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ENVIRONMENTAL RISKS OF DIESEL PASSENGER VEHICLES IN BRAZIL

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EXECUTIVE SUMMARY

Although Brazil has restricted the sale of diesel passenger cars since the 1970s, an auto industry lobby has been pressuring the government to lift the restrictions since 2013. While motor vehicle pollution contributes heavily to urban air quality problems in Brazil, this restriction has helped to limit some adverse impacts, especially compared to regions such as Europe or India where policies supporting widespread dieselization combined with lax emission standards have contributed to severe air quality problems and have resulted in adverse human health impacts. Brazilian regulators should maintain restrictions on diesel passenger cars to avoid exacerbating air quality problems, harmful impacts on human health, and increased emission of climate pollutants.

Despite progress resulting from PROCONVE, Brazil's program to control vehicle emissions, air quality in many Brazilian cities still does not comply with national standards or guidelines recommended by the World Health Organization. While current Brazilian policies restrict the sale of light-duty diesel passenger cars, diesel light-duty commercial vehicles (LCVs) can be sold in the country. Even though diesel LCVs make up only 6% of new light-duty vehicle (LDV) sales in the country, they are estimated to account for approximately 30% of nitrogen oxides (NO_X) emissions and 65% of fine particle ($PM_{2.5}$) emissions from new LDVs. Given this large impact, reducing emissions from this important source category should be a priority of Brazilian regulatory efforts. More broadly, any governmental action with an impact on vehicle emissions, such as a possible lifting of restrictions on diesel cars, should be evaluated in light of potential air quality and human health impacts.

This analysis examines the environmental risks of the commercialization of diesel passenger cars in Brazil, including a potential increase in NO_X and $PM_{2.5}$ emissions, both of which contribute to poor air quality and negatively impact human health, as well as greenhouse gases and other species that contribute to climate change. The analysis concludes that, given current regulatory standards, the wide commercialization of diesel cars would significantly increase NO_X and $PM_{2.5}$ emissions, contributing to poor air quality and adding 150,000 premature deaths through 2050. Even a moderate rate of dieselization, with diesel vehicles representing about 15% of light-duty vehicle sales after 2030, could result in as many as 32,000 additional premature deaths through 2050. Furthermore, this analysis shows that the commercialization of diesel cars also would result in increased climate impacts due to additional emissions of carbon dioxide and black carbon.

Brazil should learn from the regulatory experiences in developed countries that have implemented strong policies to mitigate environmental impacts from diesel vehicles. The United States, for example, has not only vehicle emission standards with strict limits and representative test cycles, but also relies on strong in-use compliance practices that ensure that real-world emissions comply with certified limits. Vehicle emission standards in the European Union (EU) have not been sufficient to adequately control emissions from diesel vehicles in the real world, and air quality in many cities continues to suffer as a consequence of legacy diesel fleets as well as new diesel vehicles being sold today. The EU is currently discussing proposals to strengthen in-use compliance to control diesel emissions and address air quality problems, but even under the best of cases, diesels will continue to be allowed to have two times higher NO_x emissions than gasoline vehicles.

Brazil currently does not have sufficiently strong policies to adequately mitigate the environmental impacts of diesel LDVs. Before it considers lifting the restrictions on diesel passenger vehicles, Brazil should implement the following three actions: First, Brazil should adopt vehicle emission standards equivalent to U.S. Tier 2 or Euro 6 to ensure that diesel vehicles are equipped with particle filters and to protect against the worst health and air quality impacts of diesel vehicles. Second, 500-ppm diesel fuel should be phased out completely to avoid misfueling and damaging aftertreatment control systems. Finally, Brazilian regulators should implement an effective in-use compliance and enforcement program to ensure that real-world NO_x emissions from diesel vehicles are well controlled under certification procedures.

1 BACKGROUND

The commercialization of diesel for passenger cars and commercial vehicles with capacities less than 1,000 kg (i.e., weight of driver, passengers, and cargo) has not been allowed in Brazil since the 1970s (DNC, 1994). This policy was put in place primarily to reduce the dependence on imported petroleum and the trade deficit, in response to high commodity prices in the international market following the 1973 petroleum crisis. Government policy also sought to maintain lower taxes for diesel fuel (20% for diesel and 35% for gasoline) to improve the competitiveness of public transit, and lower the costs of goods.

Even without diesel cars, diesel fuel still creates trade imbalances in Brazil due to high diesel demand from road freight, public transit, and electricity generation in isolated communities in the Amazon. Although Brazilian refineries aim to maximize diesel production, as illustrated in Figure 1, Brazil is still a net importer of diesel. Between 2000 and 2014, Brazil had net diesel imports of 94 million cubic meters, generating a total trade deficit of $50 billion (FOB). In 2014, imported diesel supplied about 19% of national diesel sales (ANP, 2015).

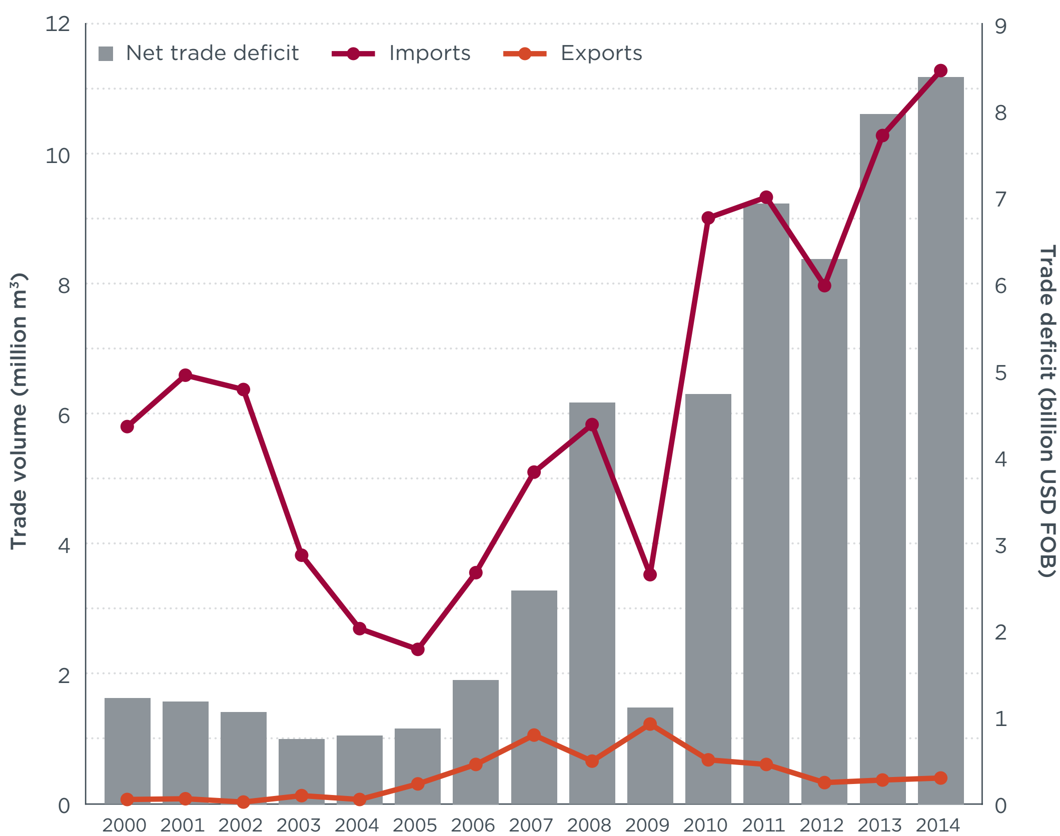

Figure 1. Diesel fuel trade statistics (ANP, 2015).

Despite the long-standing restrictions on the commercialization of diesel light-duty vehicles (LDV) in Brazil, some companies in the auto industry including Mahle, MWM International, Delphi, Bosch, BorgWarner, and Honeywell have formed an alliance to lobby Brazilian regulators to lift the restrictions (Aprove Diesel, 2015). To respond to such lobbies, the Brazilian government created a commission to evaluate the commercialization of diesel cars in Brazil (Câmara dos Deputados, 2015). This study makes a strong case that allowing diesel LDVs with current tax policies and emission standards in place would worsen air quality and place a strong burden on human health. Therefore, Brazilian regulators should keep the restrictions on diesel LDVs until vehicle emission standards are aligned with U.S. Tier 2 or Euro 6 standards, 500-ppm diesel is completely phased out, and an effective in-use compliance and enforcement program is put in place.

2 AIR QUALITY AND REGULATORY OVERVIEW

AIR QUALITY CONCERNS IN BRAZIL

The proposed introduction of diesel passenger cars to Brazil has the potential to exacerbate existing air quality problems in the country, particularly in major metropolitan areas where motor vehicles are a significant source of air pollutant emissions. Ambient air pollution is a significant human health hazard, exposure to which has been associated with 3.2 million premature deaths globally in 2010 (Lim et al., 2012). Although a large and diverse set of species contribute to ambient air quality problems, two of the principal pollutants of concern with respect to human health impacts are fine particulate matter ($PM_{2.5}$) and ozone (O_3).

