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# MEASURING THE INVISIBLE

## QUANTIFYING EMISSIONS REDUCTIONS FROM TRANSPORT SOLUTIONS

### Porto Alegre Case Study

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# EXECUTIVE SUMMARY

The metropolitan region of Porto Alegre in the state of Rio Grande do Sul, Brazil, has seen a steep rise in motorization levels due to rapid economic growth and an increased demand for transportation. The municipality of Porto Alegre understands that the city's transportation sector contributes to local and global emissions and is interested in evaluating the impact of the following transportation projects:

- (1) a fare integration scheme, to be implemented across all municipal bus lines in order to increase public bus ridership, and
- (2) a Bus Rapid Transit (BRT) system designed to reduce the number of buses and bus terminals downtown and revitalize the city center.

This study provides a first level estimation of the impact of the two projects on CO<sub>2</sub>, CO, NO<sub>x</sub>, PM<sub>2.5</sub> exhaust emissions levels from the metropolitan, municipal and BRT bus fleets, by multiplying the number of km with

emission factors. In addition, the study assesses the potential of alternative fuels and technology options to further reduce emissions.

The analysis shows that in the business as usual scenario the distances traveled and respective emissions will grow at a rate of 5–8% per decade. In addition, travel projections show that, on its own, fare integration with electronic ticketing will not significantly affect emissions levels. Based on transportation models, this report estimates an increase in emissions by 2%, when compared to the business as usual scenario. This increase is within the margin of error expected in transport models and cannot be considered conclusive.

However, the travel projections used in this study do not take into consideration the fact that electronic ticketing may lead to the collapse of the secondary market for transit tickets. This would lead to a rise in bus ridership that could imply an increase in distances traveled as well as emissions.





In any event, the integration of the fare system in Porto Alegre has been claimed to be an essential step towards bus service improvements such as the BRT.

This study shows that the BRT planned for Porto Alegre will reduce emissions by cutting the distances traveled and improving the fleet's driving cycle. CO<sub>2</sub> emissions will decrease by 8–9%, or 25,129–31,529 tons per year, in comparison to the business as usual scenario with fare integration.

We should note that there is a link between the implementation of the BRT system with fare integration and a reduction in walking times, indicating a modal shift from walking to bus use. This suggests that measures should be implemented to enhance the attractiveness of non-motorized transportation, such as improving public spaces for pedestrians and integrating the bus system with bicycling networks.

There is no information on the expected modal shift from cars to the bus system. A brief analysis shows that if 1% of the bus passengers previously traveled by car, an additional 710–836 kg of CO<sub>2</sub> emissions per year could be avoided as a result. This, together with the need to address the increasing rate of motorization, is a good reason for implementing traffic demand management measures, such as parking restrictions, congestion charging, that encourage modal shift from cars to buses.



Diesel oxidation catalysts (DOCs) can operate with fuel of higher sulphur content, but reduce particulate matter to a lesser extent than DPFs. DOCs reduce smoke and odor, as well as some toxic pollutants, but cannot remove the fine particles that pose severe health threats.

To reduce bus emissions further there are a number of alternative fuels, as well as vehicle and emission control technologies that are commercially available and that can be combined to maximize benefits.

Increasing the emission standards of the vehicles is an effective way to reduce local pollutant emissions from bus fleets. There is opportunity for upgrading Porto Alegre's municipal bus fleet that currently portrays Euro 0 to Euro 3 vehicles. Hybrid vehicles can also be considered as they are particularly efficient in city environments.

In addition, new heavy-duty diesel vehicles can be dramatically cleaner when using a combination of ultra-low-sulfur diesel and particle filters (DPFs). Currently, the diesel available in Porto Alegre contains 500 parts per million (ppm) of sulfur. The situation is expected to change in 2009, with the introduction of diesel with 50ppm sulfur content in the fuel mix as result of resolution 315/02 and federal law 8.723/93.

Biofuels receive mixed reviews on their potential to reduce GHG emissions due to the carbon debt from land use changes associated with their production. In fact, they score higher points when analyzing their impact on local pollution at the point of consumption.

The use of compressed natural gas reduces carbon monoxide, nitrogen oxides, and particulate emissions, while significantly increasing hydrocarbon emissions and, depending on the system's leakage levels, GHG emissions.

This study concludes that BRT is an effective solution to reduce both local and global pollutant emissions from Porto Alegre's transport system while the implementation of the fare integration, with electronic ticketing, may on its own increase emission levels. The benefits from these interventions can be enhanced if complemented with measures that promote modal shift from private cars to buses and that encourage the use of non-motorized transportation. This study recommends the development of a cost-benefit analysis and feasibility study for the use of cleaner fuels, vehicle and emission control technologies, to further reduce emissions.

# INTRODUCTION

All over the world, transportation projects are changing how people and goods move, with direct and indirect impacts on global and local air pollutant emissions. An increasing body of evidence points to the significance of the adverse effects of transportation emissions on air quality, human health, and climate change. To mitigate the adverse impacts from the transportation sector, transport and environment government officials, investors, and other stakeholders need information on the magnitude of emissions from transport interventions. In many cases, this quantification has become a requirement to obtain political, financial, and public support for transportation projects.

The rapid economic growth and increase in transportation demand in the metropolitan region of Porto Alegre, in the state of Rio Grande do Sul, Brazil, have led to a steep rise in motorization levels. The environment of Porto Alegre's city center and health of its citizens are compromised by the numerous bus terminals along important arterials, where buses are kept idling in confined areas surrounded by tall buildings. The municipality of Porto Alegre is planning to increase bus ridership by implementing fare integration in the metropolitan and urban lines system, and to reduce the number of buses and terminals downtown by implementing a BRT system.

The interest of the government authorities in reducing local and global emissions through transport measures has been mounting. With the goal of empowering stakeholders with the necessary information to incorporate environmental and health considerations into the decision-making process, the present study provides a first level estimation of the impact of the planned interventions. In addition, it looks at current literature to assess the potential of alternative fuel and technology options for reducing emissions. This analysis supplements other information sources and analyses, such as air quality monitoring networks, emissions inventories, exposure assessments, life-cycle assessments, and cost-benefit analyses.

This study examines the direct impacts from changes in centrally managed fleets and it does not include indirect emissions resulting from effects on cars or modal shift. The focus of this study is on emissions from fuel combustion processes, and does not include evaporative losses or the full life-cycle impacts of vehicles, fuels, and infrastructure. The analysis covers the most significant criteria pollutants and greenhouse gases emitted from on-road mobile sources: nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), particulate matter (PM); and carbon dioxide (CO<sub>2</sub>).

This report is organized as follows:

**SECTION 1 – Introduction.** This section provides the background, objectives, and scope for this project.

**SECTION 2 – Porto Alegre: Setting the Stage.** This section describes the current situation and trends in demography, economy, transport, and air quality in the region and municipality of Porto Alegre.

**SECTION 3 – Study Methodology.** This section presents the transport interventions planned for Porto Alegre and describes the methods, assumptions, and data sources used to estimate their impacts on local and global emissions.

**SECTION 4 – Results: Environmental Performance of Transport Solutions.** This section presents and discusses the results from this study, providing a comparison of the impacts on emissions of the fare integration, BRT system, and introduction of cleaner fuels and technologies.

**SECTION 5 – Conclusions.** This section presents the conclusions and recommendations for decision making in Porto Alegre.

## PORTO ALEGRE: SETTING THE STAGE

### LOCATION, POPULATION, AND ECONOMY

Porto Alegre is the southernmost capital of Brazil, in the state of Rio Grande do Sul (Figure 1). Its metropolitan region, with a total of over 3.8 million inhabitants, is the fourth largest in the country in terms of population size (IBGE, 2007). The metropolitan region of Porto Alegre has 31 municipalities. The municipality of Porto Alegre has an area of 497 km<sup>2</sup>, a population of 1,420,667 inhabitants and a density of 2,859 inhabitants per km<sup>2</sup> (IBGE, 2007).

In the state of Rio Grande do Sul, the gross domestic product (GDP) is projected to continue rising, as illustrated in Figure 2.

The rapid growth in wealth will continue to support the steep increase in transportation demand and motorization rates, with associated impacts on the environment, public health, and quality of life in the urban and metropolitan regions.

### ENVIRONMENTAL MANAGEMENT

#### Institutional framework

In Brazil, air quality management is coordinated by the National System for the Environment (SISNAMA - *Sistema Nacional do Meio Ambiente*), a group of federal, state, and municipal government agencies. The federal government establishes the basic requirements that are applicable across the board, while the state and local agencies introduce specific standards that may be more rigorous than federal requirements. The Brazilian Institute for the Environment and Natural Resources (IBAMA - *Instituto Brasileiro do Meio Ambiente e Recursos Naturais*) is the SISNAMA federal executive agency, while the National Environmental Council (CONAMA - *Conselho Nacional do Meio Ambiente*) is an advisor and deliberative body. The Foundation for Environmental Protection (FEPAM - *Fundação Estadual de Proteção Ambiental Henrique Luís Roessler*) and the Secretariat for the Environment (SEMA - *Secretaria Especial do Meio Ambiente*) are Rio Grande do Sul's state agencies. The Municipal Secretariat for the Environment (SMAM - *Secretaria Municipal do Meio Ambiente*) operates in Porto Alegre at the municipal level.

