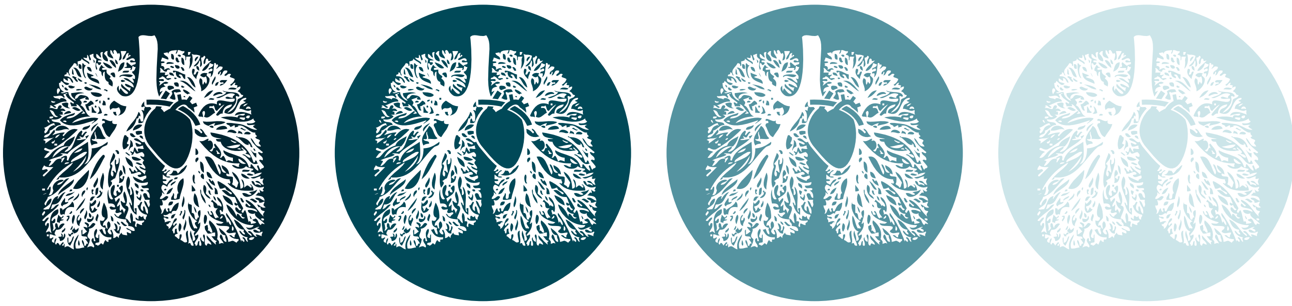
THE IMPACT OF STRINGENT FUEL AND VEHICLE STANDARDS ON PREMATURE MORTALITY AND EMISSIONS

ICCT'S GLOBAL TRANSPORTATION HEALTH AND CLIMATE ROADMAP SERIES

AUTHORS: **Sarah Chambliss, Josh Miller, Cristiano Façanha, Ray Minjares, Kate Blumberg**



THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

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MAIN AUTHORS
Sarah Chambliss, Josh Miller, Cristiano Façanha, Ray Minjares, and Kate Blumberg

Many ICCT staff contributed to this report, including Anup Bandivadekar, Vance Wagner, Francisco Posada, John German, Nic Lutsey, Alan Lloyd, Drew Kodjak, Fanta Kamakaté, Dan Rutherford, Elaine Olivares, Joe Schultz, Rachel Muncrief, and Zhenying Shao.

International Council on Clean Transportation
1225 I Street NW Suite 900
Washington DC 20005
+1 202 534 1600

communications@theicct.org
www.theicct.org

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SUMMARY FOR POLICYMAKERS

Without new actions to limit vehicle emissions, the health impacts from road transportation will increase significantly from present-day levels in many countries around the world. However, stringent limits on vehicle emissions can force the introduction of technologies that will cut emissions of local air pollutants by more than 99 percent over uncontrolled vehicles. This temporarily[1] decouples conventional pollutant emissions from growing vehicle activity and dramatically reduces emissions that contribute to serious health problems. This report provides an ambitious but pragmatic policy roadmap for tightening standards for trucks and buses, passenger vehicles, and fuels, enabling regions without a clear timeline for advanced standards to replicate the success of early policy adopters in improving air quality and public health. The tools and analyses used in this study provide an integrated framework for rapid policy assessment that can be especially useful in developing regions where technical capacity and data are limited and where action is most urgently needed.

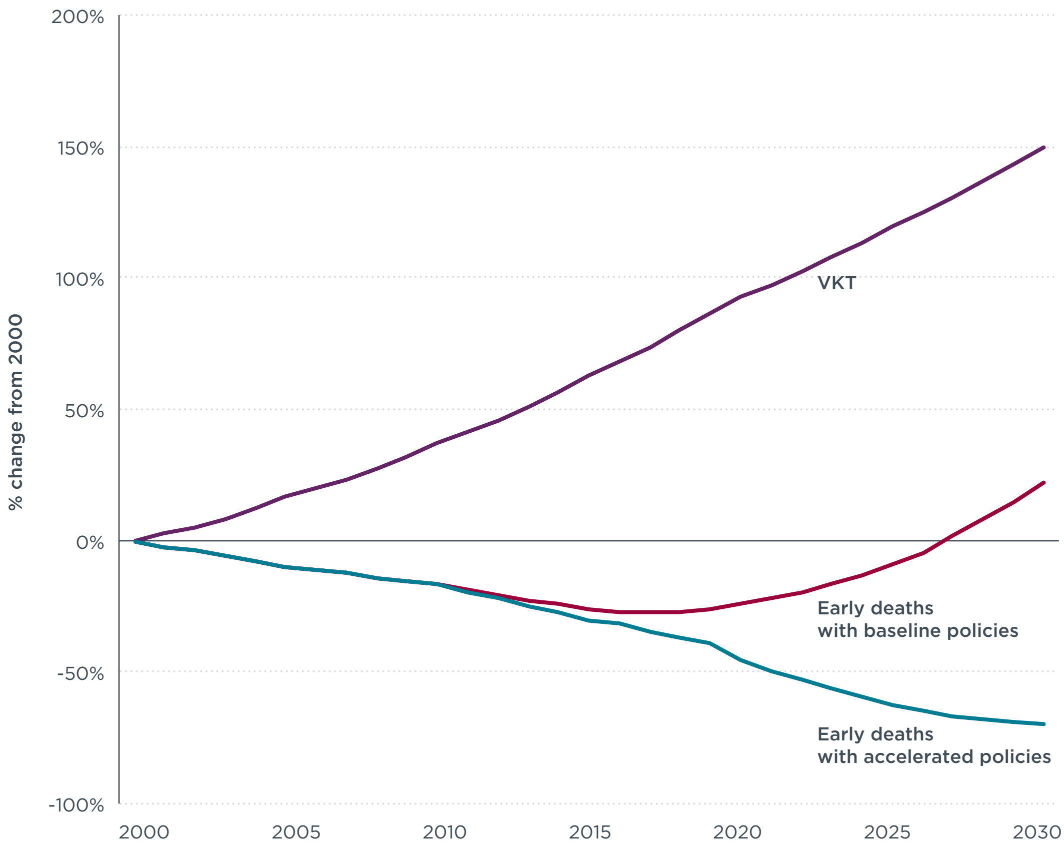

Figure S-1: Global trends in vehicle-kilometers traveled (VKT) and early deaths from vehicle-related fine particle exposure (2000–2030)

The first series shows projected changes in global VKT relative to 2000. The red and blue series show the changes in early deaths from road vehicle particulates under baseline and accelerated policies relative to 2000.

Early deaths from vehicle-related fine particle exposure in urban areas will increase by 50 percent worldwide by 2030 from 2013 levels in the absence of new policies. Much lower limits on vehicle emissions would reduce premature deaths by more than 200,000 in 2030 (equivalent to a 75 percent reduction) and would save a cumulative 25 million years of life by 2030. As this analysis does not capture rural impacts or secondary pollutant formation

1 Until sustained growth in vehicle activity drives up emissions again.

in the atmosphere, these impacts should be considered a lower bound estimate. In addition to health benefits, stringent vehicle standards would reduce emissions of short-lived climate pollutants that cause near-term warming effects. After carbon dioxide, black carbon is the most important anthropogenic emission in terms of its climate forcing—the shift in the Earth's energy balance that causes global temperature change. New policies would reduce black carbon emissions by 90 percent, yielding net climate benefits of 200 million metric tons of carbon dioxide equivalent ($MtCO_2e$) in the year 2030, assuming control of co-pollutants and a policy goal that aims to reduce peak temperature change. Benefits would be 3.5 times greater if the policy goal were to reduce near-term climate impacts.

This report comes at a critical time for policymakers. Exposure to outdoor air pollution is a leading cause of premature mortality, associated with 3.2 million early deaths globally in 2010 (Lim et al. 2012). Vehicles are a major contributor to outdoor air pollution, especially in urban areas where the world's population is projected to grow most rapidly. While this analysis is not intended to capture the full burden of the health impacts from the transportation sector, it does demonstrate the incredible potential to reduce these burdens in every region of the world. Figure S-2 shows that in countries that have introduced much cleaner vehicles (panel 1), premature deaths from vehicle particulate emissions continue to decline, while countries lacking the most stringent controls face increasing health problems (panels 2 through 4). Proactive policies will make the difference between worsening (Baseline scenario) or improving (Accelerated scenario) trends in public health. Timely action is especially important in developing countries where fleets are growing most rapidly. If all regions accelerated their progress toward best practice policies, global emissions of health-related pollutants and short-lived climate pollutants could be cut by three-quarters below 2000 levels even with a 150 percent increase in vehicle activity.

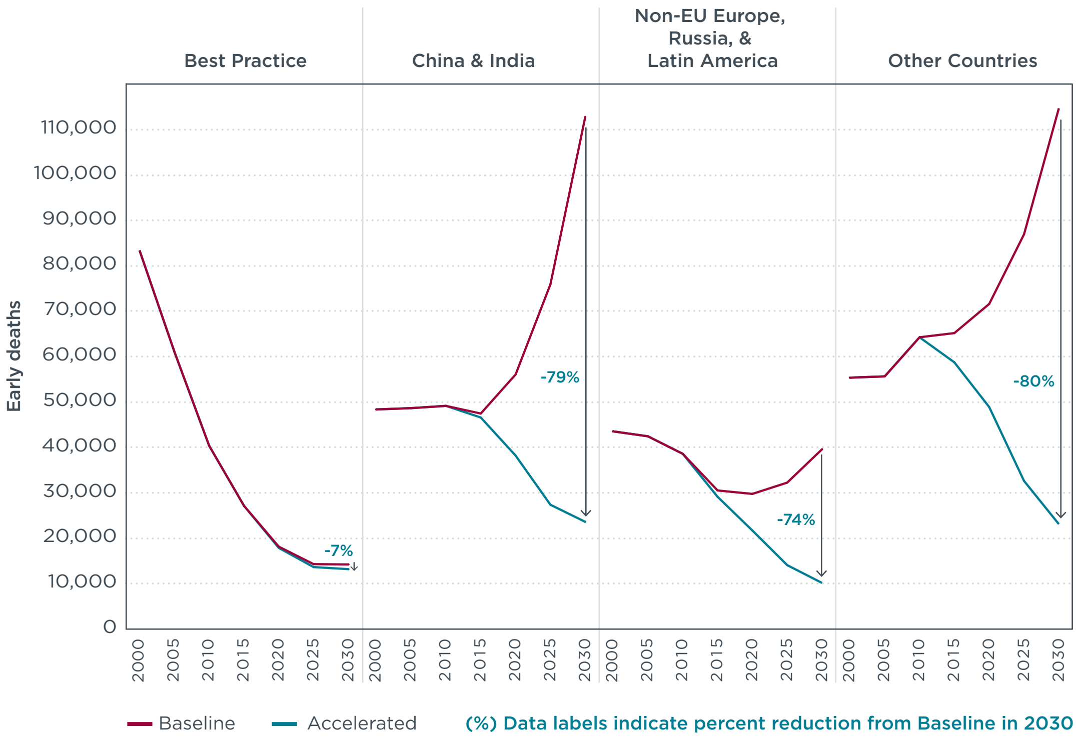

Figure S-2: Annual early deaths by region under baseline and accelerated policies (2000–2030)

Health trends in this figure are driven by total vehicle activity, vehicle emission controls, and increases in total urban population. In regions without best practice policies, the growth in VKT overcomes the benefits of current policies by 2020, and premature mortalities quickly rise. The "Best Practice" group houses the EU-28, the United States, Canada, Japan, Australia, and South Korea. The Other Countries group contains all countries in the Asia-Pacific region (with the exception of China, India, Japan, Australia, and South Korea) as well as Africa and the Middle East.

As vehicles in countries with advanced vehicle emission standards have become much cleaner, the share of global adverse health consequences from road vehicles is shifting from the United States and Europe to other regions with higher vehicle fleet growth and more-polluting vehicles. China and India will bear the two largest single-country health risks, accounting for 65 percent of the global increase in early deaths by 2030 without further policy action. In contrast, the accelerated policy timelines assessed in this report could prevent 90,000 premature deaths in these two countries in 2030 alone (Figure S-2). Other vehicle markets in Asia, the Middle East, and Africa accounted for roughly 30 percent of global premature deaths from exposure to urban on-road primary particulates in 2010, despite being responsible for just 15 percent of vehicle activity. In some of these regions, vehicles added to the fleet are imported with after-treatment control technologies that are not compatible with locally available fuel, causing damage to the vehicle. In these regions, low-sulfur fuel is necessary to comply with existing vehicle emission controls and to allow the implementation of advanced emissions after-treatment.

Diesel vehicles, primarily heavy-duty trucks and buses, are prime targets for emission reduction. Heavy-duty diesels accounted for more than 80 percent of fine particulate ($PM_{2.5}$) and nitrogen oxide (NO_X) emissions from on-road vehicles in 2010. Fortunately, there are readily available technologies to reduce these emissions. Selective catalytic reduction (SCR) and diesel particulate filters (DPFs) have enabled sweeping reductions of fine particulate emissions from diesel vehicles. SCR reduces NO_X and allows for engine tuning that produces a 75 percent reduction in fine particulates with the use of a diesel oxidation catalyst, while DPFs provide an additional 90–95 percent reduction (Figure S-3). Low-sulfur diesel (less than 50 parts per million but ideally 10 ppm) must be available to enable these technologies to function effectively.

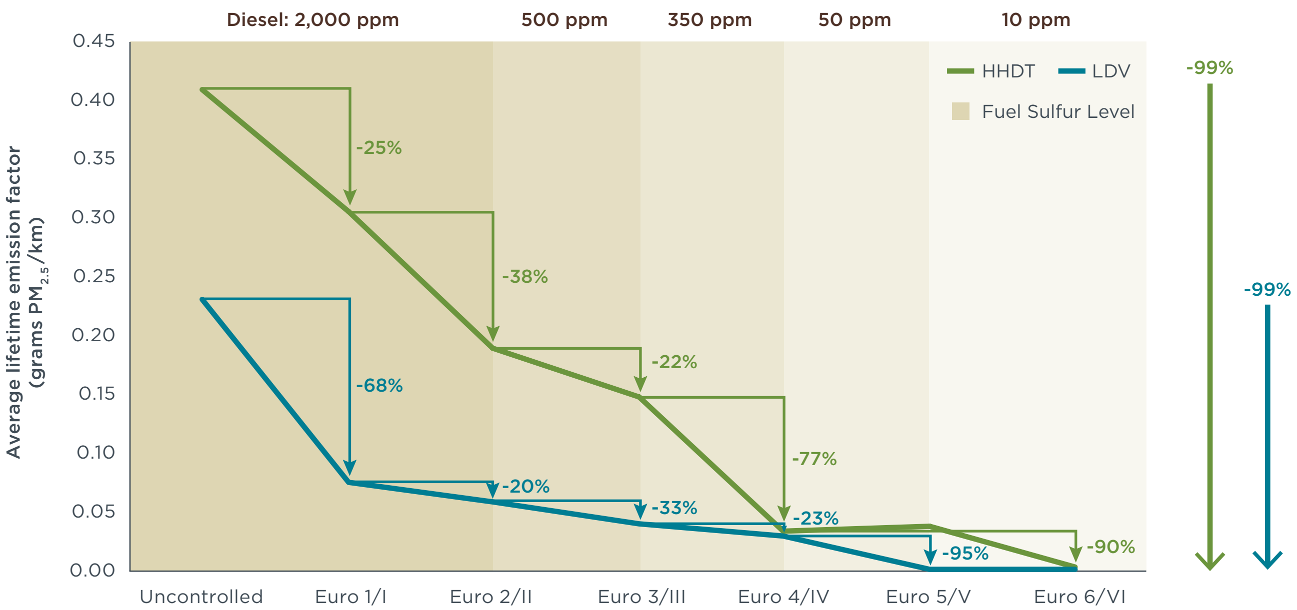

Figure S-3: Fine particulate ($PM_{2.5}$) average lifetime emission factors for diesel vehicles by emission standard and sulfur content

Emission factors of $PM_{2.5}$ (g/km) are shown for heavy heavy-duty diesel trucks and light-duty diesel vehicles. Data labels indicate the percentage reduction in emissions from the previous standard, with the series on the right depicting the total percentage reduction from conventional (uncontrolled) to Euro 6/VI. SCR systems control NO_x (not shown) and allow engine tuning to reduce $PM_{2.5}$ emissions for heavy heavy-duty vehicles meeting Euro IV standards and light-duty diesel vehicles meeting Euro 6 standards. DPFs are employed to meet Euro 5 standards for light-duty diesels and Euro VI for heavy-duty vehicles.

Optimized policy roadmaps for reducing particulates and associated early deaths vary from region to region, but they all rely on two strategies that should be implemented concurrently: tighter vehicle emission standards and more stringent fuel quality standards. In all regions, progressing to Euro 6/VI–equivalent standards for new and imported vehicles as expeditiously as possible is of paramount importance, either in a single leap or through intermediate standards. Governments should coordinate the implementation of vehicle emission standards with a national pathway to ultra-low-sulfur fuel, which is not only required for the most advanced emission controls but can also reduce emissions from the legacy vehicle fleet.

Cleaner fuels and vehicles are a good investment. In the United States, control of heavy-duty highway diesel emissions alone will result in environmental and public health benefits of $70 billion annually, at a cost of $4 billion per year (U.S. EPA 2006). In China, a national program of fuel and vehicle standards could garner $150 billion in public health benefits in 2030, at a cost between $300 and $900 per metric ton, much lower than the cost of similar programs in the United States and Europe (Blumberg et al. 2006). A recent retrospective study estimates that China has realized as much as $25 billion in health benefits already from existing vehicle emission controls. In sub-Saharan Africa, the health benefits of ultra-low-sulfur fuels would amount to approximately $43 billion over 10 years from a total refinery investment of approximately $6.1 billion (ICF International 2009). Similarly, in Mexico, an investment of approximately $4.6 billion to deliver ultra-low-sulfur fuel would generate health benefits equal to approximately $11.3 billion (SEMARNAT 2006). And in India, every dollar invested to reach the most stringent emission standards and ultra-low-sulfur fuel by 2020 would return nine dollars in benefits (Bansal et al. 2012). In each of these cases, the social welfare benefits of reduced vehicle emissions consistently exceed the costs.

This report outlines a policy roadmap for cleaner vehicles, including next-generation standards in countries that have already adopted advanced controls. These policy timelines take into account the technical and administrative considerations of regulatory development. They present an ambitious but feasible goal for advancing toward clean transportation worldwide. The implementation of these policies will yield major reductions in fine particulate emissions and associated premature deaths, as well as significant reductions in other pollutants, namely, precursors to ozone and secondary particulates. In addition, these policies have climate benefits since they reduce emissions of short-lived climate pollutants such as black carbon. This report is only able to capture a portion of the health impacts expected through cleaner fuel and vehicle standards. The full measure of benefits from these policies—including reduced risk of nonfatal diseases associated with air pollution, improved health in rural areas, and reductions in ozone and secondary particulates—creates an even stronger imperative for swift and universal regulatory action.

TECHNICAL SUMMARY

Outdoor air pollution is a leading cause of early death, chronic disease, and disability. Motor vehicles are a major contributor to outdoor air pollution, exposing vulnerable populations to especially high levels of harmful emissions in urban areas and near major roadways. Fine particles, or particulate matter with a diameter of 2.5 micrometers or less ($PM_{2.5}$), are among the most harmful vehicle pollutants and are associated with a range of health impacts including cardiovascular and respiratory diseases, lung cancer, and infant mortality.

Over the past four decades, vehicle regulations in California, the United States as a whole, Japan, Canada, and the European Union (EU) have required the manufacture and sale of progressively cleaner vehicles and fuels to protect public health. Technology-forcing standards in these regions spurred the development of catalyzed after-treatment technology in the 1970s and 1980s for gasoline-powered vehicles, complemented by the introduction of unleaded gasoline. Additional standards adopted in the past decade have spurred similar technology and fuel improvements for diesel vehicles, including the commercialization of diesel particulate filters and the sale of ultra-low-sulfur diesel fuel. Together, these technologies cut diesel emission rates in excess of 99 percent. History has shown that widespread adoption of stringent standards for cleaner vehicles and fuels is possible when governments choose to act.

ANALYTICAL FRAMEWORK

This report considers the effects of worldwide adoption of clean vehicle and clean fuel policy for the on-road transportation fleet from 2000 through 2030. The report considers the progress made under currently adopted policies (Baseline Policy scenario) and compares it against an alternative future that represents global adoption of world-class vehicle emission and fuel quality requirements (Accelerated Policy scenario) through 2030.

The report makes several advances over previous studies. First, the analysis uses a global emissions model with comprehensive, validated, and current global activity and regulatory data. Second, the report utilizes a new global-to-local-scale emissions to health impacts framework designed for rapid policy analysis. Finally, it puts forward a new policy roadmap that recognizes the timing needed to meet the legislative and technical requirements of new fuel or vehicle emission standards.

The Baseline Policy scenario assumes no new policies on vehicle emissions and fuel quality beyond those currently implemented or adopted. In the Accelerated Policy scenario, all regions progress toward Euro 6/VI–equivalent new vehicle emission limits and fuel quality by 2030. Since Africa and the Middle East today have significantly higher sulfur levels and few regulatory standards in place compared with the rest of the world, this scenario assumes that these regions will achieve an interim target of 50 parts per million (ppm) sulfur fuel and Euro 4/IV–equivalent standards by 2025. All other regions are slated to achieve 10 ppm sulfur fuel and Euro 6/VI–equivalent standards by 2025 or earlier. In regions that have already adopted advanced standards for on-road vehicles, such as the EU-28, the United States, Canada, Japan, Australia, and South Korea, next-generation standards are adopted in 2025. Next-generation standards would target new reductions in emissions of nitrogen oxides (NO_x) and nonmethane hydrocarbons (HC), which are precursors to ozone and secondary particulate matter.

The benefits of new fuel and vehicle requirements are assessed for emissions of both health-related pollutants—$PM_{2.5}$, NO_x, HCs—and short-lived climate pollutants—black carbon, organic carbon (which unlike black carbon is light reflecting and tends to offset the warming effect of black carbon), and methane (CH_4). In addition to emissions, premature mortality (measured in early deaths per year) and total years of life lost are estimated from exposure to annual average primary $PM_{2.5}$ concentrations in urban areas. Chronic health effects including cardiopulmonary mortality, lung cancer, and acute lower respiratory infections are assessed using methods developed and applied by the World Health Organization (WHO).

Climate impacts of black carbon and other short-lived pollutants are quantified in carbon dioxide–equivalent emissions using 20-year and 100-year global warming potential values (GWP). Values applied for black carbon are 3,010 (GWP-20) (meaning that a kilogram of black carbon emitted today would cause warming more than three thousand times that of carbon dioxide after a twenty-year period) and 860 (GWP-100). The values for other pollutants are given in Appendix V.

Exposure to vehicle emissions is estimated from a model that converts tank-to-wheel emissions of $PM_{2.5}$ to urban concentrations with the aid of a global intake fraction database. Intake fractions represent the share of total emissions that are actually inhaled; they depend on both the geographic and meteorological conditions that affect dispersion and the size of the population exposed. This health assessment approach offers a number of unique advantages not available beforehand: it utilizes previously developed global health, demographic, and intake fraction datasets that allow for consistent application and comparison across all regions; it provides rapid estimates of the public health response to vehicle policy that do not require resource-intensive global chemical dispersion modeling and associated high-resolution, spatially disaggregated input data; and it requires little to no knowledge about emissions from other sectors, thereby focusing the analysis on the transportation sector.

This approach is still subject to some important limitations. Deterioration factors in developing countries reflect compliance and enforcement of vehicle emission programs consistent with practices in high-income countries. In other words, actual emissions could be higher in developing countries without strong enforcement and compliance programs. The assessment of health impacts is limited to urban areas for which intake fractions have been measured and does not capture exposure in rural areas and in small cities, especially those with less than 100,000 residents. Furthermore, exposure to secondary pollutants including ozone and secondary PM was not assessed. Nonfatal health conditions such as chronic bronchitis as well as acute exposures such as 24-hour average $PM_{2.5}$ concentrations were not captured owing to limits in the health assessment methodology and data availability. In light of these constraints, the public health effects presented in this report should be interpreted as an indication of the benefits of transportation policies and not a full assessment of health results. Since the impacts quantified in this report are a subset of the expected total, the reported health benefits of new policies can be interpreted as conservative, lower-bound estimates.

RESULTS

The EU-28, the United States, Canada, Japan, Australia, and South Korea have already taken the necessary steps to slash new vehicle emissions. Current policies require the cleanest vehicles and fuels produced and are projected to reduce transportation-related emissions and health impacts in 2030 to levels 85 percent below year-2000 levels, even with a 50 percent increase in vehicle activity.

That is not true in the rest of the world. Early deaths from vehicle $PM_{2.5}$ emissions have fallen in most regions between 2000 and 2010 because of improvements in fuel quality and vehicle technologies, but currently adopted policies are not sufficient to sustain this decreasing trend. Instead, the projected growth in vehicle activity and urbanization will overtake the reductions achieved to date. In 2010, Africa, the Middle East, and smaller vehicle markets in the Asia-Pacific region accounted for roughly 30 percent of global years of life lost despite having just 15 percent of global vehicle activity. As vehicles in industrialized countries with advanced standards have become cleaner, the proportion of health problems traceable to on-road vehicles globally has shifted to developing regions.

Populous countries and regions with rapidly expanding vehicle fleets are projected to experience significantly greater health issues in 2030 than they do today, especially China, India, Africa, and the Middle East. In China and India, these will be the result of vehicle activity growth, among the highest in the world. Africa and the Middle East will suffer more directly from limited progress in transitioning to cleaner fuels and vehicles.

The rising public health impacts of transportation can be avoided. A universal transition to the cleanest vehicles and fuels would reduce global vehicle PM emissions by 90 percent and total adverse health outcomes by 75 percent from 2000 levels in 2030, despite a projected 150 percent increase in vehicle activity. This scenario would temporarily decouple future growth in vehicle activity from growth in emissions. Accelerated adoption of clean vehicle and fuel policies would save 25 million years of life cumulatively by 2030 and reduce early deaths by more than 210,000 lives in 2030, as a lower bound estimate. The greatest single health gains would occur in China and India, with benefits nearly equal to those of China and India combined distributed among countries in the Middle East, Africa, and the rest of developing Asia.

These policies generate near- and long-term net climate benefits as well—from black carbon, methane, and other short-lived climate pollutants—a reduction in 2030 amounting to 200 $MtCO_2e$ based on a GWP-100 and 710 $MtCO_2e$ based on a GWP-20. These reductions of short-lived climate pollutants are equivalent to between 10 and 35 percent of the total climate benefits estimated for potential vehicle efficiency policies in this time frame (Façanha, Blumberg, and Miller 2012).

The emission savings and health benefits calculated in this analysis are certainly underestimated. For emissions, the analysis excludes cold-start, evaporative, and tire-, brake-, and wear-related emissions; it also assumes adequate compliance and enforcement of vehicle standards from the outset. As for health benefits, the analysis excludes the effects of important pollutants (e.g., NO_x, HC, secondary PM, ozone), as well as nonfatal and acute health impacts. As a result, policymakers can expect much greater emission reduction and aggregate health improvement with the introduction of clean vehicles and fuels.

CONCLUSIONS

Successful reduction of vehicle emissions and the health problems they cause requires coordinated adoption of low-sulfur fuel and vehicle technology standards. Heavy-duty trucks and buses—most of which are powered by diesel engines—currently account for more than 80 percent of $PM_{2.5}$ emissions from on-road vehicles, so these are major targets for such regulations. Advancing standards for light-duty diesel vehicles is also important, especially in regions where they constitute a large share of the passenger car fleet or where dieselization of that fleet is likely. Countries should establish policy goals to require 10 ppm sulfur fuel and vehicles that meet Euro 6/VI–equivalent standards, either in single leaps or through intermediate standards such as Euro IV for heavy-duty vehicles and Euro 5 for light-duty vehicles.

Cost-effective and technologically feasible solutions already deployed on a large scale in developed countries can avert substantial loss of life from uncontrolled or partially controlled vehicle emissions. Stringent standards for clean vehicles and fuels can force the introduction of these technologies by 2030 in all major motor vehicle markets in the world, and much sooner in many regions.

1 INTRODUCTION

Exposure to outdoor air pollution is associated with 3.2 million early deaths globally and is among the top ten health risks worldwide (Lim et al. 2012). Motorized transportation is a major source of outdoor air pollution, particularly in highly urbanized areas in developed and emerging regions. Estimates of the contribution of motor vehicle exhaust to concentrations of ambient fine particulate matter ($PM_{2.5}$) range from 22 percent in Beijing to 53 percent in Barcelona, and exposure is highest within 300 to 500 meters of a major roadway (Ministry of Environmental Protection, 2013; HEI 2010). Exposure to traffic-related emissions is associated with asthma onset in children, impaired lung function, cardiovascular disease, and premature death (HEI 2010).

Vehicle sales and activity around the world are growing rapidly, driven by rising populations and economic activity. Global vehicle activity grew by 3 percent per year from 2000 to 2010, and new vehicle sales grew by 9 percent (ICCT 2013). Much of this global growth is driven by increasing transportation demand in emerging markets in the Asia-Pacific region, especially China and India, and in the Middle East. In those parts of the world, taken together, annualized 2000–2010 vehicle activity growth rates averaged 8 percent. In China, this figure topped 12 percent.

Increased vehicle activity typically degrades air quality, with serious public health implications. Stringent vehicle emission and fuel standards, however, have decoupled the relationship between vehicle activity and emissions for several decades since the most advanced emission controls can effectively eliminate more than 99 percent of local air pollutants from engines. This report proposes an aggressive but pragmatic policy path toward stringent vehicle and fuel standards around the world and quantifies the emissions benefits and reductions in early deaths and years of life lost that can be achieved through this policy pathway, even in the face of continuously rising vehicle sales and activity.

Vehicle emissions have been regulated since the early 1960s, when government officials in the United States first implemented emission controls on passenger cars (NRC 2006). In the 1970s, using new powers under the Clean Air Act, the U.S. Environmental Protection Agency (EPA) adopted a set of emission standards that forced changes in vehicle technology requiring the development of the catalytic converter for passenger cars to ensure more complete combustion of potential airborne pollutants. At the same time, new fuel standards required the removal of tetraethyl lead, a heavy-metal compound and neurotoxin, to enable the proper function of the catalytic converter and to reduce hazardous levels of exposure to ambient lead. This combination of successful technology-forcing vehicle standards and fuel quality standards established a model for future vehicle emission regulations in the United States and the rest of the world. Japan started imposing restrictions on vehicle emissions in the 1970s, as did many European countries. The European Union (EU) created a unified system of emission standards in the early 1990s. The United States, the EU, and Japan have led the way with the design of increasingly rigorous rules for all types of new motorized vehicles. These have provided a model for vehicle emission and fuel standards of varying degrees of stringency that have been adopted around the world. Chapter 2 includes a thorough discussion of vehicle and fuel standards worldwide.

This report quantifies a subset of the global health impacts of motorized on-road vehicles in urban areas, focusing on direct emissions of the most damaging pollutant: particulate matter with a diameter of 2.5 micrometers or less ($PM_{2.5}$). The analysis quantifies how emissions are changing under currently adopted vehicle and fuel regulations and to what extent emissions and health problems would decline in the event of progressive improvement in fuel and vehicle standards. Because this analysis is only able to capture a subset of the full health effects attributable to the global vehicle fleet, the estimated benefits of stringent fuel and vehicle standards should be considered as a lower bound.

1.1 HEALTH AND CLIMATE IMPACTS OF VEHICLE EMISSIONS

Motor vehicles are powered predominantly by internal combustion engines that use petroleum-based fuels like gasoline and diesel. Incomplete fuel combustion or high in-cylinder temperatures cause these engines to produce carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), nonmethane hydrocarbons (HC), sulfur oxides, and airborne toxins. Exposure to these pollutants is associated with a range of acute health effects and chronic diseases, some of which can result in early death (HEI 2010).

Among the most harmful vehicle emissions is $PM_{2.5}$. This category of solid and liquid particles smaller than 2.5 microns in aerodynamic diameter can penetrate deep into the lungs, inducing oxidative stress and inflammation. Long-term exposure to $PM_{2.5}$ is associated with a range of chronic diseases in adults including ischemic heart disease, lung cancer, and cerebrovascular disease, as well as respiratory infections in children (Krewski et al. 2009). Diesel exhaust, which is a significant contributor of $PM_{2.5}$ emissions in the transportation sector, is listed as a known carcinogen by the International Agency for Research on Cancer (Benbrahim-Tallaa et al. 2012). Exposure to elevated short-term concentrations of $PM_{2.5}$ has been associated with a rise in hospital admissions for respiratory infection (HEI 2012), non-fatal heart attacks, stroke, and other acute outcomes (Brook et al. 2010). $PM_{2.5}$ has also been associated with negative effects on reproduction, including decreased term birth weight and higher infant mortality (Woodruff, Parker, and Schoendorf 2006; Slama et al. 2007).

