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CLIMATE AND AIR POLLUTANT EMISSIONS BENEFITS OF BUS TECHNOLOGY OPTIONS IN SÃO PAULO

Tim Dallmann

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

BEIJING | BERLIN | BRUSSELS | SAN FRANCISCO | WASHINGTON

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International Council on Clean Transportation
1225 I Street NW Suite 900
Washington, DC 20005 USA

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

TABLE OF CONTENTS

EXECUTIVE SUMMARY

In January 2018, the city of São Paulo, Brazil, adopted an amendment to its Climate Change Law that sets ambitious intermediate and long-term emissions reduction targets for the city's transit bus fleet. The amendment, Law 16.802, sets 10-year and 20-year targets for fleetwide reductions in tailpipe emissions of fossil carbon dioxide (CO_2) and the air pollutants particulate matter (PM) and nitrogen oxides (NO_x). The ultimate aim of the amendment is to eliminate emissions of fossil fuel derived CO_2 and also reduce emissions of PM and NO_x by 95% from 2016 levels by January 2038.

With the passage of Law 16.802, São Paulo has taken an important step toward improving the environmental performance of the city's transit bus fleet. Achieving the law's goals will require near-term action by a range of stakeholders, including the municipal transit authority, SPTrans, and transit operators, in order to facilitate the introduction of cleaner engine technologies and non-fossil fuels to the fleet. The level of technology transition that will be required to meet the targets is substantial, and careful planning is needed to make sure transit operators are able to make this transition in a cost-effective manner while maintaining operational integrity and quality service.

With these needs in mind, this paper quantitatively addresses the following questions regarding technology transitions in the São Paulo public transit bus fleet:

- What is the magnitude of emissions reductions that will be required to comply with targets set forth in Law 16.802?
- To what degree can alternative transit bus technologies and fuels improve the emissions performance of diesel buses currently used in the São Paulo fleet?
- What technology procurement pathways are needed to meet intermediate and long-term fossil CO_2 and air pollutant emissions reduction targets set forth in Law 16.802?
- What are the climate impacts of alternative Law 16.802 compliant procurement pathways when fuel life-cycle emissions and non-CO_2 pollutants are considered?
- What are the costs of alternative bus technologies and fuels relative to conventional diesel buses when all ownership costs incurred over the lifetime of the bus are considered?

To address these questions, we have applied a transit bus emissions and cost model developed by the International Council on Clean Transportation (ICCT). The model evaluates annual air and climate pollutant emissions and total cost of ownership for user-defined procurement scenarios. In our analysis we consider a number of different bus engine technologies and alternative fuels that can contribute to achieving the goals of Law 16.802, including Euro VI technologies, biofuels, and electric drive buses.

The emissions modeling presented in this paper indicates that extensive, near-term transitions to cleaner engine technologies and non-fossil fuels will be needed to comply with the emissions reduction targets set in Law 16.802. We estimate that all new buses purchased beginning in 2019 and continuing thereafter will need to meet Euro VI or better emissions performance in order to achieve sufficient PM and NO_x emissions reductions to comply with intermediate, 10-year targets. A substantial fraction of these buses also will have to be fossil-fuel free in order to meet the 10-year fossil CO_2 emissions reduction requirement. This fraction is estimated to be 60% of all bus purchases if the transition starts in 2019 and increases to 70% and 80% if the transition is delayed until 2020 or 2021, respectively. If the transition to zero fossil fuel buses is delayed to 2023, it is unlikely that intermediate targets can be met without early retirement and replacement of buses that have not reached the end of their 10-year service life. Our procurement model indicates all new buses entering the fleet should be fossil-fuel free by the beginning of 2028 in order to meet the 20-year fossil CO_2 emissions target. Figure ES1 shows the emissions reduction targets set in Law 16.802 and gives an example of the emissions reductions expected under a bus procurement pathway estimated to be compliant with the requirements of the Climate Change Law amendment.

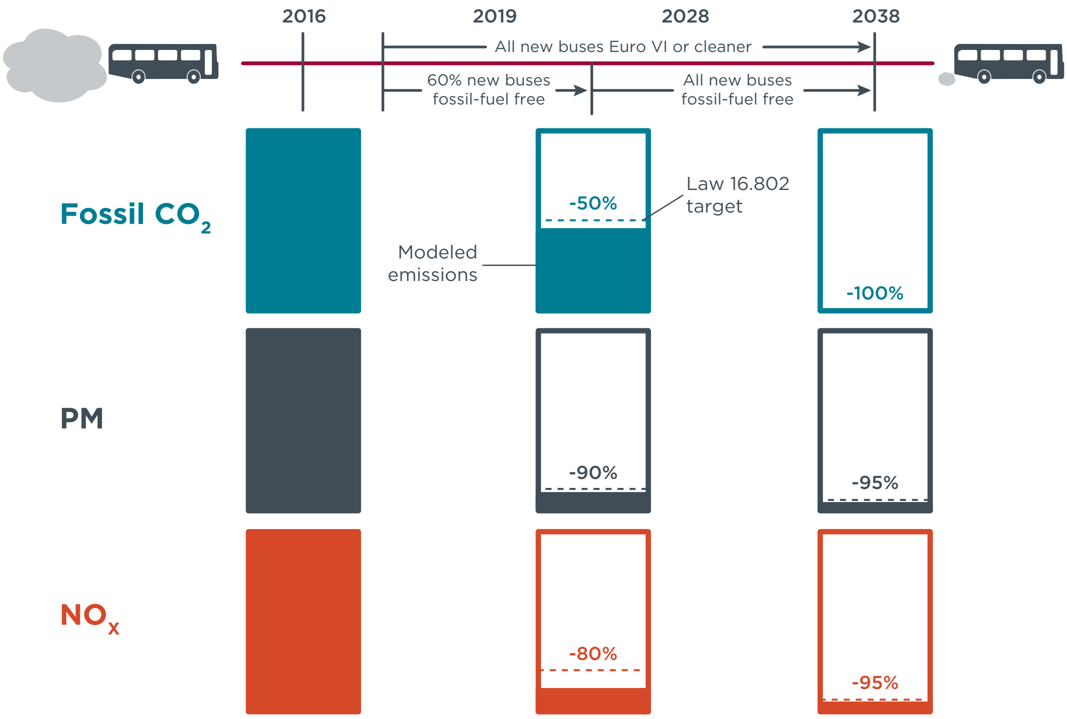

Figure ES1. Overview of Law 16.802 targets and emissions reductions estimated for the São Paulo transit bus fleet under a modeled Law 16.802 compliant procurement pathway.

The way in which Law 16.802 is formulated means only reductions in tailpipe fossil CO_2 emissions are required. The law does not regulate upstream emissions of CO_2 associated with fuel and feedstock production and transport, nor does it consider non-CO_2 climate pollutants, such as methane, nitrous oxide, and black carbon (BC). For certain fuels, in particular biofuels derived from food-based feedstocks, upstream emissions can be quite high and transitions to such fuels can limit the extent of climate pollutant emissions reductions achievable under the law. When fuel life-cycle emissions and non-CO_2 climate pollutants are considered, we found that a fleetwide transition to zero emission electric drive bus technologies would provide the greatest climate benefits of the zero fossil fuel technologies considered in this analysis. Transitions to biomethane- and ethanol-fueled bus technologies also are estimated to reduce the climate impact of the São Paulo fleet, although not to the same extent as electric buses. When assessed on a fuel life-cycle basis, CO_2 emissions benefits from buses fueled by soy-based biodiesel are more uncertain. This is primarily due to the risk of high land use change emissions for soy-based biofuels. These findings suggest that transitions to Euro VI buses fueled with soy-based biofuels, although providing some near-term climate benefits through the control of BC emissions, may not meaningfully reduce CO_2 emissions and associated warming relative to current procurement practices.

With the exception of the ethanol bus, the total lifetime costs of owning and operating alternative technology bus options were found to be within 10% of the lifetime costs of the baseline P-7 diesel bus. Euro VI diesel, diesel-electric hybrid, and battery electric buses all are estimated to offer cost savings relative to P-7 diesel buses when all costs incurred over the service life are considered. Especially in the case of battery electric buses, traditional procurement practices that favor bus technology options with the lowest purchase price may bias against technologies that have a higher purchase price but lead to substantially reduced operating costs, and potentially lower net costs, over the lifetime of the bus. Changes to existing procurement practices and implementation of innovative financing models that take into account lifetime operational savings of alternative bus technologies may be needed to accelerate the uptake of these technology options.

INTRODUCTION

The São Paulo municipal public transit system provides a vital service to the residents of the city. The system, which encompasses a fleet of more than 14,000 buses operating on 1,340 lines, is the largest in Brazil and among the largest bus fleets in the world (SPTrans, 2017). This system is critical to urban mobility in São Paulo, transporting an average of 8 million passengers per day, while helping to decrease traffic congestion in the city.

Today, more than 98% of the São Paulo transit bus fleet is powered by diesel engines. Because Brazil's pollutant emission standards for heavy-duty vehicles lag behind international best practices, these buses do not employ the best available technologies for controlling harmful pollutant emissions from diesel engines (Miller & Façanha, 2016). The most recent motor vehicle emissions inventory compiled by the Companhia Ambiental do Estado de São Paulo (CETESB, 2017) estimates that urban buses make up less than 1% of the São Paulo metropolitan area's vehicle fleet but account for 21% of vehicular emissions of nitrogen oxides (NO_x) and particulate matter (PM). These emissions have significant societal impacts, contributing to poor air quality and negative human health impacts, including heart disease, stroke, lung cancer, asthma, and chronic obstructive pulmonary diseases. Buses also are an important source of climate pollutant emissions, including carbon dioxide (CO_2) and black carbon (BC), a potent short-lived climate pollutant that makes up approximately 75% of PM emitted by older technology diesel engines (U.S. Environmental Protection Agency [U.S. EPA], 2012).

Given the importance of the public transit fleet to mobility in São Paulo, as well as its disproportionate impact on motor vehicle pollution, investments in buses are a key long-term strategy to meet the city's environmental and sustainability goals. Changes to the fuels and technologies of the bus fleet serve the dual goals of improving the quality of service provided to users of the system and reducing harmful pollutant emissions that negatively impact air quality in the city.

Unfortunately, policies intended to accelerate the transition to cleaner transit bus technologies and fuels have so far proven to be largely ineffective. The São Paulo Climate Change Law, passed in 2009, called for a 10% per year reduction in the number of city buses running on fossil fuels, with an ultimate target of a 100% non-fossil-fuel fleet by 2018 (Cidade de São Paulo, 2009). These targets proved to be overly ambitious and the original goals of the program went almost entirely unrealized; today less than 2% of the city's fleet operates on non-fossil fuels. With respect to transit buses, the law placed no restrictions on climate warming pollutants like carbon dioxide.

In light of the failure to make any real progress toward meeting the goals of the Climate Change Law and facing increasing pressure from citizens and civil society to address these shortcomings, the Municipal Chamber of São Paulo passed an amendment to the law in 2017, which was signed into law by Mayor João Doria in January 2018 (Cidade de São Paulo, 2018). The amendment, Law 16.802, sets ambitious new intermediate and long-term pollutant emissions reduction targets for the city's transit bus fleet. This moves away from the structure of the earlier law, which in practice only mandated a change in the fuels used in the fleet. Targets are set for both climate and air pollutant emissions, with the ultimate aim of eliminating emissions of fossil fuel derived CO_2 and also reducing emissions of PM and NO_x by 95% from 2016 levels by January 2038. The law does not place limits on carbon dioxide emissions from non-fossil fuels. We quantify in this report how this feature of the law could limit its success in decarbonizing the bus fleet.

The implementation of Law 16.802 will have a significant influence on the evolution of the São Paulo public transit bus fleet. The targets set in the law cannot be met with the engine technologies and fuels currently in use; transitions to cleaner engine technologies and non-fossil fuels will be required. Transit operators will need to develop long-term procurement strategies in order to plan for these technology transitions and to ensure compliance with emissions reduction targets is maintained.

A number of alternative engine technology and fuel options are commercially available today, offering varying degrees of emissions improvement relative to the fossil-fueled diesel buses currently employed in the São Paulo fleet. Diesel and compressed natural gas (CNG) engines certified to soot-free emission standards (Euro VI or US 2010 equivalent) can greatly reduce PM and NO_x emissions; hybrid buses and biofuels can contribute to meeting CO_2 emissions targets. Battery electric buses (BEBs) have zero tailpipe emissions and, because of the large percentage of Brazilian electricity produced from hydropower, offer the potential for deep life-cycle CO_2 emission reductions.

The primary goal of this paper is to quantitatively investigate the extent to which, and how quickly, these alternative transit bus technology and fuel options will need to be incorporated into the São Paulo bus fleet in order to achieve compliance with Law 16.802. We present results from a modeling study that evaluated the emissions reductions achievable under a number of different long-term bus procurement scenarios. Because the financial viability of concession contracts is an important consideration, we also evaluated the lifetime costs of alternative transit bus technologies using a total cost of ownership approach. Results presented here will provide the São Paulo transit authority, SPTrans, and transit operators in the city with a better understanding of the degree and pace of technology transition that will be required to meet the goals of Law 16.802.

POLICY BACKGROUND

Law 16.802 was published in the Official Diary of the City of São Paulo on January 18, 2018 (Cidade de São Paulo, 2018). The key regulatory provisions in the law are intermediate and long-term emissions reduction targets set for tailpipe pollutant emissions. These targets, shown in Table 1, require transit operators to reduce emissions of tailpipe fossil CO_2, PM, and NO_x from their bus fleets by 50%, 90%, and 80%, respectively, within a 10-year period following the law's passage.[1] At the end of a 20-year period, fossil CO_2 emissions must be completely eliminated from the fleet, and NO_x and PM emissions must be reduced by 95%. In both cases, emissions reductions are evaluated relative to total emissions from the regulated fleets in the year 2016.

Notably, Law 16.802 is technology neutral. This formulation allows transit operators a greater degree of flexibility in the decisions they make regarding transit bus technology and fuel transitions.

Table 1. Tailpipe fossil CO_2, PM, and NO_x emissions reduction targets adopted in Law 16.802.

Pollutant species	At the end 10 years (January 2028)	At the end of 20 years (January 2038)
Fossil CO_2	50%	100%
PM	90%	95%
NO_x	80%	95%

Emissions reduction targets apply only to tailpipe pollutant emissions and exclude upstream emissions associated with fuel and feedstock production and transport. This means that, for CO_2, only emissions from the combustion of fossil fuels in bus engines are considered under the scope of the law. Upstream emissions can account for a significant fraction of total life-cycle emissions, in particular for biofuels, and excluding these emissions can partially or entirely mask the true climate impact of alternative transit bus technology and fuel options.[2] The law does include language specifying that life-cycle emissions should be considered when selecting fuel and energy sources, however, there are no legal requirements to do so. Additionally, the law does not place restrictions on emissions of non-CO_2 climate pollutants, such as the greenhouse gases methane (CH_4) and nitrous oxide (N_2O). The potential impacts of omitting upstream emissions and emissions of non-CO_2 climate pollutants from the law will be discussed in more detail in later sections of the paper.

Additional provisions of note in Law 16.802 include:

» **Fleet turnover:** The law does not require early retirement or scrappage of existing diesel buses. Rather, the law calls for a gradual fleet transition whereby new, cleaner bus technologies are brought into the fleet when existing buses reach the end of their normal service lives (currently 10 years).

» **Prioritization of trolleybus fleet expansion:** Existing charging infrastructure for electric trolleybuses is underutilized. The law states that expansion of the trolleybus fleet should be prioritized in order to fully utilize current infrastructure capacity.

» **Establishment of monitoring program and steering committee:** The law establishes a monitoring program responsible for annual evaluations of the progress of

1 In addition to public transit bus operators, Law 16.802 also applies to waste collection companies. In this paper, we focus exclusively on evaluating the law's impact on public transit bus fleets.

2 Tailpipe emissions of fossil CO_2 are effectively zero for buses using 100% biofuel blends and for zero emission electric technologies such as battery electric buses.

individual fleets toward achieving emissions reduction targets. Additionally, the program is responsible for assessments, every 5 years, of the level at which emissions reduction targets are set. The steering committee for the monitoring program is to be made up of representatives from municipal government, transit operators, waste collection companies, and civil society organizations.

» **Evaluation:** The Municipal Administration is responsible for defining metrics and methods to be used for emissions calculations. These are to follow typical approaches used by environmental authorities.

» **Reporting:** Transit operators are responsible for submitting an annual emission report detailing kilometers driven, fuel consumption, and annual total emissions of pollutants and greenhouse gases (GHGs) for each vehicle in their respective fleets.

» **Impacts on concession contracts:** The law includes a clause stating that procurement of alternative engine technologies and fuels must be carried out within the economic-financial balance of concession contracts. In other words, any additional costs associated with the implementation of alternative engine technologies and fuels should be addressed in concession contracts.

The final point above is of particular relevance, as the city currently is undertaking a reorganization and optimization of its public transportation system, including open bidding on concession contracts for the day-to-day operation of the system. In São Paulo, as is the case in most Brazilian cities, operation of the public transit system is delegated to private entities via concession or permission. SPTrans, São Paulo's municipal transit authority, is responsible for managing the system and supervising concessionaires. This reorganization will affect many facets of the transit system, including the number and distribution of lines, concession lots, fleet size, and fleet activity, among others.

The most recent concession bidding process in São Paulo began in December 2017 with the release of a draft bidding tender for public comment. Following the public comment period, the final public notice of the bidding tender was released in April 2018. On June 8, 2018, the Municipal Court of Audit (TCM), citing irregularities in the concession bidding tender, suspended the competition. The city administration responded to the issues raised by the TCM and the bidding process was resumed on December 6, 2018 (Prefeitura de São Paulo Mobilidade e Transportes, 2018). By the publication of this report, there is uncertainty about the bidding process closing date.

