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COST-BENEFIT ANALYSIS OF BRAZIL'S HEAVY-DUTY EMISSION STANDARDS (P-8)

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EXECUTIVE SUMMARY

Heavy-duty vehicles (HDV) are a major source of emissions that result in local air pollution and have serious impacts on human health, and thus are strong candidates for emissions control. Brazil has controlled HDV emissions through the Programa de Controle da Poluição do Ar por Veículos Automotores (PROCONVE) since 1990, following the European precedent for emission limits and certification test procedures. Brazilian implementation has been an average of 5 years behind Europe with the most recent implementation in 2012 being PROCONVE P-7, which is equivalent to Euro V standards. Despite the many PROCONVE phases to date, air pollution in major metropolitan areas in Brazil is still far above the levels recommended by the World Health Organization (WHO).

In order to mitigate air quality problems and keep pace with vehicle technology progress worldwide, future PROCONVE phases are necessary. In addition to more stringent emission limits, advancing to the Euro VI-equivalent P-8 phase will significantly strengthen the regulatory program, including moving to more representative test cycles; requiring advanced on-board diagnostics (OBD) and fail-safes to ensure proper use and functioning of SCR systems; and establishing in-use conformity requirements. These improvements will ensure that P-8 achieves the expected reduction in emissions in the real world and not just in the laboratory.

Five of the leading vehicle markets — the European Union (EU), the United States (U.S.), Canada, Japan, and South Korea — already have implemented Euro VI-equivalent standards, and Mexico has proposed equivalent standards with implementation planned for 2018. If P-8 standards are implemented in 2018, Brazil will be 5 years behind the EU, and 8 years behind the U.S. in terms HDV emission standards (Figure 1).

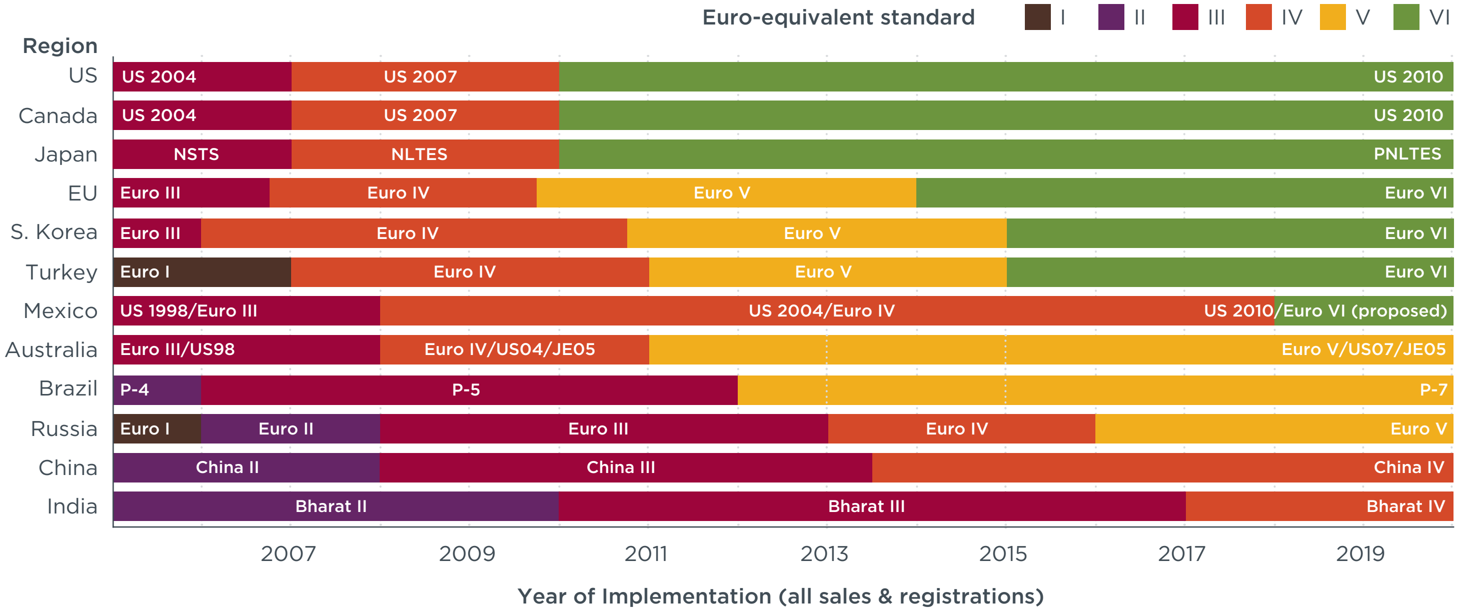

Figure 1. Timeline for implementation of nationwide emission standards for diesel heavy-duty vehicles.

Brazil has a key advantage with respect to other developing countries in that it already has ultralow-sulfur diesel (ULSD) fuel and diesel exhaust fluid (DEF) available nationwide, both of which are required for Euro VI-equivalent standards. Cost-benefit analyses are commonly conducted by regulatory agencies and independent research organizations to assess the potential impacts of policies to control air pollution from motor vehicles in major vehicle markets, including the U.S., Canada, and Mexico. Such analyses capture the most important benefits for climate and health, as well as the costs associated with better emission control technology, fuel quality, and ultimately the operation of cleaner vehicles. Following the completion of regulatory cost-benefit analyses in Mexico, China, and India, the ICCT has assessed the benefits and costs of Brazil moving to P-8 emissions standards for diesel heavy-duty vehicles, with an implementation year of 2018. This analysis monetizes the two most important impacts of P-8 standards: reduced risk of early death from exposure to fine particle emissions, and the incremental cost of vehicle emission control technology. In addition to the monetized costs and benefits, we also quantify potential emission reductions of nitrogen oxides (NO_X), carbon monoxide, hydrocarbons, and black carbon, and assess the climate benefits of black carbon reductions in terms of its carbon dioxide equivalent.

This analysis concludes that P-8 standards in Brazil are a highly cost-effective means of reducing the environmental impact of diesel HDVs in Brazil. Over a 30-year period beginning in 2018, P-8 standards would result in health benefits valued at $74 billion at a cost of $7 billion, with a benefit-cost ratio of 11:1. This is in line with international findings of cost-benefit analyses for similar HDV emission standards, with a range of 11:1 for Mexico to 16:1 for the U.S. Although manufacturers are expected to incur average incremental technology costs of $2,460 per vehicle, P-8 standards are not expected to increase fueling costs compared to the current standard because P-7 vehicles already use ULSD and DEF. Over the same time period, the cumulative benefits of P-8 standards include the prevention of 74,000 early deaths from exposure to fine particle emissions ($PM_{2.5}$) in urban areas, in addition to much lower NO_X and black carbon emissions (Figure 2). Each year of delay in the implementation of P-8 standards beyond 2018 will result in an additional 2,500 premature deaths, highlighting the critical importance of timely action.

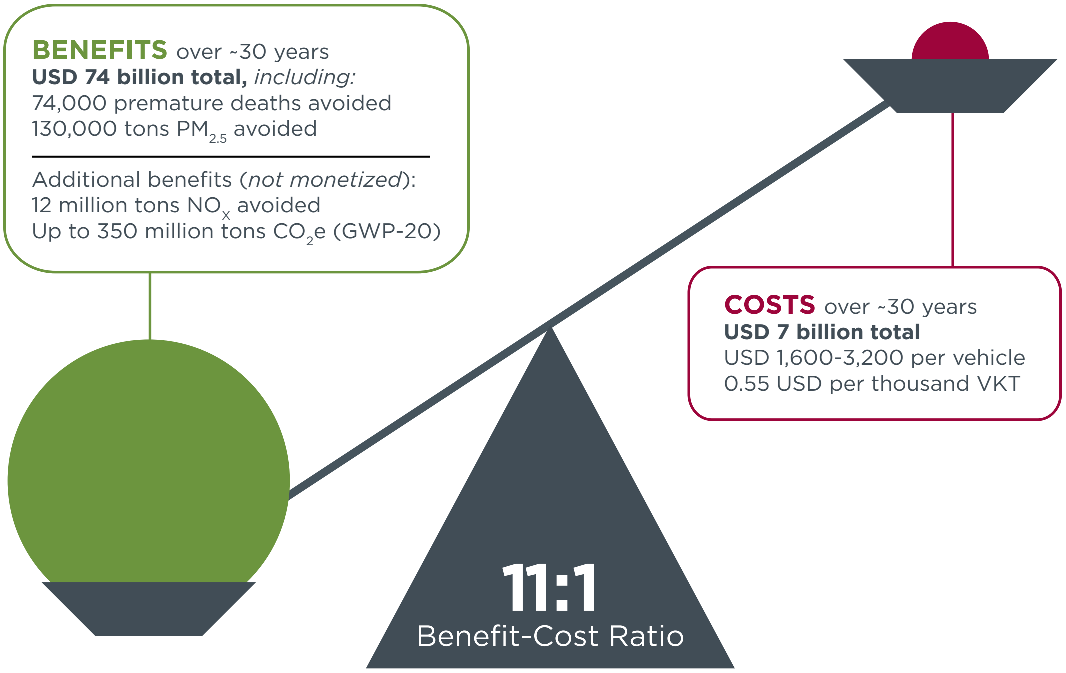

Figure 2. Cumulative benefits and costs of P-8 standards over a 30-year period (2018-2048).

1 INTRODUCTION

Heavy-duty vehicles (HDVs), including heavy-duty trucks and buses, are a major source of emissions that result in local air pollution in Brazil. Using the International Council on Clean Transportation (ICCT) Global Transportation Roadmap Model, we estimate that in 2015 trucks and buses powered by diesel accounted for 88% of $PM_{2.5}$ emissions and 89% of nitrogen oxide (NO_X) emissions from on-road vehicles in Brazil (Figure 3). These are the two pollutants emitted by vehicles that are most harmful to human health. Compared to light-duty vehicles (LDVs), HDVs are much fewer in number: Estimates by Brazil's Ministry of the Environment indicate that HDVs accounted for less than 5% of the fleet in 2009 (Ministério do Meio Ambiente, 2011); however, they tend to be driven longer distances and have much longer useful lives. These factors make HDVs a good target population for vehicle emissions control.

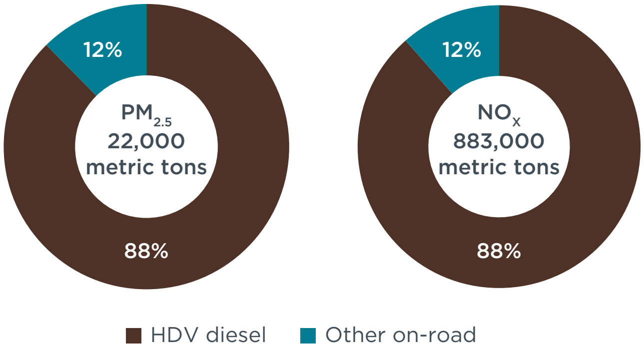

Figure 3. Fine particle and nitrogen oxide emissions from on-road vehicles in Brazil, 2015.

Brazil has controlled HDV emissions through the Programa de Controle da Poluição do Ar por Veículos Automotores (PROCONVE) since 1990, following the European precedent for emission limits and certification test procedures, implemented an average of five years behind Europe (TransportPolicy.net, 2014). Brazil implemented its latest phase, P-7 (Euro V-equivalent), in 2012. Although P-7 emission limits are more than 80% lower than those established by the first PROCONVE phase, air pollution in major metropolitan areas is still far above the levels recommended by the World Health Organization (WHO). Out of the 40 Brazilian cities covered by the WHO's Ambient Air Pollution Database in 2014, all but one exceeded the WHO recommendation of no greater than 10 micrograms per cubic meter $PM_{2.5}$ (Figure 4) (World Health Organization, 2014). Additionally, many cities in the state of São Paulo exceeded Brazil's air quality standards for PM_{10}, and a similar trend has been observed with all other monitored pollutants (CETESB, 2014).