Ozone, a secondary pollutant, has important health consequences as well. Ozone is not directly emitted from vehicles but is formed in the atmosphere from pollutant precursors such as CO, HC, and NO_x. Long-term exposure to ozone raises the risk of death from respiratory causes (Jerrett et al. 2009), and short-term exposure increases hospitalization rates for asthma and other respiratory problems (Burnett et al. 2001).

The past 20 years have seen great progress worldwide toward increasing life spans, especially as education, immunization, and economic development have greatly reduced rates of communicable diseases, a trend best illustrated by the most recent assessment of the Global Burden of Disease study (Lim et al. 2012). With this progress comes a major shift in the prevalence of global maladies from communicable diseases to chronic, non-communicable diseases like cancer and heart disease. Since exposure to $PM_{2.5,}$ ozone, and other airborne toxic substances increases the risk of developing these chronic diseases, outdoor air pollution may become an increasingly important risk to public health.

Many of the pollutants associated with adverse health outcomes are also implicated in climate change (Berntsen and Fuglestvedt 2008). These behave differently from carbon dioxide, a long-lived greenhouse gas. Many are short-lived, chemically active gases and aerosols (or aerosol precursors) such as nitrogen oxides, volatile organic compounds, carbon monoxide, black carbon, organic carbon (which unlike black carbon is light reflecting and tends to offset the warming effect of black carbon), and sulfur oxides. While carbon dioxide and other long-lived gases ultimately predominate and essentially define the long-term climate impacts of the road transport sector, short-lived pollutants are far more significant in the near term. These pollutants are important targets when policy is focused on mitigating rapid ice melt, changes in precipitation, and the rate of climate change (ARB 2013a).

Within the road transport sector, diesel engines emit especially high quantities of short-lived pollutants that cause warming, such as black carbon, a major component of $PM_{2.5}$. In the state of California, diesel engine regulations have reduced diesel black carbon by as much as 50 million metric tons in carbon dioxide–equivalent emissions over the past twenty years, equal to a 13 percent reduction in the state's annual carbon dioxide emissions (ARB 2013b). New research into the climate impacts of black carbon provides stronger evidence that control of diesel particulate emissions will reduce climate warming (Bond et al. 2013).

1.2 NATIONAL AND INTERNATIONAL POLICY RESPONSE TO VEHICLE EMISSIONS

Historically, vehicle emissions have been regulated at the national level in two fundamental ways: through comprehensive air quality management and through direct regulation of vehicles and fuels. Air quality management sets air quality targets and implements a series of policies designed to achieve these targets cost-effectively across all sectors. In comparison, direct regulation of vehicles and fuels establishes emission limits for vehicles and complementary fuel quality requirements. Since transportation strategies can vary by region under an air quality management framework, this report focuses exclusively on direct regulatory strategies for the transportation sector.

1.2.1 Vehicle Emission Standards

The mature, regularly updated vehicle emission standards in the United States and the European Union serve as a roadmap of progressively stringent regulation for many countries. Standards are set based on vehicle weight categories. Broadly, cars and light commercial vehicles are considered light-duty vehicles (LDVs), while buses and heavy commercial trucks are considered heavy-duty vehicles (HDVs). In the United States, regulations for LDVs include the Tier 1 and Tier 2 standards, and regulations for HDVs include the 2004, 2007, and 2010 standards. In the EU, the most recent standards are Euro 1 through 6 for LDVs (using Arabic numerals) and Euro I through VI for HDVs (using Roman numerals). These regulations set limits on emissions from new vehicles sold, but they do not affect vehicles already on the road. For LDVs, standards limit the pollutant mass emitted per distance traveled; for HDVs, standards limit the pollutant mass per unit of work done by the engine. When these rules were first implemented in the United States and EU, their stringency forced the development and manufacture of new, highly effective emission control technology. Each successive standard was designed to push forward the maximum achievable cost-effective emission reductions. Several required improvements in both control technology and fuel quality to meet the specified limits, so emission standards were accompanied by new fuel quality standards. Today such technologies and fuels are commercially available and readily transferable to other countries.

The European standards are directly adopted by the World Forum for Harmonization of Vehicle Regulations for the United Nations Economic Commission for Europe (UNECE 2012) and have become the de facto global standards. With some exceptions, most notably the countries of North America and Japan, most countries follow the European standards, with implementation time lags varying from a few years to decades. Euro standards enforce limits on carbon monoxide, nitrogen oxides, hydrocarbons, particulate matter, and solid particle number. To meet a given standard, a vehicle must not emit above the limit values during testing over a standardized driving cycle, adjusted by a durability factor. The Euro standards' limit values are included in Appendix I.

New vehicle models must be tested and approved as compliant with the prevailing emission standards. Compliance is measured by operating the vehicle over a set of test conditions specified by the standards. The test cycle is designed to represent the range of driving conditions that vehicles encounter in daily use. When test cycle conditions inadequately represent real-world driving conditions, emission standards can be undermined (Lowell and Kamakaté 2012). For example, European manufacturers opted for a selective catalytic reduction (SCR) system to meet NO_x limits for commercial trucks mandated by the Euro V emission standard. These systems performed poorly at low-temperature and low-speed conditions not captured by the required European Stationary Cycle/European Load Response (ESC/ELR) test cycles,[2] yet manufacturers

2 Other types of SCR systems are effective at low-temperature and low-speed conditions, but they are more expensive and more susceptible to sulfur poisoning.

remained in compliance since the test cycle does not adequately reflect real-world driving operations. As a consequence, higher than expected NO_x emissions have been measured throughout Europe, particularly in urban areas where start-and-stop conditions are most common. Vehicle experts and regulators have developed an alternative test cycle for heavy-duty vehicles, the World Harmonized Transient Cycle, to avoid this situation in the future. For emission standards to be effective, regulatory design must account adequately for such off-cycle emissions.

Programs to control emissions from vehicles already on the road (in-use vehicles) are necessary to limit emissions not covered by new vehicle standards. Broad and consistent application of in-use strategies at the national level is essential but is typically resource intensive. In-use policies must regulate vehicle owners and operators, whose numbers are much greater than the vehicle manufacturers. While vehicle manufacturers tend to have greater financial flexibility to deploy new vehicle technologies, in-use programs require public resources to invest in vehicle inspection and maintenance and to subsidize technological changes such as retrofitting and vehicle scrappage. Since direct regulation of new vehicles on a national scale has in practice been more widespread than programs targeting in-use vehicles, this study focuses on new vehicle policies.

1.2.2 Fuel Quality Standards

Post–Euro 2/II regulations require improvements in fuel quality to keep exhaust emissions in line with limit values and to enable emissions after-treatment technologies. Several fuel properties affect exhaust emissions, including fuel density, sulfur content, the cetane number for diesel, and the octane number for gasoline (Karonis et al. 1998). Sulfur content is of particular importance for emission control. Fuel sulfur is directly tied to emissions of sulfates, contributing to PM emissions. Interactions between fuel sulfur and diesel oxidation catalysts (DOCs) can result in greatly elevated levels of sulfate emissions (NREL 2002). Fuel sulfur also compromises the effectiveness of both NO_x and PM after-treatment (MECA 1998; NREL 2002). Sulfur levels above 50 parts per million (ppm) can reduce the durability of SCR systems (Chaterjee, Walker, and Blakeman 2008) and require SCR catalysts to be made with more expensive materials, compromising their cost-effectiveness, while sulfur levels above 500 ppm can cause pipe corrosion in exhaust gas recirculation (EGR) systems (ACEA 2012). Sulfur also seriously interferes with the operation of lean NO_x traps (ACEA 2012). When higher-sulfur fuel is used with a continuously regenerating diesel particulate filter (DPF), the catalytic reaction favors oxidation of sulfur over nitrogen, resulting in decreased production of the nitrogen dioxide (NO_2) needed to react with trapped particles on the filter. This raises the regeneration temperature in the system, requiring more fuel and resulting in higher accumulation of soot in the filter. High soot buildup can result in uncontrolled burning, which may damage the filter (ACEA 2000; ACEA et al. 2012). Fuel quality standards are therefore a central pillar in any vehicle emission control strategy.

Tightening diesel fuel standards to a maximum of 50 ppm sulfur content will be necessary to achieve the major $PM_{2.5}$ and NO_x reductions permitted by Euro IV–compliant technology. Further reduction of diesel sulfur to a maximum of 10 to 15 ppm would enable the most efficient operation of technologies compliant with Euro V and VI standards. Many regions have already tightened limits on fuel sulfur content. In all major vehicle markets, regulations require diesel sulfur content of at most 500 ppm, and many require 50 ppm or less in certain cities, states, or provinces. However, many developing nations with smaller vehicle markets still allow the sale of high-sulfur fuel. Some countries in Latin America and the Asia-Pacific regions have imposed modest national limits on diesel sulfur content while at the same time providing lower-sulfur diesel in some urban areas. In Africa and the Middle East, several countries impose limits of 50 ppm or less, but many others currently allow the sale of diesel with sulfur content in excess of 500 ppm.

The marginal costs to provide ultra-low-sulfur diesel (ULSD) are low, but the high upfront capital investment in refinery upgrades usually necessitates government action. In most instances, the cost of emission control systems constitutes a far greater portion of the total cost of moving to more stringent standards. For example, the cost of vehicle technology to move from Euro III to Euro VI standards in India will likely outweigh the cost of improved fuels by a factor of 10 (Bansal et al. 2012). For countries that import a large share of their fuel, requiring ULSD may incur only slightly higher import costs compared with the costs of upgrading local refineries.

1.3 TECHNOLOGY CHANGES MOTIVATED BY POLICY

To comply with new emission standards, vehicle manufacturers must reduce pollutant production by modifying the operating parameters and design of the engine (in-cylinder control) or remove pollutants from the exhaust stream before they exit the tailpipe (after-treatment control) (Chatterjee, Walker, and Blakeman 2008). For the most stringent emission standards, both approaches are necessary. In-cylinder control strategies comprise fuel injection timing, turbocharging, and exhaust gas recirculation (EGR). Common after-treatment technologies are three-way catalytic converters for gasoline engines and a range of options for diesel engines including lean NO_x traps (LNT) and SCR to reduce NO_x; diesel oxidation catalysts (DOC) to reduce CO, HC, and the soluble organic fraction (SOF) of PM emissions; and diesel particulate filters (DPF) to control PM and particle number. Table 1 summarizes the technologies adopted by vehicle manufacturers to comply with each stage of European emission standards. Standards in the United States do not distinguish by fuel type but require similar control technology.

Table 1: Technology roadmap for compliance with select European emission standards

Vehicle type	Standard transition	Technology forced	Recommended fuel sulfur content
Gasoline LDVs	Pre-Euro to Euro 1	Three-way catalyst; oxygen sensors; electronic ignition	
	Euro 2 to 3	EGR	150 ppm
	Euro 6	Some gasoline direct injection (GDI) vehicles may require particulate filters (GPF)	10 ppm
Diesel LDVs	Euro 2 to 3	Common rail and high-pressure fuel injection (HPFI); HC and PM (SOF fraction) after-treatment (DOC)	350 ppm
	Euro 4 to 5	PM after-treatment (DPF)	10 ppm
	Euro 5 to 6	NO_x reduction after-treatment (SCR or LNT)	10 ppm
Diesel HDVs	Euro III to IV	HC and PM after-treatment (DOC); NO_x after-treatment (SCR)	50 ppm
	Euro V to VI	PM after-treatment (DPF)	10 ppm

1.4 HEALTH BENEFITS REALIZED FROM AIR QUALITY IMPROVEMENTS

Health studies have demonstrated the benefits of improvements in air quality. In the United States between 2000 and 2007, average life expectancy increased by 0.35 years for every 10 micrograms per cubic meter decline in $PM_{2.5}$ concentrations (Correia et al. 2013). In southern China, government policies that arbitrarily limited coal use resulted in emission exposures nearly half of those of residents in northern China and life spans 5.5 years longer, on average (Chen et al. 2013). An assessment by the U.S. government concluded that the health and environmental benefits of the Clean Air Act have vastly outweighed the costs (U.S. EPA 2011). In 2010, the Clean Air Act is estimated to have prevented 164,000 early deaths, as well as more than 100,000 nonfatal heart attacks, more than 150,000 hospital admissions and emergency room visits, and 1.7 million cases of exacerbated asthma. These benefits came from reductions in both $PM_{2.5}$ and ozone.

Studies have shown that standards requiring changes in vehicle technology and fuels have achieved large reductions in emissions and associated health outcomes. In the state of California, which has regulated diesel engine emissions since 1967 and enacted one of the most comprehensive diesel emission control programs in the world, black carbon emissions had fallen by 90 percent, and ambient concentrations of black carbon had fallen by more than 70 percent through the year 2000 (ARB 2013b). On a smaller scale, the city of Beijing enacted targeted interventions during the 2008 Olympics, imposing new vehicle emission limits and restricting urban traffic. As a result, markers of tissue inflammation and oxidative stress showed a measurable decline (Zhang et al. 2013).

Forward-looking studies project large health benefits from improvements in air quality and reductions in vehicle emissions. In the United States, the overall toll of air pollution on mortality is projected to decline from 2005 to 2016 thanks to implementation of regulatory programs, particularly mobile-source emission controls (Fann, Fulcher, and Baker 2013). A previous analysis found that, at a global scale, adoption of vehicle emission standards equivalent to Euro 6/VI for the global fleet could avoid between 120,000 and 280,000 premature deaths in 2030 compared with taking no further policy action (Shindell et al. 2011).

1.5 REPORT OVERVIEW

This analysis calculates road vehicle emissions at a global scale under a baseline scenario that assumes prevailing emission and fuel quality standards. These emissions are compared against an alternative policy scenario in which increasingly stringent emission control policies are implemented worldwide. The health effects of each scenario are quantified and contrasted using two important measures: premature mortality and years of life lost. These are determined based on exposure in urban areas to primary $PM_{2.5}$ emissions from on-road vehicles only. Since this approach does not capture the full extent of exposure to vehicle emissions or the full range of available control measures, the study presents a conservative estimate of the magnitude of health benefits that could be realized from clean vehicle and fuels policies.

The report makes several improvements over previous studies. First, a global emissions model was developed to capture comprehensive, validated data on global vehicle activity and regional policy adoption. Second, the analysis involved the development of a global emissions-to-health-impacts framework that enables rapid projections of changes in public health in response to alternative scenarios of vehicle emissions control policy. This analysis framework is especially important for regions where data availability is poor and resources for spatially and temporally disaggregated analyses are not available. Finally, the report puts forth an ambitious new policy roadmap that is sensitive to the timing and burden of establishing new legislative and regulatory requirements for cleaner vehicles and fuels.

2 ANALYTICAL FRAMEWORK

This chapter describes the analytical methodology used to estimate tank-to-wheel (TTW) emissions of local air pollutants from vehicle activity, as well as the health impacts from vehicle emissions, while highlighting major assumptions and limitations. This is followed by a brief description of regional input data, including vehicle market trends and demographics. The chapter concludes with a description of the Baseline and Accelerated Policy scenarios.

2.1 ACTIVITY AND EMISSIONS MODELING

The activity and emissions data used in this report are provided by a global-scale model of transportation sector emissions for 2000 through 2050 (ICCT 2013). This analysis uses a subset of the energy and emissions data available in the model, focusing on TTW emissions of three local air pollutants: fine particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), and nonmethane hydrocarbons (HC). TTW emissions are the product of vehicle activity and average fleet emission factors. Average emission factors for 16 regions and seven on-road modes are calculated based on the share of the fleet meeting various vehicle emission standards using a policy implementation timeline discussed in Section 2.4 and a fleet turnover algorithm.[3] Historical vehicle activity and mode share are based on national statistical data and International Energy Agency (IEA) data where national statistics are unavailable. Projections of future vehicle activity are estimated from socioeconomic indicators, including population growth, gross domestic product at purchasing power parity (PPP-GDP), and relative fuel prices. Appendix II provides a complete description of emission calculations. This analysis uses European emission standards (Euro 1/I through 6/VI) as the basis for all modeled emission factors because that system of standards is the most widely adopted. Appendix I gives the European emission standards and their assumed equivalents in the United States and Japan.

The analysis relies on a global set of emission factors (expressed in terms of grams per kilometer) for multiple local air pollutants that are specific to vehicle types, fuel types, and emission certification levels (e.g., Euro 1/I through Euro 6/VI). These average lifetime emission factors are based on real-world vehicle tests and account for the deterioration that typically occurs in an emission control system over the life of the vehicle. Emission factors are broadly taken from COPERT, an emissions model developed for official road transport emission inventory preparation in European Environment Agency (EEA) member countries and widely adopted by research and academic institutions.

The calculation of vehicle emissions for this analysis did not include evaporative emissions, cold-start emissions, or brake-, tire-, and road-wear emissions. Evaporative HC emissions occur primarily during vehicle operation and during the "hot soak" period following vehicle operation, with a small quantity of HC evaporating gradually from parked vehicles. Total evaporative emissions depend heavily on regional temperature and other conditions beyond the scope of the modeling for this analysis, but the exclusion of evaporative emissions causes an underestimation of total HC emissions. To provide context, estimates of vehicle emissions in California's 2005 emissions inventory attribute 58 percent of volatile organic compound (VOC)/HC emissions to exhaust, 30 percent to evaporative running losses, and 12 percent to other evaporative emissions (ARB 2013c).

3 The 16 regions include the EU-28, the United States, Canada, Japan, Australia, South Korea, China, India, Brazil, Mexico, the Latin America-31 (excluding Brazil and Mexico), Russia, non-EU Europe, the Asia-Pacific-40 (excluding China, India, Japan, Australia, and South Korea), Africa, and the Middle East. The seven on-road modes encompass light-duty vehicles, two-wheeled vehicles, three-wheeled vehicles, light, medium, and heavy heavy-duty trucks, and buses.

Cold-start emissions occur before the engine and catalyst in an after-treatment system have reached efficient operating temperature, typically in the first two minutes of vehicle operation. During this period, vehicles experience higher pollutant emission rates, with the most marked effects on carbon monoxide (CO), NO_x, and HC in catalyst-equipped vehicles. The exclusion of cold-start emissions from this analysis results in a further underestimation of total HC emissions from gasoline-fueled light-duty vehicles (LDVs). A vehicle emissions inventory in Greece reports that more than 80 percent of HC exhaust emissions from gasoline-powered vehicles occur during the cold-start phase, although cold-start emissions account for less than 20 percent of HC emissions from diesel LDVs (EMISIA 2009). Cold-start emissions have less impact on emissions of other pollutants from LDVs, contributing no more than 20 percent of NO_x emissions and 14 percent of $PM_{2.5}$ emissions across vehicle categories, and often less.

Brake, tire, and road wear account for a small share of $PM_{2.5}$ emissions, although they grow more important as diesel particulate filters (DPFs) and other advanced controls for $PM_{2.5}$ become widespread throughout the fleet (Borken-Kleefeld and Ntziachristos 2012). Thus, while total emissions of different pollutants in this analysis are certainly underestimated, the largest effects are on HC emissions (and consequently ozone), which are not used here to calculate health impacts. The assessment of the health effects of primary $PM_{2.5}$ is not significantly affected by the exclusion of evaporative, cold-start, and non-exhaust-generated PM.

$PM_{2.5}$ emission factors are adjusted to account for the effect of diesel sulfur content using a mass-balance (or conservation of mass) approach, assuming a 2 percent conversion of fuel sulfur to sulfates. Higher levels of sulfur in fuel can significantly increase sulfate formation and thus PM emissions. Engine-out PM emissions for diesel engines without catalytic after-treatment were shown to increase by 0.025 grams per brake horsepower–hour for each 0.1 percent increase by weight in diesel sulfur (Baranescu 1988), corresponding to an approximate 1 to 3 percent of diesel sulfur content converted to sulfate mass. Additionally, the policy assumptions in the analysis treat fuels and vehicle emission regulations as a system. Since sulfur adversely affects the performance of catalyst-based after-treatment technology and may react with a diesel oxidation catalyst (DOC) to produce higher sulfate emissions (NREL 2002), regulations that require catalyst-based after-treatment are always assumed in this analysis to be implemented with regulations that require appropriate fuel sulfur content. Appendix II provides further description of emission and fuel sulfur effect factors.

The modeling in this study assumes that vehicles maintain emission rates near their certified emission standard for their entire useful life, which entails strong compliance and enforcement programs as well as consistent vehicle maintenance practices. Because such programs and practices are imperfect even in wealthy nations with strong governance, actual vehicle emissions under all scenarios are likely to be higher than those presented here.

2.2 CONCENTRATION AND HEALTH IMPACT MODELING

Total premature mortality and years of life lost are estimated from exposure to primary $PM_{2.5}$ emissions from on-road vehicles in urban areas. Figure 1 gives the health impact modeling framework developed for this study. National $PM_{2.5}$ emissions in each region are allocated to urban areas based on population and road density. Urban emissions are then translated to urban $PM_{2.5}$ concentrations using a set of precalculated, region-specific factors that account for local meteorological conditions, population density, and city size. Concentration values provide an input to a set of concentration-response functions from published literature that estimate the number of early deaths and years of life lost caused by transportation pollution. Appendix III gives a complete description of health impact calculations.

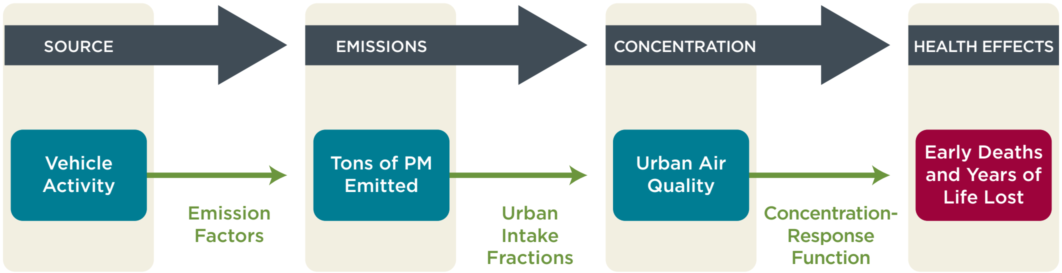

Figure 1: Framework for evaluating the health impacts of transportation emissions

The ambient pollutant concentration resulting from vehicle emissions depends on a number of different processes, including atmospheric mixing and transport, chemical reactions, and deposition. State-of-the-art air quality models integrate all of these processes, but their application at a global scale is burdensome in light of their need for significant computing resources and data, including data with high temporal and spatial resolution. This analysis relies instead on a modeling method that reasonably approximates the urban concentrations resulting from vehicle emissions while avoiding resource-intensive air quality modeling.

For this study, the ICCT developed an approach to estimate population-weighted average exposure to $PM_{2.5}$ concentrations from urban vehicle emissions for each region in the ICCT's own Global Transportation Roadmap model. The approach relies upon a set of global urban intake fractions, which function as a simple indicator of exposure to vehicle emissions. The intake fraction is a source- and location-specific metric that expresses the total mass of pollutant inhaled as a fraction of the total mass emitted. In comparing the intake fractions of different sources, one can identify where control measures would be most effective at reducing population exposure (Bennett et al. 2002). The ICCT collaborated with Joshua Apte, formerly with the University of California, Berkeley, and now at the Lawrence Berkeley National Laboratory, to develop intake fractions for conserved, mobile-source emissions within a set of 3,646 global cities (Apte et al. 2012). Calculations required for the intake fraction in each city necessitated the collection of wind speed, mixing height, and city footprint data to predict steady-state concentrations resulting from distributed emissions in a given urban area. Intake fractions were calculated for all cities in each Roadmap model region and combined with population data to derive an estimate of population-weighted average intake fraction for each Roadmap model region. Since intake fractions do not capture exposures in rural areas, emissions in each Roadmap model region were adjusted to reflect urban emissions only based on the share of highways and population within cities. The resultant urban $PM_{2.5}$ emissions for each Roadmap model region were combined with population-weighted average intake fraction to yield population-weighted average exposure to primary $PM_{2.5}$ concentrations from urban vehicle emissions.

Taking the change in urban primary $PM_{2.5}$ concentrations from motor vehicle emissions, this analysis estimates the associated variations in lung cancer and cardiopulmonary disease in adults using concentration-response functions derived from Krewski et al. (2009) and acute respiratory infections in children under the age of five using a concentration-response function from Cohen et al. (2004).

This analysis does not provide a full assessment of health outcomes associated with on-road vehicle pollution. For example, nonfatal conditions such as disability from lung cancer, cardiopulmonary disease, respiratory infections, and other diseases such as asthma and chronic obstructive pulmonary disease are not included. And while urban intake fractions allow for the calculation of average population exposure, this metric does not capture the variation in individual exposure within urban areas nor spikes in $PM_{2.5}$ concentrations that occur on a daily or seasonal basis. Acute health responses to changes in daily exposures are not recorded, including hospitalizations from sudden stroke, heart attack, or exacerbation of asthma. In addition, exposure to secondary $PM_{2.5}$ and ozone was not quantified, given the additional burden of estimating emissions from non-transportation-related sources. In summary, the total contribution of vehicle pollution to health problems is likely higher than the estimates given by this report, and the policy benefits are likely to be greater.

2.3 REGIONAL SCOPE AND VEHICLE MARKET TRENDS

The results of this report are divided into five regional groups based on stringency of vehicle emission controls, vehicle market trends, and geographic location: (1) the Best Practice group, which includes the European Union and five countries that have adopted the most stringent emission and fuel standards for most vehicle types; (2) China and India; (3) Latin America; (4) Russia and non-EU Europe; and (5) the Other Countries group, comprising countries in all of Africa, the Middle East, and the remainder of the Asia-Pacific zone. Figure 2 illustrates these groupings, followed by a detailed description of each. Figure 3 gives trends in economic activity and population for each group from 2000 through 2030. Figure 4 gives vehicle activity by mode for each regional group in the year 2010. Figure 5 gives historical trends in population growth, economic activity, and vehicle activity for each regional group.

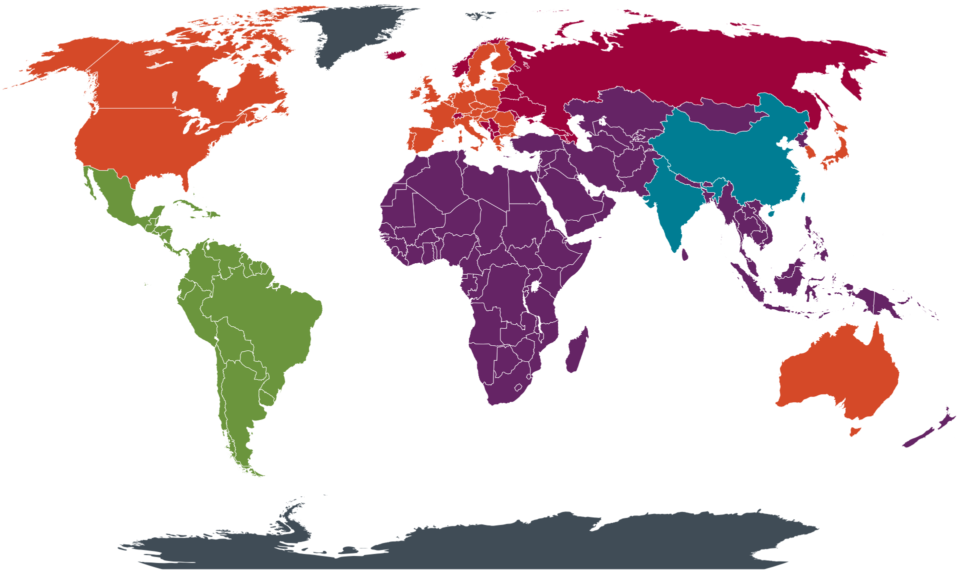

Figure 2: Regional groupings

2.3.1 Best Practice Group

This group is composed of the EU-28 (the 28 member states of the European Union), the United States, Canada, Japan, Australia, and South Korea. It accounts for less than one-seventh of the world's population but has the highest share of PPP-GDP. Countries in this group are projected to experience average annualized economic growth of 2 percent from 2010 to 2030, while their combined population is forecast to expand by less than 0.5 percent. The majority of global historical on-road vehicle activity took place in the Best Practice group, with the largest growth in the United States and the EU-28. Vehicle activity in this group is dominated by light-duty vehicles (LDVs). As shown in Figure 5, this group experienced the slowest growth in vehicle activity in the years 2005–10, in part as a result of the economic recession. Nonetheless, activity in this group is still expected to increase over the long term with economic recovery.

2.3.2 China and India

China and India are set apart by their rapid economic growth and large populations. PPP-GDP has grown by 9.5 percent per year in China and 7.1 percent per year in India over the past decade. The average PPP-GDP of this group is projected to grow by 6.1 percent annually through 2030. Population growth is expected to slow in China but will continue to exceed 1 percent per year in India; by 2030, India is on course to surpass China as the most populous nation. Vehicle activity in these countries has nearly tripled since 2000. Annual activity growth from 2005 to 2010 was higher than that of any other region, and China and India had the third- and fourth-highest national vehicle activity levels in 2010, respectively. Vigorous economic expansion in these countries is expected to drive further increases in vehicle activity through 2030. Motorcycles and heavy-duty vehicles each account for a substantial share of overall activity, with motorcycles dominating vehicle activity in India.

2.3.3 Latin America

The Latin America group is projected to experience annual population growth of 0.9 percent and annual economic growth (PPP-GDP) of 3.2 percent between 2010 and 2030. Vehicle activity has increased relatively quickly in this regional group, with both Brazil and Mexico now among the top ten vehicle markets in the world. Light-duty vehicles account for the most activity in Latin America. Heavy-duty vehicles and motorcycles constitute a smaller share of activity in Brazil and Mexico than in the remaining Latin American countries (referred to as the Latin America–31 in this report) and other developing regions.

2.3.4 Non-EU Europe and Russia

This group takes in any country in Europe that is not a member of the EU-28, along with Russia. It has the smallest share of world population and vehicle activity. Population is projected to decrease slightly between 2010 and 2030, but PPP-GDP is forecast to increase by better than 3.5 percent per year, leading to gradual growth in vehicle activity. LDVs constitute the largest share of activity in this group.

2.3.5 Other Countries Group

This group includes all countries on the African continent and in the Middle East, plus 40 countries in the Asia-Pacific region (referred to as the Asia-Pacific-40 in this report) not already included in other groups. The Other Countries group constitutes a relatively small but growing share of global economic activity, yet it contains a large share of world population. It has the largest projected annualized population growth, 1.6 percent through 2030, and 4.2 percent annual economic growth predicted going forward. Vehicle activity grew quickly in the Middle East and the Asia-Pacific-40from 2000 through 2010 but more slowly in Africa. Asia-Pacific-40 countries took up a large proportion of global vehicle activity in 2010, with Africa and the Middle East assuming more modest shares. In contrast to the other groups, heavy-duty vehicles and light-duty vehicles account for similar levels of activity in this regional grouping. Similar to China and India, motorcycles make up a substantial share of vehicle activity in the Asia-Pacific-40.

This analysis recognizes that any regional grouping is an approximate representation of all its members, and using it as broadly characterized will inherently mask important differences. Among countries within a particular group there are disparate levels of economic development, demographic trends, vehicle sales and activity, maturity of environmental protection laws, and the stringency of regulations. While this analysis generalizes regulatory trends within these regions to serve a global-scale analysis, further investigation of subregions or individual countries and their unique circumstances can and should be pursued to refine the results given here.