#### Environmental planning

In 1989, CONAMA established the National Program for the Control of Air Quality (PRONAR - *Programa Nacional de Controle da Qualidade do Ar*). PRONAR set

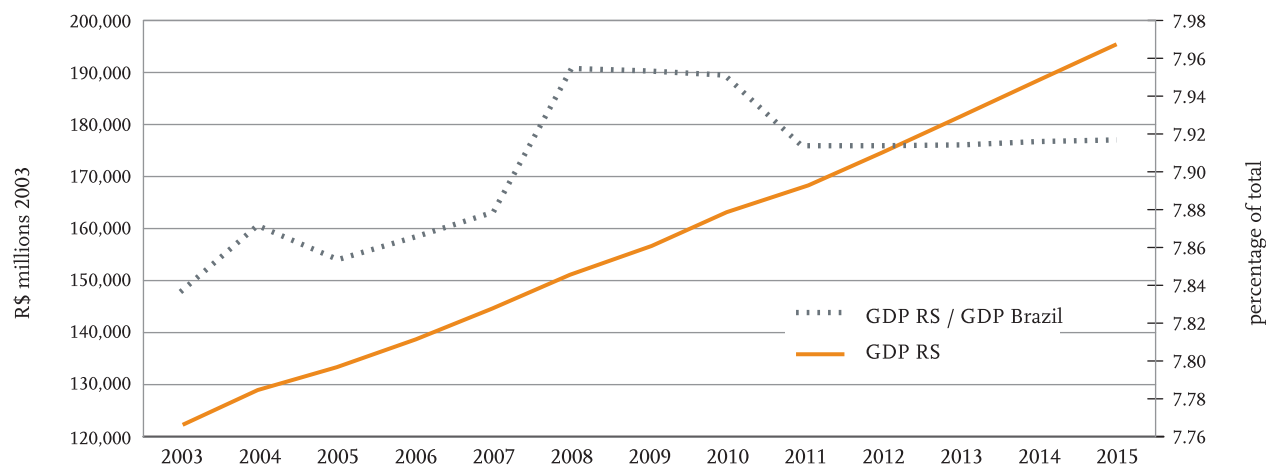
FIGURE 1 | RIO GRANDE DO SUL LOCATION MAP



Source: Boundaries (ESRI, 2006)



FIGURE 2 | GDP FORECAST FOR BRAZIL AND RIO GRANDE DO SUL (2003–2015)



Source: Booz Allen, FIPE, HLC, 2006

maximum emission limits for stationary sources, based on area usage, and set nation air quality standards (primary standards - maximum tolerable concentration levels; and secondary standards - below which the impact is minimum) to reduce the negative effects of atmospheric pollution nationwide. In 1990, CONAMA issued new air pollutant emission standards (resolution 003/1990) and determined that states are responsible for establishing air monitoring programs, air quality standards, and emergency plans for critical episodes of air pollution.

In 1986, CONAMA established the Program for the Control of Air Pollution from Mobile Sources (PROCONVE - *Programa de Controle de Poluição do Ar por Veículos Automotores*), which defines maximum emission limits for light-duty passenger and commercial vehicles and for heavy-duty vehicles (buses and trucks). Emission limits and certification test cycles in Brazil are based on European Union regulations. PROCONVE had several implementation phases. The first set of vehicle emission regulations, adopted in 1993 (CONAMA 8/93), was based on Euro 0/2 standards. The second set of emission standards, adopted in 2002 with implementation dates over 2006–2009 (Resolution 315, October 29, 2002), are based on Euro 3/4 standards.

PROCONVE is focused on reducing emissions from new vehicles, affecting manufacturers and importers only.

Manufacturers provide instructions to consumers on how to maintain low levels of emissions from their vehicles. However, there is no assurance that the vehicle owners follow those instructions. With that in mind, CONAMA has defined general guidelines for implementing inspection and maintenance (I/M) programs by state and municipal environment agencies. The new Brazilian National Transit code, once fully implemented, requires that vehicles be licensed only if approved in I/M programs that verify pollutant emissions and noise levels. In 1992, vehicle manufacturers added catalytic converters to new vehicles; in 1997, vehicle manufacturers added electronic fuel injections and exhaust gas recirculation valves, oxygen sensors, high-energy ignition, secondary-air injection, and canisters. Even though PROCONVE has been a very successful program, the growth of the vehicle fleet has made transportation the main contributor of emissions in Brazil's metropolitan regions.

Climate change is being addressed at the national level by the National Plan for Climate Change (*Plano Nacional de Mudanças Climáticas*), pending its inauguration in 2009. In October 2007, the municipality of Porto Alegre approved the Program for Reduction of Carbon Dioxide Emissions (*Programa de Prevenção, Redução e Compensação de emissões de Dióxido de Carbono*), which includes provisions for improving passenger public transportation.

FIGURE 3 | FIXED AND MOBILE AIR QUALITY MONITORING STATIONS



Source: FEPAM, 2002

### Air quality monitoring

Porto Alegre's air quality monitoring network is currently underperforming, due to lack of maintenance and financial capacity. FEPAM, the environment secretary at the state level, has 12 nonoperational manual stations for sulfur dioxide ( $\text{SO}_2$ ), total suspended particles (TSP), and PM; and 10 operational automatic stations that monitor the pollutant concentrations for  $\text{PM}_{10}$  (1 station), nitrogen dioxide ( $\text{NO}_2$ ) (1 station), CO (not operational),  $\text{SO}_2$  (2 stations) and tropospheric ozone ( $\text{O}_3$ ) (7 stations). Meteorological parameters such as wind direction and speed, temperature, relative humidity, atmospheric pressures, total radiation, and ultraviolet radiation are also monitored. One of the automatic stations is mobile (Figure 3). The information from automatic stations arrives at FEPAM on a continual basis and is used to develop dispersion analysis indices for public outreach. (FEPAM, 2008)

SMAM, the municipal secretariat, has two stations to monitor PM and CO. In addition, a number of private-sector entities, such as refineries and thermoelectric sites, monitor  $\text{SO}_2$ , total suspended particles (TSP), CO,  $\text{O}_3$ , hydrocarbons (HCs),  $\text{PM}_{10}$ ,  $\text{NO}_2$ , and meteorological parameters.

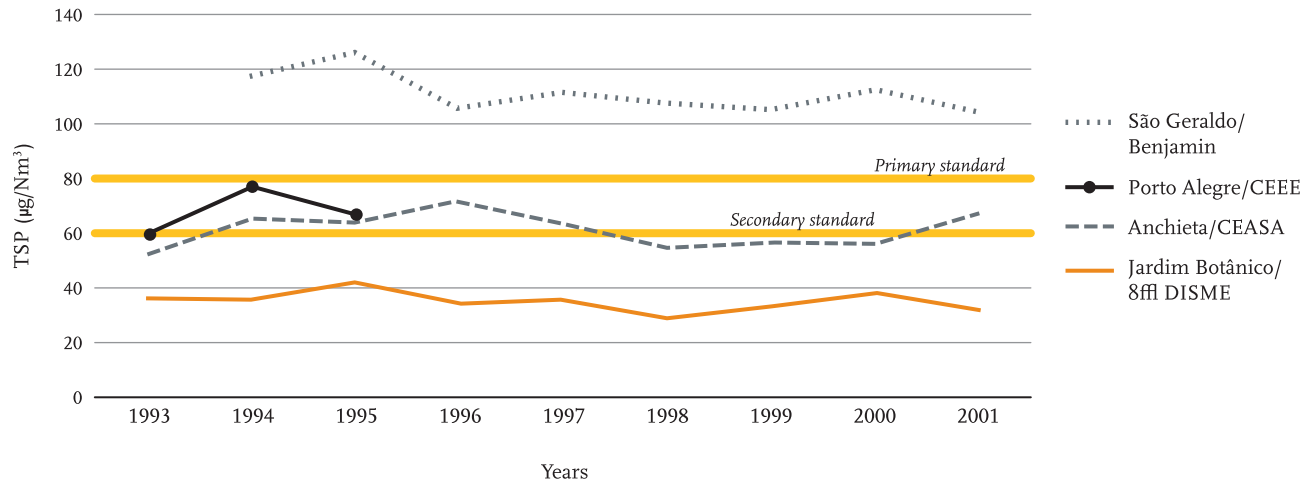
Porto Alegre's air quality monitoring network registers good air quality throughout the year. However, during 2003–2005, there were eight episodes of poor air quality, monitoring stations near the road often show PM concentrations above the defined air quality standards.

As Figure 4 illustrates, the annual average TSP concentrations near major roads (São Geraldo/Benjamin) exceed the primary standard. These high concentrations occur in bus stations and terminals, where many people gather daily for long periods of time. This is especially worrisome, because exposure to PM and  $\text{O}_3$  is linked to illnesses such as acute respiratory infections, asthma, and chronic obstructive pulmonary disease.

Porto Alegre's air monitoring network shows that  $\text{O}_3$  concentrations are higher in spring and summer, while CO concentrations are the highest in the winter and in bus stations. Concentrations of  $\text{SO}_2$  decreased after 1997, as a result of a reduction of sulfur content in the metropolitan diesel fuel.

The 1991 emissions inventory for Porto Alegre shows that vehicles are the primary source of  $\text{NO}_x$ , CO, and HC emissions. In 2001, the metropolitan region of Porto

FIGURE 4 | ANNUAL AVERAGE CONCENTRATIONS OF TSP IN FOUR MONITORING STATIONS



Source: FEPAM, 2002

Alegre (MRPA) developed a mobile emissions inventory based on vehicle type, model, year, and emission factors. Since it was difficult to measure the distance traveled by the fleet, the emissions inventory used as a reference the consumption of gasoline, ethanol, and diesel in the region.

As illustrated in Figure 5, most vehicles use gasoline, followed by ethanol and diesel. In 2001, gasoline was the main contributor of CO, HCs, and formaldehyde (CHO) emissions; diesel was the main contributor of NO<sub>x</sub> and sulfur oxide (SO<sub>x</sub>) emissions; and diesel and tire wear were the main contributors of PM emissions (40% each). The main source of CO<sub>2</sub> emissions was the combustion of diesel fuel and gasoline, totaling 3,473 thousand tons that year.

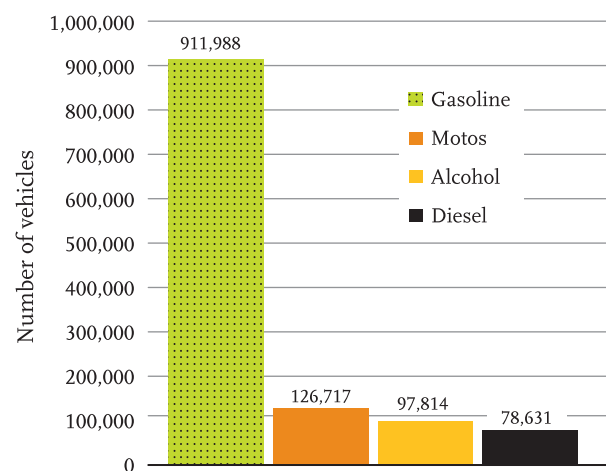
Results are presented in Figure 6. We could not obtain clarification on why the emissions from motorbikes (motos) are given in a separate category.