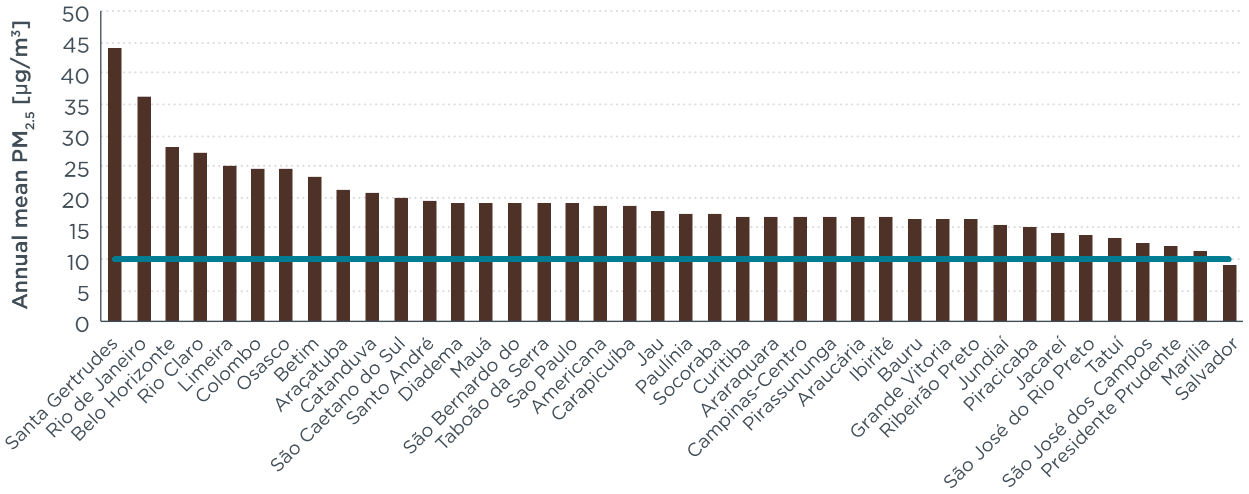

Figure 4. Annual mean $PM_{2.5}$ in Brazilian cities compared with WHO recommendation of 10 μg/m³.

In order to mitigate air quality problems, offset future increases in vehicle activity, and keep pace with vehicle technology progress worldwide, future PROCONVE phases are necessary. Six of the leading vehicle markets — the European Union (EU), the United States (U.S.), Canada, Japan, South Korea, and Turkey — have already implemented the next phase of standards, which are Euro VI-equivalent, and Mexico has proposed equivalent standards with implementation planned for 2018 (Blumberg & Posada, 2014). If P-8 standards are implemented in 2018, Brazil will be 5 years behind the EU, and 8 years behind the U.S. in terms of the stringency of emission standards for diesel heavy-duty vehicles (Figure 5).

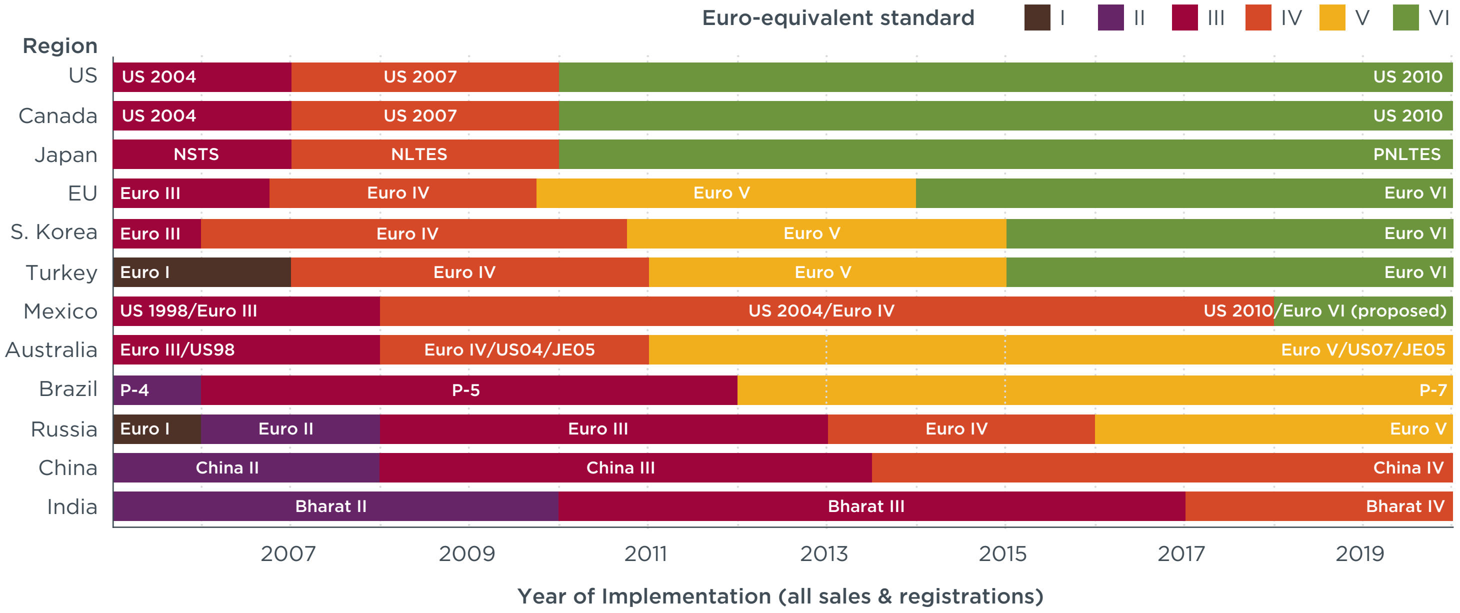

Figure 5. Timeline for implementation of nationwide emissions standards for diesel heavy-duty vehicles.

As described in an ICCT study of the current P-7 standards, advancing to P-8, which is equivalent to Euro VI, would improve upon P-7 in several ways:

- **More stringent emission limits.** The Euro VI standards require manufacturers to reduce NO_x emissions by 80% and PM emissions by 50% compared to Euro V, essentially ensuring the use of diesel particulate filters (DPFs). When compared to a noncompliant P-7 vehicle, Euro VI standards could reduce NO_x emissions by more than 90%. In addition, Euro VI standards include limits for particle number to strengthen the control of fine particles.
- **More advanced OBD requirements.** Euro VI standards introduce many OBD improvements over previous generations, including more stringent OBD threshold values and type approval based on the World Harmonized Transient Cycle (WHTC); the adoption of in-use performance ratios (IUPRs), which indicate how often the conditions subject to monitoring occurred and how frequently the monitoring was conducted; and additional monitoring requirements for exhaust gas recirculation (EGR) flow, EGR cooling system, boost, and fuel injection systems (Posada & Bandivadekar, 2015).
- **More representative test cycles.** The WHTC certification test cycle used in Euro VI resembles real-world driving much more closely than the ESC and ELR cycles used in the Euro III through V regulations. This change in certification test cycles to include cold starts and low-speed driving effectively forces manufacturers to use better catalysts (e.g., copper-zeolites versus vanadium), resulting in more similar emission rates between in-use and homologated vehicles.
- **In-use conformity requirements.** Euro VI standards have specific in-use conformity language, which specifies that emissions must be effectively limited under all in-use operating conditions, and not just in those that resemble test conditions. Euro VI also tightens the in-use NTE limit to 1.5 times the WHTC on-cycle test limit, and requires in-use vehicle testing to demonstrate compliance. This essentially puts the onus on manufacturers to produce vehicles that comply with emission limits not only on test conditions, but also on a wide variety of in-use conditions.

Source: Façanha (2015)

To comply with current P-7 standards, Brazil has 10 ppm ultralow-sulfur diesel (ULSD) fuel and diesel exhaust fluid (DEF) available nationwide, both of which are required for Euro VI-equivalent standards. It is worth noting that 500 ppm diesel continues to be sold outside of metropolitan regions. While phasing out 500 ppm diesel nationwide could eliminate the risk of misfueling for P-7 and P-8 diesel vehicles, this analysis assumes that all P-7 and P-8 vehicles are correctly fueled with S10. We did not consider the incremental costs or benefits of providing S10 to diesel vehicles at P-5 or earlier stages of emission control. In addition to ULSD, P-7 vehicles also require a liquid reductant additive (sold as ARLA-32 in Brazil but known as DEF in the U.S.) for the NO_x after-treatment systems to function. ARLA-32, a mixture of 32.5% urea (by weight) in water, has been available throughout Brazil since 2012.

Cost-benefit analyses are commonly conducted by regulatory agencies and independent research organizations to assess the potential impacts of policies to control air pollution from motor vehicles in major vehicle markets, including the U.S., Canada, and Mexico (U.S. Environmental Protection Agency [EPA], 2000; Department of the Environment, 2014; Miller, Blumberg, & Sharpe, 2014). Such analyses capture the most important benefits for climate and health, as well as the costs associated with better emission control technology, fuel quality, and overall operation of cleaner vehicles. In doing so, a cost-benefit analysis can help environmental regulators make better informed decisions and ensure that the societal benefits of regulations outweigh their costs. Following the completion of regulatory cost-benefit analyses in Mexico, China, and India, the ICCT has assessed the benefits and costs of Brazil moving to Euro VI-equivalent P-8 emission standards for diesel heavy-duty vehicles in 2018. This analysis monetizes the most important impacts of P-8 standards: reduced risk of early death from exposure to fine particle emissions, the incremental cost of vehicle emission control technology, and the incremental costs to maintain P-8 vehicles. In addition to the monetized costs and benefits, we also quantify potential emission reductions of NO_X, carbon monoxide, hydrocarbons, and black carbon, and assess the climate benefits of black carbon reductions in terms of its carbon dioxide equivalent.

2 METHODS

SCOPE OF ANALYSIS

This section defines the policy scenarios that were modeled, as well as the time frame, currency, and discounting assumptions used for this cost-benefit analysis. We also define the vehicle types that are evaluated with respect to the costs and benefits of implementing P-8 standards and provide a shortlist of the technical factors that were not monetized as part of this study. A qualitative analysis of those factors is presented under Sensitivity Analysis in the Results section.

Policy scenarios

The core analysis of P-8 standards considers the costs to vehicle owners and operators and the benefits to society in terms of reduced risk of early death from exposure to vehicle exhaust emissions. Costs and benefits of the P-8 standards were estimated by comparing two policy scenarios:

- **P-7 full compliance:** New diesel heavy-duty vehicles meet P-7 (Euro V) requirements starting in 2012 and are supplied with S10 diesel and appropriate levels of ARLA-32.
- **P-8 in 2018:** New diesel heavy-duty vehicles meet P-8 (Euro VI) requirements starting in 2018 and continue to use S10 diesel and appropriate levels of ARLA-32.

Sensitivity analysis

Considering the inherent uncertainties involved in conducting a cost-benefit analysis of environmental policies, this study includes several sensitivity analyses to examine whether conclusions hold over a range of possible analytical choices. These analyses consider alternate assumptions regarding the Value of a Statistical Life (VSL), discount rates, varying levels of compliance with current P-7 standards, the costs of delayed implementation, and the likely impacts of factors that were not monetized in this analysis. With respect to vehicle emissions, we ran three additional scenarios to evaluate the impacts of varying use of ARLA-32 and compliance with NO_x emission limits under P-7, as well as the impacts of a delayed implementation of P-8:

- **P-7 partial compliance:** Same as the P-7 scenario, except only 68% of vehicle-kilometers traveled (VKT) are supplied with appropriate levels of ARLA-32. These vehicles are assumed to emit NO_x at levels equivalent to the previous P-5 standard (Euro III-equivalent).
- **P-8 in 2020:** New diesel HDVs meet P-8 (Euro VI) requirements starting in 2020 (reflecting a 2-year delay) and continue to use S10 diesel and appropriate levels of ARLA-32.
- **P-8 in 2022:** New diesel HDVs meet P-8 (Euro VI) requirements starting in 2022 (reflecting a 4-year delay) and continue to use S10 diesel and appropriate levels of ARLA-32.

Time frame, currency and discounting

Costs and benefits were evaluated over the period 2018 to 2048, covering 30 years after the first year of assumed P-8 implementation. While the standards would apply to all new HDV sales, it can take up to two decades for these vehicles to replace the more than 90% of vehicle activity. Moreover, early deaths caused by cardiopulmonary disease and lung cancer can occur over a 20-year period following exposure to harmful vehicle emissions (EPA, 2011). The time frame selected for this analysis considers both the early period, when a small share of the fleet is covered by the standards, as well as the later period when nearly all vehicles in the fleet have been replaced. This rationale is consistent with the EPA's methods for choosing a time frame of analysis for the latest HDV emissions standards in the U.S. (EPA, 2000). Benefits and costs are discounted to reflect society's preference for payoffs today compared to payoffs in future years. The main analysis uses a discount rate of 5%, with a sensitivity analysis conducted using rates of 0% and 10% as recommended by Brazil's Ministry of Health (Ministério da Saúde, 2009).[1] Throughout this report, monetized benefits and costs are reported in currency units of 2015 USD abbreviated as $. Because exchange rates can fluctuate significantly on a daily basis, we present most estimates in units of USD. In cases where we also report in terms of Brazilian Real (R$), we apply a 2015 exchange rate of 1 Brazilian Real equal to 0.25 USD.

Vehicle class definitions

Vehicle activity and emissions were modeled using the ICCT Roadmap model, which groups the seven vehicle classes used by Associação Nacional dos Fabricantes de Veículos Automotores (ANFAVEA), the country's association of automobile manufacturers, into four vehicle types, including buses and three types of heavy-duty trucks (HDTs) — light, medium, and heavy (Table 1). This new segmentation allowed us to use empirical data derived from other sources (e.g., emission factors from the COPERT model). Only diesel vehicles were considered in this analysis.