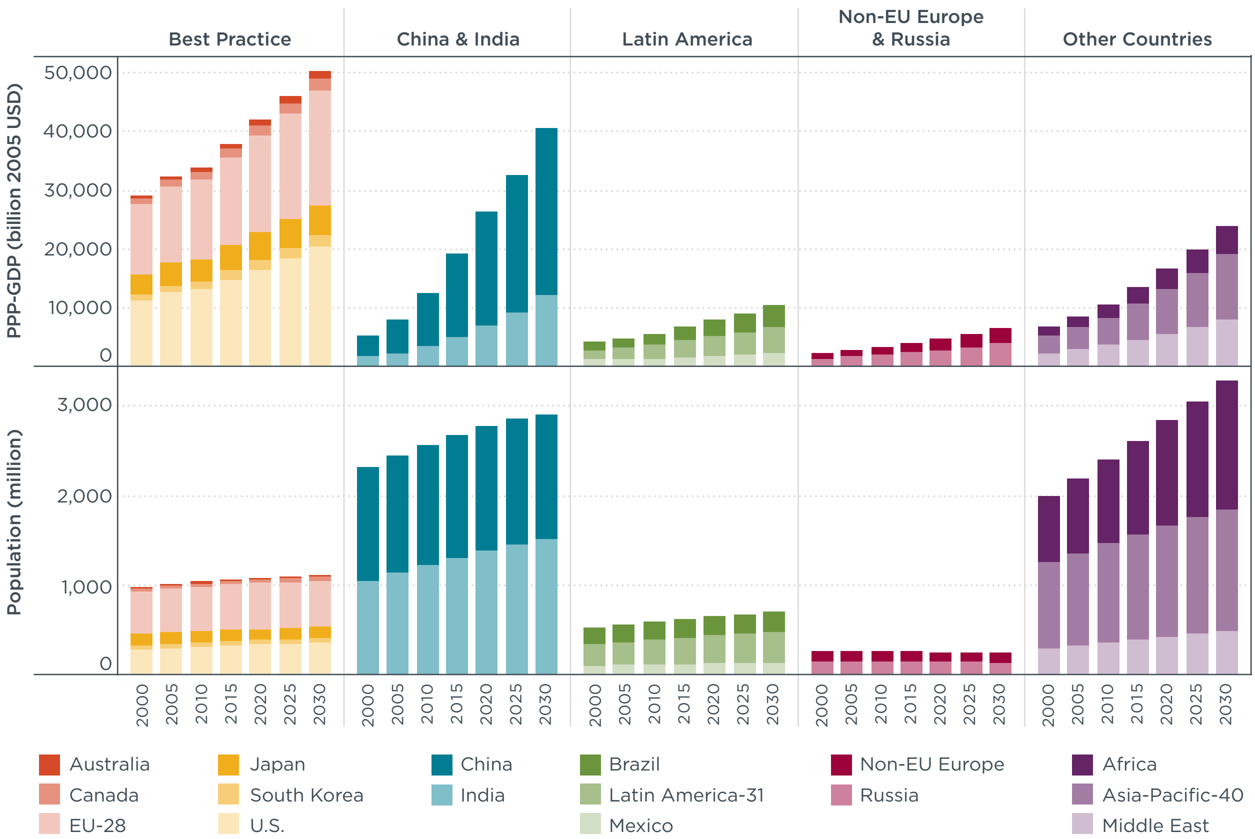

Figure 3: PPP-GDP and population by region, 2000–2030

Population projections from the UN Department of Economic and Social Affairs, Population Division (2012). Economic activity is expressed in gross domestic product at purchasing power parity exchange rates (PPP-GDP), with historical data from the International Monetary Fund (2013) and modeled projections (ICCT 2013).

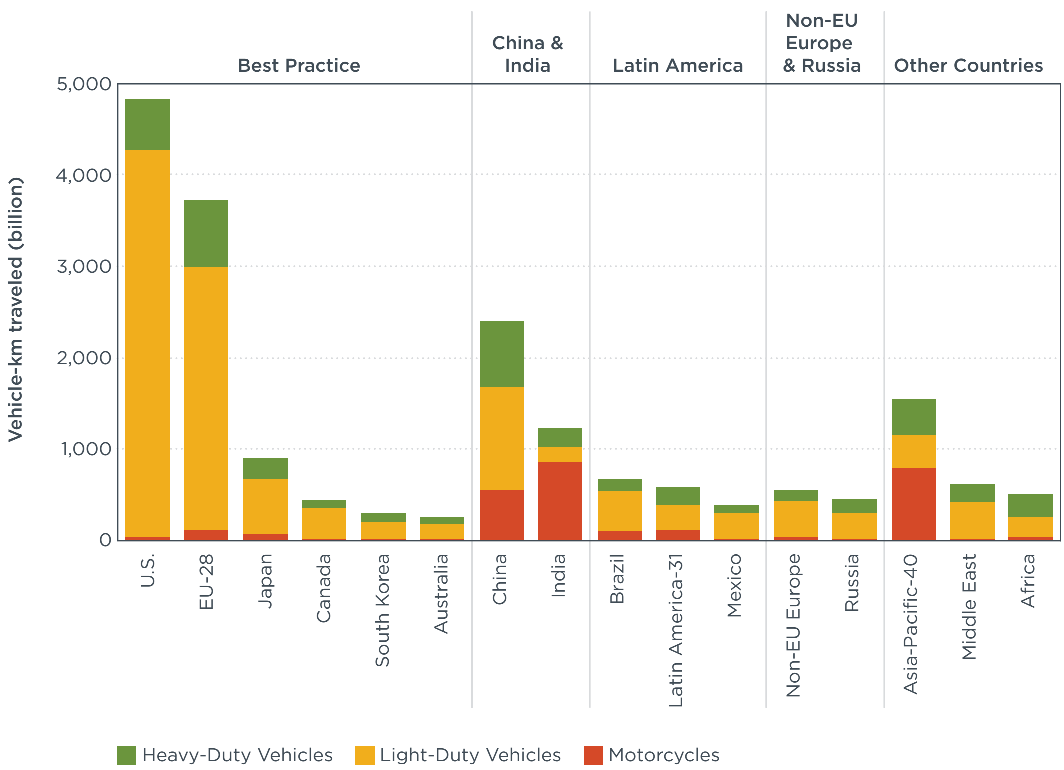

Figure 4: Vehicle activity by mode and region, 2010 (ICCT 2013)

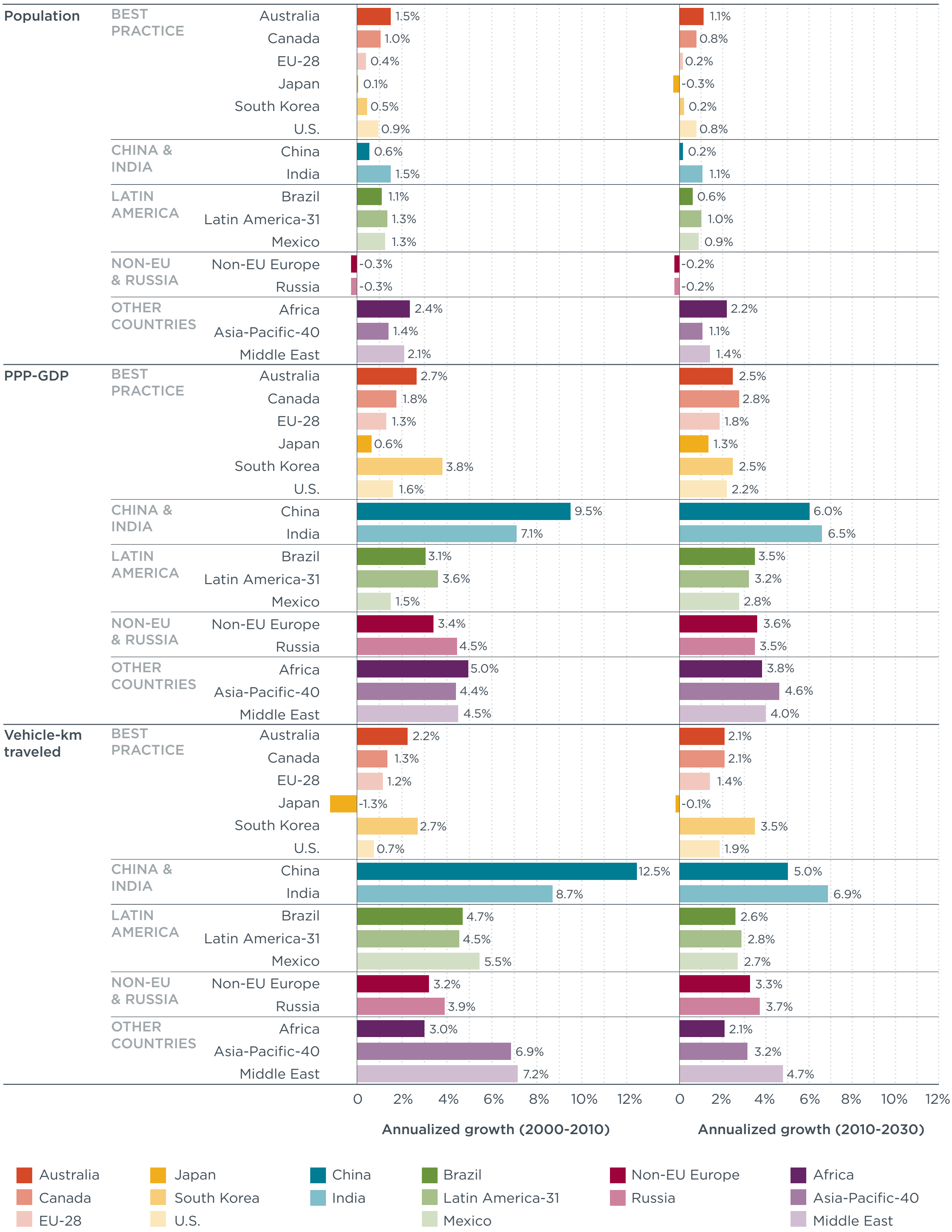

Figure 5: Trends in economic activity, population, and vehicle activity, 2000-2010 and 2010-2030

2.4 POLICY SCENARIOS

Two policy scenarios were developed for this study. The Baseline Policy scenario represents future change in emissions and health impacts assuming existing emission and fuel standards remain in place (no additional policies beyond those adopted to date). The Accelerated Policy scenario represents future change in emissions and health impacts in response to a shift to more stringent fuel quality and emission standards through 2030. The two scenarios use identical assumptions of future change in mode share, vehicle activity, and fuel type. Figures 6 to 8 give the Accelerated Policy timelines for light-duty, heavy-duty, and two- and three-wheeled vehicles, respectively. Figure 9 gives the timeline for necessary changes in fuel sulfur content that match the Accelerated Policy timelines presented.

LIGHT-DUTY VEHICLE POLICY TIMELINES

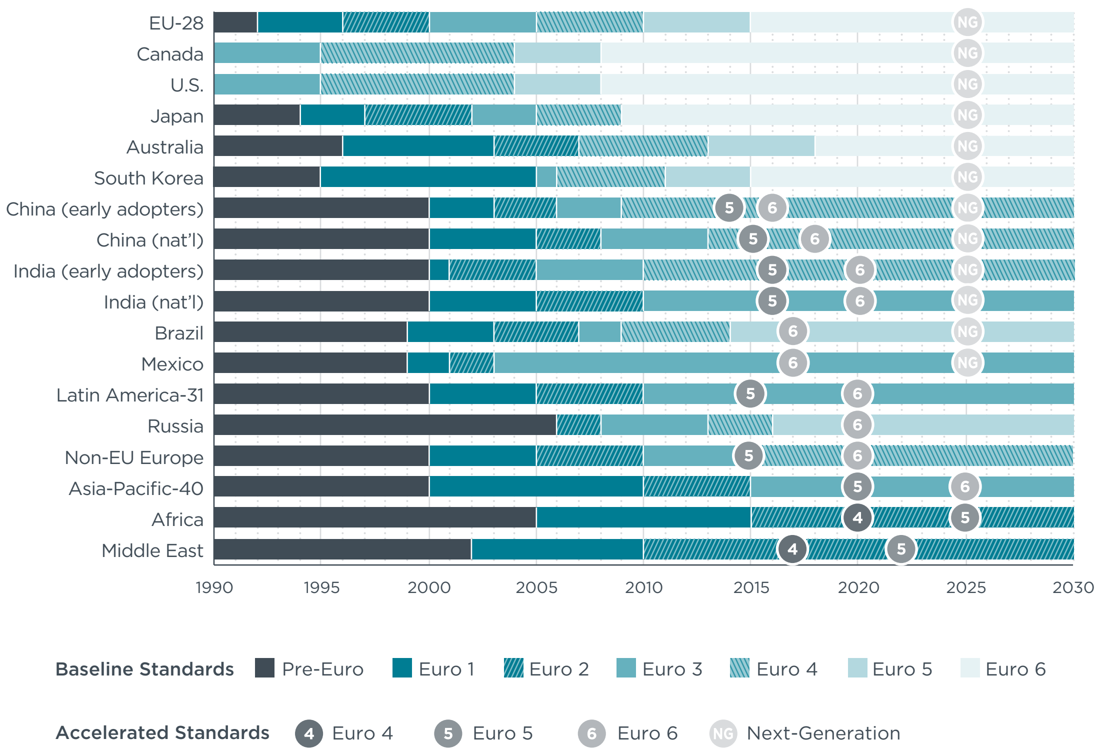

Figure 6: Baseline and Accelerated Policy timeline for light-duty vehicles

HEAVY-DUTY VEHICLE POLICY TIMELINES

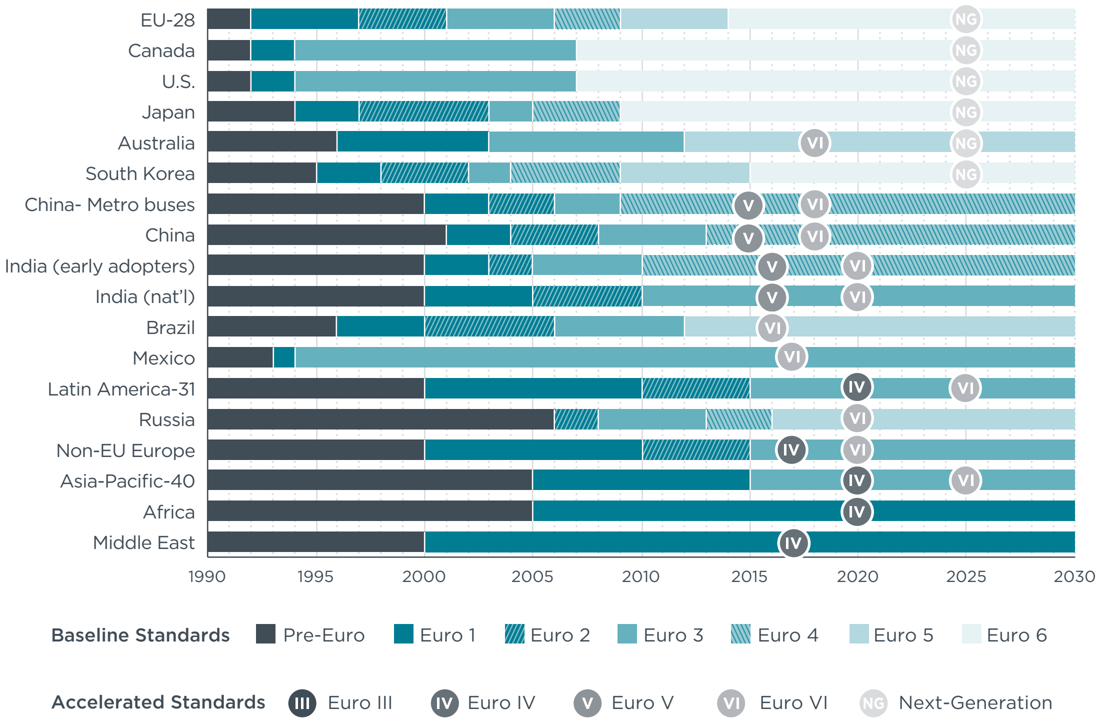

Figure 7: Baseline and Accelerated Policy timeline for heavy-duty vehicles

TWO- AND THREE-WHEELED VEHICLE POLICY TIMELINE

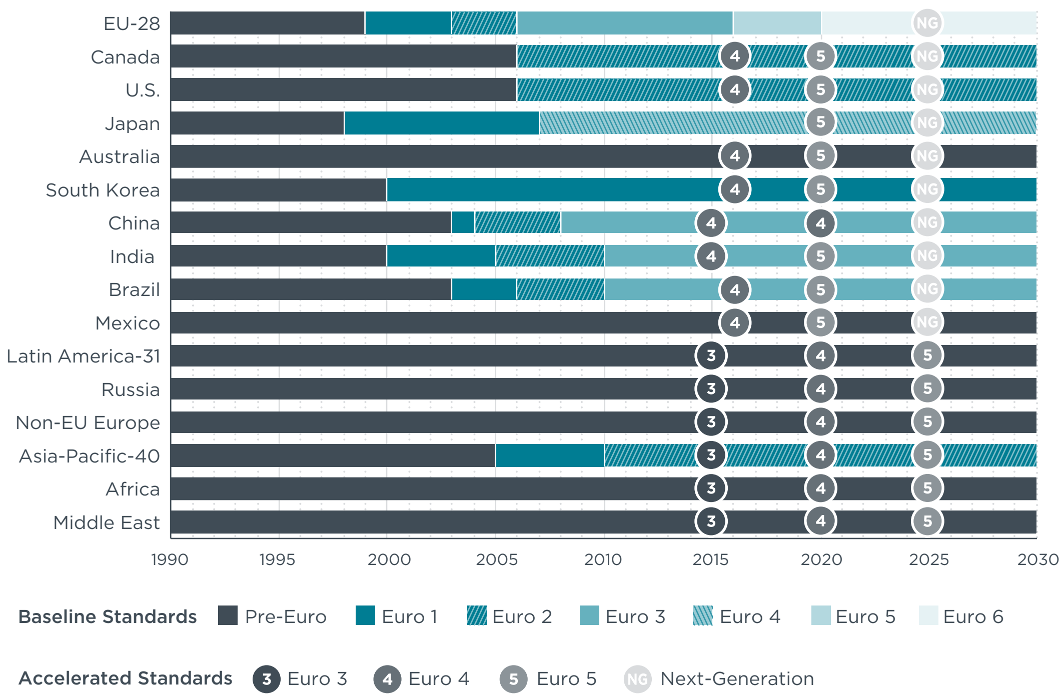

Figure 8: Baseline and Accelerated Policy timeline for two- and three-wheeled vehicles

The category of two-wheeled vehicles contains a range of engine classes that must meet different emission limits. This analysis includes policies pertaining to motorcycles with 50–150cc engines, as those are most commonly used worldwide.

DIESEL SULFUR REDUCTION TIMELINE

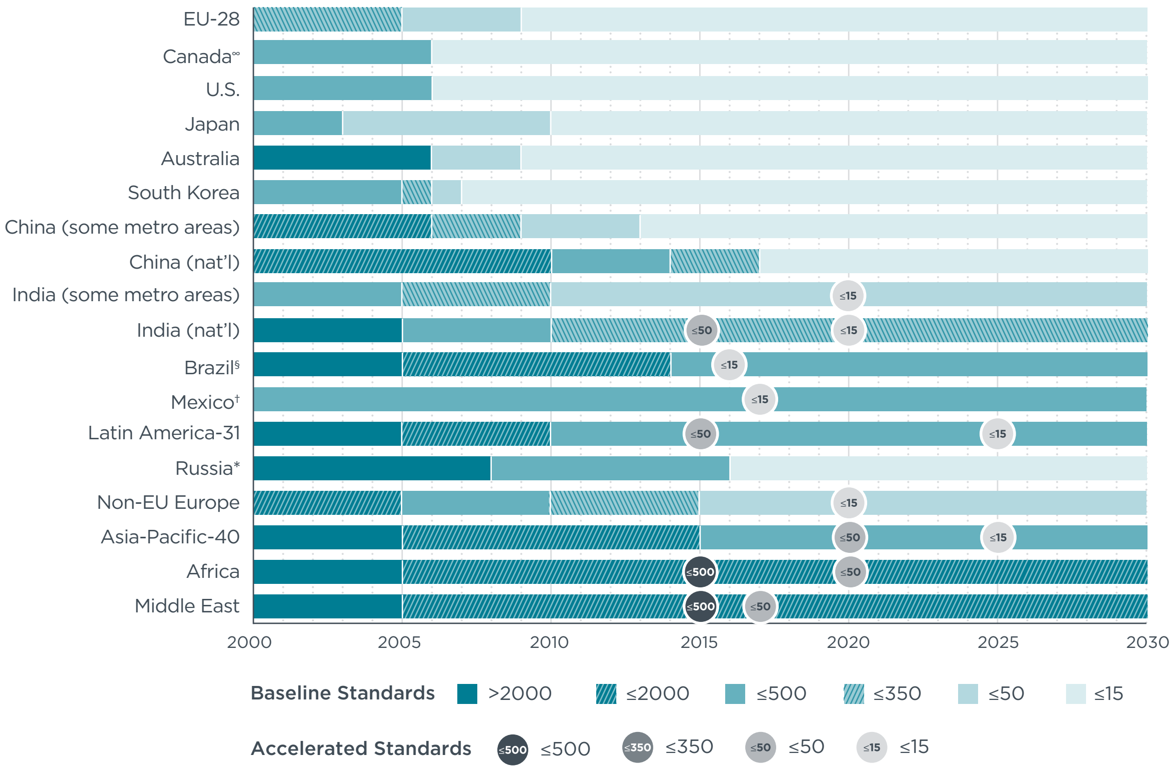

Figure 9: Timeline for reducing diesel sulfur content in Baseline and Accelerated Policy scenarios

∞ The Northern Supply Area of Canada is allowed a several-year delay to meet new standards.
§ Supply of 10 ppm fuel will increase as a growing share of the fleet in Brazil meets PROCONVE P-7 standards.
† Lower-sulfur diesel available in some urban areas: China (Beijing, Shanghai, Guangzhou), India (Delhi and others), Mexico (Mexico City), Latin America–31 (Santiago, Chile), and Africa (Johannesburg).
* Diesel fuel with 2,000 ppm sulfur was allowed in Russia until 2008, but 10, 50, 350, and 500 ppm diesel were also available.

2.4.1 Baseline Policy Scenario

In the past 15 years, countries in all regions have adopted vehicle emission standards and fuel sulfur limits. In recent times, Russia, Brazil, China, India, and Mexico have actively advanced regulations, reacting to deteriorating air quality caused by rapid growth in vehicle activity. Other low- and middle-income countries have introduced emission standards at various levels. A number of recently adopted regulations, including Euro 6/VI standards in several regions, are to be implemented by 2020. These are all assumed under the Baseline Policy scenario. The following outlines the detailed assumptions in each regional group.

BEST PRACTICE GROUP

All countries in this group currently require ultra-low-sulfur diesel (15 ppm or lower) and have adopted Euro 6/VI standards or their equivalent in terms of stringency for most vehicle types. The EU has created a system of progressively stricter emission standards—Euro 1 through 6 standards for LDVs and Euro I through VI for commercial trucks—that are followed closely by many nations around the world. Euro standards differ for diesel- and gasoline-powered vehicles and have two timelines for light- and heavy-duty vehicles. Euro 1/I began in 1992, and progressively more stringent standards have been adopted at regular intervals. Euro 6/VI limits for all new LDVs and HDVs will begin in 2015 and 2014, respectively. Emission standards for two-wheeled vehicles have been updated less frequently in Europe, but the European Council has recently adopted motorcycle emission standards ending with Euro 5 in 2020. The Euro standard limit values are included in Appendix I.

U.S. federal regulation of on-road emissions began in 1974 and differs in structure from the European standards. U.S. standards use different test cycles, and they impose equivalent emission limits on gasoline- and diesel-powered vehicles in contrast to the European approach, which discriminates by fuel type. The United States implemented Euro 6–equivalent PM controls with Tier 2 bin 8 LDVs and model-year 2007 HDVs, although the NO_x requirements for U.S. HDVs were not as stringent as Euro VI until model-year 2010. U.S. limits on two-wheeled vehicle emissions are still lax, roughly equivalent to Euro 2, but motorcycles account for a very small share of total vehicle activity in the United States. Since 1988, Canada has aligned its on-road vehicle emission standards with U.S. standards. In early 2013, the EPA proposed new Tier 3 standards that would tighten emission limits for LDVs and some light HDVs, and Canada has formally announced its intention to align its emission standards with the proposed U.S. Tier 3 standards. Since these standards are not yet adopted, they are not included in the Baseline Policy scenario for either country.

Japan imposed restrictions on vehicle emissions beginning in the 1970s and currently uses a regulatory framework that differs from that of either the United States or the EU. The most recent Japanese emissions regulations, the Post New Long-Term Emission Standards, apply to model-year 2009 HDVs and LDVs. These standards enforce limits similar in stringency to the Euro 6/VI standards. Japan has the most stringent standards for two-wheeled vehicles currently in place, equivalent to the Euro 5 standards that have been adopted in Europe but not yet implemented.

Australian emission standards are modeled after Euro standards, but, for some stages and vehicle types, U.S. or Japanese standards are also accepted. Australia has adopted Euro 6 standards for LDVs and Euro VI for light heavy-duty trucks but remains at Euro V for medium and heavy heavy-duty trucks and buses. There are no known emission standards in place for two-wheeled vehicles.

The history of vehicle emission control legislation in South Korea differs from the pattern of gradually tightening standards followed in other countries/regions in the Best Practice group. South Korea implemented fast-paced changes in emission standards, moving from Euro 1– to Euro 4–equivalent standards over a period of five years beginning in 2005 and leapfrogging over Euro 2 standards. For HDVs, South Korea moved through Euro III standards in 2002, Euro IV standards in 2004, and Euro V–equivalent standards in 2009. The Ministry of Environment has adopted Euro 6/VI standards for implementation for all LDVs and HDVs in 2015.

CHINA AND INDIA

Standards in China are modeled after the Euro standards system, starting in 2000 with China 1 (equivalent to Euro 1). For LDVs and buses, China implemented emission standards in a number of cities (indicated as early adopters in Figures 6–9) two years before implementing them nationally. Currently China has three tiers of standards in place for LDVs: China 5 in Beijing; China 4 in Shanghai as well as Guangzhou and nine other cities in Guangdong province; and China 3 at the national level. Metropolitan buses in Beijing were required to meet China IV standards in 2009, and all HDVs are required to meet China IV in 2013. Emission standards for motorcycles and three-wheeled vehicles are relatively stringent, currently the equivalent of Euro 3. China has multiple sulfur limit levels, with 500 ppm available nationally but 50 ppm available in cities with China 4 or 5 standards. Recent rulings by the State Council, the country's chief administrative authority, established targets of 50 ppm diesel fuel available nationwide by the end of 2014 and 10 ppm available by the end of 2017.

Indian Bharat standards, also modeled after Euro standards, began in 2000. Currently the national standard is Bharat 3/III, with Bharat 4/IV implemented in a growing number of cities as 50 ppm sulfur fuel is made available.[4] Urban Bharat 4 standards apply to all LDVs, but Bharat IV standards apply only to metropolitan buses. Motorcycle and three-wheeled vehicle emission standards are equivalent to Euro 3. Low-sulfur fuel (50 ppm) is on the market in cities with Bharat 4/IV standards and several additional cities. Diesel with 350 ppm sulfur is distributed in the rest of the country.

LATIN AMERICA

The PROCONVE standards in Brazil are modeled after both EU and U.S. standards. PROCONVE L5 standards, equivalent to Euro 3/4, are currently in force for LDVs, and Brazil has adopted PROCONVE L6, equivalent to U.S. Tier 2 bins 2–7, for implementation from 2013 to 2015. New HDVs are required to meet Euro V–equivalent PROCONVE P7 standards. During the transition to low-sulfur fuel, 10 ppm diesel is available in major metropolitan regions and in select stations nationwide to supply new Euro V trucks, with 1,800 ppm diesel available elsewhere. The high-sulfur 1,800 ppm diesel will be replaced with 500 ppm diesel in 2014, and an increasing supply of 10 ppm diesel will be made available to meet the growing needs of vehicles newly compliant with PROCONVE P7 standards.

Mexico has adopted a set of standards that blend U.S. and European regulations. Mexico currently requires new gasoline-fueled LDVs to meet U.S. Tier 2 bin 10 standards and diesel LDVs to meet Euro 3 standards. HDVs are required to meet Euro III–equivalent standards. Regulations state that tighter standards will be phased in when ultra-low-sulfur fuel becomes nationally available, but the 2009 target date for providing such fuel was not met. Proposed regulations would set a new target date for nationwide ultra-low sulfur-fuel at the end of 2016. This proposal is not included in the Baseline Policy scenario.

The remaining 31 countries in Latin America are treated as a single region called Latin America–31. The greatest vehicle activity[5] among these countries occurs in Argentina, Chile, Colombia, Ecuador, Peru, and Venezuela. Argentina, Chile, and Peru have pursued emission standards most aggressively. Argentina has adopted Euro 4/IV and will move to Euro 5 for LDVs by 2015. Peru has adopted Euro 3/III for LDVs/HDVs, and Chile has adopted Euro 5 for LDVs in all cities, with full national implementation in 2013, and Euro IV for HDVs. In each of these countries, low-sulfur fuel is provided for the vehicles meeting higher Euro standards, although national limits are looser. Ecuador, Guatemala, and Venezuela have much less stringent standards, mostly requiring only Euro 2 for LDVs, with HDV standards uncertain. Many small Latin American countries impose age-based restrictions on new or used vehicles imported into the country but do not have emission limits. The generalized timeline sets the region at Euro 3 LDV and Euro II HDV standards starting in 2010 and anticipates a move to Euro III HDV standards in 2015.

NON-EU EUROPE AND RUSSIA

Russia follows the Euro standards with a different implementation schedule. It requires that both HDVs and LDVs meet Euro 4/IV standards and will stipulate that all vehicles produced and sold meet Euro 5/V standards in 2016. Russia offers multiple fuel grades with varying sulfur content: 10 ppm diesel will be available for Euro 5/V vehicles by 2016, but diesel with higher sulfur content will continue to be supplied until the end of 2015.

Seventeen European countries are not members of the European Union and are included in this regional grouping. Ukraine, Switzerland, Norway, Belarus, and Azerbaijan are the major contributors to the vehicle activity of these non-EU countries. Switzerland, Norway, and Iceland are closely aligned with the EU-28 and have adopted Euro 6/VI. Ukraine and

4 As of June 2013, Bharat 4/VI is implemented in 30 cities, with 10 more expected to follow through 2014.

5 Vehicle activity is based on the International Road Federation's World Road Statistics data. Because national statistical data on vehicle activity are not available for many countries within this and other aggregate regions, population and GDP were also used to estimate the share of activity.

Belarus stand out among the rest. Ukraine currently has fuel sulfur of 350 ppm, with a goal to adopt Euro 5 standards in 2016. Belarus has fuel sulfur of 350 ppm and adopted Euro 4 in 2011. Azerbaijan currently has a limit of 1,000 ppm for diesel, with a goal of achieving 50 ppm by 2015. The country requires Euro 4/IV standards to be met by imported vehicles. Most other non-EU countries require imported LDVs to meet Euro 2 or 3 standards.

OTHER COUNTRIES

Generalized timelines for policy adoption were developed for the Middle East, Africa, and the Asia-Pacific-40. These are based on the progress that countries in each region have made overall in advancing new vehicle emission and fuel quality standards or other emission limits. For simplicity, a single policy timeline was developed for each of the three aggregate regions that constitute the Other Countries group. The diversity of standards within each aggregate region is discussed below in order to convey the information that served as the basis for each timeline that was developed.

Adding to the complexity of this task is the common application among these countries of import restrictions in lieu of vehicle emission standards. The emission status of new and used imported vehicles is difficult to track and model for any country, impairing the ability to infer what standards the imported vehicles actually meet. Ironically, countries without age-based restrictions may see imports of vehicles meeting higher emission standards simply owing to market availability. For example, a recent survey reported that the majority of HDVs in Addis Ababa are less than 10 years old, and more than 20 percent of heavy-duty trucks and buses are designed to meet Euro III or IV standards (United Nations Environment Programme, Global Fuel Economy Initiative 2013). These are relatively high-quality vehicles for this region. However, the very high sulfur content of diesel fuel sold in Ethiopia (>4,000 ppm) can negatively interact with the emission control systems on the vehicle and cause serious performance issues. These vehicles are often stripped of their emission control systems as a result. In light of this example, the 20 percent or more of vehicles that meet Euro III or IV when imported cannot be expected to achieve Euro III/IV emission standards in practice. The mismatch between available fuel and the standards met by imported vehicles is a major concern.

Because of a lack of information for this regional group, broad policy assumptions lead to health estimates that are more uncertain compared with other regional groups.

ASIA-PACIFIC-40: Of the 40 countries within this region, those with the highest level of vehicle activity are Indonesia, Pakistan, Vietnam, and Kazakhstan, followed by Bangladesh, Thailand, New Zealand, the Philippines, and Malaysia. The countries with the most stringent policies have been Thailand and New Zealand. Thailand recently implemented Euro 4/IV and 50 ppm fuel, while New Zealand currently requires Euro 5/V and 15 ppm fuel. Other countries continue to move forward with new LDV emission standards. Indonesia has Euro 3 standards in place. Malaysia, the Philippines, and Vietnam currently require Euro 2 but have committed to Euro 4 for LDVs in the next five years. Bangladesh and Pakistan have age-based import restrictions and Euro 2 standards for LDVs, but many other countries have few or no standards or restrictions. The generalized timeline adopted in this report sets the region at Euro 2 LDV standards in 2010 and anticipates a shift to Euro 3 in 2015 as policies in the pipeline are implemented.