## TRANSPORTATION MANAGEMENT

### Institutional framework

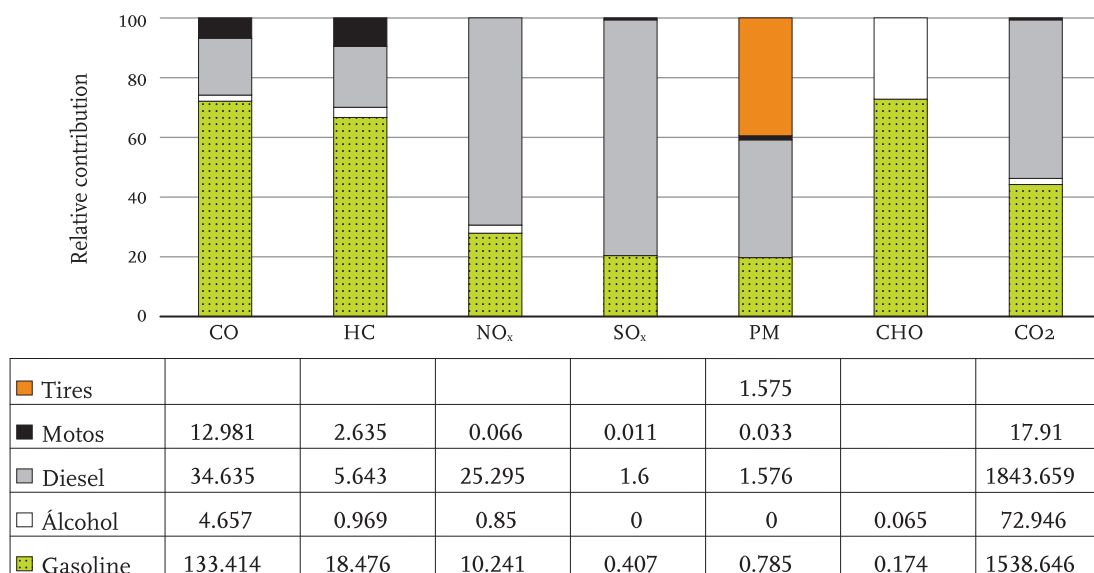
Transportation is managed at the national level by the Ministry of Transportation (*Ministério dos Transportes*); at the state level by the Secretariat of Transportation for Rio Grande do Sul (*Secretaria dos Transportes do Rio Grande do*

FIGURE 5 | NUMBER OF VEHICLES IN OPERATION BY FUEL TYPE IN MRPA IN 2001



Source: FEPAM, 2002

FIGURE 6 | VEHICULAR EMISSIONS FOR THE MRPA (1,000 tons in 2001)



Source: FEPAM, 2002

Sul); at the metropolitan level by the Foundation for Metropolitan and Regional Planning (Metroplan - *Fundação Estadual de Planejamento Metropolitano e Regional*); and at municipal level by the Public Corporation for Transportation and Transit (EPTC - *Empresa Pública de Transportes e Circulação*).

### Transportation planning

The National Plan for Transport and Logistics (PNLT - Plano Nacional de Logística e Transportes 2008-2013), released in April 2007, provides the strategic direction at national level for the transportation sector. The PNLT establishes the goal of increasing rail transport from 25% to 32% and maritime transport from 13% to 29%, in 15–20 years. Road freight would be reduced from the current 58% to 33%.

Several plans influence the transport system in Porto Alegre. The Public Transportation Master Plan of 2000 (PDSTC - *Plano Diretor Setorial de Transporte Coletivo*) calls for the expansion of the transversal bus network and the physical and operational integration of the public transportation system, through terminals and electronic payment of tariffs.

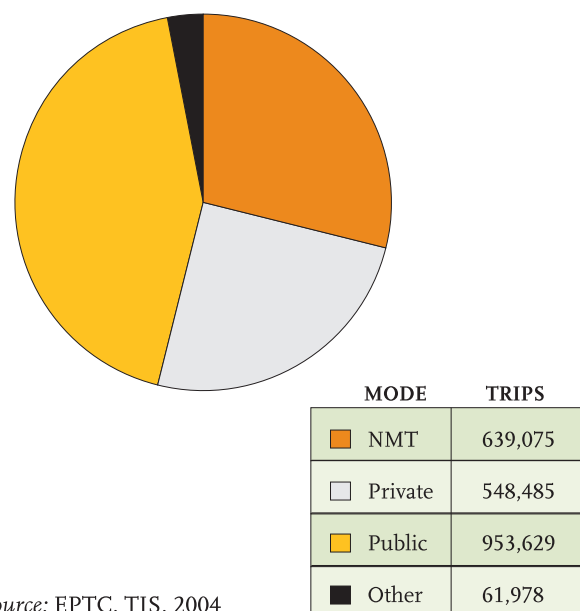
The Integrated Plan for Transportation and Urban Mobility of Porto Alegre Metropolitan Region (PITMUrb – Plano Integrado de Transporte e Mobilidade Urbana da Região Metropolitana de Porto Alegre) proposes the development of an integrated transit network in the Metropolitan Region of Porto Alegre, by 2033. The integrated transit network planned is comprised of a circular metro line with 37.4km length (extending northwards the existing suburban train line by 9.3km), and of bus corridors with 199.5km length. Furthermore, the plan foresees the use of an electronic fare system, of stations with integrated transport modes (8 metro/bus and 7 bus/bus) and of a rationalized operational system.

### Transportation demand and supply

In 2002, 3.4 million motor vehicles were registered in the state of Rio Grande do Sul. This number has been growing at an average rate of 5% per year. Based on this trend, the fleet is expected to grow to approximately 5 million vehicles by 2010. The Metropolitan Region of Porto Alegre comprises 40% of these vehicles. Table 1 provides an overview of Porto Alegre's vehicle fleets.

TABLE 1	OVERVIEW OF PORTO ALEGRE'S TRANSPORTATION FLEETS
FLEETS	DETAILS
Suburban Rail	One line, six stations, 33.8 km long 170,000 passengers per day 8,268 km per day
Metropolitan Buses	561 lines, 1,500 vehicles, operated by 20 companies 37,000 passengers per day 240,000 km per day
Municipal Buses	318 lines, 1,590 vehicles 953,000 passengers per day 9,318,000 km per month
Municipal Minibuses	29 lines, 403 vehicles 70,000 passengers per day 78,000 km per day
Other Motor Vehicles	627 school buses serving 294 schools 3,915 taxis with an average age of 5 years 521,283 private cars (2.6 inhabitants/vehicle) Motorcycles (data not found)
Source: EPTC, PMPA, SMT, 2003	

FIGURE 7 | MODAL SHARE IN THE MUNICIPALITY OF PORTO ALEGRE

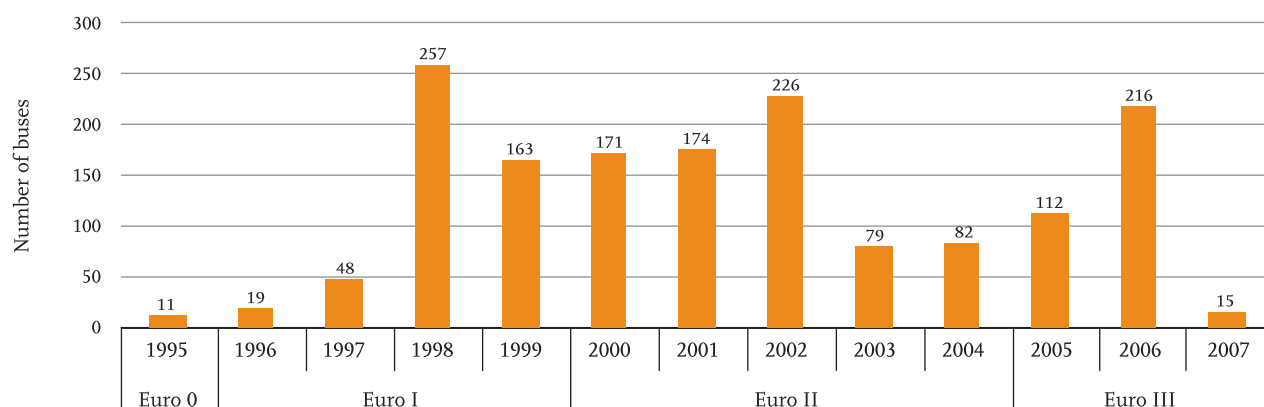


Source: EPTC, TIS, 2004

The 2004 Home-Based Origin-Destination survey revealed that 71% of all trips in Porto Alegre are motorized (Figure 7). The municipal bus fleet has an average age of 5 years and should have a maximum age of 10 years. In-

centives exist for operators to keep the fleet relatively new. Figure 8 shows the age and Euro standards of the municipality bus fleet in 2007.

FIGURE 8 | MUNICIPAL BUS FLEET AGE DISTRIBUTION



Source: EPTC, 2007



Porto Alegre municipal government authorities are currently updating their bus fleet database to include distances traveled and fuel consumption.

The municipality of Porto Alegre is planning to implement two major transport interventions: fare integration, with electronic ticketing, and a BRT system. The BRT sys-

tem is aimed at regenerating the city center by removing terminals and reducing the number of buses in circulation, while the physical and operational integration of the public transportation system is intended to make the public bus system more attractive and thus increase ridership. These two interventions are described in more detail in the next section of this report.

## STUDY METHODOLOGY

This study estimates the emissions levels of CO<sub>2</sub>, CO, NO<sub>x</sub>, and PM<sub>2.5</sub> of four transportation scenarios being considered for the city of Porto Alegre.

This study uses a distance-based approach that consists in multiplying the annual distances traveled by the municipal, metropolitan and BRT fleets with emission factors characteristic of the fleet and driving conditions.

The calculations do not include secondary effects such as one-off traffic disruptions due to new terminal construction; upstream impacts related to how fuels are produced, downstream impacts related to changes in traffic outside the project boundary.

