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Inventory of conventional air pollutants emissions from road transportation for the state of Rio de Janeiro

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HIGHLIGHTS

- ► We estimate road transportation emissions for Rio de Janeiro from 1980 to 2010.
- ► *C* gasoline was most responsible for CO (74%) and diesel for PM (91%).
- ► Emissions/vehicle for Rio de Janeiro are (12% to 59%) smaller than Brazilian.
- ► 1,760,370 t of emissions was avoided using non-petroleum-based fuels.
- ► Strategies to reduce the emissions of these air pollutants were proposed.

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ABSTRACT

Road transportation has contributed to increased emissions of conventional air pollutants and, consequently, to the increase in problems associated with the environment and human health, depending on the type of pollutant and the concentration of it. To support the development of public policies aimed to decrease total tonnes of emissions, we used a bottom-up approach to estimate the amount of air pollutants, such as carbon monoxide (CO), total hydrocarbons (THC), nitrogen oxides (NO_x), particulate matter (PM), and aldehydes (RCHO), that are emitted by road transportation in the state of Rio de Janeiro (RJ) from 1980 to 2010. The results from 2010 show that cars are responsible for 55% of CO emissions, 61% of THC emissions, and 93% of RCHO emissions. Due to the use of hydrated ethanol and compressed natural gas (CNG) instead of petroleum based fuels during the period analyzed, 1,760,370 t of air pollutant emissions were avoided. Compared to Brazil, in 2010, RJ had a quantity of emissions per vehicle from 12% (CO) to 59% (PM) smaller than the national average. As strategies to reduce air pollutant emissions, we consider reducing the intensity of use, with a proportional reduction in emissions, and increased the use of biodiesel.

1. Introduction

Due to an energy dependency on petroleum products such as gasoline and diesel fuel, road transportation has contributed decisively to the emission of atmospheric pollutants, with consequent problems for the environment and human health (Faiz, 1993; Colvile et al., 2001; Saija and Romano, 2002; Öner and Altun, 2009; Uherek et al., 2010; and Progiou and Ziomas, 2011).

According to the Brazilian Ministry of Mines and Energy (MME), Ministério de Minas e Energia [Ministry of Mines and Energy], 2011, in 2010, the transportation sector consumed 53.1% of petroleum derivatives, of which 90% was used in road transportation. By analyzing the Brazilian states, we see that the state of Rio de Janeiro follows the national trend and stands out with the second highest Gross Domestic Product (GDP) in the country (11.3%) (IPEA, 2011). During the next five years (2012 to 2016), it will host international events such as the World Cup in 2014, and the Olympic Games in 2016.

Because of Rio de Janeiro's contribution to the Brazilian economy and its global exposure, it is important to identify the state's contribution to atmospheric pollutant emissions from road transportation in order to highlight upcoming opportunities to show the rest of the world how a country can successfully make the transition to cleaner transportation.

In the last two decades, the automobile industry has invested in technologies to reduce the emissions of air pollutants from

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road motor vehicles, prompted by stricter legislations. To support the development of public policies aimed to decrease total tonnes of emissions, it is essential to preparing an inventory of air pollutants emitted by the transportation sector in the state of Rio de Janeiro, specifically road transportation by its importance.

In this context, this study aimed to (1) estimate the quantity of conventional air pollutants such as carbon monoxide (CO), total hydrocarbons (THC), nitrogen oxides (NO_x), particulate matter (PM), and aldehydes (RCHO) emitted by road transportation in the state of Rio de Janeiro from 1980 to 2010; (2) compare the fleet size of road motor vehicles, fuel consumption, and emission of these pollutants in the state of Rio de Janeiro with those of Brazil; (3) verify the avoided emissions by using non-petroleum based fuels, such as hydrated ethanol and CNG, and (4) propose strategies to reduce the emissions of those air pollutants.

Therefore, a bottom-up approach was applied, which allowed for the identification of the main conventional air pollutants emitted in the studied region, as well as the contribution of each category of road motor vehicles in emitting these pollutants.

This study is divided into 7 sections. In Section 2, the conventional air pollutants that are emitted by road motor vehicles are identified. Section 3 describes a general view of policies for reducing air pollutant emissions from road motor vehicles. The methodology used to estimate the emissions of air pollutants is described in Section 4. Section 5 introduces and discusses the results from the inventory of air pollutant emissions from road transportation in the state of Rio de Janeiro. In Section 6, the strategies used to reduce air pollutant emissions from road motor vehicles are listed. Finally, in Section 7 we show final considerations, limitations, and suggestions for further studies.