The Asia-Pacific-40 as a whole has achieved less progress on heavy-duty emission standards. Thailand and Vietnam recently adopted Euro IV, and New Zealand requires Euro V, but other nations require at most Euro II. The Baseline Policy scenario in this report assumes Euro II standard adoption in 2010, with no stronger standards in the future. For motorcycles, countries in the Asia-Pacific-40 will most often follow the same standards as the EU, implemented at a five- to seven-year time lag.

Diesel sulfur limits vary broadly among the Asia-Pacific countries, with limits as high as 5,000 ppm in Bangladesh and 3,500 ppm in Indonesia and as low as 50 ppm in Singapore and Thailand and 15 ppm in New Zealand. The baseline assumed diesel sulfur level is 2,000 ppm through 2010, declining to 500 ppm as countries implement Euro II emission standards.

AFRICA: The model considers 52 countries in Africa, with the greatest share of vehicle activity taken by South Africa, Nigeria, and Angola, followed by Morocco and Algeria. Of those, only Nigeria has adopted Euro 3 standards for LDVs. South Africa instituted Euro 2 in 2006, and all others have either only age-based import restrictions or no known standards. Only South Africa is known to have limits for heavy-duty vehicles, with Euro II adopted in 2006. Several countries in North Africa impose limits of 50 ppm on diesel fuel sulfur content, while limits range from 500 to 5,000 ppm throughout sub-Saharan Africa. Countries across Africa have supported regional air quality frameworks that aim to reduce diesel sulfur to 50 ppm by 2020, but the targets are not legally binding. The baseline assumption for Africa sets the region at Euro 1 in 2005 and Euro 2 in 2015 for LDVs, with the move to Euro 2 presumed to be driven by the higher market availability of vehicles meeting post–Euro 1 standards. The timeline for HDVs is Euro I in 2005, with no further progress thereafter.

MIDDLE EAST: Among the 16 countries in the Middle East, the greatest vehicle activity occurs in Turkey, Iran, Egypt, Iraq, and Saudi Arabia. Turkey has exceptionally stringent standards relative to the rest of the region, along with Israel, which follows the EU standards and implementation schedule. Turkey implemented Euro 5/V in 2012 and requires ultra-low-sulfur fuel. Iran and Saudi Arabia have implemented Euro 3, while other countries including Egypt require only that LDVs meet Euro 1 standards. The baseline assumption for the region puts in place Euro 1 standards in 2002 and Euro 2 standards in 2010. With the exception of Israel and Turkey, all countries have either Euro I or pre-Euro standards for HDVs, so the baseline assumption in this report keeps the region at Euro I, with no further progress assumed. Turkey, Israel, and Oman require ultra-low- or low-sulfur diesel. In all other countries, fuel sulfur content ranges from 500 to more than 5,000 ppm. The baseline scenario assumes diesel sulfur of 2,000 ppm through 2010 and 1,500 ppm beyond 2010.

2.4.2 Accelerated Policy Adoption

The Accelerated Policy scenario envisions a rapid but feasible transition in all regions to tighter emission and fuel quality standards. Policy timelines for emerging countries with major vehicle markets (i.e., China, India, Brazil, Mexico, and Russia) were developed based on communication with local and international policy experts. Timelines account for proposed or planned regulations for vehicles and the availability of low-sulfur diesel fuel. The implementation schedule also accounts for necessary regulatory lead time and coordination between vehicle emission and fuel efficiency standards.

In the Latin America–31 region and the Asia-Pacific-40 region, an Accelerated Policy timeline assumes implementation of Euro 6/VI standards by 2025, with five-year periods spent adjusting to each intermediate standard, including the leapfrogging of some intermediate stages. To achieve the most from new vehicle regulations, these timelines skip standards that require only incremental improvements to existing vehicle engine systems. For HDVs, this means skipping Euro V and moving directly from Euro IV to Euro VI standards. For LDVs, this means moving directly from Euro 3 to Euro 5. To support the new emission standards, both these regions are assumed to move rapidly to provide 50 ppm diesel fuel by 2020, and ultra-low-sulfur diesel (15 ppm or below) by 2025.

Because baseline policies in the Africa and the Middle East regions are still at an early stage generally, this analysis uses an Accelerated Policy timeline in these regions progressing to Euro 5 for LDVs and Euro IV for HDVs within the modeled period of 2013 through 2030. Moving to Euro IV requires a dramatic reduction in diesel sulfur content in these regions. The Accelerated Policy timeline assumes a move to 50 ppm sulfur diesel by 2020, with an intermediate shift to 500 ppm diesel in 2015. With the provision of 50 ppm diesel in the Middle East in 2017 and in Africa in 2020, both can plausibly leapfrog to Euro 4/VI standards; this leap, which is large relative to the regions' progress thus far, is supported by the wide availability of Euro 4/VI engines on the international market. LDV standards are assumed to progress to Euro 5 in 2022 in the Middle East and 2025 in Africa. Euro 5 diesel after-treatment systems can function with 50 ppm fuel, although using 10 ppm is both more efficient and cost-effective (NREL 2002).

All countries advance motorcycle emission standards under this Accelerated Policy scenario. China and India, where two- and three-wheeled vehicles constitute a larger share of total vehicle activity, are assumed to implement Euro 4 standards one year before the EU-28 and to follow the same implementation schedule as the EU-28 for all future standards. The other countries in the Best Practice group, along with Brazil and Mexico, are assumed to adopt motorcycle standards of a stringency equal to those in the EU-28 and to follow the same implementation timeline. These countries are assumed to adopt an additional stage of next-generation standards in 2025. All other regions are assumed to progress from Euro 3 to Euro 5 from 2015 through 2025.

The Accelerated Policy scenario assumes the development of a next-generation standard to succeed Euro 6/VI and to be adopted during the 2015–30 time frame. For LDVs, next-generation standards are based on the proposed U.S. Tier 3 standards. These standards, modeled after California's Low-Emission Vehicle (LEV) III standards, would be phased in from 2017 to 2025. They represent a major reduction in NO_X and HC from Euro 6 levels, as well as a further tightening of $PM_{2.5}$ emission limits. Major technological developments necessary to meet next-generation standards are likely to focus on NO_X reduction strategies. Gasoline direct-injection (GDI) vehicles may require in-cylinder control strategies or particulate filters to comply with the next-generation PM limit.

Tier 3 standards will apply to some light heavy-duty trucks, but as yet there has been no proposed legislation putting forward next-generation standards for heavier heavy-duty trucks or buses. The California Air Resources Board has proposed research evaluating the feasibility of NO_x limits that are more than 90 percent lower than current HDV emission limits (ARB 2013d). This is closely tied to the continuing technical improvements in emission control systems and the limits they could support in the coming decade. The analysis bases next-generation standards for heavy HDVs on these potential technological advances. Appendix II provides full details of the reductions posited for all next-generation standards.

The Accelerated Policy scenario assumes that China, India, Brazil, and Mexico adopt next-generation standards for LDVs in 2025, in line with the goal of harmonizing standards across major vehicle markets. Only the countries in the Best Practice group are expected to adopt next-generation HDV standards within the modeled time frame, given that the regulatory process for such rules is still at an early stage.

3 RESULTS

This chapter summarizes the quantitative results of the analysis. Trends in vehicle activity and emission rates are given, along with the changes in vehicular emissions, premature mortality, and years of life lost under the Baseline and Accelerated Policy scenarios.

3.1 VEHICLE ACTIVITY TRENDS

Figure 10 gives vehicle activity by regional group from 2000 through 2030. The majority of vehicle activity historically occurred in the countries within the Best Practice group, and these countries will remain the locus of the majority of light-duty vehicle (LDV) activity in future years. Total heavy-duty vehicle (HDV) activity in China and India is projected to grow quickly and rival HDV activity in the Best Practice group by 2030. Motorcycle activity, which historically accounted for a low share of total vehicle activity, will increase in importance in China, India, and other countries in the Asia-Pacific region. By 2030, these countries will see 85 percent of global motorcycle activity.

LDV activity constituted the majority of vehicle activity worldwide. The countries within the Best Practice group, where bigger incomes allow for much higher rates of vehicle ownership and activity, tallied the highest share of LDV kilometers driven. LDV activity in the Best Practice group is projected to grow by 50 percent above year-2010 levels by 2030, a relatively moderate pace that reflects lower economic and population growth forecasts compared with other regions. In contrast, LDV activity in China and India will grow more than 20-fold, while in the other regions it will double or triple.

Growth in HDV activity—which is typically highly correlated with economic expansion—will not be as high as LDV activity growth overall but is still projected at 46 percent above year-2000 levels by 2030 in the Best Practice group and 300 percent in China and India combined. Comparison of HDV activity with other passenger modes is not straightforward because of differences in vehicle utility, size, and loads. The relative share of HDV activity as a proportion of total vehicle activity is much higher in developing countries—and especially in the Other Countries group—because of lower vehicle ownership and much higher rates of public transit use.

The number of motorcycles in developing countries has grown significantly and will continue to increase at a rapid rate in emerging economies. This is especially the case in India and other countries in the Asia-Pacific region, where motorcycles account for the largest share of the fleet. Motorcycle activity is projected to grow by 5 to 7 percent annually from 2000 to 2030.

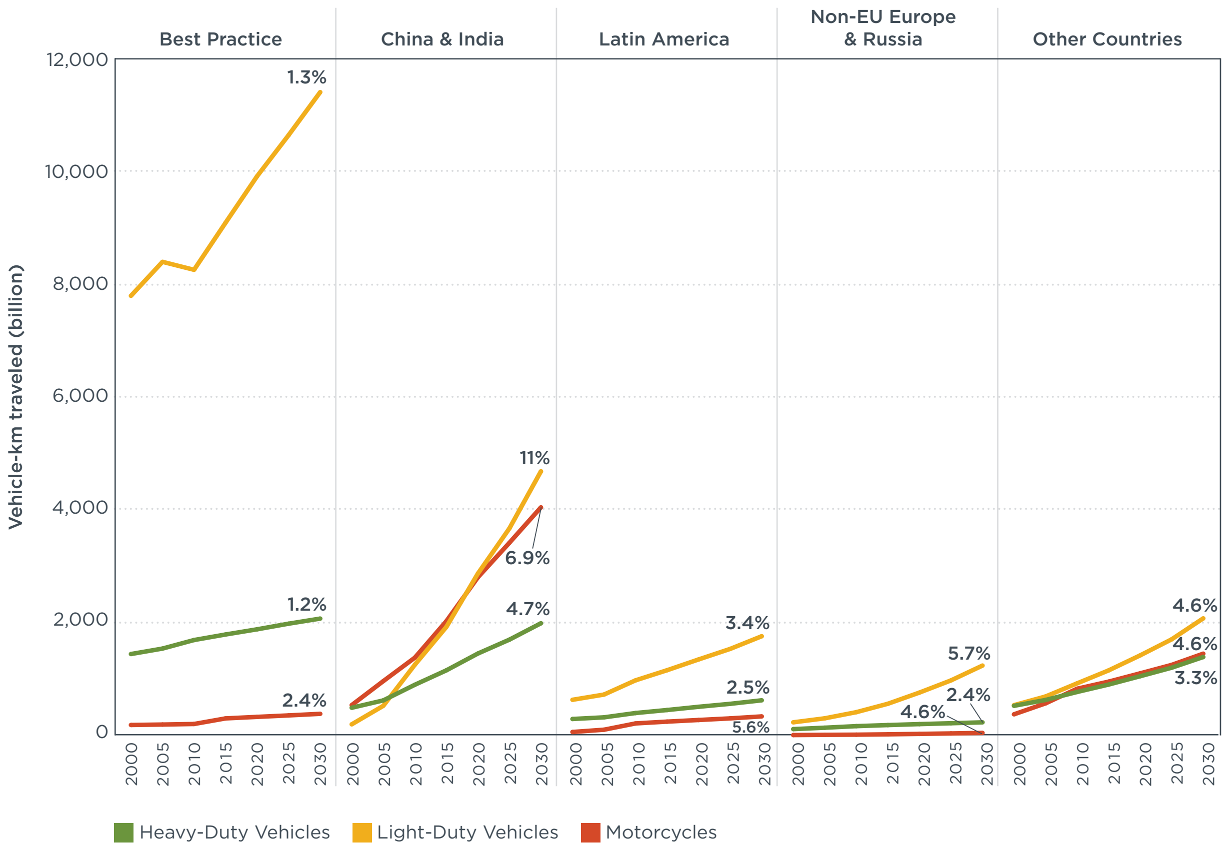

Figure 10: Vehicle activity by regional group, 2000–2030

Labels show annualized growth from 2000-2030. The Best Practice group houses the EU-28, the United States, Canada, Japan, Australia, and South Korea; the Other Countries group contains all countries in the Asia-Pacific region, with the exception of China, India, Japan, Australia, and South Korea, as well as Africa and the Middle East.

3.2 EMISSIONS TRENDS

This section provides historical and future trends in emissions of local air pollutants (fine particulate matter, nitrogen oxides, and nonmethane hydrocarbons) and short-lived climate pollutants (black carbon, methane, organic carbon, and sulfates), highlighting the effects of progressive vehicle emission and fuel standards over baseline policies.

3.2.1 Emissions of Local Air Pollutants

Figure 11 depicts historical and future trends in emissions of fine particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), and nonmethane hydrocarbons (HC) in each of the regional groups evaluated in this study. Activity trends are also shown to contextualize emissions trends.

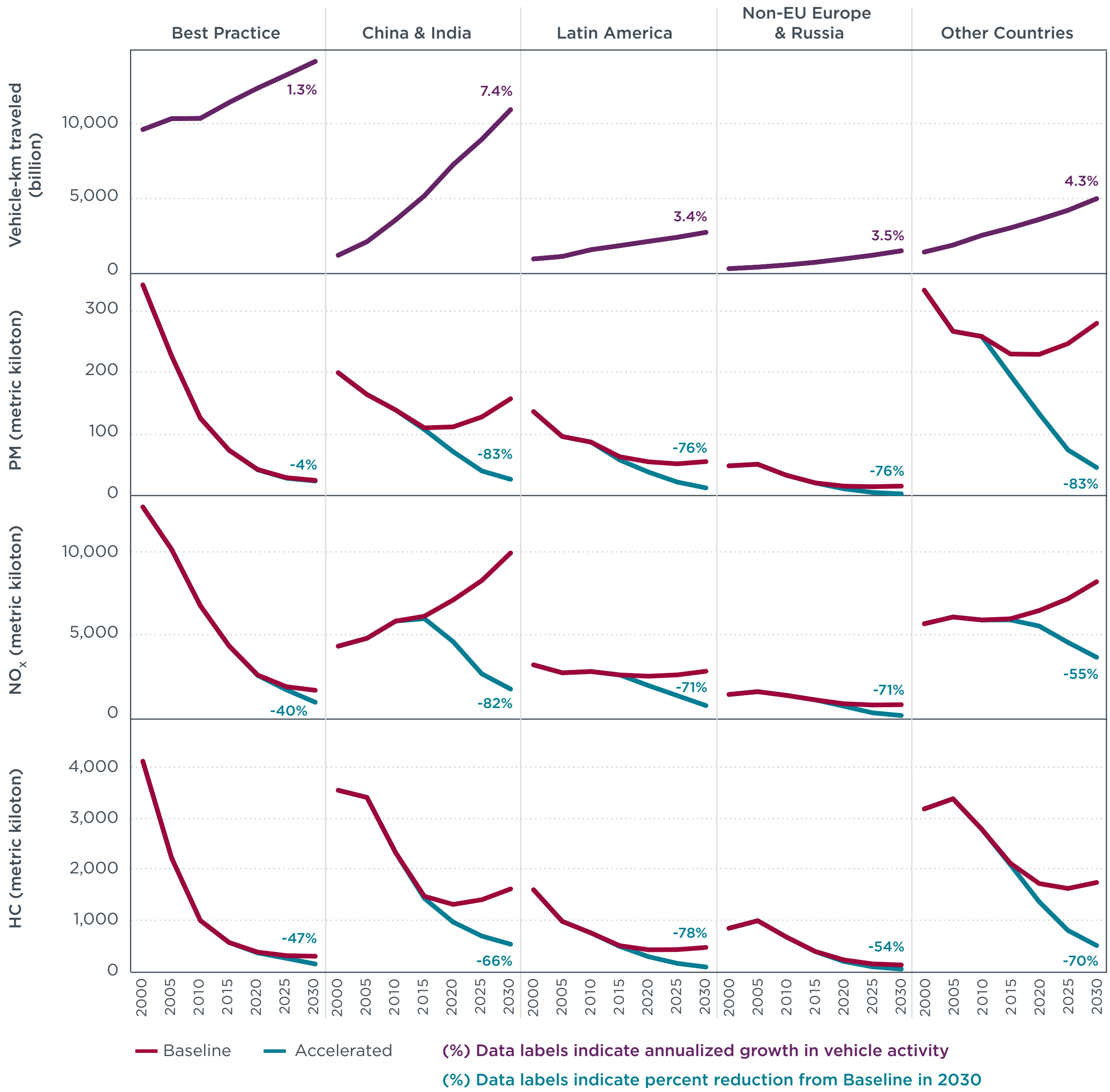

Figure 11: Trends in total activity and tank-to-wheel emissions

The Best Practice group houses the EU-28, the United States, Canada, Japan, Australia, and South Korea; the Other Countries group contains all countries in Asia-Pacific region, with the exception of China, India, Japan, Australia, and South Korea, as well as Africa, and the Middle East.

Reductions in vehicle emissions from 2000 through 2015 are driven primarily by recent progress in vehicle emission and fuel standards. These reductions occur rapidly and continue despite increases in activity. The countries within the Best Practice group account for the largest share of emission reductions achieved thus far, shifting emissions trends downward even while vehicle activity continues to grow. Adoption of next-generation emission standards (post–Euro 6/VI) would provide a further 50 percent reduction in NO_x and a 40 percent reduction in HC in the Best Practice group in 2030 compared with the baseline. Additional reductions would be expected beyond 2030 as more new vehicles meeting those standards are added to the fleet.

While all regions show decreased $PM_{2.5}$ and HC emissions from 2000 to 2015, NO_x emissions have remained relatively constant in some regions. In China and India, they have actually increased. While the early stages of Euro standards implementation provide significant reductions in $PM_{2.5}$ emission rates, the most dramatic reductions in NO_x emission rates do not come until Euro IV and beyond. Furthermore, projected growth in vehicle activity after 2015 will overwhelm the benefits of currently adopted standards, especially for China, India, and the Other Countries group.

Under a Baseline Policy scenario, $PM_{2.5}$ emissions in China and India are forecast to increase from 2015 through 2030—a reversal of the steady decline from 2000 through 2015. Both countries have achieved significant emissions reductions through the adoption of increasingly progressive vehicle emissions standards in the past fifteen years—many cities in India now require Euro IV–equivalent fuels and vehicles, and China recently implemented Euro 4/IV–equivalent standards nationwide. However, these policies are not sufficient to offset the continuing rapid growth in vehicle activity. Without further policy change, emissions of $PM_{2.5}$ are projected to increase after 2010 in India and after 2020 in China. In an Accelerated Policy scenario, China and India achieve a combined 80 percent reduction of $PM_{2.5}$ emissions and an 80 percent reduction of NO_x emissions in 2030 compared with the Baseline Policy scenario.

In Latin America, this study predicts a decrease in $PM_{2.5}$ and HC emissions through 2015 under existing policies, with emissions of those pollutants stabilizing after 2015. NO_x emissions are expected to remain stable from 2005 through 2030. Policy progress in Latin America is counteracting emissions growth that would otherwise be expected with moderate increases in vehicle activity, but such policies are not strong enough to drive long-term declines in emissions.

Non-EU Europe and Russia, which are also forecast to experience tempered growth rates in vehicle activity, are likely to follow trends similar to Latin America in both $PM_{2.5}$ and HC emissions under existing policies. Reductions will continue through 2020 and then stabilize in future years. Expected progress toward full implementation of Euro IV/V–equivalent standards and low-sulfur fuel will result in reductions of NO_x emissions through 2020.

The Other Countries group will experience a trend in emissions similar to the China and India group under the Baseline Policy scenario. Emissions of $PM_{2.5}$ are projected to decline slightly through 2015, then will rise again with new vehicle activity. NO_x emissions are relatively unchanged through 2015, then will rise through 2030. HC emissions will decline through 2030. The overall magnitude of $PM_{2.5}$ emissions will be nearly double that of the China and India group, although NO_x and HC emissions will remain roughly equivalent to those of the two emerging giants. The potential reductions in $PM_{2.5}$ emissions in the Other Countries group under an Alternative Policy scenario appear to be the largest of any regional group. NO_x and HC emission reductions are similarly large, although the magnitude of reductions is not quite as great as for China and India.

Without further progress toward more stringent emission standards, most regions are bound to see no change or rising trends in vehicle emissions by 2030. A Euro 6/VI regulatory pathway would lead to greater reductions in emissions in Latin America, non-EU Europe, and Russia. In the cases of China, India, and countries in the Asia-Pacific-40, as well as Africa and the Middle East, the successful implementation of progressive standards could reverse emissions trends and result in substantial additional reductions of all pollutant species in spite of unprecedented rates of growth in vehicle activity.

3.2.2 Emissions of Short-Lived Climate Pollutants

The change in emissions under the Accelerated Policy scenario can be converted to a carbon dioxide equivalent to estimate climate benefits. Because of the briefer lifetime of these pollutants in the atmosphere, the duration of their effects is limited in comparison with long-lived species such as carbon dioxide (CO_2). For this reason, these pollutants are referred to as short-lived climate pollutants (SLCPs). The global warming potential (GWP) of carbon dioxide over different time spans is often used as a benchmark to compare the climate impacts of various SLCPs. The GWP is used here to convey the climate impacts of a pulse emission of a pollutant in terms of an equivalent amount of carbon dioxide after a given time period (Fuglestvedt et al. 2010).

Two sets of GWP values are applied to describe climate impacts after a 20-year and 100-year time period (GWP-20 and GWP-100, given in Appendix V). Emissions estimates based on the GWP-20 should be interpreted in the context of a policy goal that aims to reduce the rate of climate change (i.e., temperature change per year). Estimates based on the GWP-100 value should be interpreted in the context of a goal to mitigate peak temperature change (e.g., limiting climate change to no more than two degrees Celsius). The shorter-term GWP-20 estimates are larger since strategies to curtail short-lived climate pollutants are more effective at reducing the rate of climate change than they are at suppressing peak temperature change. Whatever the policy aim, SLCPs should be a part of any climate change mitigation strategy.

Figure 12 illustrates the trajectories of SLCP emissions—black carbon, methane, organic carbon, and sulfates—for different regions under the Baseline and Accelerated Policy scenarios. The countries in the Best Practice group were responsible for the largest share (approximately 50 percent) of CO_2-equivalent (CO_2e) emissions in 2000. In response to existing policies, CO_2e emissions in the Best Practice group will fall more than 80 percent below 2000 levels by 2030. These reductions will drive the global trend in SLCP emissions through 2020, when increased emissions from China, India, and the Other Countries group (Africa, the Middle East, and the Asia-Pacific-40) shift the trend upward. By 2030, India is projected to be the largest regional contributor to on-road emissions of SLCPs, accounting for 24 percent of the total. Under the Baseline Policy scenario, global SLCP emissions will have declined by 20 percent overall from 2000 to 2030 but will be increasing annually after 2020.

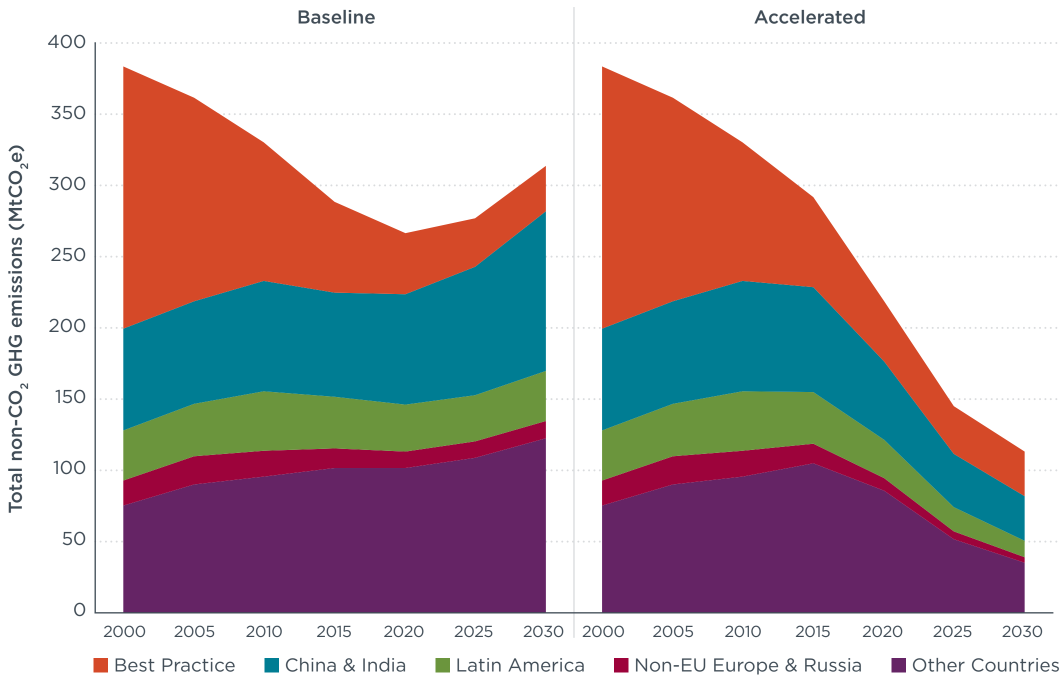

Figure 12: Net global non-CO_2 tank-to-wheel greenhouse gas (GHG) emissions from on-road vehicles under the Baseline and Accelerated Policy scenarios (GWP-100)

The Best Practice group houses the EU-28, the United States, Canada, Japan, Australia, and South Korea; the Other Countries group contains all countries in the Asia-Pacific region, with the exception of China, India, Japan, Australia, and South Korea, as well as Africa and the Middle East.

Table 2 summarizes the net near-term and long-term climate benefits of the Accelerated Policy scenario relative to the Baseline scenario, expressed as a function of their 20-year and 100-year GWP, respectively. Worldwide adoption of Euro 6/VI–equivalent standards for on-road vehicles would drastically curtail future emissions of SLCPs, with an expected reduction of 64 percent by 2030 compared against the Baseline scenario. This translates to net near-term climate impacts of about 710 million metric tons of carbon dioxide equivalent ($MtCO_2e$), or long-term impacts of about 200 $MtCO_2e$.[6] To place these estimates in context, a recent study estimated that, by 2030, greenhouse gas (GHG) emission reductions from all future policies (i.e., those not yet adopted) aimed at improving vehicle efficiency would produce climate benefits amounting to 2 gigatons ($GtCO_2e$) in 2030.[7] Therefore, worldwide adoption of Euro 6/VI–equivalent standards would yield near-term benefits equivalent to 36 percent and long-term benefits equivalent to 10 percent of the potential climate benefits from future vehicle efficiency policies. Reductions in black carbon emissions account for roughly 95 percent of the climate benefits of worldwide Euro 6/VI–equivalent standard adoption, while reductions in methane make up the remaining benefits. Since organic carbon and sulfates, which cause cooling, are reduced, 14 percent of the total climate benefits of cutting black carbon and methane are offset.

In the Accelerated Policy scenario, India will achieve the greatest reduction of SLCP emissions and together with China will account for 40 percent of global climate benefits from SLCP reductions in 2030. Non-EU Europe and Russia will generate 4 percent of the benefits, Latin America, 11 percent, and the Other Countries group, the remaining 44 percent.

6 Near term refers to the integrated radiative forcing over a 20-year time horizon from a single pulse emission averaged over a year. Near-term impacts are associated with the rate of temperature change (i.e., degrees Celsius per year). Long term refers to the integrated radiative forcing over a 100-year time horizon from a single pulse emission averaged over a year. Long-term impacts are associated with peak temperature change (e.g., degrees Celsius in 2100).

7 International Council on Clean Transportation, *Global Transportation Energy and Climate Roadmap.* This study included long-term climate effects of carbon dioxide, methane, and nitrogen dioxide based on their global warming potential using a 100-year time horizon.

Table 2: Global non-CO_2 climate benefits of the Accelerated Policy scenario relative to the Baseline Policy scenario in 2030 ($MtCO_2e$). Positive numbers indicate a warming effect and negative numbers indicate a cooling effect.

	2030 Annual Climate Benefits		Cumulative Climate Benefits (2015–30)	
	GWP-20	GWP-100	GWP-20	GWP-100
Black Carbon (BC)	760	220	5,770	1,650
Methane (CH_4)	30	10	280	100
Nitrous Oxide (N_2O)	-10	-10	-50	-60
Organic Carbon (OC)	-60	-20	-440	-130
Sulfates	-30	-10	-340	-90
Total	**710**	**200**	**5,230**	**1,470**

3.2.3 Fleet Turnover and Average Emission Rates

Emission rates (in grams of pollutant per vehicle-kilometer traveled), alongside vehicle activity, are one of the fundamental indicators of total vehicle emissions. With the implementation of increasingly stringent vehicular standards, fleetwide average emission rates will continue to drop over time as vehicles meeting the new standards enter the fleet and displace older, higher-emitting models, a process that can take decades to complete.

Strong growth in vehicle activity drives the demand for new vehicles, which amplifies the benefits of new vehicle standards and accelerates reductions in average vehicle emission rates. In other words, there is an added benefit of introducing standards for new vehicles in countries with rapidly growing fleets. Figure 13 illustrates how new heavy-duty vehicle standards can bolster the share of activity by cleaner vehicles and how these drive NO_x emission reductions in China. In the Baseline Policy scenario, many new Euro IV vehicles enter the fleet starting in 2013 and ultimately account for the majority of vehicle activity in 2030. Although Euro IV provides substantial reductions in NO_x emissions over Euro III, activity growth offsets the reduction in vehicle emission rates. In the Accelerated Policy scenario, Euro V vehicles also begin to enter the fleet in 2015, with subsequent introduction of Euro VI vehicles in 2018. Because Euro V and VI vehicles provide much greater NO_x reductions, by 2030, the total NO_x emissions in the Accelerated Policy scenario are less than 15 percent of the emissions in the Baseline Policy scenario.

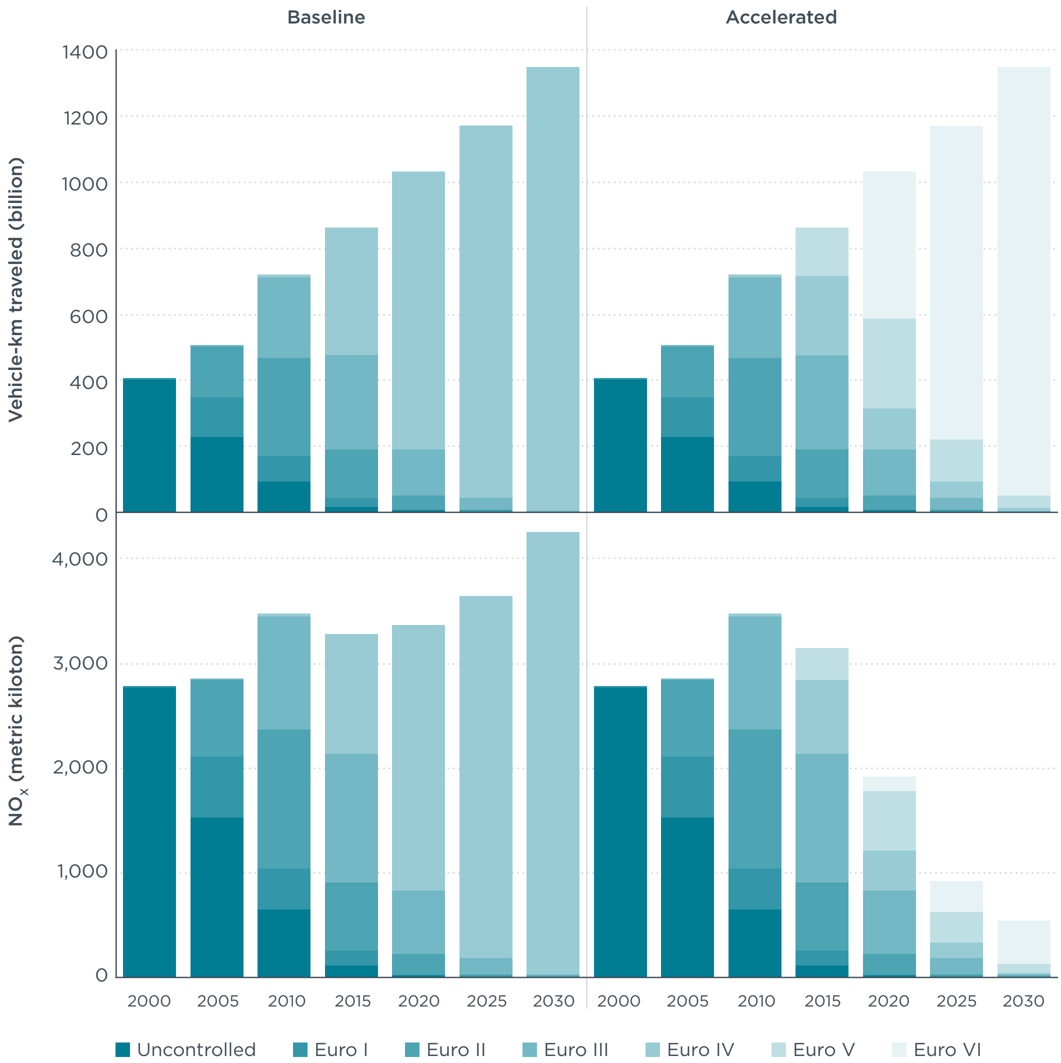

Figure 13: Share of HDV activity and NO_x emissions by emission control level in China

Figure 14 illustrates fleet-average emission rates of $PM_{2.5}$ and NO_x for different regions under the Baseline and Accelerated Policy scenarios. While emission rates decrease for all regions under the Baseline scenario, a considerable gap remains between emission rates across different regions by 2030. In contrast, worldwide policy adoption leading toward Euro 6/VI standards could drive convergence in fleet-average emission rates, although slower implementation in some regions will cause gaps to remain in 2030. This is especially the case for NO_x emission rates in the Other Countries group because the study assumes that the implementation of Euro 5/V and 6/VI standards, which prompt the largest improvements in NO_x emission rates, will occur only after 2030.