### TRANSPORT SCENARIOS

The government authorities of Porto Alegre are considering four scenarios for the public bus transport system:

#### ■ Scenario BAU - Business as Usual

This scenario is constructed based on the municipal routes that were operating in 2005 and metropolitan routes that were operating in 2002.

#### ■ Scenario Int - Implementation of fare integration in the urban system

This scenario has the physical and operational conditions of Scenario BAU and considers the implementation of electronic ticketing and fare integration in the municipal bus lines. In this scenario, the passenger will be charged 50% of the fare price when buying a second bus ticket (50% discount on transfers).

#### ■ Scenario Int BRT 1 - Phase 1 of BRT System

This scenario considers the implementation of three BRT lines: two for the metropolitan system passengers and one for the municipal system passengers. The metropolitan BRT lines start at the transfer stations

of Azenha and Cairu and end in the city center, while the municipal BRT line connects these two stations. Short routes with an itinerary near the corridors were kept operating to avoid passenger transfers. Similarly, circular and transversal routes kept the same operation as in Scenario Int. The fare system is the same as in Scenario Int, with two additions: passengers can make free transfers between the traditional municipal bus lines and the municipal BRT and between the traditional metropolitan lines and the metropolitan BRT.

#### ■ Scenario Int BRT 2 - Phase 2 of BRT System

Scenario Int BRT 2 considers the expansion of the BRT system as far as Terminal Triangulo, with the creation of an urban BRT line between Triangulo and Azenha and the creation of a metropolitan BRT line between Triangulo and the city center. The point of integration between urban and metropolitan lines becomes Triangulo, instead of Cairu. The fare system is the same as in Scenario Int BRT 1.

Figure 9 presents a map of the BRT system.

The comparison of the four transport scenarios was based on modeled projections of transport demand and supply for 2005 (base year), 2015, and 2025 (LOGIT, 2006). This study used modeled projections for the base year, as opposed to real observations, because real data were only available for the municipal fleet. In addition, models are simplified representations of reality, and even when the model is calibrated, the results between reality and simulation may not be identical. If we had compared future simulations with current real observations it would have been difficult to understand whether the variations resulted from modifications in the situation or from simplifications and imperfections of the models used.

### EMISSION FACTORS

The emission factors for CO, NO<sub>x</sub>, PM<sub>2.5</sub> and the fuel consumption coefficients were drawn from a study led

FIGURE 9 | MAP OF BUS RAPID TRANSIT SYSTEM



Source: Adapted from LOGIT, 2006

by the *Instituto de Pesquisas Tecnológicas* (IPT, 2006). The IPT study measured the emissions and fuel consumption of buses with Euro 3 emissions standard operating on diesel with 500 ppm sulfur content (D500), and running on driving cycles representative of non-segregated corridors (metropolitan fleet), segregated corridors (municipal fleet), and segregated BRT corridors. The emission factor for CO<sub>2</sub> were obtained from Brazil's national emissions inventory (Ministério da Ciência e Tecnologia, 2006). Table 2 provides the emission factors and fuel efficiency coefficients used for the fleets under each driving cycle.

The following simplifications occurred in the calculations. The emission factors used do not take into consideration the age of the vehicles in the actual fleet circulating in Porto Negro, nor do they accommodate for the fact that Porto Alegre's municipal fleet has been using B2 (a fuel blend of 2% of biodiesel) since 2007, and that after 2013 B5 will be mandatory nationwide. Likewise, these emission factors do not take into consideration the fact that after 1st of January 2009, diesel with 50 ppm sulphur content should be made available in metropolitan areas (Resolution 315/02; Federal law 8.723/93).

PARAMETER	BRT FLEET (SEGREGATED)	MUNICIPAL FLEET (SEGREGATED)	METROPOLITAN FLEET (NON SEGREGATED)	SOURCE
Fuel (km/l)	3.44	2.06 ± 0.11	1.66 ± 0.21	IPT, 2006*
CO <sub>2</sub> (g/l)	2,799	2,799	2,799	Ministério, 2006
CO <sub>2</sub> (g/km)	814	1,359	1,686	Calculated
CO (g/km)	1.33 ± 2.81	3.23 ± 0.49	5.16 ± 1.44	IPT, 2006*
NO <sub>x</sub> (g/km)	7.55 ± 3.31	13 ± 0.7	17.07 ± 0.9	IPT, 2006*
PM <sub>2.5</sub> (g/km)	0.167 ± 0.018	0.215 ± 0.033	0.385 ± 0.220	IPT, 2006*

\* Volkswagen Volksbus 17-260 operating on D500, engine MWM 6.12 TCAE Euro 3 (6 cil. e 7,2 l.), 191 kW @ 2,500 rpm e 900 Nm @ 1,300 rpm, manual transmission Eaton FS-6406B, axis Busscar Urbanus Plus, length 13,3 m and weight 11.000 kg, passengers: 37 seats, 39 standing.

With the goal of evaluating the environmental performance of suitable fuel and technology alternatives, this study draws on available literature. It should be noted that the results presented here do not provide exact estimations of the impacts of alternative options for Porto Alegre's fleets, since they are based on different vehicle

technologies, driving conditions, etc. Nevertheless, the results provide an indication of the likely impacts to expect in Porto Alegre.

The emission factors used for the comparison of DPFs and DOCs are presented in Table 3. These show some discrepancy from the values presented in Table 2 for the municipal fleet due to the use of different vehicle technology.

Note that during the measurement campaign the DOC was not adjusted to the sulfur content in the fuel, leading to abnormally high PM levels.



PARAMETER	D500	D500 DOC	D50	D50 DPF
Fuel (km/l)	1.68	1.76	1.7	1.75
CO (g/km)	11.5	7.08	10.3	1.61
NO <sub>x</sub> (g/km)	12.8	11.9	12.4	10.1
PM <sub>2.5</sub> (g/km)	0.171	0.33	0.68	0.015

Mercedes-Benz O500 UA 2836, motor OM 457 LA Euro 3 (6 cil. and 12 liters), 260 kW @2000 rpm and 1600 Nm @1100rpm, automatic transmissions Voith Diwa 864.3E, axis Induscar Caio Millennium, Length 18,5 m and weight 18.180 kg, 36 seats, 83 standing  
Source: IPT, 2006

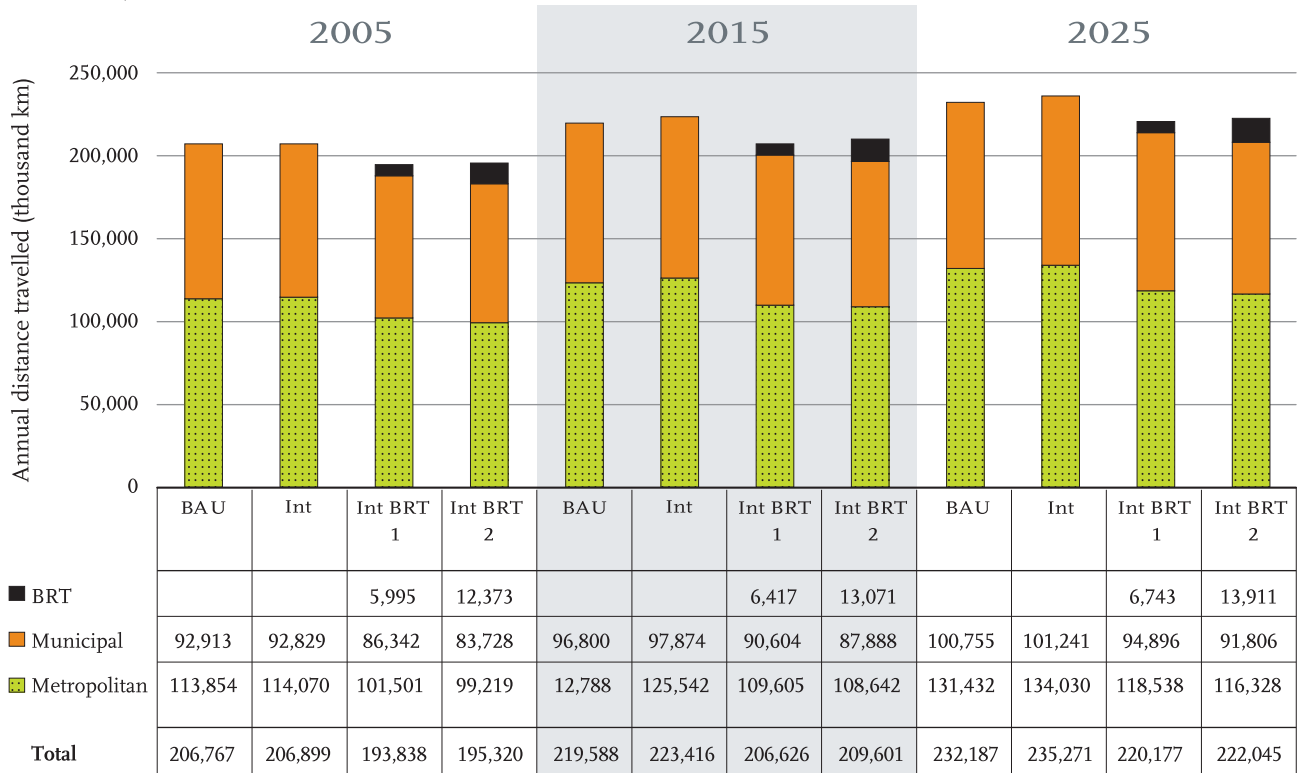
## RESULTS: ENVIRONMENTAL PERFORMANCE OF TRANSPORT SOLUTIONS

### IMPROVING THE TRANSPORT SYSTEM

The number of bus passengers and distances traveled are projected to rise by 5-8% per decade in the business as usual scenario (Figure 10 & 11). The transport simulations show that the implementation of the fare integration, with electronic ticketing, will further increase the number of passengers and km traveled, by up to 2%, when compared to the business as usual scenario (BAU).

Local transport experts foresee that, as electronic ticketing and travel cards are instituted, the secondary market for travel tokens will collapse. This will increase bus ridership, distances traveled and emissions levels. The extent of this effect is not possible to evaluate through conventional transportation planning models. Thus the simulated forecast of distances traveled and of the impact of fare integration presented in this study may be significantly underestimated.

