AIR QUALITY AND HEALTH IMPACTS OF HEAVY-DUTY VEHICLES IN G20 ECONOMIES

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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.

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EXECUTIVE SUMMARY

This study aims to quantify and enhance understanding of the multiple benefits of key policies for reducing air pollutant emissions from heavy-duty vehicles (HDVs) in G20 economies. Among transportation subsectors, on-road diesel vehicles are the leading contributor to air pollution and associated disease burdens. Within that group, HDVs are the main contributor to exhaust emissions and health effects, accounting for 86% of on-road diesel nitrogen oxides (NO_x) emissions in 2015. Besides the impact on air quality and public health, black carbon (BC) from diesel engine exhaust severely affects the climate as the particles produce significant near-term climate warming.

The study analyzes the health and climate impacts associated with projected diesel HDV exhaust emissions under four scenarios: currently adopted policies, expanded adoption of current world-class standards (Euro VI-equivalent), potential next-generation emission standards, and accelerated fleet renewal programs. We find that:

Expanded implementation of world-class standards in G20 countries in the 2023–2025 timeframe would substantially reduce HDV exhaust emissions and associated health impacts. Whereas NO_x emissions are projected to increase by as much as 60% in countries yet to adopt such standards, expanded world-class standards could instead reduce NO_x by 45%–85% over the next two decades. Likewise, these filter-forcing regulations are expected to drive large decreases in BC emissions from HDVs. In G20 countries that have adopted these standards, BC emissions are projected to fall by 85%–99% over the next two decades compared with 2020 levels. The near-term climate benefits of these BC reductions are significant on a global scale—equivalent to reducing billions of tonnes of carbon dioxide (CO_2). For countries that normally import used vehicles, regulating new sales is not sufficient to curb pollutant emissions. Restricting imported used vehicles' emissions is important to realize the full benefits of protecting public health and mitigating climate change.

Next-generation standards are key to sustaining NO_x emission reductions from HDVs. These standards could bring NO_x levels down by 60%–95% from 2020 levels in 2040, compared with the 40%–80% projected under Euro VI-equivalent standards. Implementation of next-generation standards in G20 countries could avoid more than $5 trillion of health damages over the next three decades. These potential benefits are significant not only for countries that have already implemented current world-class standards but also for countries that are planning to implement Euro VI-equivalent standards within the next several years.

Next-generation standards coupled with accelerated fleet renewal policies would achieve the greatest benefits by a wide margin. Cumulative avoided premature deaths attributable to diesel HDV emissions in G20 economies from 2020 to 2050 would total 4 million under the next-generation plus 16-year renewal scenario. This is four times the number under the expanded world-class plus 16-year renewal scenario. In EU member countries like Germany, France, and Italy accelerated fleet renewal policies coupled with next-generation standards are expected to achieve at least twice the monetary health benefits as either world-class, Euro VI-equivalent with fleet renewal or next-generation alone. Next-generation policies combined with accelerated fleet renewal policies are expected to yield $6.8 trillion of cumulative health benefits from 2020 to 2050.

These findings highlight the scale of the opportunity at hand to expand adoption of filter-forcing standards, develop cleaner next-generation emission standards, and couple these standards with accelerated fleet renewal programs to remove vehicles with older technologies. For countries that have not yet adopted Euro VI-equivalent standards, doing so and implementing them by 2025 is important both to protect public health and to secure the near-term climate benefits of BC mitigation. Next-generation emission standards are key to sustaining and augmenting the air quality improvements associated with current world-class standards. Over the next two decades, this effect is most prominent for countries that have been early adopters of world-class standards. Realizing the air quality and health benefits identified in the next-generation scenario would require finalizing and expanding the adoption of such policies in other G20 countries. Complementary accelerated fleet renewal programs together with next-generation standards could markedly accelerate this progress.

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ACRONYMS

BC	black carbon
CO_2e	CO_2-equivalent emissions
DALY	disability-adjusted life year
DPF	diesel particulate filter
GBD	Global Burden of Disease
GHG	greenhouse gas
GWP	global warming potential
EPA	U.S. Environmental Protection Agency
HDDE	heavy-duty diesel engine
HDV	heavy-duty vehicles
OC	organic carbon
PM	particulate matter
VKT	vehicle kilometers traveled
VSL	value of a statistical life

INTRODUCTION

BACKGROUND

Transportation tailpipe emissions resulted in 385,000 premature deaths and $1 trillion of health damages globally in 2015 (Anenberg, Miller, Henze, & Minjares, 2019). Among transportation subsectors, on-road diesel vehicles were the leading contributor to air pollution and associated disease burdens. Heavy-duty vehicles (HDVs) are the main contributor to exhaust emissions and health impacts, accounting for 86% of on-road diesel NO_x emissions in 2015 (Anenberg et al., 2017).

Besides its impact on air quality and public health, the transport sector produced 7.0 gigatonnes (Gt) of carbon dioxide-equivalent direct greenhouse gas (GHG) emissions in 2010, or 23% of total energy-related carbon dioxide (CO_2) emissions (IPCC, 2014). Growth in GHG emissions has continued in the past decade or more despite the adoption of more-efficient vehicles and policies to address the issue (IPCC, 2014). Meanwhile, worldwide consumption of fossil diesel fuel by on-road vehicles has more than doubled since 1990 (IEA, 2020). In addition to the effects of CO_2 emissions, black carbon (BC) from diesel engine exhaust results in severe impacts on the climate as the particles produce significant near-term climate warming. Heavy-duty vehicles accounted for 78% of on-road diesel BC emissions in 2017, though they made up less than a quarter of the diesel vehicle fleet (Miller & Jin, 2018).

The G20 economies—19 leading countries plus the European Union—account for around two-thirds of the world's population and 80% of transportation energy demand, on-road vehicle stock, and vehicle activity. An estimated 84% of global transportation-attributable deaths occurred in G20 countries, and 70% took place in the four largest vehicle markets in 2015: China, India, the European Union, and the United States (Anenberg, Miller, Henze, Minjares, 2019). G20 economies also accounted for an overwhelming 94% of the global monetary health damages from transportation tailpipe emissions in 2015 (Anenberg, Miller, Henze, & Minjares, 2019).

To mitigate the health and climate effects of emissions from diesel HDVs, many markets have imposed standards for new vehicles. Figure 1 shows the implementation year for emission standards for new sales heavy-duty diesel engine (HDDE) vehicles in G20 economies (Miller & Braun, 2020). The emission standards are shown as Euro equivalents. For example, Euro VI-equivalent standards include U.S. 2010, China VI, Euro VI, Bharat Stage (BS) VI in India, PROCONVE P-8 in Brazil, and Post New Long-Term in Japan, among others. One major difference of Euro VI-equivalent standards, besides lower emission limits, is that they require the use of diesel particulate filters and thus can drastically reduce particulate matter (PM) and black carbon emissions. Currently, eight countries and regions have already implemented Euro VI-equivalent standards, including Canada, the European Union, India, Japan, South Korea, Turkey, the United Kingdom, and the United States. Three countries have adopted Euro VI-equivalent standards, including China effective in 2021, Mexico in 2022, and Brazil in 2023. G20 countries that have not adopted Euro VI-equivalent standards are Argentina, Australia, Indonesia, Russia, Saudi Arabia, and South Africa.

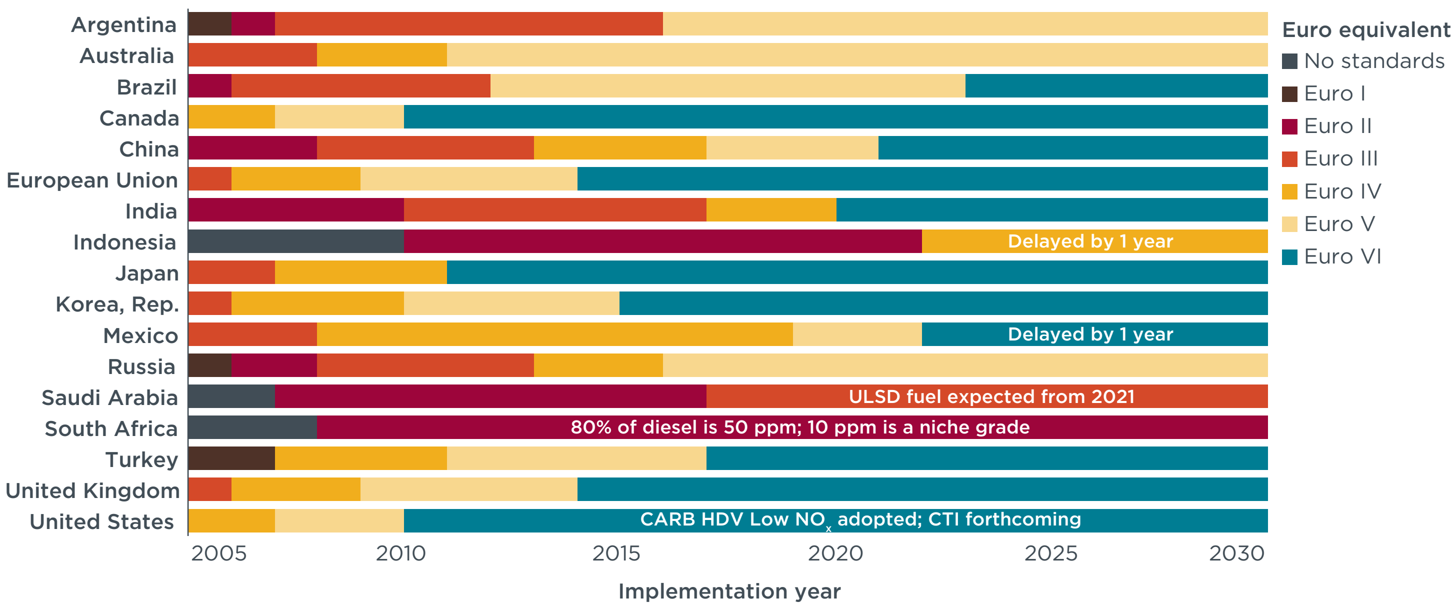

Figure 1. Implementation year (all sales and registration) of heavy-duty diesel engine emission standards in G20 economies. (France, Germany, and Italy, which hold separate G20 memberships, are included in the EU data.)

In 2020, varied progress was made on HDV emission standards. On one hand, regulators in Brazil, Mexico, and Indonesia faced automaker pressures to delay the implementation of adopted Euro VI-equivalent standards. Decreased vehicle sales amid the COVID-19 pandemic was the main reason manufacturers, yet lessons from Europe indicate that vehicle sales can be sustained without weakening regulations by supporting clean vehicles and the accelerated replacement of older vehicles (Wappelhorst, 2020a, 2020b).

On the other hand, India implemented BS VI in April 2020 without significant delay just three years after its BS IV standards. In addition, a long-awaited scrappage program is under development. In China, the implementation of China VI is scheduled for 2021. No postponement was requested. In the United States, the California Air Resources Board adopted its HDV low-NO_x regulation, which will tighten NO_x limits by 75% below current standards in 2024 and by 90% in 2027. At the national level, further development of the U.S. Environmental Protection Agency (EPA) Cleaner Trucks Initiative are forthcoming. In Europe, Euro VII standards are under development and are expected to be announced in 2022.

While considering the implementation of more stringent standards, it is also necessary to accelerate the retrofit or replacement of older vehicles with cleaner or zero-emission vehicles. In addition, emissions from used vehicle imports must be addressed to realize the full benefits of new vehicle standards in protecting public health and mitigating climate change (Miller & Jin, 2019). Among G20 economies, Mexico, Russia, and Saudi Arabia allow the importation of used vehicles (see the Methods section).

STUDY OBJECTIVES AND SCOPE

This study aims to quantify and enhance understanding of the impacts of key policies for reducing air pollutant emissions from HDVs in G20 economies. The study analyzes current and projected diesel HDV exhaust emissions, mainly NO_x and $PM_{2.5}$, or particles 2.5 microns or less in diameter; exposure to ambient particulate matter and ozone (O_3)

from these emissions; associated premature deaths and years of life lost; valuation of health damages; and climate effects of non-CO_2 emissions, including BC, methane (CH_4) and nitrous oxide (N_2O). Policy scenarios evaluated include currently adopted policies, expanded adoption of current world-class standards, potential next-generation emission standards, and accelerated fleet renewal programs.

There has been growing interest in electrification and alternative fuels, including rapid electrification of urban bus fleets in megacities throughout the world. One example is the Zero Emission Bus Rapid-Deployment Accelerator, which aims to increase deployment of electric buses in Latin American cities. We included the effects of California's Advanced Clean Trucks and Innovative Clean Transit rules on tailpipe emissions in all scenarios in this study. We do not attempt to evaluate the effects of additional HDV electrification but hope to do so in a future study. The analysis in this report should be viewed as a concerted effort toward a cleaner transport sector in addition to HDV electrification, not at the expense of electrification programs.

METHODS

SCENARIOS

We incorporated four policy scenarios into our analysis, described in detail below.