2. Conventional air pollutants from road motor vehicles

Road motor vehicle technology (power supply and fuel systems, motor, and after treatment systems for exhaust gases), the type and quality of fuel used, maintenance and driving conditions, planning and land use, and meteorological factors (atmospheric pressure and ambient temperature) determine the type of air pollutants emitted (Thambiran and Diab, 2011).

Faiz (1993) classifies air pollutants into two categories: conventional pollutants, which mostly have a local impact, and greenhouse gases, which have a global impact. The local impact is related to problems such as urban air quality and human health. These are mostly responsible for air pollution in large cities, justifying the selection of the city of Rio de Janeiro for this study.

According to Faiz et al. (1996), air pollutant emissions could originate either from burning engine fuel (exhaust emissions) or fuel evaporation from power systems or engine crankcases (evaporative emissions), which may occur during vehicle use or when vehicles are at rest. Evaporative emissions can also occur in fuel distribution system, specially from CNG, ethanol and C gasoline, that are light fuels. However this study considered only end use emissions.

Exhaust emissions are composed of various substances such as carbon monoxide (CO), total hydrocarbons (THC), aldehydes (RCHO), nitrogen oxides (NO_x), and particulate matter (PM). In turn, evaporative emissions are composed of non-methane hydrocarbons ($NMHC_{evaporative}$) (Faiz et al., 1996).

United States Environmental Protection Agency (EPA) (2012), describes the six more common air pollutants as ozone (O_3), particulate matter (PM), carbon monoxides (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x) and lead.

However, we opted to consider CO, NO_x, PM, Aldehydes (RCHO) and total hydrocarbons (THC), the latter forming part of evaporative and exhaust emissions, because these pollutants are stated as air pollutants in Brazil for automotive emissions. Besides, those are the pollutants measured and considered in the Brazilian inventory (MMA, 2011), which allows a comparison between our inventory and the Brazilian one.

SO_x and O_3 were not considered because the emission factors for these pollutants are not available in the level of details that are necessary to apply the methodology. Lead was also not considered because it is not used in Brazil as ethanol is as an ant-knocking additive in gasoline. Except for flexible-fuel vehicles, which in 2010, represented 30% of the fleet, vehicles equipped with Otto Cycle engines mostly use gasoline as fuel and have emissions factors of CO, THC, and $NMHC_{evaporative}$ higher than vehicles equipped with Diesel cycle engines. Emissions of aldehydes (RCHO) are more closely related to the use of ethanol (hydrated ethanol, C gasoline and CNG, in this case when the vehicle is using the original fuel that can be C gasoline or ethanol). Vehicles equipped with Diesel cycle engines have emissions factors of NO_x and PM higher than vehicles equipped with Otto cycle engines (Heywood, 1988; Faiz et al., 1996).

Table 1
Emission limits established by PROCONVE and PROMOT in Brazil.
Source: MMA (1993, 2002a, 2002b, 2003 and 2008).

Phases [a, b]	PROCONVE–Vehicles with Otto engines						PROMOT–Motorcycles				
	L1	L2	L3	L4	L5	L6	M1	M2		M3	
								< 150 cc	≥ 150 cc	< 150 cc	≥ 150 cc
Emission Limits											
Date of implementation	1989	1992	1997	2007	2009	2014	2003	2005		2009	
CO (g/km)[c]	4.00	12.00	2.00	2.00	2.00	1.30	13	5.5		2	
HC (g/km)[d]	2.10	1.20	0.30	0.16	0.05	0.05	3	1.2	1	0.8	0.2
NO_x (g/km)[e]	2.00	1.40	0.60	0.25	0.12	0.08	0.3	0.3		0.15	
PM (g/km)[f]	–	–	–	–	–	–	–	–	–	–	–
RCHO (g/km)[g]	–	0.15	0.03	0.03	0.02	0.02	–	–	–	–	–

Notes:
[a] Li-Phase *i* of PROCONVE for light vehicles, where i: 1 to 6;
[b] Mj-Phase *j* of PROMOT for motorcycles, where *j*: 1 to 3.
[c] Carbon monoxide;
[d] Hydrocarbons;
[e] Nitrogen oxides;
[f] Particulate matter—this pollutant is stated only for vehicle with Diesel engines;
[g] Aldehydes.

3. Policies to reduce air pollutant emissions from road motor vehicles

According to Lin et al. (2003), Ribeiro and Cardoso (2003), and EPA (2010), atmospheric pollution in urban areas, mostly from the use of passenger and cargo road transportation, has been a great contributor of cardiovascular, respiratory, and gastrointestinal diseases, eye problems, skin lesions, and some types of cancer.