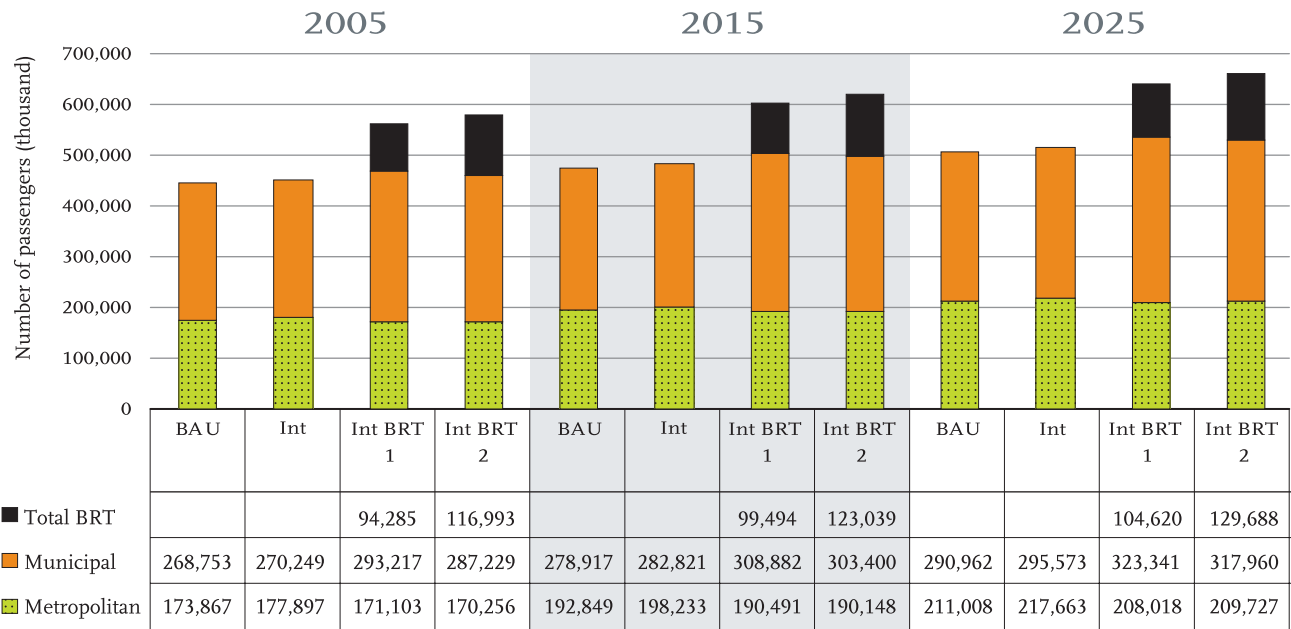
FIGURE 10 | ANNUAL DISTANCE TRAVELED BY METROPOLITAN, MUNICIPAL, AND BRT BUSES



Source: Based on data from LOGIT, 2006



FIGURE 11 | ANNUAL NUMBER OF PASSENGERS IN METROPOLITAN, MUNICIPAL, AND BRT FLEETS



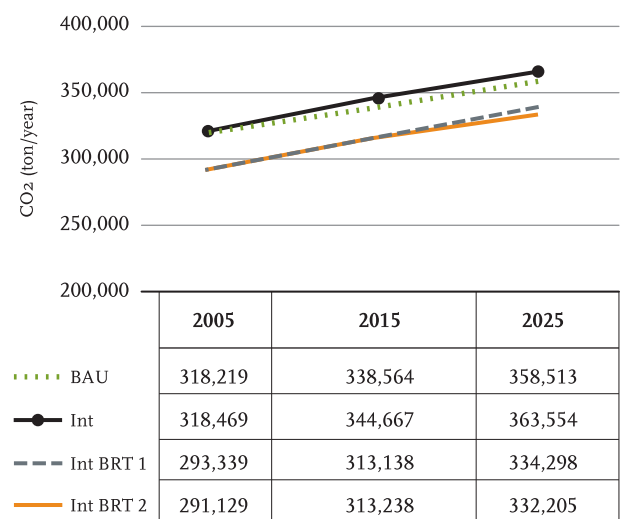
Source: Based on data from LOGIT, 2006

The introduction of the BRT system will reduce distances traveled by 6–8%, while dramatically increasing the number of passengers by 24–25%. This suggests that the BRT corridors will improve route design and the system’s operational efficiency.

The introduction of the BRT corridor and fare integration is expected to induce a modal shift from non-motorized to bus transportation, as indicated by a 5-9% reduction in walking times (LOGIT, 2006). On the other hand, transport demand studies in Porto Alegre have not taken into consideration the potential modal shift from cars and other more polluting transport modes, in order to provide a conservative estimation of bus ridership. Box 1 gives an indication of the significance of a modal shift from cars to buses to CO<sub>2</sub> emissions.

Emissions levels are projected to rise by 5–8% per decade, following the increase in distances traveled. The introduction of the BRT system will enable an 8–10% reduction of emission levels when compared to the fare integration case, amounting to 25,129–31,529 tons of CO<sub>2</sub> emissions, 78-97 tons of CO emissions, 254-318 tons of NO<sub>x</sub>, 5-7 tons of PM 2.5 per year. However, even with the

FIGURE 12 | TRENDS IN CO<sub>2</sub> EMISSIONS



# BOX 1 COMPARING CO<sub>2</sub> EMISSIONS FROM CARS AND BUSES PER UNIT OF TRAVEL

As illustrated in Table 4 below, buses are 3–7 times less fuel efficient than cars, per vehicle; but are 6–13 times more fuel efficient than cars, per passenger. Buses emit 4–9 times more CO<sub>2</sub> emissions than cars, per vehicle; but 5–10 times less CO<sub>2</sub> emissions than cars, per passenger. Here again, we can feel the impact of the different driving cycles for mixed traffic, segregated, and BRT corridors.

TABLE 4 FUEL EFFICIENCY AND CO<sub>2</sub> EMISSIONS PER TRAVEL UNIT

PARAMETER		BUS ON BRT	BUS ON SEGREGATED CORRIDOR	BUS ON MIXED TRAFFIC
FUEL EFFICIENCY	Per bus (veh.km/l) <sup>1</sup>	3.44	2.06	1.66
	Per car (veh.km/l) <sup>2</sup>	12	12	12
	Per bus passenger (pax.km/l) <sup>3</sup>	172	103	83
	Per car passenger (pax.km/l) <sup>4</sup>	13.68	13.68	13.68
CO <sub>2</sub> EMISSIONS	Per bus (veh.g/km) <sup>6</sup>	814	1,359	1,686
	Per car (veh.g/km) <sup>7</sup>	181	181	181
	Per bus passenger (g/km) <sup>3</sup>	16	27	34
	Per car passenger (g/km) <sup>4</sup>	159	159	159

## Notes

g = gram; km = kilometer; pax = passenger; veh = vehicle.

1. IPT, 2006.

2. FEPAM, 2002. Note: Lee Schipper believes that 12 km/l fuel efficiency for a car is high and expects this to be 10 km/l.

3. 50 passengers per bus (private communication with LOGIT, March 2008).

4. 1.14 passengers per car (U.S. DOT 2003).

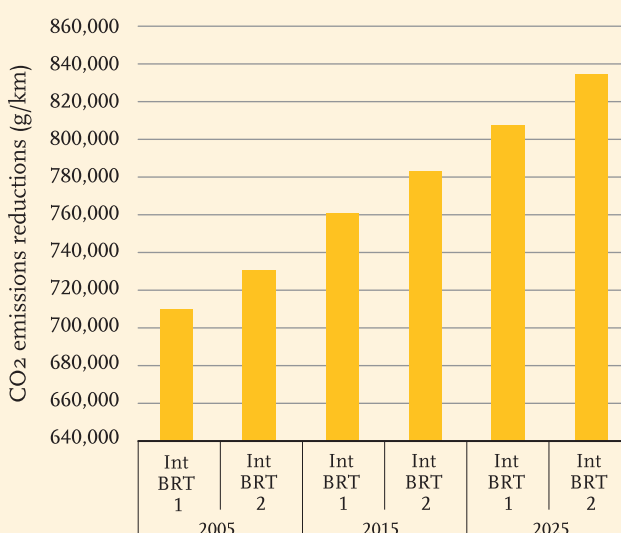
5. CO<sub>2</sub> emission factors are for Euro3 buses operating on D500, and for cars operating on gasoline.

6. Ministerio de Ciência e Tecnologia, 2006.

7. IPCC, 2006

Assuming that 1% of the bus passengers previously traveled by car, we estimate that the implementation of the fare integration and BRT corridors will reduce CO<sub>2</sub> emissions by 710,423–836,037 grams per year due to modal shift, as illustrated in Figure 13.

FIGURE 13 CO<sub>2</sub> EMISSION REDUCTIONS IF 1% OF BUS RIDERS FORMERLY TOOK THE CAR



Policies that encourage modal shift, such as congestion charges, fuel and vehicle property taxes, and parking management, increase the potential of reducing emissions from cars, as has been observed in Bogotá and México City.

introduction of the BRT system, by 2025 emission levels will have surpassed the 2005 BAU case. These trends are illustrated in Figure 12 for CO<sub>2</sub> emissions. Additional graphs and tables, presenting the emission levels for CO<sub>2</sub>, CO, NO<sub>x</sub> and PM 2.5, are provided in Appendix 1.

## ALTERNATIVE-FUEL, VEHICLE, AND EMISSION CONTROL TECHNOLOGIES

This study considers the environmental performance of alternative-fuels, vehicle, and emission control technologies for Porto Alegre's bus fleets, based on analysis presented in available literature. We introduce here the potential emission impacts of vehicle emission standards, emission control technologies, biodiesel, cleaner diesel, compressed natural gas (CNG), and hybrid buses.

### Shifting to cleaner diesel fuel

The shift from diesel with 500ppm sulfur content (D500) to cleaner diesel (D50 and D15) is expected to lead to a reduction of 56% of PM, 10% of CO, and 5% of NO<sub>x</sub> per km traveled. These results were obtained for articulated Euro 3 buses, without any tailpipe treatment technology. These reductions are due to both the lower sulfur and the higher cetane content of the cleaner fuels (IPT, 2006).