- **Adopted:** Policies adopted by December 2020.
- **Expanded world-class:** In addition to adopted policies, we assume that Indonesia and South Africa will implement Euro VI-equivalent standards in 2025, and Argentina, Australia, Russia, and Saudi Arabia will do so by 2023.[1] This means that all G20 countries will have implemented Euro VI-equivalent standards by 2025. To achieve the Climate & Clean Air Coalition goal of reducing global black carbon emissions to 75% below 2010 levels by 2030, Euro VI-equivalent standards need to be implemented for on-road diesel vehicles by 2025 (Miller & Jin, 2019). Black carbon is a potent short-term climate pollutant. Achieving this goal is expected to avoid 0.5°C of additional warming in the next 25 years and help meet the goals of the Paris Climate Agreement. We also assume that imported used vehicles will be required to meet new-vehicle regulations, starting with Euro VI-equivalent standards.
- **Expanded world-class and 16-year accelerated fleet renewal:** Accelerated fleet renewal policies are added to the expanded world-class scenario, resulting in 100% of in-use HDVs meeting Euro VI equivalents and next-generation standards 16 years after they are applied to new vehicles. For countries that have already implemented Euro VI-equivalent standards by December 2020, their fleet renewal policies start in 2021. For countries that have not implemented Euro VI-equivalent standards, their fleet renewal policies start in the year after their implementation of such standards. Pre-Euro VI-equivalent vehicles are assumed to be gradually replaced over this time period. For example, in the United States, under a 16-year accelerated fleet renewal scheme, we assume that pre-U.S. 2010 HDVs will be gradually replaced by U.S. 2010 or cleaner vehicles over 16 years until 100% of in-use HDVs are EPA 2010-certified or better in 2026. In reality, it might take different countries different amounts of time to completely renew in-use fleets. The 16-year assumption provides a way to compare across G20 countries and show the potential effect of fleet renewal policies.
- **Next-generation standards:** This scenario assumes that countries have implemented the policies included in the adopted and expanded world-class scenarios. For next-generation standards, we assume hypothetical implementation dates that account for ongoing discussions in California, the United States, the European Union, and China, with other countries adopting similar standards several years later. Canada, China, the European Union, and the United States would implement next-generation emission standards in 2027; countries that adopted Euro VI equivalents by December 2020 would follow suit in 2028; and all other G20 economies in 2030. We assume these next-generation standards would achieve reductions in NO_x compared with current world-class standards, but we did not evaluate potential reductions in particulate emissions from next-generation standards in this study. Table 1 shows the implementation year and NO_x limit for next-generation standards in G20 economies.
- **Next-generation and 16-year accelerated fleet renewal:** Building upon the next-generation scenario, 100% of in-use HDVs would meet Euro VI equivalents and next-generation standards 16 years after they are applied to new vehicles. The fleet renewal assumptions are as described above.

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1 The assumed implementation timelines are based on factors including communications with stakeholders, current policy progress in these countries, technology availability, and climate goals.

For accelerated fleet renewal, there are multiple ways to achieve similar effects. Examples of large-scale programs include California's in-use HDV retrofit and replacement rules, China's Clean Diesel Action Plan, widespread adoption of urban low-emission zones throughout Europe, and a scrappage program targeted towards older vehicles to encourage deployment of Euro VI or zero-emission vehicles under discussion in Germany (Federal Cabinet, 2020). The assumptions in this scenario are to gradually retire vehicles that are not of the latest standards as opposed to those of a certain age.

Table 1. Implementation year (all sales and registration) of heavy-duty diesel engines next-generation emission standards in G20 economies.

Country	Implementation year	NO_x limit
European Union, United Kingdom, United States, Canada	2027	90% reduction from current limit
China	2027	90% reduction from China VI limit
Brazil, India, Japan, South Korea, Mexico, Turkey	2028	90% reduction from Euro VI- equivalent limit
Argentina, Australia, Indonesia, Russia, Saudi Arabia, South Africa	2030	90% reduction from Euro VI- equivalent limit

EMISSIONS

We estimated current and projected HDV emissions in G20 economies using the ICCT's Roadmap model (International Council on Clean Transportation, 2021b). The model considers factors such as energy consumption and efficiency, fuel quality, vehicle activity, sales, stock and emission controls by country/region, vehicle type, fuel type, and year. We built on previous assessments of HDV emission impacts (Anenberg et al., 2017; Miller & Jin, 2018, 2019). The main vehicle sub-sectors included in this analysis are heavy-duty trucks (HDTs), medium-duty trucks (MDTs), and buses. Technology-specific emission factors are based on the EPA's Motor Vehicle Emission Simulator (MOVES) model, the European Monitoring and Evaluation Programme and the Handbook Emission Factors for Road Transport. We adjusted PM and NO_x emission factors certified to U.S. and EU regulatory pathways based on real-world performance data, including remote sensing measurements (Bernard, Dallmann, Tietge, Badshah, & German, 2020; Carslaw et al., 2011; Dallmann et al., 2018, 2019; Ghaffarpasand, Beddows, Ropkins, & Pope, 2020), recent PEMS testing (Badshah, Posada, & Muncrief, 2019; Posada, Badshah, & Rodríguez, 2020), and planned updates to MOVES. We used the same $PM_{2.5}$ speciation profile across regions based on MOVES2014 values to derive emission factors for PM components such as BC.

We considered the effects of high-emitting vehicles, or vehicles that produce emissions substantially higher than regulatory limits due to emission control system malfunction, tampering, poor maintenance, or failure. We applied shares of high-emitting vehicles and emission multipliers to all regions based on region-specific estimates and general compliance and enforcement level for PM and NO_x. These reflect shares of high-emitting vehicles of different vehicle types and control levels after their useful life (see below).

Vehicles don't usually start out as high emitters; rather, tampering, mal-maintenance and malfunction are more prevalent as vehicles age. We follow EMFAC (California Air

Resources Board, 2018) and MOVES's approach to estimate emission deterioration with age, as shown in Figure 2, where emission rate increases linearly from the end of the warranty period up to the useful life, assuming vehicle owners are incentivized to fix any issues within the warranty period. As in MOVES, we define the point of age at the end of emission warranty period as warranty age and at the end of useful life as useful life age. Mileage was applied to these ages based on region-specific data that show how quickly different types of vehicles accumulate miles. We used TRACCS (TRACCS, 2013) data for the EU and activity data from the Vehicle Emission and Control Center of China, which is also consistent with the estimate from Huo, Zhang, He, Yao, and Wang (2012). We used the same ages for the United States as in MOVES. In addition, we distinguished warranty and useful life ages by control level. For example, China did not implement warranty requirements until China VI. China VI, Euro VI, and U.S. 2004+ require longer useful life.

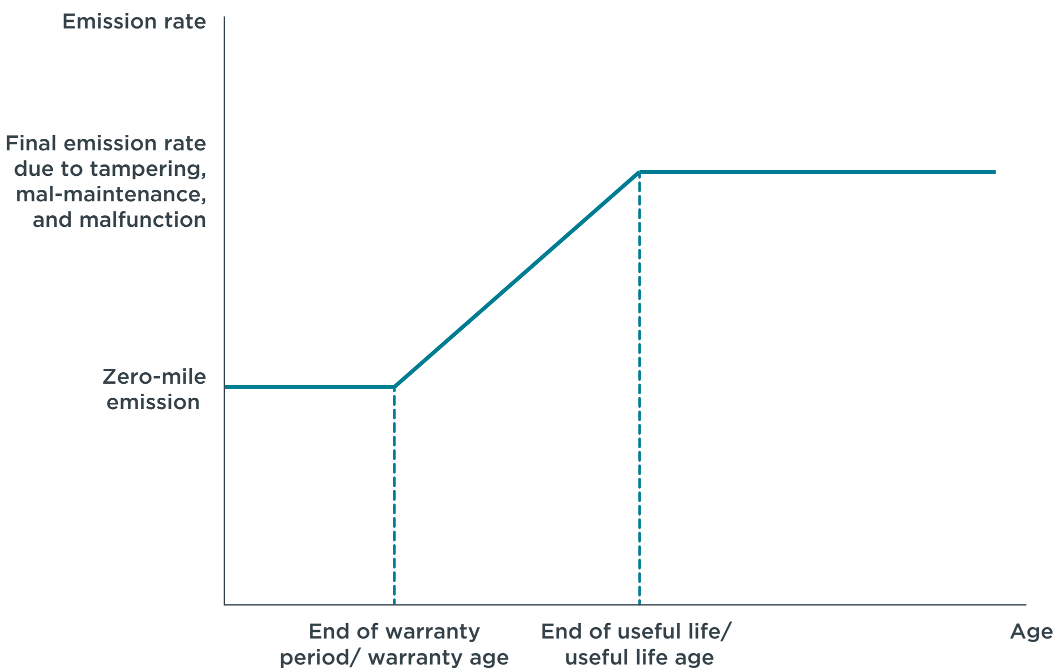

Figure 2. Qualitative depiction of the implementation of age effects. Source: MOVES2014 technical report

We considered the effect of adopted policies including California's Advanced Clean Trucks and Innovative Clean Transit rules on electric vehicle sales share (no other HDV electrification efforts are evaluated, see study scope). We included impact of biodiesel blend on NO_x and PM emissions from fossil diesel based on findings in O'Malley, Searle, and Kristiana (2021) and Searle (2018). The effect varies by country due to differences in feedstock, fuel sulfur level, and blend level. In this paper, we applied this effect to the United States, Indonesia, and Brazil.

We evaluated the effects of used vehicle imports in countries that allow them. These include Mexico, Russia, and Saudi Arabia. For 2020, we assume that imported used vehicles comply with U.S. 2004 in Mexico, Euro V in Russia and Euro II in Saudi Arabia. Used vehicle importation could be a major source of uncertainty in these countries because without explicit used-vehicle emission requirements, the emissions rate of used imports depends largely on enforcement and compliance. Examples of regulations on imported used vehicles include bans, age limits, or restrictions based on vehicle emissions certification.

For certain countries and regions with sufficient data, we performed a more detailed calibration. For the United States, detailed stock, activity, and energy consumption estimates derived from MOVES are aggregated to the Roadmap vehicle type (Table 2). MOVES-derived technology- and fuel-specific emission factors are used for most air pollutants; however, real-world NO_x measurements from The Real Urban Emissions (TRUE) U.S. remote sensing database (Bernard et al., 2020) are used to estimate NO_x emission factors for diesel HDTs and MDTs, covering model years 2004 and newer.

Table 2. Mapping of MOVES HDV segments to Roadmap HDV segments

MOVES vehicle type	Roadmap vehicle type
Long-haul tractor-trailers	HDT
Short-haul tractor-trailers	HDT
Motor homes	MDT
Single-unit long-haul trucks	MDT
Single-unit short-haul trucks	MDT
Refuse trucks	MDT
School buses	Bus
Transit buses	Bus
Intercity buses	Bus

AIR QUALITY AND HEALTH IMPACTS

To evaluate the specific disease burden resulting from emissions of vehicle exhaust pollutants, we developed the Fast Assessment of Transportation Emissions (FATE) model in collaboration with researchers at the University of Colorado Boulder and George Washington University (International Council on Clean Transportation, 2021).

Figure 3 shows schematics of a typical health impact assessment that can be used, for example, to determine the impact of the implementation of a new policy. Text in black shows inputs/outputs, and text in blue shows processes or data needed to derive the input needed for the next step. We discuss details of these steps below.

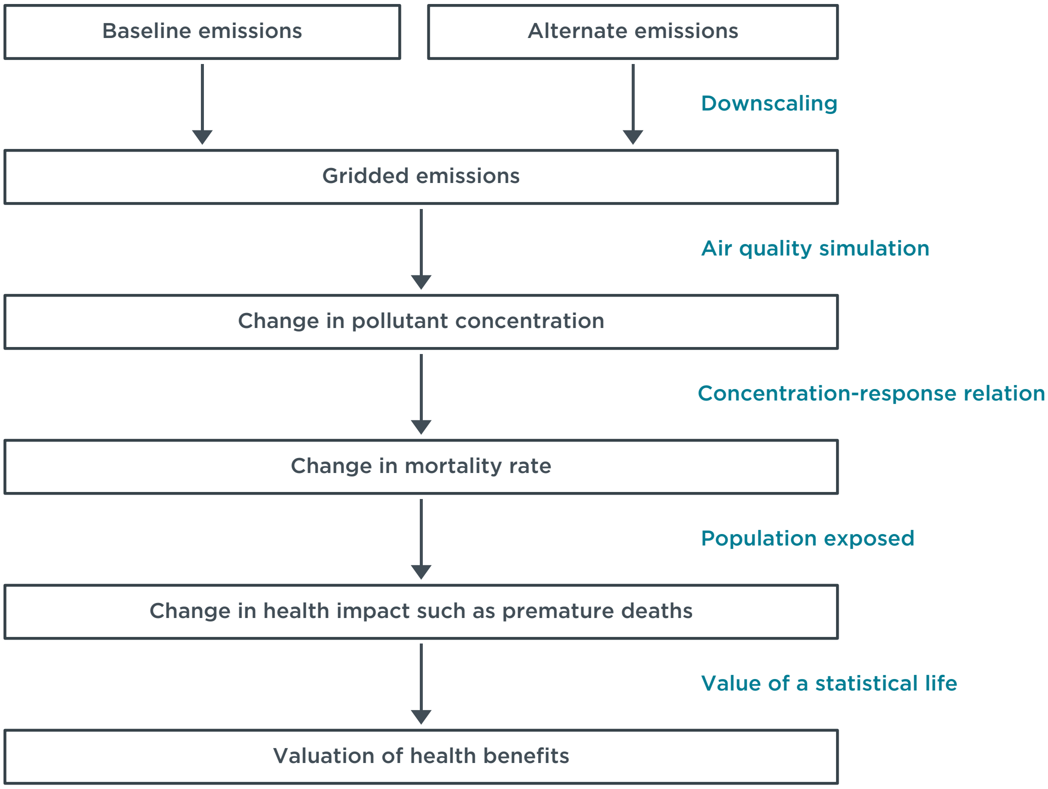

Figure 3. Schematics of a typical health impact assessment.