To minimize these impacts, Brazil was the first country in South America to adopt legislation focused on reducing air pollutants emissions from motor vehicles (Szwarcfiter, 2004). This initiative began with controlling engine emissions of gases and vapors and led to the creation of the Program to Control Air Pollution from Motor Vehicles (Programa de Controle da Poluição do Ar por Veículos Automotores-PROCONVE) by the Brazilian National Council of the Environment (Conselho Nacional do Meio Ambiente-CONAMA) in 1986 under Resolution number 18/86, in addition to the Program to Control Air Pollution from Motorcycles and Related Vehicles (Programa de Controle de Poluição do Ar por Motocicletas e Similares—PROMOT) in 2002 under Resolution number 297/02.

These programs aimed to establish air pollutant emission limits for motor vehicles with Diesel cycle engines (light commercial vehicles, buses, and trucks) and Otto cycle engines (cars and light commercial vehicles) and for motorcycles and related vehicles. The programs followed a pattern of gradual implementation phases, so that the automobile industry and fuel suppliers could gradually adapt and the emissions of conventional air pollutants could be reduced over time, as shown in Tables 1 and 2.

These initiatives have positively impacted the reduction of air pollutant emissions. It was estimated that even though the total number of vehicles circulating in Brazil has increased by 341% from 1980 to 2010, it was possible to reduce the emissions of almost all of the pollutants considered in this study (CO, THC, PM, and RCHO), with the exception of NO_x, as shown in Table 3.

In addition to following the limits established by PROCONVE and PROMOT all over the country, the state of Rio de Janeiro was the first state in the federation to implement an inspection and maintenance program for the motor-vehicle fleet.

Table 2
Emission limits established by PROCONVE–Diesel cycle engines, in Brazil.
Source: MMA (1993, 2002b and 2008).

Phases [a]	P1[h]	P2	P3	P4	P5	P6[b]	P7
Emission Limits							
Date of Implementation	–	1992	1994	1998	2006	–	2012
CO (g/kW h)[c]	14.00	11.20	4.90	4.00	2.10	1.50	1.50
HC (g/W h)[d]	3.50	2.45	1.23	1.10	0.66	0.46	0.40
NO_x (g/W h)[e]	18.00	14.40	9.00	7.00	5.00	3.50	2.00
PM (g/kW h)[f]	–	0.60	0.40	0.15	0.10	0.02	0.02
RCHO (g/kW h)[g]	–	–	–	–	–	–	–

Notes:
[a] Pi-Phase *i* of PROCONVE for vehicles with Diesel cycle engine, where *i*: 1 to 7;
[b] Phase P6 of PROCONVE has not entered into effect;
[c] Carbon monoxide;
[d] Hydrocarbons;
[e] Nitrogen oxides;
[f] Particulate matter;
[g] Aldehydes these pollutant are stated only for vehicle with Otto engines;
[h] In this phase, none of the pollutants were controlled.

4. Methodology to estimate emissions of conventional air pollutants

To estimate the emissions of conventional air pollutants from road transportation, a bottom-up approach was used considering the following main data sets: (1) road motor vehicle fleet in circulation (*Fc*), (2) intensity of use (*Iu*), and (3) emission factor (*Ef*), according to Eq. (1). This methodology is similar to that adopted by Szwarcfiter et al. (2005), Baidya and Borken-Kleefeld (2009), the Environmental Sanitation Technology Agency of the state of Sao Paulo (CETESB) (2011a), Huo et al. (2011), and the Brazilian Ministry of Environment (MMA) (2011).

$$E_{M,C,Y,P} = \left(\sum_{M=1}^{m} \sum_{C=1}^{n} Fc_{Y,M,C} * Iu_{Ajust_{Y,M,C}} * Ef_{P,Y,M,C} \right) / 10^6 \quad (1)$$

where *E* is Air emissions from road vehicles [t/year], *Fc* is Estimated road motor vehicle fleet in circulation [units], Iu_{Adjust} is Adjusted intensity of use [km/year], *Ef* is Emission factor [g/km], *Y* is Year, where *Y* varies from 1980 to2010, *P* is Type of pollutant, where *P* is CO, THC, NO_x, PM, and RCHO, *M* is Category, where *M* varies from 1 to *m* (using the categories shown in Table 4).