### Retrofitting with DPFs while using cleaner diesel fuel

The application of diesel particle filters (DPFs) and D50 enables a reduction of CO by 85%, HC by 90%, PM by 80%, and NO<sub>x</sub> by 20% per km traveled, when compared to emissions from buses running on D500. These results were obtained for articulated Euro 3 buses.

Figures 14 and 15 illustrate the impacts of cleaner diesel and emission control technologies (ECTs) on CO emissions when applied to Porto Alegre's BRT and municipal fleets, respectively. It can be seen that the emission reductions are higher when retrofitting the municipal fleet. This is easily explained by the fact that the municipal fleet runs longer distances. In both cases, the fuel-technology option that offers the lowest emissions is the use of D50 with DPFs.

Similar impacts were observed in test-campaigns performed in Mexico City, demonstrating that catalyst-based DPF technology can remove virtually all diesel engine-generated solid elemental carbon particles from diesel exhaust - including 99% or more of the solid particles (SMA, 2006).

FIGURE 14 APPLICATION OF CLEANER FUEL AND ECT ON BRT FLEET – 2005  
(BRT Phase 1 with Fare Integration)

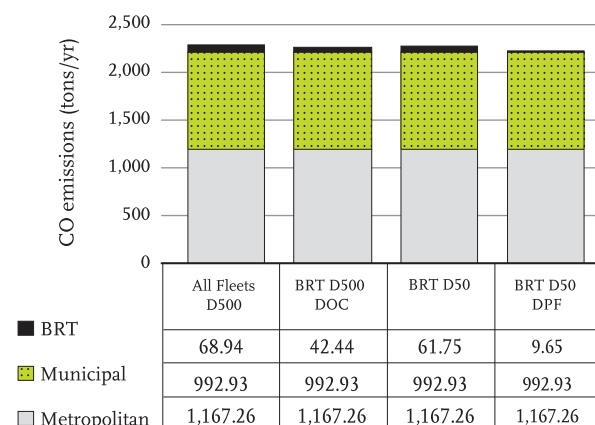
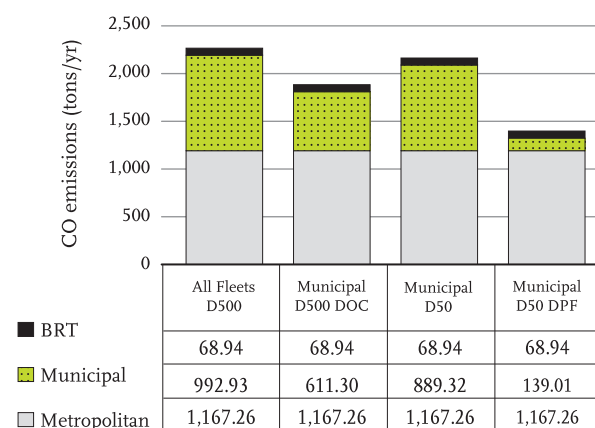
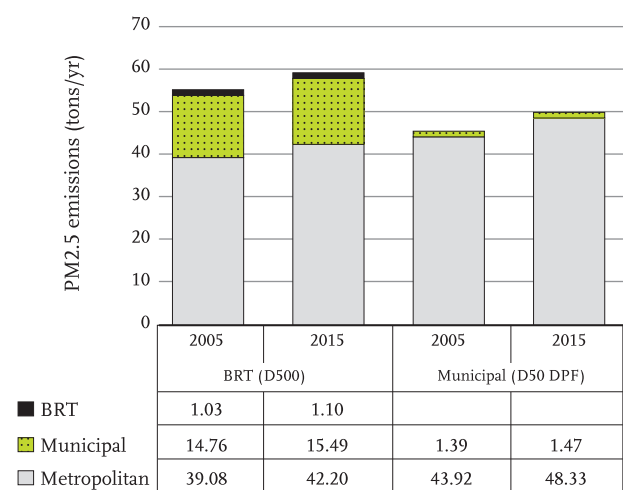


FIGURE 15 CLEANER FUEL AND ECT IN MUNICIPAL FLEET – 2005  
(BRT Phase 1 with Fare Integration)



The upstream oxidation catalyst converts nitrogen monoxide (NO) in the exhaust to NO<sub>2</sub>, which then transfers oxygen to the collected soot, oxidizing it to gaseous CO or CO<sub>2</sub>. This mechanism provides for the regeneration of the particulate filter and promotes the oxidation of unburned HCs and CO (Schipper et al., 2006).

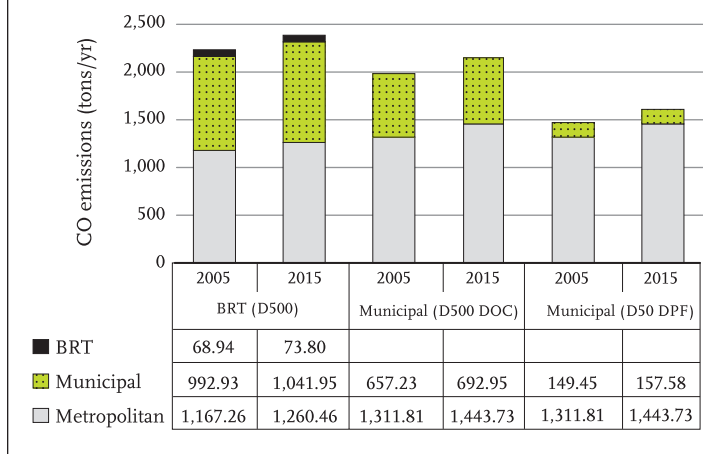
FIGURE 16 | **COMPARISON OF PM<sub>2.5</sub> EMISSIONS BETWEEN BRT PHASE 1 AND RETROFITTING MUNICIPAL FLEET WITH D50 DPF**



Note that the performance of DPFs is very sensitive to sulfur content. A study by NREL shows that fuel sulfur levels lower than 150ppm are required to achieve reductions in total PM. DPFs reduced PM emissions by 95% when using 3-ppm sulfur fuel, by 73% when using 30-ppm sulfur fuel, and by nearly 0% when tested with 150-ppm sulfur fuel. With 350ppm sulfur fuel, PM levels increased by more than 100% (NREL, 2001).

Retrofitting the municipal fleet with DPFs while using D50 provides 39% greater CO emission reductions and 17% greater PM<sub>2.5</sub> emission reductions than implementing Phase 1 of BRT system (Figures 16 and 17). Note that the emission factors used were from the 2006 *Instituto de Pesquisas Tecnológicas* study, and are for articulated buses operating on the municipal driving cycle. This creates a discrepancy with the absolute emission levels presented in earlier figures. Nevertheless, this comparative analysis still facilitates the understanding of the impacts of using cleaner fuels and alternative emission control technologies in the municipal fleet.

FIGURE 17 | **COMPARISON OF CO EMISSIONS BETWEEN BRT PHASE 1 AND RETROFITTING MUNICIPAL FLEET WITH DOC, AND WITH D50 DPF**



It should be noted that emission control technologies have a negligible impact on fuel consumption and respective CO<sub>2</sub> emissions. A U.S. Department of Energy National Renewable Energy Laboratory (NREL) study shows that the installation of the DPF may cause a nearly 2% fuel economy penalty (NREL, 2006).

### Using biodiesel in bus fleets

A study by the U.S. Environmental Protection Agency (EPA) shows that the amount of biodiesel used in fuel blends has a non-linear benefit (EPA, 2002). Soybean oil represents over 95% of present vegetable oil production in Brazil. The use of soybean-based B20 (20% biodiesel blend) can reduce total unburned HC emissions by 20%, and CO and PM concentrations by 12%, but can increase NO<sub>x</sub> emissions by 2% (a contributing factor in the formation of smog and ozone). The study also shows that B20 reduces polycyclic aromatic hydrocarbons (PAHs) and nitrated polycyclic aromatic hydrocarbons (nPAHs) by 13% and 50%, respectively — very important for reducing health risks (EPA, 2002).

The CO<sub>2</sub> benefits attributable to biodiesel are a result of the renewability of the biodiesel itself, and are not based on comparative exhaust CO<sub>2</sub> emissions. Literature provides mixed results on the life-cycle impacts from biodiesel. Concerns are raised over the carbon debt from direct and indirect land use changes associated with the production of biofuels (Fargione, 2008).

### Retrofitting with DPFs while using biodiesel blends

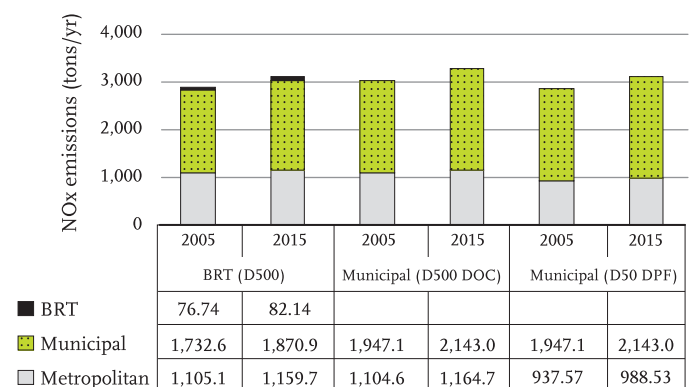
A study performed by NREL suggests that using biodiesel blends in engines equipped with DPFs can yield significant benefits. Biodiesel causes a significant increase in filter regeneration rates, and the use of B20 with the DPF produced an additional PM reduction of 67%, as compared to a petro diesel plus DPF configuration. However, the use of B20 caused a 2.9% increase in fuel consumption, consistent with the lower energy content of this fuel; and the installation of the DPF caused a nearly 2% fuel economy penalty for both ultra-low-sulfur diesel and B20 (NREL, 2006).

### Retrofitting with DOCs

Diesel oxidation catalysts (DOCs) remove gaseous HCs (including a portion of toxic and odor-causing hydrocarbons), CO, and a portion of particulate emissions termed the soluble organic fraction (SOF). DOCs remove virtually no solid particles, including elemental carbon particles (black soot), inorganic metals (lube oil ash), and adsorbed heavy PAHs that remain entrained as particles when they pass through the DOCs' channels. Measurement campaigns performed in Mexico City found that DOCs, together with diesel with 15 ppm sulfur content (D15), can reduce PM by 13–44%, CO by 43–77%, and NO<sub>x</sub> by 5–14%, when compared to the reference scenarios of 1991 vehicles operating on diesel with 350-ppm sulfur content (D350) (CTS, 2006).