National emissions were downscaled before inputting to FATE, which responds to emissions at a 2º x 2.5º spatial resolution. To downscale the national emissions, we used roadway length and population to calculate share of emissions in each grid cell. The downscaling method is based on the EPA's modeling practice (EPA, 2015) and a previous study (Anenberg et al., 2017). For buses, 75% of the weight was given to population as they mostly operate in populated areas, and 25% was given to roadway length. For all other vehicle categories, 75% of the weight was given to roadway length, and 25% to population. This means that urban areas with more population and areas along major highways are allocated a higher share of national emissions.

For air quality simulation, we applied adjoint coefficients from the GEOS-Chem atmospheric chemistry model[2] to convert gridded BC, organic carbon (OC), NO_x, sulfur dioxide (SO_2), and ammonia (NH_3) emissions to population-weighted average $PM_{2.5}$ exposure, and convert NO_x, carbon monoxide (CO) and nonmethane volatile organic compounds to population-weighted average O_3 exposure associated with HDV exhaust emissions in each G20 country. These coefficients were derived for each G20 country individually by running GEOS-Chem iteratively and using meteorology and population density for a recent year. These adjoint coefficients do not attempt to account for changes in meteorology or population density over time.

We estimated the health effects of exposure to ambient $PM_{2.5}$ and O_3 following the field-leading methods developed by the Institute for Health Metrics and Evaluation for the Global Burden of Disease (GBD) 2019 (Institute for Health Metrics and Evaluation, 2020). The major health impacts from NO_x emissions assessed here are through its

2 GEOS-Chem is a global 3-D model of atmospheric chemistry driven by meteorological input and used by researchers around the world to assess a variety of atmospheric composition problems.

contributions to $PM_{2.5}$ and ozone formation. We did not evaluate the health impacts of direct NO_2 exposure, since these are not covered in the GBD methods, and evaluating NO_2 impacts requires a higher-resolution scale of spatial analysis. We report results for two health metrics: premature deaths and disability-adjusted life years (DALYs), which is the sum of years of life lost due to premature mortality and years of healthy life lost due to disability.[3] The GBD 2019 health methods include updates to baseline disease rates, ambient pollutant concentrations, and relative risks. They also consider population age distributions for heart disease and stroke. We evaluated health impacts by specific endpoint, including stroke, ischemic heart disease, chronic obstructive pulmonary disease, lower respiratory infection, lung cancer, and diabetes mellitus type 2. The model can estimate future impacts out to 2050 using population projections from United Nations World Population Prospects (United Nations, 2019), health rates projections from the GBD Foresights Project, and baseline emission projections from the Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants project (ECLIPSE) (International Institute for Applied Systems Analysis, 2021).

VALUATION OF HEALTH EFFECTS

The value of a statistical life (VSL) is often a critical parameter in cost-benefit policy analysis. It estimates willingness to pay for small reductions in mortality risk. We estimated the valuation of health damages by applying country-specific VSL methods from a previous study (Anenberg, Miller, Henze, Minjares, & Achakulwisut, 2019). The default approach follows the methodology in Viscusi and Masterman (2017).[4] A base VSL value of $9.6 million, applicable for the United States in 2015, was adjusted to present day dollars using Bureau of Labor Statistics inflation rate calculation. The VSL for each country was calculated based on the ratio of World Bank data on gross national income per capita (Atlas method[5]) of the country concerned with respect to that of the United States. We applied a 3% discount rate for cumulative valuation. We extended them to 2050 using long-term income projections from an Organization for Economic Cooperation and Development study (Guillemette & Turner, 2018) and projections from Shared Socioeconomic Pathways (Riahi et al., 2017).

CLIMATE EFFECTS

We estimated the climate effects of HDV non-CO_2 emissions using metrics of global warming potential (GWP), defined as the time-integrated radiative forcing due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO_2 (Myhre et al., 2013). To compare the effects of policies on emissions of different non-CO_2 pollutants, we used global warming potential values over a 20-year time horizon (GWP20) and over a 100-year time horizon (GWP100) to calculate CO_2-equivalent (CO_2e) emissions to account for short- and long-term climate benefits. Climate impacts of BC, CH_4, and N_2O are included in this analysis.

3 We include only fatal health outcomes in this analysis, so the DALYs include only years of life lost due to premature mortality in this case.

4 Another method is also available in the model based on a methodology applied by the World Bank (Narain & Sall, 2016). See a brief discussion of these two methods in the supplementary materials in Anenberg, Miller, Henze, Minjares, and Achakulwisut (2019).

5 The Atlas method is based on exchange rates and inflation rates. Viscusi and Masterman (2017) write: "We prefer the Atlas method over the purchasing power parity GNI per capita data because the World Bank's income classification groups are calculated using the Atlas method. VSLs can be transferred using either method of calculating income."

RESULTS

EMISSIONS

Figure 4 shows share of total vehicle kilometers travelled (VKT) compared with their associated share of tailpipe NO_x and BC emissions by Euro-equivalent standard in 2020 in G20 economies. Total VKT is the multiplication of total stock and VKT per vehicle. Points that fall above the diagonal line indicate that vehicles of this standard have an outsized impact on emissions relative to their vehicle activity.

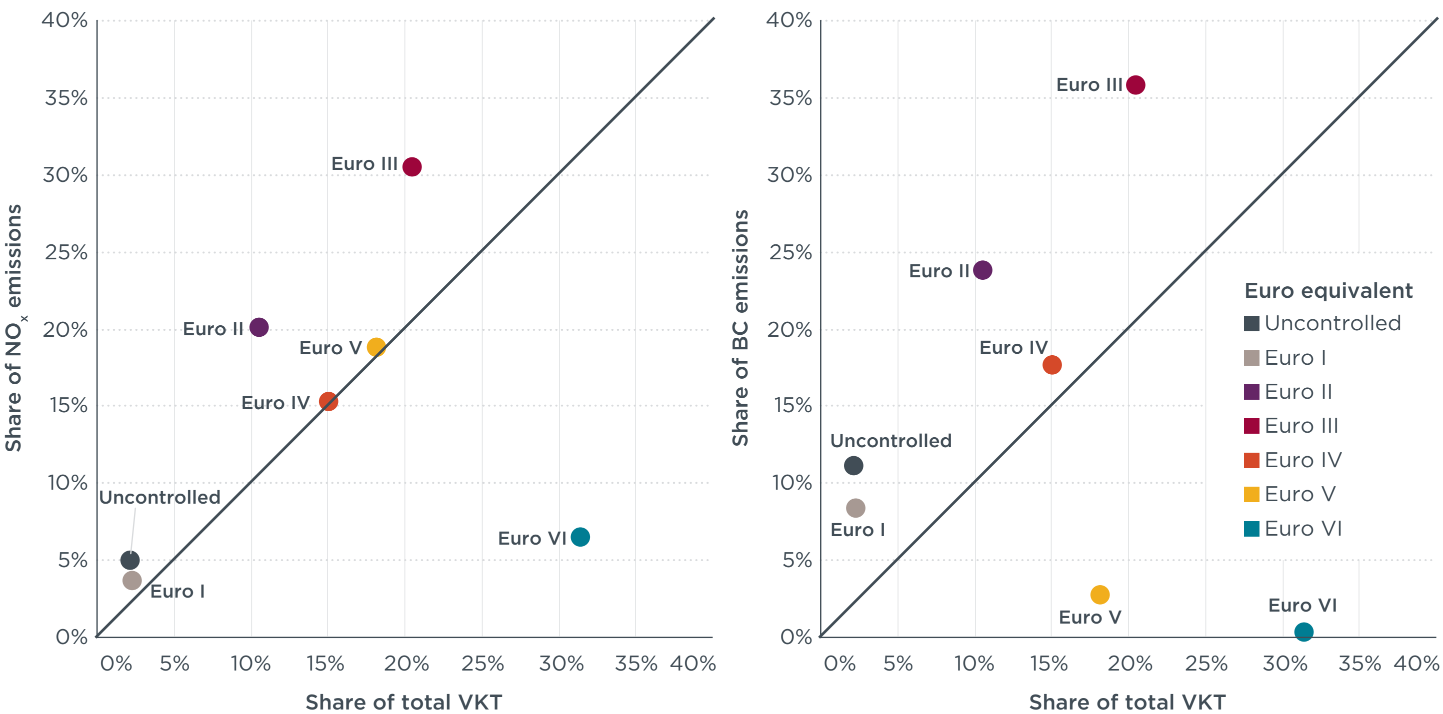

Figure 4. Share of total VKT (x-axis) and pollutant emissions (y-axis) by Euro-equivalent emissions standard, 2020. Points above the diagonal line indicate that vehicles of this standard have an outsized impact on emissions relative to their vehicle activity.

Uncontrolled and Euro I-equivalent vehicles make up for 2% of the overall VKT but account for 4% of NO_x and 10% of BC emissions. Countries that lag in emission standards and have a larger vehicle base are likely to have more of these vehicles. Accelerated fleet renewal programs could speed up the retirement of these dirty old vehicles and the transition to cleaner ones. Vehicles type-approved to Euro VI-equivalent standards account for more than 30% of the VKT but contribute only 6% of the total NO_x and less than 1% of total BC emissions.

Though Euro V falls below the diagonal line in the BC figure, there's notable variability among the different Euro V-equivalent standards. For example, U.S. 2007, which requires diesel particulate filters, has much lower BC emission rates than Euro V and China V standards for HDVs, which don't require diesel particulate filters.

Figure 5 shows projected diesel exhaust NO_x emissions from HDVs in each policy scenario for all G20 economies. Under the expanded world-class scenarios, NO_x emissions are projected to decline by 32% in 2040 compared with adopted policies, and next-generation policies can bring a further reduction of 39 percentage points. The reduction from the expanded world-class scenario and next-generation scenario show the effect of both newly produced and imported vehicles complying with new standards. Implementing accelerated fleet renewal policies on top of world-class standards is expected to reduce NO_x emissions by 40% in 2040, while combining fleet renewal policies with next-generation standards is projected to reduce NO_x emissions by 88% in 2040. This shows the importance of implementing next-generation standards to maintain the gains achieved by Euro VI-equivalent standards and avoid backsliding as would otherwise occur after 2035 as vehicle growth outweighs the effect of the expanded world-class plus 16-year renewal policies (the green line).

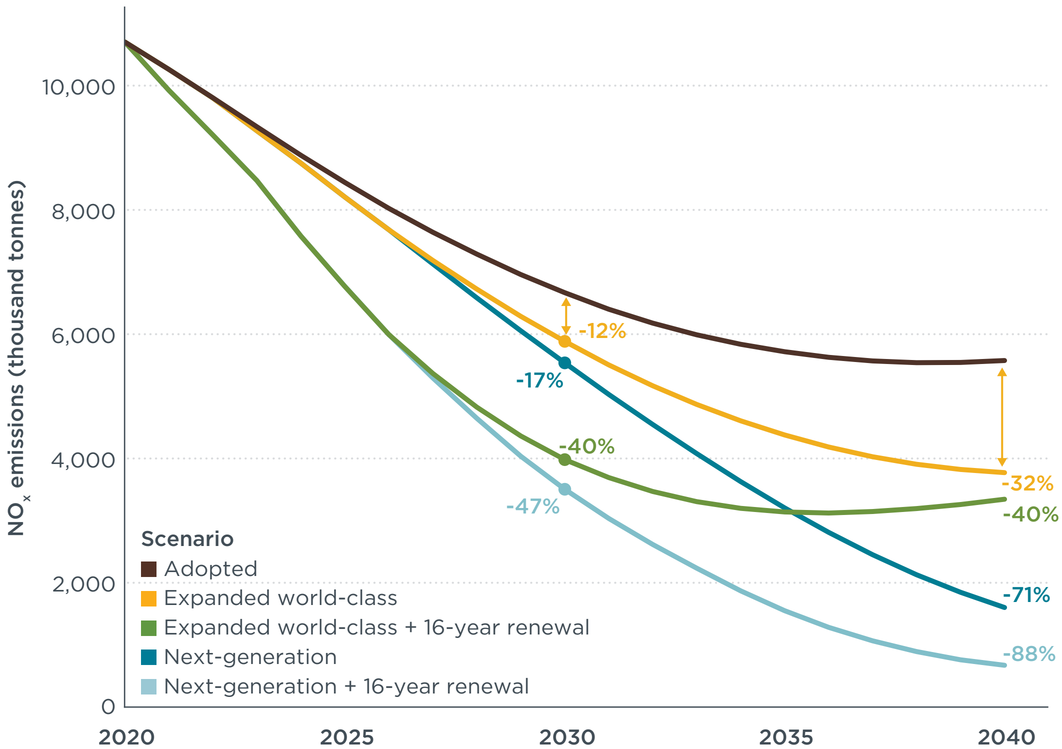

Figure 5. Diesel HDV exhaust NO_x emissions from 2020 to 2040 in G20 economies. Data labels show the percent change in NO_x emissions compared with adopted policies in 2030 and 2040.