RESEARCH SCOPE

The emissions reduction targets set in Law 16.802, and the extent to which they are enforced, will dictate how quickly and to what degree clean transit bus engine technologies and non-fossil fuels will need to be introduced into the São Paulo fleet. The level of technology transition that will be required to meet the targets is substantial, and careful planning is needed to ensure transit operators are able to make this transition in a cost-effective manner while maintaining operational integrity and quality service.

With these needs in mind, this paper aims to quantitatively address the following questions regarding technology transitions in the São Paulo public transit bus fleet:

» What is the magnitude of emissions reductions that will be required to comply with targets set forth in Law 16.802?

» To what degree can alternative transit bus technologies and fuels improve the emissions performance of diesel buses currently used in the São Paulo fleet?

» What technology procurement pathways are needed to meet intermediate and long-term fossil CO_2 and air pollutant emissions reduction targets set forth in Law 16.802?

» What are the climate impacts of alternative Law 16.802 compliant procurement pathways when fuel life-cycle emissions and non-CO_2 pollutants are considered?

» What are the costs of alternative bus technologies and fuels relative to conventional diesel buses when all ownership costs incurred over the lifetime of the bus are considered?

To address these questions, we have applied a transit bus emissions and cost model developed by the International Council on Clean Transportation (ICCT). The model was developed using detailed inputs for the current São Paulo diesel bus fleet, including information on the fleet distribution by bus type and age, annual bus activity and fuel consumption, bus purchase prices, fuel costs, and maintenance costs (e.g., tires, lubricants, parts, and accessories). A literature review was conducted to supplement the core São Paulo dataset with similar information for alternative technology buses. The model evaluates annual air and climate pollutant emissions and total cost of ownership for user-defined procurement scenarios.

In the following sections, we first present emissions estimates for the São Paulo bus fleet in 2016, the baseline year against which emissions reductions required by Law 16.802 will be compared. We then describe bus engine technology and alternative fuel options that can contribute to meeting the goals of Law 16.802. Modeling results for the emissions reductions achievable in alternative long-term procurement scenarios are then presented, with a focus on those pathways that are projected to achieve compliance with Law 16.802. We further explore the climate impacts of Law 16.802 compliant procurement pathways when non-CO_2 climate pollutants and fuel life-cycle emissions are considered. Finally, we detail methodologies and results of a total cost of ownership assessment of the lifetime capital and operating expenses incurred for diesel and alternative transit bus technologies.

BASELINE FLEET AND EMISSIONS

Pollutant emissions reduction requirements set in Law 16.802 are defined as percentage reductions relative to total emissions from the regulated fleets in the baseline year, 2016. In this section we review characteristics of the baseline São Paulo municipal public transit bus fleet and present estimates of emissions from this fleet for the pollutants regulated by Law 16.802—tailpipe fossil CO_2, PM, and NO_x. Based on these estimates, we calculate the magnitude of emissions reductions that will be needed to achieve compliance with intermediate and long-term targets set by Law 16.802. Unless otherwise noted, all data used in this section are sourced from annual reports published by SPTrans, which detail operational and financial characteristics of the public transit bus fleet (SPTrans, 2017).

BASELINE FLEET

In 2016, the fleet consisted of a total of 14,703 buses, distributed across eight different bus types. Details of the baseline fleet are included in Table 2. The most common bus types employed include mini, básico, and padron buses. These bus types, along with midibuses, also had the highest utilization rates as measured by the average per bus annual vehicle kilometers traveled (VKT). VKT estimates presented here represent scheduled, or revenue, miles. Data are not available for non-revenue miles, for example when a bus is traveling to or from a depot or station and not carrying passengers.

Table 2. Characteristics, fleet size, and annual activity for bus types deployed in baseline (2016) São Paulo municipal public transit bus fleet.

Bus type	Vehicle length (m)	Number seats (#)	Total passenger capacity (#)	Buses in fleet (#)	Scheduled annual activity (million km/yr)	Scheduled annual activity per bus[a] (km/yr/bus)
Miniônibus	8.4 – 9.0	20	35	3,585	251	70,100
Midiônibus	9.6 – 11.5	25-33	54-68	1,616	114	70,400
Básico	11.5 – 12.5	35	74	2,972	215	72,200
Padron[b]	12.5	32	87	3,583	259	72,300
Padron (15m)	15.0	38	110	203	13	61,800
Articulado	18.3	37	129	1,344	86	63,600
Articulado (23m)	23.0	54	174	990	64	64,700
Biarticulado	≤ 27.0	53	198	209	8	36,600

[a]Calculated by dividing the scheduled annual activity for a given bus type by the number of buses of the respective type in the fleet.
[b]The baseline fleet also includes 201 electric trolleybuses, not shown in the table. Annual activity for trolleybuses is estimated to be 51,800 kilometers per year per bus.

As shown in Figure 1, 99% of the baseline fleet was powered by diesel engines. Alternative technology buses employed at that time included electric trolleybuses, which accounted for the remainder of the fleet. The diesel fleet was split approximately equally between buses certified to PROCONVE P-5 and P-7 emission standards. PROCONVE standards are the national emission standards for heavy-duty vehicles (HDVs) in Brazil and set limits on the amount of pollution that can be emitted by new vehicles sold in the country. Brazilian standards are based on the corresponding regulatory program for HDVs in Europe, and P-5 and P-7 standards are generally equivalent to Euro III and Euro V standards, respectively. The European Union has implemented more stringent Euro VI standards, which greatly reduce pollutant emission limits relative to Euro V standards and introduce more stringent testing procedures that support better real-world control of emissions.

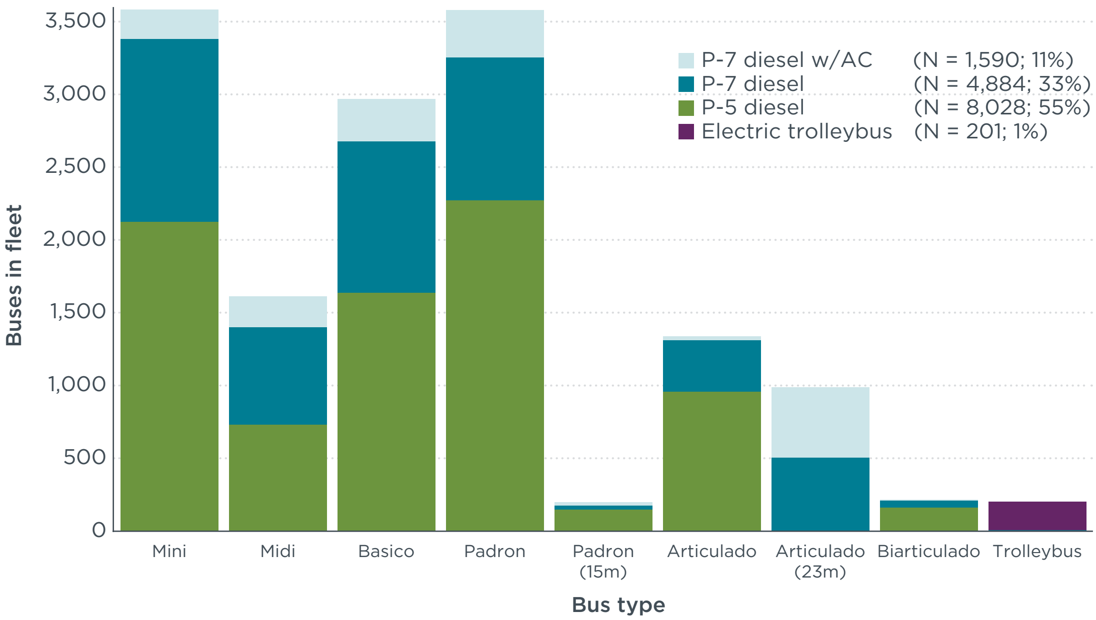

Figure 1. Composition of the São Paulo municipal transit bus fleet in 2016 by bus type and emission control level.

PROCONVE P-7 standards have been in force since 2013. Brazil has recently announced the next phase of PROCONVE standards for HDVs, P-8, which follow the Euro VI standard. P-8 standards will be implemented beginning in 2022 for new models of trucks and buses and in 2023 for all models (Conselho Nacional do Meio Ambiente [CONAMA], 2018). The corresponding 10 parts per million (ppm) sulfur diesel fuel, required for Euro VI standards, already is widely available in the city of São Paulo.

Approximately 25% of the P-7 diesel buses in the 2016 fleet were equipped with air conditioning (AC). The average age of the fleet in 2016 was 5.9 years.

EMISSIONS MODELING METHODOLOGY

Tailpipe fossil CO_2 and air pollutant emissions for the baseline fleet were evaluated using a transit bus emissions and cost model developed by the ICCT. The model calculates annual historical and future tailpipe fossil CO_2 emissions from the São Paulo fleet ($E_{CO_2,TP}$, units of million tonnes per year) using the following equation:

$$E_{CO_2,TP} = \sum_{b,e,f} EC_{b,e} \times EF_{CO_2,f} \times VKT_{b,e,f} \times 10^{-12} \tag{1}$$

where, b, e, and f refer to bus type, engine technology, and fuel type, respectively. $EC_{b,e}$ is the energy consumption of a given bus type and engine technology expressed in units of kilowatt hours per kilometer (kWh/km). Energy consumption reflects the amount of energy required to move a bus a unit distance, as well as the energy required to power auxiliary loads, such as AC and lighting. For buses powered by internal combustion engines, energy consumption is directly proportional to fuel consumption. $EF_{CO_2,f}$ is the tailpipe fossil CO_2 emission factor for a given fuel in units of g/kWh and is a measure of the CO_2 emissions produced by the combustion of fossil fuels in internal combustion engines. For petroleum diesel fuel, EF_{CO_2} is assumed to be 270 g/kWh (Argonne National Laboratory [ANL], 2018). In accordance with the Climate Change Law, which aims to eliminate CO_2 emissions from fossil fuels only, EF_{CO_2} for biofuels and electricity is considered zero. Finally, $VKT_{b,e,f}$ is the annual activity for all buses of a common type, engine technology, and fuel type expressed in units of kilometers per year.

We evaluate annual tailpipe emissions of the air pollutants PM (E_{PM}, tonnes per year) and NO_x (E_{NO_x}, tonnes per year) by applying the following equations:

$$E_{PM} = \sum_{b,e,f} EF_{PM,b,e} \times VKT_{b,e,f} \times 10^{-6} \tag{2}$$

$$E_{NO_x} = \sum_{b,e,f} EF_{NO_x,b,e} \times VKT_{b,e,f} \times 10^{-6} \tag{3}$$

where $EF_{PM,b,e}$ and $EF_{NO_x,b,e}$ are PM and NO_x emission factors for a given bus type and engine technology, expressed in units of grams per kilometer.

Where possible, emissions modeling input data for the baseline fleet are sourced directly from SPTrans. These data include annual activity (see Table 2) and fuel consumption (see Table 3) by bus type (SPTrans, 2017). Separate fuel consumption values are reported for buses equipped with AC.

Table 3. Fuel and energy consumption for diesel buses operating in São Paulo.

Bus type	No AC		With AC	
	Fuel consumption (L/100km)	Energy consumption (kWh/km)	Fuel consumption (L/100km)	Energy consumption (kWh/km)
Miniônibus	30	3.0	35	3.5
Midiônibus	40	4.0	47	4.7
Básico	46	4.6	53	5.3
Padron	55	5.5	63	6.3
Padron (15m)	65	6.5	75	7.5
Articulado	71	7.1	80	8.0
Articulado (23m)	75	7.5	85	8.5
Biarticulado	80	8.0	90	9.0

Note: Fuel consumption values reported by SPTrans were converted to energy consumption using the lower heating value for low sulfur diesel fuel (128,488 Btu/gal) reported by the U.S. Department of Energy Alternative Fuels Data Center. www.afdc.energy.gov/fuels/fuel_properties.php

Tailpipe fossil CO_2 emission factor values for fuel used in the baseline diesel bus fleet are calculated assuming all buses used B7 fuel, a blend of 93% petroleum diesel and 7% biodiesel by volume, which was the commercial diesel specification in 2016. Since that time, Brazil has increased the biodiesel blend level in diesel fuels to 10%. Biodiesel blend levels for commercial diesel fuels are expected to further increase to 15% by 2023 (Conselho Nacional de Política Energética, 2018). In our analysis, we assume all biodiesel is produced from soybean oil, the most common feedstock used in Brazilian biodiesel production (Ministério de Minas e Energia, 2017).

Air pollutant emission factors are taken from the Handbook Emission Factors for Road Transport (HBEFA, 2017) database. HBEFA reports pollutant emission factors for three types of urban buses—midi, standard, and articulated—by engine technology and emission control level. PM and NO_x emission factors used in this analysis are included in the appendix. Other emission factor sources were considered; however, none provided the same degree of coverage of alternative technology and fuel types as is provided by the HBEFA database. For example, the concession bidding tender includes a proposed methodology for calculating emissions from buses, including air pollutant emission factors (Prefeitura de São Paulo Mobilidade e Transportes, 2018). However, PM and NO_x emission factors are reported only for diesel buses certified to P-5 and P-7 emission standards, and no data are included for advanced technology diesel engines (Euro VI) or alternative engine and fuel types. While these data would be sufficient for baseline emissions calculations for the 2016 fleet, they are not adequate for the evaluation of the impacts of technology transitions to cleaner engine technologies and fuels.

TAILPIPE FOSSIL CO_2 EMISSIONS

Estimates of tailpipe fossil CO_2 emissions from the baseline bus fleet are shown in Figure 2, with colored and patterned bars used to differentiate contributions by bus technology. Emissions from the São Paulo fleet in 2016 were calculated to be 1.24 million tonnes CO_2 per year. Based on this estimate, annual fleetwide fossil CO_2 emissions will need to be reduced by 0.62 million tonnes per year to comply with the 10-year target of a 50% reduction from the baseline emissions level. To comply with the final fossil CO_2 target, the use of fossil fuels will need to be completely phased out in the next 20 years.

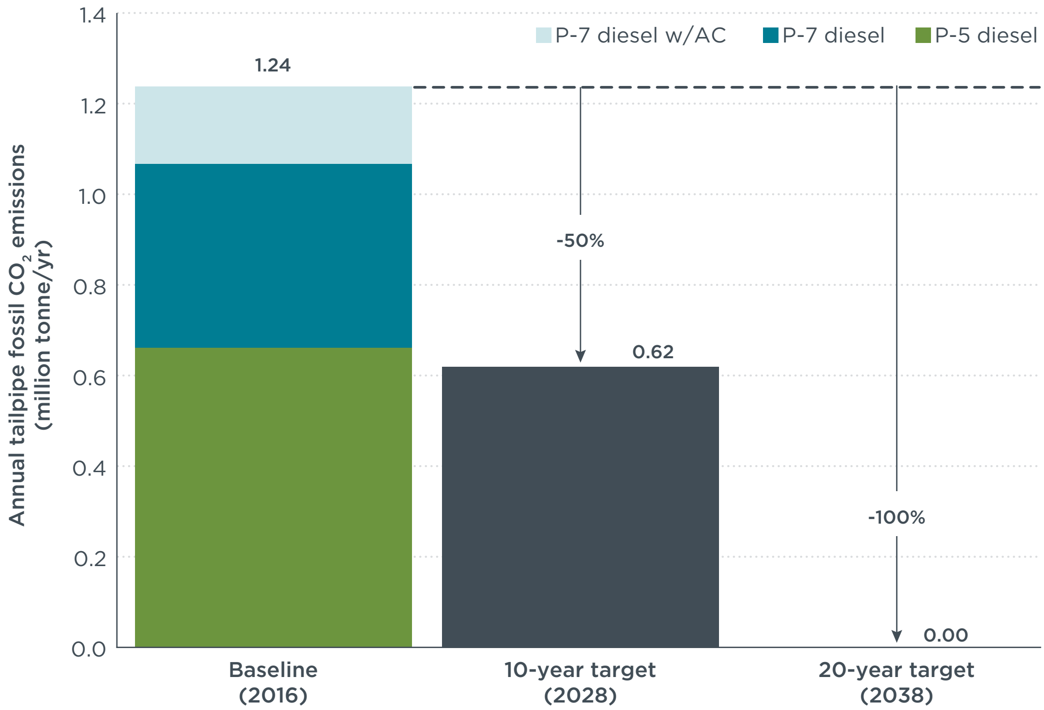

Figure 2. Tailpipe fossil CO_2 emissions for the baseline São Paulo municipal transit bus fleet and intermediate and final emissions reduction targets. Trolleybuses in the baseline fleet have zero tailpipe emissions of fossil CO_2 and thus are not included here. Emissions disaggregated by bus type are included in the appendix.

Following Equation 1, there are several ways in which fossil CO_2 emissions from the fleet can be reduced: (1) by reducing the annual activity of the fleet, (2) by transitioning to buses with more efficient engines and power trains and thus lowering fleetwide energy consumption, and (3) by increasing the use of fuels that have zero tailpipe emissions of fossil CO_2. In a practical sense, the emissions reduction potential of reduced annual activity is limited by the need for the fleet to maintain scheduled service across the transportation network. And because buses are among the most efficient forms of urban transit, per passenger-kilometer, greater investment in bus activity is a key strategy to decarbonize the transport sector. Thus, the deep emissions reductions required by Law 16.802 will need to come primarily from transitions to more efficient engine technologies and non-fossil fuels.

AIR POLLUTANT EMISSIONS

Figure 3 presents estimates for annual emissions of the air pollutants PM and NO_x from the baseline fleet, along with projected emissions thresholds the fleet will need to reach in order to comply with Law 16.802. Electric trolleybuses in the baseline fleet have zero emissions of PM and NO_x. Emissions disaggregated by bus type are included in the appendix.

