of such cooperation are already underway in South America, Southeast Asia, Southern Africa, and Western Africa (Climate & Clean Air Coalition et al., 2018; UN Environment, 2018; Posada, 2019; Posada et al., 2019). In regions such as South America and Southeast Asia, regional collaborations have resulted in joint technical work plans that lay out the steps to adopting and implementing soot-free standards. For these regions, the next logical step is to implement these joint technical work plans; in other regions, we recommend adapting these work plans to reflect the circumstances of participating countries. In both cases, the findings of this assessment stress the urgency for action and the societal benefits of rising to the challenge.

UNCERTAINTIES AND RECOMMENDATIONS FOR FURTHER RESEARCH

Estimates of on-road diesel vehicle emissions are subject to multiple sources of uncertainty.[17] For a global assessment, the comprehensiveness and quality of information available for emissions estimates varies substantially among regions. Such estimates rely on high-quality input data, including energy consumption, vehicle sales, stock, activity, retirement rates, emission factors, vehicles and fuels policies, and other datasets. Because not all of the information needed is available from national government sources, parameterization and model estimates (often from international agencies and research groups) are needed to construct a complete picture of global emissions. The level of compliance with standards and corresponding emissions performance of vehicles is another important determinant of real-world emissions. The share of high emitters and their emissions levels vary across countries. Although we do take high emitters into consideration, more accurate quantification of their contribution to BC emissions requires more evidence.

We recommend that future research seeks to compare actual and regulated fuel quality, which would require real-world fuel quality sampling; and that additional real-world emissions testing be conducted to identify the share of high emitters and improve the characterization of vehicle BC emission factors. If stock data by vehicle type and emission control level are identified and found to be reliable, we could apply detailed survival curve calibrations for additional countries (see Appendix). Possible sensitivity analyses could assess the effects of varying assumptions for used vehicle imports, including their emissions performance and trade flows; for the fraction of high emitters (vehicles with malfunctioning emission controls due to poor design, inadequate maintenance or tampering); and for different shapes of survival curve.

The estimates of societal costs in this assessment are based on global average damage functions for BC, OC, and SO_2. This assessment focuses on these pollutants because they are among the most directly affected by the transition to vehicles with diesel particulate filters and the use of ultralow-sulfur diesel. Other pollutants such as nitrogen oxides, carbon monoxide, volatile organic compounds, and other particulate matter components (besides BC and OC) contribute to the societal costs of diesel vehicle emissions, including adverse health impacts from $PM_{2.5}$ and ozone exposure (Anenberg et al., 2017; Anenberg et al., 2019). Research detailing how the societal costs of emissions vary by location, pollutant, and time period would support more comprehensive estimates of the societal costs of diesel vehicle emissions.

17 See page 32 of Anenberg et al. (2019).

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APPENDIX

LIST OF METHODOLOGICAL CHANGES

The 2018 assessment contains a technical appendix that describes the methods and data sources used to estimate and project the air pollutant exhaust emissions from on-road light-duty and heavy-duty diesel vehicles for more than 190 countries (Miller & Jin, 2018). This 2019 assessment largely applies the same methods and data sources. This section provides an explanation of refinements or updates made to the methods and data sources since the previous assessment.

Detailed vehicle fleet validations

We identified four major countries for which sufficient historical vehicle stock data were available to support a detailed fleet validation. We obtained official data for the number of in-use vehicles by vehicle type, emission control level, and fuel type. We then calibrated the vehicle survival curves in the model to achieve alignment of modeled stock estimates and official stock data by vehicle type, vehicle emission control level, and fuel type. We assumed a default value of 5 for k, and the resulting T_m values are an approximation of the average vehicle retirement age.[18] These calibrations were performed for China, Germany, Italy, and the United Kingdom.

Fuel sulfur and vehicle emission standards

We updated fuel sulfur inputs and new vehicle emission standards for all countries with available information (see Supplemental Data for details). Details on the stringency and implementation dates of adopted emission regulations for new light-duty and heavy-duty diesel 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.