C is Type of fuel, where *C* varies from 1 to *n* (using the types of fuel shown in Table 4)

Air pollutant emissions were estimated for the period 1980 to 2000 for the pollutants and categories of vehicles shown in Table 4. This level of detail was necessary to quantify and identify the air pollutant emission in a disaggregated way, enabling specialized management of each source of air pollution.

4.1. Modeling vehicular fleet in circulation

To estimate emissions, it was necessary to obtain data on the circulating fleet by year, category, and type of fuel.

The Department of Vehicle Registration of the state of Rio de Janeiro (DETRAN) provides a database similar to that used for the registration of new vehicle sales by category and type of fuel. To estimate the lifetime of vehicles it was necessary to determine scrapping curves for vehicles that fit the characteristics of the fleet used in Rio de Janeiro (Fig. 1).

Table 3
Motor vehicle fleet size, air pollutant emissions and distance traveled by year for1980 and 2010 in Brazil.
Source: MMA (2011).

Year	Total Fleet (number of vehicles)	Emissions (*t*)					km/year[a]
		CO	THC	NO_x	PM	RCHO	
1980	9,307,366	4,702,658	848,022	716,330	42,675	7330	$174,728 \times 10^6$
2010	41,055,938	1,372,103	257,709	966,578	28,807	7103	$672,075 \times 10^6$
% Change	341%	−71%	−70%	35%[2]	−32%	−3%	285%

Note:
[2]The increase in NO_x could be attributed to the old Brazilian fleet of heavy vehicles (buses and trucks) still in operation, with an average age ranging between 17 and 21 years.
[a] Estimated by the use of total energy consumption and fuel economy.

Table 4
Categories of vehicles, type of fuel and air pollutants considered in this study.
Source: Author's elaboration.

Category of vehicle	Types of fuel		Air pollutants considered				
			Carbon monoxide (CO)	Nitrogen oxides (NO_x)	Particulate matter (PM)	Aldehydes (RCHO)	Total hydrocarbons (THC) [a]
Cars and light commercial vehicles	*C* gasoline[b]		X	X	X	X	X
	Hydrated ethanol		X	X	–	X	X
	CNG		X	X	–	X	X
	Flexible fuel[c]	*C* gasoline[b]	X	X	X	X	X
		Hydrated ethanol	X	X	–	X	X
Motorcycles	*C* gasoline[b]		X	X	X	–	X
	Hydrated ethanol		X	X	X	–	X
	Flexible fuel [c]	*C* gasoline[b]	X	X	X	–	X
		Hydrated ethanol	X	X	–	–	X
Light commercial vehicles	Diesel[d]		X	X	X	–	X
Light trucks			X	X	X	–	X
Medium trucks			X	X	X	–	X
Heavy trucks			X	X	X	–	X
Urban buses			X	X	X	–	X
Highway buses			X	X	X	–	X

Notes:
Legend: *X* means the atmospheric emissions from the intersection of vehicle category, type of fuel, and pollutant were considered;-means the emissions from the intersection of vehicle category, type of fuel, and pollutant were not considered, because emissions factors were not available.

[a] Determined from $NMHC_{exhaust}+NMCH_{evaporative}+CH_4$;
[b] *C* gasoline has an added percentage of anhydrous ethanol determined by the National Petroleum Agency (in 2010 it was approximately 25%);
[c] Flexible-fuel vehicles are vehicles with Otto cycle internal combustion engines that can be filled with more than one kind of fuel (*C* gasoline and hydrated ethanol), mixed in the same tank, and burned in the combustion engine simultaneously;
[d] From January 2008 a mixture of biodiesel and petroleum diesel was used throughout Brazil, with the following proportions: 2% biodiesel and 98% petroleum diesel until June 2008, 3% biodiesel and 97% petroleum diesel from July 2008 until December 2009, and 5% biodiesel and 95% petroleum diesel after January 2010.

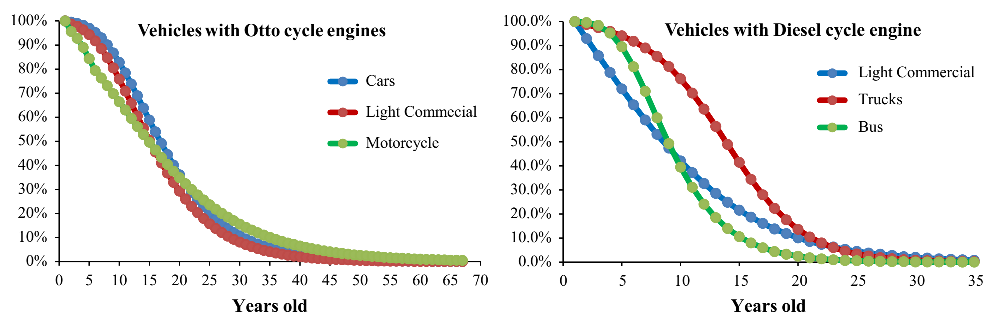

Fig. 1. Scrap curves for vehicles with Otto and Diesel cycle engines in Rio de Janeiro.
Source: Author's elaboration.