Figure 6 shows projected diesel exhaust BC emissions from HDVs by policy scenario for all G20 economies. Diesel particulate filters, which are required in Euro VI-equivalent standards, are very effective at removing PM when they are functioning properly. As shown, reductions in the expanded world-class scenario total 78% compared with the adopted policies scenario in 2040 and 92% when combined with additional fleet renewal policies.

We focused on NO_x when making assumptions about next-generation emissions standard limits and did not evaluate any potential reduction in particulate emissions because their Euro VI-equivalent emission factors are generally already below what the standards require. Next-generation standards such as Euro VII could be designed to avoid backsliding and further reduce particulate emissions (Rodríguez & Posada, 2019); however, we haven't evaluated those potential benefits in this analysis.

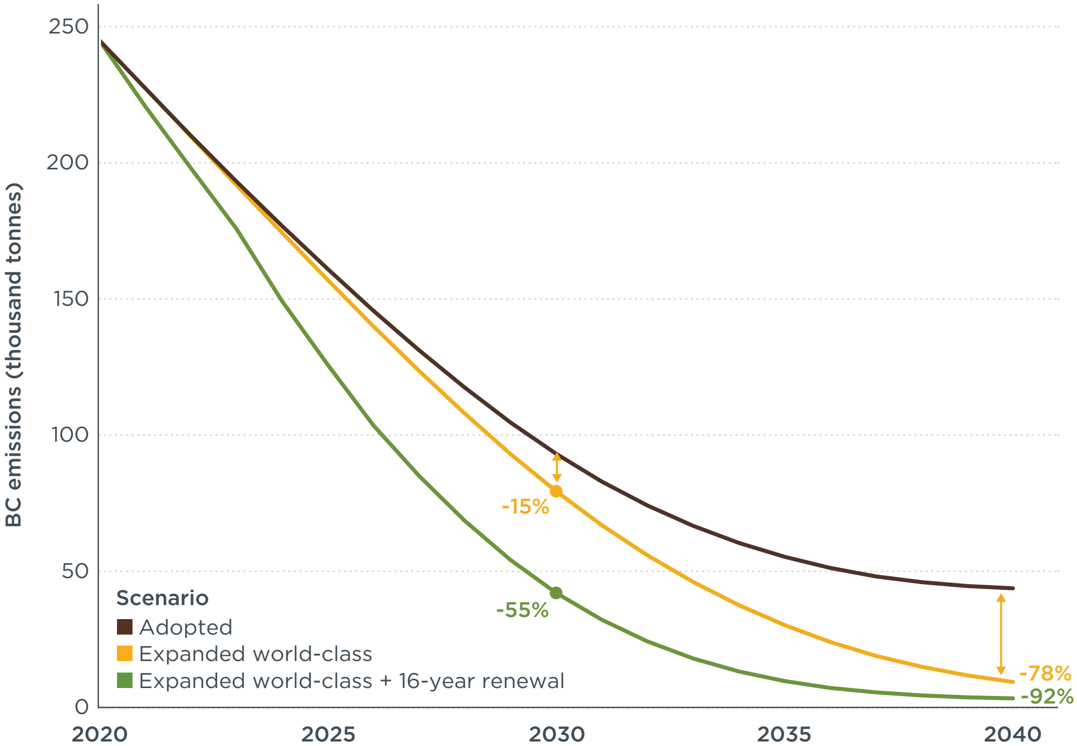

Figure 6. Diesel HDV exhaust BC emissions from 2020 to 2040 in G20 economies. Data labels show the percent change in BC emissions compared with adopted policies in 2030 and 2040.

Figure 7 shows projected normalized diesel HDV NO_x emissions from 2020 to 2040 by policy scenario and G20 economy. The y-axis shows the percent change in NO_x emissions from 2020. Countries that have not adopted Euro VI-equivalent standards and other EU countries as a group are shown in the second row in panel charts across this report if not specified otherwise.

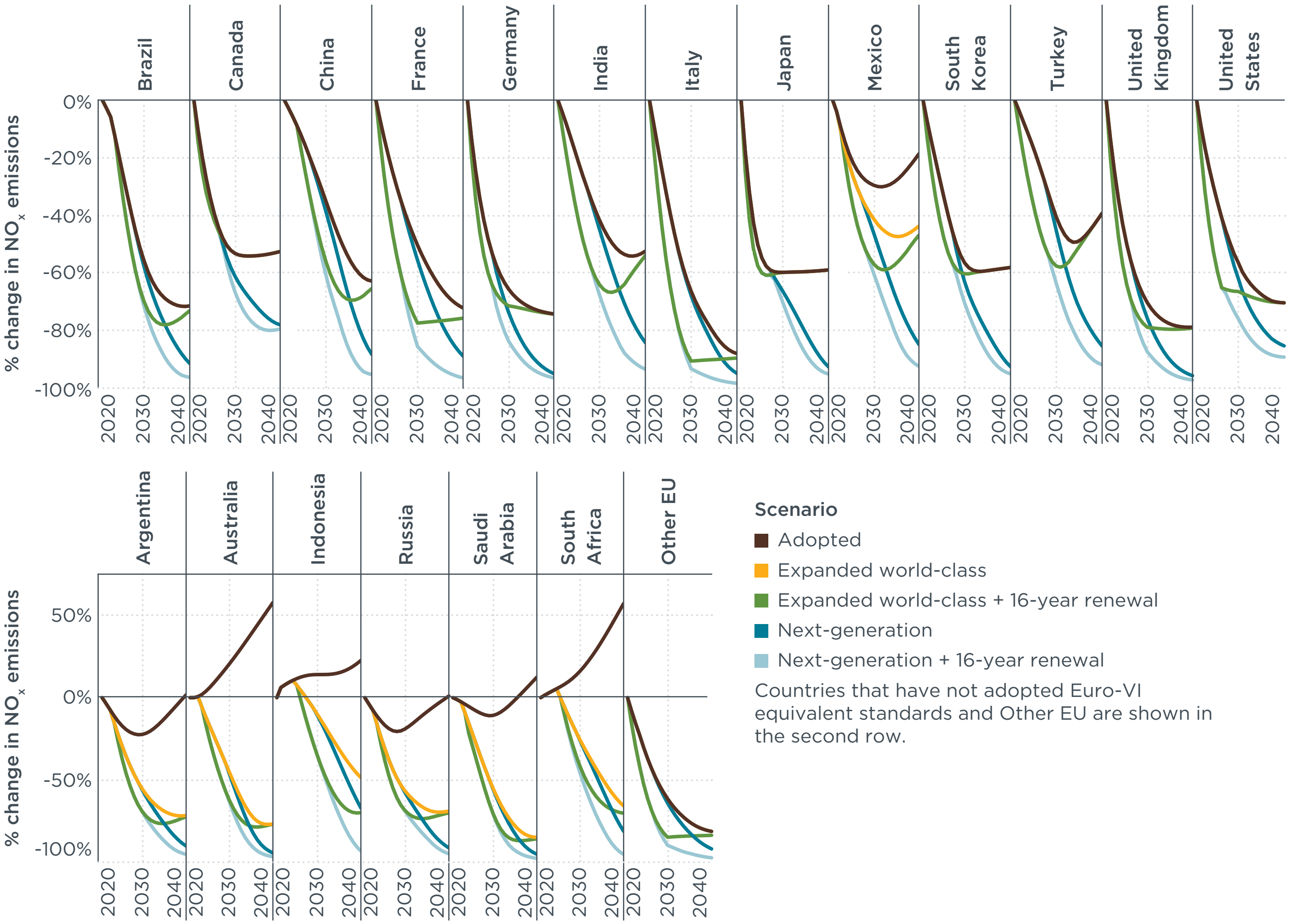

Figure 7. Normalized diesel HDV NO_x emissions from 2020 to 2040 by G20 economy. The y-axis shows the percent change in NO_x emissions from 2020.

Increases in NO_x are projected in countries that have not adopted Euro VI; in these countries, expanded world-class standards could reduce NO_x by 45% to 85% compared with increases of as much as 60%. Argentina and Russia are projected to have a small dip in emissions before 2028 as the remaining effect of their last implemented standards, but emissions are expected to increase after that without additional policies. On the other hand, countries that have adopted Euro VI-equivalent standards are expected to record a decrease in NO_x emissions in the next 20 years.

Next-generation standards are key to sustaining NO_x reductions for countries that have already implemented current world-class standards but also for countries that are planning to implement Euro VI-equivalent standards within the next several years. Next-generation standards could reduce NO_x levels by 60% to 95% below 2020 levels in 2040, compared with the 40% to 80% projected with Euro VI-equivalent standards. Coupling next-generation standards with fleet renewal policies could further reduce NO_x emissions.

Part of the trends in Mexico, Russia and Saudi Arabia are driven by used vehicle imports, which we assume on average have worse emissions than new vehicles. For example, in Mexico, NO_x emissions are estimated to fall by 23 percentage points in 2040 if used imports comply with Euro VI-equivalent standards starting in 2023, illustrated by the difference between the expanded world-class and adopted policies scenarios. Controlling emissions from imported used vehicles is important for realizing the potential air quality and health benefits brought by new emission standards.

Similar to the NO_x emissions trend, under adopted policies, countries that are expected to post an increase or rebound in BC emissions by 2040 are those that haven't adopted Euro VI-equivalent standards for new vehicles or vehicle imports, including Mexico and the first six countries on the second row (Figure 8). As in Figure 6, we did not include next-generation scenarios. For Mexico, the rebound is driven by used imports that are not required to meet Euro VI-equivalent standards in the adopted policies scenario. For Argentina, Australia, Indonesia, and Russia, although BC emissions are projected to decline initially as their latest emission standards replace the oldest HDVs, emissions are projected to increase after 2040 in the adopted policies scenario. Policies in the expanded world-class scenario are expected to reduce BC emissions by 85% in countries like Indonesia and South Africa to more than 95% in countries like Australia and Saudi Arabia in 2040 compared with the 2020 level. Reductions in Indonesia under the adopted policies scenario are contingent on its successful implementation of Euro IV-equivalent standards.