Used vehicle import policies

We updated inputs on used vehicle import policies for all countries with available information. The dataset for such policies now contains information for 120 countries. Common examples of used vehicle import policies include outright bans for some or all vehicle types, restrictions based on vehicle emissions certification, and restrictions based on vehicle age. In countries without explicit used vehicle emissions requirements or screening programs, we have lowered expectations of vehicle emissions performance, assuming emissions are uncontrolled. This assumption is informed by reports that in countries where poor fuel quality is incompatible with advanced technologies on used vehicle imports, these technologies are likely to be removed (Roychowdhury, Chandola, Shukla, & Chattopadhyaya, 2018). This assumption increases emissions estimates for the baseline and adopted scenarios, because these assume no new policies to control used imported vehicle emissions.

Countries with multiple diesel fuel grades

In countries with multiple fuel grades, the estimated average sulfur content of diesel reflects a volume-weighted average of all diesel fuel grades used for road transport.

18 See page 28 of Miller & Jin (2018).

For this reason, the set of countries with at least one fuel grade that is ultralow-sulfur is larger than the set of countries where all on-road diesel averages less than 10 to 15 ppm. For example, as of July 2019, multiple diesel fuel grades are permitted in Argentina, Brazil, Indonesia, and South Africa:

» Argentina: 16.5% of diesel is 10 ppm, 29% is 500 ppm, and the rest is 1,000 ppm.

» Brazil: an estimated 70% of diesel is 10 ppm, and 30% is 500 ppm.

» Indonesia: most diesel is 2,500 ppm or 500 ppm; availability of 50 ppm is limited.

» South Africa: 80% of diesel is 50 ppm; 10 ppm is a niche grade; the rest is 500 ppm.

In Argentina, for example, 10 ppm diesel is already available for Euro V (or Euro VI) trucks; however, because higher sulfur diesel grades make up a larger share of the fuels market, the volume-weighted average sulfur content of on-road diesel is estimated to be roughly 690 ppm. Over the next several years, fuel refiners will need to increase the supply of 10 ppm diesel to account for the growing share of activity by Euro V trucks. Completing a transition to 10 ppm average diesel fuel would both reduce the risk of misfueling and reduce in-use fleet emissions of $PM_{2.5}$ and sulfur dioxide.

OTHER SECTORAL ASSESSMENTS

Non-road diesel engines such as agricultural and construction equipment, rail, and marine vessels are important sources of BC emissions but are outside the scope of this assessment. Because meeting the Scientific Advisory Panel's target for global anthropogenic BC reduction also depends on BC reductions from non-road diesel engines and non-transportation sources, further research is needed to evaluate progress and remaining mitigation potential from each of these sources. To provide additional context for the findings of this assessment, we include below a preliminary analysis of identified sectoral BC pathways that could achieve a 75% reduction in global BC emissions from 2010 to 2030.

Table A1 shows sectoral BC emissions in 2010 and potential BC emissions in 2030 according to mitigation scenarios developed by IIASA for the ECLIPSE project (Klimont et al., 2017). Under a short-lived climate pollutant (SLCP) mitigation scenario that assumes implementation of measures with identified air quality and climate benefits, global BC emissions from the domestic combustion and energy sectors could be reduced to 85% below 2010 levels by 2030. Emissions from shipping in 2030 were not available for the SLCP scenario; estimates are instead shown for the maximum technically feasible reductions (MTFR) scenario. The MTFR scenario assumes implementation of "best available technology" measures; it considers the economic lifetime of technologies and selected other constraints, but it assumes no institutional or political barriers. Under the MTFR scenario, global BC emissions from international shipping could be reduced to 38% below 2010 levels by 2030 (Klimont et al., 2017). Taking the total of these sectoral emissions estimates, implementing the measures in the SLCP (MTFR for shipping) scenario could reduce global BC emissions to 76% below 2010 levels by 2030, meeting the Scientific Advisory Panel target for BC reduction; however, accounting for institutional or political barriers could decrease the level of BC mitigation achievable in some sectors. Therefore, to increase the likelihood of meeting the Scientific Advisory Panel target, it may be prudent to build in a margin of error by aiming for slightly deeper BC emissions reductions.