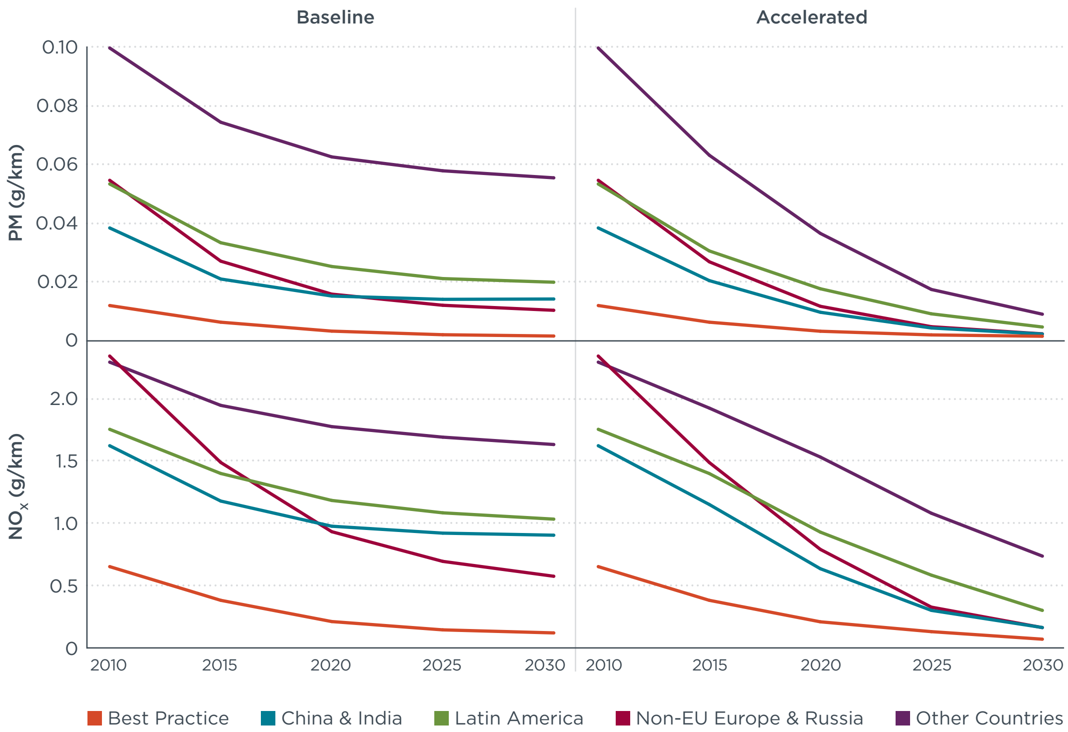

Figure 14: Fleet-average emission factors by regional group

The Best Practice group houses the EU-28, the United States, Canada, Japan, Australia, and South Korea; the Other Countries group contains all countries in the Asia-Pacific region, with the exception of China, India, Japan, Australia, and South Korea, as well as Africa and the Middle East.

3.2.4 Emissions by Mode

Some of the biggest emission gains come from tackling HDVs and diesel engines. Diesel engines are the paramount vehicular emissions source in all regions that have not yet adopted Euro VI standards. In the absence of additional policy action, HDVs will continue to contribute the bulk of primary $PM_{2.5}$ and NO_x emissions through 2030 in all regional groups excluding those that have adopted Euro VI–equivalent standards.

Figure 15 illustrates the share of $PM_{2.5}$ emissions by mode for different regions under the two scenarios evaluated in this study. The greatest opportunities for reducing $PM_{2.5}$ emissions are in progressing to Euro IV and Euro VI, standards that require the use of diesel oxidation catalyst/selective catalytic reduction and diesel particulate filter after-treatment, respectively, to cut emissions from diesel vehicles, which in most regions are primarily heavy-duty trucks and buses. Euro VI for HDVs could yield the largest absolute reduction in particulate emissions of any mode or standard. Compared with emissions under baseline policies, the move to Euro VI standards for HDVs would be responsible for 65 percent of emission reductions in China and India and roughly 70 to 95 percent of emission reductions in all but the Best Practice group.

Particulate matter from passenger vehicles is important in regions with a high share of diesel engines in the passenger fleet. By 2030, passenger diesel vehicles will make up 60 percent of India's LDV fleet, 23 percent in non-EU Europe, 13 percent in the Asia-Pacific-40, and 11 percent in China. The importance of dealing with primary particulates from LDVs and motorcycles—which use gasoline or other nondiesel fuels for the most part—increases over time as more HDVs meet Euro VI–equivalent requirements. For example, LDVs will contribute the majority of $PM_{2.5}$ emissions in the Best Practice group in 2030.

Historically, only a small share of total vehicle emissions is attributable to two- and three-wheeled vehicles. However, with recent rapid growth in sales and activity in China, India, and other countries in the Asia-Pacific and other emerging markets, such vehicles now add significantly to both $PM_{2.5}$ and NO_x emissions in some regions. These lighter modes of transportation present a clear opportunity for policy improvement: fewer countries have adopted stringent standards for two- and three-wheeled vehicles than for LDVs or HDVs, and only the EU-28 has adopted Euro 5. Advancing to Euro 5 standards or next-generation standards for these vehicles across all regions would result in an annual savings of 29 metric kilotons of $PM_{2.5}$ in 2030.

Figure 15: On-road primary $PM_{2.5}$ emissions by mode (metric kilotons)

The final column shows the percentage reduction in emissions in the Accelerated Policy scenario compared to the Baseline scenario in 2030. The Best Practice group houses the EU-28, the United States, Canada, Japan, Australia, and South Korea; the Other Countries group contains all countries in the Asia-Pacific region, with the exception of China, India, Japan, Australia, and South Korea, as well as Africa and the Middle East.

Figure 16 illustrates the share of NO_x emissions by mode for different regions under the two scenarios evaluated in this study. As with particulates, HDVs account for the majority of on-road NO_x emissions, contributing 70 percent in 2000 and 80 percent in 2010. Pre–Euro VI standards for HDVs offer only modest reduction of NO_x emission rates, which together with activity growth drive the continued increase in HDV NO_x emissions under the Baseline Policy scenario in China, India, Latin America, and the Other Countries group (Africa, the Middle East, and the Asia-Pacific-40). Euro VI standards for HDVs will be responsible for the majority of on-road NO_x emission reductions in the Accelerated Policy scenario, accounting for more than 85 percent of reductions in China and India and more than 90 percent of reductions in all regions other than the Best Practice group.

Unlike $PM_{2.5}$ emissions, NO_x from LDVs and two- and three-wheeled vehicles also increases quickly in some regions as activity grows, especially in China and India. Without additional standards beyond those in the Baseline scenario, motorcycle emissions are forecast to increase in all regional groupings but the Best Practice and the non-EU Europe and Russia groups.

In summary, the implementation of stringent emission limits on heavy-duty diesel vehicles results in the greatest reduction of $PM_{2.5}$ and NO_x emissions in countries that have not yet adopted Euro 6/VI standards.

Figure 16: On-road NO_x emissions by mode (metric kilotons)

The final column shows the percentage reduction in emissions in the Accelerated Policy scenario compared to the Baseline scenario in 2030. The Best Practice group houses the EU-28, the United States, Canada, Japan, Australia, and South Korea; the Other Countries group contains all countries in the Asia-Pacific region, with the exception of China, India, Japan, Australia, and South Korea, as well as Africa and the Middle East.

3.3 HEALTH IMPACT TRENDS

The study's assessment of trends in public health in response to vehicle emissions under Baseline and Accelerated Policy scenarios is restricted to premature mortality and years of life lost from exposure to tailpipe emissions of primary $PM_{2.5}$ in urban areas. These represent a significant share of the problems caused, although considering them in isolation underestimates the total health impairments caused by vehicle emissions. The impacts of secondary pollutants, both secondary PM and ozone, and the impacts of exposure in rural areas would add to the estimates presented here. The nonfatal health effects of vehicle pollution result in further harm and are discussed in the following section.

3.3.1 Benefits of Accelerated Policies

Worldwide adoption of progressive vehicle emission and fuel standards in the Accelerated Policy scenario could prevent approximately 210,000 premature mortalities in urban areas in 2030, providing a gain of nearly 25 million life years cumulatively from 2015 to 2030 (Table 3). India has the largest potential for health benefits, with approximately 6.2 million years of life gained, followed by the Middle East and Africa (4.5 and 4.4 million), the Asia-Pacific region (3.4 million), and China (3.1 million). The Latin America group and the non-EU Europe and Russia group could save roughly two million and one million years of life, respectively. And although many benefits have already been realized from standards adopted by countries in the Best Practice group, further policy progress in this region could yield additional benefits adding up to about 76,000 years of life through 2030.

Premature mortality and years of life lost are similar but not identical indicators. Both reflect the sum of early deaths associated with on-road $PM_{2.5}$ emissions in urban areas, but while premature mortality is the unadjusted sum of all early deaths, years of life lost also integrates age and life expectancy at the time of death. In regions with aging populations, as is the case for many developed countries, premature mortality may be associated with a lower number of years of life lost than in regions with younger populations, such as Africa and the Middle East.

Table 3: Health benefits of the Accelerated Policy scenario compared with the Baseline Policy scenario

Region	Premature Mortalities (thousands)			Years of Life (thousands)			
	2030 Baseline	2030 Accelerated	2030 Reduction	2030 Baseline	2030 Accelerated	2030 Reduction	2015-2030 Cumulative Reduction
Best Practice group	**14**	**13**	**1**	**130**	**120**	**10**	**80**
EU-28	4	4	0	40	40	0	0
United States	4	4	0	40	40	0	10
Canada	0	0	0	0	0	0	0
Japan	3	3	0	20	20	0	10
Australia	0	0	0	0	0	0	10
South Korea	3	2	1	30	20	10	50
China & India	**113**	**23**	**90**	**1,710**	**340**	**1,370**	**9,280**
China	55	14	41	660	170	490	3,120
India	58	9	49	1,050	170	880	6,160
Latin America	**31**	**7**	**24**	**390**	**100**	**290**	**2,260**
Brazil	4	1	3	40	20	30	260
Latin America-31	18	4	14	220	50	170	1,270
Mexico	9	2	7	120	30	90	730
Non-EU Europe & Russia	**9**	**3**	**6**	**120**	**40**	**80**	**650**
Non-EU Europe	4	1	3	60	10	50	400
Russia	5	2	3	60	30	40	260
Other Countries	**115**	**23**	**92**	**2,070**	**410**	**1,660**	**12,270**
Africa	31	6	25	670	120	550	4,380
Asia-Pacific-40	46	12	34	760	200	560	3,360
Middle East	38	5	33	640	90	550	4,520
Global Total	**282**	**69**	**213**	**4,410**	**1,010**	**3,410**	**24,540**

Figure 17 illustrates trends in years of life lost across regional groupings. The two groups with highest premature mortality in the Baseline scenario—China/India and the Other Countries—experience the greatest health benefits under the Accelerated Policy scenario. While just 15 percent of current and projected future vehicle activity occurs in the Other Countries group, it suffers 50 percent of global years of life lost from exposure to on-road primary particulates. Health impacts in this regional group are forecast to decline in the near term as countries reduce fuel sulfur content and as recently adopted emission standards are fully implemented. However, health issues will increase after 2020 without further reductions in vehicle emission rates. The majority of years of life lost within the Other Countries group will occur among the Asia-Pacific-40, and this region could realize the greatest potential benefit from adoption of more progressive vehicle emission and fuel standards.

As India and China are the two most populous countries, they bear a large share of the burden. Despite a significant decrease in $PM_{2.5}$ emissions from 2000 through 2010 (Figure 11), the health incidences in these countries declined at a slower rate over that period. When emissions spread through densely populated areas, a large number of people are put at risk. With increasing urbanization in these countries, exposure to vehicle emissions will grow even as emission totals decrease. Thus, health complications rise in China in the Baseline Policy scenario from 2015 through 2020 despite concurrent decreases in $PM_{2.5}$ emissions. In India after 2010 and China after 2020, impacts increase faster than $PM_{2.5}$ emissions. With expected population growth and urbanization, India will surpass China as the region with the most premature deaths and years of life lost from vehicle emissions.

Implementation of Euro 6/VI or equivalent standards could reverse the trend of ever greater years of life lost from vehicle $PM_{2.5}$ emissions in China, India, Africa, the Asia-Pacific-40, and other regions. While years of life lost in China and India are projected as more than doubling between 2000 and 2030 in the Baseline scenario, the Accelerated Policy scenario results in a 60 percent reduction from year-2000 levels. This represents an 80 percent reduction in years of life lost in the Accelerated Policy scenario compared with the Baseline in 2030. Similarly, the Other Countries group (Africa, the Middle East, and the Asia-Pacific-40) would expect years of life lost to increase by 80 percent in 2030, but under an Accelerated Policy these impacts would instead decrease by more than 60 percent over the same time frame.

Latin America, non-EU Europe, and Russia command a smaller share of the global population than the other developing region groups and would thus reap smaller benefits in absolute terms. Countries in these regions would nonetheless expect under an Accelerated Policy scenario to realize a nearly 80 percent reduction in years of life lost in 2030, comparable to the percentages anticipated in China and India.

Although the Best Practice group will experience growth in vehicle activity of 50 percent by 2030 from 2000 levels, health effects in these countries will rapidly decrease over time because of the introduction of progressively stricter vehicle emission and fuel standards. Vehicle emission standards beyond Euro 6/VI considered in the Accelerated Policy scenario are not associated with $PM_{2.5}$ reductions, and so the health benefits are not estimated here. This study did not quantify the additional health benefits from lower NO_x and HC vehicle emissions. Health impacts under the Baseline and Accelerated Policy scenarios would be essentially the same for the Best Practice group, with only modest gains from decreased motorcycle emissions.

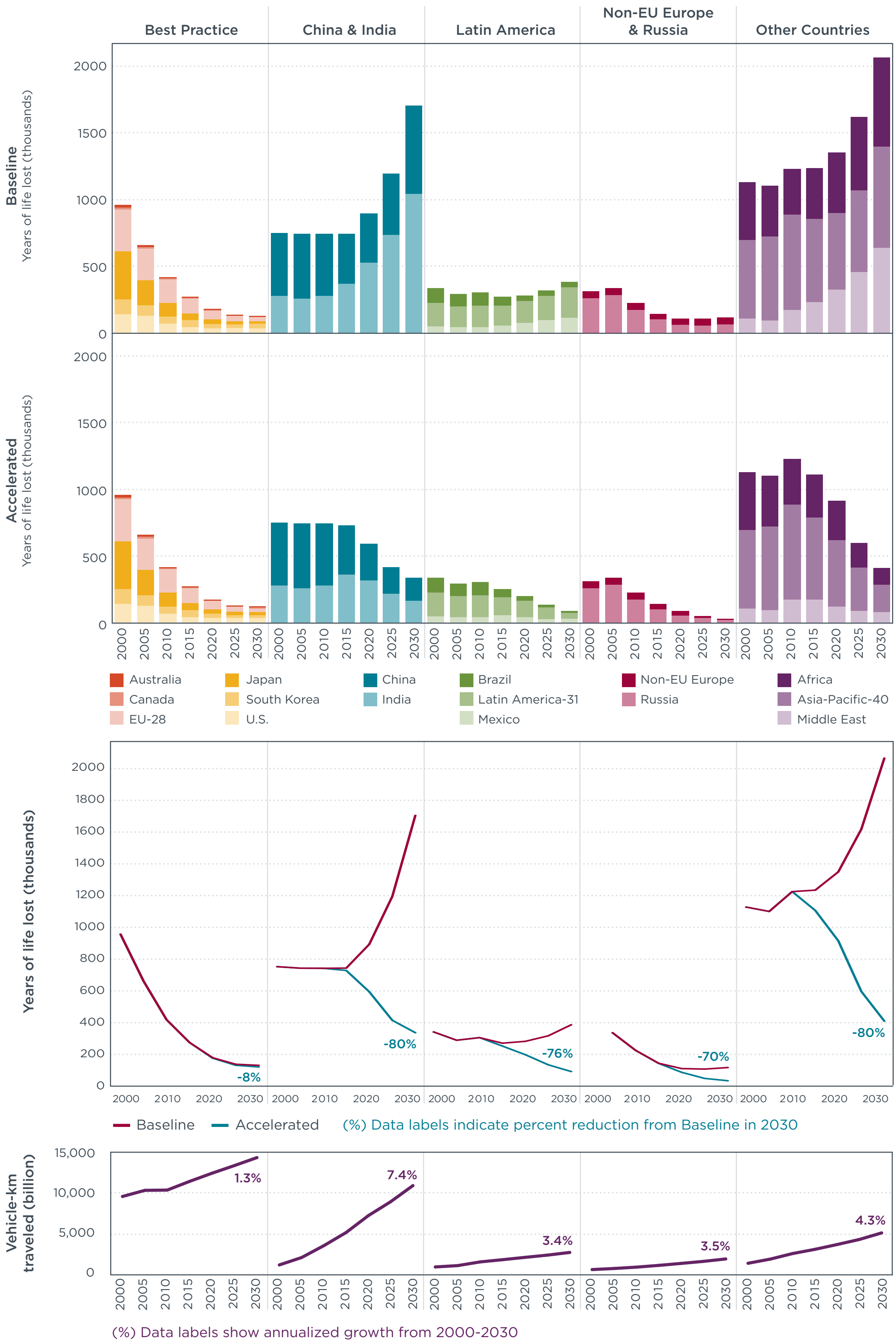

Figure 17: Years of life lost due to on-road primary $PM_{2.5}$ emissions

Trends in premature mortality are not shown since they mimic these trends. The Best Practice group houses the EU-28, the United States, Canada, Japan, Australia, and South Korea; the Other Countries group contains all countries in the Asia-Pacific region, with the exception of China, India, Japan, Australia, and South Korea, as well as Africa and the Middle East. Trends in vehicle activity are repeated here to provide context for the health impact trends.

Nonfatal Health Impacts

The health impacts presented in this analysis do not cover the full measure of adverse effects of transportation pollution. These can include problems unrelated to early death, which range from minor symptoms like eye irritation and reduced days of activity to more severe outcomes like hospitalization or heart failure. The lack of global-scale incidence data for these health issues and the lack of high temporal resolution in air quality estimates limited the health outcomes that could be included in the analysis. Other studies have evaluated nonfatal health impacts, and their results can provide a reference for the scale of other potential health benefits associated with reductions in $PM_{2.5}$.

Table B-1: Premature mortalities and associated nonfatal health impacts from outdoor air pollution ($PM_{2.5}$) (totals marked with * also include health impacts of ozone)

Study	Region (year)	Premature Mortalities	Hospitalizations (Respiratory and Cardiac Illness)	Emergency Room Visits	Restricted Activity Days
Kuschel et al. 2012	New Zealand (2006)	1,000	600	Not estimated	1.4 million
Guttikunda and Goel, 2013	Delhi (2010)	7,000–16,000	31,000	480,000	51.2 million
U.S. EPA 2011	United States (2010)	164,000	86,000*	86,000	84 million*
U.S. EPA 2011	United States (2020)	237,000	135,000*	120,000	110 million*

In summing up the health toll of outdoor air pollution, early deaths predominate, whether evaluated using cost-benefit analysis or measured in terms of disability-adjusted life years (DALYs). In the monetary valuation of the health effects of the U.S. Clean Air Act, reduction in premature mortalities accounted for 96 percent of the economic value of health benefits. In the Global Burden of Disease study for 2010, years of life lost, the metric associated with mortality, accounted for 95 percent of total DALYs, which combine years of life lost and years lived with disability from cardiovascular and respiratory disease, stroke, and lung cancer. Still, nonfatal health conditions affect many people and are important to consider when evaluating the overall benefit of pollution reduction.

3.3.2 Health Impact Rates

Figure 18 illustrates age-adjusted, transportation-attributable mortality rates across regions under the Baseline and Accelerated Policy scenarios. A mortality rate reflects the risk of fatal vehicle emissions exposure in terms of deaths per 1,000,000 population. Since countries with large populations and an older age structure would be expected to have a higher share of early deaths, all things being equal, age-adjusted mortality rates normalize differences in both population size and age distribution in order to provide a more fair comparison among regions. In regions with higher age-adjusted, transportation-attributable mortality rates, on-road $PM_{2.5}$ emissions pose a greater threat to public health than in regions with lower rates.

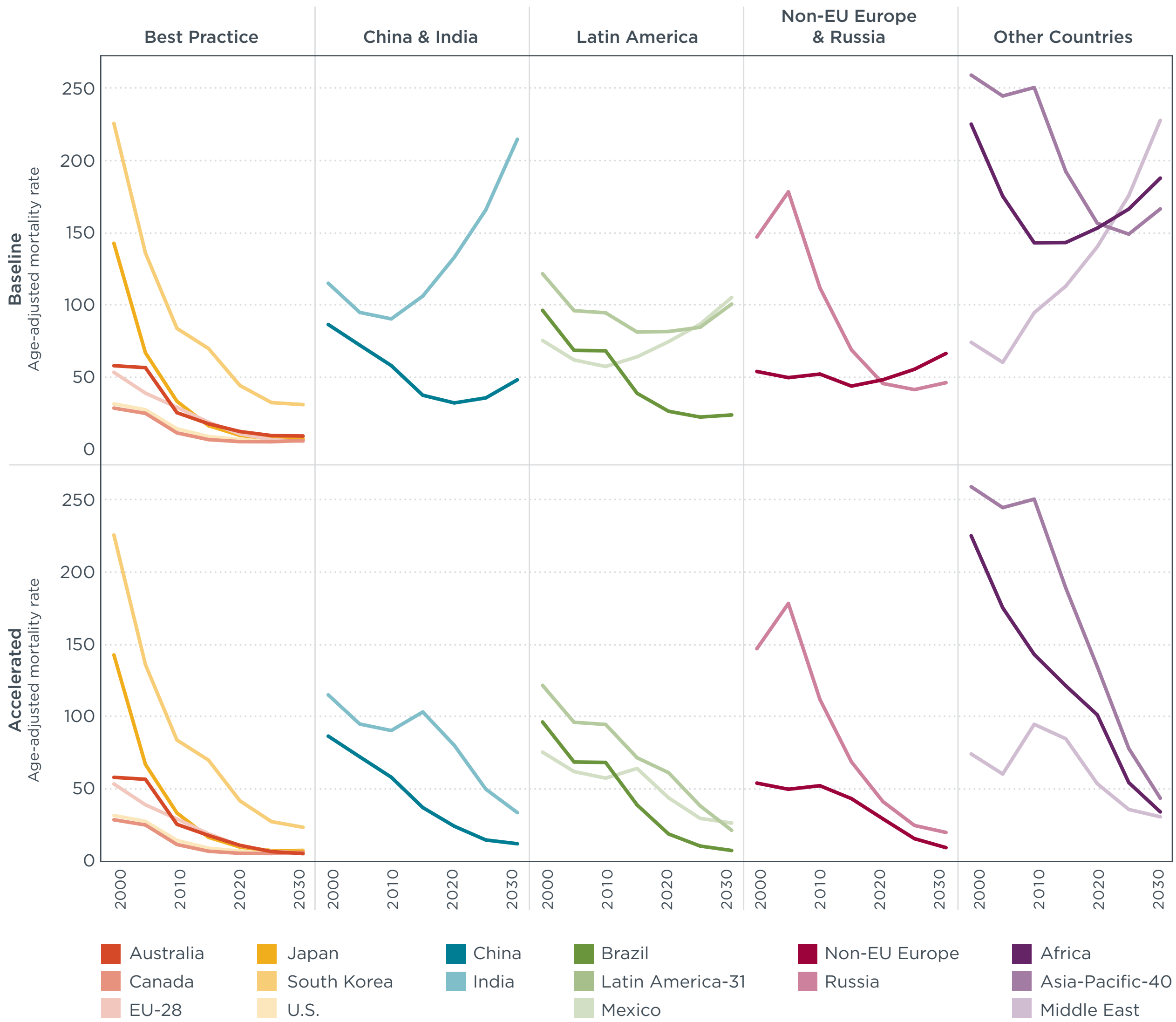

Figure 18: Age-adjusted, transportation-attributable mortality per million population

These rates only reflect changes in risk from vehicle emissions. They do not indicate projected changes in the total mortality rate, nor do they incorporate projected changes in the background incidence of cardiopulmonary or cardiovascular disease attributable to developments affecting other risk factors.

Under the Accelerated Policy scenario, mortality rates are substantially reduced across all regions, and many begin to converge at the rate achieved by countries in the Best Practice group in 2030. While the highest health impact rates (in India and the Middle East) are projected to be more than thirty times that of the lowest (EU-28) in 2030 under the Baseline scenario, worldwide adoption of Euro 6/VI could reduce this to a fivefold difference by 2030. Disparities in rates across regions persist for several reasons: the differing pace of vehicle activity growth (because higher levels of motorization and vehicle activity per capita will lead to higher mortality rates, all else being equal); the share of vehicle activity by fuel type (until Euro 6/VI standards are in place, diesel vehicles generate more on-road particulate exposure than gasoline vehicles, resulting in more severe health problems, assuming equal driving distances and cycles); the timeline for adoption of Euro 6/VI or equivalent standards (because earlier adoption leads to a higher share of cleaner vehicles by 2030); and variation in health effects per unit of particulate emissions.

The Best Practice group will achieve rapid decreases in transportation-attributable mortality rates through the adoption of stringent vehicle emissions standards. A relatively high mortality rate in South Korea reflects high per capita vehicle activity combined with a comparatively high-emitting fleet. South Korea has followed a policy timeline that is delayed by several years with regard to other countries in the Best Practice group. South Korean cities may also be penalized by their urban layout and geographical conditions, which reflect high population density and naturally limited ventilation that would tend to increase population-level exposure relative to other cities.

Under the Baseline scenario, India stands apart for its accelerating rate of early deaths attributable to transportation. One development contributing to this trend is rapid urbanization. The number of people living in cities in India is expected to increase by 60 percent between 2010 and 2030—the fastest rate of growth of any major region except Africa. While mortality rates control for population size and would not be expected to change through population growth alone, they do capture an increase in the population exposure per unit of emissions that comes with increasing urbanization. Along with this trend in urbanization, vehicle activity in India is forecast nearly to triple over the same twenty-year period—the highest rate of growth in the world. Amid swift urban population growth and increased vehicle activity, much of India remains at emission standards equivalent to Euro III.

The trend of dieselization in India's light-duty vehicle fleet poses an additional health burden. In 2000, diesel vehicles accounted for roughly 20 percent of LDV activity; in 2030, they are forecast to make up more than half and will emit more than 97 percent of the total $PM_{2.5}$ mass stemming from LDVs. In accordance with the adopted policies in the Baseline scenario, diesel LDVs will meet emission limits equivalent to Euro 3 or Euro 4; however, for light-duty vehicles, the steepest single-step reduction in particulate emissions occurs between Euro 4 and Euro 5. All this contributes to an unparalleled increase in health impact rates forecast in the Baseline scenario. Meanwhile, adoption of Euro 6/VI or equivalent standards, especially for diesel LDVs and HDVs, could reduce health incidences in India by 80 percent in the year 2030.

Transportation-attributable mortality rates in the various countries of Latin America, non-EU Europe, and Russia will decrease in the near term in the Baseline scenario, but these reductions will not be sustained beyond 2020 because of growth in vehicle activity and increased total exposure to vehicle emissions as an effect of intensifying urbanization.

While the rates of health impairment and mortality tend to diminish out to 2020, regions that have not yet adopted Euro 6/VI or equivalent standards will experience an increase beyond 2020 as growth in vehicle activity outpaces marginal reductions in fleet emission rates from the adopted vehicle emission standards considered in the Baseline Policy scenario.

3.3.3 Comparison of Health Results with Previous Studies

As with most modeling-based analyses, there is uncertainty in the calculation of global health impacts from motor vehicles. Comparing the results of this analysis with other studies can help contextualize these findings, along with the uncertainties in modeling assumptions and input data.

There have been few global-scale assessments of the health consequences of transportation-generated pollution. One recent analysis by Shindell et al. (2011) bears many similarities to the one presented here. It compares the impacts of transportation pollution under a baseline policy scenario with those that would follow worldwide adoption of stringent emission standards. Shindell and colleagues consider a broader range of pollutants and health problems than does this study; they use a global composition-climate model (G-PUCCINI) to forecast global air quality and climate change and produce health impact estimates that include secondary particulates and ozone. Figure 19 shows that, despite differences in emissions calculations and air quality modeling techniques, the two analyses produce comparable health outcome estimates. Although the analysis here considers only urban exposure to primary $PM_{2.5}$, the health benefit estimates for Latin America and Africa surpass the range projected by Shindell and colleagues. The estimated benefits in China and India from this analysis fall in the lower end of the range given by the Shindell report, in part because of the exclusion of ozone. Shindell and colleagues estimate that ozone may cause more than half of the premature mortalities in China and India. Were the analysis laid out here to consider the effects of ozone, secondary $PM_{2.5}$, and rural exposure, the estimated policy benefits might be greater than those estimated by Shindell et al.

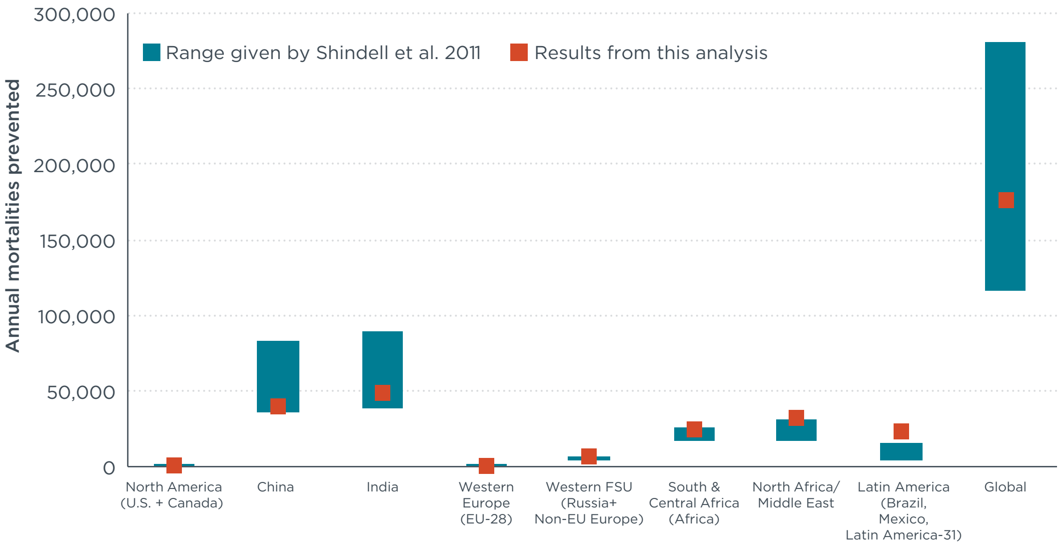

Figure 19: Comparison of benefits estimates between this analysis and Shindell et al. (2011)

The values shown are the annual mortality differences between the Baseline scenario and the tight-standards scenario (similar to this report's Accelerated Policy) in the year 2030.