Fine particulate matter consists of liquid or solid particles with diameters less than 2.5 microns suspended in air. Because of this small size, $PM_{2.5}$ can be breathed deeply into the lungs and has been associated with a broad range of health effects, including pulmonary and cardiovascular disease (Pope & Dockery, 2006; Brook et al., 2010). Ground level ozone is formed in the atmosphere through reactions of precursor species – nitrogen oxides (NO_X) and volatile organic compounds (VOCs) — and sunlight. Ozone is a strong respiratory irritant; short-term exposure can exacerbate existing respiratory conditions, such as asthma, while chronic O_3 exposure can decrease lung function and increase the risk of death from respiratory causes (Jerrett et al., 2009).

Recent measurements of ambient concentrations of $PM_{2.5}$ and O_3 in Brazilian cities have shown levels exceeding recommended values and national regulatory limits. For example, Figure 2 shows annual average $PM_{2.5}$ concentrations in 40 Brazilian cities as reported in the World Health Organization's Ambient Air Pollution Database (WHO, 2014). Among these 40 cities, only one meets the WHO $PM_{2.5}$ air quality guideline value of 10 µg m^{-3}, and levels in the most polluted cities are up to four times greater than the guideline value. Brazil has a national standard for PM_{10} concentration, but not for $PM_{2.5}$. Similarly, a review of São Paulo regulatory monitoring data shows regular exceedances of the national ambient quality standard for ozone (IEMA, 2015). Between 2000 and 2014 there were on average 21 exceedances of the O_3 standard per year at each of the São Paulo metropolitan area monitoring stations. Over this time period, there has been no clear change in levels of O_3 pollution in the area despite governmental efforts to control emissions of ozone precursors (Carvalho et al., 2015).

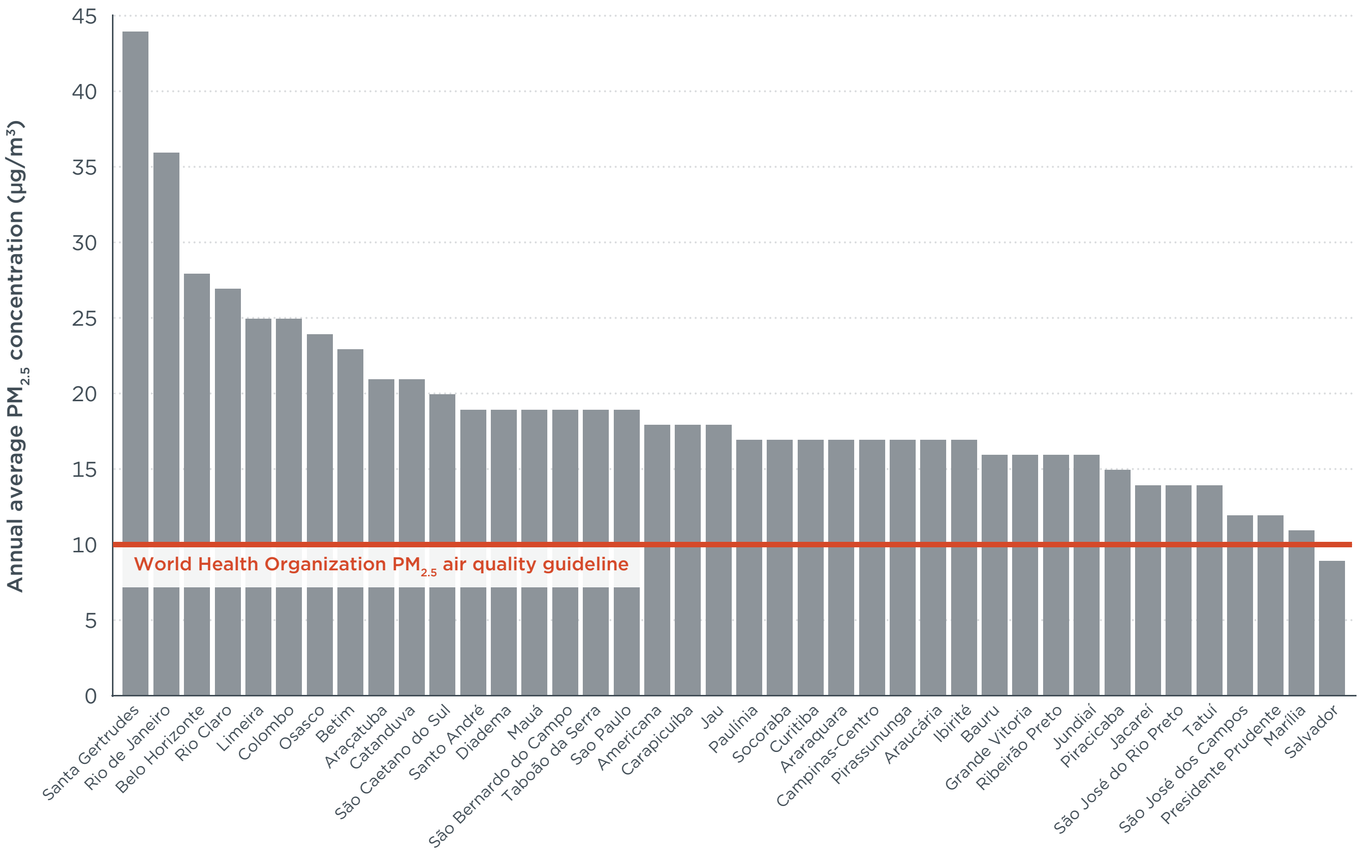

Figure 2. Annual average $PM_{2.5}$ mass concentrations in Brazilian cities (WHO, 2014).

Addressing ambient air quality issues requires a full understanding of the sources responsible for pollutant emissions. To this end, researchers have performed studies to estimate the contribution of individual source categories to ambient $PM_{2.5}$ concentrations. One such study, Andrade et al. (2010), investigated contributions of specific sources, including motor vehicles, to $PM_{2.5}$ pollution in six Brazilian cities: São Paulo, Rio de Janeiro, Curitiba, Belo Horizonte, Recife, and Porto Alegre. The fraction of ambient $PM_{2.5}$ attributed to motor vehicles ranged from 18% in Belo Horizonte to 55% in Curitiba. On average, motor vehicle emissions were estimated to be responsible for 40% of the $PM_{2.5}$ pollution in these Brazilian cities. These findings clearly show that any strategy to mitigate urban air quality problems in Brazil should include the continued control of motor vehicle emissions as a principal component. Any change to current policies toward motor vehicles, such as the proposed introduction of diesel passenger cars, should be considered in relation to its impact on urban air quality and human health.

LDV REGULATORY BACKGROUND

Motor vehicle emissions in Brazil are regulated through the Programa de Controle da Poluição do Ar por Veículos Automotores (PROCONVE). First implemented in 1986, PROCONVE establishes limits on the amount of air pollutants allowed to be emitted from new vehicles sold in the country. Both heavy- and light-duty vehicles (HDV, LDV) are regulated under this program, with LDVs defined as those vehicles with a gross weight less than or equal to 3856 kg. LDVs are further split into two categories based on application: light passenger vehicles and light commercial vehicles (LCV). Light passenger vehicles are defined as vehicles designed for the transportation of up to 12 passengers, while vehicles designed for goods movement, transport of more than 12 passengers, or with characteristics for specific off-road uses are regulated as LCVs (IBAMA, 2011). Current policies restrict the sale of diesel passenger cars in Brazil; however, diesel LCVs with capacities greater than 1000 kg are allowed.

Emissions from new LDVs sold in Brazil are currently regulated through the PROCONVE L6 standard, which was fully implemented beginning in 2013 for diesel cycle engines and in 2015 for Otto cycle engines. Were diesel passenger cars to be introduced into the Brazilian fleet, they would be subject to PROCONVE L6 emission standards. PROCONVE L6 standards for LDVs are summarized in Table 1. In general, emission standards for LCVs weighing less than 1700 kg are similar to those for light passenger vehicles. Standards for LCVs with mass greater than 1700 kg are less stringent. Vehicles are certified following Brazilian NBR 6601 Standard procedures, which include a dynamometer test cycle based on the FTP-75 test cycle. Durability requirements for LDVs in Brazil are 80,000 km or 5 years.

Table 1. Details of current Brazilian LD vehicle regulatory program, PROCONVE L6

Vehicle Type	Description	Diesel engines allowed?	NO_x emission standard g/km	PM emission standard g/km	Test cycle	Durability	OBD
Passenger vehicle	Vehicle used for transport of up to 12 passengers	No	0.08	0.025	NBR 6601[c]	80,000 km or 5 years	OBDBr_2[a] OBDBr_D[b]
Commercial vehicle (≤1700 kg)	Vehicle used for transport of more than 12 passengers, goods movement, or specific off-road applications	For vehicles with capacity > 1000 kg	0.08	0.03			
Commercial vehicle (>1700 kg)		Yes	0.25[a] or 0.35[b]	0.04			

[a] Gasoline or ethanol powered vehicles
[b] Diesel powered vehicles
[c] Based on the FTP-75 test cycle

It is useful to compare Brazilian emission limits with those in other regions where diesel passenger cars are more prevalent, notably the European Union (EU). Figure 3 shows a comparison of PROCONVE L6 NO_x and particulate matter (PM) emission limits with the current Euro 6 standards for diesel passenger cars in the EU. A key difference between the Brazilian and European standards is the level at which the PM emission standard is set. The current PM standard for passenger vehicles in Brazil is 0.025 g/km, equivalent to the Euro 4 standard implemented in the EU a decade ago, and five times greater than the current EU standard of 0.005 g/km. Furthermore, unlike the Euro 6 standards, PROCONVE L6 does not include a particle number emission limit. The inclusion of a particle number limit in European standards was necessary to ensure that new diesel vehicles were equipped with the most advanced PM control technology available, the diesel particle filter (DPF).