DOCs are more sulfur tolerant than DPFs. However, if the sulfur content is high, the concentration of precious metals in the catalyst needs to be reduced, to prevent the conversion of SO<sub>2</sub> into sulfur trioxide (SO<sub>3</sub>). Otherwise, SO<sub>2</sub> will react with the humidity of the exhaust gas and generate sulfuric acid, which corrodes the exhaust system, contributes to acid rain, and increases PM levels. A NREL study shows that fuel sulfur content ranging from 3ppm to 350ppm did not affect emissions of PM soluble organic fraction or the suppression efficiency of the DOC. Although there is some statistical evidence that sulfate emissions increased with higher-sulfur fuel, the resulting impact on PM was negligible and not statistically significant (NREL, 2001).

**FIGURE 18 | COMPARISON OF NO<sub>x</sub> EMISSIONS FROM IMPLEMENTATION OF BRT PHASE 1 WITH RETROFITTING MUNICIPAL FLEET WITH DOC, AND WITH D50 DPF**



Interestingly, when comparing the implementation of Phase 1 of the BRT system and fare integration with retrofitting the municipal fleet with DOCs it can be seen that the latter offers a 12% greater CO emissions reduction (Figure 17) but a 6% lower NO<sub>x</sub> reduction (Figure 18).

DOCs typically do not adversely impact fuel consumption and do not affect the level of CO<sub>2</sub> emissions (Western Regional Air Partnership, 2005)

### Raising the fleet's emission standards

It is clear from the literature that vehicle emission standards have an important impact on emissions of local pollutants. When comparing emissions from heavy-duty vehicle engines running on a test bench, the move from Euro 1 to Euro 2 reduces PM<sub>10</sub> by 63%; from Euro 2 to Euro 3, by 33%; and from Euro 3 to Euro 4, by 78%. Except for NO<sub>x</sub>, that shows a clear reduction, no impact is found when moving from Euro 4 to Euro 5. Euro vehicle emission standards have no effect on CO<sub>2</sub> emissions. (Nylund and Erkkilä, 2005).

### Switching diesel to CNG

Natural gas makes an ideal fuel for vehicle combustion engines because of its high octane rating and low volatile organic compounds. Being a gas, it mixes easily with air prior to combustion, offering lower idling speeds, better performance, easier cold starting, and a more complete combustion, which all help to reduce tailpipe emissions (Cleaner Vehicles Task Force, 2000). When compared to diesel with



360ppm sulfur content, the emission reductions for a bus operating on CNG are around 52% for CO, 86% for NO<sub>x</sub>, and 68% for particulates. CNG emissions have very low levels of SO<sub>x</sub> and do not contain benzene or 1,3-butadiene (Cleaner Vehicles Task Force, 2000). However, CNG emits higher levels of total hydrocarbons (HC); over 80% of which are composed of methane with low potential to react in the atmosphere to create ground-level ozone. For heavy-duty vehicles (> 3.5 tonnes) total GHGs from CNG are comparable or slightly increased when compared to diesel operation (Cleaner Vehicles Task Force, 2000).

### **Replacing the fleet with hybrid buses with DOCs**

Transit agencies have reported that hybrid buses offer fuel economy improvements on the order of 10–50%, depending on such variables as series or parallel hybrid design, system optimizations, and the type of bus route (Hybrid Center, 2007). The IPT study indicates that Electra hybrid buses reduce NO<sub>x</sub> by 11% and PM<sub>2.5</sub> by 46% (with a high level of statistical uncertainty), while increasing emissions of CO by 21%, HC by 54%, and fuel consumption (and respective CO<sub>2</sub> emissions) by 51%. When Electra hybrid buses operate with DOCs and with optimized operation through adjustments in the control system, it is possible to reduce fuel consumption by 20% and CO and HC emissions by 21% and 37%, respectively, comparatively to the original Electra hybrid buses. In contrast, NO<sub>x</sub> and PM emissions increase by 2% and 63%, respectively, but within the uncertainty boundary (IPT, 2007).

## CONCLUSIONS

**T**he Porto Alegre Case Study provides revealing conclusions for sustainable transportation.

The proposed Bus Rapid Transit system (BRT) is projected to reduce CO<sub>2</sub> and local pollutant emissions from bus fleets, through improvements in route design and efficiency of operations.

The first step for the implementation of the BRT is the integration of fares across the bus networks and the implementation of electronic ticketing. Simulations of travel demand reveal that this initial step on its own may eventually increase CO<sub>2</sub> and local pollutant emissions.

The reduction in bus transfer costs encourages passengers to reduce walking times and use the bus for short trips. In addition, local transport experts foresee the collapse of the secondary market for travel tokens, which would attract pedestrians to the bus system.

We infer that benefits could be generated by complementing the fare integration and BRT interventions with measures that improve the attractiveness of non-motorized transportation and with measures that encourage modal shift from more polluting transport modes such as cars.

Furthermore, the analysis shows that cleaner fuels and emission control technologies can have a significant impact when applied to fleets of high mileage. In fact, numerous fuel and technology options can be applied to the bus fleets to further reduce transportation emissions.

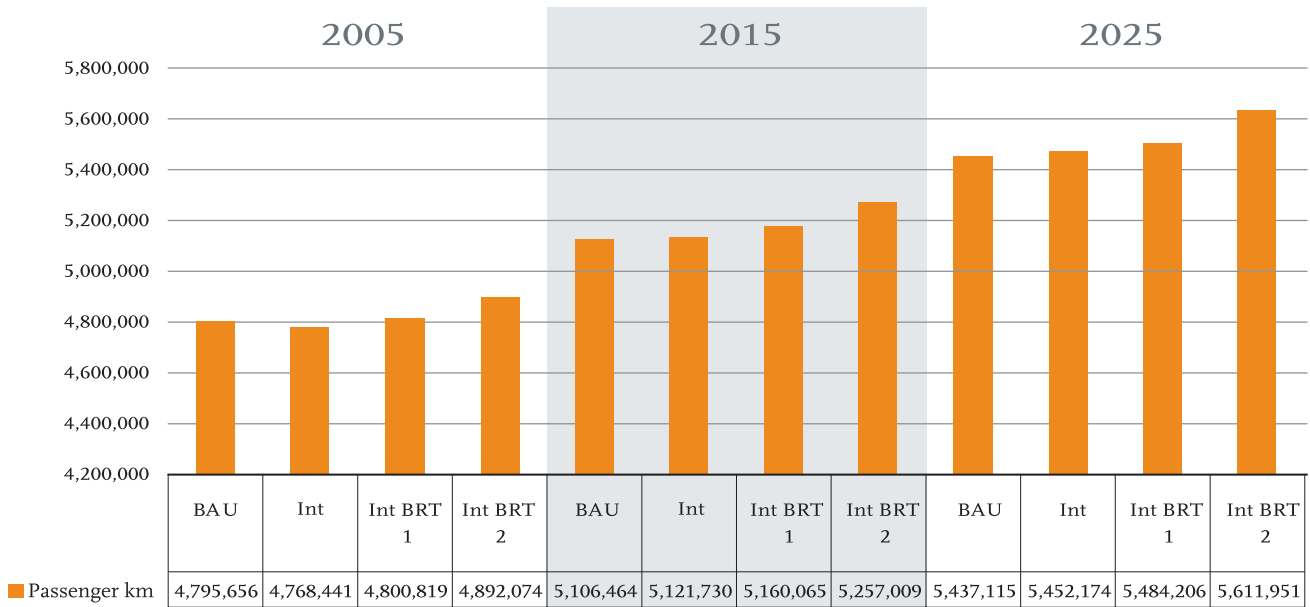
To validate the comparison between vehicle and fuel alternatives for the specific case of Porto Alegre, the authors recommend the development of cost-benefit analysis and feasibility studies for introducing vehicles with higher emissions standards; retrofitting the fleet with diesel oxidation catalysts, or diesel particle filters while using ultra-low-sulfur diesel or biodiesel blends; switching from diesel to CNG; and replacing buses with hybrid vehicles.