P-5 diesel buses are the leading source of air pollutant emissions from the baseline fleet. These buses account for 55% of the total fleet vehicle kilometers traveled but are responsible for 81% of total PM emissions and 65% of total NO_x emissions. The disproportionate emissions impact of the P-5 diesel fleet is a consequence of the elevated PM and NO_x emission factors associated with the older technology diesel engines used in these buses. As such, fleet overhaul strategies should prioritize the replacement of these older, dirtier buses with low-emitting alternatives.

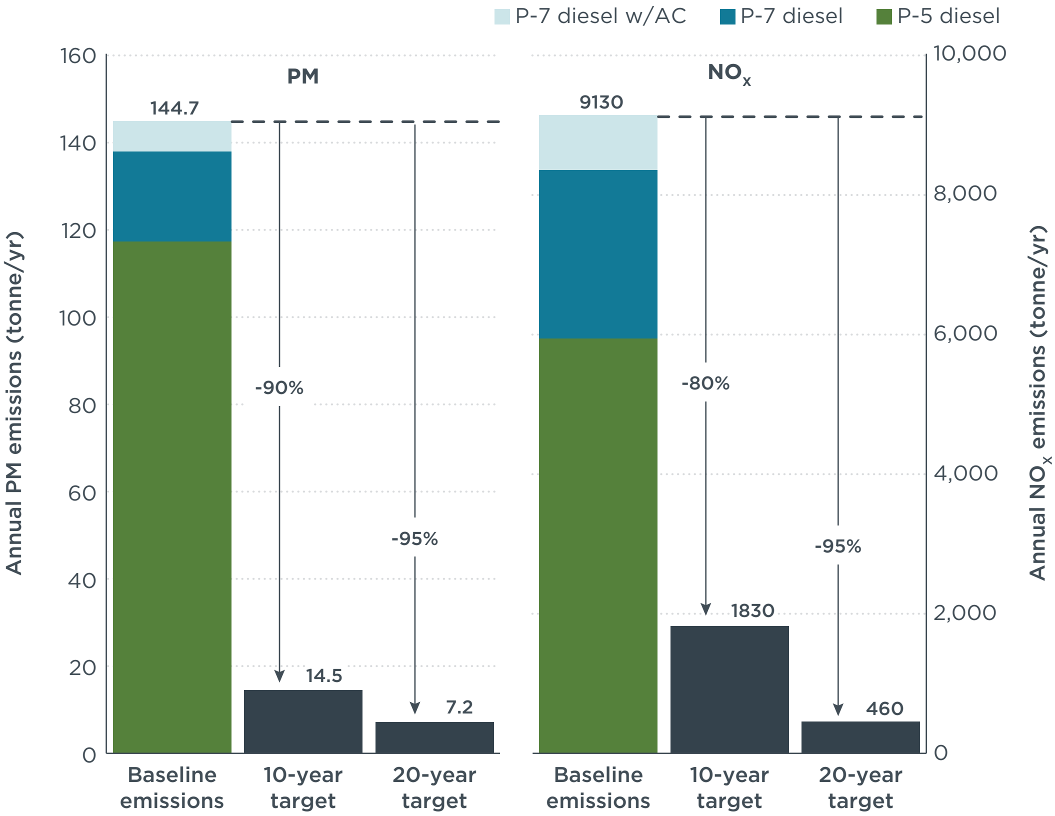

Figure 3. PM and NO_x emissions from the baseline São Paulo municipal transit bus fleet, showing estimates of intermediate and final emissions reduction targets for each pollutant.

Although the emissions performance of P-7 diesel buses is improved relative to the P-5 diesel buses, these buses still account for a considerable fraction of NO_x, and to a somewhat lesser extent, PM emissions from the baseline fleet. Notably, emissions of PM and NO_x from just the P-7 diesel buses in the baseline fleet exceed projected 10-year emissions reduction targets. This implies that replacing P-5 diesel buses with buses certified to the current Brazilian standards for HDVs, PROCONVE P-7, will not be sufficient to achieve the air pollutant emissions reduction targets set in Law 16.802. Transitions to bus technologies that substantially improve on the emissions performance of P-7 diesel buses will be needed. Because Law 16.802 requires the majority of emissions reductions to occur in the first 10 years of the law's implementation, these transitions will need to occur relatively quickly.

ADVANCED ENGINE TECHNOLOGY AND FUEL OPTIONS

The analysis of the baseline bus fleet presented in the previous section suggests that current procurement practices—which is to say replacement of P-5 diesel buses with P-7 diesel buses—will not be sufficient to meet emissions reduction targets set in Law 16.802. Transitions to cleaner engine technologies and non-fossil fuels will be needed. In this section we identify a range of alternative transit bus technologies and fuels that lower emissions of PM, NO_x and fossil CO_2 relative to P-5 or P-7 diesel buses using B7 fuel and thus can contribute to achieving compliance with Law 16.802.

EURO VI TECHNOLOGY

As detailed above, the current phase of Brazilian emission standards for HDVs, PROCONVE P-7, lags behind international best practices. Brazilian P-7 standards are generally equivalent to European Euro V standards. The European Union, recognizing the need for better control of harmful emissions from HDV engines, implemented Euro VI standards beginning in 2013. A number of important provisions were introduced in the Euro VI regulation that have resulted in significantly improved real-world emissions performance for HDV engines certified to these standards. These include more stringent pollutant emission limits and the introduction of certification test cycles that better represent real-world driving conditions including cold-start requirements, in-service conformity testing requirements, and extended durability periods (Chambliss & Bandivadekar, 2015). Importantly, the Euro VI standards introduced a particle number emission limit, which effectively has mandated the use of the most effective technology for controlling PM emissions from diesel engines, the diesel particulate filter (DPF), in Euro VI diesel engine designs. The Euro VI regulation also strengthened anti-tampering measures for selective catalytic reduction (SCR) systems used to control NO_x emissions, a provision that is especially relevant for Brazil, where loopholes in the P-7 regulation have led to higher than expected NO_x emissions from vehicles certified to this standard (Façanha, 2016).

The effectiveness of the Euro VI standards in controlling emissions from HDV diesel engines is demonstrated in Figure 4, which shows PM and NO_x emission factors for standard sized diesel urban buses across three levels of emission control. The PM emission factor for Euro VI buses is estimated to be 91% lower than for Euro V buses and 97% lower than for buses certified to Euro III standards. Similar reductions are reported for the Euro VI NO_x emission factor relative to previous emission control stages. The relative emissions reductions shown here for Euro VI diesel buses are also reflective of emissions reductions that can be expected of other engine technologies certified to Euro VI standards, such as CNG engines, when compared to Euro III or V diesel buses. It is important to note that the magnitude of emissions reductions offered by Euro VI technologies is only slightly less than that offered by zero emission technologies such as battery electric buses.

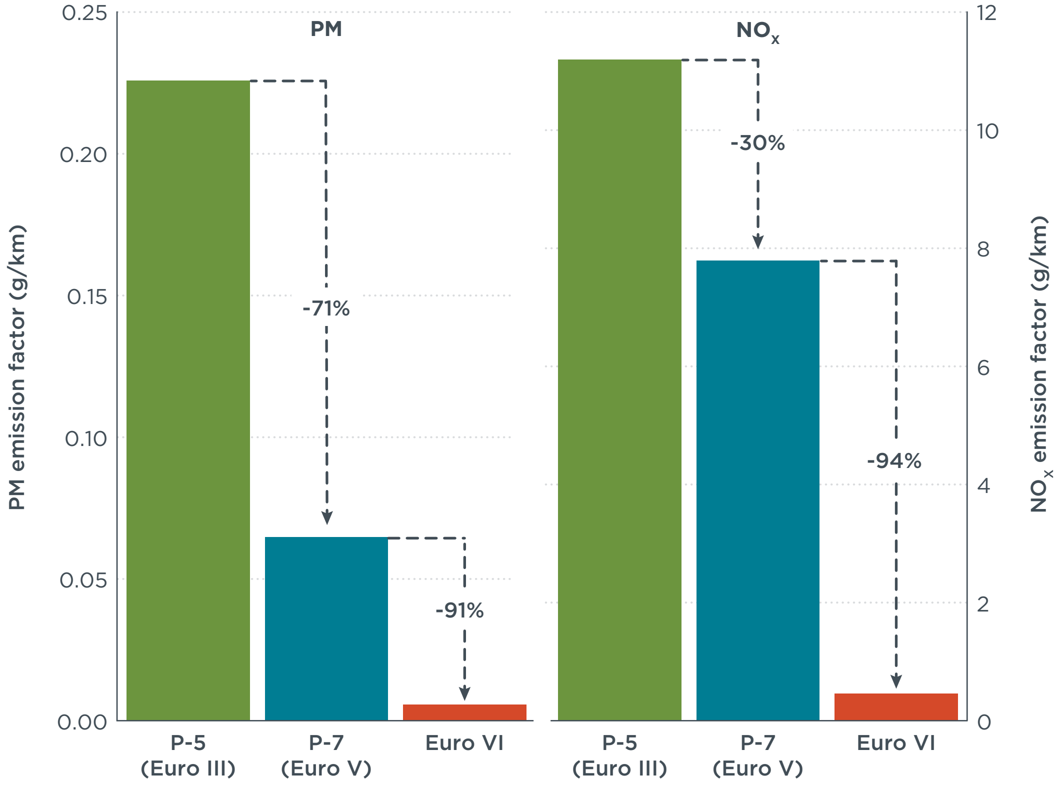

Figure 4. PM and NO_x emission factors for standard sized diesel urban buses by emission control level. Emission levels for the Euro VI diesel bus and reductions relative to previous emission stages are reflective of other Euro VI certified engine technologies (e.g., diesel-electric hybrid, CNG). Data sourced from HBEFA (2017).

Euro VI engines are effective at controlling emissions of black carbon, an important short-lived climate pollutant. Up to 75% of diesel particulate matter emitted from older technology diesel engines contains BC. However, Euro VI engines reduce diesel BC emissions by 99 percent, primarily through the application of a diesel particulate filter. Law 16.802 does not require BC reductions, but the law nevertheless produces near-term climate benefits by setting fleetwide limits on PM emissions.

Given the considerably improved PM and NO_x emissions performance of Euro VI engine technologies relative to P-5 and P-7 diesel engines and the level at which 10-year emissions reduction requirements are set for these pollutants in Law 16.802, Euro VI technologies should be prioritized in the near-term procurement strategies of transit operators. The recent adoption of PROCONVE P-8 standards for heavy-duty trucks and buses in Brazil means that all new buses purchased for the São Paulo fleet should meet Euro VI emissions performance by 2023. A key question we seek to address in this analysis is whether earlier introduction of Euro VI technologies, ahead of the roll out of P-8 standards, will be needed for the São Paulo fleet to achieve compliance with Law 16.802 PM and NO_x emissions reduction targets.

Although a transition to Euro VI engine technologies provides a clear path toward meeting Law 16.802 air pollutant emissions reduction targets, as long as fossil fuels are used to power these engines progress toward reducing fossil CO_2 emissions will be limited. Engine efficiency improvements and hybridization could decrease the fuel consumption of the fleet and contribute somewhat to the intermediate fossil CO_2 emissions reduction target of 50%. However, it is not likely that efficiency improvements alone can achieve the emissions reductions needed to meet this target. For example, we estimate the energy consumption of a Euro VI diesel-electric hybrid bus equipped with

AC to be only about 15% lower than a non-air-conditioned P-5 or P-7 diesel bus (see Table 4). Other Euro VI engine technologies provide even less of an efficiency benefit, if any, relative to engine technologies employed in the baseline fleet.

Thus, the uptake of fuels with zero tailpipe emissions of fossil CO_2 will need to be significantly increased in order to meet intermediate, 10-year targets. Of course, in the long term, the entire fleet will need to be fossil-fuel free in order to meet the 20-year target of a 100% reduction in fossil CO_2 emissions.

Table 4. Energy consumption for urban transit buses by engine technology (example shown for padron type bus).

Engine technology	Energy consumption (kWh/km)[a]	Assumption	Data source
P-5, P-7 diesel	5.5	As reported by SPTrans	SPTrans, 2017
P-7 diesel w/AC	6.3	As reported by SPTrans	
Euro VI diesel	6.0	-5% relative to P-7 diesel with AC	Dallmann, Du, & Minjares, 2017
Euro VI diesel-electric hybrid	4.8	-20% relative to Euro VI diesel	
Euro VI biodiesel/renewable diesel **Euro VI ethanol**	6.0	Equivalent to Euro VI diesel	
Euro VI CNG	6.6	+10% relative to Euro VI diesel	
Battery electric	1.8	-70% relative to Euro VI diesel	

[a]Note: All Euro VI buses and the battery electric bus are assumed to have AC.

BIOFUELS

There are several urban transit bus fuel options that have zero tailpipe emissions of fossil CO_2, including biofuels used in internal combustion engines and electricity used to power battery electric buses or trolleybuses.[3] To a limited extent, biofuels already are being used in transit buses operating in São Paulo. Seeking to promote the use of biofuels, the Brazilian government has set biodiesel blending targets for commercial diesel fuels sold in the country (Federal Law No. 13.263, 2016). As mentioned above, soy oil is the predominate feedstock for biodiesel production in Brazil, with this fuel pathway accounting for 76% of total biodiesel production in 2016 (Ministério de Minas e Energia, 2017). Between 2016 and 2018 the biodiesel volume blending level for commercial diesel has increased from 7% (B7) to 10% (B10) ("Brazil ups biodiesel blend," 2018). The blending level is expected to further increase by 1% annually through 2023, when a biodiesel content of 15% (B15) will be reached. São Paulo has conducted pilot programs to evaluate the use of ethanol produced from sugarcane as well as higher percentage biodiesel blends (B20) in transit buses. Finally, biomethane produced from the anaerobic digestion of biomass feedstocks or from landfill gas and used in CNG engines provides another biofuel option for transit operators.

As detailed above, biofuels, by definition, have zero tailpipe emissions of fossil CO_2 and thus can contribute meaningfully to achieving compliance with Law 16.802. However, reductions in tailpipe fossil CO_2 emissions do not necessarily equate with lower climate impacts, particularly because fuel life-cycle emissions reductions are not taken into account. Upstream emissions from the production of these fuels and the feedstocks from which they are derived can be significant. This is especially true for biofuels produced

3 Hydrogen used in fuel cell electric buses offers another zero fossil CO_2 alternative. We do not consider this technology option directly in our analysis, as it has not reached the same level of technological maturity as other transit bus options. However, over the long term, as the technology is further developed, it is expected to provide a viable zero emissions electric option for transit operators. While not directly considered here, conclusions drawn in this paper regarding transitions to non-fossil fuel alternatives are also applicable to hydrogen fuel cell electric bus technologies.

from food-based feedstocks, like soybean oil biodiesel, where land use change emissions can outweigh tailpipe CO_2 emissions reductions achieved from transitions to these fuels.

ELECTRIC DRIVE

Zero emission electric drive buses, such as battery electric buses and electric trolleybuses, provide additional zero fossil CO_2 alternatives for transit operators. Global sales of battery electric buses are growing rapidly as this technology is developed and more widely commercialized (Bloomberg New Energy Finance, 2018). To date, much of this growth has been centered in China, where environmental and industrial policies have accelerated transitions to this technology (Asian Development Bank, 2018). However, a growing number of cities in other regions also are taking steps to incorporate zero emission electric buses into their fleets, with, for example, London, Paris, and Los Angeles having made political commitments to transition to 100% zero emission electric bus fleets. Additionally, California has adopted a regulation that sets zero-emission bus purchase requirements for transit operators in the state (California Air Resources Board [CARB], 2018).

In the context of Law 16.802, zero emission electric buses offer the potential for substantial reductions in both air and climate pollutant emissions from the São Paulo fleet (Slowik, Araujo, Dallmann, & Façanha, 2018). These buses have zero emissions of tailpipe fossil CO_2, PM, and NO_x. As shown in Table 4, battery electric buses have significant efficiency benefits relative to diesel, CNG, or hybrid buses. Also, because of the high fraction of electricity generated from hydropower sources in Brazil, the life-cycle CO_2 emission intensity for electricity used to power these buses is relatively low compared to regions with higher carbon intensity electricity grids (Dallmann, Du, & Minjares, 2017). Several battery electric bus pilot and demonstration projects have been carried out in São Paulo to date.

Trolleybuses have a long history of use in the São Paulo municipal transit system and similarly provide a zero emission electric alternative for transit operators in the city. The existing trolleybus charging infrastructure network in São Paulo is underutilized. As will be discussed in the following section, an expansion of the trolleybus fleet in São Paulo, to the extent to which existing infrastructure capacity can be fully utilized, is called for in Law 16.802 and the concession bidding tender.

PROCUREMENT PATHWAYS TO MEET EMISSIONS REDUCTION TARGETS

In this section, we present emissions modeling results for a number of long-term bus procurement scenarios for the São Paulo municipal transit fleet. Calculated fossil CO_2, PM, and NO_x emissions for each procurement scenario are compared against 10-year and 20-year emissions reduction targets set in Law 16.802 in order to evaluate the degree and pace of technology transition that will be required to achieve compliance with the law.

Emissions modeling for long-term procurement scenarios follows Equations 1–3, with annual pollutant emissions from the fleet calculated for each year of the modeling period, 2016–2040. Annual emissions estimates for the years 2027 and 2037 are compared against emissions in the baseline year, 2016, in order to evaluate compliance with emissions reduction targets. The way in which the model is structured means that estimates for the years 2027 and 2037 are representative of emissions at the time of the compliance dates for 10-year and 20-year targets, which are January 2028 and January 2038, respectively. Table 5 summarizes the engine technology and fuel options considered in our model.

Table 5. Transit bus engine technology and fuel options considered in bus emissions modeling.