Table 1. Vehicle definitions

Roadmap Vehicle Type	Class	Definition	Average Engine Size (L) in 2012	Share of sales in 2012
LHDT	Semi-Light Truck	3.5 t < GVWR < 6 t	3.6	1.6%
MHDT	Light Truck	6 t ≤ GVWR < 10 t	4.2	20.1%
	Medium Truck	10 t ≤ GVWR < 15 t	4.5	7.5%
	Semi-heavy Truck	Straight truck: 15 t ≤ GVWR ≤ 45 t Tractor-trailer: GVWR ≥ 15 t and GCWR < 40 t	6.5	30.4%
HHDT	Heavy Truck	Straight truck: GVWR > 45 t Tractor-trailer: GVWR ≥ 15 t and GCWR ≥ 40 t	11.1	25.1%
Bus	Microbus	Conventional urban minibus: GVWR generally 5 to 12 t	4.2	3.1%
	Bus	Urban and intercity buses: GVWR generally 8 to 41 t	6.9	12.2%

t: metric tons; GVWR: Gross vehicle weight rating; GCWR: Gross combination weight rating
Truck definitions from ANFAVEA (2014); average engine size and sales share based on 2012 data provided by IEMA.

Technical factors that were not monetized in this study

This analysis draws upon the EPA's *Guidelines for Preparing Economic Analyses* (EPA, 2010b) in that it compares a policy intervention with a realistic baseline, applies a range of discount rates to put costs and benefits into present value terms, considers the most important costs and benefits to assess whether the policy is cost effective, and outlines remaining uncertainties and their potential impacts on the outcome of the analysis.

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[1] This range accounts for an even wider spectrum of possible societal preferences than the range used by the U.S. EPA (EPA, 2010b). For additional details, see "Sensitivity to discount rate and VSL" in the Results section.

The ICCT has applied this approach previously in a cost-benefit analysis of heavy-duty emissions standards in Mexico (Miller et al., 2014). While this analysis captures the most important costs and benefits, several factors were either not considered or were quantified but not included in the estimates of net present value associated with implementing the policy:

- Changes in fuel consumption of new vehicles equipped with DPFs to meet Euro VI-equivalent limits for emissions and particle number.
- Reduced incidence of early deaths resulting from exposure to ozone and fine particles formed in the atmosphere. These impacts would be in addition to those quantified in our health impact methods (Chambliss, Miller, Façanha, Minjares, & Blumberg, 2013).
- Nonfatal health impacts from exposure to vehicle exhaust and secondary pollution.
- Value of climate impacts of reduced black carbon emissions.
- Any increases in agricultural productivity resulting from reduced black carbon emissions.

Considering the likely impacts of each of these factors, including all of the above factors would be expected to increase the estimated net benefits associated with implementing P-8 standards (see “Likely impact of additional technical factors” in the Results section).

VEHICLE ACTIVITY AND SALES

An analysis of historical data on gross domestic product (GDP) and VKT by HDVs indicates that these variables are closely linked (**Figure 6**). Data from Brazil’s central bank indicate a slowing of the economy in 2014 followed by contraction in the first two quarters of 2015 (Banco Central do Brasil, 2015). Considering the growth that has followed each economic contraction in Brazil since 1980, we assume that over the long term (through 2050[2]), economic growth is roughly consistent with the historical trend observed from 1980 to 2014. Similarly, given the close historical relationship between economic growth and vehicle activity in the HDV sector, we forecast growth in VKT based on this trend in GDP.

Taking into account projections of VKT per vehicle provided by IEMA, we calculate the future vehicle sales through 2050 needed to maintain a vehicle stock consistent with projections of VKT shown in Figure 6.[3] These calculations take into account fleet turnover and declining annual distance traveled as vehicles age. Overall, these projections indicate that annual HDV sales will increase from about 143,000 in 2018 to about 207,000 in 2048, an increase of 44% (**Figure 7**).

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[2] Note that the time frame of the cost-benefit analysis extends to 2048, which is 30 years after assumed P-8 implementation in 2018.

[3] Long-term projections of VKT, stock, and sales were not available from Brazilian sources.

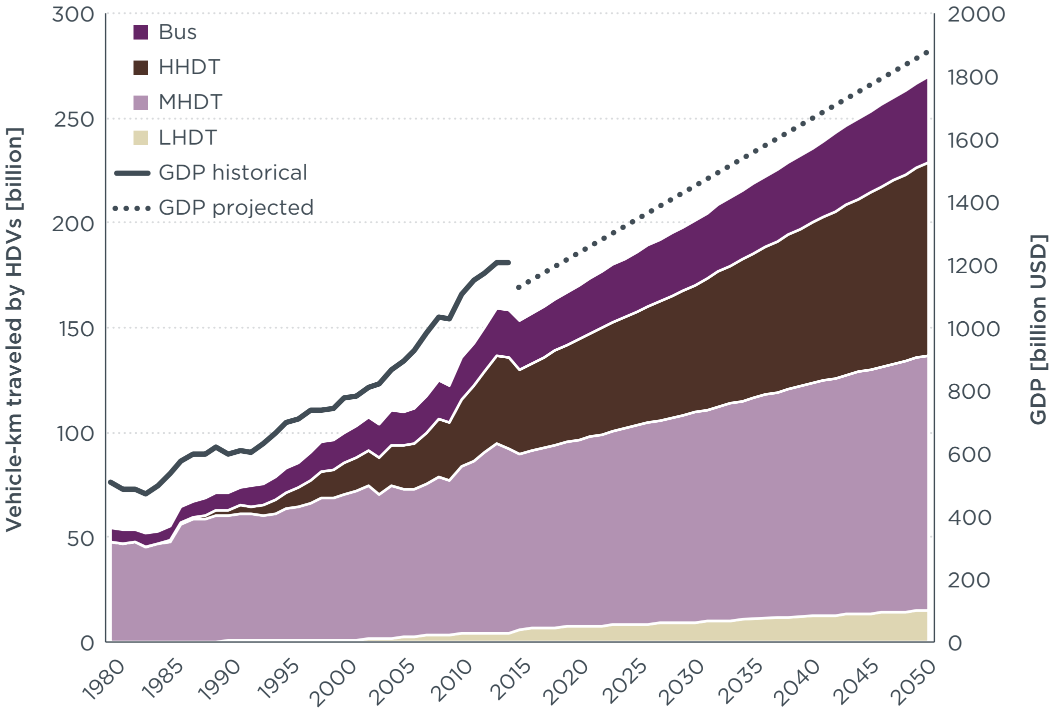

Figure 6. Projected vehicle-km traveled by diesel heavy-duty trucks and buses, 2018-2050.

Historical vehicle activity estimates provided by IEMA. Historical GDP data from the World Bank (2015a).

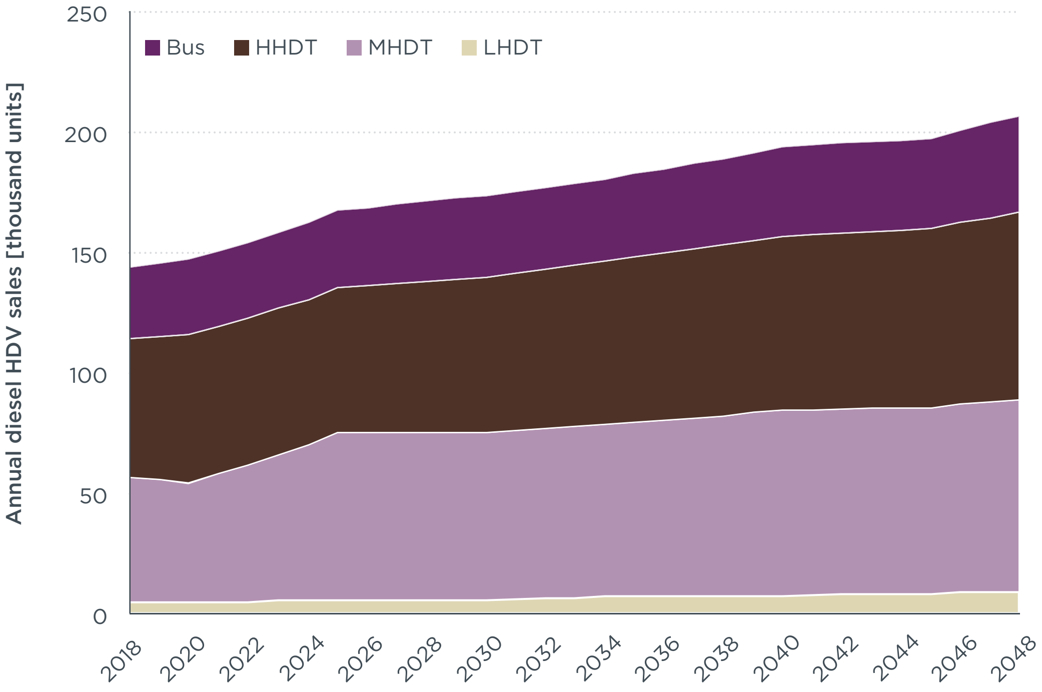

Figure 7. Projected sales of diesel heavy-duty trucks and buses, 2018-2048.

Figure 8 compares the share of vehicle activity by level of emission control in the P-7 and P-8 scenarios. As shown in Figure 8, under the P-8 scenario, P-8 vehicles could account for roughly 90% of nationwide VKT by diesel HDVs in 2035.

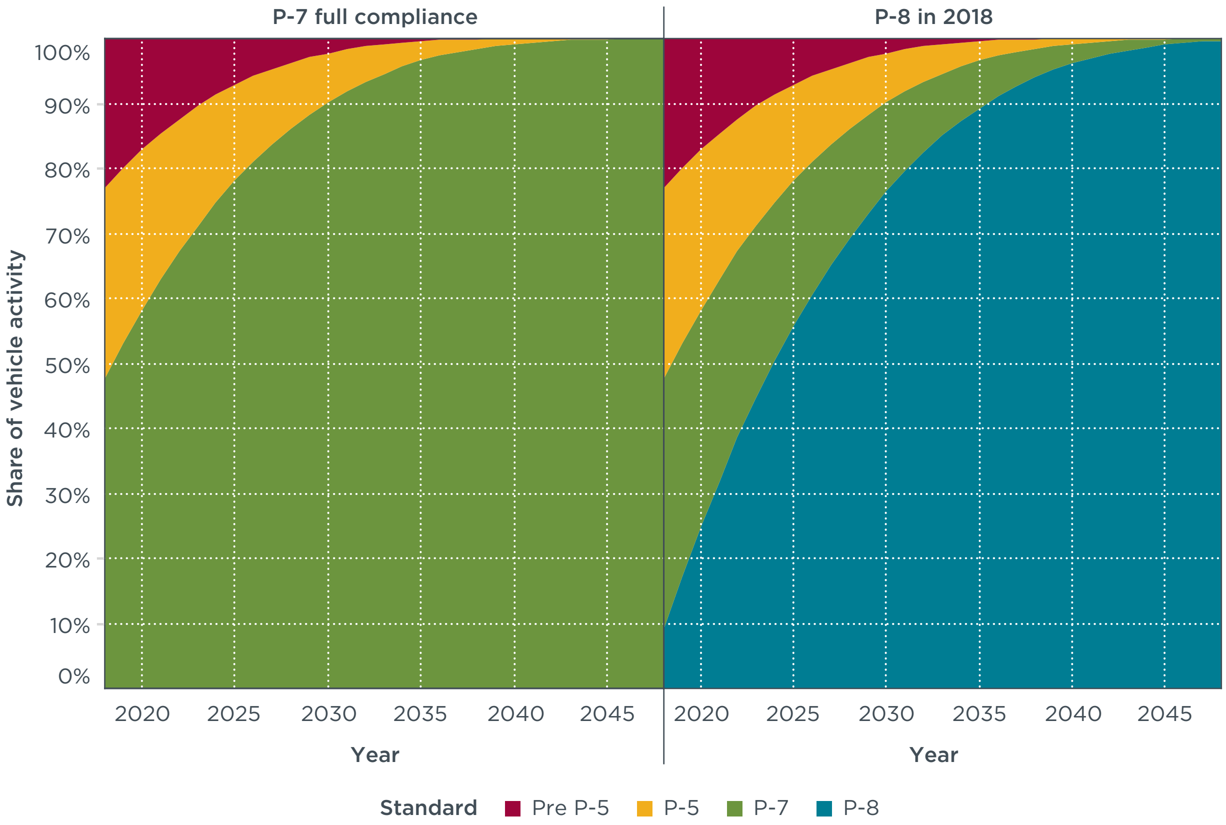

Figure 8. Share of diesel HDV activity by emission certification level.