In contrast to PM emission standards, which lag European regulatory limits, Brazilian PROCONVE L6 NO_x emission standards are set at the same level as current Euro 6 standards for diesel passenger cars, 0.08 g/km. However, the Euro 6 NO_x standard for diesel passenger cars is less stringent than the corresponding standard for gasoline passenger cars. New diesel cars sold in the EU are allowed to emit 33% more NO_x than comparable gasoline cars. In contrast, U.S. regulations apply the same emission limits to all passenger vehicles, regardless of fuel type. Consequently, the U.S. Tier 2 NO_x emission limit for new diesel cars is about 45% lower than PROCONVE L6 and Euro 6 standards, as can be seen in Figure 3. This distinction is significant, as the lower emission limit in the U.S. has helped lead manufacturers to deploy best-available NO_x control technologies in a larger fraction of diesel LDVs sold in the U.S. relative to cars sold in the EU (Yang, Franco, Campestrini, German, & Mock, 2015).

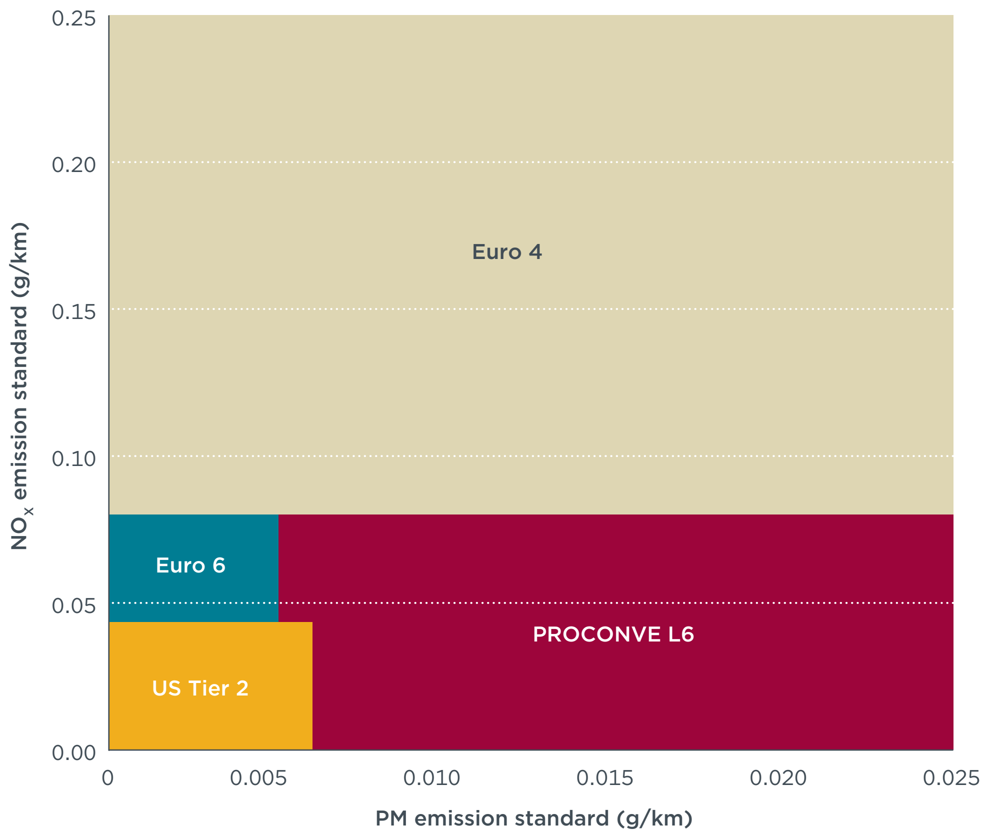

Figure 3. Comparison of pollutant emission standards for LD diesel passenger vehicles in the United States, Europe, and Brazil.

In addition to more stringent emission limits than those currently in place in Brazil, test procedures used for vehicle certification in the U.S. are also more rigorous. The test cycle used for LDV certification in Brazil follows the FTP-75 test cycle developed for certification testing by the U.S. Environmental Protection Agency. Recognizing the limitations of the FTP-75 cycle in fully representing real-world driving conditions, the U.S. has included additional test cycles as requirements of the currently applied Federal Test Procedure for certification of LDVs. These additional test cycles are included in the Supplemental Federal Test Procedures (SFTP) and are designed to address shortcomings in the FTP-75 representation of aggressive, high speed driving and the use of air conditioning. Brazil has not adopted the more robust SFTP, and as a result, driving patterns that increase pollutant emissions, such as aggressive driving, are not represented in certification testing.

When considering NO_x emission standards for diesel LDVs , there is growing evidence of large disparities between NO_x emission rates measured in the laboratory during certification or type-approval testing and those measured during real-world driving conditions in Europe. Real-world vehicle emission studies have consistently shown NO_x emissions from diesel cars operating under realistic driving conditions substantially exceed emission standards (Carlslaw et al., 2011; Weiss et al., 2012; Franco et al., 2014; Bishop & Stedman, 2015). These findings are in contrast to those for gasoline cars, which generally perform closer to emission limits during real-world driving testing (Weiss et al., 2011; Chen & Borken-Kleefeld, 2014). These trends are clearly evident in Figure 4, which shows a comparison of in-use NO_x emissions from gasoline and diesel cars with regulatory limits. The lack of significant reductions in real-world NO_x emissions from diesel cars even with the tightening of emission standards has contributed to persistent air quality problems in areas with high levels of light duty (LD) fleet dieselization (Beevers et al., 2012).

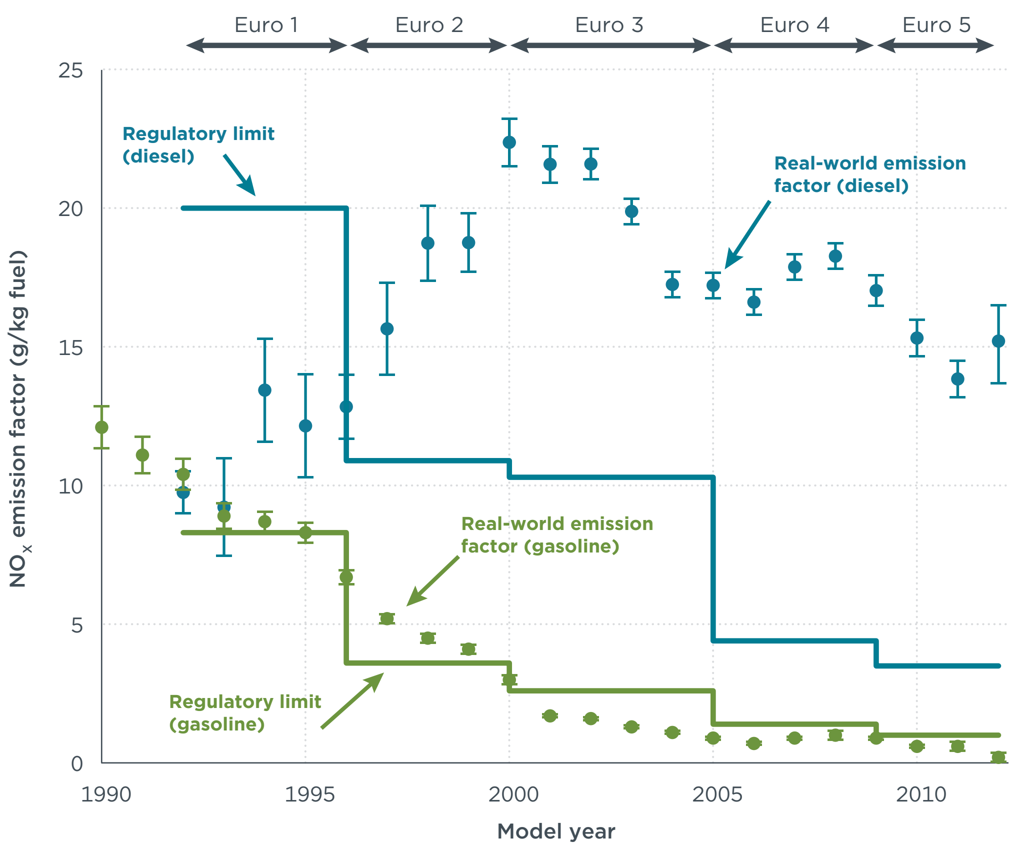

Figure 4. Comparison of LD diesel passenger vehicle in-use NO_x emissions (circles) with corresponding regulatory limits (lines) by vehicle model year. Measurements of in-use emission factors were conducted in Zurich, Switzerland, between 2000 and 2012 using vehicle remote sensing. Although not shown here, results for diesel and gasoline LCVs show similar patterns as those for LD passenger vehicles. Data presented here are courtesy of Jens Borken-Kleefeld and follow Chen and Borken-Kleefeld (2014).