Engine/power train technology	Fuel	Fuel feedstock
Euro VI diesel	B10-B15 diesel[a]	Petroleum / soybean oil
	B20 diesel	Petroleum / soybean oil
	Biodiesel (B100)	Soybean oil
	Renewable diesel (R100)[b]	Soybean oil
Euro VI diesel-electric hybrid	B10-B15 diesel[a]	Petroleum / soybean oil
Euro VI compressed natural gas (CNG)	Fossil CNG	Fossil natural gas
	Biomethane	Landfill gas
Euro VI ethanol	ED95[c]	Sugarcane
Battery electric bus	Electricity	National grid electricity mix for year 2016

[a]Commercial diesel fuel is assumed to have biodiesel blend ratio of 7% in 2016, 8% in 2017, 10% in 2018, 11% in 2019, 12% in 2020, 13% in 2021, 14% in 2022, and 15% in 2023 and onward. CO_2 emissions for blends of petroleum diesel and biodiesel are calculated using volumetric blend rates and energy densities of the respective fuels.
[b]Renewable diesel is a liquid hydrocarbon fuel derived from biomass feedstocks. Renewable diesel can be produced through a number of different production pathways—hydrotreating of fats or oils, biomass gasification followed by a Fischer-Tropsch synthesis, biomass pyrolysis, or biological production of a hydrocarbon oil. In this analysis we consider renewable diesel produced through the hydrotreating of a soybean oil feedstock. Renewable diesel is distinct from biodiesel, which refers to a liquid fuel consisting of fatty acid alkyl esters produced in a transesterification process from feedstocks such as vegetable oil, animal fat, or waste oil. The chemical properties of renewable diesel are more similar to petroleum diesel than those of biodiesel.
[c]ED95 fuel consists of 95% ethanol and 5% additives, which act as an ignition improver and lubricant.

To model fleet turnover and the introduction of new technologies to the fleet, we follow provisions of Law 16.802 and assume buses are replaced following 10 years of service with a bus of a similar type. Exceptions to this fleet turnover model are early retirements and additional bus purchases required to meet the projected fleet size and composition changes expected under SPTrans system reorganization plans.

FLEET EVOLUTION WITH SYSTEM REORGANIZATION

Long-term emissions modeling for the São Paulo bus fleet must consider changes to the transportation network expected under the system optimization plan proposed by SPTrans in the recent concession bidding tender (Prefeitura de São Paulo Mobilidade e

Transportes, 2018). System reorganization will lead to changes in fleet size, composition (i.e., the distribution of buses by type), and activity, all of which will influence emissions and hence, progress toward meeting emissions reduction targets, irrespective of any changes in the engine technologies or fuels used to power the fleet.

For our modeling, we assume the fleet composition following system reorganization will follow projections included in the concession bidding tender released by SPTrans. Figure 5 shows the projected fleet composition with system reorganization compared to the baseline fleet. Under system reorganization, the total fleet size is expected to decrease from 14,703 to 12,994 buses. Service levels will be maintained by deploying larger capacity bus types, which are capable of transporting a greater number of passengers. For example, mini and básico buses are deemphasized in the future fleet, while the use of midi, padron, and articulado buses is expected to grow. The trolleybus fleet is projected to increase by 25 buses in order to fully utilize existing charging infrastructure. New charging infrastructure would be needed to further expand the trolleybus network.

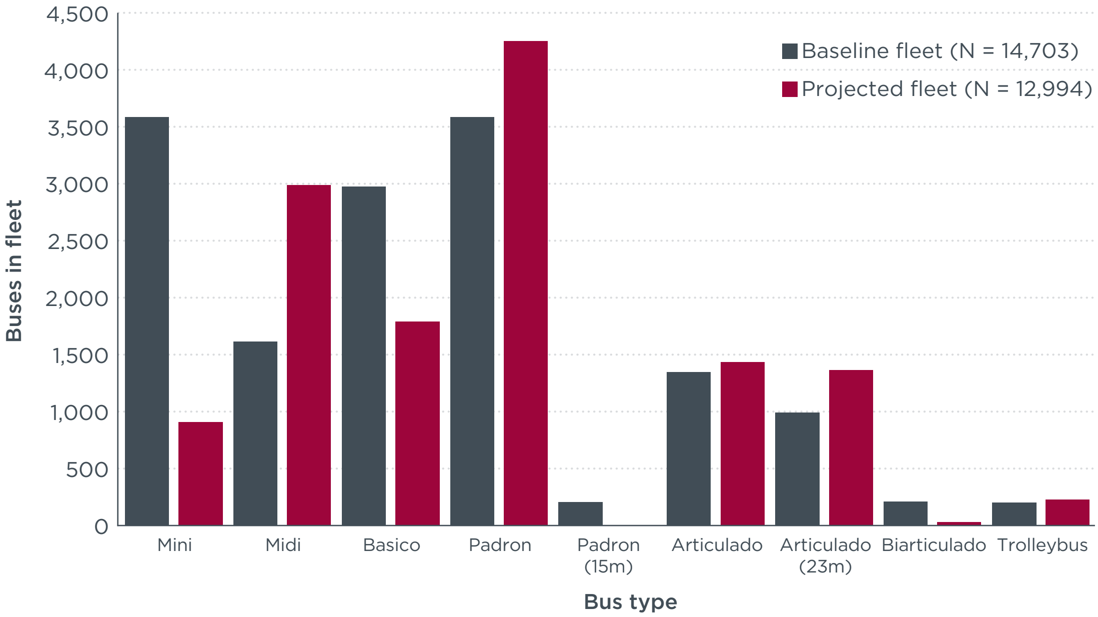

Figure 5. Projected fleet composition with system reorganization compared to baseline fleet. Data labels show change in number of buses of each type with system reorganization.

Total fleet activity, expressed as annual scheduled mileage, is expected to decrease by approximately 10% with system reorganization and optimization. Figure 6 shows projections for the annual activity for each of the bus types used in the São Paulo fleet as compared with baseline activity. Following the emphasis on higher capacity bus types in the planned system reorganization, relative activity also shifts toward larger bus types. This dynamic is reflected in the increase in not only the total activity of, for example, articulado buses, but also the per bus activity for these bus types, which is shown in the inset plot of Figure 6. Not only will there be more buses of these types in the fleet, but each bus will, on average, be driven more each year.

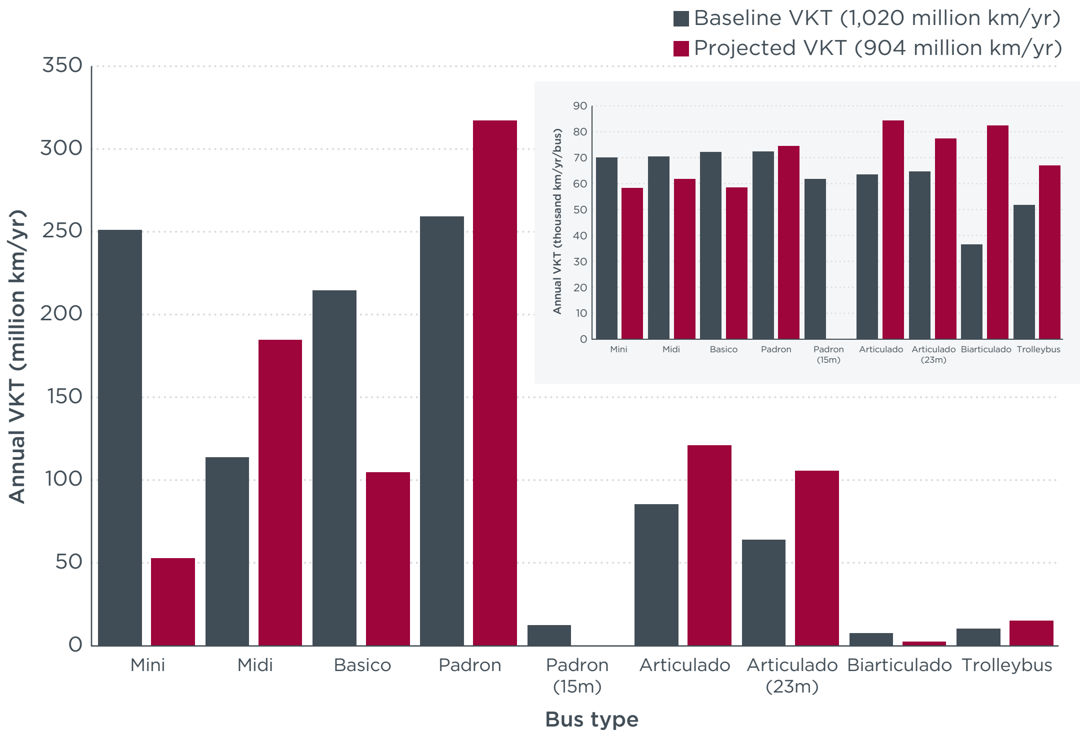

Figure 6. Projected annual activity by bus type with system reorganization, compared with baseline fleet activity. Inset plot shows per vehicle activity for each bus type.

In our model, we assume the system reorganization will be phased in over a 3-year period from 2019 through 2021, with the 2022 fleet composition and activity matching projections included in the concession bidding tender. Changes to the number of buses of each type in the fleet are modeled to occur linearly over the 3-year transition period, with early retirement or additional bus purchases applied where needed to achieve the final projected fleet size.

BUSINESS-AS-USUAL PROCUREMENT SCENARIO

The reference, or business-as-usual (BAU), scenario assumes all new buses entering the fleet are powered by diesel engines certified to the national emission standards prevailing in the year of purchase—PROCONVE P-7 for the years 2017–2022 and P-8 (Euro VI) from 2023 onward. We assume all buses use commercial diesel fuels and account for expected increases in biodiesel blend levels (B10 to B15 in the 2018–2023 time frame) in our modeling. Finally, we assume each new bus is equipped with AC, following requirements laid out in the concession bidding tender.

Emissions modeling results for the BAU procurement scenario are presented in Figure 7, with the top panel displaying the technological evolution of the fleet from 2016 to 2040 and the bottom panel showing corresponding changes in annual emissions of fossil CO_2, PM, and NO_x relative to the baseline year of 2016. We show relative emissions changes rather than the absolute magnitude of annual emissions in order to more directly compare with the emissions reduction targets mandated in Law 16.802, which are indicated with colored makers in the bottom panel of Figure 7.

Emissions estimates for the BAU procurement scenario suggest a transition to Euro VI diesel buses starting in 2023, when P-8 standards are fully implemented, will not deliver sufficient reductions of NO_x and PM emissions to meet 10-year targets set in Law 16.802. For this scenario, we estimate that, when projected changes in fleet size and activity are taken into account, PM and NO_x emissions at the 10-year compliance date are respectively 75% and 56% lower than baseline year 2016 emissions. These emissions reductions fall short of the Law 16.802 targets of 90% for PM and 80% for NO_x. Over the long term, the fleetwide transition to Euro VI engine technologies delivers sufficient emissions reductions to meet 20-year targets. These results indicate São Paulo will need to transition to buses meeting P-8/Euro VI, or better, emissions performance ahead of the implementation of national P-8 standards in order to achieve compliance with intermediate Law 16.802 emissions reduction targets.

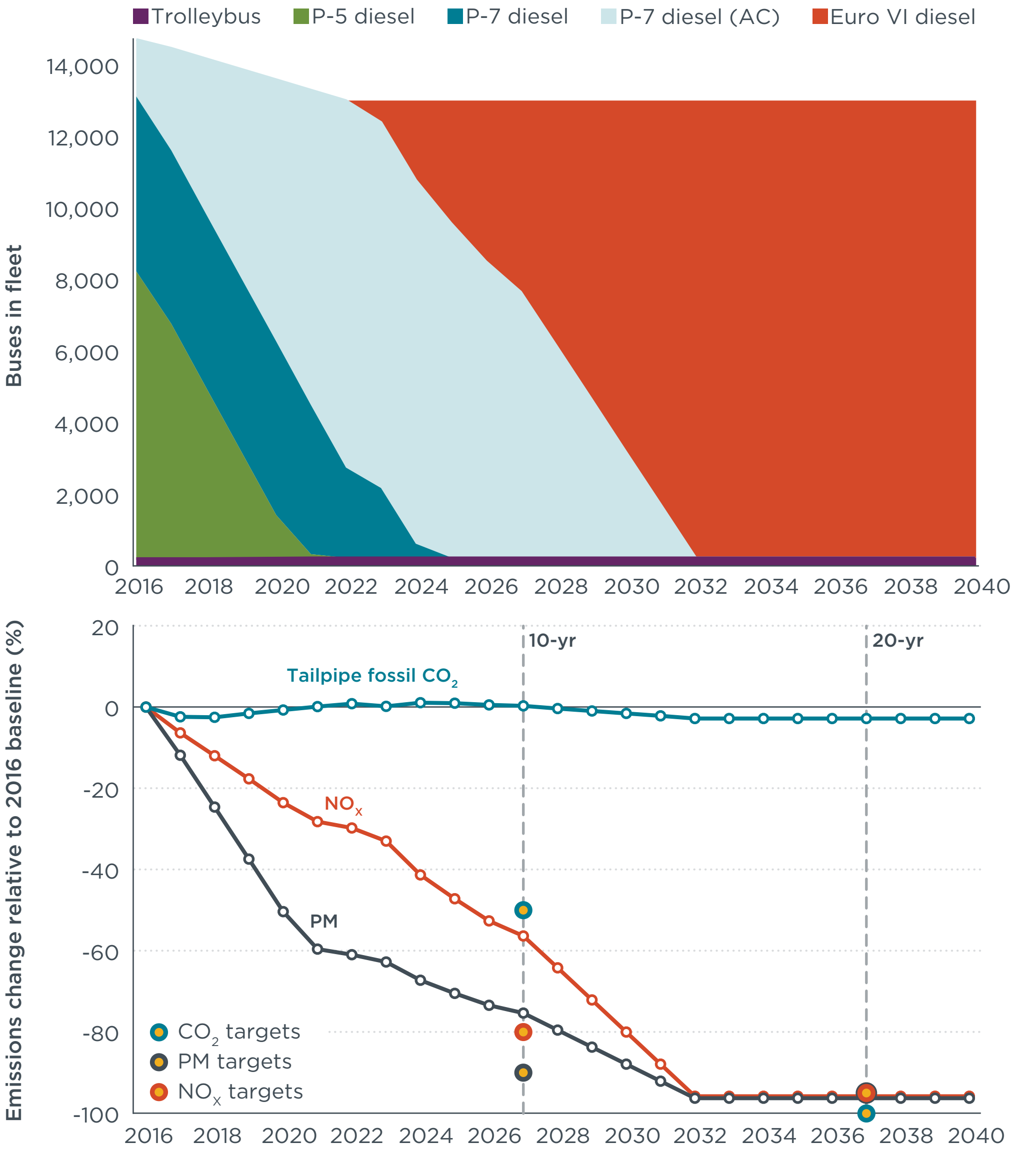

Figure 7. Projected changes in fleet composition (top panel) and emissions (bottom panel) for the BAU procurement scenario.

We find that the BAU procurement pathway does not appreciably change emissions of fossil CO_2 from the São Paulo fleet. Some emissions benefits are realized from decreased systemwide VKT under system reorganization and the use of higher volume percentage biodiesel blends (B15). However, these are offset by the increased use of AC across the fleet. The additional fuel energy required to power AC systems results in a higher energy consumption rate for these buses relative to the non-AC diesel buses that made up the majority of the baseline fleet (see Table 4). An extensive shift to more efficient engine technologies, and more importantly zero fossil CO_2 fuels, is needed in order to meet the 10-year and 20-year fossil CO_2 emissions reduction targets.

PROCUREMENT PATHWAYS TO MEET PM AND NO_x TARGETS

Results from the BAU procurement scenario suggest transit operators in São Paulo will need to move in advance of national standards to procure Euro VI technologies for their bus fleets. The majority of PM and NO_x emissions reductions required by Law 16.802 will need to occur over the first 10 years of the law's implementation. Near-term technology procurement decisions will heavily influence the ability of the fleet to comply with Law 16.802, as buses purchased over the next several years will still be in service when 10-year targets must be met. There is a risk that São Paulo will not be able to meet 10-year PM and NO_x targets if transitions to Euro VI technologies are delayed until the implementation of national P-8 standards in 2023.

To further investigate the impact of the timing of Euro VI transitions on the ability of the São Paulo fleet to meet Law 16.802 PM and NO_x emissions targets, we modeled four separate procurement scenarios in which such a transition occurs, at the earliest, in 2019 or is delayed to future years, through 2022. For each scenario, we assume that all new buses purchased beginning in the transition year, and continuing thereafter, are diesel buses certified to Euro VI-equivalent emissions standards. New bus purchases prior to the transition year are assumed to be P-7 diesels, and the total number of new buses entering the fleet is the same in each scenario. Results are compared against the BAU scenario, in which the transition to Euro VI procurement begins in 2023.

Although we apply PM and NO_x emission factors for diesel buses in order to model Euro VI emissions performance, results are representative of other Euro VI-certified technologies, such as biodiesel or CNG engines. Although some variation in emissions is expected among the different Euro VI technologies, the magnitude of emissions reduction relative to baseline P-5 and P-7 diesel buses is expected to be similar.

Figure 8 shows estimates of calendar year 2027 PM and NO_x emissions from the bus fleet for each Euro VI procurement scenario. These estimates are representative of emissions at the end of the first 10 years of Law 16.802's implementation. Dashed lines show the estimated level of the 10-year emissions reduction target for each pollutant. These results indicate a transition to Euro VI (or cleaner) engine technologies in 2019, at the latest, is required to achieve the level of emissions reductions needed to meet the 10-year PM target. The 10-year NO_x target is met with Euro VI procurement beginning in 2019 or 2020. This means that, assuming normal fleet replacement practices, it is likely that both PM and NO_x targets will not be met if the transition to Euro VI procurement is delayed to 2020 or later. Such a delay would require additional measures, such as early vehicle retirement (i.e., retirement at 9 years or earlier) in order to meet the emissions reduction targets.