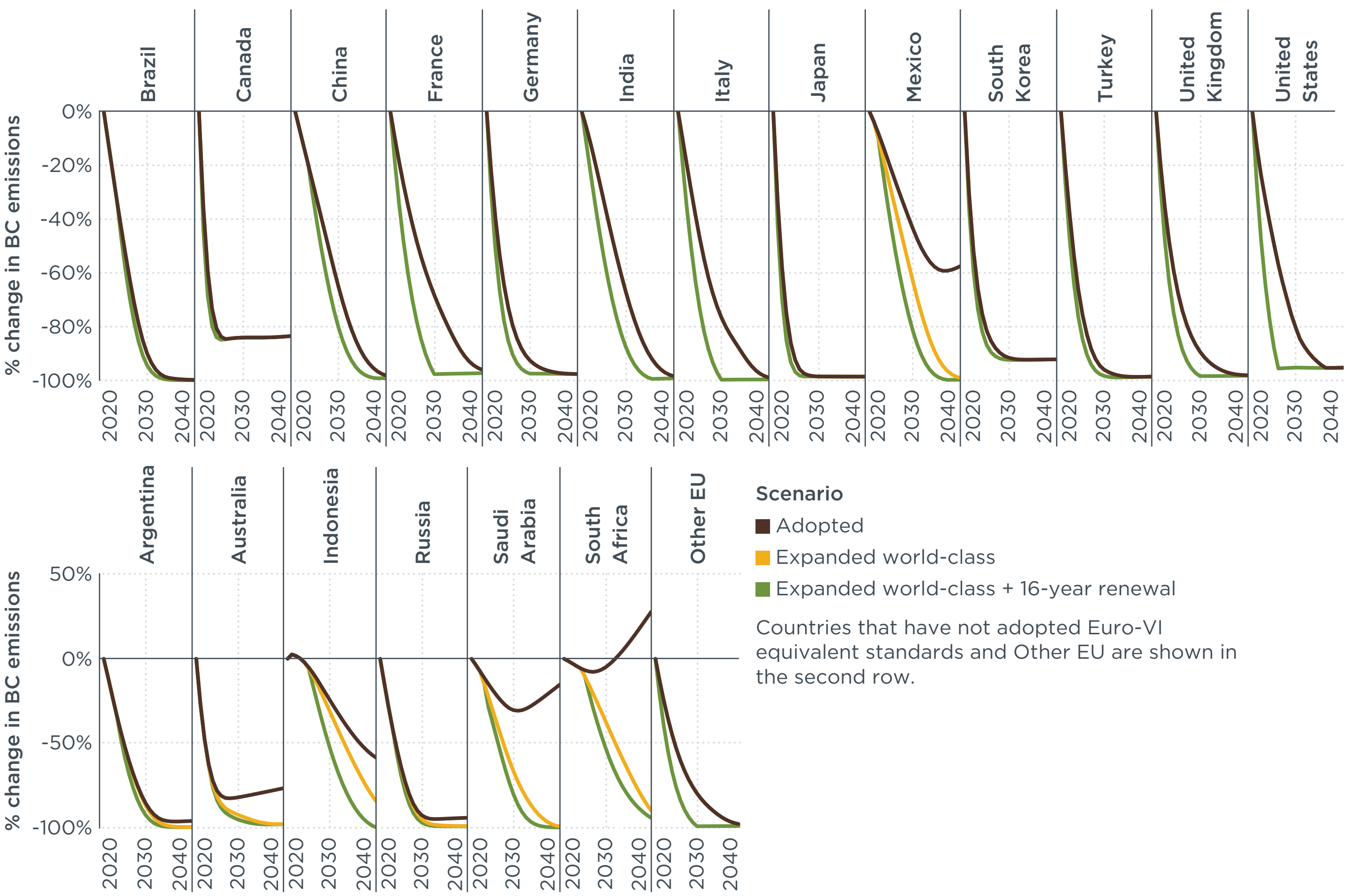

Figure 8. Normalized diesel HDV exhaust BC emissions from 2020 to 2040 by G20 economy. The y-axis shows the percent change in BC emissions from 2020.

Functional diesel particulate filters are very effective at reducing exhaust PM, and countries that have adopted Euro VI-equivalent standards, which require diesel particulate filters, are expected to record a substantial decrease in BC emissions in the next 20 years. Coupling world-class standards with fleet renewal policies could accelerate BC benefits by as much as a decade in countries like the United States, France, Italy, the United Kingdom, and elsewhere in the European Union, compared with adopted policies.

CONCENTRATIONS

Figure 9 shows the projected change in ambient $PM_{2.5}$ exposure attributable to HDV exhaust emissions in 2040 by policy scenario and G20 economy. This figure shows the effect of new policy scenarios on reducing $PM_{2.5}$ exposure from HDVs. For countries that have not yet adopted world-class emission standards, implementing such standards is expected to reduce $PM_{2.5}$ exposure by an average of 62% in 2040 compared with 2020 levels—ranging from 50% in Indonesia to 80% in Australia.

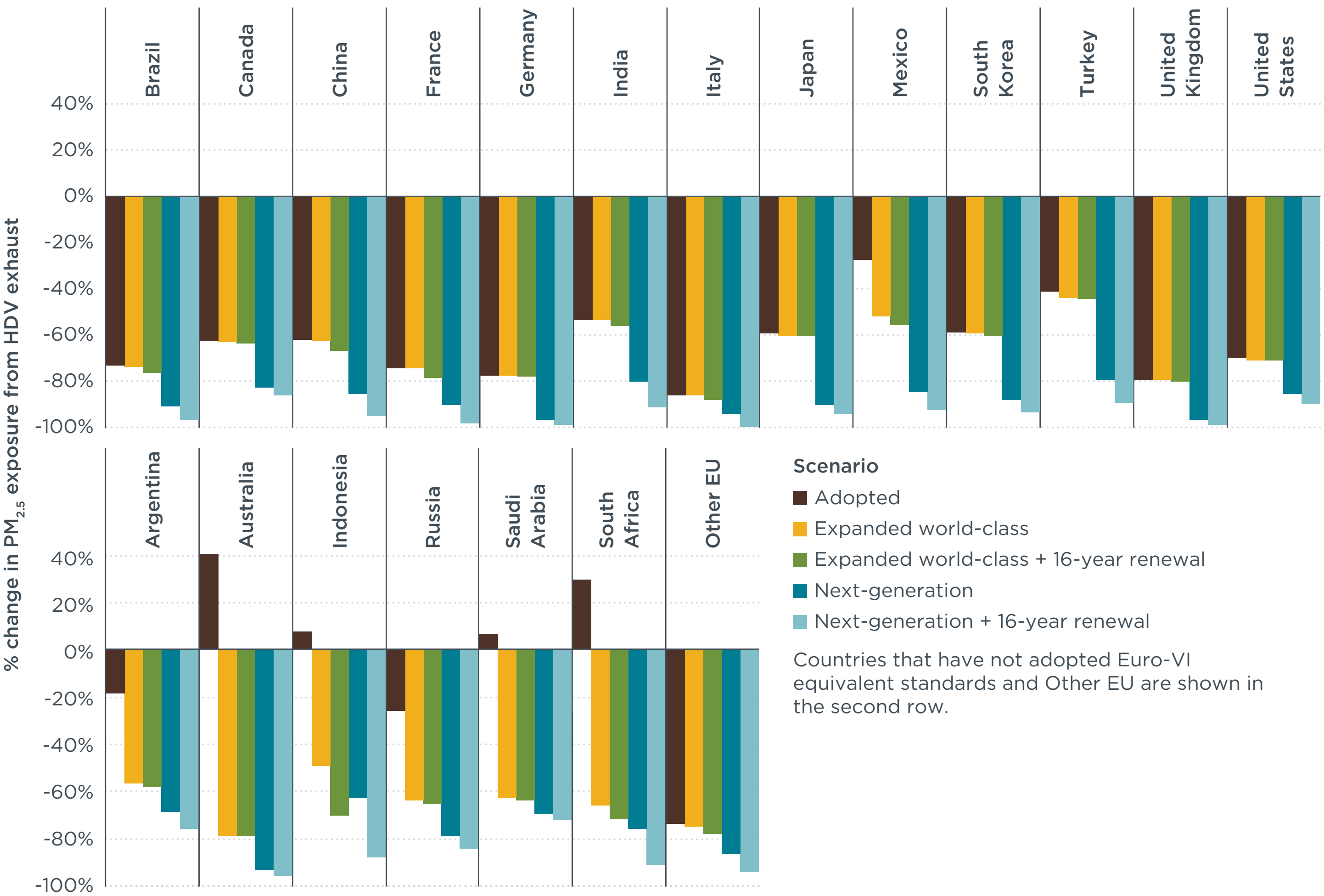

Figure 9. Change in ambient $PM_{2.5}$ exposure attributable to diesel HDV exhaust emissions by G20 economy in 2040. The y-axis shows the percent change in exposure from 2020.

For all G20 economies in 2040, next-generation policies are projected to reduce $PM_{2.5}$ exposure by 85% from 2020 levels, which is a further 15 percentage-point reduction compared with the expanded world-class scenario. Next-generation standards together with fleet renewal policies are projected to reduce $PM_{2.5}$ exposure by 93% from 2020 levels.

Similarly, for ozone exposure, implementing world-class standards in countries that have not yet adopted them is expected to reduce ozone exposure by 45% in Indonesia to 77% in Australia, compared with increases of as much as 50%.

For all G20 economies shown in Figure 10, next-generation policies in 2040 are projected to reduce ozone exposure by 83% compared with 2020 levels. When combined with fleet renewal policies, they are projected to reduce ozone exposure by 92% from 2020 levels.

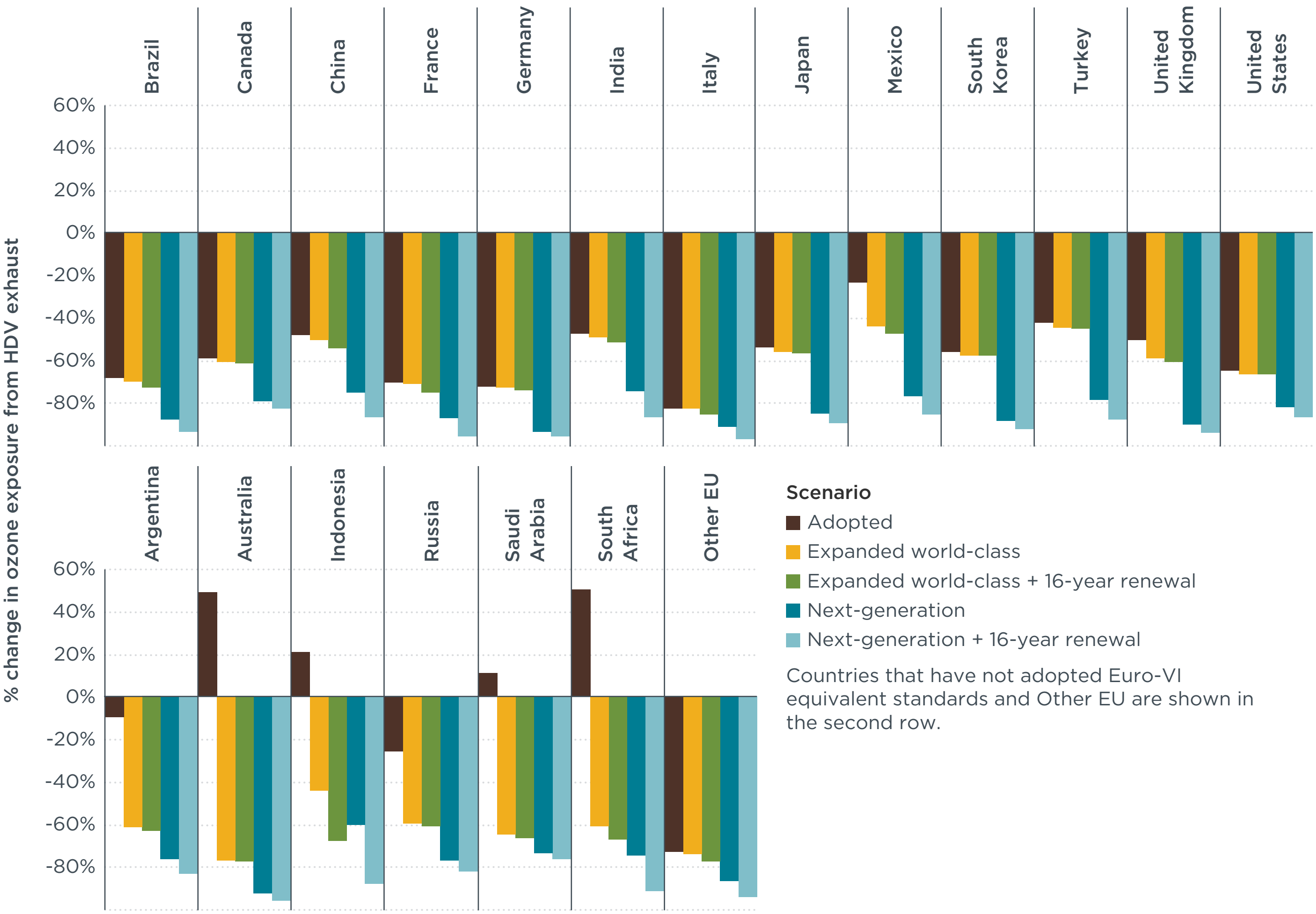

Figure 10. Change in ambient ozone exposure attributable to diesel HDV exhaust emissions by G20 economy in 2040. The y-axis shows the percent change in exposure from 2020.

HEALTH EFFECTS

Figure 11 shows avoided $PM_{2.5}$ and ozone deaths attributable to diesel HDV emissions for each new policy scenario in 2040 compared with adopted policies. Confidence intervals here represent uncertainly in the concentration-response function only. Due to the substantial differences in the magnitude of avoided deaths, results are shown on a different y-axis scale for the six countries with the most avoided deaths plus other EU (second row).