Measures are being taken to address this problem in Europe through the inclusion of a real-world test component during the certification process. For vehicle air pollutant emissions, the introduction of the Real Driving Emissions (RDE) procedure is expected to yield emission test results that are more in line with real-world driving experience (Franco et al., 2014). For RDE, instead of testing the vehicle only in a laboratory (i.e., the current method applied in Brazil), additional testing will be conducted on the road under normal driving conditions. Vehicle emissions will be analyzed and recorded using portable emissions measurement systems (PEMS) equipment. The general framework of the RDE procedure was adopted by EU member states in May 2015, with a monitoring phase to start immediately and full application beginning in 2017.

In summary, data show that diesel vehicle emissions are not properly controlled under current regulatory mechanisms in Europe. Given that Brazil has adopted similar but less stringent requirements than those adopted in Europe and the U.S., it is clear that current Brazilian test and certification procedures are not sufficient to ensure real-world NO_X emissions from diesel LDVs are in line with emission standards.

FUEL QUALITY

In addition to emission standards for new vehicles, standards regulating fuel quality are an important component of vehicle emission control programs. One important fuel parameter targeted by such standards is the amount of sulfur that is allowable in transportation fuels. Sulfur in fuel contributes to emissions of PM and sulfur dioxide and limits the efficiency and effectiveness of modern aftertreatment control technologies. Reducing the sulfur content of transportation fuels provides environmental and public health benefits through reductions of direct pollutant emissions and improved performance of emission control systems. With the introduction of PROCONVE L6 standards in Brazil, 50-ppm sulfur gasoline was made available countrywide. In contrast, diesel fuel sulfur levels vary by region. In major metropolitan areas, diesel fuel sulfur levels are limited to 10 ppm (S10 diesel), while countryside fuel sulfur limits are set at 500 ppm (S500 diesel). The recent tightening of emission standards for heavy-duty trucks in Brazil has increased the availability S10 diesel at service stations outside of metropolitan areas; however, the presence of S500 diesel limits possibilities for the introduction of diesel passenger cars equipped with advanced emission control systems.

CURRENT LD DIESEL MARKET

While current regulations preclude the sale of diesel passenger cars in Brazil, larger (i.e., with capacity higher than 1,000 kg) LD diesel vehicles classified as commercial vehicles can be sold in the country. Sales data for LDVs in Brazil, including passenger and commercial vehicles, show diesel vehicles accounted for 6% of total sales between 2012 and 2014 (ADK, 2015). For the subset of LDVs classified as commercial vehicles, diesel vehicles made up 25% of total sales over the same time period. Examples of top-selling diesel LCVs from 2012-2014 are shown in Table 2. The top two selling models, the Toyota Hilux and the Mitsubishi L200, which together account for 22% of diesel LCV sales, are pickup trucks that are suitable for passenger transport in addition to commercial applications. Similarly, the third top-selling model, the Toyota Hilux S4, is a sport utility vehicle that is likely used primarily in passenger transport applications.

Table 2. Characteristics of top selling diesel LCVs in Brazil, 2012-2014 (ADK, 2015).

Make	Model	Body	Engine displacement (L)	Engine power (kW)	Gross vehicle weight (kg)	Percent total diesel LCV sales (%)
Toyota	Hilux	pickup	3.0	127	2960	15
Mitsubishi	L200	pickup	3.2	127	2950	7
Toyota	Hilux SW4	sport utility vehicle	3.0	127	2600	6
Hyundai	HR	delivery truck	2.5	97	3400	5
Volkswagen	Amarok	pickup	2.0	134	3100	5

Despite accounting for a small fraction of LDV sales in Brazil, diesel LCVs have a disproportionate impact on air pollutant emissions. Figure 5 shows relative contributions of diesel and Otto cycle vehicles to total LDV sales and pollutant emissions for new vehicles sold in the country in 2014. While diesel vehicles accounted for only 6% of LDV sales in 2014, they accounted for approximately 30% of the NO_x and 65% of the $PM_{2.5}$ emissions by LDVs sold in Brazil in 2014. This demonstrates the disproportionate impact that any increase in LD diesel sales would have on emissions of these pollutants of great concern.

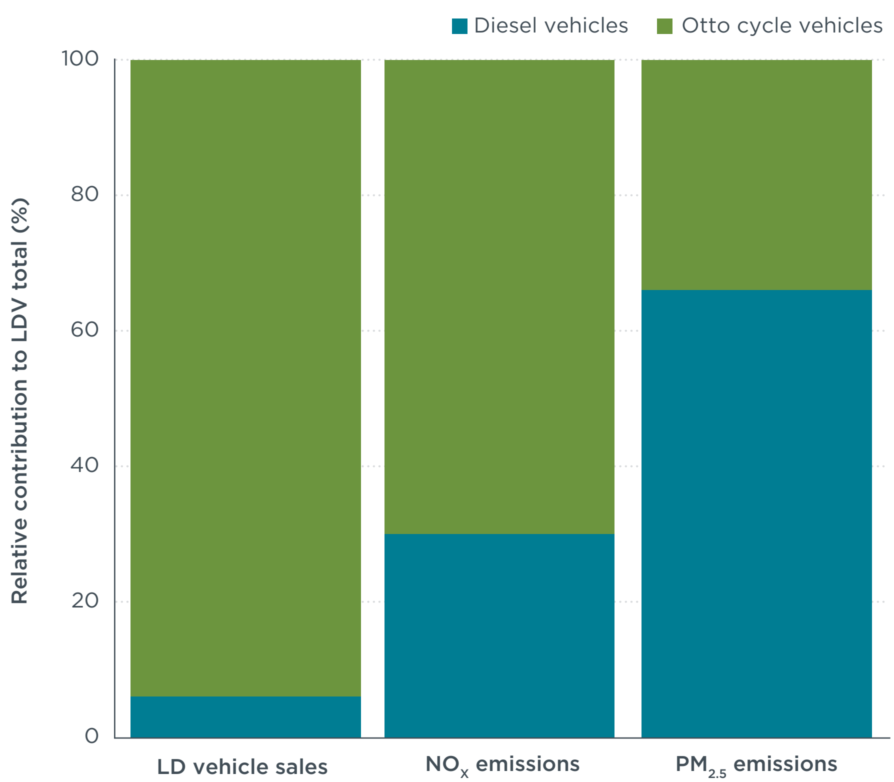

Figure 5. Relative contributions of diesel and Otto cycle engines to sales of and emissions from new LDVs sold in Brazil in 2014. This analysis considers both LD passenger and commercial vehicles. New Otto cycle vehicles are assumed to be at an equivalent technology level as Euro 6. New diesel vehicles are modeled as Euro 4 equivalent with respect to $PM_{2.5}$ emissions and Euro 6 equivalent with respect to NO_x emissions.

3 ENVIRONMENTAL RISKS OF LD FLEET DIESELIZATION

To evaluate the consequences of LD fleet dieselization in Brazil, this analysis estimates projected changes in diesel vehicle activity, pollutant emissions, and human health impacts resulting from the proposed introduction of diesel passenger cars to the country between 2015 and 2050. This analysis uses ICCT's Global Transportation Roadmap model, a tool designed to estimate changes in transportation emissions in response to various policy measures (ICCT, 2014a). This investigation considers two dieselization scenarios and compares them against a baseline scenario, in which no changes are made to current Brazilian LDV policies.

The baseline scenario assumes 6% of new LDV sales, both commercial and passenger, are powered by diesel engines. This percentage remains constant throughout the entire period of modeling. The moderate dieselization scenario assumes that, upon revocation of LD diesel vehicle restrictions, diesels begin to gain market share in 2020, with sales increases of 1% per year between 2020-2030, and stabilizing at 15% of total LD sales from 2030-2050. In the fast dieselization scenario, diesel passenger car sales begin to grow in 2015 at a rate of 3% per year, similar to the rate observed in European countries in the mid-1990s (Minjares, Blumberg, & Posada, 2013). This growth rate is sustained for 15 years, with diesel sales remaining at 45% of new vehicle sales from 2030-2050. This level of dieselization is similar to the current European market penetration of LD diesel vehicles, which accounted for 53% of new registrations in 2013 (ICCT, 2014b). The effects of these dieselization pathways on LD diesel activity are summarized in Figure 6.