Importantly, for the scenarios in which Euro VI transitions occur in 2021, 2022, or 2023, PM and NO_x emissions from just the P-7 diesel buses present in the fleet in 2027 exceed projected Law 16.802 emissions thresholds. This means that even if zero emission electric buses were procured in these scenarios, instead of Euro VI buses, emissions reduction targets still would not be met.

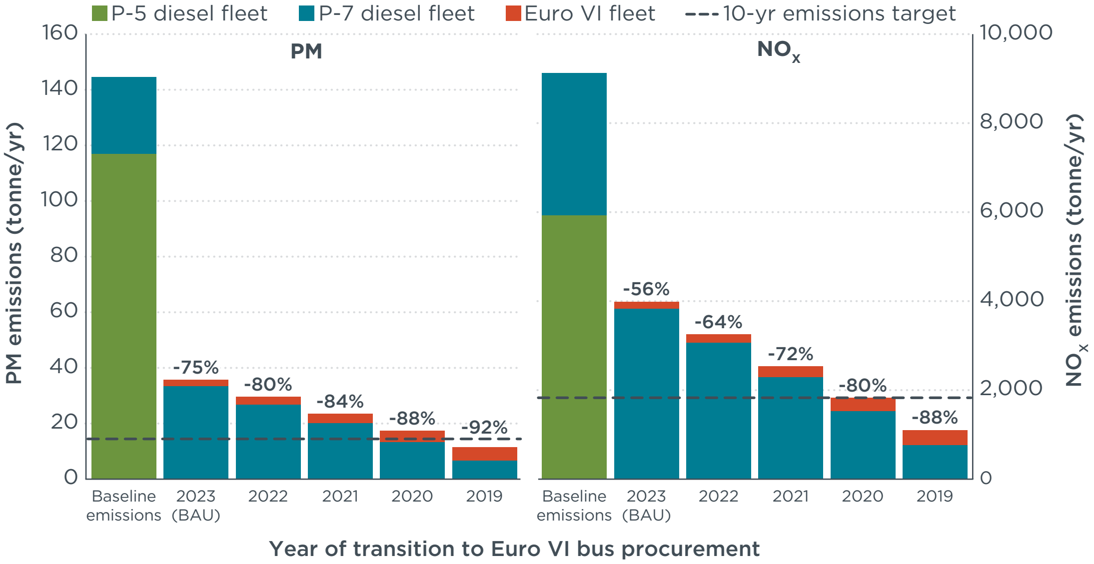

Figure 8. PM and NO_x emissions estimates for the São Paulo transit bus fleet under alternate Euro VI transition procurement scenarios. Baseline emissions estimates correspond to calendar year 2016 emissions. Emissions estimates for calendar year 2027 are shown for five scenarios, assuming 100% of new buses meet Euro VI equivalent emissions performance beginning in 2023, 2022, 2021, 2020, or 2019.

The finding that a transition to Euro VI engine technologies is needed in 2019 in order to meet both PM and NO_x emissions reduction targets is predicated on the use of emission factors reported in the HBEFA database. SPTrans, in the recent concession bidding tender, has recommended the use of alternative emission factors for P-5 and P-7 diesel buses. These emission factors are derived from estimates published in a national motor vehicle emissions inventory prepared by the Brazilian Ministry of the Environment (Ministério de Meio Ambiente [MMA], 2011). Because MMA does not report emission factors for other bus engine technologies, we did not use these emission factor estimates in our base modeling. However, it is worthwhile to consider whether the emission factor data source influences our conclusions regarding the required timeline for Euro VI transitions for the São Paulo bus fleet. To this end, we repeated our emissions analysis of the five Euro VI transition procurement scenarios using emission factor estimates for P-5 and P-7 diesel buses reported in the concession bidding tender, supplemented with HBEFA estimates for Euro VI technologies. Results of this assessment are presented in Table 6, which shows modeled 10-year PM and NO_x emissions reductions for each scenario estimated using the two emission factor data sources.

There is little difference in the emissions reductions estimated using MMA emission factors for P-5 and P-7 diesel buses when compared to the base analysis. In each case, compliance with Law 16.802 is achieved only through a Euro VI transition beginning in 2019. Delays in the procurement of these lower emitting engine technologies will make it difficult to achieve the deep fleetwide emissions reductions required by Law 16.802.

Table 6. PM and NO_x emissions reductions at the end of a 10-year implementation period under five Euro VI procurement scenarios and calculated using two emission factor data sources. Shaded cells indicate scenarios in compliance with 10-year emissions reduction targets.

Year of Euro VI transition	HBEFA emission factors		MMA emission factors[a]	
	PM	NO_x	PM	NO_x
2023	-75%	-56%	-76%	-65%
2022	-80%	-64%	-79%	-71%
2021	-84%	-72%	-83%	-76%
2020	-88%	-80%	-87%	-82%
2019	-92%	-88%	-91%	-88%

[a]Euro VI emission factors are not provided in MMA dataset and are thus assumed to be equivalent to those reported in the HBEFA database.

Figure 9 shows the fleet technological evolution and emissions reduction estimates for the procurement scenario in which all new buses purchased in 2019 and onward are powered with Euro VI diesel engines using commercial diesel fuels. This procurement scenario achieves sufficient reductions in emissions of PM and NO_x pollution to meet intermediate and long-term targets set in Law 16.802. However, as was the case with the BAU scenario, continued use of diesel engines powered by fossil-dominated fuel blends does not improve fossil CO_2 emissions from the fleet. To meet fossil CO_2 emissions reduction targets, the transition to Euro VI engine technologies will need to be accompanied by a shift to non-fossil fuels.

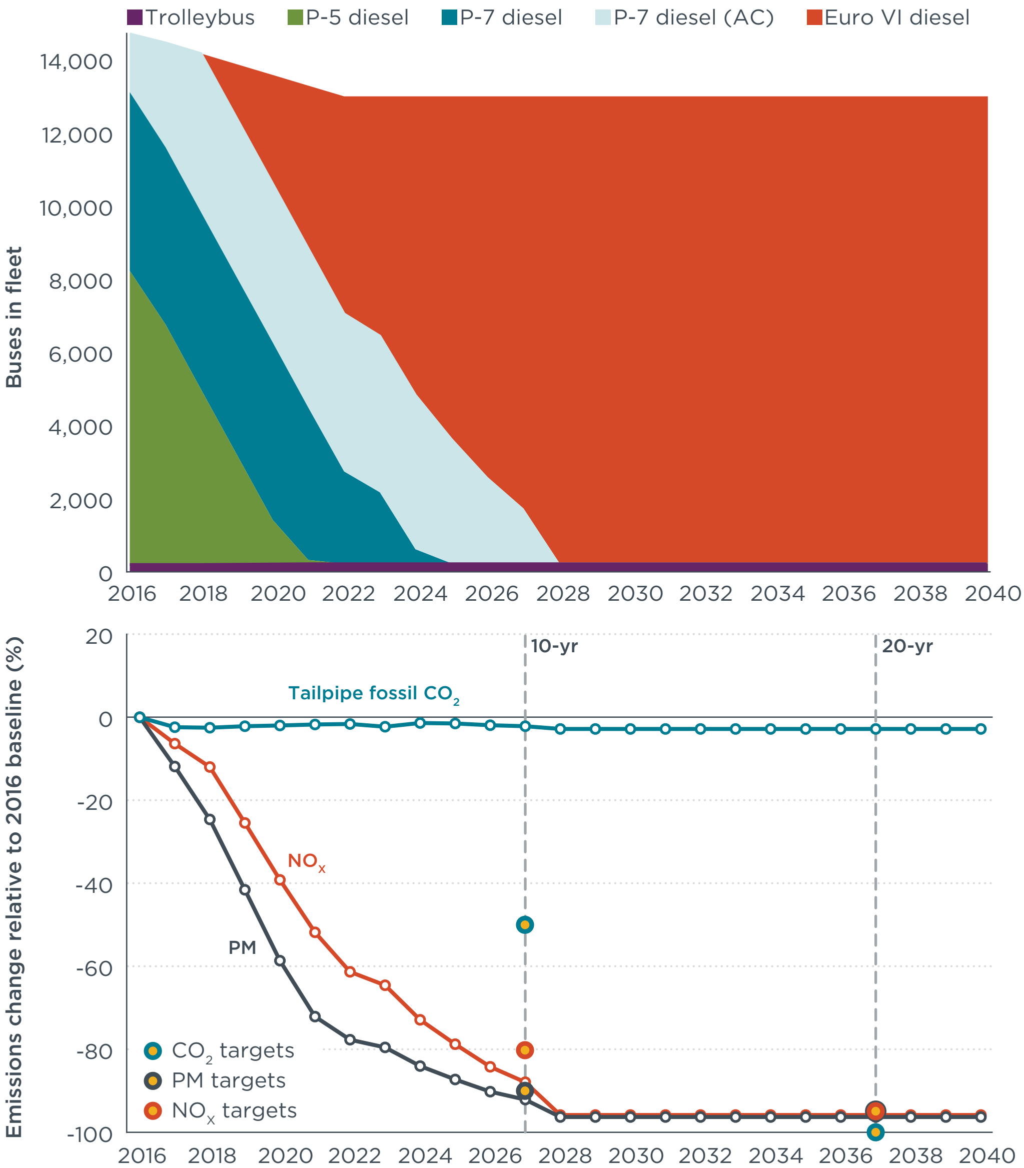

Figure 9. Projected changes in fleet composition (top panel) and emissions (bottom panel) for a procurement scenario in which all new bus purchases beginning in 2019 are assumed to be Euro VI diesels equipped with AC and using commercial diesel fuels.

PROCUREMENT PATHWAYS TO MEET TAILPIPE FOSSIL CO_2 TARGETS

In the previous section, we established that a transition to Euro VI or cleaner engine technologies beginning in 2019 likely is needed to meet PM and NO_x emissions reduction targets set in Law 16.802. However, if these buses are powered with fossil fuels, progress toward meeting fossil CO_2 targets will be limited. In this section we consider the extent to which more efficient engine technologies and non-fossil fuels will be needed for the São Paulo fleet to achieve compliance with intermediate and long-term fossil CO_2 emissions reduction targets.

As a starting point, we consider the degree to which engine technology and fuel combinations considered in our model can improve on the fossil CO_2 emissions performance of bus technologies and fuels used in the baseline fleet. Figure 10 presents our estimates of the tailpipe fossil CO_2 emissions from alternative transit bus engine technologies and fuels relative to emissions from a P-5 or P-7 diesel bus using B7 fuel. Results are presented for a padron type bus and indicate the relative per kilometer change in emissions that can be expected from replacing a baseline diesel bus with an alternative technology option (ANL, 2018).

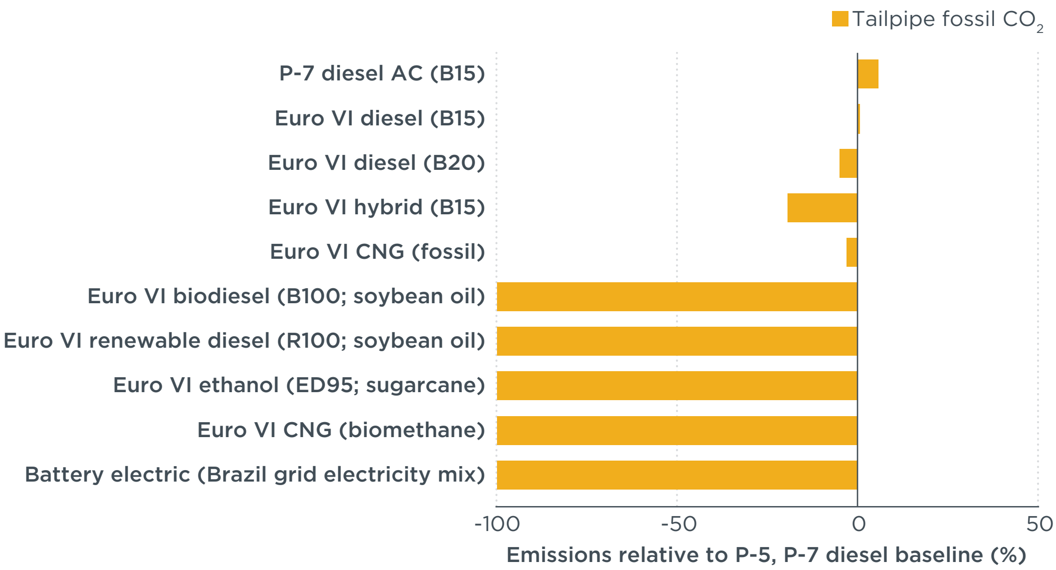

Figure 10. Changes in tailpipe fossil CO_2 (g/km) emissions for alternative urban transit bus engine and fuel combinations relative to P-5 and P-7 diesel buses using B7 fuel. Results are shown for a padron type bus, although these data also are representative of other bus types in the São Paulo fleet. All Euro VI bus technologies and battery electric buses are assumed to be equipped with AC.

Several conclusions can be drawn from this technology comparison:

- We estimate the use of AC in P-7 diesel buses fueled with B15 fuel increases fossil CO_2 emissions by 6% relative to baseline diesel buses when expressed on a g/km basis. Euro VI diesel buses offer efficiency benefits relative to P-5 and P-7 diesels, although replacing a baseline (non-AC) P-5 or P-7 diesel bus with a Euro VI diesel, equipped with AC and using B15 fuel, would not appreciably change per kilometer fossil CO_2 emissions.
- Euro VI diesels using higher percentage biodiesel blends (B20), Euro VI CNG buses using fossil CNG, and Euro VI diesel-electric hybrids all offer relatively low fossil CO_2 emissions reductions relative to baseline P-5 and P-7 diesels, ranging from 3%–20%. These technologies do not deliver the deep tailpipe fossil CO_2 emissions reductions that will be needed to comply with Law 16.802.
- Five engine technology/fuel combinations have zero tailpipe emissions of fossil CO_2: battery electric buses; Euro VI diesel buses using 100% blends of renewable diesel or biodiesel; Euro VI ethanol buses; and Euro VI CNG buses fueled with biomethane.

These findings imply a significant shift to engine technologies and fuels that have zero tailpipe emissions of fossil CO_2 will be required to meet the 10-year target of a 50% reduction in emissions from the transit bus fleet. To meet PM and NO_x targets, all new buses purchased in 2019 and thereafter will likely need to have Euro VI or better emissions performance. A certain percentage of these new buses also will need to be fossil-fuel free. As detailed above, these options include internal combustion engines certified to Euro VI-equivalent emissions standards and fueled with biofuels or zero emission electric buses. Under the fleet turnover model applied in our analysis, all new buses entering the fleet in 2028 and thereafter will need to be fossil-fuel free in order to meet the 20-year target of a 100% reduction in fleetwide emissions of tailpipe fossil CO_2.

In Figure 11, we present one example of a procurement scenario in which Law 16.802 emissions reduction targets are met through near-term procurement of Euro VI diesel and zero fossil fuel engine technologies and a full transition to zero fossil-fuel technology procurement beginning in 2028. In this scenario, we assume that 60% of all new buses entering the fleet between 2019 and 2027 are zero fossil fuel and that 40% are Euro VI diesels using commercial diesel fuels. This procurement model results in a total of 6,770 fossil-fuel free buses operating in the fleet at the beginning of 2028, and a 100% fossil-fuel free fleet by the beginning of 2038. In this case, estimated fleetwide reductions in emissions of both air pollutants, as well as fossil CO_2, are sufficient to achieve compliance with Law 16.802.

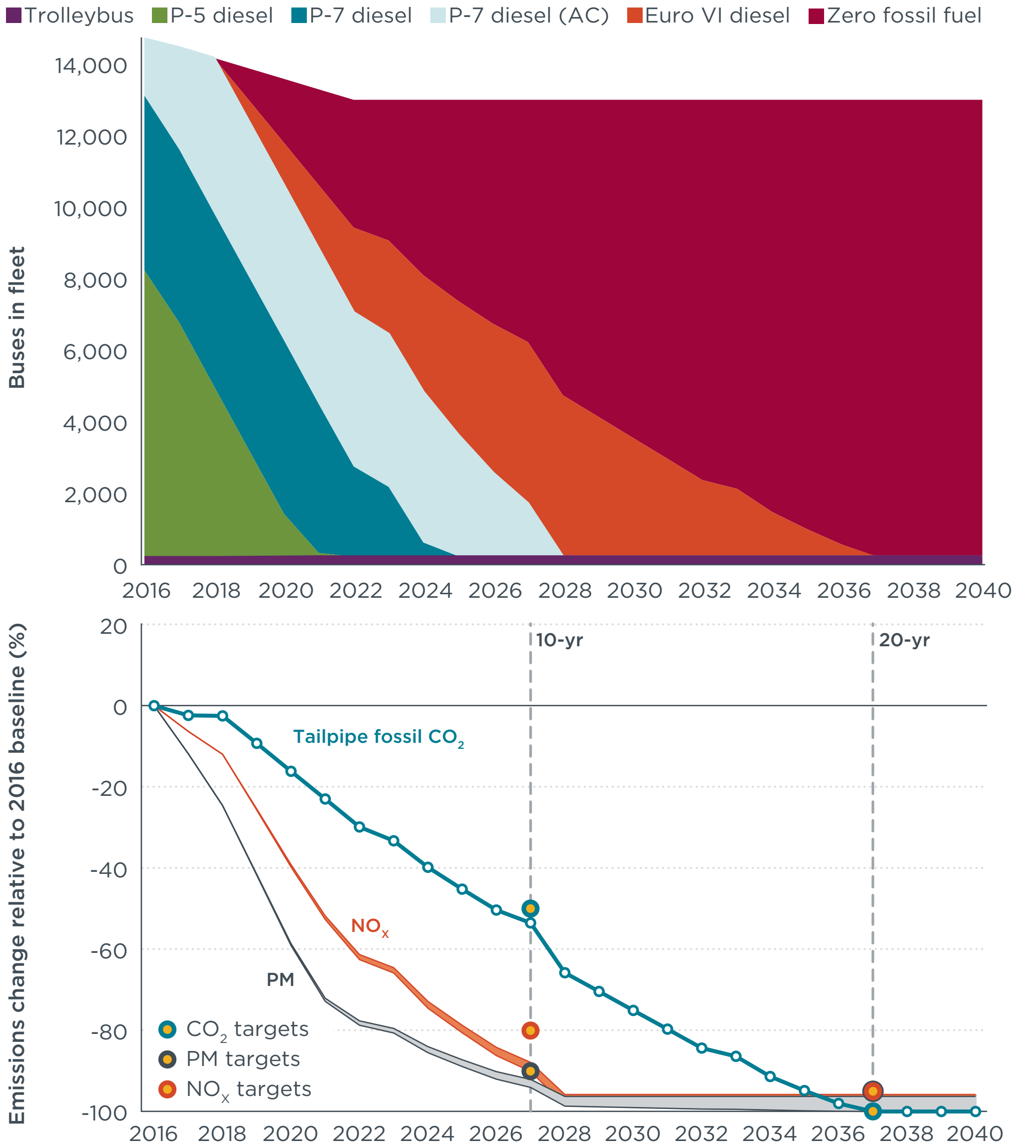

Figure 11. Projected changes in fleet composition (top panel) and emissions (bottom panel) for procurement scenario in which intermediate and final emissions reduction targets are met through near-term procurement of Euro VI diesel and fossil-fuel free bus technologies and long-term transition to 100% non-fossil fuel bus procurement. For PM and NO_x emissions reductions the range in estimates reflects the slightly improved emissions performance of zero emission battery electric bus options as compared with Euro VI-certified internal combustion engines.