4 CONCLUSIONS

This report examines the global health impacts of on-road fine particulate matter ($PM_{2.5}$) emissions in urban areas from a worldwide shift toward more progressive fuel and new vehicle emission standards. Its analysis yields a wealth of information, from global trends in vehicle activity and emissions of local air pollutants to specific policy considerations in individual countries. This chapter highlights some of the major policy implications drawn from the findings of the analysis.

National standards for vehicle emissions and fuels can be highly effective at reducing on-road emissions and associated health problems.

Europe, the United States, Canada, Australia, Japan, and South Korea have shown that well-designed new vehicle emission and fuel standards can be highly effective in reducing emissions and the associated health impacts of road transportation. Together, the policies that have already been adopted in these countries are projected to reduce particulate matter from on-road vehicles and premature mortality by 80 to 90 percent below 2000 levels by 2030. These standards have been supported by strong compliance and enforcement policies to ensure that manufactured vehicles meet emission limits and that engines and after-treatment systems continue to function throughout the vehicle's lifetime. Recent emission standards—Euro 6/VI and U.S. Tier 2/HD 2010—include in-use testing requirements that bolster the effectiveness of these programs. Developing such programs in other countries will be essential to ensuring that advances toward more progressive standards result in the intended emission reductions.

Accelerated adoption of standards for vehicles and fuels has significant potential to improve human health, with substantial benefits for climate as well.

In contrast to the improvement expected in the Best Practice group, early deaths from on-road $PM_{2.5}$ are projected to increase in other regions through 2030 in the absence of progress beyond currently adopted policies. Advancing to Euro 6/VI or equivalent standards in China, India, Latin America, non-EU Europe, Russia, and the Asia-Pacific-40—and Euro 5/IV in the Middle East and Africa—could reverse the worrisome trend. At the global level, the new timeline put forward in the Accelerated Policy scenario could prevent approximately 210,000 early deaths in the year 2030, providing a gain of 25 million years of life cumulatively from 2015 to 2030. These health benefits could be realized even in the context of increasing urbanization and high rates of growth in vehicle activity driven by economic development. Furthermore, early implementation of vehicle emission standards would be most beneficial in regions with rapidly rising vehicle sales because vehicles meeting higher standards more quickly become a larger share of the total fleet.

The potential emission reductions from vehicle and fuel standards are beneficial not only for health but also for reducing near- and long-term climate effects of transportation. Globally, the standards outlined in the Accelerated Policy scenario could avoid cumulative near-term impacts of 5.2 metric gigatons of carbon dioxide equivalent ($GtCO_2e$) and long-term impacts of 1.4 $GtCO_2e$ between 2015 and 2030. Reductions in black carbon emissions make up roughly 95 percent of the climate benefits of accelerated policy adoption, while reductions in methane account for the remaining benefits. Vehicle emission and fuel efficiency standards can be complementary, and future policies may see more harmonization between health- and climate-oriented regulations.

Although costs were not evaluated in this analysis, other studies have found that the benefits of even the most stringent fuel and vehicle standards outweigh the costs. The major costs imposed by these policies are (1) the increased outlays associated with refinery upgrades and operations to remove sulfur from fuels and (2) the per vehicle costs of control technologies to reduce emissions. Refinery upgrades to switch to ultra-low-sulfur diesel require a high up-front investment, yet the per liter cost is ultimately low. A recent study of desulfurization costs found significant variation by region—from 1 cent per liter in India to 3 cents per liter in Mexico—depending on the age and complexity of the existing refineries (ICCT 2012). The cost of control technology varies by vehicle type, and the price of meeting Euro 6/VI standards compared to no emissions control can range from a $500 increase for a gasoline-fueled car to a $6,800 (roughly 5 percent) increase for a heavy-duty commercial truck (ICCT in press). The economic benefits of such policies include not only the valuation placed on lives saved but also direct savings in health care costs averted and the gains in terms of worker productivity resulting from fewer days spent recovering from health problems or caring for a sick child. Additional value is realized through climate benefits. Many studies have found that the value of some or all of these benefits greatly surpasses the costs of the policies. In the United States, control of heavy-duty highway diesel emissions alone will result in environmental and public health benefits of $70 billion annually at a cost of $4 billion per year (U.S. EPA 2006). In China, a national program of fuel and vehicle standards could deliver $150 billion in public health benefits in 2030 at a cost between $300 and $900 per metric ton, much lower than the cost of programs in the United States and Europe (Blumberg et al. 2006), and in India, every dollar invested to reach Bharat VII standards and ultra-low-sulfur fuel by 2020 would return nine dollars in benefits by 2030 (Bansal et al. 2012). In sub-Saharan Africa, the health benefits of ultra-low-sulfur fuels would equal approximately $43 billion over 10 years from a total refinery investment of around $6.1 billion (IFC 2009). Similarly, in Mexico, an investment of about $4.6 billion to deliver ultra-low-sulfur fuel would generate health benefits equal to approximately $11.3 billion (SEMARNAT 2006). Moving to cleaner fuels and vehicles is a cost-effective way to improve air quality and public health.

Emerging vehicle markets are now responsible for the largest share of emissions and health impacts from on-road vehicles.

As vehicle fleets in countries with advanced standards in place become cleaner over time, the share of total early deaths from on-road vehicle $PM_{2.5}$ emissions has shifted to the rapidly growing markets of China and India and to countries in the Asia-Pacific region, Africa, and the Middle East. While China and India have made significant progress toward advanced emission standards, both are forecast to experience increasing health problems in the absence of continued policy progress because of growing vehicle activity. Similarly, developing countries bear a disproportionate health risk from on-road emissions: while only 15 percent of current global vehicle activity takes place in the Asia-Pacific-40, Africa, and the Middle East, these regions account for roughly 50 percent of global years of life lost from exposure to urban on-road primary particulates.

This suggests clear near-term priorities for a global emissions strategy that could be adopted by emerging vehicle markets. In China and India, it is imperative to continue the national push for clean fuels and vehicles that both governments have been pursuing throughout the past decade. Among the smaller countries, those with less stringent standards should seek to align with regional policy leaders—such as Chile and Brazil in South America, South Africa in sub-Saharan Africa, and Singapore and Thailand in Southeast Asia—and to continue along the path toward ultra-low-sulfur fuel and Euro 6/VI–equivalent emission standards. Progress can be driven by regional coordination and political agreements, like the collaboration among East African countries in developing unified fuel standards and the newly formed Association of Southeast Asian Nations (ASEAN) Clean Fuels and Vehicles Forum. International organizations like the United Nations Environment Programme Partnership for Clean Fuels and Vehicles, the UN Economic Commission for Europe's WP.29, and the International Council on Clean Transportation offer important technical support to create a policy roadmap and design effective new standards. Ultimately, however, national or city governments are the ones responsible for adopting and upholding new policies.

In countries with weak vehicle emission and fuel quality regulations, leapfrogging to milestone standards provides significant benefits and builds momentum for further progress.

Standards that require state-of-the-art control technology, specifically, diesel particulate filters for PM control, maximize emission reductions. Euro 6/VI or equivalent standards that require such technology are an aggressive but feasible goal for many regions by 2030. While many developing countries may also be able to achieve this regulatory aim, attaining that policy stage may seem out of reach in many countries that currently are twenty years or more behind standards already adopted in the Best Practice group. For regions where the average control technology requirements and the quality of available fuel are at Euro 2/II levels or below, Euro 4/IV is an achievable intermediate goal within the 2030 time frame. Euro 4/IV standards require that both heavy-duty vehicles (HDVs) and light-duty vehicles (LDVs) be equipped with exhaust after-treatment and diesel oxidation catalysts, plus a selective catalytic reduction system or exhaust gas recirculation for heavy-duty diesel vehicles. For optimal functioning of after-treatment mechanisms, Euro 4/IV regulations also require that diesel fuel with 50 ppm sulfur content or lower be nationally available. The shift from Euro I to Euro IV, including both fuel sulfur reduction and after-treatment processes, yields a $PM_{2.5}$ emission rate reduction of more than 90 percent for medium- and heavy-heavy-duty trucks, the two highest-polluting vehicle classes in regions with early-stage emission control policy.

Heavy-duty vehicle nitrogen oxide (NO_x) emission rates decrease by about 40 percent from Euro I to Euro IV. While this is a substantial improvement, Euro V and VI impose a much greater degree of control of NO_x emissions, reducing them by a further 85 to 90 percent from Euro IV. In the near term, countries can benefit greatly from a move to Euro 4/IV, but further progress will be needed to meet air quality goals and to continue to mitigate the associated health impacts as growth in vehicle activity continues.

The greatest opportunities for reducing premature mortality can be realized by adoption of Euro IV and Euro VI / U.S. 2010 requirements for diesel vehicles, primarily heavy-duty trucks and buses.

Diesel engines without after-treatment technology have very high PM emission rates compared with gasoline engines. Similarly, reducing NO_x emissions from diesel vehicles requires considerably more control technology than for gasoline vehicles. As a result, heavy-duty trucks and buses—most of which are powered by diesel engines—currently account for more than 80 percent of global PM and NO_x from on-road vehicles. This imbalance is driven by the relatively high emissions of diesel engines lacking advanced after-treatment technology and by the increased power requirements of heavy-duty vehicles. For diesel vehicles, the steepest reductions in PM are required in transitioning from Euro III to IV for HDVs and from Euro 4 to 5 for LDVs, with Euro 6/VI standards—designed to require a particulate filter for all diesel vehicles—bringing diesel PM emissions near the naturally lower levels emitted by gasoline vehicles.

Advancing to Euro 5 is especially important in regions in which diesel accounts for a significant share of the light-duty fleet. In the case of India, national vehicle emission standards are currently equivalent to Euro III for HDVs and Euro 3/4 for LDVs, stopping short of the greatest reductions in PM emissions for both vehicle classes. In the absence of new policies, national health complications will increase at unparalleled rates. In stark contrast, adoption of Euro 6/VI or equivalent standards, especially for diesel LDVs and HDVs, could reduce premature mortality in India from on-road emissions by 50,000 lives in 2030.

National pathways toward low- and ultra-low-sulfur fuel are critical to reducing the health consequences of on-road vehicles.

Ideally, standards for clean fuels and vehicles should be introduced as a package in order to optimize benefits. Reducing the sulfur content of fuel enables the implementation of vehicle standards that require advanced emission control technologies in new vehicles and immediately cuts emissions from the legacy fleet—especially from diesel vehicles. New vehicle emission standards that rely on cleaner fuels can push forward the needed infrastructure investments by refineries.

In countries where most or all vehicles are imported, trade restrictions based on age or vehicle emission control technology are an important complement to new vehicle emission standards. Tightening standards for secondhand vehicles from abroad, along with strengthened enforcement to prevent vehicle smuggling, can result in the import of vehicles with control technology that surpasses current new vehicle standards. In these cases, low-sulfur fuel standards are especially important for ensuring that vehicles with emission controls can operate with the appropriate fuel. Tightening standards to 50 ppm sulfur diesel will be necessary to achieve the major $PM_{2.5}$ and NO_X reductions offered by Euro IV technology. Further tightening to 10–15 ppm sulfur diesel could enable the full extent of reductions from technologies compliant with Euro V and VI standards.

In the case of Brazil, substantial efforts were made to ensure that, during the transition to low-sulfur fuel, 10 ppm diesel would be available in select cities and at filling stations nationwide to supply new Euro V trucks, with 1,800 ppm diesel elsewhere (500 ppm diesel will become available nationwide in 2014). In India and China, some cities have advanced vehicle standards ahead of national timelines by ensuring local provision of low-sulfur fuel, especially for captive municipal fleets; concerns about misfueling and noncompliant vehicles from other regions continue to provide a rationale for national harmonization. In India, low-sulfur fuel (50 ppm) is available in cities with Bharat 4/IV standards and in several additional cities. Diesel with 350 ppm sulfur is sold in the rest of the country. Recent rulings by China's State Council established targets for having 50 ppm diesel available nationwide by the end of 2014 and 10 ppm diesel by the end of 2017. Adoption of pathways to nationwide low- and ultra-low-sulfur fuel in other countries could enable fleetwide emission reductions and continued progress toward stringent vehicle standards.

The next generation of emission standards has significant potential to help meet air quality goals and make further improvements in public health.

While all regions show decreased $PM_{2.5}$ and nonmethane hydrocarbon (HC) emissions from 2000 to 2015, NO_X emissions have remained relatively constant in some regions and have even increased in China and India. While the early stages of Euro standards provide significant reductions in $PM_{2.5}$ and HC emission rates, the most dramatic cuts in NO_X emission rates do not come until Euro 4/IV and beyond. Because of continued concern over air quality problems in urban areas, some Best Practice group countries continue to develop and adopt post–Euro 6/VI standards. The U.S. EPA's Tier 3 standards for light-duty vehicles represent a major reduction in NO_X and HC from Euro 6/Tier 2 levels. As yet there has been no proposed legislation putting forward next-generation standards for heavy-duty vehicles, but the California Air Resources Board has discussed new, voluntary NO_X limits that are more than 90 percent lower than the current HDV emission limits. This reflects the continuing technical improvements in emission control systems and the levels of stringency they could support over the coming decade.

The next generation of emission standards (post–Euro 6/VI), assumed to be implemented in 2025 in Best Practice countries and several others as part of the Accelerated Policy scenario, could provide a further 50 percent reduction in NO_X and HC in 2030 compared with current policies, with additional reductions expected beyond 2030 as older vehicles continue to exit the fleet.

5 OUTLOOK FOR FUTURE RESEARCH

This study highlights the importance of accelerated introduction of new vehicle and fuel standards for emissions and health. Vehicle technologies that can reduce particulate and nitrogen oxide emissions by more than 99 percent (from uncontrolled engines) are already being deployed in most developed countries. In addition, the technologies to reduce fuel sulfur content to 10 ppm—the level required to comply with the latest vehicle emission standards—are already commonplace in developed countries and are increasingly being commercialized in some developing countries. While new vehicle and fuel standards are critical components of a comprehensive transportation policy package, many areas could benefit from additional research.

Strong **enforcement and compliance policies** need to be in place to ensure that new vehicle and fuel standards are well implemented and their benefits closely monitored. This is especially important for countries without a strong compliance track record. Future analyses can highlight the importance of such policies by evaluating the effects of poor enforcement and compliance.

Even assuming perfect compliance, vehicle emission standards target new fleets only, so their full benefits only materialize as fleets turn over. **In-use vehicle emission reduction policies** can complement new vehicle standards by improving the existing fleet and driving near-term emission reductions that contribute to urban air quality improvements. Such policies include inspection and maintenance programs, spotter programs, remote sensing, enhanced fleet maintenance, scrappage and retrofit programs, low-emission zones, anti-idling programs, and overloading prevention for heavy-duty trucks. Future analyses can focus on the benefits of in-use emission reduction policies and place those in context with the benefits from new vehicle and fuel standards.

Another area for future research is the emission effects of **alternative fuels.** Compressed natural gas (CNG) has significant potential to reduce emissions from diesel engines. Many developing countries with ample and low-cost natural gas and without stringent new engine or fuel standards demonstrate a continuing interest in CNG. Biofuels can have either positive or negative influence on emissions, depending on the specific fuel and pollutant. As various countries consider different environmental priorities such as local air quality and climate change, it will be important to evaluate how alternative fuels can play a role in reducing emissions and health impacts from transportation.

Zero-emission vehicles (ZEVs), namely, battery electric and hydrogen fuel cell vehicles, are existing technologies with zero tailpipe emissions. From a health perspective, both passenger and freight ZEVs can play a role in improving air quality in cities, especially if the energy comes from renewable sources or if upstream emissions occur in less densely populated areas. Although ZEVs account for a tiny share of current vehicle sales, their adoption will eventually become more widespread as technologies evolve, costs decrease, and vehicle efficiency standards make their introduction in major vehicle markets more advantageous. Future analyses can consider the role of ZEVs in reducing emissions and health consequences in cities, with adequate consideration of upstream effects.

It is also important to evaluate how **activity-related policies** can complement vehicle technology strategies. Demand management and land-use policies can reduce transportation emissions by curbing activity (especially from high-emitting vehicles in densely populated areas) and reducing congestion (smoother traffic conditions are associated with lower emission rates). Another public health benefit of such strategies is likely to be lower fatality rates from traffic injuries. In addition, mode shift strategies can encourage the use of more efficient modes of transportation such as nonmotorized transport, public transit, and freight rail. Regulations for clean buses and trucks can play a vital role in ensuring that infrastructure investments and land-use policies result in low-emission public transportation and freight systems.

As developed countries take the lead on the introduction of new vehicle and fuel standards, the burden of health issues will shift to developing countries, especially those in the Other Countries group. Future analyses should include **deep exploration of aggregated countries and regions,** with a focus not only on potential policy packages but also on data collection and model development to represent health effects accurately.

Among the reasons for delays in implementing new standards for vehicles and fuels in many countries are the additional costs incurred by vehicle manufacturers and refineries. Follow-up analyses should examine the **costs and benefits of new emission reduction technologies,** ideally with focus on regions that rely on this information to support their policymaking processes.

Our understanding of the health and climate implications of vehicle pollutants is still evolving, and in this study a narrow focus on health impacts from primary pollutants was explored. Future work should investigate the **health effects of secondary pollutants** such as ozone, sulfates, and nitrates formed in the atmosphere. These are associated with known chronic and acute health conditions, and they contribute to changes in atmospheric conditions that result in enduring temperature and precipitation shifts. Furthermore, exploration of **near-road health impacts,** within 300 to 500 meters of a major roadway, as well as alternative assumptions concerning the **toxicity of diesel particulate matter,** would improve the resolution and the comprehensiveness of a global health assessment of traffic emissions.

This study analyzed health impacts that lead to early deaths, although these are not the only health-related consequences from exposure to traffic emissions. Nonfatal effects, including years living with disabilities such as chronic obstructive pulmonary disease, ischemic heart disease, and asthma, are significant in their own right. Analysis of **nonfatal health outcomes** would paint a broader picture of how public health is impaired by transportation-generated pollution. An interesting follow-on could also incorporate **mortality estimates for traffic-related injuries,** based on the vehicle activity growth projections for each of the regions analyzed in this report.

APPENDIX I: EURO STANDARDS LIMIT VALUES AND U.S./EU/JAPAN STANDARDS EQUIVALENCE TABLES

Table A1-1: European Union emission standards for category M1 vehicles (passenger cars)

Diesel	Test Cycle	Grams per Kilometer (g/km)				
		CO	HC	HC+NO_x	NO_x	PM
Euro 1	ECE+EUDC	2.72	—	0.97	—	0.140
Euro 2, IDI	ECE+EUDC	1.00	—	0.70	—	0.080
Euro 2, DI[A]	ECE+EUDC	1.00	—	0.90	—	0.100
Euro 3	NEDC	0.64	—	0.56	0.50	0.050
Euro 4	NEDC	0.50	—	0.30	0.25	0.025
Euro 5	NEDC	0.50	—	0.23	0.18	0.005[C]
Euro 6	WLTP	0.50	—	0.17	0.08	0.005[C]
Gasoline						
Euro 1	ECE+EUDC	2.72	—	0.97	—	—
Euro 2	ECE+EUDC	2.20	—	0.50	—	—
Euro 3	ECE+EUDC	2.30	0.2	—	0.15	—
Euro 4	NEDC	1.00	0.1	—	0.08	—
Euro 5	NEDC	1.00	0.1[B]	—	0.06	0.005[C,D]
Euro 6	WLTP	1.00	0.1[B]	—	0.06	0.005[C,D]

A After September 30, 1999, vehicles with direct-injection engines had to meet the indirect-injection limits
B Nonmethane hydrocarbon limit = 0.068 g/km
C 0.0045 g/km using the Particle Measurement Programme measurement procedure
D Applicable only to vehicles with direct-injection engines

Table A1-2: European Union emission standards for heavy-duty diesel engines

	Test Cycle	Grams per Kilowatt-Hour (g/kWh)			
		CO	HC	NO_x	PM
Euro I	ECE R-49	4.5	1.1	8.0	0.36[a]
	ECE R-49	4.5	1.1	8.0	
Euro II	ECE R-49	4.0	1.1	7.0	0.25
Euro III	ESC & ELR	2.1	0.66	5.0	0.10 0.13[b]
Euro IV	ESC & ELR	1.5	0.46	3.5	0.02
Euro V	ESC & ELR	1.5	0.46	2.0	0.02
Euro VI	WHSC	1.5	0.13	0.4	0.01

a For engines ≤ 85 kW, the PM limit value is 0.612 g/kWh
b For engines <0.75 dm^3 swept volume per cylinder and a rated power speed of more than 3,000/min

The current format of the ICCT Global Transportation Roadmap model requires that emission standards in different countries or regions be matched to an equivalent Euro standard. Table A1-3 shows the stages of the other major world standards, those created in Japan and in the United States, that are assumed to be equivalent to stages of the Euro standards. Not all Euro standards have U.S. or Japanese analogues (e.g., Euro V), and some U.S. standards are not included in the table because there was no close Euro analogue (e.g., U.S. model-year 2004 heavy-duty standards).

Table A1-3: Emission standards equivalency table

	EU Standard	Year	U.S. Standard	Year	Japan Standard	Year
Gasoline LDV	Euro 1	1992	Model-Year 1980	1980	Model-Year 1994	1994
	Euro 2	1996	Tier 0	1987	Model-Year 1997	1997
	Euro 3	2000	Tier 1	1995	New Short-Term	2000
	Euro 4	2005	Tier 2, Bin 9	2004	New Long-Term	2005
	Euro 5	2010	-	-	-	-
	Euro 6	2015	Tier 2, Bin 8	2008	Post New Long-Term	2009
Diesel LDV	Euro 1	1992	Model-Year 1980	1980	Model-Year 1994	1994
	Euro 2	1996	Tier 0	1984	Model-Year 1997	1997
	Euro 3	2000	Tier 1	1995	New Short-Term	2002
	Euro 4	2005	-	-	New Long-Term	2005
	Euro 5	2010	Tier 2, Bin 9	2004	-	-
	Euro 6	2015	Tier 2, Bin 8	2008	Post New Long-Term	2009
HDV	Euro I	1992	Model-Year 1992	1992	Model-Year 1994	1994
	Euro II	1997	-	-	Model-Year 1997	1997
	Euro III	2001	Model-Year 1994	1994	New Short-Term	2003
	Euro IV	2006	-	-	New Long-Term	2005
	Euro V	2009	-	-	-	-
	Euro VI	2014	Model-Year 2007	2007	Post New Long-Term	2009

Equivalence was determined based on a comparison of limit values and technology associated with each standard. While limit values indicate the stringency of the standards to some degree, they are evaluated based on different test cycles in the European Union, the United States, and Japan, so they are not directly comparable across countries. The fine particulate matter ($PM_{2.5}$) and nitrogen oxides (NO_X) limit values for the standards given in Table A1-3 are shown in Figure A1-1 through Figure A1-5. Because this analysis focuses on the health effects of $PM_{2.5}$, the limits for $PM_{2.5}$ were given more weight when determining standard equivalency. For example, the U.S. model-year 1994 heavy-duty standard was considered equivalent to Euro III because of the stringency of its $PM_{2.5}$ limits, in spite of the much less stringent NO_X limits (see Figures A1-4 and A1-5).

Because Japanese and U.S. standards are not directly equivalent to Euro standards, modeled emissions for the United States and Japan, as well as for countries that base their standards on the United States (Canada and Mexico), are likely to be somewhat less accurate than for countries using Euro standards.

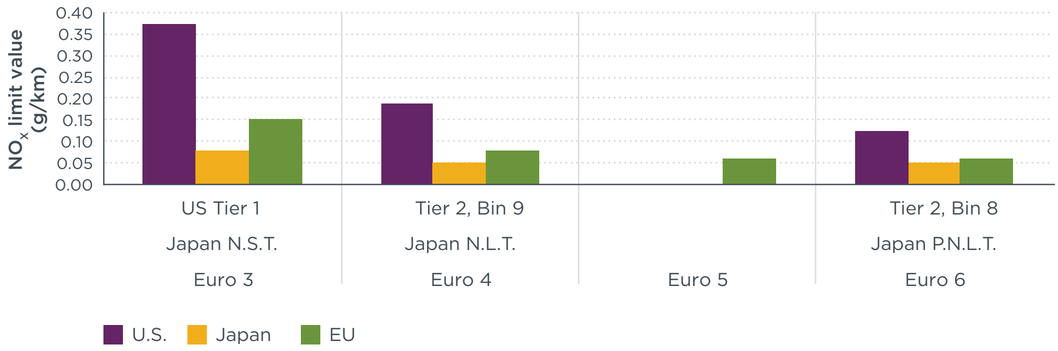

Figure A1-1: NO_x standards for light-duty gasoline vehicles

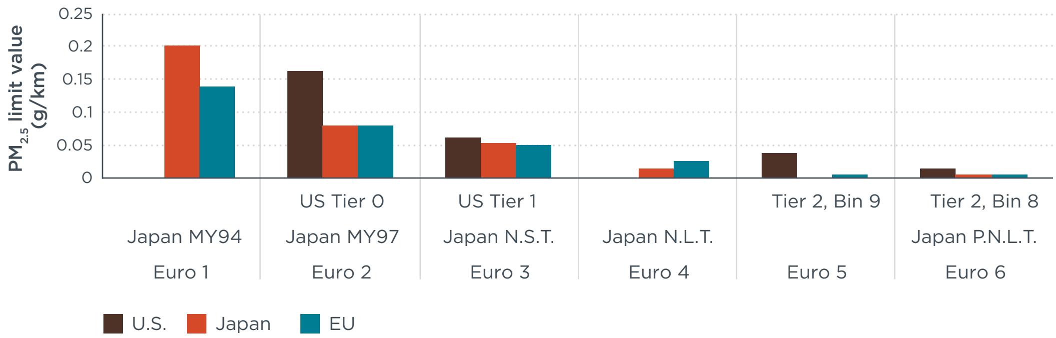

Figure A1-2: $PM_{2.5}$ standards for light-duty diesel vehicles

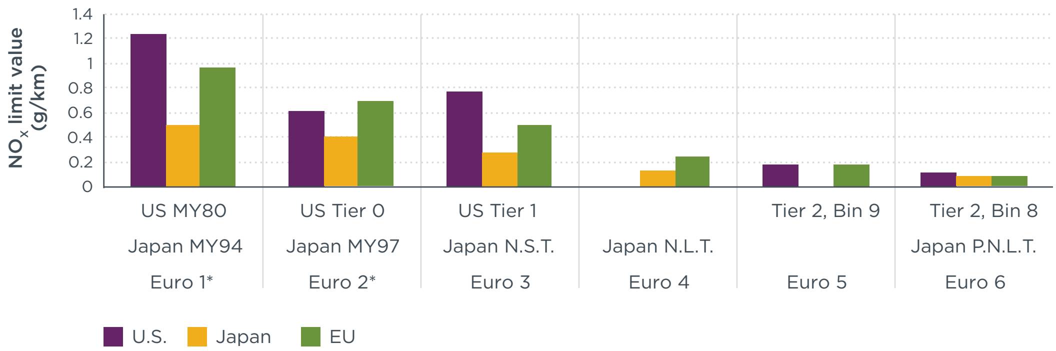

Figure A1-3: NO_x standards for light-duty diesel vehicles

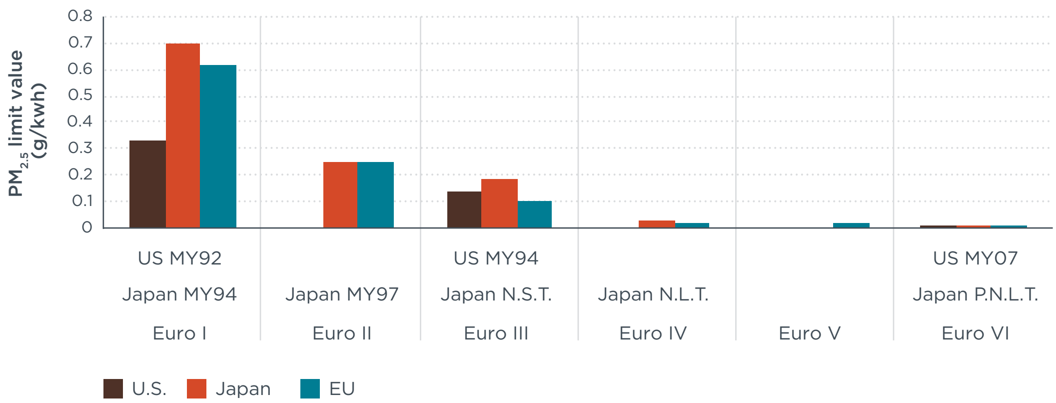

Figure A1-4: $PM_{2.5}$ standards for heavy-duty vehicles

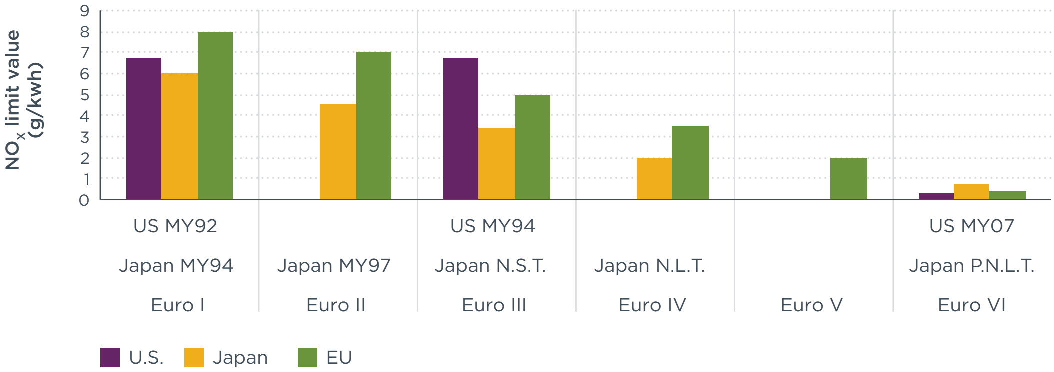

Figure A1-5: NO_x standards for heavy-duty vehicles

APPENDIX II: GLOBAL TRANSPORTATION ROADMAP MODEL

This analysis relies on the ICCT's Global Transportation Roadmap model (hereafter referred to as the Roadmap model) for estimates of historical and future transportation activity and emissions of local air pollutants. The Roadmap model draws upon the best available data for global and national transportation activity, emissions, and policies, in order to quantify the potential of current and future transportation sector policies to reduce energy consumption and emissions. The model was developed to provide insights on questions most critical to government regulators, policymakers, and other stakeholders, including:

» What is the current growth rate in energy use, greenhouse gas (GHG) emissions, and local air pollutant emissions from the transportation sector by mode and by region?

» What are the energy and emission benefits of prior, existing, and future transportation policies?

» How do countries and regions compare in terms of vehicle efficiency, emission rates, and mode shares?

The Roadmap model was reviewed by transportation modeling experts to ensure the validity and adequacy of calculation methods and algorithms, and it is publicly available on the ICCT website, alongside the model documentation (ICCT 2013). The model is updated annually, and its outputs are validated against the results of other major national and international transportation emission models.

MODEL SCOPE

Using socioeconomic forecasts in which population, gross domestic product (GDP), and fuel prices are central, the model estimates future transportation activity and mode shares. By relying on exogenous input parameters related to vehicle technology, efficiency, new vehicle emission standards, and fuels, the model estimates corresponding well-to-wheel (WTW) emissions to 2050. The following points characterize the scope of the Roadmap model:

POLLUTANTS Selected GHGs—carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) —and local air pollutants—nitrogen oxides (NO_x, consisting of nitric oxide and nitrogen dioxide), exhaust fine particulate matter ($PM_{2.5}$), nonmethane hydrocarbons (HC), carbon monoxide (CO), black carbon, and sulfur dioxide (SO_2)—were taken into consideration. WTW emissions of GHGs and local air pollutants include the fuel life cycle, comprising the refining, processing, distribution, and combustion of fuels. The Roadmap does not assess life cycle emissions from vehicle manufacturing, distribution, or end-of-life processes (i.e., disposal or recycling), nor does it examine the transportation infrastructure life cycle. This analysis reports tank-to-wheel (TTW) emissions of $PM_{2.5}$, NO_x, and HC, and a separate health module estimates health impacts from $PM_{2.5}$ in urban areas.