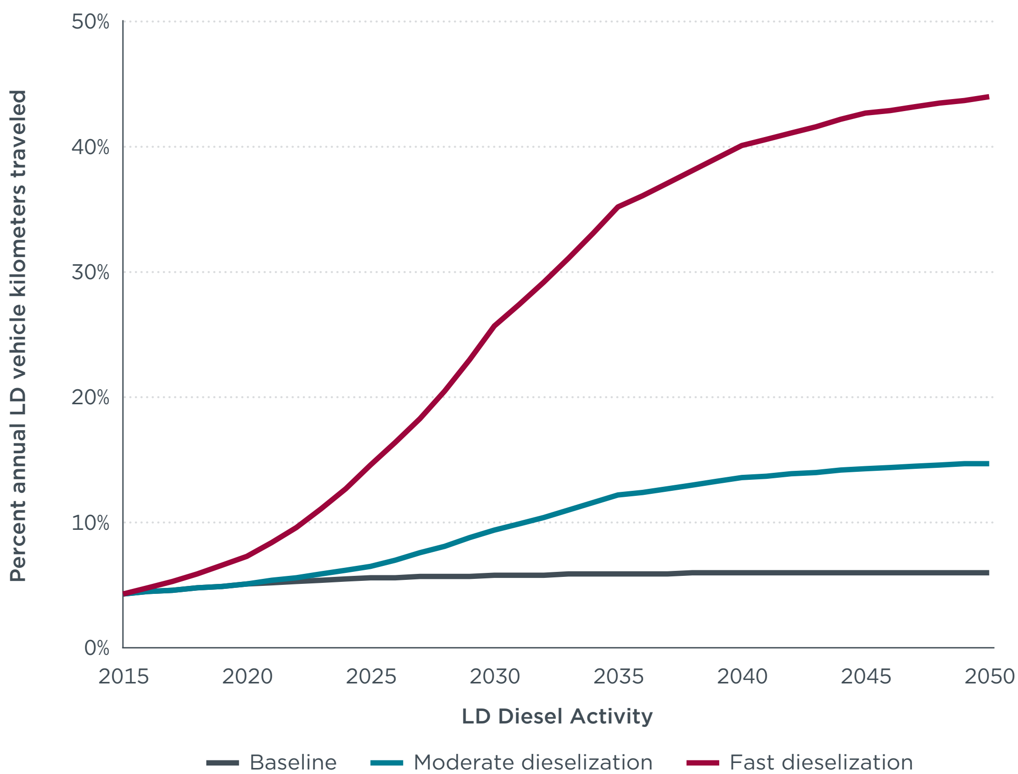

Figure 6. LD diesel activity shown as a percentage of total LD vehicle-kilometers traveled for three dieselization scenarios.

This analysis focuses on $PM_{2.5}$ and NO_X emissions, which are among the pollutants of greatest concern from the transport sector and which tend to be emitted at a greater rate from diesel engines than from gasoline engines. In addition to these conventional pollutant emissions, this analysis also considers the impact of LD fleet dieselization on emissions of carbon dioxide (CO_2) and other climate pollutants such as methane (CH_4), nitrous oxide (N_2O) and black carbon (BC).

$PM_{2.5}$ EMISSIONS

The primary concern related to the introduction of diesel cars to Brazil is the potential for increased fine particulate matter emissions from the passenger vehicle fleet. Diesel PM is a toxic pollutant and is listed by the World Health Organization as a known human carcinogen (Benbrahim-Tallaa et al., 2012). Reducing PM emissions from on-road diesel vehicles has long been recognized as an important strategy in reducing the public health burden of motor vehicles, and advances in engine technology and emissions controls have greatly reduced PM emissions from modern diesel engines.

Unfortunately, current PM emission standards in Brazil are not stringent enough to compel the use of the key technology needed to control diesel PM emissions, the DPF. As noted above, the current PM emission standard for passenger vehicles in Brazil, PROCONVE L6, is equivalent to the EU Euro 4 standard. A review of technologies used to meet the Euro 4 standard in Europe suggests that manufacturers will be able to meet the PROCONVE L6 PM standard without DPFs (Posada, Bandivadekar, & German, 2012). If this is the case, emission rates from diesel passenger cars in Brazil will be substantially higher than either gasoline cars or diesel cars sold in countries with more stringent PM emission standards. Figure 7 shows a comparison of lifetime $PM_{2.5}$ emission factors for LDVs by emission control level. The lifetime average emission factor for a Euro 4 level diesel car, 0.031 g/km, is 30 times greater than the emission factor for gasoline cars and 15 times greater than emission factors for modern diesel cars equipped with DPFs. In addition to relatively high emission rates, the lack of a countrywide supply of ultra-low sulfur diesel fuel will also serve to discourage DPF-equipped diesel cars in Brazil should LD diesel restrictions be rescinded.

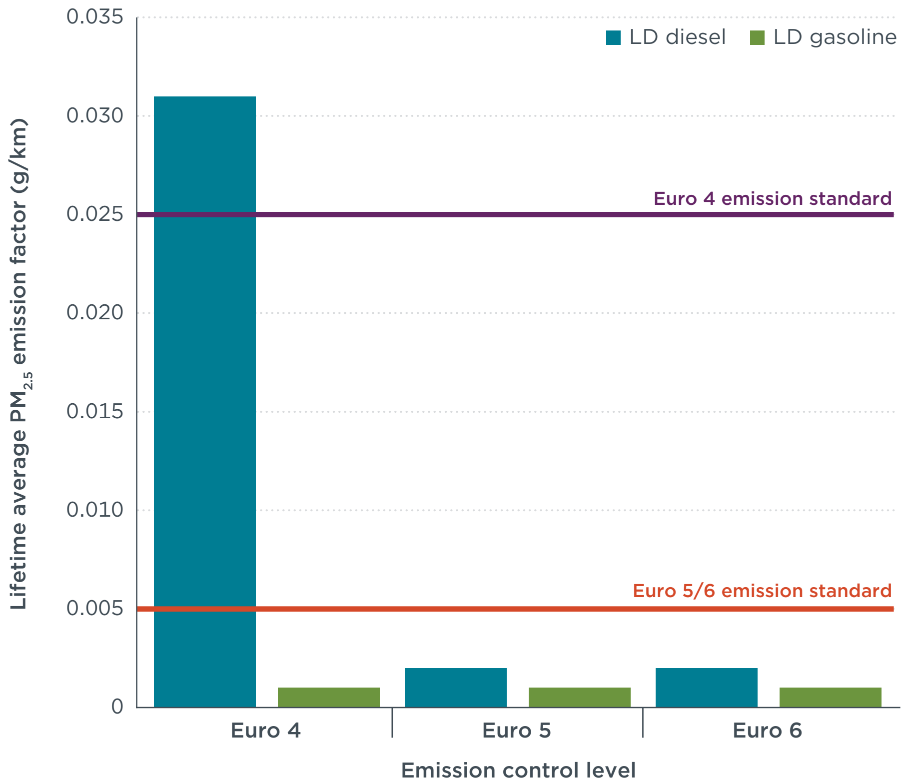

Figure 7. Comparison of $PM_{2.5}$ emission factors for LD diesel and gasoline vehicles by emission control level. Emission factors are derived from the COPERT4 road transport emissions model and represent the average PM emission factor for given technology level vehicle over the course of its lifetime (Chambliss et al., 2013).

Under all scenarios including the baseline, $PM_{2.5}$ emissions from diesel passenger vehicles are expected to increase substantially. The top panel of Figure 8 shows projected annual LDV $PM_{2.5}$ emissions in Brazil for the baseline and two dieselization scenarios modeled in this study. Under both dieselization scenarios, $PM_{2.5}$ emissions from the LDV fleet increase significantly relative to baseline conditions. In 2050, annual emissions of $PM_{2.5}$ are projected to be five and two times greater than baseline emissions in fast and moderate dieselization pathways, respectively. Cumulatively, rapid dieselization of the Brazilian LD fleet results in an additional 270,000 metric tons of $PM_{2.5}$ emissions relative to the baseline scenario from 2015-2050. Similarly, the moderate dieselization scenario yields 60,000 metric tons of excess $PM_{2.5}$ emissions relative to the baseline over the same time window.