VEHICLE TAILPIPE EMISSION FACTORS

While P-7 standards regulate tailpipe emissions of carbon monoxide (CO), hydrocarbons (HC), NO_x, particulate matter (PM), and smoke, the cost-benefit component of this analysis focuses on the impact of emissions that are most harmful to health ($PM_{2.5}$). Apart from those impacts included in the cost-benefit analysis, we report potential emission reductions for NO_x, CO, and HC, as well as black carbon (BC) and its associated climate impacts in terms of its CO_2-equivalent. Tailpipe emissions were estimated using the ICCT Roadmap model, which incorporates a global set of lifetime average emission factors derived from the European Environment Agency's COPERT model (Katsis, P., Ntziachristos, L., & Mellios, G., 2012). Because this analysis used modeled rather than real-world emission factors, conducting real-world emission tests of HDVs in use in Brazil could provide valuable data to cross-check the results of this study. These emission factors, for diesel vehicles, are expressed in grams per VKT and are differentiated by pollutant, vehicle type, and emission certification level. To estimate fleetwide vehicle emissions, these factors are multiplied by annual VKT for each pollutant, vehicle type, fuel type, and emission certification level in a given year, and converted to metric tons of emissions. For more information on the Roadmap model's methods for calculating tailpipe emissions, see Appendix II in Chambliss et al. (2013). **Figure 9** summarizes absolute emission factors for $PM_{2.5}$ and NO_X, as well as the percentage change in emission factors from uncontrolled levels to Euro III (P-5), Euro III to Euro V (P-7), and Euro V to Euro VI (P-8). $PM_{2.5}$ emission factors were derived from tests using a specified reference fuel; these factors are adjusted in the Roadmap model according to the sulfur content of diesel fuel.

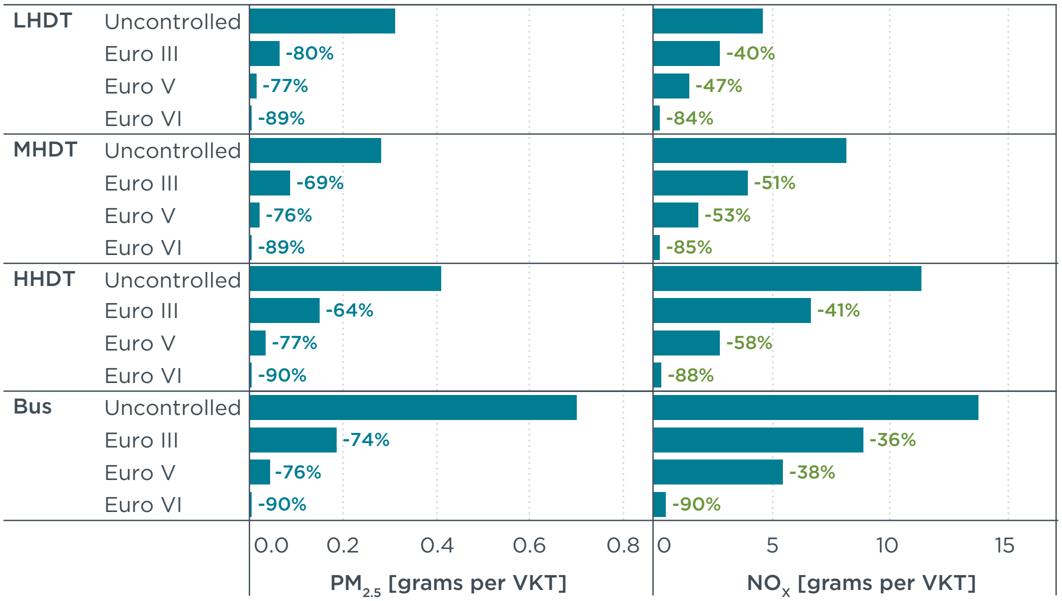

Figure 9. $PM_{2.5}$ and NO_X emission factors, grams per VKT.

Data labels indicate change from the previous standard. Source: ICCT analysis of COPERT 4, version 10.0.

HEALTH BENEFITS

The ICCT has developed a streamlined methodology for estimating the number of early deaths from lung cancer, cardiopulmonary disease, and acute respiratory infection resulting from exposure to tailpipe emissions of $PM_{2.5}$ in urban areas (Chambliss et al., 2013; Minjares et al., 2014). This methodology converts $PM_{2.5}$ emissions to air quality concentrations using a precalculated set of intake fractions that includes population density, weather, and topographical characteristics for 127 cities in Brazil. It does not count population exposures outside these 127 cities, which consists mostly of rural areas, nor does it capture exposure to secondary forms of particulate matter. Air quality concentrations and population data are then combined with concentration-response functions that estimate the change in incidence of early death given a change in pollution concentration. For additional details on the ICCT's methods for estimating health impacts, see Appendix III in Chambliss et al. (2013).

Consistent with the methodology applied by the U.S. EPA, estimates of early deaths resulting from exposure to emissions in a given year were distributed over the following 20 years to better reflect when these deaths would actually occur (EPA, 2011). This "mortality lag" implies that while this analysis considers the costs and emission benefits associated with P-8 standards from 2018 to 2048, it does not capture the portion of delayed health benefits that would accrue from 2049 to 2068 as a result of exposure to $PM_{2.5}$ emitted from 2029 to 2048. In doing so, it provides a conservative estimate of health benefits.

Share of activity in urban areas

To estimate health impacts resulting from exposure to emissions in densely-populated urban areas, nationwide vehicle activity was disaggregated to urban areas based on differentiated shares by vehicle type. Conservatively low activity shares were selected to ensure health benefits were not overestimated (Table 2).

Table 2. Assumed share of activity in urban areas by vehicle type

Vehicle type	Share of activity in urban areas
LHDT	31%
MHDT	26%
HHDT	17%
Bus	49%

Based on a global methodology for assessing health impacts of on-road vehicles as described in Chambliss et al. (2013).

Monetization of health impacts

As in previous studies conducted in Mexico and China (Miller et al., 2014; Shao & Wagner, 2015), this analysis applies a standard VSL approach to monetize the benefits of avoided early deaths from exposure to vehicle emissions (EPA, 2000; EPA, 2011; Minjares et al., 2014). Rather than assigning a normative value to a human life as the term might suggest, this approach “reflects the aggregation of individuals’ willingness to pay for fatal risk reduction and therefore the economic value to society to reduce the statistical incidence of premature death in the population by one” (He & Wang, 2010). By reflecting individuals willingness to pay to reduce the risk of premature death, VSL allows governments to evaluate the social benefit of actions that reduce the risk of premature death. Ideally, estimates of VSL should be based on local empirical studies that reflect a combination of stated preference and revealed preference methods; however, in countries where sufficient empirical data are not available, estimates can be adjusted from other countries using a “benefit transfer” approach (Minjares et al., 2014). In the absence of sufficient empirical evidence in Brazil, we applied the benefit transfer approach as described in Miller et al. (2014):

> For analyses of environmental policies in the U.S., the EPA recommends using a central VSL estimate of $7.4 million (2006 USD) adjusted to the year of analysis (EPA, 2010a). This value was derived from a meta-analysis of 26 contingent valuation and labor market studies conducted predominantly for the U.S. population between 1976 and 1991. EPA adjusted the findings of these studies to 2006 USD, fitted these values to a Weibull Distribution, and estimated a central value of $7.4 million.
>
> The key assumption of the benefit transfer approach is that differences in per-capita income are the most important determinants of differences in willingness to pay for mortality risk reduction between populations. Other factors such as age and the type of fatality under consideration have a conceptual basis for influencing willingness to pay for mortality risk reduction, but more research is needed to reliably adjust for these factors (Minjares et al., 2014). The benefit transfer approach adjusts VSL based on the following equation, adapted from Hammitt and Robinson (2011):
>
> $$VSL_b = VSL_a \; x \; \frac{PPP\ GNI\ per\ capita_b^{\,e}}{PPP\ GNI\ per\ capita_a}$$

Where country *a* is the country for which the original VSL estimate was derived, country *b* is the target country of the analysis, *PPP GNI per capita* is the gross national income per capita adjusted based on purchasing power parity, and *e* is the income elasticity. PPP-GNI per-capita is the World Bank's favored measure for assessing monetary well-being across countries (Minjares et al., 2014). The income elasticity represents the percent increase in willingness to pay (WTP) for a reduction in mortality risk that accompanies a percent increase in per-capita income. With increasing income, for example, an elasticity of 0.5 means that for a 10% increase in income, VSL increases by 5%. With a decrease in income (as with the benefit transfer approach), the same elasticity of 0.5 means that for a 10% decrease in income, VSL decreases by 5%. Thus when transferring VSL estimates from a high-income country to a lower income country, high elasticities (e.g., 2.0) result in lower VSLs than low elasticities (e.g., 0.5), since VSL is more sensitive to changes in per-capita income.

Studies have estimated a range of income elasticities, from 0.5 to 0.6 (Viscusi & Aldy, 2003) and 0.8 (OECD, 2012) in developed countries, to 1.0 as a central estimate based on recommendations by World Bank staff (Minjares et al., 2014), and greater than 1.0 in lower income populations (Hammitt & Robinson, 2011). The main estimates for this paper apply an income elasticity of 1.0.

Source: Miller et al. (2014)

Table 3 indicates the steps followed in this analysis to adjust the U.S. EPA's recommended VSL to Brazil. Such an approach results in an estimate of $2.44 million (2015 USD) for the income-adjusted VSL in Brazil in 2015, assuming an income elasticity of 1. This value increases to $2.52 million in 2018 and $3.46 million in 2048 according to projected growth in per capita income. As in Miller et al. (2014), we conducted a sensitivity analysis using VSL estimates derived using elasticities of 0.5 and 2 (see the section on "Sensitivity to discount rate and VSL"). As shown in **Figure 10,** the choice of income elasticity has a substantial impact on VSL estimates using the benefit-transfer approach.

Table 3. Assumptions for adjusting the U.S. EPA recommended VSL to Brazil

Step	Result	Source
1. Identify the EPA's recommended VSL for application in the U.S.	7.4 million (2006 USD)	EPA (2010a)
2. Convert 2006 USD to 2015 USD	8.75 million (2015 USD)	BLS (2015)
3. Take the ratio of per-capita income (PPP-GNI per capita) in Brazil and the U.S. in the most recent year	0.28 = (15,590 / 55,860)	World Bank (2015b)
4. Define the relationship between per capita income and VSL (income elasticity)	1.0	Minjares et al. (2014)
5. Forecast long-term per capita income growth using on historical trends	Annual 1% to 1.1% increase	Historical data (World Bank, 2015a)

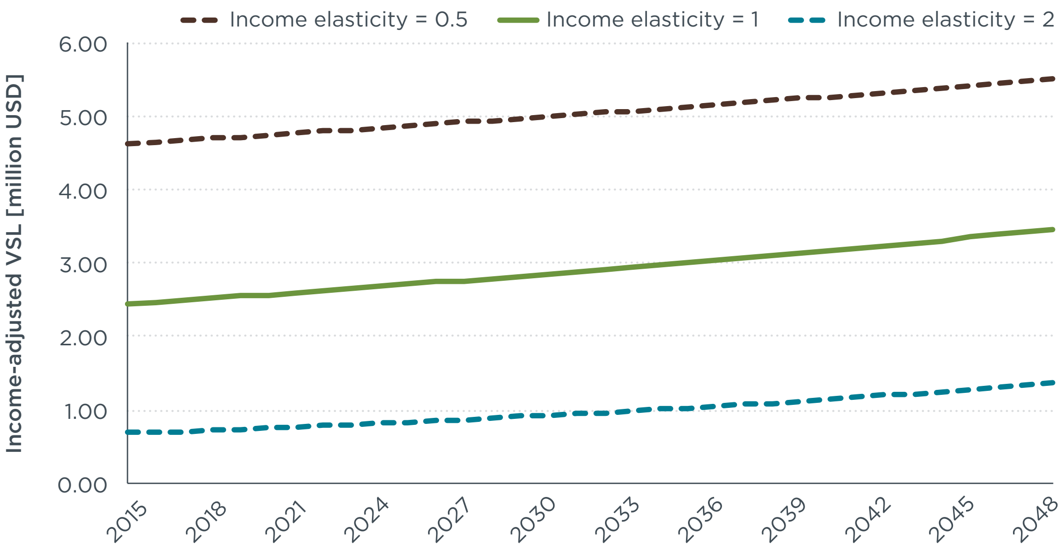

Figure 10. Income-adjusted VSL estimates for Brazil with elasticities of 0.5, 1.0, and 2.0

CLIMATE BENEFITS

Black carbon (BC) is a component of fine particulate matter that is also a potent short-lived climate pollutant (SLCP). Organic carbon (OC) and sulfates, also components of fine particulate matter, have climate cooling effects. BC emissions can constitute up to 75% of tailpipe PM from diesels with Euro V-equivalent emission controls and ULSD (EPA, 2012). This analysis quantified the potential climate benefits of P-8 standards in terms of global warming potential (GWP) and global temperature potential (GTP) over a 20-year and 100-year time horizon. These potential climate benefits are provided as a reference to policymakers, but are not incorporated into our cost-benefit estimates.