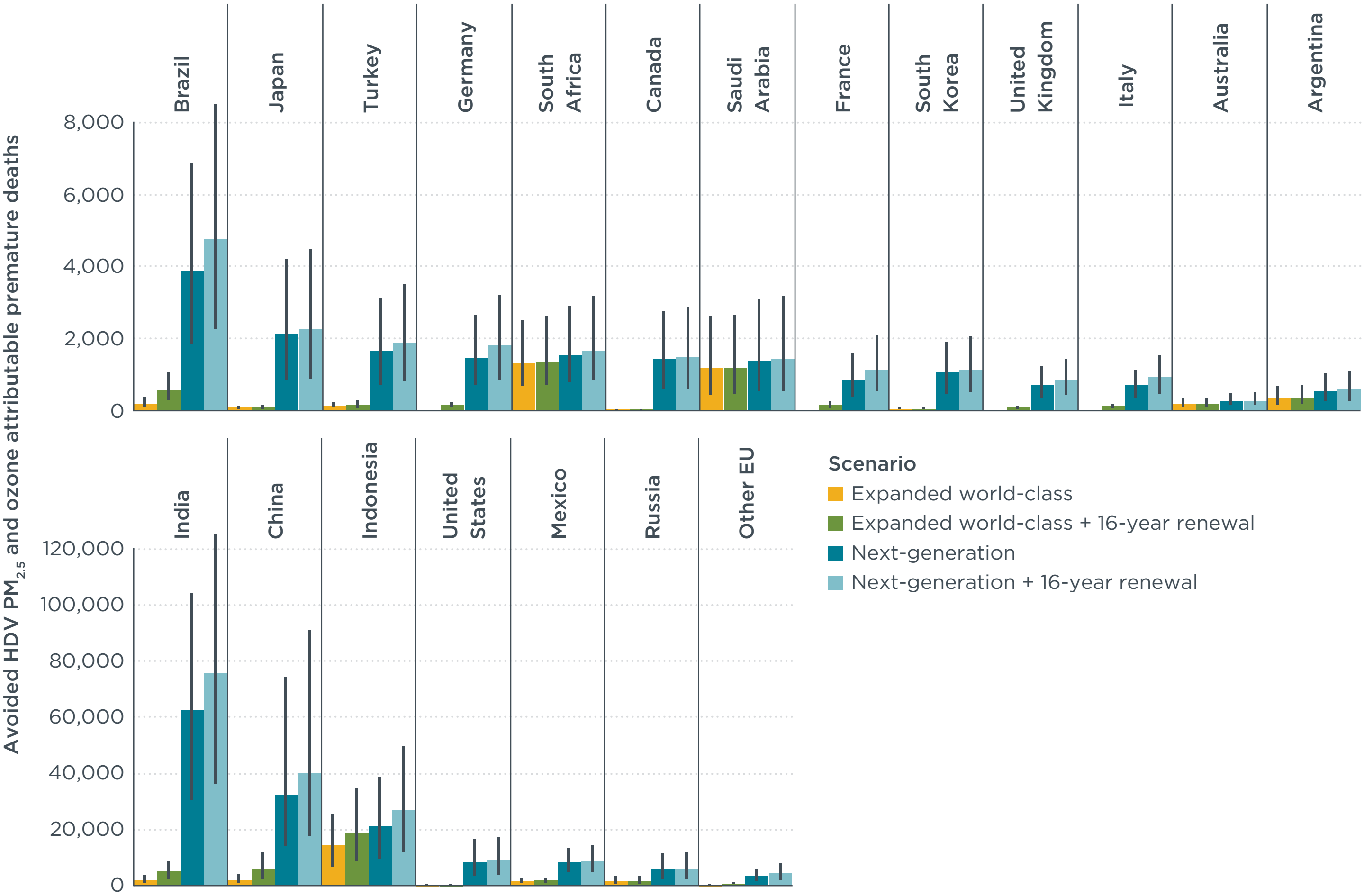

Figure 11. Avoided $PM_{2.5}$ and ozone deaths attributable to diesel HDV emissions in 2040 compared with adopted policies. Uncertainty bars reflect the 95% confidence interval in the relative risks only. Due to the substantial differences in avoided deaths, results are shown on a different y-axis scale for the six countries with the most avoided deaths plus other EU (second row). Economies are ordered by number of avoided premature deaths in the next-generation plus 16-year renewal scenario. The order and arrangement apply to all figures in the health impact and valuation sections for consistency.

In total, the expanded world-class scenario is projected to avoid 24,000 premature deaths in 2040; the expanded world-class plus 16-year fleet renewal scenario would avoid 37,000; the next-generation, 158,000; and the next-generation plus 16-year fleet renewal, 189,000. For context, these estimates of the number of premature deaths that can be avoided with specific policies are equivalent to 13%–104% of the 181,000 premature deaths globally from on-road diesel vehicle tailpipe emissions in 2015 (Anenberg, Miller, Henze, & Minjares, 2019).

The substantial differences among G20 economies are in part driven by population as well as how clean the current standard is. For example, countries with more population and lagging emission standards could avoid more premature deaths by adopting standards similar to countries with less population and cleaner emission standards. The six countries with the most avoided premature deaths (India, China, Indonesia, the United States, Mexico and Russia) account for about 79% of population in G20 economies and 87% of avoided deaths and associated disability-adjusted life years in the next-generation and accelerated renewal scenarios. The number of annual avoided premature deaths in other regions ranges from hundreds in countries like Argentina and Australia to thousands in economies like Brazil, Japan and Saudi Arabia under the next-generation and accelerated renewal scenarios. Indonesia would have the greatest health benefits from implementing Euro VI-equivalent standards in the expanded world-class scenario, avoiding more than 13,800 premature deaths and 257,000 associated DALYs. China, India, and Russia would follow.

Figure 12 shows the breakdown of annual avoided premature deaths attributable to ambient $PM_{2.5}$ and ozone exposure. The split between $PM_{2.5}$ and ozone related health benefits varies considerably from country to country. Many factors contribute to this variation, including natural levels of each pollutant and the nonlinearity of the response of ozone formation to NO_x reductions. On average across G20 countries, 55% of total avoided premature deaths are attributed to ozone reductions and 45% are attributed to $PM_{2.5}$ reductions. The relatively equal weight of these impacts underscores the importance of considering both when evaluating the benefits of vehicle emission control programs.

Figure 12. Avoided $PM_{2.5}$ and ozone deaths attributable to diesel HDV emissions in 2040 compared with adopted policies. Due to the substantial differences in avoided deaths, results are shown on a different y-axis scale for the six countries with the most avoided deaths plus other EU (second row). Changes in $PM_{2.5}$ exposure consider changes in BC, OC, NO_x, SO_2, and NH_3 emissions. Changes in ozone exposure consider changes in NO_x, CO, and nonmethane volatile organic compound emissions.

Figure 13 and Figure 14 show cumulative avoided $PM_{2.5}$ and ozone premature deaths and DALYs attributable to diesel HDV emissions from 2020 to 2050 under each new policy scenario compared with adopted policies using central relative risk estimates.

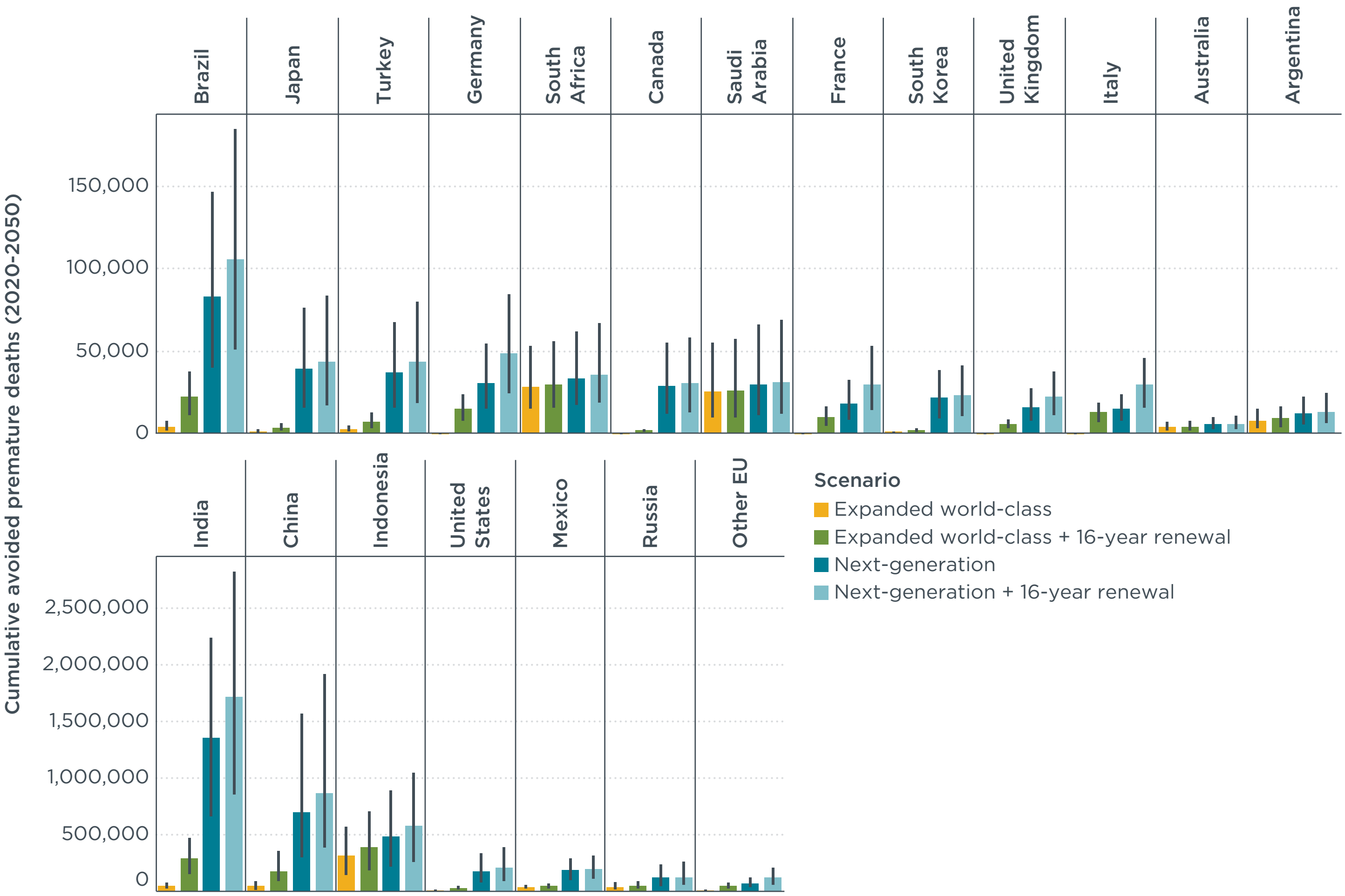

Figure 13. Cumulative avoided $PM_{2.5}$ and ozone premature deaths attributable to diesel HDV emissions 2020–2050 compared with adopted policies. Uncertainty bars reflect the 95% confidence interval in the relative risks only.

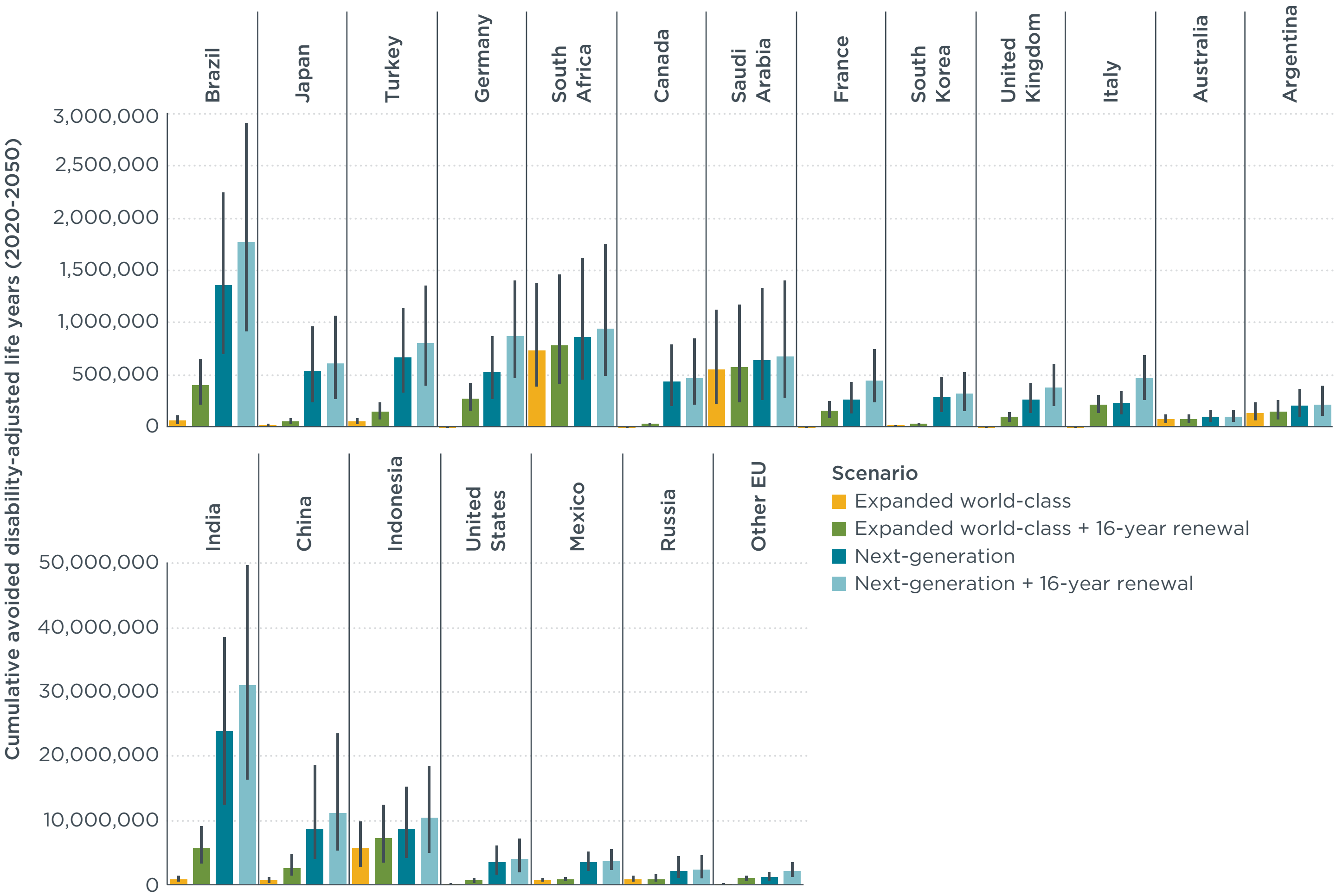

Figure 14. Cumulative avoided $PM_{2.5}$ and ozone DALYs attributable to diesel HDV emissions 2020–2050 compared with adopted policies. Uncertainty bars reflect the 95% confidence interval in the relative risks only.