For cars, light commercial vehicles with Otto cycle engines, motorcycles, and buses (urban and highway), the Gompertz function was applied, while for light commercial vehicles with Diesel cycle engines and trucks (light, medium, and heavy), a renormalized logistic function was applied, as shown in Table 5.

Estimates of the road motor vehicle fleet in the state of Rio de Janeiro showed a continuous increase since 1980, reaching approximately 3 million vehicles in 2010 and representing approximately 7% of Brazil's fleet. As a matter of concern, in the last two decades, compared to cars, the number of motorcycles has increased 326%.

In 2010, individual transport (cars and motorcycles) represented more than 88% of the road motor vehicle fleet. Buses and trucks represented 3% and light commercial vehicles represented 9%. These last vehicles can be used to transport people or cargo. Sixty three percent of the vehicles were less than 10 years old and 8% were over 20 years old (Fig. 2).

The fleet of cars and light commercial vehicles powered by gasoline and hydrated ethanol can be estimated using the database provided by the DETRAN-RJ and the scrapping curves shown in Table 5. In opposition, the vehicles converted to CNG were estimated using the intersection of data regarding vehicles powered by CNG provided by DETRAN-RJ (2011) and data regarding vehicles converted to CNG by year; these sets of data were provided by Vieira (2011) and GASNET (2011), respectively. Vehicles that were converted to CNG were retired from the fleet they originally belonged to and became part of the fleet powered by CNG to avoid double counting vehicles.

4.2. Definition of intensity of use

The intensity of use is the estimated average distance traveled by each of the vehicles in the circulating fleet over a unit of time (year). In the state of Rio de Janeiro, there is no database that provides this information consistently. Therefore, for cars, light commercial vehicles (with Otto or Diesel cycle engines), and motorcycles, the reference intensities of use were based on data provided by MMA (2011), CETESB (2011a) and Szwarcfiter (2004). The intensities of use employed for urban and highway buses and light, medium, and heavy trucks were defined based on data provided by Freitas (2011), Borba (2008), Cachiolo (2011), CETESB (2011a), Ribeiro (2011), and MMA (2011).

Table 5
Scrap curves used for vehicles with Otto and Diesel cycle engines in Rio de Janeiro.
Source: Based on MMA (2011), Ribeiro (2011), ANTT (2010), and Rechder and Fonseca (2003).

Cycle	Vehicle	Coefficient			Equation
		a	b	t_0	
Otto	Cars	1.798	−0.137	–	$S.t = 1 - e^{-e^{(a+b \cdot t)}}$
	Light commercial	1.618	−0.141	–	
	Motorcycles	1.317[a]	−0.175[a]	–	
		0.923[b]	−0.093[b]		
Diesel	Bus	2.01	−0.300	–	
	Trucks	0.3	–	12.85	$S.t = \frac{1}{(1+e^{(a*(t-t_0))})} + \frac{1}{(1+e^{(a*(t+t_0))})}$
	Light commercial	0.2	–	4.00	

Notes:
Legend: S(t) – fraction of remaining vehicles with age t; t – age of vehicle [years]; a, b, and t_0 – variable parameters according to type of vehicle.

[a] Motorcycles <5 years old;
[b] Motorcycles ≥ 5 years old.

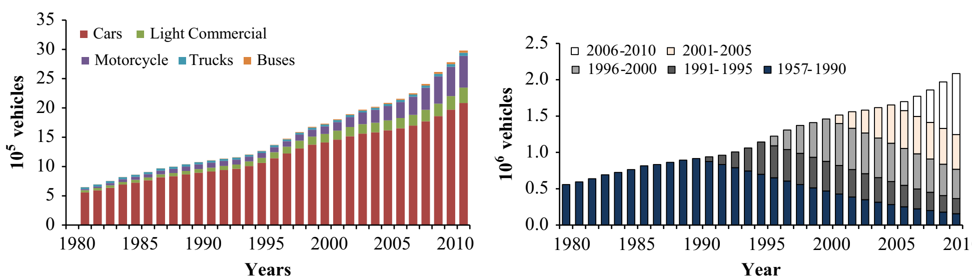

Fig. 2. Evolution of estimated road motor vehicle fleet by category and age in Rio de Janeiro.
Source: Author's elaboration.