MODES The model encompasses light-duty vehicles (LDVs), buses, motorcycles, three-wheelers, heavy-duty trucks (HDTs, subdivided into light, medium, and heavy HDTs), passenger and freight locomotives, passenger aircraft, and freight marine vessels. While this report considers only the health impacts of TTW $PM_{2.5}$ from on-road vehicles, future analyses may seek to quantify health impacts from other pollutants and modes.

COUNTRIES The model focuses on the ten countries/regions with the greatest annual new vehicle sales: the United States, the EU-28 (the 28 member states of the European Union), China, India, Japan, Brazil, Canada, South Korea, Mexico, Australia, and Russia. The model also analyzes five broader regions: 31 countries in Latin America (excluding

Brazil and Mexico), non-EU Europe, 40 countries in the Asia-Pacific (excluding China, India, Japan, South Korea, and Australia), Africa, and the Middle East.

TIME HORIZON 2000 to 2050, in five-year increments. In order to inform upcoming policymaking efforts, this report focuses on near-term regulatory time frames out to 2030. In so doing, the analysis is limited to the deployment of vehicle technologies currently being commercialized.

FUEL TYPES Gasoline, ethanol (grain, sugarcane, and cellulosic), diesel (conventional and low sulfur), biodiesel (oil based and ligno-cellulosic), compressed natural gas (CNG), liquefied petroleum gas (LPG), hydrogen, electricity, jet fuel, and residual fuel are all examined. In this report, separate sets of emission factors are considered for gasoline, diesel, CNG, and LPG. Emission factors for biofuels and blends are not assumed to differ from the corresponding fuel type (gasoline or diesel).

VEHICLE TECHNOLOGIES These take in conventional, hybrid, plug-in hybrid, battery electric, and fuel cell vehicles. In the 2030 time frame, battery electric and fuel cell vehicles are expected to account for only a tiny share of the vehicle fleet; these vehicles are assumed to produce zero tailpipe emissions. The majority of hybrids and plug-in hybrids are expected to be sold in countries with advanced emission standards; while these vehicles may have lower emissions than conventional vehicles, the emission factors for passenger vehicles with advanced emission controls are assumed to approximate an average of hybrid and nonhybrid technologies.

On-Road Calculation Methods

Figure A2-1 illustrates the methodology used by the Roadmap model for on-road emissions calculations.

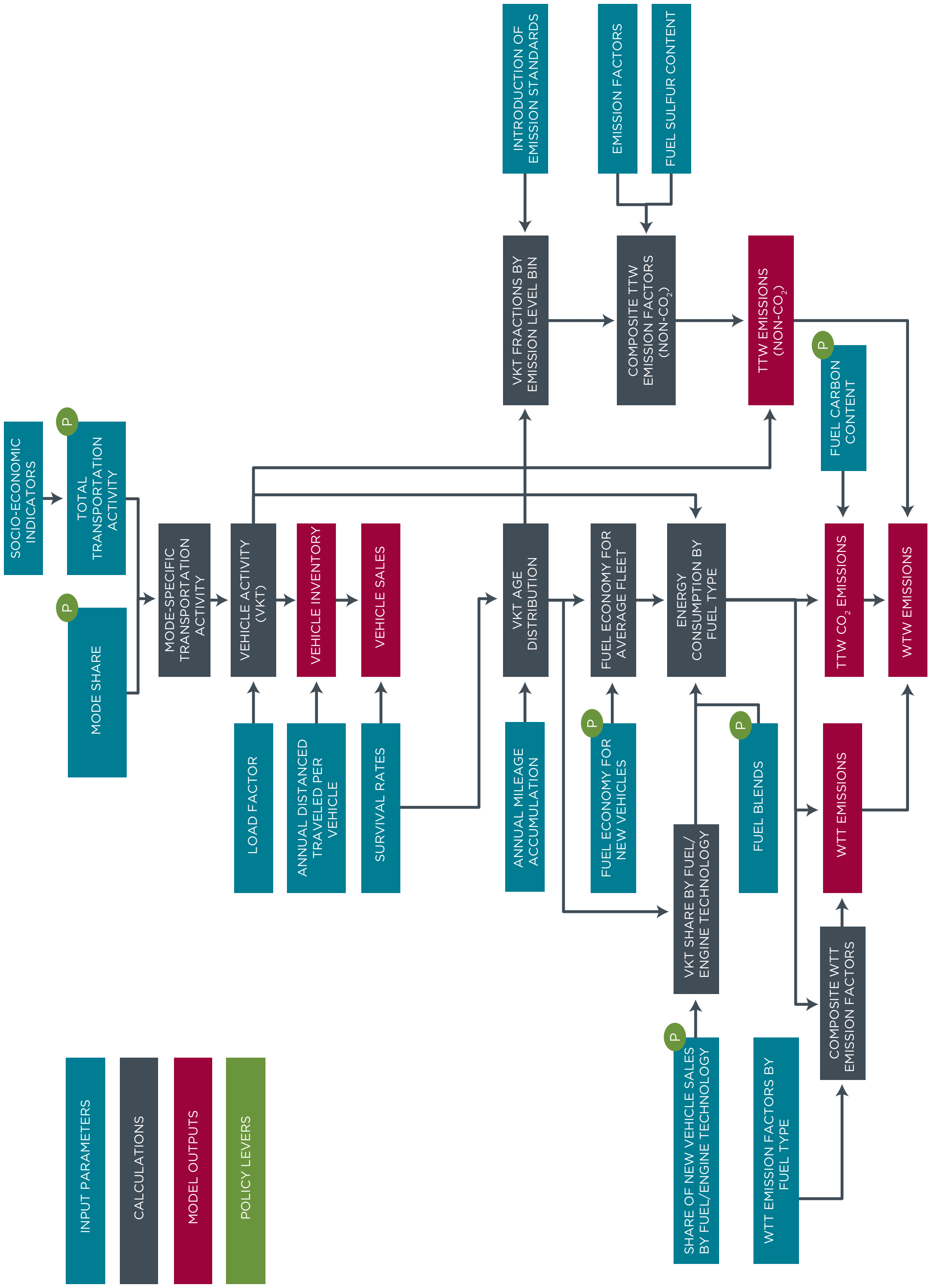

Figure A2-1: On-road calculation methods

Historical land-based transportation activity (passenger-km and metric ton–km) and mode shares are taken from multiple data sources, and variations in land-based transportation activity and mode shares are estimated from changes in socioeconomic indicators (population, GDP, and relative fuel prices). The main formula used for predictions of transportation activity and mode share is a Gompertz S-curve growth function that relates socioeconomic indicators to activity and mode share. Load factors (passengers/vehicle or metric tons/vehicle) are used to convert transportation activity into vehicle activity (vehicle kilometers traveled, or VKT). The breakdown of vehicle activity by technology type is determined from vehicle sales and a turnover algorithm. The turnover algorithm utilizes survival curves developed using a Weibull distribution reliability function to estimate average vehicle retirement age for a given region and mode. Vehicle stock and sales are calculated via the model and can be compared with actual sales and inventory figures in order to validate and calibrate the model. Fuel consumption is the product of vehicle activity and fleet-average fuel efficiency, which is estimated using new fleet efficiency and a turnover algorithm. Owing to a lack of globally consistent forecasts for congestion and roadway capacity, the model considers neither rebound effects (changes in consumer behavior) as a consequence of increased fuel efficiency nor decreased activity as a result of traffic congestion (though these effects may cancel out to some degree); however, the model does include assumptions to convert test-cycle vehicle efficiency to in-use efficiency. The breakdown of fuel consumption by type is exogenously specified based on energy consumption statistics for gasoline, diesel, biofuels, and other kinds of fuel. TTW emissions of CO_2 are calculated as the product of fuel consumption (by type) and carbon content of fuels, while TTW emissions of local air pollutants are calculated as the product of TTW emission factors and either vehicle activity (for on-road modes) or transportation activity (for rail and aviation). Average TTW emission factors are based on new vehicle emission standards and a turnover algorithm. Well-to-tank (WTT) emissions of all pollutants are calculated as the product of fuel consumption (by type) and WTT emission factors. Emissions from marine vessels are estimated directly from International Maritime Organization projections.

Emission factors for CO_2 and SO_2 are based on the carbon and sulfur content of fuel, respectively. Emission factors for all other pollutants are based on a weighted average of emission rates from vehicles in each emission standard category. For more information on the development of emission factors, please refer to the section below in this appendix dedicated to them.

Policy Effects

The primary policy levers assessed in this analysis are national vehicle emission standards (applicable to new vehicles) and low-sulfur diesel standards. Timelines for new vehicle emission standards can be entered separately for each vehicle and fuel type (e.g., gasoline light-duty vehicles, diesel heavy-duty trucks). Emission standards can be phased in over a period of several years or assume full compliance in the first year of introduction. The turnover algorithm combines new vehicle emission standards with the rate of vehicle stock turnover to estimate the share of VKT by each fuel type and emission standard level, which is used to compute fleet-average TTW emission factors.

On-road electric and fuel cell vehicles are assumed to generate zero TTW emissions, and the model allows the user to enter expectations of changes in vehicle technology shares over time. While substantial market penetration of electric and fuel cell vehicle technologies could substantially reduce overall TTW emissions, these vehicles are projected to account for only a small share of the overall vehicle fleet through 2030.

On-road vehicle emission rates for each emission standard level are adjusted based on the sulfur content of gasoline/diesel. Timelines for reducing the average sulfur content of diesel can be entered for each region, and the shares of ultra-low-sulfur diesel and conventional diesel fuel are estimated from weighted average sulfur content. The model uses calculated emission rate multipliers based on studies of sulfur effects to estimate reductions in TTW $PM_{2.5}$ as a result of improvements in fuel quality.

External Review and Validation

The ICCT has collaborated closely with government agencies in each of the countries/regions highlighted in this report to ensure that the Roadmap model includes the most representative and credible publicly available data. The ICCT also collaborated extensively with the International Energy Agency (IEA) on data collection and emissions modeling. Many updates were done to the model using the IEA's Mobility Model (MoMo) for areas where the Roadmap model lacked data. The input parameters and model outputs from the Roadmap model were compared against numerous global and national transportation data sources and emissions inventory models, and the results of such comparisons are displayed together with the Roadmap model documentation. The Roadmap model and supporting documentation are available for download on the ICCT's website (ICCT 2013).

EMISSION FACTORS

This section provides additional details regarding the emission factors included in the Roadmap model, which relies on a global set of emission factors (in grams per kilometer) that are specific to vehicle types, fuel types, and emission certification levels (e.g., Euro 1/I through Euro 6/VI). These average lifetime emission factors are designed to take into consideration the deterioration that typically occurs in an emission control system over the life of the vehicle. To account for deterioration, the emissions were totaled for the entire vehicle lifetime and then divided by that vehicle's total lifetime kilometers traveled.

To ensure the use of the best available emission factors, an analysis was conducted to review the emission factors in the main vehicle emission tools employed by various government agencies and research organizations in the United States and Europe. Although they were designed to estimate vehicle emissions in each of their respective regions (California, the United States as a whole, and the European Union), these models have been broadly adopted by policymakers and researchers worldwide. The primary goals of this analysis were to understand the different methodologies for generating vehicle emission estimates and to select the most appropriate emission factors for the Roadmap model. The models analyzed were

1. EMission FACtor (EMFAC) model, version 2011—the (California) Air Resources Board
2. MOtor Vehicle Emissions Simulator (MOVES), version 2010a—the U.S. Environmental Protection Agency
3. Mobile Source Emission Factor Model (Mobile6), version 6.3—the U.S. Environmental Protection Agency
4. The Handbook on Emission Factors for Road Transport (HBEFA), version 3.1—developed by a consortium of research organizations in Europe and led by the Graz University of Technology
5. COPERT 4, version 10.0—the European Environment Agency and the Joint Research Centre
6. The Speciated Pollutant Emission Wizard (SPEW) —Professor Tami Bond of the University of Illinois

After reviewing all six models, COPERT 4 was selected as the most adequate source for the Roadmap model's emission factors, mostly because the emission standards in the Roadmap model are defined based on the European classification scheme for vehicle standards (Euro 1/I through Euro 6/VI). As many countries model their vehicle emission regulatory programs after Europe's, using emission factors that are consistent with the European standards can minimize errors caused by inferring values for those standards from similar but not identical U.S. vehicle regimes. Additionally, COPERT 4 is well developed and supported by a strong research and academic team, which ensures that up-to-date standards and technologies are reflected in the model. The comprehensive and public documentation provides information on methodologies and calculation processes. Finally, the comparison seems to indicate that COPERT 4's emission factors are broadly in line with other models, even though differences are always expected depending on the vehicle type, pollutant, and certification level.

Emission factors were calculated according to methods provided in COPERT 4 documentation (Ntziachristos et al. 2009). Simplifications were made to construct global average profiles for some input parameters necessary for the development of emission factors. Table A2-1 includes the assumptions for average vehicle speed and the share of time driven in each driving cycle (urban, rural, and highway). Additionally, for heavy-duty vehicles, the Roadmap assumes the vehicle loads are 50 percent, and the slope of the road is 0 percent, the recommended COPERT defaults. For Euro V trucks, selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) ratios are set as 75 percent and 25 percent for the fleet, based on the COPERT analysis for 2008 and 2009 statistics (EMISIA and European Environment Agency 2012). COPERT provides a more detailed categorization of vehicle types than the Roadmap model, so emission factors developed for the Roadmap reflect a weighted average of all vehicle types in each vehicle category. For those types with no emission factors available in COPERT (e.g., diesel two-wheelers, gasoline-powered buses, gasoline-fueled heavy-duty trucks, etc.), values are calculated using ratios extracted from EPA's Mobile6 model.

Table A2-1: Input speed and driving cycle share profile

	Average Speed (km/h)			Driving Share (%)		
Vehicle Type	**Urban**	**Rural**	**Highway**	**Urban**	**Rural**	**Highway**
Two-Wheelers	30	60	60	65	20	15
Three-Wheelers	30	60	60	65	20	15
LDV (Gasoline)	20	60	90	44	42	14
LDV (Diesel)	20	60	90	35	35	30
Light HDT	20	60	90	35	35	30
Medium HDT	20	60	90	20	40	40
Heavy HDT	20	60	90	10	45	45
Buses	20	60	90	53	22	25

To understand better how this set of emission factors matches up with those from other models, this analysis compares representative values from all models listed above. Differences should be expected because of various methodologies and input parameters in each model. No attempt was made to harmonize the input parameters in each model, but several considerations were made when comparing the emission factors in order to minimize the scale of variance across models: 1) to include only hot (no cold-start) emission factors in this study, 2) to choose representative vehicle types in each of the models that correspond to the Roadmap vehicle categories, and 3) to select vehicle model years for EMFAC, MOVES, and Mobile6 that correspond to the European progression in emission standards (i.e., Euro 1/I, 2/II, 3/III,..., 6/VI).

After developing lifetime average emission factors for each of the six models based on the assumptions described, comparisons with the existing EU limits are drawn. Figure A2-2 illustrates the comparison of a key set of PM2.5 emission factors for diesel heavy HDTs since those are responsible for a large share of the health problems addressed in this report. Each line in the chart illustrates emission factors from one model (from Uncontrolled to Euro VI). Because of the challenge in determining equivalent values between U.S. and European systems, some points for U.S.-based models are missing. Dashed lines are adopted to connect the available points for those models.

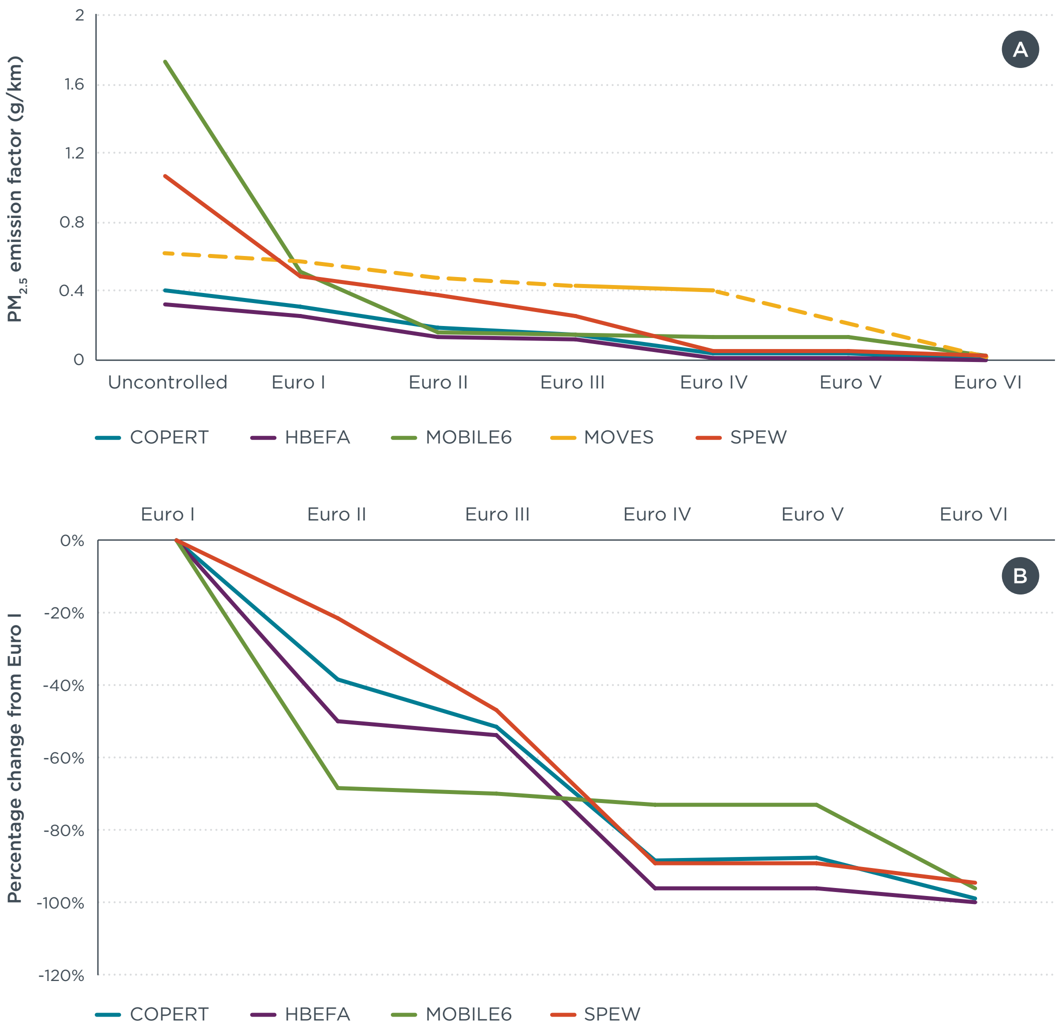

Figure A2-2: Heavy HDT diesel $PM_{2.5}$ emission factor reduction by model

Overall, U.S. models produce higher values than others. COPERT emission factors fall within range of the other models' outputs, although the uncontrolled value is low compared with many others. Because the European standard value is based on grams per unit of energy rather than unit of distance, it is not possible to compare emission factors directly with the limit value. Instead, Figure A2-2, Chart B, gives the relative reduction from Euro I. For the EU standard, a significant decrease can be observed between Euro I and Euro IV, with no obvious change after that as limit values become increasingly small. Mobile6 varies most significantly from the standard trend. The other four models, including COPERT, all have trend lines similar to the standard.

The large degree of variation between models shown in this example occurs throughout the dataset, especially for those points at the early stages of Euro standards. Generally, U.S. models' results are higher than European models'. Values from U.S. models show higher variance and inconsistency, although the underlying reasons are unclear. Uncertainty in determining equivalency between vehicles designed to meet U.S. and European standards probably contributes to the inconsistency. The two European models, COPERT and HBEFA, produce similar outputs across the range of vehicle modes and emission standards, which is to be expected given that COPERT relies on HBEFA for its emission factors.

Across the comparative analysis spectrum of emission factors for multiple vehicle types and pollutants, COPERT results tend to remain in the "middle of the pack," especially for those vehicle types that contribute the most to national emission inventories. While this is not a reason to conclude that COPERT's emission factors are more accurate or better represent real vehicle emissions than other models, it provides a good indication that they do not seriously underestimate or overestimate emissions, given the state of the practice prevailing among established emission models.

Uncertainty and Limitations

There are uncertainties and limitations in the development of emission factors used in the Roadmap model. First, most emission models attempt to capture real-world emission factors by incorporating results from vehicle testing and deterioration factors, but discrepancies between modeled and real-world emission factors will always exist. Second, the use of a single technology-based emission factor set for all regions poses problems and uncertainties. For example, there are issues with the equivalency between European and U.S. emission standards, creates difficulties in using European-based emission factors for regions that do not follow the European emission standard system. There are also problems with vehicle classification in different countries, which means that country activity needs to be interpreted to fit into the vehicle categories adopted by the Roadmap model. Finally, the use of emission factors designed for developed countries in developing regions can carry uncertainties. For instance, there are issues with assuming the same deterioration rates across different countries. Another underlying assumption is that enforcement and compliance in developing countries is equivalent to developed countries, which is not typically true. The use of adjustment factors for developing countries would be arbitrary, given the lack of quantitative data to back them up, but there still needs to be an understanding that the emission factors in the Roadmap model might underestimate emissions in developing countries.

One potential criticism is whether the speed profile used to generate "global" emission factors is representative for all countries and regions in the model. A sensitivity analysis illustrates the effects of vehicle speed on emission factors. Figure A2-3 illustrates how diesel bus NO_x and diesel heavy HDT $PM_{2.5}$ emission factors vary across a wide speed range by each vehicle emission standard. The default assumptions are 50 percent load and 0 percent slope. Each line represents the speed-dependent emission factors by standard. It is evident (and expected) that emission factors from earlier standards are higher than those from advanced standards for the same speed. For each standard (line), the variation in emission factors is greatest at low average speed (10–30 km per hour), but for other speed ranges, the variations are minor. Similar patterns can also be found for other vehicle modes and pollutant types. A speed profile biased toward high- or low-speed driving conditions could significantly change emission factors, which would be the case in very congested traffic or free-flow highway traffic. This could present complications regarding the analysis of urban emissions, in road conditions that are typically highly congested. This could be another reason to regard the emission factors in the Roadmap model as conservative and having a slight bias toward underestimating urban emissions.

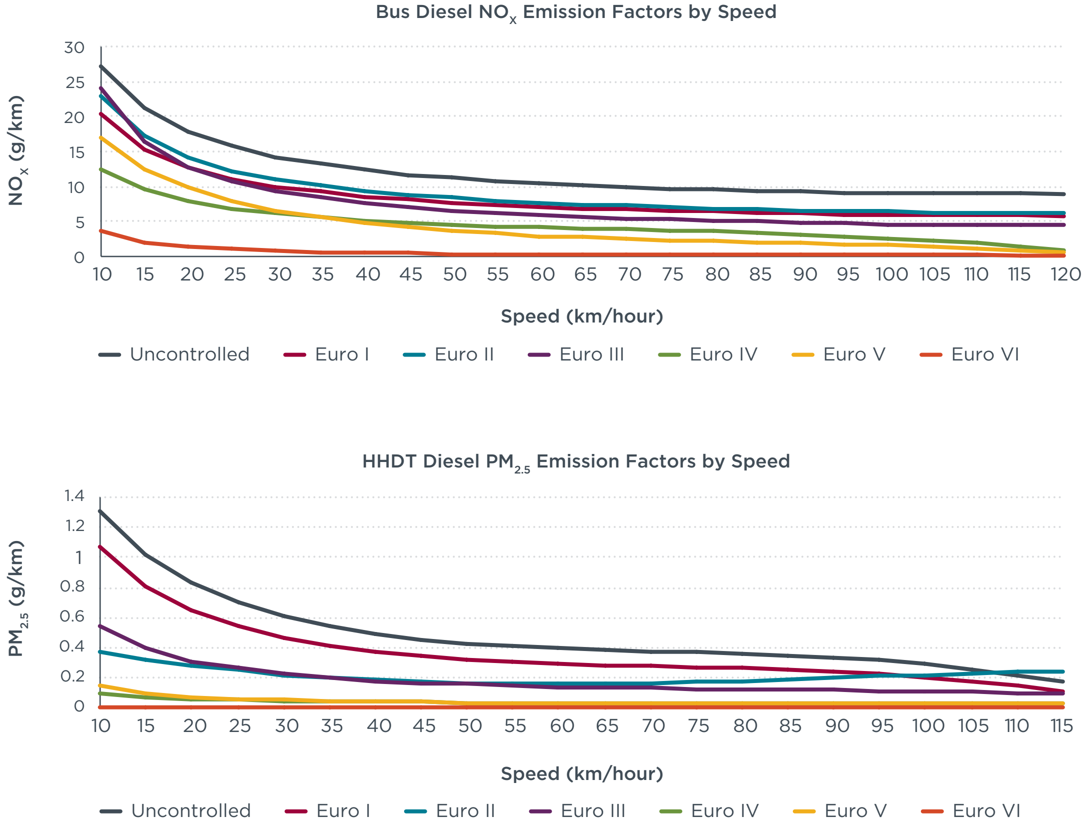

Figure A2-3: Sensitivity of emission factors to speed

Several simplifications were applied in the development of emission factors for the Roadmap model, such as aggregating different vehicle types, assuming no slopes in the road contour profile, and ignoring the effects of cold-start emissions. Those all contribute to higher uncertainty in results of this analysis. A comparison with other COPERT-based average emission factors is used to reveal how the aforementioned simplifications and assumptions affect the emission factors used for this study. Two sources are employed for the analysis. One is the COPERT Tier 2 emission factors, which are the average calculated values for the EU-15 (the European Union's 15 members prior to its 2004 expansion) in 2005 (Ntziachristos et al. 2009). The other one represents the France-specific average emission factors, which are also calculated with COPERT (Borken-Kleefeld and Ntziachristos 2012). For both sources, cold-start emission factors are included, and values are expressed for aggregate vehicle types. Figure A2-4 gives examples for gasoline LDV NO_x and diesel heavy HDT $PM_{2.5}$ data. For both types of emission factors, variations exist, but these are no higher than 50 percent. For LDVs, the major difference comes from the impact of cold-start emission factors, and for heavy HDTs, the major variation comes from the assumptions of load factor and road slope (there is no cold-start emission factor for heavy-duty vehicles in COPERT). In other words, for this report, ignoring cold-start emissions and road grade does not seem to alter average emission factors significantly.

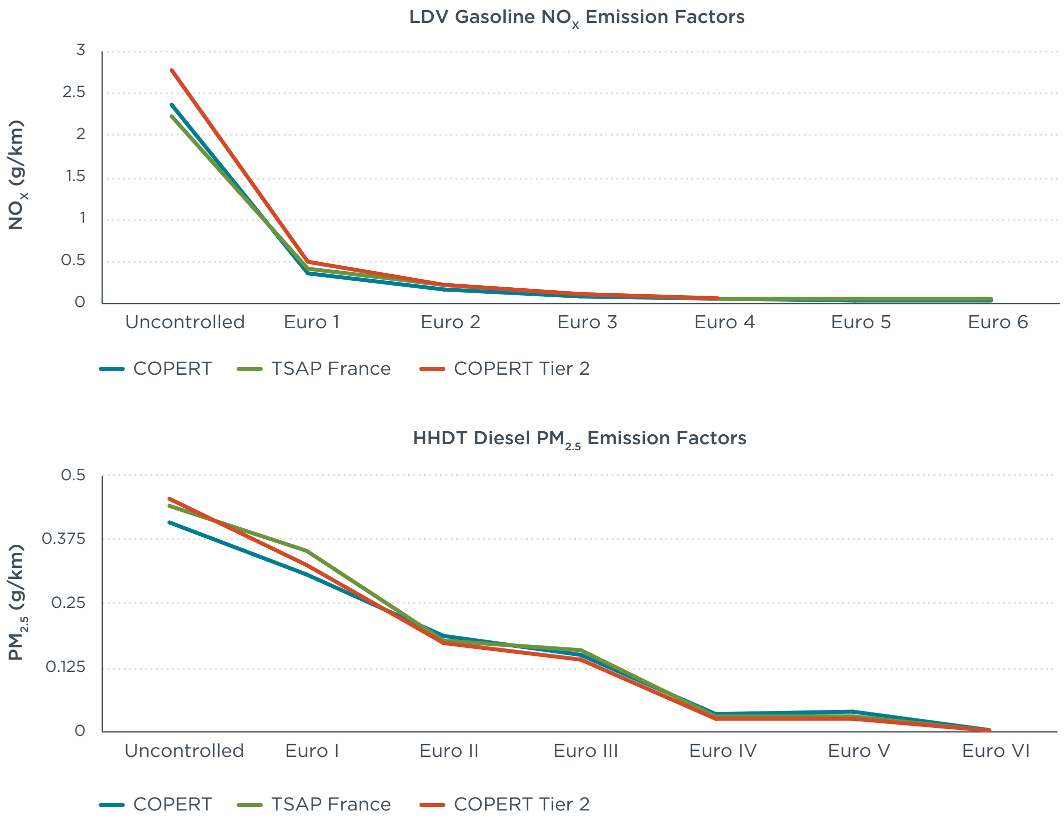

Figure A2-4: Comparison across COPERT emission factors

SULFUR EFFECTS

Primary particulate matter emissions are composed mainly of black carbon, organic carbon, and sulfates. The sulfur contributions to PM emissions are airborne sulfates, which are determined by the sulfur content in the fuel. Previous studies have relied on one of two basic methodologies. The first includes real vehicle tests with the use of fuel with differing sulfur content. The results of such tests are typically inconclusive or incomplete, given that they do not provide enough information to model properly sulfur effects over a wider range of vehicle types and levels of fuel sulfur content. The second methodology relies on a mass-balance approach, which assumes that a given share of the sulfur in the fuel is emitted as sulfates, while the remaining share is largely emitted as sulfur dioxide. Because of the high uncertainty surrounding this issue, a mass-balance approach is the one adopted in this study.

Following the principle of conservation of mass, the sulfur in fuel will be converted either to sulfates or other sulfides. Research shows that regularly around 1 to 3 percent of the sulfur in the fuel will be converted to sulfates (Corro 2002). So a constant 2 percent assumption is used in this method to capture the sulfate share in the particulates. The methodology used in this analysis is consistent with EPA's guidance (Glover and Cumberworth 2003). Sulfur effects are generated for diesel LDVs and HDVs.

Next-Generation Emission Standards

To model the adoption of next-generation standards in the Accelerated Policy scenario, new HDV and LDV emission factors must be assumed for vehicles meeting new standards. To estimate next-generation NO_x and HC emission factors, Euro 6/VI factors were reduced in proportion to the limit value reduction for each mode category. For example, Tier 3 standards represent an 88 percent reduction in NO_x and HC limit values for LDVs compared to Euro 6 standards, so the next-generation emission factors were reduced by 88 percent from Euro 6 emission factors. For $PM_{2.5}$, the reduction in limit values is not assumed to translate into a reduction in vehicle emission factors; the new limit values were designed to protect against new vehicles models with higher $PM_{2.5}$ emissions (e.g., some types of gasoline direct-injection engines) entering the fleet without emission controls, but they do not compel new emission controls for most diesel and gasoline engines. Next-generation $PM_{2.5}$ emission factors are assumed to be identical to those for Euro 6/VI.

Table A2- 2: NO_x and HC emission factors (EF) for vehicles meeting next-generation emission standards

Mode	Model regulation	Percentage NO_x/HC reduction	Euro 6/ VI NO_x EF (diesel vehicles, g/km)	Next-generation NO_x EF (g/km)	Euro 6/ VI HC EF (g/km)	Next-generation HC EF (g/km)
LDV	Tier 3	88%	0.26	0.031	0.019	0.0023
Light HDT	Tier 3	87%	0.23	0.031	0.010	0.0013
Medium HDT	ARB	85%	0.27	0.041	0.014	0.0021
Heavy HDT	ARB	85%	0.33	0.050	0.023	0.0034
Bus	ARB	85%	0.55	0.082	0.030	0.0045

APPENDIX III: HEALTH MODELING METHODS

Among the large number of pollutants emitted by motorized transportation the most significant disease burden is associated with fine particulate matter ($PM_{2.5}$), which is produced directly from combustion and through atmospheric reactions among other pollutants. Motor vehicles emit $PM_{2.5}$ directly and also emit precursor species including sulfur dioxide (SO_2), oxides of nitrogen (NO_x), volatile organic compounds (VOCs), and ammonia (NH_3). Studies have repeatedly shown that both short- and long-term exposure to ambient concentrations of $PM_{2.5}$ are associated with early death and chronic disease (Pope and Dockery 2006; Pope 2007; Pelucchi et al. 2009; HEI 2010). Projections suggest that future economic growth, particularly among rapidly developing economies, will lead to a doubling of the global vehicle fleet to 2 billion cars by 2030. The implications of this rapid growth for public health and the environment warrant efforts to quantify the future impacts of vehicle emissions growth.