Cumulative avoided premature deaths attributable to diesel HDV emissions in G20 economies from 2020 to 2050 would total more than 1 million under the expanded world-class plus 16-year renewal scenario and 4 million under the next-generation plus 16-year renewal scenario.

These cumulative avoided premature deaths are associated with an estimated 10 million avoided DALYs under the expanded world-class scenario, 20 million under the expanded world-class plus 16-year renewal scenario, 57 million with next-generation standards, and 72 million when next-generation standards are coupled with fleet renewal policies.

VALUATION OF HEALTH EFFECTS

Figure 15 shows valuation of cumulative avoided health damages (in 2020 U.S. dollars) from $PM_{2.5}$ and ozone mortality attributable to diesel HDV emissions from 2020 to 2050, using a 3% social discount rate. The values are shown under each new policy scenario compared with adopted policies. Since per capita income is a major factor in determining country-specific VSL estimate, certain economies such as the United States and Germany show higher monetary health benefits compared with their share of avoided premature deaths from diesel HDV tailpipe emissions.

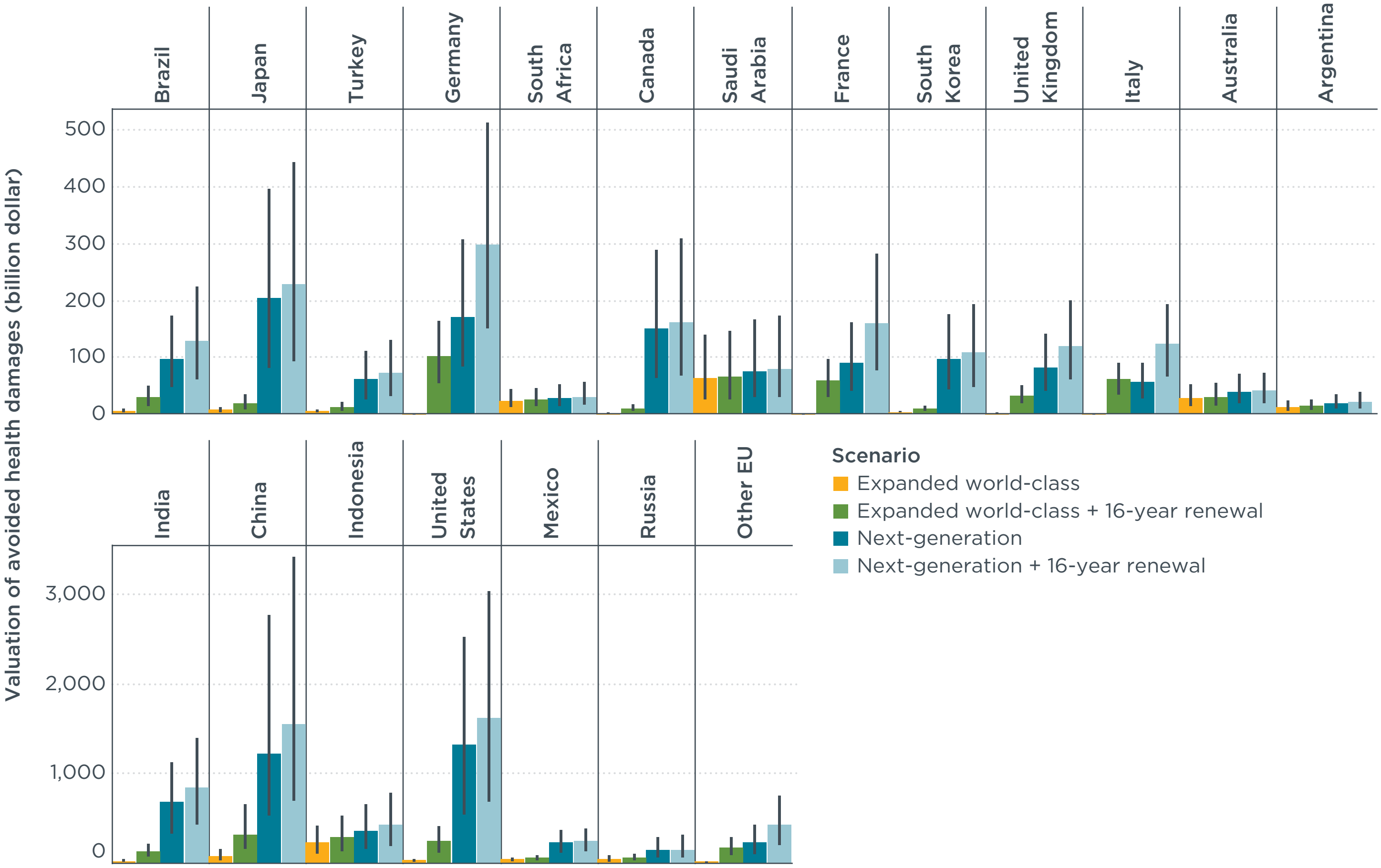

Figure 15. Valuation of cumulative avoided health damages (billions of dollars) from $PM_{2.5}$ and ozone mortality attributable to diesel HDV emissions compared with adopted policies, 2020–2050. A 3% social discount rate is applied to future years. Uncertainty bars reflect the 95% confidence interval in the relative risks only.

In EU member countries like Germany, France, and Italy, accelerated fleet renewal policies together with next-generation standards are expected to achieve at least twice the health benefits of either world-class with fleet renewal or next-generation standards alone. The total avoided health damages from 2020 to 2050 from diesel HDV tailpipe emissions are approximately $580 billion under the expanded world-class scenario, $1.7 trillion with additional fleet renewal policies, $5.3 trillion under the next-generation standards scenario, and $6.8 trillion when next-generation standards are linked with fleet renewal policies. For context, the global welfare loss associated with transportation-attributable $PM_{2.5}$ and ozone deaths in 2015 was $1.1 trillion (Anenberg, Miller, Henze, & Minjares, 2019).

CLIMATE EFFECTS

Figure 16 shows non-CO_2 climate pollutant emissions (GWP20) from diesel heavy-duty vehicles under adopted policies and the mitigation potential of new policy scenarios from 2020 to 2040. The solid lines indicate emissions trajectory in each scenario, and the wedge between them shows the mitigation potential with each new scenario. Climate pollutants considered are BC, CH_4, and N_2O. Among them, BC is the largest contributor to non-CO_2 climate pollutant emissions from diesel HDVs. As we did not evaluate the potential changes in BC, CH_4, and N_2O emission limits in next-generation standards, we did not include them in this section. To show the short-term and long-term warming potential, we show CO_2e in GWP20 to capture impacts from short-lived climate pollutants and CO_2e in GWP100 in parentheses in the figure.

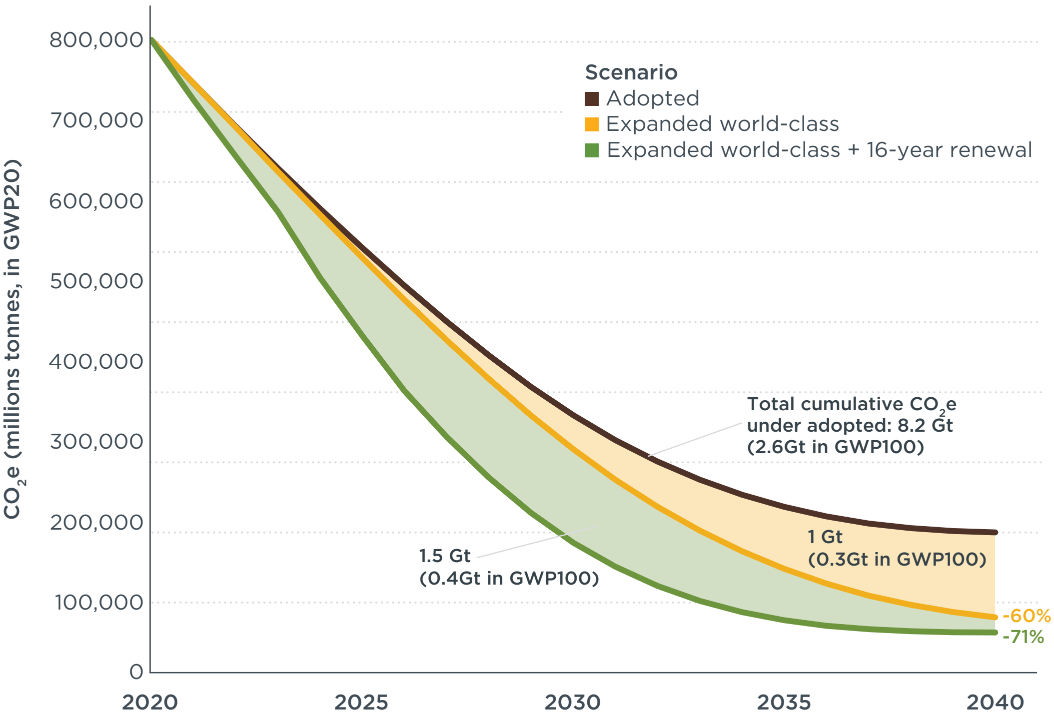

Figure 16. Non-CO_2 climate pollutant emissions (GWP20) from diesel heavy-duty vehicles under adopted policies and mitigation potential of new policy scenarios, 2020–2040. Colored data labels show the percentage change in emissions under corresponding scenarios compared with adopted policies in 2040. Data labels associated with the wedge show mitigation potential of each new policy scenario compared with the previous one as shown in the legend. Data labels in parentheses show mitigation potential and cumulative emissions in GWP100.

Compared with the adopted scenario, the expanded world-class scenario is projected to reduce non-CO_2 climate pollutant emissions by 60% in 2040, and coupled with fleet renewal scenarios, the reduction would be 71% in 2040. As shown, cumulative mitigation potential from 2020 to 2040 is 1 Gt CO_2e under the expanded world-class scenario compared with the adopted scenario, and an additional 1.5 Gt CO_2e with accelerated fleet renewal policies. In other words, expanded world-class policies plus accelerated fleet renewal (16 years) is projected to reduce 2.5 Gt, or 30% of the total of 8.2 Gt of cumulative emissions from 2020 to 2040. For comparison, achieving internal combustion engine technology potential for HDVs in 2030 and 100% zero emission HDV sales by 2040 in the European Union could avoid an estimated 1.7 Gt of CO_2 from 2021 to 2050 (Buysse et al., 2021).

Breaking down the overall trend to contributions from G20 economies, Figure 17 shows the cumulative climate benefits (GWP20) of the new policy scenarios compared with adopted policies. Saudi Arabia, Mexico, South Africa, and Indonesia show the greatest mitigation potential in the expanded world-class scenario due to the emission reduction of adopting Euro VI-equivalent standards for new fleets and imported vehicles. With accelerated fleet renewal, more countries show considerable mitigation potential as they retire older fleets. Saudi Arabia is projected to have the greatest mitigation potential from 2020 to 2040, accounting for 24% of the total, followed by

China, 17%; India, 12%; Mexico, 11%; Indonesia, 11%; South Africa, 9%; and the United States, 3%.