Table 6
Reference intensity of use by category of road motor vehicle [km/year] in Rio de Janeiro.
Source: Based on Freitas (2011), Cachiolo (2011), Szwarcfiter (2004), MMA (2011), CETESB (2011a), and Borba (2008).

Cars	LCV	Cars/LCV_GNC	LCV_D	M	LT	MT	HT	UB	HB
20,000	20,000	30,000	20,000	12,000	16,530	60,000	90,000	90,000	90,000

Legend: LCV: light commercial vehicle–Otto cycle; LCV_GNC: light commercial vehicle–Otto cycle that use CNG; LCV_D: light commercial vehicles-Diesel cycle; M: motorcycles; LT: light trucks; MT: medium trucks; HT: heavy trucks; UB: urban buses; HB: highway buses;

Table 7
Fuel economy by category in Rio de Janeiro.
Source: Based on Szwarcfiter (2004), Borba (2008), Freitas (2011), Cachiolo (2011), MMA (2011),and CETESB (2011a).

Category of vehicle	Cars and LCV					M			LCV_D	LT	MT	HT	UB	HB
Fuel	*C* gasoline	Hydrated ethanol	CNG [a]	Flexible fuel *C* gasoline	Flexible fuel hydrated ethanol	*C* gasoline	Flexible fuel *C* gasoline	Flexible fuel hydrated ethanol	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Minimum yield (km/l)	8.9	6.9		10.3	6.9									
			12.0			40.0	40.0	25.0	9.1	3.9	3.0	2.6	2.3	3.0
Maximum yield (km/l)	12.0	8.7		12.0	8.0									

Note: LCV: light commercial vehicle–Otto cycle; LCV_D: light commercial vehicles-Diesel cycle; M: motorcycles; LT: light trucks; MT: medium trucks; HT: heavy trucks; UB: urban buses; HB: highway buses;

[a] Average fuel economy km/m^3.

Table 6 shows the reference intensity of use for each of the categories of road motor vehicles. The annual distances traveled by the vehicle assume a linear decline, based on MMA (2011), as the age of the vehicle increases.

Because the intensity of use for a vehicle is the factor that in Rio de Janeiro, as well as in Brazil, usually has the most uncertain values, it was necessary to adjust the value based on the consumption of fuel observed for road transportation in the state

Table 8
Average emission factors considered in this study.
Source: MMA (2011) and CETESB (2011b).

Category of vehicle	Type of fuel		Emission factor (g/km)																	
			CO			THC[a]			NO_X			$NMHC_{evaporative}$			PM			RCHO[b]		
			1990	2000	2010	1990	2000	2010	1990	2000	2010	1990	2000	2010	1990	2000	2010	1990	2000	2010
Cars	*C* gasoline		34.58	6.69	2.65	4.17	0.99	0.48	1.45	0.58	0.32	1.08	0.30	0.17	0.002	0.002	0.001	0.056	0.021	0.010
	Hydrated ethanol		18.24	15.71	14.90	2.44	3.10	2.67	1.37	1.23	1.20	0.62	1.43	1.06	NA	NA	NA	0.158	0.137	0.130
	Flexible fuel[c]	*C* gasoline	–	–	0.48	–	–	0.14	–	–	0.05	–	–	0.06	–	–	0.001	–	–	0.003
		Hydrated ethanol	–	–	0.60	–	–	0.13	–	–	0.06	–	–	0.05	–	–	NA	–	–	0.013
	CNG		0.560			0.246			0.290			–			–			0.004		
Light commercial	*C* gasoline		30.99	4.79	1.50	4.14	0.67	0.25	1.51	0.52	0.19	1.35	0.16	0.07	0.002	0.002	0.001	0.053	0.018	0.006
	Hydrated ethanol		17.56	13.07	11.86	2.42	2.61	2.13	1.41	1.14	1.04	0.61	1.13	0.78	NA	NA	NA	0.148	0.112	0.104
	Flexible fuel	*C* gasoline	–	–	0.45	–	–	0.13	–	–	0.04	–	–	0.06	–	–	0.001	–	–	0.003
		Hydrated ethanol	–	–	0.59	–	–	0.12	–	–	0.05	–	–	0.05	–	–	NA	–	–	0.013
	CNG		0.560			0.246			0.290			NA			–			0.004		
	Diesel		0.77	0.77	0.77	0.28	0.20	0.08	4.46	3.14	2.14	NA	NA	NA	0.275	0.128	0.041	NA	NA	NA
Trucks	Light	Diesel	1.81	1.52	0.94	0.66	0.53	0.24	10.39	8.05	5.37	NA	NA	NA	0.641	0.400	0.126	NA	NA	NA
	Medium		2.32	2.02	1.26	0.85	0.71	0.34	13.33	10.61	7.12	NA	NA	NA	0.822	0.551	0.186	NA	NA	NA
	Heavy		2.70	2.24	1.33	0.99	0.79	0.31	15.52	12.02	7.63	NA	NA	NA	0.958	0.591	0.159	NA	NA	NA
Bus	Urban	Diesel	3.06	2.33	1.44	1.12	0.79	0.30	17.62	11.67	8.20	NA	NA	NA	1.087	0.475	0.148	NA	NA	NA
	Highway		2.32	1.77	1.09	0.85	0.60	0.23	13.37	8.86	6.22	NA	NA	NA	0.825	0.361	0.112	NA	NA	NA
Motorcycles	*C* gasoline		19.70	19.70	5.26	2.60	2.60	0.75	0.10	0.10	0.12	NA	NA	NA	0.029	0.029	0.009	NA	NA	NA
	Flexible fuel	*C* gasoline	–	–	0.85	–	–	0.17	–	–	0.08	NA	NA	NA	–	–	0.004	–	–	NA
		Hydrated ethanol	–	–	0.58	–	–	0.16	–	–	0.07	NA	NA	NA	–	–	NA	–	–	NA