The aim of this study is to quantify the global public health impacts of future vehicle emissions growth and the potential benefits of actions to reduce future emissions. A task of this scale faces various challenges. A forward-looking perspective requires a tremendous amount of data to predict future vehicle populations, changes in vehicle emission factors, and changes in vehicle activity. Estimates of population-level exposure require data and tools that sufficiently capture variations in ambient air quality over time, as well as shifts in population distribution and characteristics. Where there is a nonlinear relationship between pollutant exposure and physiological effects, an estimate of the health effect of a change in vehicle emissions must also account for background exposure.

The International Council on Clean Transportation has identified tools, procedures, and data to respond to these challenges. What follows is the outline of a method that has been developed to quantify the health impacts of future transportation-related emissions.

CONCEPTUAL APPROACH

Assessment of health impacts from a mobile source consists of several basic steps. First is the determination of the total **emissions** of each pollutant of concern from the source or sources over a given time interval. Second is the determination of the resultant change in **concentrations** of the pollutant in the environment. Third is the determination of the **population exposed** to the range of concentrations of the pollutant. A fourth quantity, the change in total **dose** for different exposed populations, ultimately defines the health effects of a pollutant, but often ambient concentrations are used as a proxy for individual dose. These basic steps result in an estimate of ultimate **health effects** (Smith 1993).

Health effects modeling conducted in academic or regulatory settings typically relies on modeled emissions inventories mapped in a geographic information systems (GIS) framework. Spatially and temporally disaggregated emissions are combined with meteorological data to provide input into a chemical transport model that calculates pollutant concentrations in individual grid cells for a Eulerian model or in a plume for Gaussian or Lagrangian models. Concentration data are overlaid with population data maps to calculate health effects. This modeling approach is used by state environmental and transportation agencies in the United States to comply with regulations under the Clean Air Act. Tools developed by the U.S. Environmental Protection Agency (EPA) to support this approach include the Community Multiscale Air Quality modeling system (CMAQ) and the Environmental Benefits Mapping and Analysis Program (BenMAP). In Europe, national air quality planning is supported by the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model developed by the International Institute for Applied Systems Analysis (IIASA). This modeling approach provides comprehensive and detailed exposure and impact results, which can be aggregated to an urban, state, or national scale.

Global-scale concentration modeling has been applied in a few recent studies investigating the health consequences of air pollution (Anenberg et al. 2010; Shindell et al. 2011; Lim et al. 2012), but the data and computational processing needs can be prohibitive. Few chemical transport models can be run at a global scale, and these require access to tremendous processing power and resources to achieve fine enough spatial resolution at which to assess population exposures adequately. Since such models require emission inventories for all economic sectors and cannot be run based on transportation emissions alone, they place a large data burden on model users to generate global, spatially disaggregated emissions with temporal resolution. In addition, regions where data regarding the spatial distribution of emissions are inconsistent or unavailable require assumptions that increase the uncertainty associated with disaggregated emissions. Without reliable, high-resolution inputs, seemingly high-resolution outputs will lack both precision and accuracy. A global modeling exercise that considers multiple time points in future years, assesses multiple policy scenarios, and requires spatially disaggregated emissions for all sectors at a global scale including their change over time was considered too onerous for the purposes of this study.

The ICCT has developed a modeling framework for assessing population exposures to transportation emissions that reasonably approximates the urban concentrations resulting from vehicle emissions without requiring extensive air quality modeling. Transportation-related emissions are given by the Global Transportation Roadmap model, a Microsoft Excel–based model developed by the ICCT that provides annual emission estimates for 16 national and multinational regions, given for the years 2000–2050 in five-year increments. A health module to the Roadmap model has been developed to translate emissions in the Roadmap model into health impacts. The health module converts emissions from the Roadmap model to changes in urban concentrations using a set of precalculated intake fractions (Apte et al. 2012). By combining these urban intake fractions with the share of regional emissions in urban areas, the health module gives the average contribution of transportation-related emission sources to ambient urban $PM_{2.5}$ concentrations. The health impacts of annual average exposure to $PM_{2.5}$ contribution are evaluated using the concept of the Population Attributable Fraction (PAF), similar to the approach followed by the World Health Organization (WHO)/Institute for Health Metrics and Evaluation's Global Burden of Disease studies. Health outcomes are given both as annual premature mortalities and disability-adjusted life years (DALYs) for each region in each year. Figure A3-1 illustrates the conceptual pathway in the health module and compares this against a more conventional approach using chemical transport modeling.

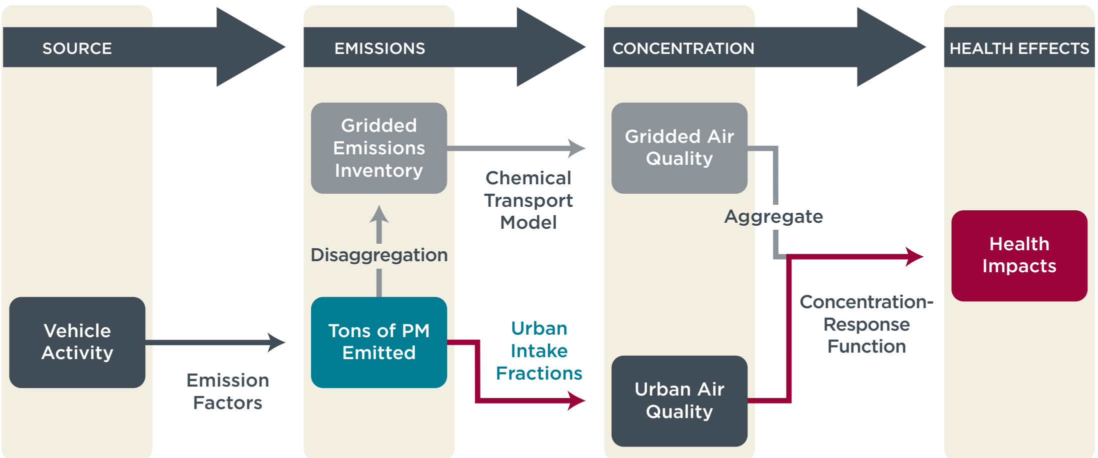

Figure A3-1: Conceptual approach for estimating health impacts in the Roadmap model (red arrows) compared against a conventional chemical transport modeling approach; the framework is based on Smith (1993)

The health module allows users to compare estimates of the health benefits from primary $PM_{2.5}$ emission reduction through new vehicle or fuel standards as well as through other transportation policies (e.g., penetration of advanced vehicle technologies, mode shifts, travel demand management, etc.) using the Roadmap model. This method provides a number of advantages. All necessary numerical operations are executed in Excel, allowing for rapid calculation. The model relies on global datasets, allowing for consistent application across all regions. The estimation of health impacts requires minimal assumptions about emissions from other sectors, thus isolating the benefits of transportation policies.

This simplified approach imposes some limitations on the health analysis. The assumptions used to develop the intake fractions are only valid for conserved[8] pollutants; therefore, the health module only quantifies the health effects of primary $PM_{2.5}$. It also limits the scope of the analysis to the set of urban areas for which intake fractions have been calculated, so health damages from transportation-attributable $PM_{2.5}$ in rural areas are not included in this analysis. Future work to refine the health module may be able to minimize these trade-offs.

METHODOLOGY

The following section describes the calculations used in the Roadmap model to estimate health impacts. This calculation includes estimating urban emissions within regions, converting emissions to urban $PM_{2.5}$ concentrations, and applying appropriate concentration-response functions.

URBAN EMISSIONS

The Roadmap model provides annual emission estimates for 16 national and multinational regions. The allocation of emissions to urban areas is based on assumptions about urban driving activity and is also informed by the calculation of emission factors for the Roadmap model. The annual emissions for a given transport mode and pollutant are the product of the average emission factor (EF) and total activity,

$$M_T = EF_T \times A_T \qquad \textbf{Equation (1)}$$

where M_T is the total emissions of a given pollutant (in grams);

EF_T is the emission rate averaged over all driving conditions and all emission standard levels (g/km);

A_T is the vehicle activity expressed as the total distance travelled (km).

The EFs used in the Roadmap model are weighted averages of three representative EFs for urban, rural, and highway driving conditions. Note that “urban” refers to the low-speed driving that is typical of areas with high population density but is not defined as occurring in a city. Let H_T, R_T, and U_T be the proportions of total vehicle activity driven in highway, rural, and urban driving contexts, with a sum of one.

$$H_T + R_T + U_T = 1 \qquad \textbf{Equation (2)}$$

If EF_H, EF_R, and EF_U are the average emission factors for highway, rural, and urban driving, then EF_T is the mean value of EF_H, EF_R, and EF_U weighted by H_T, R_T, and U_T.

8 A conserved pollutant is one for which the first-order decay rate is much lower than the rate at which the pollutant is removed from the city via advection (i.e., dispersal by wind). These pollutants include carbon monoxide (CO), benzene, and primary constituents of $PM_{2.5}$ (Apte et al. 2012)

$$EF_T = \frac{EF_H \times H_T + EF_R \times R_T + EF_U \times U_T}{H_T + R_T + U_T} = EF_H \times H_T + EF_R \times R_T + EF_U \times U_T \qquad \textbf{Equation (3)}$$

The calculation of mass emissions M_C that take place in the set of cities within a region is analogous to the calculation of total regional emissions, shown in equation 4,

$$M_C = EF_C \times A_C \qquad \textbf{Equation (4)}$$

where M_C is the emissions of a given pollutant in urban areas (g);

EF_C is the emission rate averaged over all city driving conditions (g/km);

A_C is the vehicle activity within cities (km).

H_T, R_T, and U_T can be expressed as the sum of the portion of highway, rural, or urban driving that takes place within a city and the portion that takes place everywhere else (noncity, noted with subscript N).

$$H_T = H_C + H_N;\ \ R_T = R_C + R_N;\ \ U_T = U_C + U_N \qquad \textbf{Equation (5)}$$

For the allocation of emissions to urban areas in the health module, H_C is assumed to be equal to the proportion of total regional highway mileage within the set of cities. U_C is assumed to be equal to the proportion of the population that is included in the set of cities. Urban populations are taken from the United Nations Department of Economic and Social Affairs, Population Division, *World Urbanization Prospects: The 2011 Revision* (2012). Finally, it is assumed that there is no activity within cities that falls under rural driving conditions (R_C=0). Under these conditions, the average city emission factor is calculated as the mean of highway and urban emission factors weighted by H_C and U_C.

$$EF_C = \frac{EF_H \times H_C + EF_U \times U_C}{H_C + U_C} \qquad \textbf{Equation (6)}$$

City vehicle activity A_C is equal to the share of total highway and urban driving that occurs in cities.

$$A_C = A_T \times (H_C + U_C) \qquad \textbf{Equation (7)}$$

Combining equations 4, 6, and 7 gives the following equation.

$$M_C = \left(\frac{EF_H \times H_C + EF_U \times U_C}{H_C + U_C} \right) \times A_T \times (H_C + U_C) = (EF_H \times H_C + EF_U \times U_C) \times A_T \qquad \textbf{Equation (8)}$$

Using equations 1 and 8, the proportion of total emissions that take place within the set of cities can be determined as shown below.

$$\frac{M_C}{M_T} = \frac{(EF_H \times H_C + EF_U \times U_C) \times A_T}{EF_T \times A_T} = \frac{(EF_H \times H_C + EF_U \times U_C)}{EF_T} \qquad \textbf{Equation (9)}$$

The health module estimates urban emissions using equation 9. Fleet-average emission factors under highway, urban, and average driving conditions (EF_H, EF_U, and EF_T) are taken from the Roadmap model. The proportion of highway and urban driving in cities (H_C and U_C) is taken from external data on road density (Netherlands Environmental Assessment Agency [PBL] 2009) and urban population (United Nations Department of Economic and Social Affairs, Population Division, 2012).

TRANSLATING EMISSIONS TO URBAN CONCENTRATIONS

The health module combines intake fractions with urban $PM_{2.5}$ emissions to determine the contribution of transportation-related sources to annual ambient $PM_{2.5}$. The equation to relate city-specific emissions to concentrations is as follows,

$$C_{trans} = \frac{iF \times E}{P \times BR} \qquad \textbf{Equation (10)}$$

where C is the annual concentration of $PM_{2.5}$ from on-road emissions;

iF is the city-specific intake fraction for on-road emissions;

E is the total on-road emissions within the city;

P is the city population; and

BR is the annual individual breathing rate, assumed to be 5,292.5 m^3/year (U.S. EPA 2009).

The intake fraction is a metric used to quantify the emissions-to-intake relationship for any given chemical species from a particular source. A dimensionless parameter, the intake fraction of an emission source can take any value from zero to one. An intake fraction of 0.00002 (20 ppm) means that, out of a million grams of emissions of a given pollutant, 20 will be inhaled. An intake fraction is an extrinsic property of an emissions source, meaning that the intake fraction for a source is context-specific and depends on the conditions causing dispersal of emissions and the presence of nearby population to inhale it (Bennett et al. 2002). Intake fractions can be generalized for a type of source in a given area. Equation 11 describes a generalized intake fraction calculation (Apte et al. 2012),

$$iF = \frac{\text{Population intake}}{\text{Total emissions}} = \frac{\int_{T_1}^{\infty}(\sum_{i=1}^{P} = C_i\ (t) \times Q_i(t))}{\int_{T_1}^{T_2} E(t)dt} \qquad \textbf{Equation (11)}$$

where iF is the source-specific intake fraction;

T1 and T2 are the starting and ending times of an emissions process;

P is the number of people exposed;

Qi(t) is the volumetric breathing rate (m^3/s) for individual i at time t;

Ci(t) is the incremental concentration (g/m^3) at time t in individual i's breathing zone that is attributable to the emissions process; and

E(t) is the emission rate from the process (g/s) at time t.

The approach applied in the health module uses a set of intake fractions developed for 3,646 cities worldwide with a combined population of 2.0 billion in the year 2000 (Apte et al. 2012). Intake fractions in this dataset are calculated using city-specific, single-compartment Eularian models and meteorological data. Such dispersion models assume that on-road emissions within an urban area are evenly distributed and that the pollutants of interest are well mixed. These intake fractions are valid for conserved, nonreactive emissions. This approach can be reasonably applied to $PM_{2.5}$, carbon monoxide (CO), and benzene within urban areas since their decay rate is much lower than the rate at which they leave the city air compartment (calculated as wind speed over city length, u/L).

Apte's dataset provides city-specific intake fractions for the year 2000. These intake fractions are expected to change over time with changes in city area and population. It has been demonstrated that the intake fraction of nonreactive vehicle emissions is proportional to linear population density (LPD), an urban metric defined as the population of the city divided by the square root of the city's area (Marshall, Teoh, and Nazaroff 2005). Furthermore, the relationship between LPD and population growth has been shown to fit the form $\frac{LPD_{new}}{LPD_{old}} = \left(\frac{Pop_{new}}{Pop_{old}}\right)^b$, where b is an empirically derived constant (Marshall 2007). The value of b for each Roadmap region was calculated using a linear regression run with LPD and population values in the year 2000 from the data underlying the iF dataset (Angel et al. 2010). Intake fractions are thus projected into future years based on population growth as shown in equation 12. The model bases city population growth on projections from the United Nations (United Nations, Department of Economic and Social Affairs, Population Division, 2012).

$$iF_t = iF_{t-1} \times \left(\frac{P_t}{P_{t-1}}\right)^m$$ **Equation (12)**

where iF_t is the intake fraction in year t;

iF_{t-1} is the intake fraction in a previous model year;

P_t is the city population in year t;

P_{t-1} is the city population in a previous model year; and

m is a region-specific coefficient determined by linear population density.

In the health module, a population-weighted average intake fraction is calculated for each region and used with equation 10 to estimate the average change in urban $PM_{2.5}$ concentration resulting from a change in urban regional emissions. The population-weighted metric is recommended as a better reflection of the distribution of intake fractions than a flat average (Apte et al. 2012).

TRANSLATING URBAN EXPOSURE INTO HEALTH IMPACTS

Health impact calculations are based on the PAF concept, which ascribes a fraction of deaths from a discrete cause within the specified population to a particular risk factor (Murray et al. 2003). The formula to estimate premature deaths using the PAF is shown in equation 13,

$$AB(C_o) = P \times y_o \times PAF(C_o)$$ **Equation (13)**

where $AB(C_o)$ is the health burden attributable to C_o;

C_o is the observed concentration (μg/m³);

P is the at-risk population exposed to concentration C_o;

y_o is the incidence of mortality from a given disease among the at-risk population at concentration C_o (deaths/year);

PAF is the fraction of deaths in the at-risk population P from the given disease that are attributable to exposure to C_o.

The PAF is calculated from relative risk (RR) values (equation 14). The RR is a ratio focused on the current risk of mortality faced by the urban population due to long-term exposure to $PM_{2.5}$; PAF is computed by subtracting the counterfactual exposure level RR (which is one by definition) from the current exposure level RR and dividing by the current exposure level risk ratio.

$$PAF(C_o) = \frac{RR(C_o)-1}{RR(C_o)}$$ **Equation (14)**

where PAF is the fraction of deaths from a given disease attributable to C_o;

C_o is the observed concentration (μg/m³);

$RR(C_o)$ is the risk ratio of death from a given disease at concentration C_o.

The counterfactual is the lower-bound risk the population would face at some minimum exposure level (equation 15). Health effects studies have not found a minimum exposure threshold below which there is no increased risk of premature mortality, but because of the ubiquity of low-level concentrations of nonanthropogenic $PM_{2.5}$, a counterfactual of zero is unrealistic. The health module assumes the minimum concentration observed in the ACS study, 5.8 μg/m³ (Krewski et al. 2009), as the counterfactual concentration.

$$RR(C_O) = \frac{y_O}{y_{min}} \qquad \textbf{Equation (15)}$$

where y_o is the incidence of mortality from a given disease among the at-risk population at concentration C_o (deaths/year);

y_{min} is the hypothetical incidence of mortality from the given disease among the same population at the counterfactual (minimum) concentration.

By definition, at the counterfactual concentration C_{min}, $RR(C_{min})=1$. Substituting equations 4–6 yields a single relationship for the attributable burden of disease associated with a baseline exposure at C_o (equation 16).

$$AB(C_O) = P \times y_O \times \frac{RR(C_O)-1}{RR(C_O)} = P \times y_{min} \times [RR(C_O)-1] \qquad \textbf{Equation (16)}$$

An analogous expression can be used to estimate the attributable burden of disease at any alternative concentration C* (equation 17),

$$AB(C^*) = P \times y_O \times \frac{RR(C_O)-1}{RR(C_O)} = P \times y_{min} \times (RR(C^*)-1) \qquad \textbf{Equation (17)}$$

where AB(C*) is the health burden attributable to exposure to a concentration C*;

C_o is the observed concentration (μg/m³);

C* is a hypothetical alternative concentration (μg/m³);

y_o is the incidence of mortality from a given disease among the at-risk population at concentration C_o (deaths/year);

y_{min} is the hypothetical incidence of mortality from the given disease among the same population at the counterfactual (minimum) concentration.

The substitution of y_{min} for y_o allows the attributable burden of disease for an arbitrary concentration C* to be calculated without reference to an observed mortality rate connected to an observed concentration of $PM_{2.5}$. The major advantage of using y_{min} is shown in the modeling of future years. The calculation of the burden attributable to the difference between the concentration assumed in a baseline scenario, $C_{baseline}$, and a hypothetical concentration C* achieved by an alternate scenario is shown in equation 18,

$$AB(C^*) = P \times y_{baseline} \times \frac{RR(C^*)-1}{RR(C_{baseline})} \qquad \textbf{Equation (18)}$$

where AB(C*) is the health burden attributable to exposure to a concentration C*;

$C_{baseline}$ is the expected concentration in some future year (μg/m³);

C* is a hypothetical alternative concentration in that year (μg/m³);

P is the at-risk population in that year;

$y_{baseline}$ is the incidence of mortality from a given disease among the at-risk population at concentration $C_{baseline}$ (deaths/year).

To calculate the health burden associated with an alternate concentration C* in a future year, one must assume a future P and $y_{baseline}$. The assumption that a change in $PM_{2.5}$ concentration has a negligible influence on population growth is consistent with other model assumptions, so it is valid to apply exogenous population growth projections to provide a future P. The same is not true for projections of cause-specific mortality rates: the model necessarily assumes that mortality rates will vary based on predicted change in $PM_{2.5}$ concentrations, so exogenous predictions of future mortality rates are not valid input data. Predicting overall change in cause-specific mortality is beyond the capability of this model. By calculating the y_{min} value in a year with complete data for C_o and y_o, one can hold y_{min} constant through time and model all future variation of cause-specific mortality rates as being a function only of $PM_{2.5}$ concentration changes predicted within the model. While this is not a realistic expectation—certainly future lifestyle changes may impact disease and mortality rates—it prevents the change in projected burden from being confounded by changes in other risk co-variates that are not considered by the model.

Equation 19 shows the formula derived from equations 4–8 that is used in the model to calculate disease burden attributable to a change in concentration,

$$\Delta AB(C^*,\Delta C) = P \times y_{min} \times (RR(C^*+\Delta C) - RR(C^*)) = P \times y_{min} \times \Delta RR \qquad \textbf{Equation (19)}$$

where $\Delta AB(C^*, \Delta C)$ is the change in health burden attributable to a change in exposure of ΔC (μg/m³) from C* (μg/m³);

C* is the annual ambient $PM_{2.5}$ concentration predicted in the model (μg/m³);

ΔC is a change in $PM_{2.5}$ concentration (μg/m³) caused by an intervention such as the implementation of more stringent vehicle emission standards;

P is the at-risk population;

y_{min} is the incidence of mortality from a given disease among the susceptible population at the counterfactual (minimum) concentration.

Average regional y_{min} values are calculated for the year 2005 using regional baseline mortality rates (y_o) available from the WHO and a global dataset of $PM_{2.5}$ concentrations estimated from satellite measurements and the TM5 global atmospheric model (Brauer et al. 2011). The at-risk population (P) is all urban residents within the relevant age category for a given disease. The populations of the 3,646 cities included in the model are based on nationally reported data from the year 2000 and estimated for subsequent model years based on UN urban growth projections. The shares of the population within the relevant age categories are taken from UN population statistics. Ambient annual concentrations for the 3,646 cities in the year 2005 are based on an intersection of city footprints with global data from Brauer et al., done using GIS. To gauge the urban ambient annual $PM_{2.5}$ concentration in all other years, the estimated concentration attributable to on-road transportation in 2005 is subtracted from the total to give the concentration attributable to all other emission sources. The nontransportation concentration is scaled for use in past or future years based on the change in regional $PM_{2.5}$ emissions estimated by IIASA according to the International Energy Agency's World Energy Outlook energy scenarios (Cofala et al. 2011). Total ambient $PM_{2.5}$ concentrations for years other than 2005 are given as the sum of on-road transportation concentrations and all other source concentrations.

Health impacts evaluated in the health module include premature mortality in adults over 30 from lung cancer and a range of cardiopulmonary diseases including upper and lower respiratory infection, hypertensive heart disease, ischemic heart disease, cerebrovascular disease, inflammatory heart disease, chronic obstructive pulmonary disease, and asthma. Concentration-response functions are taken from the extended analysis of the American Cancer Society (ACS) study (Krewski et al. 2009). For children under the age of five, premature mortality from acute respiratory infection (ARI) is considered; concentration-response functions are taken from the WHO Global Burden of Disease 2004 update (Cohen et al. 2004).

For acute respiratory infection, the RR is calculated based on a log-linear concentration-response function (equation 20). The RR for ARI is based on ambient annual PM_{10} rather than $PM_{2.5}$, so PM_{10} concentrations are estimated as roughly twice the calculated $PM_{2.5}$ concentrations.

$$RR = \exp\left[\beta(C^* - C_{ME})\right] \qquad \textbf{Equation (20)}$$

where β is an empirically determined coefficient specific to a disease category;

C^* is the annual ambient PM_{10} concentration predicted in the model;

C_{ME} is the minimum exposure level (counterfactual).

The change in risk attributable to transportation emissions is calculated as shown in equation 21,

$$\Delta RR\__T = \exp\left[\beta(\Delta C_T)\right] \qquad \textbf{Equation (21)}$$

where ΔRR_T is the risk ratio specific to transportation;

β is the empirically determined coefficient specific to a disease category; and

ΔC_T is the change in concentration attributable to transportation emissions.

ΔRR_T can be used in equation 10 to determine the premature mortalities from ARI that are associated with transportation emissions.

Recent epidemiological analysis integrating exposure to $PM_{2.5}$ from a number of sources and at a wide range of concentrations suggests that the concentration-response function for cardiopulmonary disease and lung cancer may be better modeled in the power law formula shown in equation 22 (Pope et al. 2011),

$$RR = \left(\frac{C^*}{C_{ME}}\right)^{\beta} \qquad \textbf{Equation (22)}$$

where β is an empirically determined coefficient specific to a disease category;

C^* is the annual ambient $PM_{2.5}$ concentration predicted in the model;

C_{ME} is the minimum exposure level (counterfactual).

This formula is notable because at high concentrations the marginal increase in relative risk caused by a unit increase in concentration exposure is smaller than the marginal RR change prompted by the same unit increase at low concentrations. This relationship is illustrated in Figure A3-2.

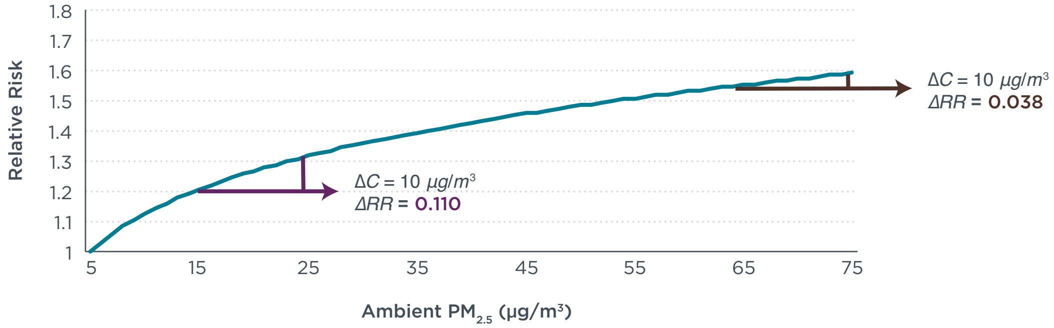

Figure A3-2: Consequences of a non-linear concentration-response function

In the power law form of the concentration-response function, the marginal increase in relative risk attributable to a unit increase in concentration exposure is smaller at high concentrations (shown in brown) than the marginal RR change attributable to the same unit increase at low concentrations (shown in purple).

This property of the concentration-response function complicates the calculation of the attributable health burden of a single emission source. If a source contributes ΔC µg/m³ to the total concentration C*, that contribution can be thought to occur at any intermediate concentration within the range of C_{ME} to (C*-ΔC). The change in risk ratio ΔRR resulting from the change ΔC can then take any value between the two boundary conditions, shown in equations 14 and 15 for a ΔC caused by all transportation emissions, C_T. Equation 23 gives the case in which the change in concentration is assumed to take place at the maximum of the concentration range, resulting in a minimum value of ΔRR. Equation 24 gives the case at the minimum of the concentration range, resulting in a maximum value of ΔRR.

$$\Delta RR_{min} = \left(\frac{C^*}{C_{ME}}\right)^{\beta} - \left(\frac{C^* - C_T}{C_{ME}}\right)^{\beta}$$ **Equation (23)**

where C* is the annual ambient $PM_{2.5}$ concentration predicted in the model;

C_T is the concentration due to on-road emissions;

C_{ME} is the minimum exposure level (counterfactual); and

β is the coefficient for the disease category.

$$\Delta RR_{max} = \left(\frac{C_{ME} + C_T}{C_{ME}}\right)^{\beta} - \left(\frac{C_{ME}}{C_{ME}}\right)^{\beta} = \left(\frac{C_{ME} + C_T}{C_{ME}}\right)^{\beta} - 1$$ **Equation (24)**

where C_T is the concentration due to on-road emissions;

C_{ME} is the minimum exposure level (counterfactual); and

β is the coefficient for the disease category.

The model calculates the health burden of transportation at both boundary conditions and reports the average value. Mortalities are calculated separately for each five-year age category from 30 to 80 as well as from 0 to 4. Mortalities in each age category are compared against a standardized life expectancy table to calculate years of life lost, and DALYs are given as the sum of the years of life lost with no age weighting or discounting (Murray et al. 2012).

APPENDIX IV: BASELINE DATA

Data used in the Roadmap model and presented in this analysis, including projections of activity and emissions of fine particulate matter ($PM_{2.5}$), nitrogen oxides (NO_X), and nonmethane hydrocarbons (HC), are available for download at http://www.theicct.org/global-health-roadmap.

APPENDIX V: GWP VALUES

The climate benefits reported in this analysis combine the CO_2–equivalent impact of five pollutants: black carbon (BC), organic carbon (OC), sulfate (SO_4), methane (CH_4), and nitrous oxide (N_2O). A recent review by Bond et al. (2013) provided information to estimate GWP values for BC, OC, and SO_4. Values for CH_4 and N_2O are taken from the Intergovernmental Panel on Climate Change's Fourth Assessment Report (Forster et al. 2007). Estimates are given for both 20-year and 100-year time horizons to reflect complementary policy goals aimed at limiting both the rate of climate change and peak global temperature change.

Table A5-1: GWP values for various pollutants ($MtCO_2e$)

Pollutant	GWP-20	GWP-100	Source
BC	3010	860	derived from Bond et al. 2013
OC	-510	-150	derived from Bond et al. 2013
SO_4	-360	-100	derived from Bond et al. 2013
CH_4	72	25	given in Forster et al. 2007
N_2O	289	298	given in Forster et al. 2007

LIST OF ACRONYMS AND ABBREVIATIONS

ARB	Air Resources Board (California)
BC	black carbon
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2e	carbon dioxide-equivalent
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
EEA	European Environment Agency
EGR	exhaust gas recirculation
ELR	European Load Response (test cycle)
EPA	Environmental Protection Agency (United States)
ETC	European Transient Cycle (test cycle)
GDP	gross domestic product
GHG	greenhouse gas
GWP-20	global warming potential over a 20-year time horizon
GWP-100	global warming potential over a 100-year time horizon
HC	nonmethane hydrocarbons
HDT	heavy-duty truck
HDV	heavy-duty vehicle
ICE	internal combustion engine
IEA	International Energy Agency
IMF	International Monetary Fund
LDV	light-duty vehicle
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LNT	lean NOX trap
$MtCO_2e$	million metric tons of carbon dioxide-equivalent
MY	model year
NO_2	nitrogen dioxide
NO_x	oxides of nitrogen
OC	organic carbon
$PM_{2.5}$	fine particulate matter with an aerodynamic diameter less than 2.5 micrometers
PPP-GDP	gross domestic product at purchasing power parity
ppm	parts per million
SCR	selective catalytic reduction
SLCP	short-lived climate pollutants
TTW	tank to wheel
ULSD	ultra-low-sulfur diesel, with <15 ppm sulfur content
WHO	World Health Organization
WTT	well to tank
WTW	well to wheel
ZEV	zero-emission vehicle

COUNTRIES IN AGGREGATE REGIONS

Africa: Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe

Asia-Pacific-40: Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Cook Islands, Dem. People's Republic of Korea, Fiji, Indonesia, Kazakhstan, Kiribati, Kyrgyzstan, Lao People's Democratic Republic, Malaysia, Maldives, Marshall Islands, Federated States of Micronesia, Mongolia, Myanmar, Nauru, Nepal, New Zealand, Niue, Pakistan, Palau, Papua New Guinea, Philippines, Samoa, Singapore, Solomon Islands, Sri Lanka, Tajikistan, Thailand, Timor-Leste, Tonga, Turkmenistan, Tuvalu, Uzbekistan, Vanuatu, Viet Nam

EU-28: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom

Latin America–31: Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bolivia, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela

Middle East: Bahrain, Egypt, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, Turkey, United Arab Emirates, Yemen

Non-EU Europe: Albania, Andorra, Armenia, Azerbaijan, Belarus, Bosnia, Georgia, Iceland, Monaco, Montenegro, Norway, Moldova, San Marino, Serbia, Switzerland, FYR Macedonia, Ukraine

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