If the transition to zero fossil fuel bus procurement is delayed beyond 2019, a greater percentage of new buses entering the fleet each year will need to be fossil-fuel free. For example, if the transition is delayed to 2020, we estimate that approximately 70% of new buses entering the fleet between 2020 and 2027 will need to be fossil-fuel free. Similarly, a delay to 2021 would require about 80% of all new buses to be fossil-fuel free between 2021 and 2027. Finally, our modeling indicates that if the start of zero fossil fuel bus procurement is delayed to 2022, 95% of new bus purchases between 2022 and 2027 will need to be zero fossil fuel in order to meet the 10-year fossil CO_2 target. If this transition is delayed further, targets would be difficult to meet without early retirement and replacement of buses that have not yet reached their 10-year service lives. These findings are summarized in Figure 12, which shows the total number of new buses entering the fleet for alternative zero fossil fuel procurement pathways.

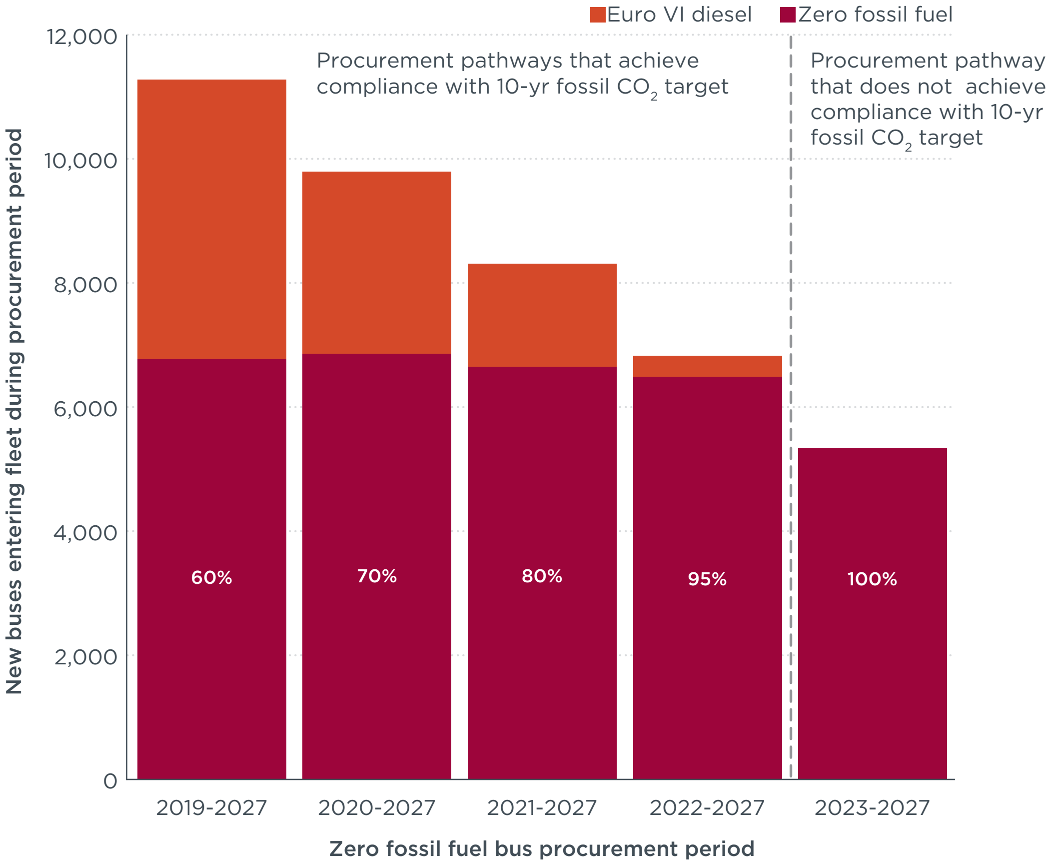

Figure 12. Alternative zero fossil fuel bus procurement pathways. Each bar shows the number of new buses, by technology, entering the fleet for a given procurement period. Labels indicate the percentage of new buses that are assumed to be zero fossil fuel for each procurement period. For each scenario, all new buses entering the fleet prior to the beginning of the respective zero fossil fuel bus procurement period are assumed to be Euro VI diesels.

Note that we present only tailpipe fossil CO_2 results in Figure 11, as these emissions reductions are independent of the zero fossil fuel technology selected (i.e., all zero fossil fuel technologies deliver the same level of emissions reduction relative to the baseline fleet). The emissions reductions shown in the above scenario are achieved regardless of the selection of non-fossil technology—or mixture of technologies—as long as procurement is at the level cited in the previous paragraphs.

CLIMATE IMPACTS OF LAW 16.802 COMPLIANT PROCUREMENT PATHWAYS

Law 16.802 is formulated to reduce the use of fossil fuels in São Paulo's buses, hence the decision to use tailpipe fossil CO_2 emissions as the metric for regulating climate pollutant emissions. As previously mentioned, this approach is not adequate for the evaluation of the climate impacts of non-fossil fuel types used in transit buses, such as biofuels or electricity, where upstream emissions from fuel and feedstock production and transport can be significant. In addition to CO_2, the production of transportation fuels and their feedstocks, as well as their use in vehicles, leads to emissions of other climate pollutants. These include the greenhouse gases CH_4 and N_2O, as well as other pollutants such as BC. Because Law 16.802 regulates only tailpipe fossil CO_2 emissions, there is a risk that implementation of the law could lead to unintended consequences by supporting technology and fuel options that would not result in the desired climate emissions reductions.

In the previous section we presented findings that indicate near-term and extensive transitions to zero fossil fuel transit bus options are likely needed in order to meet Law 16.802 tailpipe fossil CO_2 emissions reduction targets. In considering Law 16.802 compliant procurement pathways, we made no distinction among zero fossil fuel technologies, as each option qualifying as fossil-fuel free delivers the same degree of tailpipe fossil CO_2 emissions reductions relative to the baseline fleet. In this section, we extend our analysis to consider fuel life-cycle CO_2 emissions and non-CO_2 climate pollutants in order to more comprehensively evaluate the climate impacts of zero fossil fuel transit bus options.

Data to estimate fuel life-cycle GHG emissions are sourced from the Argonne National Laboratory AFLEET model (ANL, 2018), which reports life-cycle emission data for a broad selection of transportation fuels derived from the ANL GREET1 2018 model.[4] For crop-based biofuels, indirect land use change (ILUC) emissions can be significant. ILUC emissions occur when increased biofuel demand displaces food crops, leading to conversion of non-agricultural land to cropland elsewhere. ILUC emissions typically are estimated using economic models. Recent ILUC modeling studies conducted for increased biofuel demand in the state of California (CARB, 2016) and the European Union (Valin et al., 2015) suggest ILUC emissions can account for a significant portion of the life-cycle GHG emissions for certain biofuels, including fuels produced from soybean oil. Both studies include ILUC estimates for sugarcane ethanol; however, to our knowledge, similar, comprehensive ILUC modeling has not yet been conducted for other Brazilian biofuels.

There is some uncertainty in applying ILUC factors developed for other regions to Brazil; however, assuming ILUC emissions pose zero risks diminishes the true climate impact of increased biofuel demand. Thus, we have chosen to present results in this section for two cases. Base results are presented for the case where ILUC emissions are not included in the analysis. In addition, a range is shown for the case where ILUC factors for liquid biofuels are included in the emissions analysis. The endpoints of the range represent results calculated using ILUC factors reported by CARB (2016) and Valin et al. (2015).[5]

4 The fuel life-cycle CO_2 emission factor for electricity (144 g/kWh) was calculated using the 2016 Brazilian electricity generation mix: 65.8% hydropower, 9.8% natural gas, 8.8% biomass, 5.8% wind 4.5% coal, 2.7% nuclear, and 2.6% oil (International Energy Agency, 2018).

5 Values reported by Valin et al. (2015) have been adjusted linearly to match the 30-year amortization period applied in the CARB assessment. Here, we make a simplifying assumption that all land use change GHG emissions are CO_2.

Figure 13 builds on Figure 10, which showed the per kilometer tailpipe fossil CO_2 emissions for alternative transit bus technologies and fuels relative to baseline diesel buses, by adding similar estimates for fuel life-cycle CO_2 emissions. Figure 13 shows that relative changes in life-cycle and tailpipe emissions are similar for buses using fossil dominated fuel blends (B15, fossil CNG). Buses powered by biofuels and battery electric buses all have zero tailpipe emissions of fossil CO_2; however, fuel life-cycle emissions can vary considerably, especially when ILUC emissions are included for crop-based biofuels. Under the assumptions used in this analysis, life-cycle CO_2 emissions from battery electric buses and buses using biomethane from landfills are significantly lower than emissions from baseline diesel buses using B7 fuel. Emissions reductions for these non-fossil fuel buses range from 85%–95%.

Life-cycle CO_2 emissions estimates for buses fueled with soybean oil renewable diesel or biodiesel are sensitive to the treatment of ILUC emissions. In the base case, where ILUC emissions are set to zero, both options deliver considerable CO_2 savings relative to the baseline diesel bus. However, when ILUC emissions are considered, emissions benefits are reduced, and, in the case where the higher soybean oil ILUC factor reported in Valin et al. (2015) is applied, life-cycle CO_2 emissions are actually up to 60% greater than those estimated for the baseline diesel bus. These findings suggest there is considerable uncertainty in the CO_2 emissions benefits, if any, that would be gained from transitions to soy-based biofuels.

Results for the ethanol bus are less sensitive to the treatment of ILUC emissions. Both international studies report similar estimates for the sugarcane ethanol ILUC factor, and these estimates are considerably lower than estimates for the soybean oil biodiesel ILUC factor. As a result, the ethanol bus maintains significant life-cycle emissions benefits relative to the baseline diesel bus, even when ILUC emissions are included.

For all biofuel buses, emissions estimates are sensitive to the fuel feedstock assumed for modeling. Biofuels with lower life-cycle CO_2 emission intensities than what is assumed here would offer a greater degree of CO_2 emissions benefits (and vice versa for biofuels with higher CO_2 emission intensities).

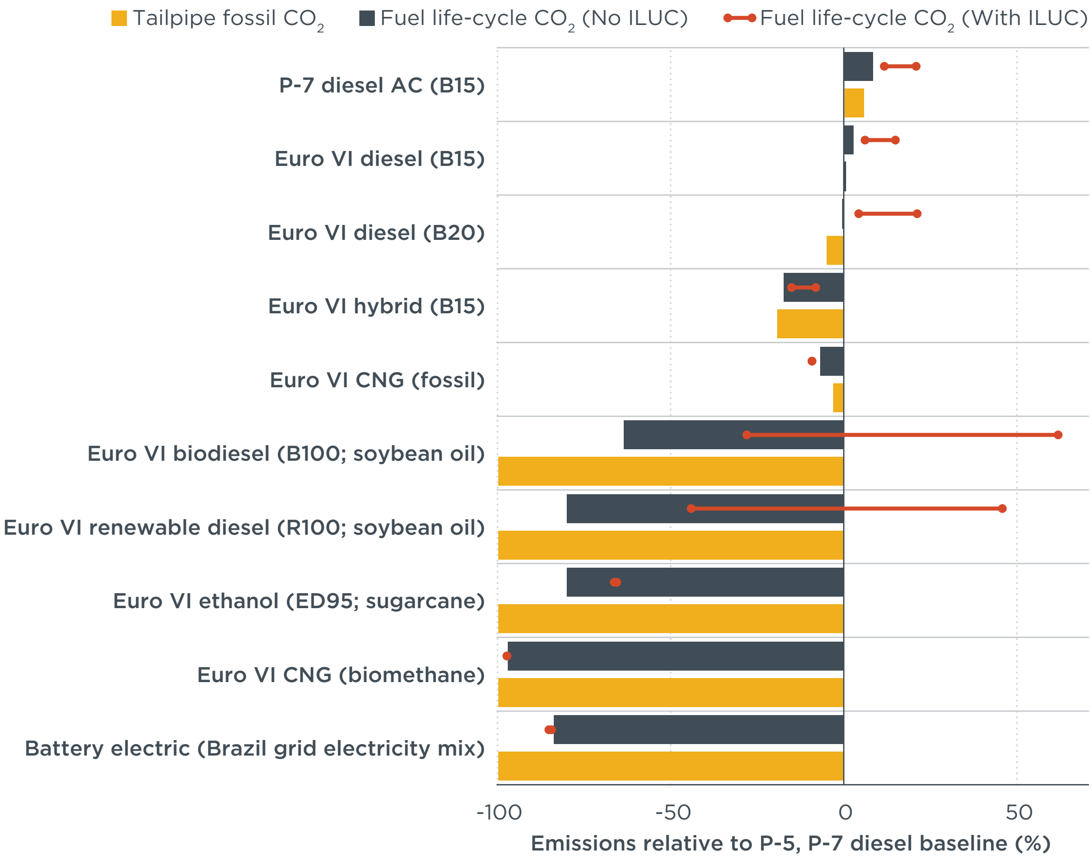

Figure 13. Changes in tailpipe and fuel life-cycle CO_2 (g/km) emissions for alternative urban transit bus engine and fuel combinations relative to P-5 and P-7 diesel buses using B7 fuel. Results are shown for a padron type bus, although these data also are representative of other bus types in the São Paulo fleet. All Euro VI bus technologies and battery electric buses are assumed to be equipped with AC.

Figure 14 presents cumulative climate pollutant emissions from the São Paulo bus fleet for the period 2016–2040. Estimates are shown for four different Law 16.802 compliant procurement scenarios indexed to the BAU scenario. Here, we consider fuel life-cycle emissions of the greenhouse gases CO_2, CH_4, and N_2O, as well as tailpipe emissions of BC.[6] The Law 16.802 compliant procurement scenarios each follow the technology pathway presented in Figure 11 and differ only in the non-fossil technology option selected for procurement. Results for soy-based renewable diesel are similar to those shown for soy biodiesel and are thus excluded from the figure.

These results show that all Law 16.802 compliant procurement scenarios reduce emissions of BC relative to the BAU scenario. In each case, cumulative BC emissions over the 25-year modeling period are reduced by approximately 30%. Older technology diesel buses present in the baseline fleet are responsible for most of the BC emitted during the modeling period.

Emissions of other climate pollutants show greater variability across procurement scenarios. Our estimates indicate a transition to biomethane fueled CNG buses provides the greatest CO_2 emissions benefit of the non-fossil fuel options; however, this scenario also is associated with more than a factor of two increase in CH_4 emissions relative to the BAU scenario. Fuel life-cycle CO_2 emissions reductions in the biodiesel procurement scenario are, as described above, sensitive to the treatment of ILUC emissions. In the

6 CO_2, CH_4, and N_2O emissions are estimated following the approach outlined in Equation 1. BC emissions are calculated by applying technology specific $PM_{2.5}$ speciation profiles developed by the U.S. EPA to modeled PM emissions estimates for each procurement scenario (U.S. EPA, 2018).

biodiesel scenario, cumulative CH_4 emissions were estimated to be approximately 30% lower than in the BAU scenario, while N_2O emissions are 4.3 times as high. Similar increases in N_2O emissions are observed for the ethanol procurement scenario, although transitions to ethanol buses were found to yield greater CO_2 emissions benefits than other liquid biofuel options. Finally, the battery electric bus procurement scenario was the only Law 16.802 compliant scenario in which emissions of all climate pollutants were reduced relative to the BAU scenario. In this case, cumulative emissions of CO_2, CH_4, and N_2O from 2016–2040 are all 30%–50% lower than emissions in the BAU scenario.