Note:
Note: NA: Emission factor not available.

[a] Equals $NMHC_{exhaust}+CH_4$;
[b] Aldehydes are emissions related to the use of C gasoline and ethanol. It is also found in CNG when the vehicle burns the original fuel (C gasoline or ethanol) because we considered bi-fuel vehicles, once it is possible to use CNG or the original fuel.
[c] The flexible-fuel vehicle started to be produced en 2003.

of Rio de Janeiro, according to Eq. (2).

$$IU_{Ajust_{Y,M,C}} = Iu_{ref_{Y,M,C}} * \frac{C_{observed\ c,y}}{\left(\sum_j Fr_{Y,M,C} * Iu_{ref_{A,M,C}} * R_{Y,M,C}\right)} \quad (2)$$

where Iu_{Adjust} = reference intensity of use adjusted for year (Y), category (M) and type of fuel (C) in kilometers, Iu_{ref} = reference intensity of use of vehicle by category (M), year (A), and type of fuel (C) in kilometers, Fr = vehicle fleet per year (Y), category (M) and type of fuel (C) in units, R = performance of vehicle by year (Y), category (M) and type of fuel (C) in liters per kilometer, and $C_{observed}$ = fuel consumption (C) by year (Y).

To calculate consumption and, consequently, adjusted intensity of use, the fuel economy shown in Table 7 were used.

4.3. Emission factors

The emission factors of air pollutants vary as a function of the pollutant analyzed, the category of vehicle, type of fuel, and vehicle year. Emission factors used for vehicles with Otto cycle engines are based on data from tests used to approve vehicles by CETESB (2011a), which is an agency of Sao Paulo's state government responsible for controlling, supervising, monitoring, and licensing pollution-generating activities across the country. The factors used for Diesel cycle engines were calculated based on data from MMA (1993, 2002b, 2008 and 2011).

For evaporative emissions from power systems in cars and light commercial vehicles equipped with Otto cycle engines, the diurnal emission (e_d), losses in motion (e_s), and the evaporative emissions of the vehicle that occur when the vehicle is at rest (e_r) were considered. Because 20% of the average annual minimum temperatures and 85% of the average annual average temperatures are greater than or equal to 20 °C (INMET, 2011), a conservative position was adopted in evaluating evaporate emission factors for the temperature range of 20–35 °C.

The use of vehicles affects emission factors. Because of that, for vehicles manufactured before 1995, when most of them were not equipped with catalytic converters, it was considered an increase of 0.000125% relative to the new-vehicle emission factor for each kilometer traveled until 160,000 km is reached and then remained constant beyond this distance for the pollutants CO, NMHC, and RCHO (MMA, 2011).

For cars and light commercial vehicles, powered by C gasoline and hydrated ethanol, manufactured between 1996 and 2008,

Table 9
Total air pollutant emissions from road transportation by category and fuel–2010 in Rio de Janeiro.
Source: Author's elaboration.