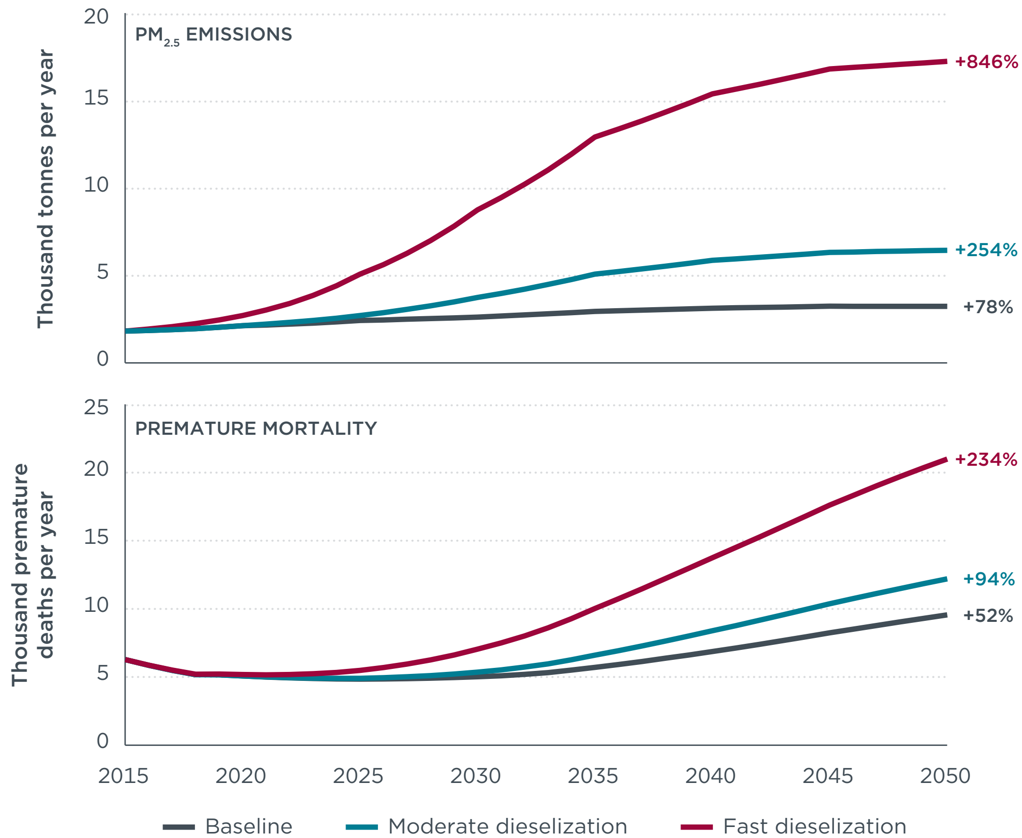

Figure 8. Effects of passenger vehicle dieselization on LDV $PM_{2.5}$ emissions and premature mortality in Brazil. Percentages indicate relative changes in 2050 from 2015 values.

Even in the baseline scenario, the impacts of LD diesel vehicles are considerable. In this scenario, the only LD diesel vehicles included are those classified as LCVs, which account for just 4%-6% of total LDV activity (Figure 6). However, despite making up a small fraction of total annual vehicle kilometers traveled, diesel LCVs are responsible for between 60% and 70% of annual $PM_{2.5}$ emissions from the LDV fleet. In the baseline scenario, emissions of $PM_{2.5}$ from LDVs increase from 1,800 to 3,300 tonnes per year between 2015 and 2050. Approximately 85% of this growth in emissions is attributable to increased diesel LCV activity. These findings suggest that motor vehicle policies aimed at controlling $PM_{2.5}$ emissions from diesel LCVs currently allowed in Brazil would yield substantial reductions in $PM_{2.5}$ emissions from the LDV fleet.

The bottom panel of Figure 8 shows estimates of premature mortality attributable to LDV $PM_{2.5}$ emissions for each scenario considered in this study. These estimates are derived using established methodologies that link changes in vehicle primary $PM_{2.5}$ emissions to changes in urban ambient concentrations and resultant human health responses (Chambliss et al., 2013). Between 2015 and 2050, the fast dieselization pathway results in approximately 150,000 additional premature deaths relative to the baseline scenario. Even in the moderate dieselization scenario, in which gasoline vehicles still dominate total activity, premature deaths are estimated to increase by 32,000 relative to the baseline. In 2050, moderate and fast dieselization pathways yield increases in annual premature mortality attributable to LDVs in Brazil of 28% and 119%, respectively, relative to the baseline scenario in which restrictions on LD diesel passenger cars remain in place.

These estimates of premature mortality are limited to the impacts of primary $PM_{2.5}$ in urban areas, and do not account for health impacts from secondary $PM_{2.5}$, ground-level ozone, or other local air pollutants. Because the health impacts quantified in this study are a subset of the expected total, the reported premature mortality from dieselization in Brazil should be interpreted as conservative, lower-bound estimates.

Under this framework, the cumulative health costs resulting from the introduction of diesel cars to Brazil are estimated to be $114 billion and $24 billion for fast and moderate dieselization scenarios, respectively. The costs of these health impacts were monetized using a standard value of a statistical life (VSL) approach, which reflects individuals' aggregate willingness to pay to reduce the incidence of premature death in the population by one, multiplied by the number of additional premature deaths in each year resulting from increased fine particle emissions (U.S. EPA, 2011; Minjares et al., 2014). These impacts are discounted using a rate of 5% and added up over the time frame of the analysis. For this study, the VSL was derived from the U.S. EPA recommended value of $7.6 million (2006 USD) and adjusted to account for lower average per capita income in Brazil.

These results show the potential for significant risks to air quality and human health with the introduction of diesel cars to Brazil. Increased $PM_{2.5}$ emissions under the two dieselization scenarios are the direct result of the introduction of non-DPF equipped diesel cars to the Brazilian fleet. Current PROCONVE L6 emission standards do not provide stringent enough limits to compel the use of DPFs, nor is a particle number standard included to do so. Furthermore, even if PM emission standards were to be lowered for diesel LDVs, the use of DPFs on diesel cars sold in the country would be limited because of the risk of misfueling with S500 diesel that is still available outside of metropolitan regions. Policies to address these issues, such as more stringent emission limits and fuel quality standards, should be in place prior to the consideration of the lifting of current restrictions on diesel cars in Brazil.

NO_X EMISSIONS

In addition to increased $PM_{2.5}$ emissions, there also is a risk that dieselization of the Brazilian passenger vehicle fleet will lead to an increase in NO_X emissions. This is a concern because direct exposure to NO_X is associated with respiratory conditions (Hoek et al., 2013). NO_X also is a precursor to the formation of ozone, and exposure to ozone can reduce lung capacity in young children, increase rates of asthma, and lead to early death (Jerrett et al., 2009).

Results from this analysis of the effects of dieselization on LDV NO_X emissions in Brazil are shown in Figure 9. In the baseline scenario, current LDV emission control policies are predicted to result in a 30% reduction in NO_X emissions in 2050 relative to 2015 levels. These reductions occur despite an 84% increase in total LDV activity in the country over the same time period, and largely reflect the emission reduction benefits accrued from the introduction of PROCONVE L6 and slow retirement of older gasoline vehicles in the fleet.

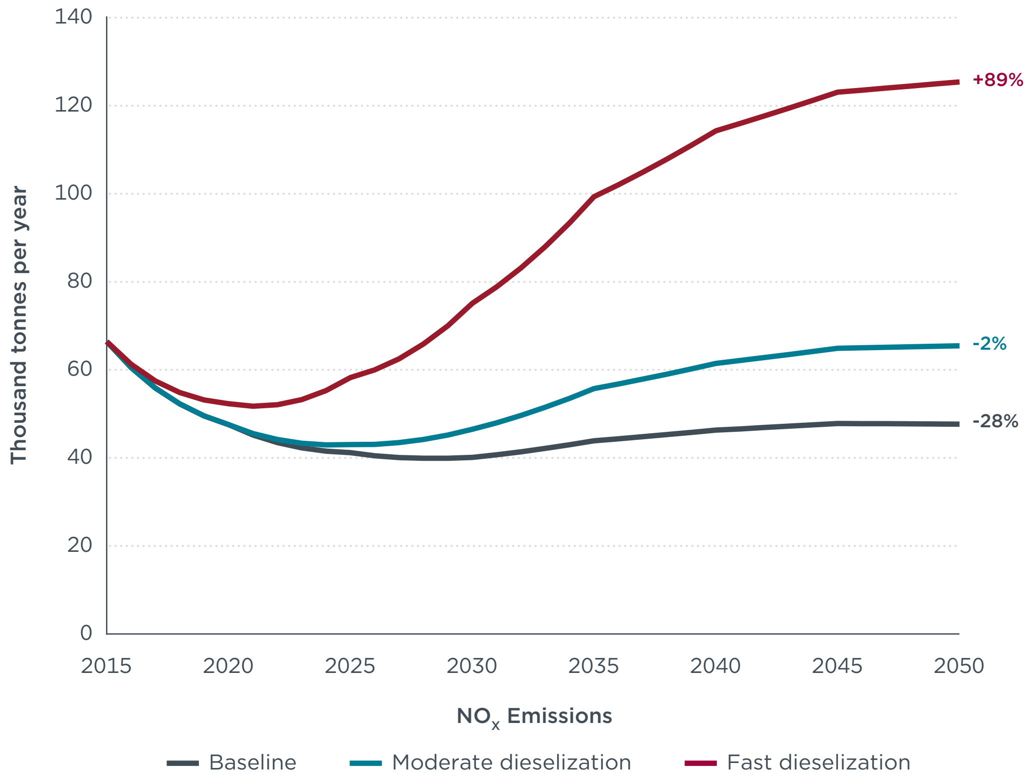

Figure 9. Effects of passenger vehicle dieselization on LDV NO_x emissions in Brazil. Percentages indicate relative changes in 2050 from 2015 values.

NO_x emission reductions calculated for the baseline scenario are not sustained with the introduction of LD diesel vehicles to the Brazilian fleet. In the moderate dieselization scenario, initial reductions in fleet NO_x emissions between 2015 and 2030 are negated by the increased penetration of diesel cars into the LD fleet after 2030, and consequently, there is no significant change in annual NO_x emissions between 2015 and 2050. As was the case with $PM_{2.5}$ emissions, the increase in NO_x emissions in the dieselization scenarios is driven primarily by the difference in NO_x emission factors for modern gasoline and diesel cars. For NO_x, emission factors for Euro 6 control level diesel cars are about seven times greater than those for Euro 6 level gasoline vehicles. Consequently, even small percentages of diesel vehicles in the LDV fleet can contribute a disproportionately large amount of NO_x emissions.