While GWP is widely used among global policymakers, it is an imperfect measure of the climate impacts of SLCPs, because it takes into account only radiative forcing and atmospheric lifetime rather than total temperature change. In 2007, the Intergovernmental Panel on Climate Change (IPCC) introduced the GTP metric aimed at resolving limitations of the GWP applied to short-lived pollutants and to communicate a temperature end point (i.e., temperature change) that is more relevant to climate policy (Forster et al., 2007). For short-lived pollutants, the GTP tends to be smaller than the GWP. Table 4 gives the GWP and GTP values applied for emissions of BC, OC, and sulfates. In each year, emissions of these pollutants were multiplied by their respective values to estimate climate impacts in terms of carbon dioxide equivalent (CO_2e).

Table 4. Global warming and temperature impacts of short-lived climate pollutants

Pollutant	GWP-20	GWP-100	GTP-20	GTP-100	Source / Notes
CO_2	1	1	1	1	By definition, the GWP and GTP of CO_2 are equal to 1
BC	3200	900	920	120	IPCC AR5 (Myhre et al., 2013)
OC	-240	-65	-71	-9	IPCC AR5 (Myhre et al., 2013)
Sulfate	-360	-100	-41	-6.3	Derived from Bond et al. (2013)

IPCC AR5: Fifth Assessment Report, Working Group 1.

VEHICLE TECHNOLOGY COSTS

Vehicle technology costs were calculated by estimating the per-vehicle incremental cost of technology needed to meet Euro VI (P-8) compared with Euro V (P-7), and multiplying these incremental costs by the number of vehicles sold in each calendar year. Incremental technology costs were estimated using a bottom-up engineering cost analysis that considers direct costs to manufacturers, including variable costs that depend on engine size, as well as fixed costs (Table 5). The ICCT has conducted similar analyses for light-duty vehicle technologies (Posada, Bandivadekar, & German, 2012). While some manufacturers may mark up the cost of emission controls to generate profits, the incremental costs of meeting the more stringent standard are still captured by the direct cost to manufacturers. These costs are expected to result in a conservative estimate of net benefits for several reasons. Because these technologies are mature and already produced in large volumes in the U.S., Canada, EU, and other countries that have implemented advanced standards, we do not assume further cost reductions due to technology learning. These estimates also exclude the potential for cost reductions associated with lower labor costs in Brazil.

Average incremental technology costs for each vehicle type were estimated based on the sales-weighted average engine size for that vehicle type (Table 5). In summary, meeting P-8 standards instead of P-7 would cost an average of $2,460 per vehicle, with lower costs for smaller engines and higher costs for larger engines. **Table 6** shows these same cost estimates converted to 2015 Brazilian Real. The exact cost may fluctuate depending on the exchange rate and manufacturing location.

Table 5. Incremental cost of Euro VI technologies with respect to Euro V (PROCONVE P-7 technology) (2015 USD)

	Engine Size (Liters)						
Euro VI Technologies	**3.6 L**	**4.2 L**	**4.5 L**	**6.5 L**	**6.9 L**	**11.1 L**	**Notes**
Fuel injection 2200-2500 bar	20	25	26	37	40	63	(2) FEV 2012
Variable geometry turbocharger	45	53	57	82	87	140	Expert feedback
EGR improvements	15	15	15	20	20	26	Estimate
Combustion improvements	36	36	36	36	36	36	EPA 2000
Engine calibration	28	28	28	28	28	28	EPA 2000
Closed crankcase filtration	17	19	21	31	33	52	EPA 2000
Air and fuel management costs (50%) (1)	162	176	182	233	242	345	—
OBD	371	371	371	371	371	371	(3) EPA 2008
SCR improvements from Euro V	353	364	369	406	413	491	(4) ICCT 2012
DPF	720	819	870	1,202	1,269	1,965	ICCT 2012
Total additional direct manufacturing cost	**1,606**	**1,731**	**1,792**	**2,213**	**2,296**	**3,172**	

(1) Air and fuel management costs are accounted for at a 50% rate given that the air and fuel management changes in technology are designed to improve not only emissions but also fuel economy of the vehicle.
(2) Increase from 2000 bar used for Euro V.
(3) EPA Technical Support Document to OBD Regulation for HDV OBD. www.epa.gov/obd/regtech/420r08019.pdf
(4) Closed loop — NO_x sensor added; shift from vanadium to zeolite catalyst

Table 6. Incremental cost of Euro VI technologies with respect to Euro V (PROCONVE P-7 technology) (2015 Brazilian Real)

Euro VI Technologies	Engine Size (Liters)					
	3.6 L	4.2 L	4.5 L	6.5 L	6.9 L	11.1 L
Fuel injection 2200-2500 bar	R$ 82	R$ 98	R$ 102	R$ 147	R$ 160	R$ 254
Variable geometry turbocharger	R$ 180	R$ 213	R$ 229	R$ 327	R$ 348	R$ 561
EGR improvements	R$ 61	R$ 61	R$ 61	R$ 82	R$ 82	R$ 102
Combustion improvements	R$ 143	R$ 143	R$ 143	R$ 143	R$ 143	R$ 143
Engine calibration	R$ 110	R$ 110	R$ 110	R$ 110	R$ 110	R$ 110
Closed crankcase filtration	R$ 70	R$ 78	R$ 86	R$ 123	R$ 131	R$ 209
Air and fuel management costs (50%) (1)	R$ 647	R$ 704	R$ 728	R$ 933	R$ 970	R$ 1,379
OBD	R$ 1,485	R$ 1,485	R$ 1,485	R$ 1,485	R$ 1,485	R$ 1,485
SCR improvements from Euro V	R$ 1,412	R$ 1,457	R$ 1,477	R$ 1,625	R$ 1,653	R$ 1,964
DPF	R$ 2,881	R$ 3,278	R$ 3,478	R$ 4,808	R$ 5,074	R$ 7,861
Total additional direct manufacturing cost	**R$ 6,424**	**R$ 6,924**	**R$ 7,169**	**R$ 8,851**	**R$ 9,182**	**R$ 12,689**

Estimated using an exchange rate of 1 Brazilian Real (R$) to 0.25 USD in 2015.

Table 7. Per-vehicle incremental costs from Euro V to Euro VI

Currency	LHDT	MHDT	HHDT	Bus	Sales-weighted average
2015 USD	1,606	1,991	3,172	2,183	2,459
2015 R$	R$ 8,730	R$ 12,689	R$ 6,424	R$ 7,964	R$ 9,834

VEHICLE MAINTENANCE COSTS

HDVs equipped with DPFs will likely incur incremental maintenance costs to clean the filters periodically. These costs, which are primarily labor-related, can run about 200 USD in the U.S. (Minjares et al., 2014). We adjusted the estimated cost of a single DPF cleaning to reflect the difference in labor costs between the U.S. and Brazil, estimating 62 USD based on the ratio of manufacturing labor costs in Brazil to the U.S. in 2012 (Bureau of Labor and Statistics, 2013). This cost per DPF cleaning was converted to an estimated cost per VKT assuming a maintenance interval of 75,000 km — the interval typically recommended by U.S. original equipment manufacturers for vehicles with severe service requirements, high idle times, and less highway driving (Minuteman Trucks Inc., 2015). This interval results in a cost estimate of 0.55 USD per thousand VKT, equivalent to a DPF cleaning every 1-2 years for P-8 HDVs operating in Brazil. For each year from 2019-2048, assuming no maintenance costs during the first year of operation, total incremental maintenance costs in the P-8 scenario were calculated as the product of VKT by P-8 vehicles and the cost per VKT.

DIESEL EXHAUST FLUID COSTS

Diesel HDVs commonly use SCR systems to comply with NO_x emission limits under the current P-7 standards. In Brazil, these systems use ARLA-32 to reduce NO_x from the engine into two gases — nitrogen and water vapor — that are harmless to human health (Petrobras, 2015). In this analysis, the volume of ARLA-32 consumed is estimated to be 4% of diesel fuel consumption for both P-7 and P-8 vehicles. Assuming there would be no change in the volume of ARLA-32 needed to meet P-8 standards, there would be no incremental costs compared to P-7. Manufacturers are reaching lower NO_x emissions while maintaining similar urea consumption rates by improving the NO_x conversion efficiency of the SCR system. This SCR improvement is based on two main elements. First, the SCR catalyst is upgraded from vanadium to zeolites, which provide better NO_x conversion efficiency over a wider range of exhaust temperatures. Second, urea injection is more closely monitored, as NO_x sensors are now installed before and after the SCR system for better conversion efficiency and lower ammonia (NH_3) slip. Note that NH_3 is regulated under the Euro VI program. (Chambliss & Bandivadekar, 2015). Also note that most manufacturers did not have NO_x sensors for Euro IV and Euro V applications and relied on engine data to deliver the urea to the SCR system. All of the costs associated with improved catalysts and additional NO_x sensors are included in the estimated costs presented in Table 5.

CUMULATIVE NET BENEFITS

In order to sum benefits and costs occurring over multiple years, it is necessary to apply a discount rate, which converts future benefits and costs into present value terms (i.e., the value today that society places on future payoffs). Cumulative estimates of discounted benefits and costs are referred to as the present discounted value (PDV) of these payoffs. In this analysis, cumulative net benefits are calculated as the PDV of benefits minus the PDV of costs over the time horizon considered, specifically from 2018 to 2048.

3 RESULTS

EMISSION REDUCTIONS

In 2015, MHDTs contributed 43%-44% of $PM_{2.5}$, BC, and NO_X from diesel HDVs, with HHDTs and buses also contributing a substantial share of emissions (Figure 11). Of the estimated 20,000 tons of $PM_{2.5}$ emitted from diesel HDVs in Brazil, we estimate BC accounted for 60% of PM emissions by mass. While direct exposure to $PM_{2.5}$ emissions is especially harmful to human health by increasing the risk of premature death, NO_X emissions are an important contributor to secondary PM and ozone, both of which raise the risk of hospitalization and death from respiratory problems (Jerrett et al., 2009; Burnett et al., 2001). In 2015, diesel HDVs in Brazil emitted 40 times as much NO_X as $PM_{2.5}$ (by mass).

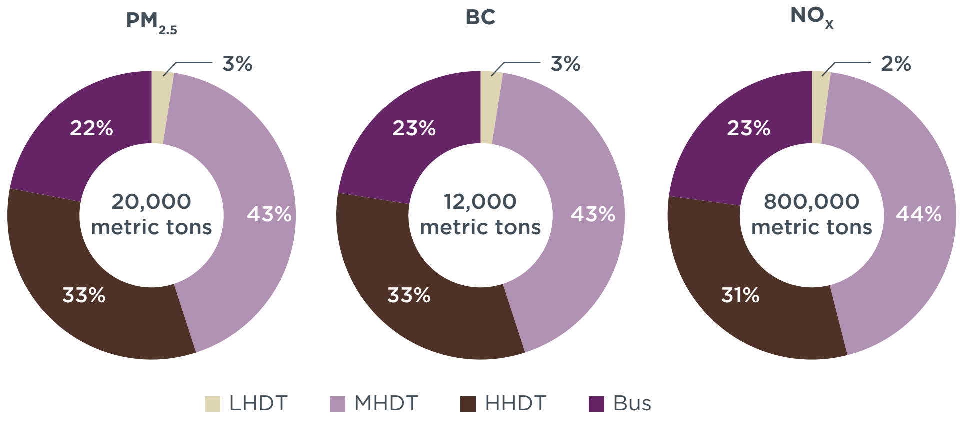

Figure 11. Share of diesel emissions by HDV type in 2015.

Figure 12 shows projected annual emissions of these three pollutants with and without implementation of P-8 standards. Over about a 30-year period (2018-2048), effective implementation of P-8 standards could reduce emissions by 89%-99% from current levels, equivalent to a cumulative reduction of 130,000 tons of $PM_{2.5}$, 110,000 tons of BC, 12 million tons NO_X, 2.7 million tons of CO, and 24,000 tons of HC (Table 8).[4]

Table 8 Cumulative emission reductions with P-8 standards, 2018-2048

Pollutant	Cumulative emissions (2018-2048) [thousand tons]		Cumulative emissions with P-8 compared to P-7 [thousand tons]
	P-7 full compliance	P-8 in 2018	Δ with P-8 in 2018
$PM_{2.5}$	270	150	-130
BC	190	80	-110
NO_X	19,900	7,900	-12,000
CO	8,100	5,400	-2,700
HC	339	314	-24

Source: ICCT Global Transportation Roadmap Model

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4 All tons reported are metric tons. Estimates are typically rounded to two significant digits.