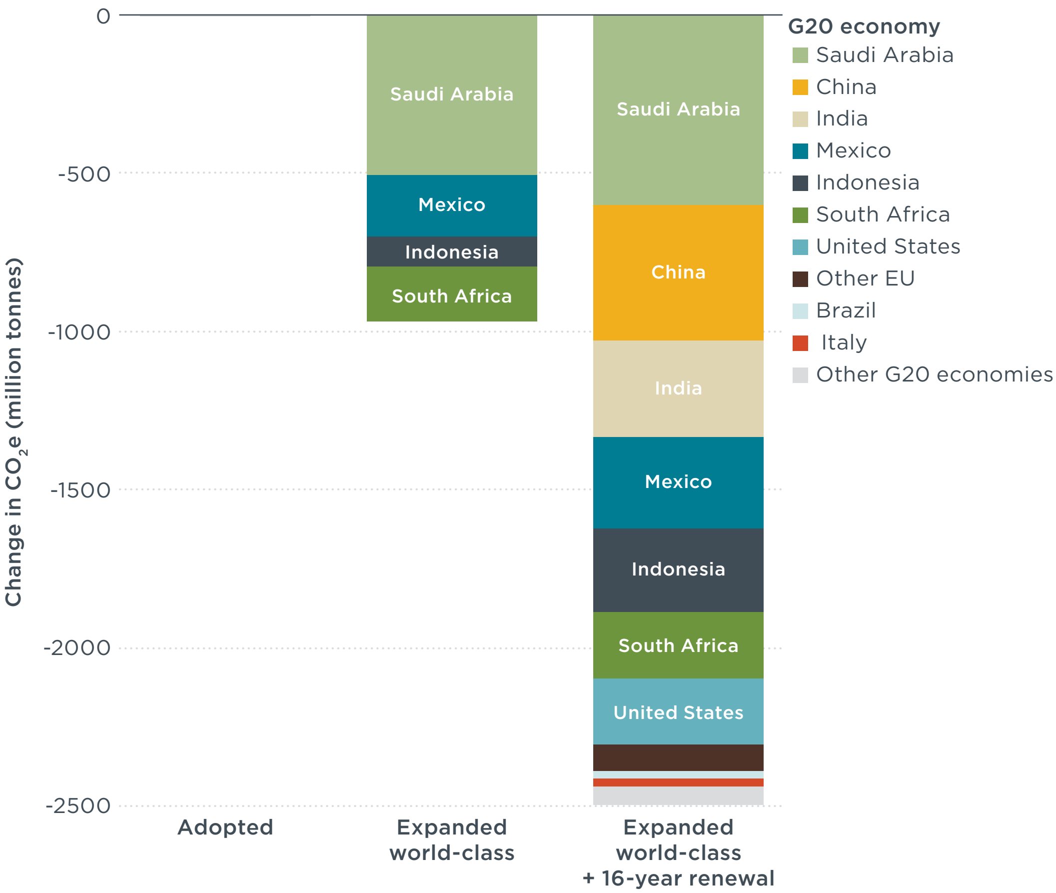

Figure 17. Cumulative mitigation potential (GWP20) for diesel HDVs under new policy scenarios compared with adopted policies, 2020–2040, ordered by mitigation potential in the next-generation plus 16-year renewal scenario.

CONCLUSIONS

In this paper, we developed multiple potential policy scenarios for the implementation of current world-class Euro VI-equivalent emission standards, next-generation standards, and accelerated fleet renewal programs for HDVs in G20 economies. We evaluated the potential of these scenarios to reduce HDV exhaust emissions, benefit air quality and health, and mitigate non-CO_2 climate impacts. We find that:

Expanded implementation of world-class standards in G20 countries in the 2023–2025 timeframe would substantially reduce HDV exhaust emissions and associated health impacts. Whereas NO_x emissions are projected to increase by as much as 60% in countries that have yet to adopt such standards, expanded world-class standards could instead reduce NO_x by 45% to 85% over the next two decades. Likewise, the requirement of diesel particulate filters associated with these standards is expected to drive large decreases in BC emissions from HDVs. In G20 countries that have adopted these standards, BC emissions are projected to fall by 85% to 99% over the next two decades compared with 2020 levels. The near-term climate benefits of these BC reductions are significant on a global scale—equivalent to reducing billions of tonnes of CO_2. For countries that normally import used vehicles, regulating new sales will not be sufficient to curb emissions. Restricting emissions from imported used vehicles will be important to realize the full benefits of new-vehicle standards in protecting public health and mitigating climate change.

Next-generation standards are key to sustaining NO_x emission reductions from HDVs. Next-generation standards could bring NO_x levels as much as 60% to 95% below 2020 levels in 2040, compared with the 40% to 80% projected with Euro VI-equivalent standards alone. Implementation of next-generation standards in G20 countries could avoid more than $5 trillion in health damages over the next three decades. These potential benefits are significant not only for countries that have already implemented current world-class standards but also for countries that are planning to implement Euro VI-equivalent standards within the next several years.

Next-generation standards coupled with accelerated fleet renewal policies would achieve the greatest benefits by a wide margin. Cumulative avoided premature deaths attributable to diesel HDV emissions in G20 economies from 2020 to 2050 would total 4 million under the next-generation plus 16-year renewal scenario. This is four times as many as under the expanded world-class plus 16-year renewal scenario. In EU member countries like Germany, France, and Italy, accelerated fleet renewal policies together with next-generation standards are expected to achieve at least twice the monetary health benefits as either world-class Euro VI-equivalent with fleet renewal or next-generation alone. Next-generation policies combined with accelerated fleet renewal policies are expected to yield $6.8 trillion in cumulative health benefits from 2020 to 2050.

The dominant contribution of diesel vehicles and engines to global transportation-attributable health impacts and the significant share of this burden experienced in G20 economies underscores the importance of collaboration among G20 countries to reduce these impacts. The findings of this study highlight the scale of the opportunity at hand to expand adoption of filter-forcing standards, develop cleaner next-generation emission standards, and couple these standards with accelerated fleet renewal programs to remove vehicles with older technology. For countries that have not yet adopted Euro VI-equivalent standards, doing so by 2023 or at the latest by

2025 is important both to protect public health and secure near-term climate benefits of BC mitigation.

Next-generation emission standards are key to sustaining and augmenting the air quality improvements associated with current world-class standards. Over the next two decades, this effect will be most prominent for countries that have been early adopters of world-class standards. In the United States, the California Air Resources Board has broken ground with its HDV low-NO_x regulation, which will tighten NO_x limits by 75% below current standards in 2024 and 90% in 2027. Other examples of the next generation of emission standards—Euro VII standards in the European Union and the equivalent in the United States from the EPA's Cleaner Trucks Initiative—are under development. Realizing the air quality and health benefits identified in the next-generation scenario of this analysis would require finalizing and expanding the adoption of such policies in other G20 countries.

Yet a strategy focused on new-vehicle standards alone would take decades to realize the full benefits for the in-use vehicle fleet due to the long lifetimes of vehicles and equipment. We find that complementary accelerated fleet renewal programs along with the next-generation standards could markedly speed this progress. Examples of such programs include policies that accelerate the scrappage, retrofit, or replacement of older vehicles and engines or restrict the operation of older vehicles and engines, such as urban low-emission zones.

Our analysis is subject to several uncertainties. Some of these include the emissions performance of used imported vehicles in countries that allow them; distribution of vehicle activity by age or technology; transferability of vehicle emission factors and real-world emissions data to similar vehicle technologies in other jurisdictions; incidence of high-emitting vehicles; spatial distribution of transportation emissions; emissions inventories used for air quality analysis; baseline disease rates; and concentration-response functions.

Opportunities for further research include expanding the scope to cover zero-emission HDVs and policies, covering more countries, assessing the potential impacts on particulate emissions of next-generation standards, and evaluating the impacts of policies targeting specific fleets or implemented in subnational jurisdictions.

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APPENDIX

The tables below show mean estimates of annual avoided NOx and BC emissions in 2040, cumulative avoided premature deaths and disability-adjusted life years, and cumulative valuation of health benefits 2020-2050 of new policy scenarios compared with adopted policies.

Table A1. Annual avoided diesel HDV NO_x emissions (thousand tonnes) compared with adopted policies, 2040.

	Expanded world-class	Expanded world-class + 16-year renewal	Next-generation	Next-generation + 16-year renewal
Argentina	100	100	120	130
Australia	160	160	180	180
Brazil	0	20	160	210
Canada	0	0	20	30
China	0	110	630	880
France	0	10	20	30
Germany	0	0	20	30
India	0	40	420	570
Indonesia	500	680	620	840
Italy	0	0	10	20
Japan	0	0	50	50
Mexico	70	80	180	200
Russia	220	230	290	300
Saudi Arabia	510	520	560	580
South Africa	240	260	270	310
South Korea	0	0	50	50
Turkey	0	0	70	80
United Kingdom	0	0	20	20
United States	0	0	200	260
Other EU	0	30	90	140
Total	**1,800**	**2,230**	**3,970**	**4,900**

Table A2. Annual avoided diesel HDV BC emissions (thousand tonnes) compared with adopted policies, 2040.

	Expanded world-class	Expanded world-class + 16-year renewal
Argentina	0.1	0.1
Australia	0.1	0.1
Brazil	0.0	0.0
Canada	0.0	0.0
China	0.0	1.4
France	0.0	0.0
Germany	0.0	0.0
India	0.0	0.5
Indonesia	4.3	7.4
Italy	0.0	0.0
Japan	0.0	0.0
Mexico	5.9	6.1
Russia	0.3	0.3
Saudi Arabia	16.6	16.8
South Africa	7.1	7.5
South Korea	0.0	0.0
Turkey	0.0	0.0
United Kingdom	0.0	0.0
United States	0.0	0.0
Other EU	0.0	0.1
Total	**34.4**	**40.5**

Table A3. Cumulative avoided $PM_{2.5}$ and ozone premature deaths attributable to diesel HDV emissions compared with adopted policies, 2020–2050.

	Expanded world-class	Expanded world-class + 16-year renewal	Next-generation	Next-generation + 16-year renewal
Argentina	7,600	8,500	11,700	12,800
Australia	3,800	4,000	5,300	5,500
Brazil		21,700	82,500	105,000
Canada		1,300	28,400	30,200
China		170,700	688,700	864,200
France		9,500	17,400	29,400
Germany		14,400	30,000	48,500
India		285,700	1,351,500	1,712,000
Indonesia	310,800	386,800	480,200	570,300
Italy		12,600	14,600	29,300
Japan		3,000	38,900	43,100
Mexico		40,600	179,300	191,300
Russia	34,500	41,600	113,400	121,700
Saudi Arabia	24,800	25,800	29,500	30,800
South Africa	27,900	29,500	32,700	35,400
South Korea		1,700	21,000	22,900
Turkey		6,900	36,400	43,000
United Kingdom		5,000	15,800	22,000
United States		25,300	173,700	206,000
Other EU		47,100	64,100	117,400
Total	**409,500**	**1,141,700**	**3,415,200**	**4,240,800**

Table A4. Cumulative avoided $PM_{2.5}$ and ozone disability-adjusted life years attributable to diesel HDV emissions compared with adopted policies, 2020–2050.

	Expanded world-class	Expanded world-class + 16-year renewal	Next-generation	Next-generation + 16-year renewal
Argentina	128,000	143,000	195,000	215,000
Australia	66,000	69,000	91,000	95,000
Brazil		399,000	1,348,000	1,767,000
Canada		22,000	431,000	462,000
China		2,466,000	8,575,000	11,136,000
France		156,000	251,000	445,000
Germany		272,000	516,000	862,000
India		5,707,000	23,871,000	30,954,000
Indonesia	5,627,000	7,123,000	8,628,000	10,373,000
Italy		210,000	217,000	461,000
Japan		45,000	535,000	596,000
Mexico		790,000	3,338,000	3,589,000
Russia	666,000	811,000	2,157,000	2,325,000
Saudi Arabia	538,000	566,000	638,000	670,000
South Africa	733,000	777,000	857,000	932,000
South Korea		26,000	280,000	309,000
Turkey		139,000	656,000	792,000
United Kingdom		91,000	255,000	369,000
United States		534,000	3,285,000	3,957,000
Other EU		881,000	1,059,000	2,054,000
Total	**7,758,000**	**21,227,000**	**57,182,000**	**72,364,000**

Table A5. Valuation of cumulative avoided health damages (billions of dollars) from $PM_{2.5}$ and ozone mortality attributable to diesel HDV emissions compared with adopted policies, 2020-2050. A 3% social discount rate is applied to future years.

	Expanded world-class	Expanded world-class + 16-year renewal	Next-generation	Next-generation + 16-year renewal
Argentina	10	10	20	20
Australia	30	30	40	40
Brazil	0	30	100	130
Canada	0	10	150	160
China	70	320	1,220	1,540
France	0	60	90	160
Germany	0	100	170	300
India	20	130	670	840
Indonesia	230	290	360	420
Italy	0	60	50	120
Japan	10	20	200	230
Mexico	40	50	220	240
Russia	40	50	140	150
Saudi Arabia	60	70	70	80
South Africa	20	20	30	30
South Korea	0	10	100	110
Turkey	0	10	60	70
United Kingdom	0	30	80	120
United States	20	240	1,320	1,620
Other EU	10	170	230	420
Total	**580**	**1,710**	**5,310**	**6,800**

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