Figure 10 shows estimates of activity and NO_x emissions for each scenario broken down by fuel type. In the moderate dieselization scenario, while diesel cars account for only 15% of total LD activity in 2050, they are responsible for 55% of total NO_x emissions from the LD fleet. This effect is even more pronounced in the fast dieselization scenario, where diesel vehicles become the dominant source of LD NO_x emissions as of the year 2024 and account for 85% of total emissions in 2050. Such large increases in NO_x emissions with the introduction of diesel cars to Brazil could exacerbate existing air quality problems and jeopardize progress that has been made to control emissions of NO_x from LDVs in the country.

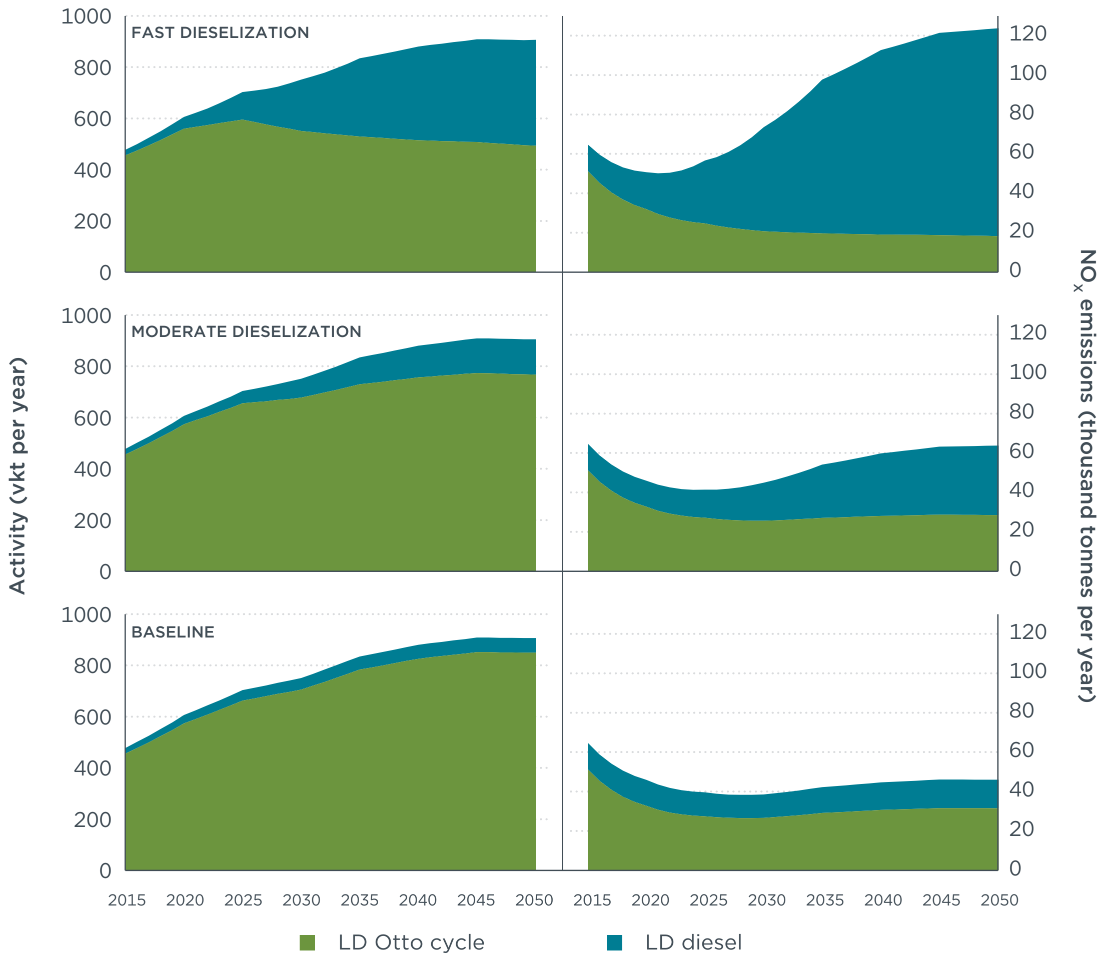

Figure 10. Projected LDV activity (left panels) and NO_x emissions (right panels) separated according to engine type. LD Otto cycle and diesel contributions are shown for each scenario in green and blue, respectively.

While these results make clear the potential negative impacts of dieselization on LDV NO_x emissions, it is also important to note that they most likely represent a conservative estimate. As previously noted, there is a large body of evidence showing that NO_x emissions from diesel cars are higher during real-world driving conditions than when measured in the laboratory using simulated driving cycles. To a certain extent, differences between in-use and laboratory emissions for diesel cars are reflected in emission factors used in this study, particularly for Euro 5 and older vehicles. However, due to uncertainties in the real-world performance of control technologies used for Euro 6 vehicles and lack of representative test data, it is likely that NO_x emission factors for these vehicles are underestimated in this analysis (ERMES, 2015). As most new diesel cars are assumed to be at the Euro 6 level in this analysis, any underestimate in the NO_x emission factor will lead to a conservative estimate of excess NO_x emissions resulting from LD fleet dieselization.

On a broader note, it is becoming clear that there are fundamental problems with the current NO_x emissions performance of diesel cars and the test procedures used to certify this performance. Current vehicle certification and type-approval practices are not adequate to ensure the environmental performance of LD diesel vehicles in normal driving conditions. Manufacturers have been able to design cars that meet regulatory limits when measured in the laboratory, but far exceed these limits when driven in the real world. While new NO_x aftertreatment control technologies offer opportunities to address NO_x emissions from diesel cars, manufacturers have yet to show that these technologies can be deployed in effective fashion across the range of diesel cars being produced today.

Efforts are underway in Europe to attempt to control NO_x emissions from diesel engines. The planned inclusion of a real-world testing component in the European certification process is an effort to close this loophole and ensure the real-world performance of diesel cars is in line with regulated limits. This is a step in the right direction and similar procedures should be pursued in other countries, especially those with high levels of fleet dieselization. The lessons learned from the European dieselization experience are myriad and ongoing. The Brazilian proposal to rescind its diesel car restrictions comes at a time when there is a growing realization that European policies to promote diesel cars have contributed to persistent urban air quality problems. As Europe attempts to address these issues through policy changes, even considering the use of bans, it is important for Brazil to have the best vehicle testing and enforcement practices in place to ensure the best possible environmental performance should diesel cars be introduced to the country. These steps also would have the benefit of better controlling real-world NO_x emissions from diesel LCVs that are currently available for sale in the country.

CLIMATE IMPACTS

One of the key advantages of diesel LDVs cited by proponents of dieselization is the greater efficiency and lower fuel consumption of these engines relative to Otto cycle engines. While diesel engines are more efficient for vehicles of a similar size, this efficiency advantage does not always result in significant CO_2 emission reductions due to a number of factors. First, diesel fuel has a higher density and carbon weight fraction than gasoline or ethanol fuels. This means the consumption of one liter of diesel fuel emits more CO_2, the pollutant responsible for the largest share of climate impacts, than the consumption of one liter of gasoline or ethanol. Second, the European dieselization experience has shown that diesel LDVs tend to be larger and have more powerful engines, thus negating a fraction of the efficiency and CO_2 savings offered by a switch to diesel engines (Zachariadis, 2013). Third, increased efficiency of new gasoline engines also has contributed to narrowing the efficiency gap between gasoline and diesel engines (Cames and Helmers, 2013). Finally, Brazil is a somewhat unique case in that sugarcane ethanol is used extensively as a transportation fuel. Studies have shown that Brazilian sugarcane ethanol is a relatively low carbon intensity fuel, and emits about 60%-70% less CO_2 than gasoline and diesel on a well-to-wheel basis (Regulation of Fuels and Fuel Additives, 40 CFR Part 80, 2010). As such, the introduction of diesel vehicles in Brazil would serve to displace sugarcane ethanol, and gasoline, and result in a net increase in CO_2 emissions.

The findings of this analysis indicate that Brazilian LDV CO_2 emissions increase under the dieselization scenarios, as shown in Figure 11. In 2050, CO_2 emissions in the moderate and fast dieselization scenarios are, respectively, 5% and 22% greater than emissions in the baseline scenario. Cumulatively, fast dieselization results in an additional 600 million metric tons of CO_2 emissions from the Brazilian LDV fleet between 2015 and 2050. Note that these results show well-to-wheel CO_2 emissions, which take into account upstream emissions from fuel production and distribution in addition to tailpipe emissions resulting from the combustion of transportation fuels.