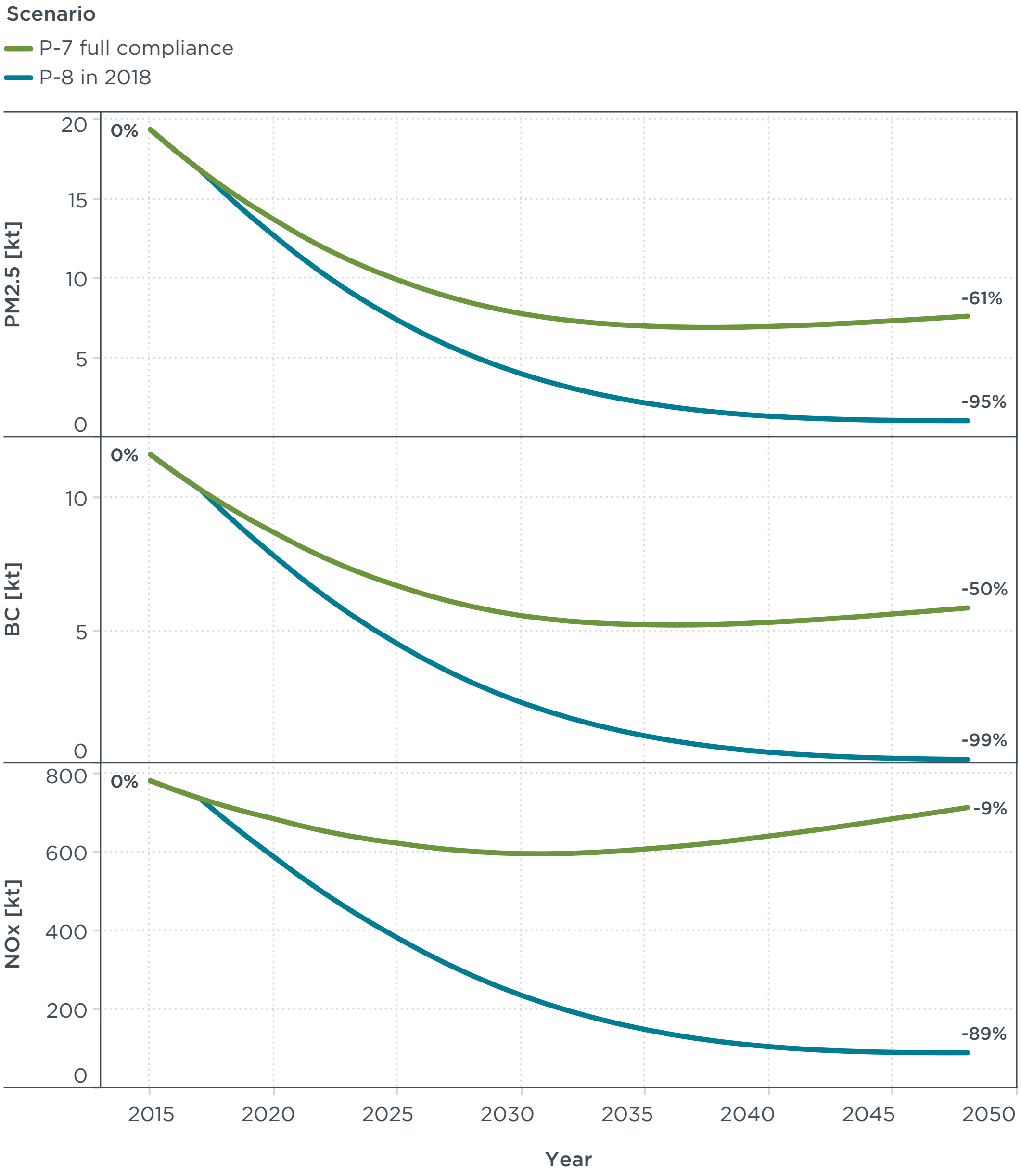

Figure 12. Annual tailpipe emissions of $PM_{2.5}$, BC, and NO_x from diesel heavy-duty vehicles.

Data labels indicate percent change in emissions relative to 2015. "kt" indicates thousand metric tons. Estimates are generated using the ICCT Global Transportation Roadmap Model.

Compliance with P-7 standards

Diesel HDVs commonly use SCR systems to comply with NO_x emission limits under the current P-7 standards. In Brazil, these systems use ARLA-32 to reduce NO_x from the engine into two gases - nitrogen and water vapor — that are harmless to human health; however, estimates from AFEEVAS, the association of manufacturers of vehicle emission control equipment in South America, suggest that sales of ARLA-32 are not keeping pace with expected demand and P-7 standards might not result in their full intended emissions benefits (Façanha, 2015). There are additional issues with high real-world NO_x emissions from Euro IV and Euro V HDVs (Muncrief, 2015), and these are factored into the emission factors applied in this analysis.

P-8 standards are expected to improve upon the compliance provisions of the current P-7 standards with new test cycles that better represent real-world NO_x emissions; fail-safes that detect low ARLA-32 levels, incorrect liquid, or faults in the SCR system; and progressive driver inducements that include warnings, performance reduction, or immobilization in the case of severe problems (Posada & Bandivadekar, 2015). For this reason, P-8 standards are expected to resolve any NO_x compliance issues that may exist under the current standards.

Figure 13 compares NO_x emissions from diesel HDVs under three compliance scenarios:

- **P-7 partial compliance:** New diesel HDVs meet P-7 (Euro V) requirements starting in 2012 and are supplied with S10 diesel, except only 68% of VKT are supplied with appropriate levels of ARLA-32. These vehicles (traveling 32% of VKT) are assumed to emit NO_x at levels equivalent to the previous P-5 standard (Euro III-equivalent).
- **P-7 full compliance:** New diesel HDVs meet P-7 requirements starting in 2012, are fueled with S10 diesel, and 100% of VKT by new vehicles use appropriate levels of ARLA-32.
- **P-8 in 2018:** New diesel HDVs meet P-8 (Euro VI) requirements starting in 2018 and continue to use S10 diesel and appropriate levels of ARLA-32.

In the case that one in three vehicle-kilometers traveled by P-7 vehicles use insufficient ARLA-32, the NO_x benefits of advancing to P-8 standards could be roughly 50% greater than their benefits compared to a scenario with full P-7 compliance (Figure 13). Because the cost-benefit component of this analysis covers only the mortality impacts of tailpipe $PM_{2.5}$ emissions, a valuation of benefits resulting from improved NO_x compliance falls outside the scope of this study; however, we expect that incorporating such benefits would increase the net benefits of advancing to P-8 standards (EPA, 2014).

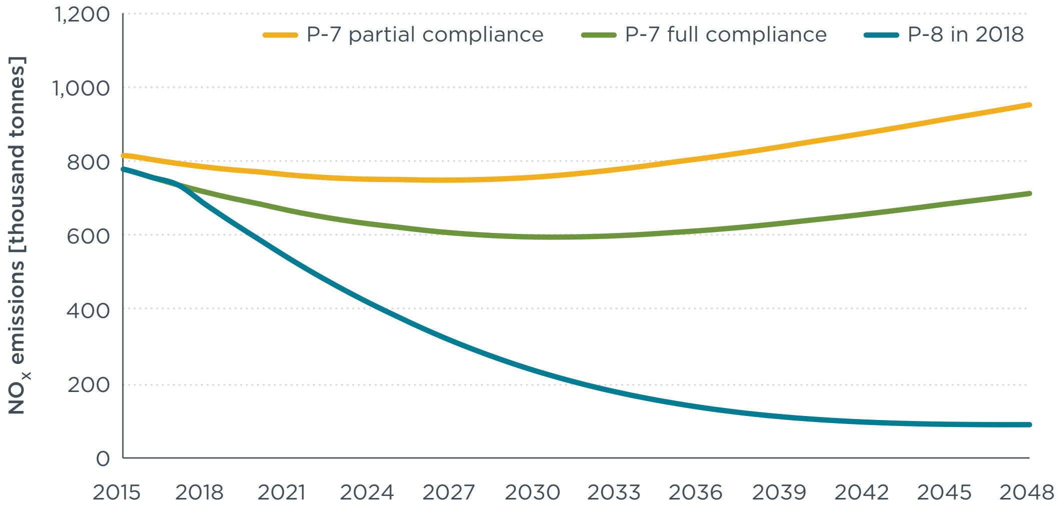

Figure 13. Annual emissions of nitrogen oxides from diesel HDVs by compliance scenario.

HEALTH BENEFITS

The estimated reductions in tailpipe emissions of $PM_{2.5}$ would reduce the number of early deaths from cardiopulmonary disease, lung cancer, and acute respiratory disease resulting from exposure to $PM_{2.5}$ concentrations in urban areas. Effective implementation of P-8 standards could avoid more than 5,500 early deaths annually by the year 2048, equivalent to 74,000 early deaths avoided over the period of 2018-2048 (Figure 14). The value of these avoided premature deaths was estimated using a VSL derived from the U.S. EPA recommended value and adjusted for the average per capita income in Brazil assuming an income elasticity of 1. The blue line reflects the undiscounted value of annual health benefits using this income-adjusted VSL for Brazil. The value of health benefits appears to increase more quickly in later years as the VSL increases with income growth.

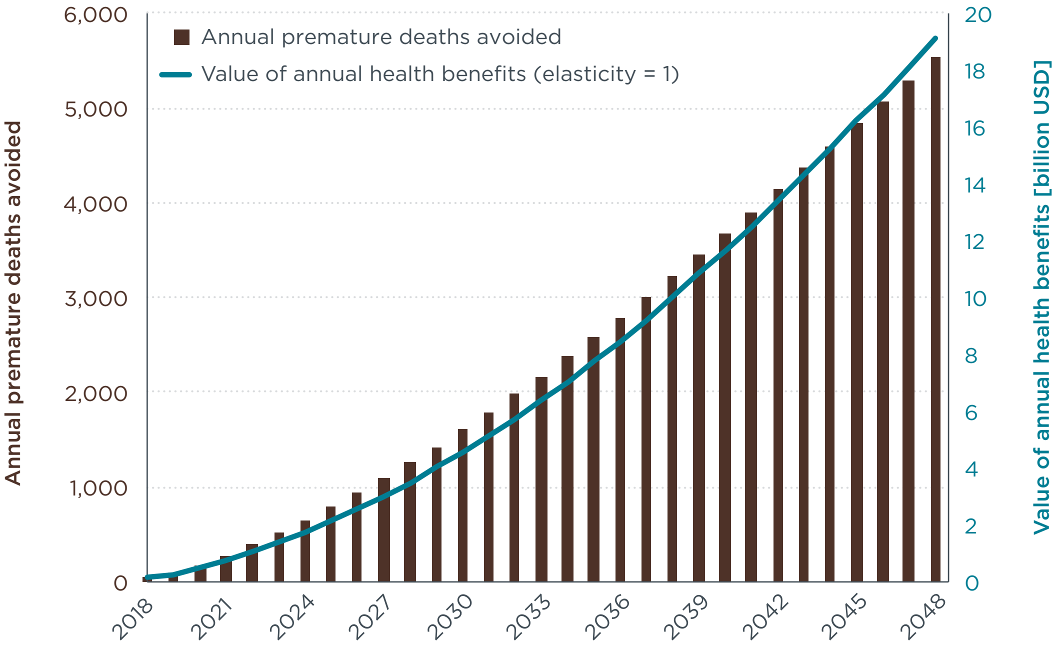

Figure 14. Annual premature deaths avoided and value of health benefits with P-8 implementation in 2018.

CLIMATE BENEFITS

From 2018-2048, P-8 standards could eliminate 110,000 tons of BC, with climate benefits offset by less than 2% due to concomitant reductions in climate-cooling OC and sulfate emissions. The cumulative net climate benefits of reduced BC, OC, and sulfate emissions are equivalent to 92 million metric tons of CO_2 ($MtCO_2e$) using a 100-year GWP, and up to 350 $MtCO_2e$ using a 20-year GWP (Table 9).

Table 9. Cumulative reduction in climate pollutant emissions ($MtCO_2e$)

Climate impact ($MtCO_2e$)	Global warming potential		Global temperature potential	
	GWP-20	GWP-100	GTP-20	GTP-100
BC	352	93	101	13
OC and Sulfate	-4	-1	-1	-0.2
Net CO_2e (Mt)	348	92	100	13

VEHICLE TECHNOLOGY COSTS

Figure 15 shows the annual undiscounted incremental costs of vehicle technology to meet P-8 standards from 2018-2048. These costs take into account a projected 44% increase in sales of new HDVs from 2018-2048 and assume that per-vehicle incremental technology costs remain constant over time.[5] Assuming a 5% discount rate, cumulative technology costs (shown on the right axis) amount to 5.9 billion (2015 USD) by 2048.