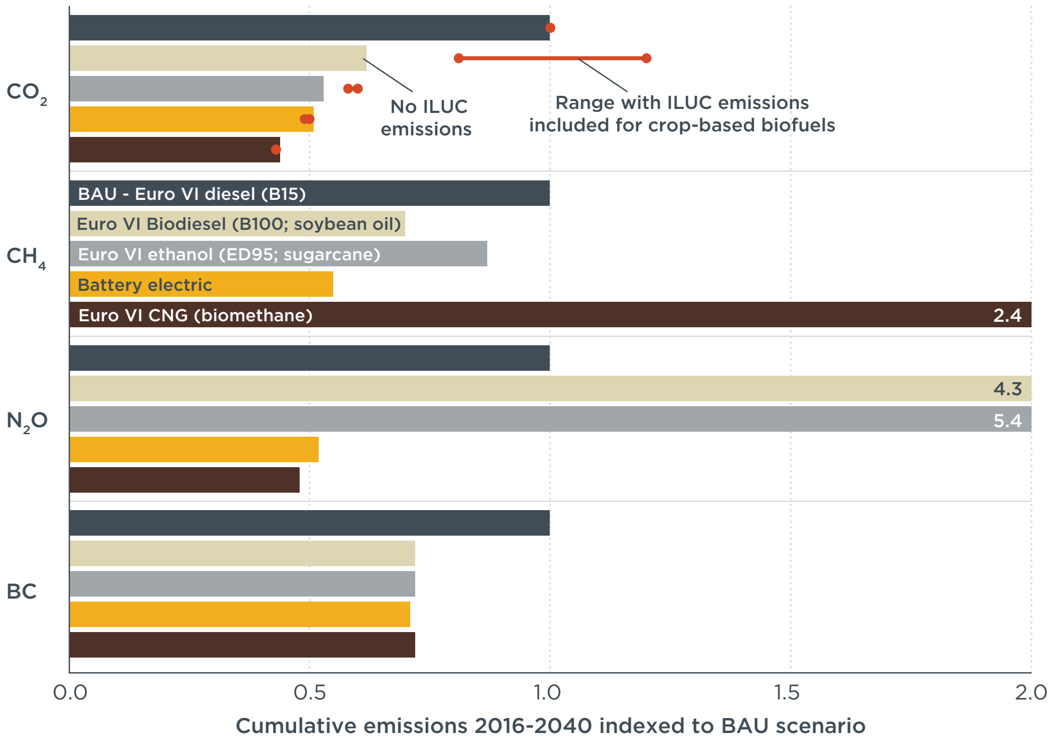

Figure 14. Cumulative climate pollutant emissions, 2016–2040, for Law 16.802 compliant procurement scenarios indexed to BAU scenario. For each compliant scenario, it is assumed that 60% of new buses entering the fleet between 2019 and 2027 and 100% of new buses from 2028 onward are of the indicated zero fossil fuel engine technology and fuel combination.

As a final step in evaluating the climate impacts of alternative Law 16.802 compliant procurement scenarios, annual climate pollutant emissions estimates for each scenario were combined with absolute global temperature change metrics (Shindell et al., 2017) to estimate global average temperature change from 2016 to 2040 associated with emissions from the São Paulo transit bus fleet. Results are shown in Figure 15, broken down by CO_2 and non-CO_2 pollutant contributions. In the base analysis, the temperature change in 2040 associated with 2016–2040 emissions for each Law 16.802 compliant procurement scenario is lower than that of the BAU scenario, with the greatest relative reduction (60%) estimated for the battery electric scenario. When ILUC emissions are included, the biofuel scenario provides no improvement relative to the BAU case. For compliant procurement scenarios, the temperature change associated with non-CO_2 emissions peaks in 2020 and drops substantially in the 2020–2030 time frame, demonstrating the benefits of controlling short-lived climate pollutants, such as BC. The post-2030 increase in the temperature change associated with non-CO_2 pollutants in the biomethane scenario is associated with higher emissions of CH_4 for this technology pathway. Transitions to battery electric buses are projected to nearly eliminate the temperature change associated with non-CO_2 emissions by 2040.

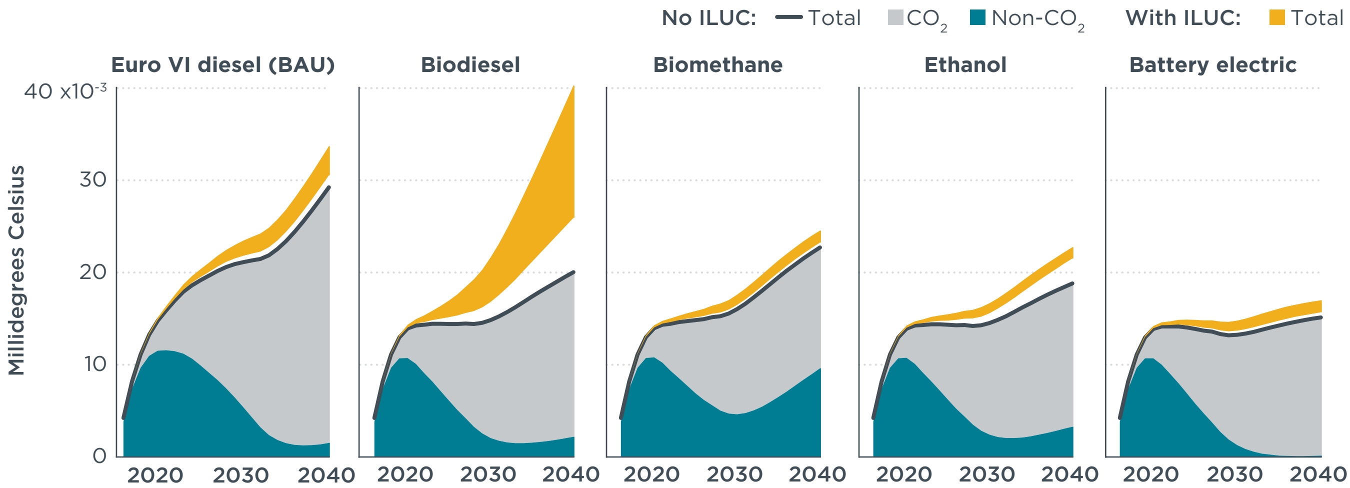

Figure 15. Temperature pathways of 2016–2040 São Paulo transit bus emissions for BAU and Law 16.802 compliant procurement scenarios. Non-CO_2 pollutants include CH_4, N_2O, BC, NO_x, and particulate organic carbon. One millidegree is equal to one thousandth of a degree Celsius.

TOTAL COST OF OWNERSHIP ASSESSMENT

So far, our analysis has considered only the emissions performance of alternative engine technology and fuel options. Long-term procurement scenarios were developed without consideration of either the cost of these technologies and fuels or potential barriers and challenges to their implementation. Cost, especially, is an important component to consider. If soot-free and zero emission technologies and fuels are not financially competitive with baseline P-5 and P-7 diesel buses, it may not be viable for operators to transition to them at the scales needed to comply with Law 16.802 without changes to remuneration methods used in concession contracts. On the other hand, if the costs incurred by operators to own and operate cleaner buses are equal to or less than the costs of technologies and fuels currently in use, the case for technology transitions becomes stronger.

In this section, we explore the costs of alternative transit bus technologies through a total cost of ownership (TCO) assessment of the capital and operating expenses incurred throughout the lifetime of a representative padron type bus operating in the São Paulo fleet. TCO is defined as the sum of the costs to acquire, operate, and maintain the vehicle and its associated fueling infrastructure over a specified ownership period. Table 7 summarizes the components of TCO that are considered for this analysis. Because the objective is to evaluate those costs that depend on the selection of bus technology, some cost components—such as the costs of administration, staffing, license and registration, and insurance—are not evaluated. Including those costs would not be expected to change the outcome of this analysis.

Table 7. Components of total cost of ownership (Miller, Minjares, Dallmann, & Jin, 2017).

Category	Component	Definition
Bus and infrastructure purchase	Down payment	Initial cash outlay for bus or infrastructure purchase. The remainder is assumed to be covered by a loan.
	Loan payments	Principal and interest payments over a specified loan period.
	Resale value	If the duration of the planned operation is shorter than the bus service life, this positive cash flow considers the resale value of the depreciated vehicle.
Operations and maintenance	Fueling	Annual cost to fuel the vehicle, determined by fuel efficiency, distance traveled, and fuel price.
	Other operational	Includes the cost of ARLA 32 for diesel and diesel-electric hybrid buses with selective catalytic reduction systems.
	Bus maintenance	Cost of regular bus maintenance; includes tires, parts, lubricants, etc. Does not include personnel costs.
	Infrastructure maintenance	Where not already included in the retail fuel price, includes the cost of infrastructure maintenance and operations.
	Bus overhaul	For bus purchases that do not include a warranty for the service life of the vehicle, a major mid-life overhaul would include the cost of battery replacement for electric buses and engine overhaul for other buses. For this analysis, battery warranties are assumed to cover the bus operating life.

The total cost of ownership is estimated for seven separate transit bus engine technology and fuel options. We focus on padron type buses here, as they are the most common bus type used in the São Paulo fleet. However, relative comparisons among technologies are generally representative for other bus types as well. To calculate the TCO for each bus technology, we follow methodologies developed by Miller, Minjares, Dallmann, and Jin (2017) for an analysis of the cost of soot-free transit bus fleets in 20 global megacities, further refined for the specific case of São Paulo by Slowik, Araujo, Dallmann, and Façanha (2018). Key cost modeling inputs for baseline P-7 diesel buses are taken directly from annual reports published by SPTrans, which contain detailed financial information on the costs of operating the public transportation system in São Paulo (SPTrans, 2017). Similar input data for other bus technologies were derived from a literature review. A full listing of data sources and assumptions used in our bus total cost of ownership assessment is included in the appendix. A more extensive treatment of the TCO approach as applied to São Paulo buses can be found in Slowik, Araujo, Dallmann, and Façanha (2018). Table 8 summarizes estimated values for key cost components used in the analysis. Additional assumptions include:

» A bus service life of 10 years for all bus technologies.

» Annual activity of 71,000 kilometers per year (see Figure 6).

» Costs in future years are discounted at a rate of 7% (Akbar, Minjares, & Wagner, 2014).

» Financing terms for bus and infrastructure acquisition capital expenses consist of a 50% down payment with the remainder of expenses covered by a loan with a 5-year term and real interest rate of 7.6%.

» Depreciation of 8% annually for all bus types. The value of the depreciated vehicle at the end of its ownership term is treated as a positive cash flow.

Table 8. Estimated values for key cost components used in padron bus total cost of ownership analysis. Underlying data and assumptions used to derive these estimates are included in the appendix.

Bus technology		P-7 diesel	Euro VI diesel	Euro VI hybrid	Euro VI CNG	Euro VI biodiesel (B100)	Euro VI ethanol	Battery electric bus[a]
Purchase price	R$/bus	546,073	556,995	819,110	611,602	556,995	737,199	955,628
Infrastructure costs	R$/bus	0	0	0	110,000	0	0	161,000
Fueling costs	R$/km	1.85	1.75	1.40	1.18	1.93	2.18	0.83
Maintenance costs	R$/km	0.77	0.77	0.66	1.08	0.88	1.08	0.58

[a]The battery electric bus is assumed to be charged overnight at a bus depot. For information on cost estimates for other battery electric bus types/ charging strategies (e.g., on-route charging) the reader is referred to Slowik, Araujo, Dallmann, and Façanha (2018).

Figure 16 presents total cost of ownership estimates for a conventional P-7 diesel bus equipped with AC, as well as six alternative bus technologies considered in this assessment—Euro VI diesel, Euro VI diesel-electric hybrid, Euro VI CNG, Euro VI biodiesel, Euro VI ethanol, and battery electric buses. Cost estimates represent the net present value of all modeled costs incurred throughout the assumed 10-year ownership period. Total cost of ownership estimates are broken down by the four primary cost categories: net bus acquisition costs, net infrastructure acquisition costs, operating costs, and maintenance costs.

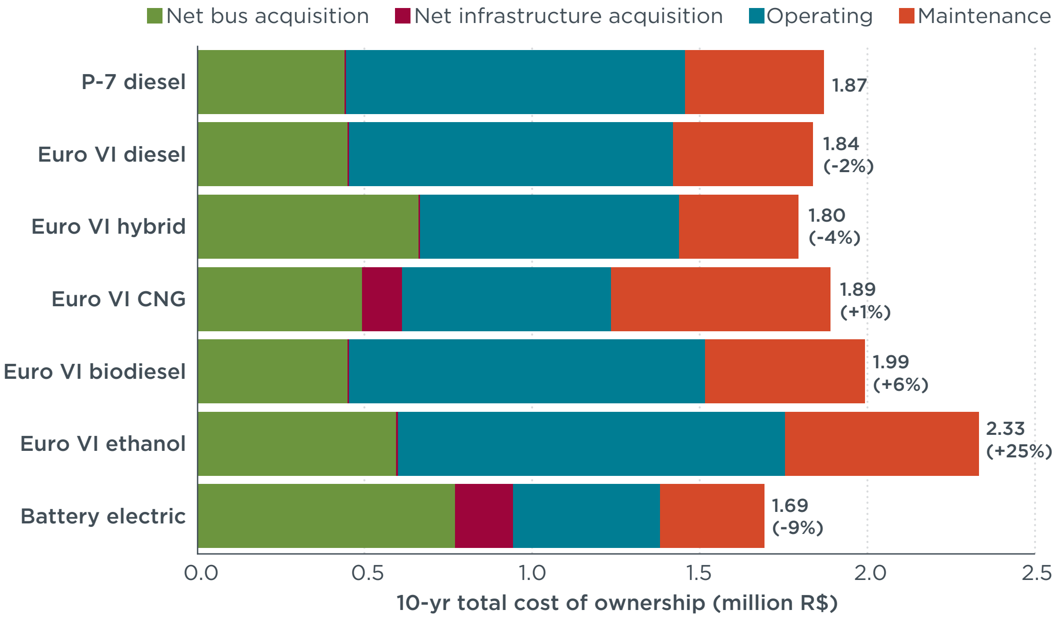

Figure 16. Total cost of ownership estimates over 10 years for conventional and alternative technology Padron LE type buses in São Paulo. Data labels indicate contributions of individual cost components to TCO estimates. Percentages show percent change in TCO relative to the baseline P-7 diesel technology. Acquisition costs include down payment and loan payments minus any bus resale value at the end of the ownership term.

In this assessment, the total cost of ownership of a conventional P-7 diesel padron type bus is estimated to be R$1.87 million. Operating costs account for more than half the total lifetime costs for the diesel bus, with the remainder approximately evenly split between bus acquisition and regular maintenance costs. The cost breakdown for the Euro VI diesel bus is similar, although in this case, a slightly higher purchase price relative to the P-7 diesel bus is offset by lower lifetime operating expenses, resulting in a slightly lower total cost of ownership (R$1.84 million). This dynamic also is reflected in the TCO breakdown for the diesel-electric hybrid bus. The purchase price for this technology is estimated to be 50% higher than the price of the baseline P-7 diesel bus. However, the improved energy efficiency and lower maintenance costs of the hybrid bus lead to operational cost savings throughout the lifetime of the bus and a TCO approximately 4% less than the P-7 diesel bus.

The total cost of ownership of the two biofuel bus types considered here—biodiesel and ethanol—is estimated to be greater than the TCO of the baseline P-7 diesel bus. In both cases, per kilometer fueling and maintenance costs are higher than those for diesel buses using commercial B10 diesel fuels, leading to elevated lifetime operating costs. The ethanol bus was estimated to have the highest TCO of any of the technology options considered here, 25% greater than that of the P-7 diesel bus.

These results show the battery electric bus to be competitive with the baseline diesel bus on a TCO basis, with life-cycle costs estimated to be 9% lower than for the P-7 diesel bus. In fact, the battery electric bus was found to have the lowest TCO of any of the bus technologies considered in this analysis. Despite the relatively higher vehicle and infrastructure acquisition costs for this technology, reduced operating and maintenance costs lead to overall savings over the operating lifetime of the bus as compared with the conventional diesel bus. The primary cost savings for the battery electric bus come from reductions in fueling costs, which are about half of those incurred for the diesel bus.

With the exception of the ethanol bus, the total lifetime costs of owning and operating alternative technology bus options were found to be within 10% of the lifetime costs of the baseline P-7 diesel bus. Euro VI diesel, diesel-electric hybrid, and battery electric buses all are estimated to offer cost savings relative to P-7 diesel buses when all costs incurred over the service life are considered. Especially in the case of battery electric buses, traditional procurement practices that favor bus technology options with the lowest purchase price may bias against technologies that have a higher purchase price but lead to substantially reduced operating costs, and, potentially, lower net costs over the lifetime of the bus. Changes to existing procurement practices and implementation of innovative financing models that consider lifetime operational savings of alternative bus technologies may be needed to accelerate the uptake of these technology options (Miller, Minjares, Dallmann, & Jin, 2017).

IMPLICATIONS AND OUTLOOK FOR FUTURE RESEARCH

With the passage of Law 16.802, São Paulo has taken an important step toward improving the environmental performance of the city's transit bus fleet. The law sets ambitious air and climate pollutant emissions reduction targets for the fleet that will require near-term action by a range of stakeholders, including SPTrans and transit operators, in order to facilitate the introduction of cleaner engine technologies and non-fossil fuels to the fleet.

Our findings indicate transit operators will need to move quickly to incorporate Euro VI and fossil-fuel free technologies into their fleets beginning in 2019. With regard to implementation of the modeled procurement strategies, the most straightforward near-term step would be for transit operators to prioritize procurement of Euro VI technologies. Any new P-7 diesel buses entering the fleet will make it more difficult to comply with 10-year PM and NO_x targets.

Of the Euro VI technologies considered in this analysis, São Paulo is best positioned to rapidly scale up the procurement of Euro VI diesel buses. The key barrier to Euro VI diesel buses, availability of low-sulfur diesel fuel, is not an issue for the city, where S10 diesel already is readily available. Similarly, ARLA 32, a required additive for the proper operation of selective catalytic reduction systems found in Euro VI diesel engines, already is being used by P-7 diesel buses in the fleet. Finally, four of the world's largest bus and engine manufacturers have committed to making soot-free engine technologies, such as Euro VI diesel or cleaner engines, available in São Paulo beginning in 2018 ("Global industry partnership," 2017). In fact, manufacturers in Brazil already are producing Euro VI diesel buses for export to Santiago, Chile, where recently implemented standards require all new buses to meet Euro VI emissions performance (United Nations Environment Programme, 2017). Relative to other engine technologies, little change in day-to-day operations would be needed to incorporate Euro VI diesel buses into fleets.