# Appendix 1

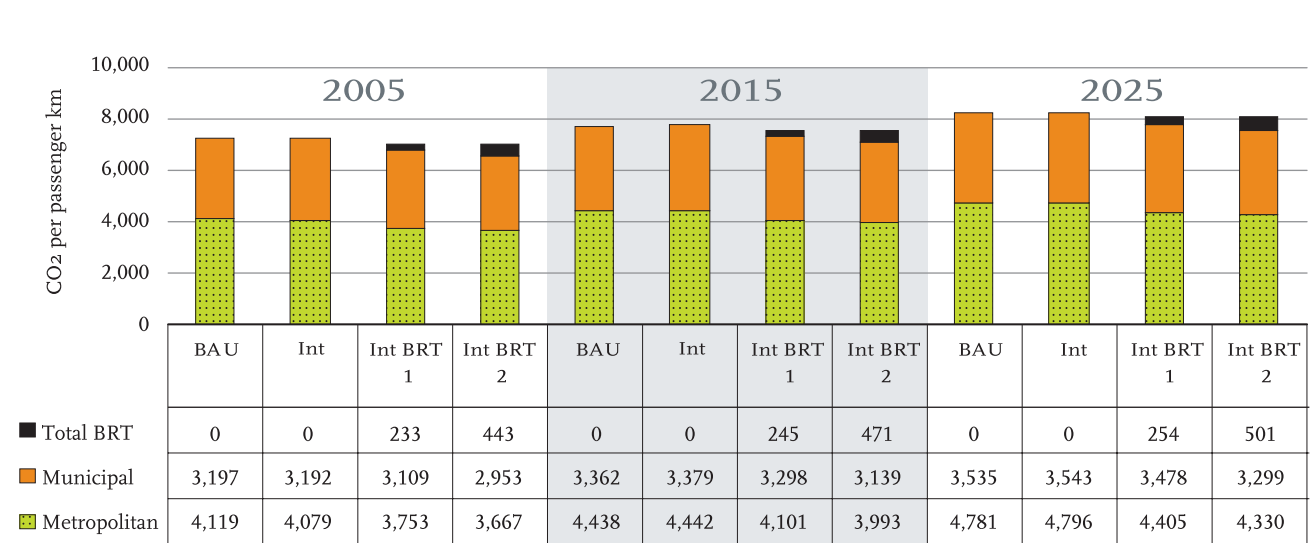
## EMISSIONS DATA FROM SCENARIO ANALYSIS

### TRENDS IN PASSENGER-KM

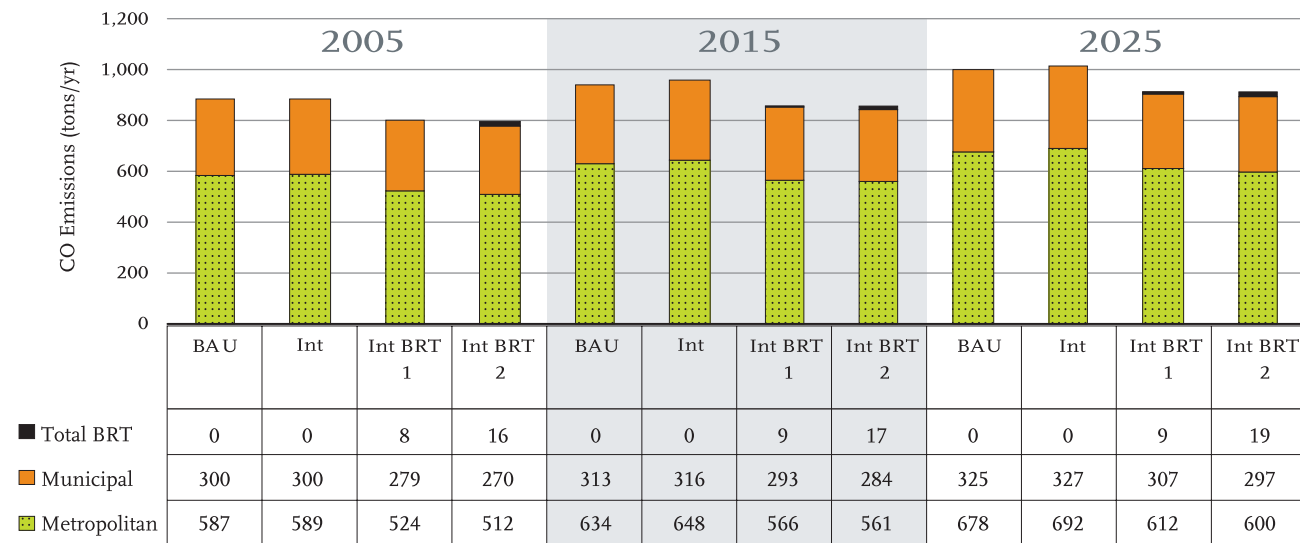


Source: Based on data from LOGIT, 2006

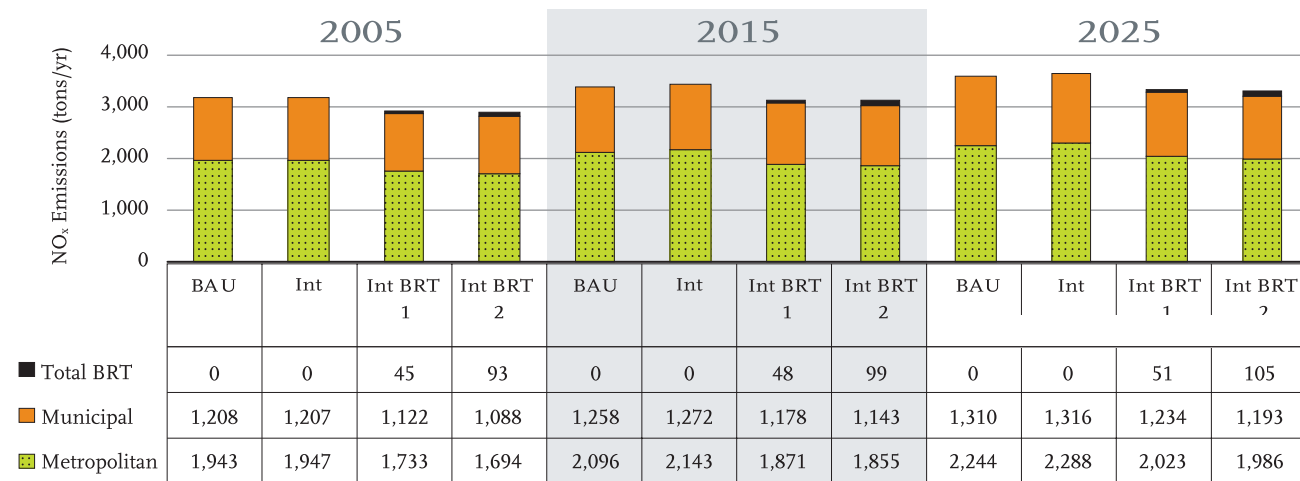
### ANNUAL CO<sub>2</sub> EMISSIONS PER PASSENGER-KM



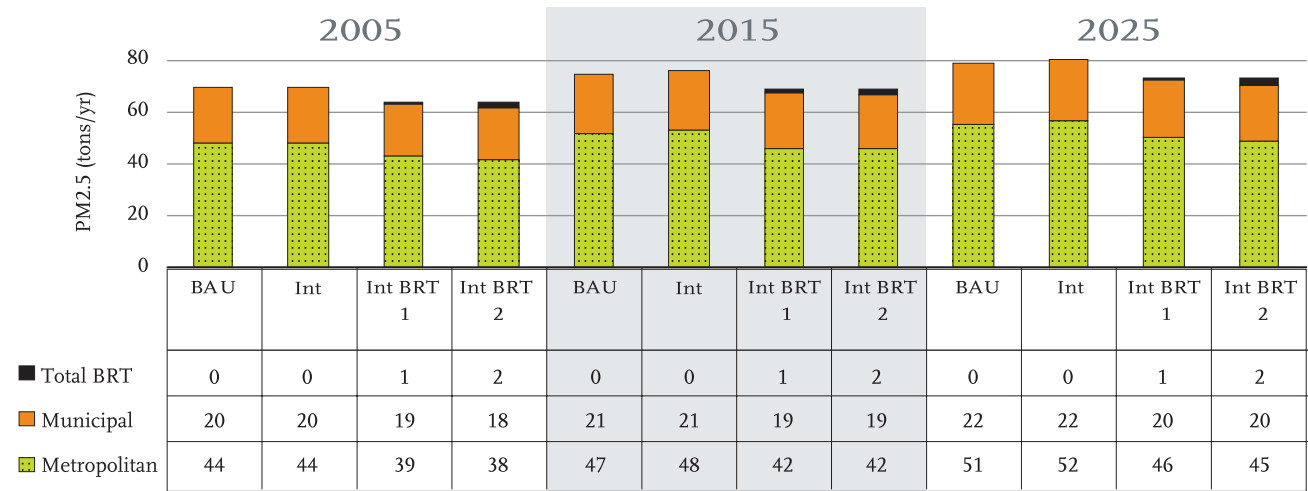
### CO EMISSIONS FROM URBAN, METROPOLITAN AND BRT FLEETS



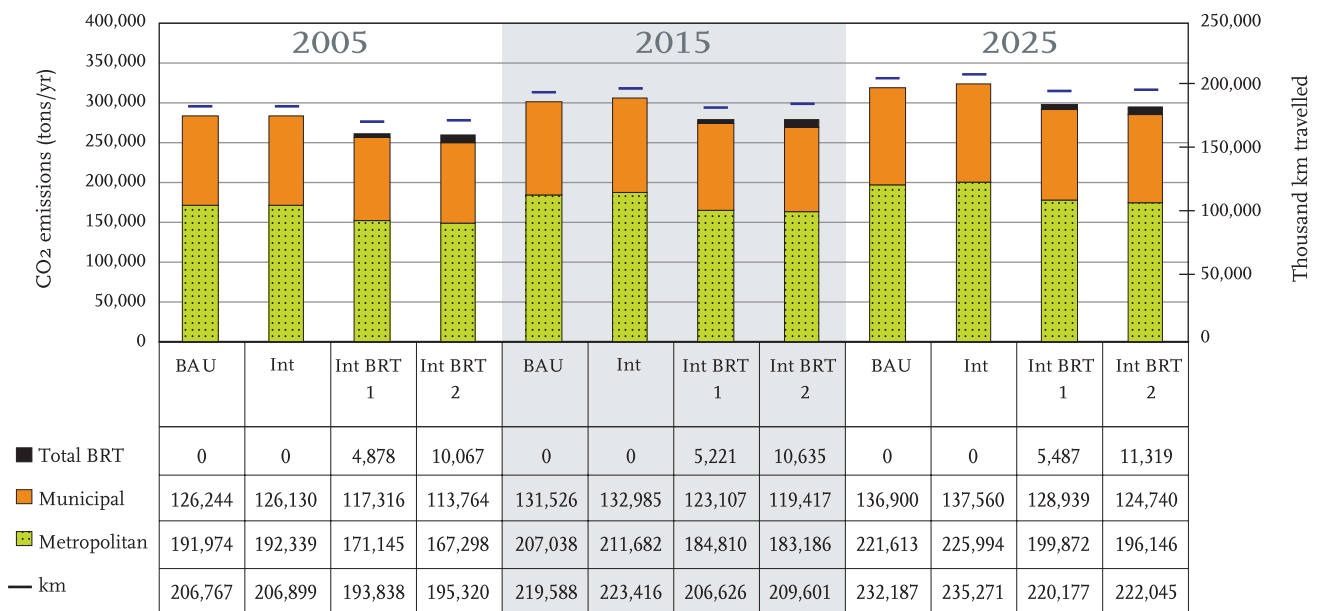
### NO<sub>x</sub> EMISSIONS FROM URBAN, METROPOLITAN, AND BRT FLEETS



### PM2.5 EMISSIONS FROM MUNICIPAL, METROPOLITAN, AND BRT FLEETS



### RELATIVE CO<sub>2</sub> CONTRIBUTION OF URBAN, METROPOLITAN, AND BRT FLEETS





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