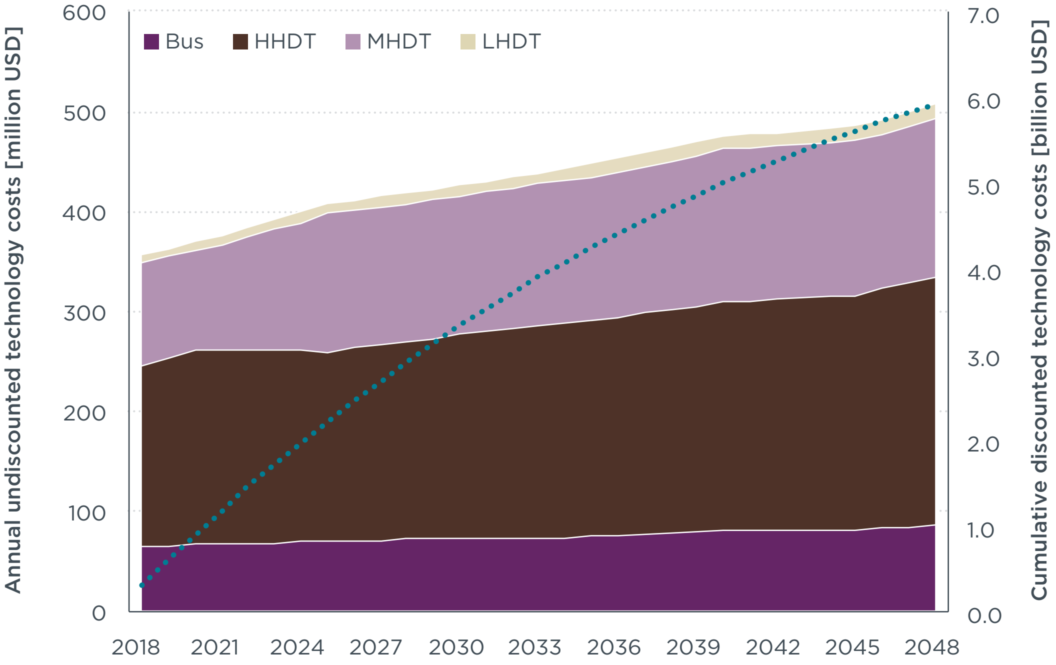

Figure 15. Annual and cumulative discounted vehicle technology costs in 2015 USD, 5% discount rate (2018-2048).

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[5] This analysis does not assume any decreases over time in the incremental cost of technology per vehicle due to learning (decreasing manufacturer costs as a result of technology development) or economies of scale. This assumption results in conservatively high estimates of incremental technology costs.

VEHICLE MAINTENANCE COSTS

Figure 16 shows estimated vehicle activity by P-8 vehicles on the left axis and annual maintenance costs on the right axis for the P-8 scenario. VKT and maintenance costs scale together because maintenance costs are the product of vehicle activity and the estimated 0.55 USD per thousand VKT for DPF cleaning.

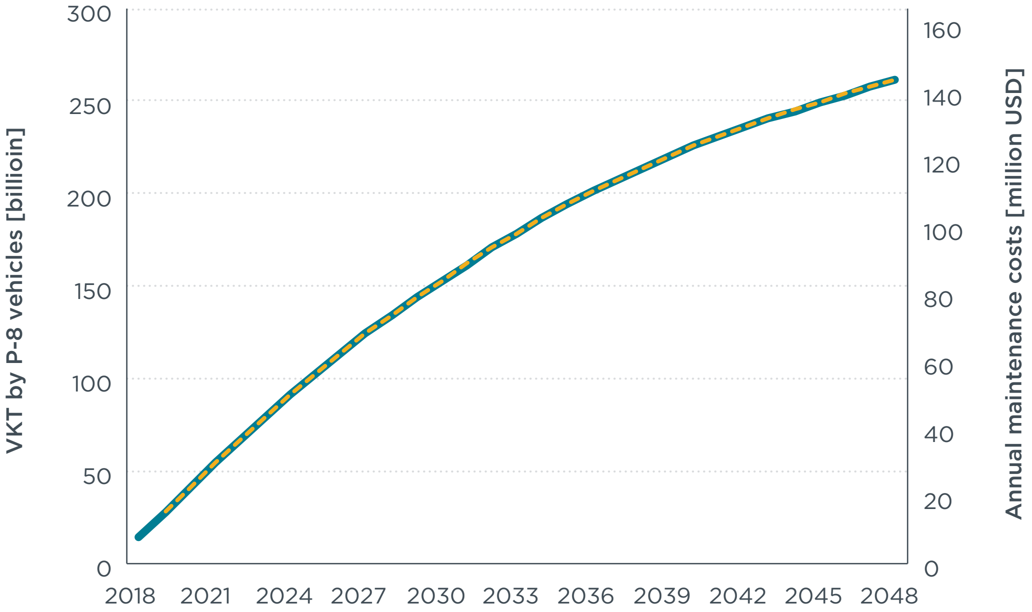

Figure 16. Vehicle activity by P-8 vehicles and annual undiscounted maintenance costs in P-8 scenario.

CUMULATIVE NET BENEFITS

Figure 17 illustrates the cumulative costs and benefits of P-8 standards from 2018-2048 using a 5% discount rate. If implemented in 2018, P-8 standards are estimated to result in health benefits valued at 74 billion USD at a cost of 7 billion USD, with a benefit-cost ratio of 11:1. Subtracting cumulative costs from benefits yields an estimate of 67 billion USD in cumulative net benefits. Given the upfront nature of vehicle technology costs, which are incurred immediately upon sale of the vehicle, and the distributed impacts of emissions on human health, which occur up to 20 years after exposure, it is particularly noteworthy that the cumulative benefits to society already exceed the costs less than 4 years after P-8 implementation.[6] One of the reasons for this quick return on investment is the fact that Brazil already has invested billions of dollars (USD) to make 10 ppm diesel available throughout the country (Petrobras, 2010). Without the adoption of P-8 standards, Brazil would not realize the full benefits of this investment.

After the first few years of P-8 implementation, the health benefits will accumulate much faster than technology costs, resulting in increasing net benefits over time up to the 30-year timeframe considered in this analysis. Sensitivity analyses to evaluate other choices of discount rate, VSL, and implementation year are described in the next section.

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[6] In the first 3 years of implementation, technology costs are greater than the health benefits occurring in those years; this is to be expected with any technology investment.

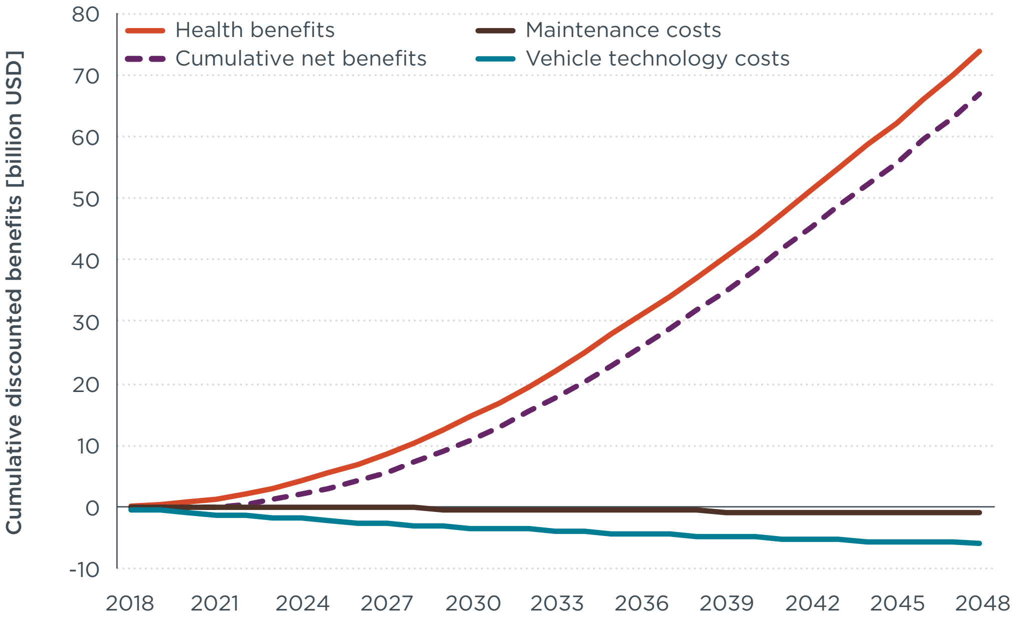

Figure 17. Cumulative net benefits of P-8 standards using a 5% discount rate.

Costs are presented as negative benefits.

The findings of this analysis are consistent with the results of similar analyses in Mexico, the U.S., and India (Table 10). These analyses examined cost-effectiveness from a societal perspective, meaning that the total societal benefits — in the form of reduced risk of early death and mitigation of climate pollutants[7] — consistently outweigh the total costs to vehicle owners and operators for improved vehicle emission control technology. The consistency of findings across studies in countries at varying levels of income and economic development, as well as the results of global studies on the health impacts of road vehicle emissions (Chambliss et al., 2013), suggest that Euro VI and EPA 2010 equivalent emission standards for HDVs could result in cumulative net benefits valued at hundreds of billions of dollars if implemented in other countries with significant sales of new HDVs.

Table 10. Cost-effectiveness of heavy-duty emission standards in Brazil, Mexico, US, India, and China

Rule	Years*	Benefits	Costs	Benefit-Cost Ratio	Source
Brazil P-8	2018-2048	$74 billion	$7 billion	11:1	This analysis
US 2010 HDV emissions	2030	$70 billion	$4.2 billion	16:1	EPA (2000)
Mexico HDV NOM-044	2018-2037	$135 billion	$12 billion	11:1	Miller et al. (2014)
China 6/VI**	2050	$86 billion	$10 billion	9:1	Shao & Wagner (2015)
India Bharat VI***	2035	$107 billion	$14 billion	8:1	Bansal & Bandivadekar (2013)

Benefit-cost ratios are rounded to the nearest whole number.

* Reporting year of costs and benefits.

** Evaluates China 6/VI standards for natural gas, diesel, and gasoline-fueled light-duty and heavy-duty vehicles. This analysis of P-8 standards focuses on the most cost-effective category, diesel heavy-duty vehicles. Therefore, we expect the analysis to find a higher ratio of benefits to costs than the China 6/VI study.

*** Includes light-duty vehicles, motorcycles, and tricycles.

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[7] Quantified but not monetized in this analysis.

SENSITIVITY ANALYSIS

Throughout this analysis, we have intentionally chosen assumptions and methods that are consistent with a conservative estimate of net benefits. These factors give us confidence that the real-world value of the regulation is even higher than the net present value estimated in this analysis:

- We considered only those health impacts resulting from exposure to primary $PM_{2.5}$ emissions in urban areas. Considering rural impacts or the impacts of secondary $PM_{2.5}$ and ozone would increase the estimated net benefits.
- We assumed that a relatively low share of vehicle activity occurs in urban areas with high exposure to transportation emissions.
- We did not capture the portion of delayed health benefits that would occur from 2049 to 2068 as a result of exposure to $PM_{2.5}$ emitted from 2029 to 2048.
- We did not assume any decreases in incremental technology costs over time as a result of learning or economies of scale (for additional details, see the section on Vehicle technology costs).

Additionally, we have conducted sensitivity analyses to examine the impacts of alternate VSLs, discount rates, varying levels of compliance with P-7 standards, as well as the costs of delayed implementation and the likely impacts of factors that were not monetized in this analysis. The following sensitivity analyses lend further confidence to the findings that the benefits of P-8 standards will far outweigh their costs, and that timely implementation is critical to minimize the number of early deaths resulting from exposure to air pollution.

Sensitivity to discount rate and VSL

The value to society of reducing the risk of an early death is a key determinant of the cost-effectiveness of policies to control fine particle emissions. As described in the methods chapter, we estimated a VSL in Brazil using the benefit transfer approach, which adjusts the VSL recommended by U.S. EPA according to differences in per capita income between the U.S. and Brazil. The key assumption in this approach is that lower per capita incomes result in lower willingness or ability to pay (WTP) for reduced risk of early death from exposure to air pollution. Considering the variation in estimates of income elasticity across studies, which reflects how sensitive changes in WTP for reduced risk of premature death are to changes in per capita income, we conducted sensitivity analysis over the range of income elasticity estimates found in the literature: 0.5 and 2.0.

While the choice of VSL affects both annual and cumulative estimates of benefits, the selection of discount rate (i.e., the rate at which society or individuals trade off between payoffs today and payoffs next year) impacts the valuation of costs and benefits summed over time. Low discount rates retain more of the value of payoffs occurring in future years compared to high discount rates, which place significantly greater weight on near-term payoffs. An ideal social discount rate should reflect the average rate at which the affected individuals are willing to trade off consumption today for consumption at a later time. Studies of social discount rates have found a range of 2%-4% for individual risk-free savings, called the "consumption rate of interest," and a range of 4.5%-7% for pretax private investments, called the "opportunity cost of capital" (EPA, 2010b). Both the U.S. EPA and Brazil's Ministry of Health recommend a central discount rate of 5%, with sensitivity analysis for lower and higher rates; however, while EPA's lower and upper bounds of 3% and 7% reflect discount rates that are typically estimated in studies of real-world rates, the Ministry of Health's estimates of 0% and 10% cover a wider range of rates than would be expected under usual circumstances (EPA, 2010b; Ministério da Saúde, 2009). Thus, while we would not expect either the low or high outcome to materialize, conducting a sensitivity analysis over a range of discount rates gives us confidence that the findings (i.e., whether net benefits are positive or negative) would be unaffected by choosing a different real-world discount rate. Figure 19 indicates that assuming an income elasticity of 1 for VSL, cumulative net benefits are positive for all discount rates between 0% and 15%.