Transit operators in São Paulo will likely need to move to Euro VI procurement ahead of the national implementation of PROCONVE P-8 emissions standards for HDVs. If this proves to be the case, a process by which these engines can be certified to P-8 level performance must be established. Work with state and national technical agencies should begin now in order to develop these processes.

Near-term Euro VI diesel procurement should put transit operators in São Paulo on the right track for meeting PM and NO_x emissions reduction targets. However, decisions regarding zero fossil fuel procurement are more challenging, as these technologies have not yet been used widely in São Paulo and may require systematic changes in the ways in which buses are purchased and operated.

Of the zero fossil fuel technologies considered here, our calculations indicate battery electric buses offer the greatest climate benefits. Our estimates indicate the lifetime costs of owning and operating a battery electric bus in São Paulo are competitive with those of a diesel bus. However, the purchase price of battery electric buses remains higher than for other bus technologies. Innovative financing and business models may be needed in order to better account for the significant operational savings offered by battery electric buses when procurement decisions are being made.

Other zero emission electric drive bus technologies, such as trolleybuses and fuel cell electric buses, were not directly considered in our analysis. Electric trolleybuses can deliver emissions savings of a similar level to what has been presented for battery electric buses. An expansion of the existing trolleybus network also could contribute to the decarbonization of the São Paulo fleet. Fuel cell electric buses have not yet reached the same level of technological maturity and commercialization as other transit bus options. However, over the long-term, as the technology is further developed, it is expected to provide a viable zero emissions electric option for transit operators in São Paulo.

From an operational perspective, transitions to zero emission electric bus fleets will require careful planning in order to ensure the technology is deployed in a manner that can match the performance of the existing diesel bus fleet. For example, battery electric buses introduce novel challenges for transit operators relating to charging strategies that are not encountered with diesel bus fleets. One of the most important near-term steps to promote zero emission electric bus transitions is to develop the institutional knowledge that will be needed for the wide deployment of these technologies in the São Paulo fleet. To a certain extent, this already has begun. Several battery electric bus pilot and demonstration projects have been carried out in the city since 2015. Results from these evaluations can support the identification of routes that are conducive to electrification with current commercial battery electric bus options. Following the electrification of individual routes, the next step would be to scale up to the depot level, and in the long term, even greater percentages of the fleet.

Our analysis suggests approximately 6,700 fossil-fuel free buses will need to be operating in the São Paulo fleet at the beginning of 2028 in order to meet the Law 16.802 10-year fossil CO_2 emissions reduction target. Battery electric buses offer the greatest emissions benefits of the fossil-fuel free technologies considered here, but it is uncertain whether they can be procured and introduced to the fleet at the level needed to meet this target. In this case, biofuel bus procurement may be needed to support progress toward meeting the 10-year fossil CO_2 target.

As detailed above, the climate impacts of biofuel options are highly variable and dependent on feedstock and fuel production pathways. Our estimates indicate increased use of soybean-based biodiesel should be avoided because of the high risk of land use change emissions associated with this feedstock. If operators choose to pursue biodiesel or renewable diesel as part of their procurement strategies to comply with Law 16.802, lower carbon intensity fuels, such as those produced from animal fats or used cooking oils, should be prioritized. Our results indicate that buses fueled with ethanol and biomethane fuels offer a fuel-life-cycle emissions benefit relative to buses using petroleum diesel or fossil CNG, and thus, from an emissions standpoint, would serve to support both the letter and spirit of Law 16.802. We estimate biodiesel and ethanol buses to have the greatest lifetime ownership costs of the technologies considered in our TCO assessment. Fueling and maintenance costs for these technologies would need to be reduced to make them financially competitive with other technology options.

The city of São Paulo has taken an important step toward cleaner transit bus fleets with the passage of Law 16.802. Achieving the ambitious emissions reduction targets set in the Law will require a high level of commitment from and coordination among the city administration, SPTrans, transit operators, and other stakeholders. The passage of Law 16.802 is a clear signal of this commitment. However, this will need to be followed by concrete actions in order to deliver the required reductions in emissions from the city's transit bus fleet. This analysis has laid out the level and pace of technology transition that will likely be needed to achieve these emissions reductions. Areas for future research and analysis include the evaluation of specific long-term procurement schedules submitted by transit operators during the concession bidding process, development of alternative finance and business models to support soot-free and low-carbon bus procurement, and more detailed assessment of implementation strategies for advanced bus technologies and fuels.

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APPENDIX

Table A1. Comparison of PM and NO_x emission factors for P-5 (Euro III), P-7 (Euro V), and Euro VI diesel buses from two data sources.

Source	Source vehicle type	NO_x emission factor (g/km)			PM emission factor (g/km)			Bus types for modeling
		P-5 (Euro III) diesel	P-7 (Euro V) diesel	Euro VI diesel	P-5 (Euro III) diesel	P-7 (Euro V) diesel	Euro VI diesel	
MMA, 2011 (via concession bidding tender)[a]	Miniônibus	5.1	2.1	No data provided for Euro VI diesel buses	0.085	0.021	No data provided for Euro VI diesel buses	Mini
	Midiônibus	6.1	2.5		0.103	0.025		Midi
	Basico	7.1	2.9		0.119	0.029		Basico
	Padron	9.9	4.0		0.165	0.040		Padron, Padron (15m)
	Articulado (18m)	12.7	5.1		0.213	0.052		Articulado,
	Articulado (23m)	13.7	5.5		0.229	0.056		Articulado (23m)
	Biarticulado	16.2	6.5		0.271	0.066		Biarticulado
HBEFA, 2017	Midi	8.6	6.3	0.42	0.165	0.049	0.005	Mini, Midi
	Standard	11.2	7.8	0.47	0.226	0.065	0.006	Basico, Padron, Padron (15m)
	Articulated	14.1	7.1	0.38	0.274	0.077	0.007	Articulado, Articulado (23m), Biarticulado

[a]PM and NO_x emission factors are reported in g/kg fuel units in the concession bidding tender. These values were converted to grams per kilometer using the estimated fuel consumption for each bus type reported by SPTrans.

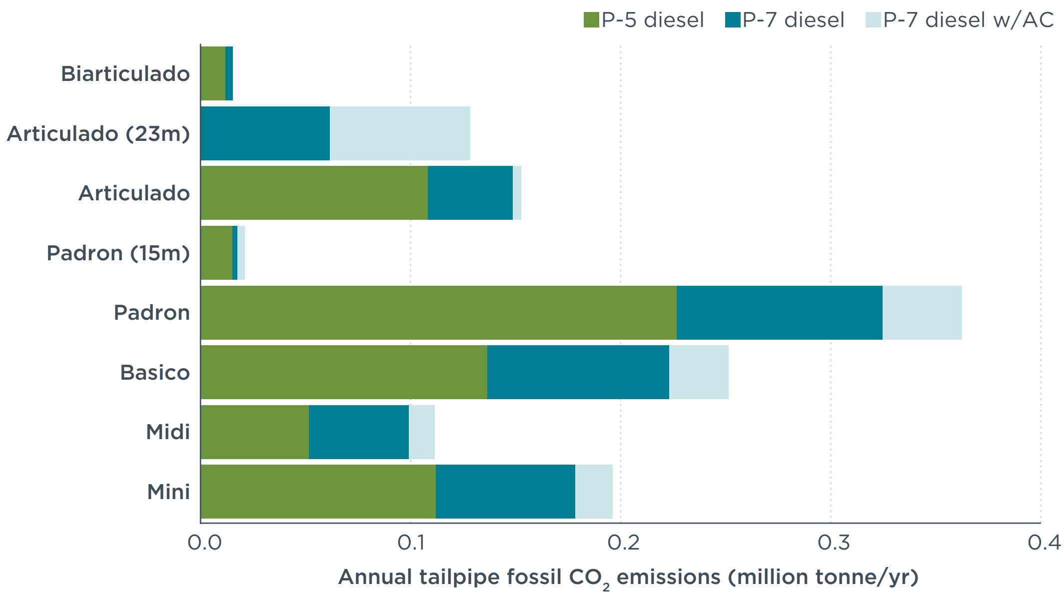

Figure A1. Tailpipe fossil CO_2 emissions for the baseline São Paulo municipal transit bus fleet by bus type and engine technology.

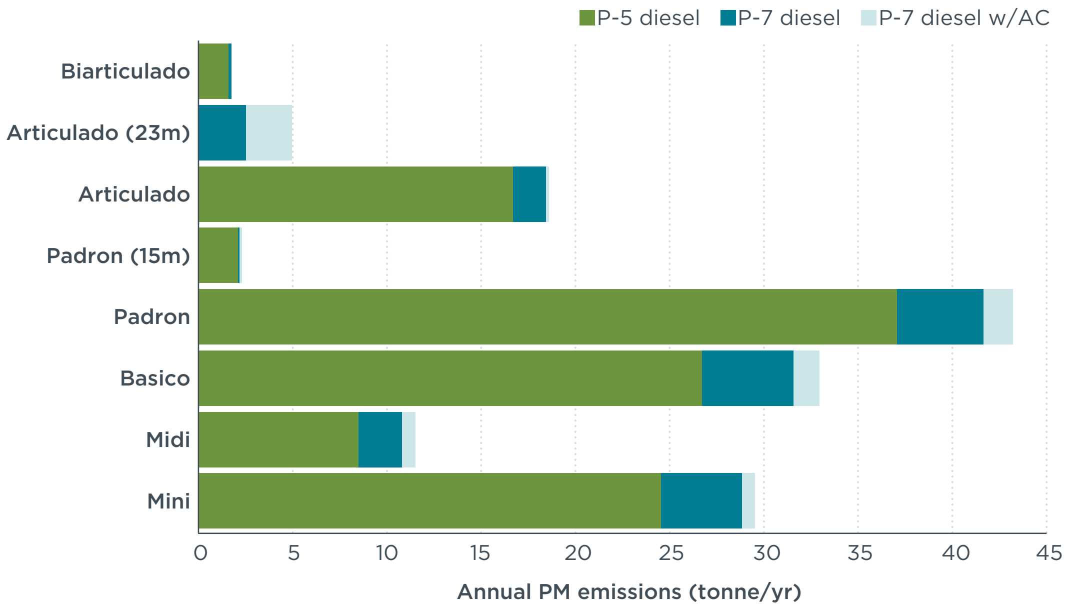

Figure A2. PM emissions from the baseline São Paulo municipal transit bus fleet by bus type and engine technology.

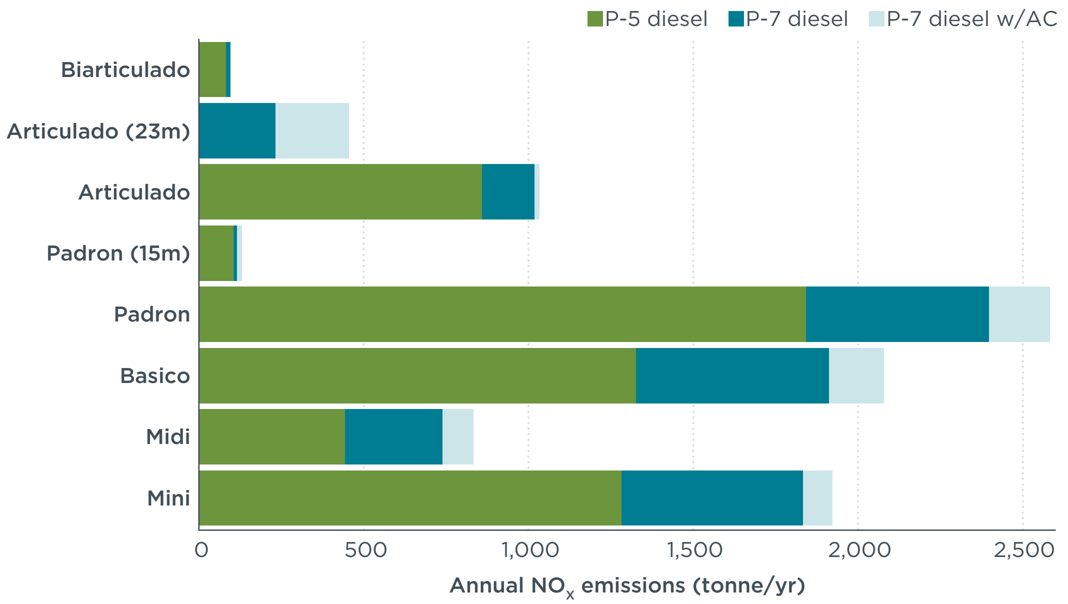

Figure A3. NO_x emissions from the baseline São Paulo municipal transit bus fleet by bus type and engine technology.

DATA SOURCES AND ASSUMPTIONS FOR TOTAL COST OF OWNERSHIP ANALYSIS

Table A2. Bus purchase price

Bus technology	Assumption	Value used for TCO modeling (R$)	Source
P-7 diesel	Reported directly by SPTrans	546,073	SPTrans, 2017[a]
Euro VI diesel	+2% relative to P-7 diesel	556,995	Posada, Chambliss, & Blumberg, 2016[b]
Euro VI hybrid	+50% relative to P-7 diesel	819,110	CARB, 2017[c]
Euro VI CNG	+12% relative to P-7 diesel	611,602	CARB, 2017
Euro VI biodiesel (B100)	Equivalent to Euro VI diesel	556,995	Posada, Chambliss, & Blumberg, 2016
Euro VI ethanol	+35% relative to P-7 diesel	737,199	SPTrans, 2017
Battery electric bus	+75% relative to P-7 diesel	955,628	CARB, 2017

[a]SPTrans. (2017). *Planilha Tarifárias do Sistema de Transporte Coletivo Urbano – 2017*. Retrieved from http://www.prefeitura.sp.gov.br/cidade/secretarias/transportes/institucional/sptrans/acesso_a_informacao/index.php?p=227887
[b]Posada, F., Chambliss, S., & Blumberg, K. (2016). *Costs of emission reduction technologies for heavy-duty diesel vehicles*. International Council on Clean Transportation. Retrieved from https://www.theicct.org/publications/costs-emission-reduction-technologies-heavy-duty-diesel-vehicles
[c]California Air Resources Board (CARB). (2017). *Fifth Innovative Clean Transit Workgroup meeting: Cost data and sources (6-26-2017)*. Retrieved from https://arb.ca.gov/msprog/ict/meeting.htm

Table A3. Infrastructure costs

Bus technology	Assumption	Source
Euro VI CNG	Per bus cost calculated assuming CNG fueling facility servicing 175 buses costs 6,000,000 USD	CARB, 2017[a]
Battery electric bus	Equipment and installation costs for a 50 kW depot charger servicing one bus are 50,000 USD.	CARB, 2017

[a]California Air Resources Board (CARB). (2017). *Fifth Innovative Clean Transit Workgroup meeting: Cost data and sources (6-26-2017)*. Retrieved from https://arb.ca.gov/msprog/ict/meeting.htm

Table A4. Fueling costs

Bus technology	Energy consumption (kWh/km)	Fuel price (R$/kWh)	Fueling costs (R$/km)
P-7 diesel	6.3	0.29[a]	1.85
Euro VI diesel	6.0	0.29[a]	1.75
Euro VI hybrid	4.8	0.29[a]	1.40
Euro VI CNG	6.6	0.18[b]	1.18
Euro VI biodiesel	6.0	0.32[c]	1.93
Euro VI ethanol	6.0	0.36[b]	2.18
Battery electric bus	1.8	0.45[a]	0.83

[a] SPTrans. (2017). *Planilha Tarifárias do Sistema de Transporte Coletivo Urbano – 2017*. Retrieved from http://www.prefeitura.sp.gov.br/cidade/secretarias/transportes/institucional/sptrans/acesso_a_informacao/index.php?p=227887
[b] AGÊNCIA NACIONAL DO PETRÓLEO, GÁS NATURAL E BIOCOMBUSTÍVEIS (ANP). (2017). Sistema de levantamento de preços. Retrieved from www.anp.gov.br/preco
[c] Prefeitura Municipal de Curitiba. (2017). *URBS Preços dos insumos e salários*. Retrieved from https://www.urbs.curitiba.pr.gov.br/pdf/transporte/rit/Precos_dos_Insumos_e_Salarios.pdf

Table A5. Maintenance costs

Bus technology	Assumption	Value used for TCO modeling (R$/km)	Source
P-7 diesel	Reported directly by SPTrans	0.77	SPTrans, 2017[a]
Euro VI diesel	Equivalent to P-7 diesel	0.77	Miller, 2017[b]
Euro VI hybrid	-14% relative to P-8 diesel	0.66	CARB, 2017[c]
Euro VI CNG	+40% relative to P-8 diesel	1.08	Personal communication Iveco
Euro VI biodiesel (B100)	+15% relative to P-8 diesel	0.88	Personal communication Scania
Euro VI ethanol	+40% relative to P-8 diesel	1.08	Personal communication Scania
Battery electric bus	-24% relative to P-8 diesel	0.58	CARB, 2017

[a]SPTrans. (2017). *Planilha Tarifárias do Sistema de Transporte Coletivo Urbano – 2017*. Retrieved from http://www.prefeitura.sp.gov.br/cidade/secretarias/transportes/institucional/sptrans/acesso_a_informacao/index.php?p=227887
[b]Miller, J. (2017). *Effect of P-8 standards on bus system costs in Brazil*. International Council on Clean Transportation. Retrieved from www.theicct.org/sites/default/files/publications/Brazil-bus-fare-briefing_ICCT_14042017_vF.pdf
[c]California Air Resources Board (CARB). (2017). *Fifth Innovative Clean Transit Workgroup meeting: Cost data and sources (6-26-2017)*. Retrieved from https://arb.ca.gov/msprog/ict/meeting.htm