Table A1. Sectoral BC emissions in 2010 and mitigation potential by 2030, thousand tonnes

Source	Sector	2010[1]	2030[2]	Percent reduction 2010–2030
GAINS model ECLIPSE V5a (Klimont et al., 2017)[4]	Transport excluding shipping	1,582	703	56%
	International shipping	120	74	38%
	Domestic combustion	4,163	621	85%
	Energy	541	79	85%
	Industry	389	106	73%
	Waste	97	84	13%
	Total[3]	7,229	1,733	76%
This study	On-road light-duty and heavy-duty diesel vehicles	994	174–209	79%–83%

[1] 2010 emissions from ECLIPSE are shown for the CLE (current legislation) scenario.
[2] 2030 emissions from ECLIPSE are shown for the SLCP scenario for all sectors except shipping. Emissions from shipping in 2030 were not available for the SLCP scenario; estimates are instead shown for the MFTR scenario. The 2030 emissions from this study correspond to the 5-year transition and leapfrog scenarios; the lower BC estimates are for the leapfrog scenario.
[3] Mitigation potential data were not available for international aviation. The absolute impact is small compared with the global total, given that international aviation emitted 10 thousand tonnes of BC in 2010 (Klimont et al., 2017).
[4] For additional details, see the ECLIPSE (Evaluating the Climate and Air Quality Impact of Short-Lived Pollutants) V5a project website (Klimont, 2017).

Within the overall transport sector, we find that the 5-year transition scenario, which assumes that all countries implement Euro 4/IV by 2020 and Euro 6/VI by 2025, would reduce BC emissions from on-road light-duty and heavy-duty diesel vehicles to 79% below 2010 levels in 2030. The leapfrog scenario, which assumes that all countries implement Euro 6/VI by 2020, would reduce BC emissions to 83% below 2010 levels in 2030. These findings suggest that on-road diesel vehicles could achieve similar levels of BC mitigation by 2030 as previously estimated for the domestic combustion and energy sectors. However, accounting for the likelihood that some countries may not be able to meet either timeline for soot-free standards, we recommend that each country and region consider the earliest practicable timeline to maximize the likelihood of meeting the global target and minimize associated societal damages.

Previous ICCT studies have conservatively estimated that the global shipping sector (international, domestic, and fishing) emitted 78 thousand tonnes of BC in 2015,[19] accounting for 21% of the sector's CO_2-equivalent emissions on a 20-year timescale (Olmer, Comer, Roy, Mao, & Rutherford, 2017). Black carbon is the second-largest contributor to shipping's climate warming impact after CO_2. Emissions legislation for diesel engines used in ships have historically lagged those for road transport but are now receiving more attention. The Marine Environment Protection Committee (MEPC)-74 instructed the Sub-Committee on Pollution Prevention and Response (PPR)-7, which will meet in early 2020, to consider concrete proposals to cut BC emissions from international shipping. Under the agreed schedule, the International Maritime Organization will consider ways to regulate BC from international shipping at MEPC-77 in fall 2021. Depending on their stringency and implementation timeline, certain measures could potentially yield steeper BC reductions than shown in the MTFR

19 GAINS BC estimates and the ICCT's use different methodologies. The ICCT estimates are conservative, as explained in Olmer et al. (2017); actual BC emissions from shipping could be higher.

scenario. Such measures could include switching from residual fuels to distillates and using diesel particulate filters; the latter are capable of reducing BC emissions from ships by 90% to 99% or greater (The International Council on Clean Transportation, 2018).

SUPPLEMENTARY DATA

The following supplementary datasets are available from the website for this publication:

1. Estimated BC emissions by diesel vehicle type, country, scenario, and year.
2. Estimated average on-road diesel sulfur levels by country in 2019 and 2025.
3. New heavy-duty diesel engine emission standards by country in 2019 and 2025.
4. Estimated share of world new diesel vehicle sales with diesel particulate filters under adopted policies in 2015, 2020, and 2025. Results are provided for 16 region groups.
5. Implementation status of Marrakech communiqué by CCAC State Partners.
6. Country and region group definitions.

THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

BEIJING | BERLIN | SAN FRANCISCO | WASHINGTON