Figure 18 shows the results of combined sensitivity analysis using three different discount rates and three different income elasticities. This range intentionally reflects a wide spectrum of normative societal preferences for the value of reducing the risk of early death and the weight given to future payoffs relative to today. Even over this wide spectrum of possible societal preferences, we find that the benefits of P-8 standards consistently outweigh the costs. Our core estimate, with a 5% discount rate and income elasticity of 1, of 67 billion USD in cumulative net benefits and a benefit-cost ratio of 11:1 over a 30-year period is intentionally conservative and lies on the lower end of this interval.

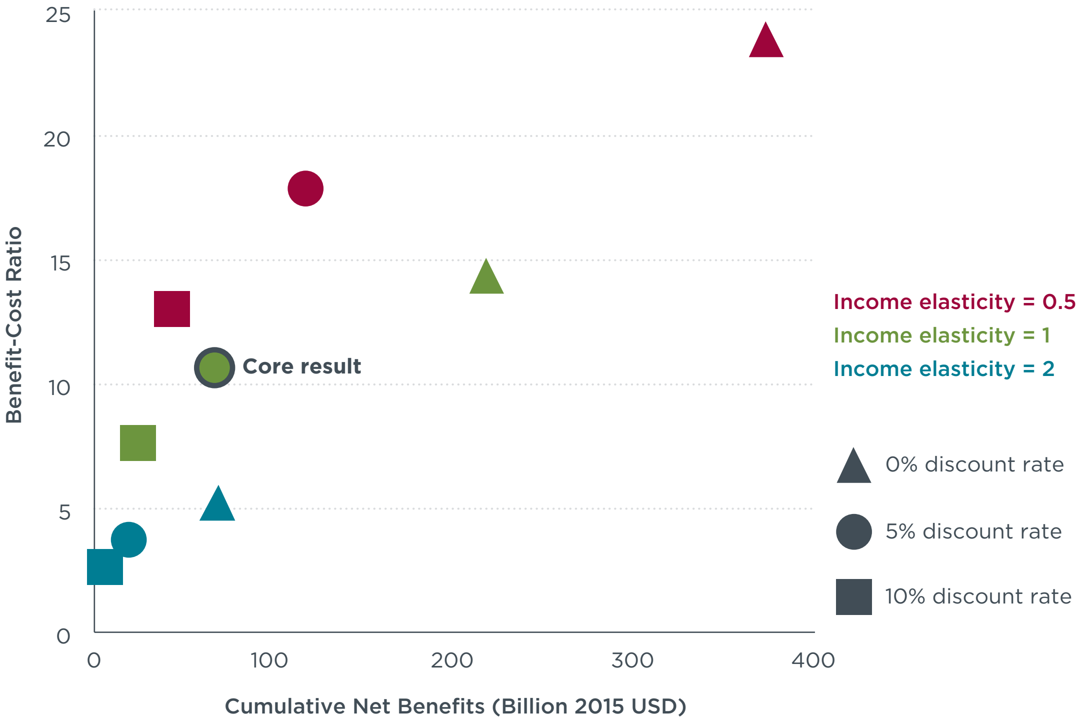

Figure 18. Sensitivity of cost-benefit results to discount rate and VSL.

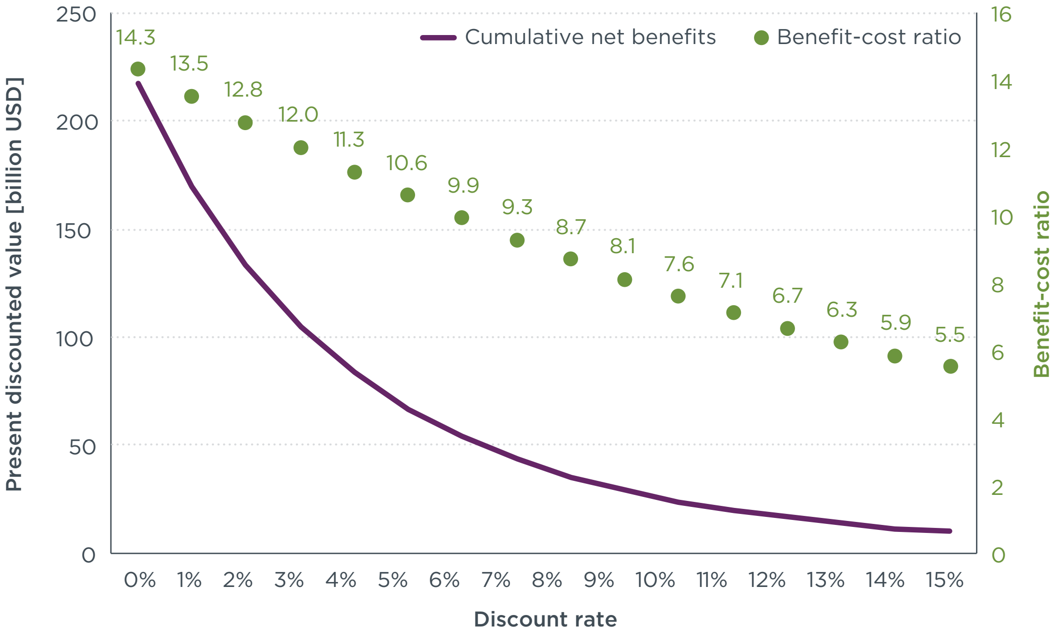

Figure 19. Sensitivity of cost-benefit results to discount rate.

Cost of delayed implementation

This analysis assessed the impact of implementing P-8 standards in 2018 and found that the benefits will far exceed the costs over the next several decades. Considering the possibility that the implementation date of the standards may be pushed later than 2018, this study also estimated the share of emissions and health benefits that would be lost if the standards were delayed by 2 to 4 years, holding the time frame of analysis constant (Table 11). As indicated in the first row, each year of delay could result in 5,000 additional tons of $PM_{2.5}$ emitted, equivalent to 3%-4% of the cumulative emissions benefits estimated over a 30-year period. Moreover, each year of delay could result in roughly 2,500 additional early deaths from exposure to $PM_{2.5}$ emissions — and the costs of a 4-year delay could result in more than 10,000 additional early deaths. From the perspective of minimizing the number of early deaths resulting from exposure to air pollution, the sooner that P-8 standards can be effectively implemented, the better.

Table 11. Cost of delaying implementation of P-8 standards by 2 to 4 years

Variable	P-8 in 2018	P-8 in 2020 [2-year delay]	P-8 in 2022 [4-year delay]
Cumulative PM2.5 reduction from P-7 [kt]	140	130	120
Lost share of emission benefits with delay		7%	14%
Additional premature deaths		5,000	10,000

Estimates are rounded to a maximum two significant digits. "kt" indicates thousand metric tons.

Likely impact of additional technical factors

While this analysis captures the most important costs and benefits, several factors were either not considered or were quantified but not included in the estimates of net present value associated with implementing the policy. Table 12 summarizes the impact that these factors would likely have on the net present value if incorporated. Considering the high ratio of benefits to costs over a range of discount rates, including these factors would not be expected to change the outcome of the analysis — namely that the benefits of implementing P-8 standards in Brazil far outweigh their costs.

Table 12. Likely impact of additional technical factors on net benefits

Factor	Comments	Likely impact on net benefits
Fuel consumption	New vehicles equipped with diesel particulate filters (DPF) to meet Euro VI requirements may incur a fuel penalty compared to vehicles without filters; however, modest improvements in engine efficiency, tuning, and other factors may offset such a penalty.	+/-
Health impacts of secondary pollution	Early deaths from exposure to primary $PM_{2.5}$ emissions typically constitute more than 90% of monetized health benefits of heavy-duty emission standards. Considering secondary pollution would add significant resource requirements, which are not necessary given that the policy is already worthwhile based on the benefits associated with reduced primary $PM_{2.5}$.	+
Social cost of black carbon climate impacts	Brazil has neither adopted a cap and trade scheme nor set a carbon-equivalent price for short-lived climate pollutants, and a valuation of climate-forcing pollutants would increase the net benefits of P-8 standards; however, this requires further methodological development with a focus on appropriate discounting of carbon dioxide-equivalent emissions.	+
Agricultural impacts of black carbon	We did not consider any increases in agricultural productivity that may result from reduced black carbon emissions from the road transport sector.	+

"+" indicates a small increase; "-" indicates a small decrease; "+/-" indicates directionality is uncertain.

4 CONCLUSIONS AND POLICY RECOMMENDATIONS

The results of this analysis indicate that adopting PROCONVE P-8 standards (Euro VI-equivalent) in Brazil is a highly cost-effective means of reducing the environmental impacts of diesel heavy-duty vehicles in Brazil. These standards will impart reasonable costs on the industry and maintain a level playing field, while significantly reducing environmental impacts of the transport sector. In summary, this analysis finds that:

- Over a 30-year period (2018-2048), P-8 standards would result in health benefits valued at $74 billion at a cost of $7 billion.
- The monetized benefits of P-8 would outweigh the costs by a factor of 11:1, consistent with the results of similar studies in Mexico, the U.S., and India.
- P-8 standards are not expected to increase fueling costs compared to the current standard, because new vehicles already use S10 fuel and ARLA-32 to comply with the P-7 standard.
- Manufacturers are expected to incur incremental vehicle technology costs ranging from $1,600 to $3,200 per vehicle depending on engine size, with a sales-weighted average of $2,460 per vehicle. These capital costs are expected to result in societal benefits that outweigh the costs within 4 years.
- Over 30 years, the cumulative benefits of P-8 standards include:
  - Prevention of 74,000 early deaths from exposure to fine particle emissions ($PM_{2.5}$) in urban areas;
  - Emission reductions of 130,000 metric tons of primary $PM_{2.5}$ and 12 million tons of NO_X;
  - Reductions of up to 350 million metric tons of CO_2-equivalent ($MtCO_2e$) using a 20-year global warming potential (GWP-20), and 92 $MtCO_2e$ using GWP-100, as a result of reduced black carbon (BC) emissions.
- Each year of delay in the implementation of P-8 standards beyond 2018 will result in an additional 2,500 premature deaths, highlighting the importance of timely action.

Apart from timely implementation of P-8 standards, there are a number of complementary policies that could accelerate the health benefits of Euro VI-equivalent vehicles and increase new vehicle sales. These include:

- Establishing fiscal incentives to encourage voluntary adoption of P-8 (Euro VI-equivalent) vehicles before 2018 (e.g., temporarily reducing or eliminating sales taxes on P-8 vehicles sold before 2018).
- Offering fiscal incentives to scrap older trucks and buses and replace them with Euro VI vehicles.
- Favoring procurement of public buses that meet Euro VI-equivalent standards.
- Reducing toll rates for vehicles that meet Euro VI-equivalent standards.
- Usage restrictions in densely populated urban areas for vehicles at earlier stages of emission control.

Given the extent to which the benefits of P-8 standards outweigh the costs, we recommend that Brazil consider these complementary policies as a means of accelerating the introduction of P-8 vehicles. It is also worth noting that 500 ppm diesel continues to be sold outside of metropolitan regions. Although dual fuel standards have been a success to date, phasing out 500 ppm diesel would eliminate the risk of misfueling P-7 and P-8 vehicles and reduce $PM_{2.5}$ emissions from in-use vehicles that meet P-5 or earlier standards. For these reasons, we recommend planning the phase out of 500 ppm fuel as a complementary policy to implementing the new P-8 standards.

LIST OF ACRONYMS

ANFAVEA	National Association of Automobile Manufacturers (Brazil)
ARLA 32	Automotive Liquid Reducing Agent
BC	black carbon
COPERT	computer program to calculate emissions from road transport (European Commission model)
CO_2e	carbon dioxide-equivalent
DEF	diesel exhaust fluid
DPF	diesel particulate filter
EPA	Environmental Protection Agency (United States)
GDP	gross domestic product
GNI	gross national income
GTP-20, GTP-100	global temperature potential over a 20- or 100-year time horizon
GWP-20, GWP-100	global warming potential over a 20- or 100-year time horizon
HD, HDV	heavy duty, heavy-duty vehicle
ICCT	International Council on Clean Transportation
IEMA	Institute for Energy and Environment
IPCC	Intergovernmental Panel on Climate Change
$MtCO_2$	million metric tons of carbon dioxide
NO_x	oxides of nitrogen
OC	organic carbon
PM, $PM_{2.5}$	particulate matter, fine particulate matter with an aerodynamic diameter less than 25 micrometers
PPP-GDP	gross domestic product at purchasing power parity
ppm	parts per million
SCR	selective catalytic reduction
ULSD	ultra-low-sulfur diesel, with <15 ppm sulfur content
USD	United States dollars
VKT	vehicle-kilometers traveled
VSL	value of a statistical life
WTP	willingness to pay

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