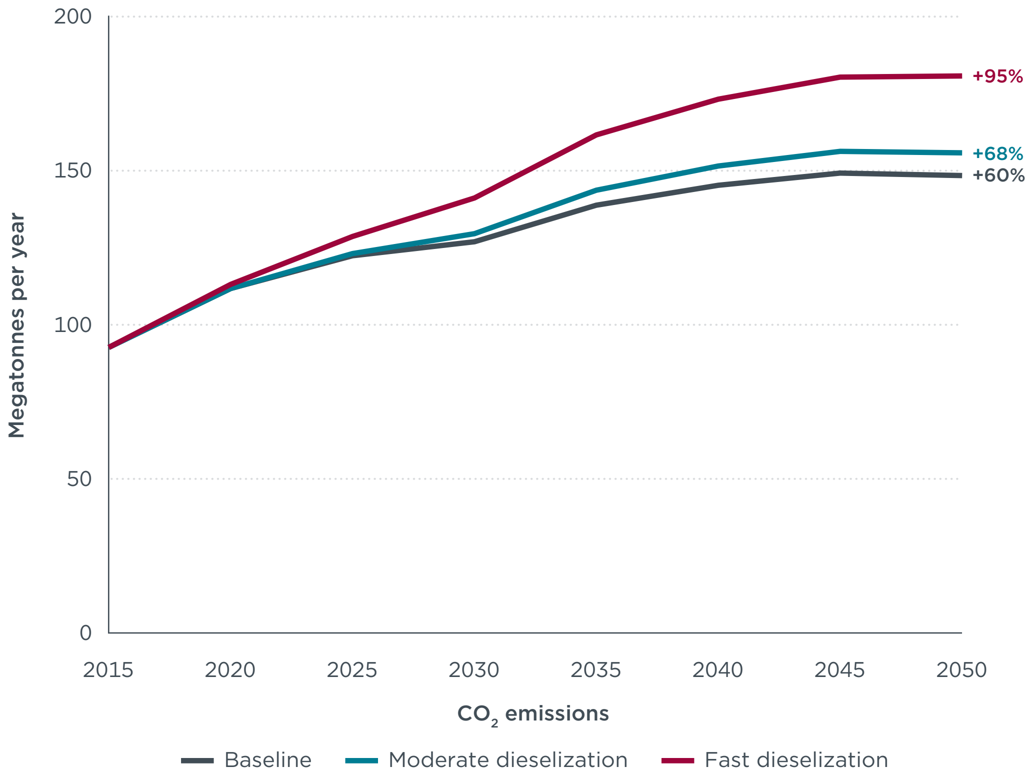

Figure 11. Effects of passenger vehicle dieselization on LD CO_2 emissions in Brazil. Note traces show well-to-wheel CO_2 emissions for each scenario. Percentages indicate relative changes in 2050 from 2015 values.

This analysis assumes the ratio of gasoline to ethanol volumetric consumption in the country is 51:49. This means that in the dieselization scenarios, gasoline and ethanol are displaced in approximately equal volumes as greater quantities of diesel fuel are consumed by the LDV fleet. In reality, this ratio fluctuates primarily due to fuel prices. However, the results from this analysis are relatively insensitive to changes in the gasoline to ethanol ratio. For example, when this ratio is changed to 65:35 in the model, corresponding to the maximum monthly average value in the country between 2011 and 2014, dieselization still results in greater amounts of CO_2 emissions than baseline projections. In this case, more gasoline is displaced relative to ethanol, and 2050 CO_2 emission levels are 3% and 10% greater for moderate and fast dieselization scenarios, respectively, relative to the baseline. In all such realistic cases, dieselization does not provide a clear CO_2 emissions benefit, and in fact may increase current CO_2 emission rates from the LDV sector.

The climate impacts of dieselization are not limited to CO_2 emissions: Other climate relevant emissions, such as BC and the greenhouse gases CH_4 and N_2O, also need to be considered. With respect to diesel engines, BC emissions are of particular importance. Black carbon, a main component of particulate matter emitted by diesel engines, is a strong absorber of solar radiation and contributes significantly to anthropogenic climate warming (Bond et al., 2013). For this analysis, annual emissions were calculated for each modeled scenario, and mass emissions of each species were converted to CO_2 equivalent mass emissions (CO_2e) using 20-year global-warming-potential values (Myhre et al., 2013; Bond et al., 2013). Results for the year 2050 are presented in Figure

12 and show the relative contributions to CO_2e emissions by species for each scenario. Note, species with a net climate cooling impact, such as organic carbon and sulfates, also were included in this analysis, though results are not included in Figure 12 because these species offset less than 1% of the net CO_2e emissions of warming species. Results indicate that the increased relative importance of non-CO_2 emissions with increased dieselization is largely driven by greater emissions of BC from the LD fleet. In the fast dieselization scenario, increased BC emissions add 30 megatonnes (MT) of CO_2e to the total short-term climate burden of LDVs in 2050. As was the case with excess $PM_{2.5}$ emissions resulting from dieselization, the additional climate impact of diesel BC emissions would be largely avoided were diesel particle filters to be required for diesel cars sold in Brazil.

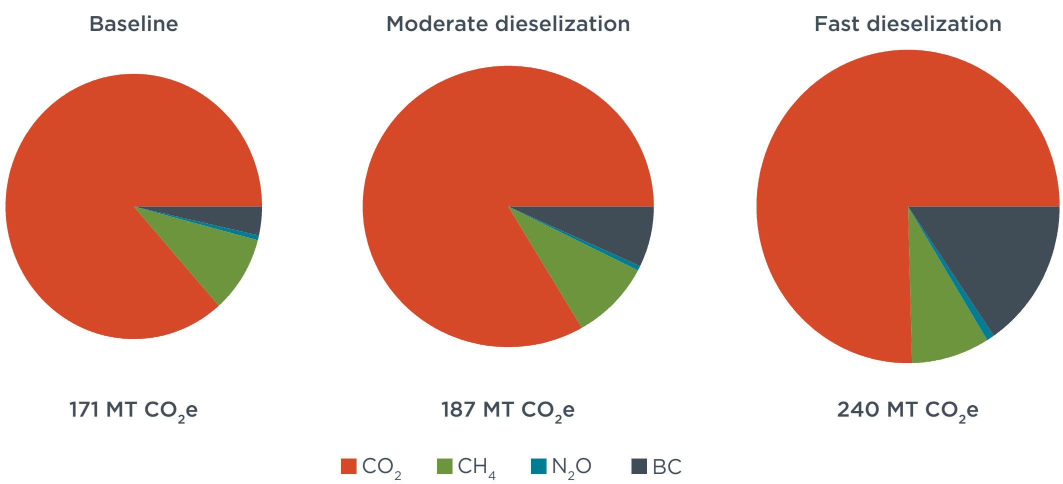

Figure 12. Greenhouse gas and black carbon emissions in 2050 for each dieselization scenario. Note, 20 year global warming potential values were used to calculate CO_2e emissions for each species.

CONCLUSIONS

Brazilian regulators should maintain restrictions on the commercialization of diesel passenger cars to avoid exacerbating air quality problems, harmful impacts on human health, and increased emissions of climate pollutants. Brazil's current emission standards and certification procedures are not stringent enough to protect against the negative emissions impacts of increased dieselization of the Brazilian fleet. This analysis shows that the relatively small number of LD diesel commercial vehicles currently allowed to be sold in the country have a disproportionately large emissions impact, and already contribute the majority of $PM_{2.5}$ and NO_X emissions from new LDVs sold in the country. The proposed lifting of restrictions on diesel passenger cars in Brazil, with no corresponding tightening of emission standards, would exacerbate these impacts.

If Brazil does remove restrictions on diesel passenger vehicles, the health and air quality impacts will be significant under any growth scenario. Under both dieselization scenarios considered in this study, diesel vehicle emissions significantly increase the air quality burden of the LD vehicle fleet. In the high growth scenario, dieselization leads to an additional 150,000 early deaths in Brazilian cities between 2015 and 2050. These environmental and human health costs come with no clear benefit, as the efficiency advantages of diesel engines are negated through increased emissions of black carbon and displacement of sugarcane ethanol, resulting in an overall increase in emissions of climate pollutants under dieselization pathways.

Brazil is well-positioned to apply lessons learned from the international regulatory experience. The U.S. provides the strongest example of effective motor vehicle emissions control, including fuel-neutral vehicle emission standards with strict limits and representative test cycles, as well as a strong in-use compliance program. European particle number standards offer additional protections to ensure that the best filter technology is employed. However, Europe continues to suffer from high PM emissions from the large fleet of pre-Euro 5 diesel vehicles. EU standards still have not adequately addressed NO_X emissions from diesel vehicles, although current proposals to strengthen in-use compliance represent a positive step to control diesel emissions and address air quality problems.

In order to reduce the environmental and health impacts of the transportation sector, Brazilian regulators should learn from these international best practices and take the following actions:

- Adopt stringent vehicle emission standards to ensure that diesel vehicles are equipped with particle filters and to protect against the worst health and air quality impacts of diesel vehicles. These standards should be equivalent to either U.S. Tier 2 or Euro 6 standards.
- Phase out 500-ppm diesel outside metropolitan areas to avoid the risk of misfueling and damaging aftertreatment control systems.
- Implement an effective in-use compliance and enforcement program, complete with real-world testing, to ensure that real-world NO_X emissions from diesel vehicles are adequately controlled under certification limits.

Until new stringent vehicle and fuel standards are in place and shown to be effectively controlling both PM and NO_X emissions from diesel vehicles, any decision to lift diesel car restrictions would run counter to environmental and health goals.

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