Items analyzed	CO		THC[a]		RCHO		NO_x		PM		Fuel consumed			
	(t)	(%)	(t)	(%)	(t)	(%)	(t)	(%)	(t)	(%)	C gasoline (l)	Hydrated ethanol (l)	CNG (m^3)	Diesel (l)
Category of vehicle														
Otto cycle														
Cars	47,794	54.7	10,436	61.4	294	92.7	7,597	15.6	23	2.7	1559×10^6	692×10^6	820×10^6	–
Light Commercial	3,654	4.2	920	5.4	23	7.3	825	1.7	2	0,2	169×10^6	52×10^6	149×10^6	–
Motorcycle	28,852	33.0	4,106	24.1	–	–	688	1.4	50	5.9	139×10^6	2×10^6	–	–
Diesel cycle														
Light commercial	342	0.4	36	0.2	–	–	944	2.0	18	2.0	–	–	–	49×10^6
Light trucks	206	0.2	52	0.3	–	–	1,179	2.4	28	3.2	–	–	–	56×10^6
Medium trucks	383	0.4	102	0.6	–	–	2,157	4.4	56	6.6	–	–	–	100×10^6
Heavy trucks	2,489	2.8	583	3.4	–	–	14,290	29.1	297	35.0	–	–	–	718×10^6
Urban buses	3,384	4.0	717	4.2	–	–	19,303	40.0	349	41.0	–	–	–	$1,024\times10^6$
Highway buses	286	0.3	60	0.4	–	–	1,629	3.4	29	3.4	–	–	–	84×10^6
Fuel														
C gasoline	64,573	73.9	10,833	63.7	149	47.0	4,947	10.2	75	8.8	1867×10^6			
Hydrated ethanol	9,215	10.5	1,777	10.4	124	39.1	792	1.6	–	–	746×10^6			
CNG	6,512	7.5	2,852	16.8	44	13.9	3,372	6.9	–	–	969×10^6			
Diesel	7,090	8.1	1,551	9.1	–	–	39,502	81.3	778	91.2	2033×10^6			

Note:
[a] Equals $NMHC_{exhaust} + NMHC_{evaporative} + CH_4$.

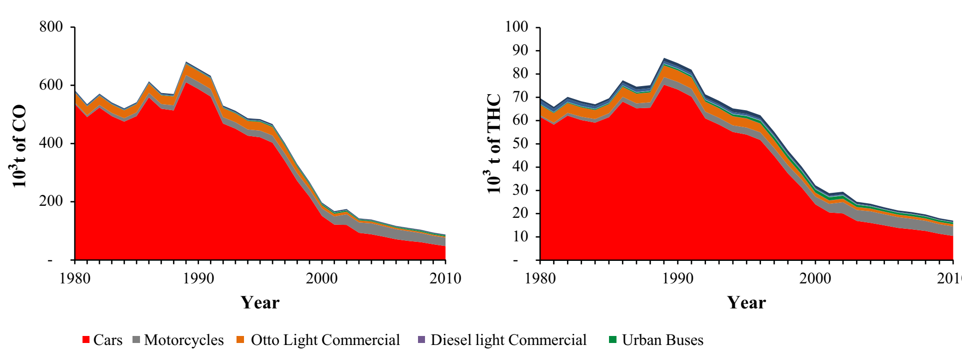

Fig. 3. Emissions of CO and THC by road motor vehicle category in Rio de Janeiro.
Source: Author's elaboration.

it was considered an increased in pollutant-emission factors for every 80,000 km traveled: CO (0.263 and 0.224), NMHC (0.023 and 0.024), RCHO (0.00065 and 0.00276) and NO_x (0.03 and 0.02) (MMA, 2011). Table 8 shows a summary of the average emission factors for the years 1990, 2000, and 2010.

5. Discussion

Applying the methodology described in item 4, it was possible to obtain an estimate of conventional air pollutant emissions from road transportation for the period 1980–2010 in the state of Rio de Janeiro.

5.1. Estimating atmospheric pollutants from road transportation

Table 9 shows the total emission of pollutants CO, THC, RCHO, NO_x, and PM by vehicle category and type of fuel for the year 2010.

Figs. 3 to 5 show the evolution of estimated air pollutant emissions from road transportation for the period 1980 to 2010.

Vehicles with Otto cycle engines showed a higher contribution in CO emissions (approximately 92%), especially from cars (54.7% in 2010). When analyzing the fuel type used, C gasoline showed the highest contribution to emissions (73.9% in 2010).

Regarding the contribution of each vehicle category to THC emissions, cars had the greatest contribution in total THC emissions (61.3% in 2010). Notably, C gasoline was the fuel with the highest contribution to THC emissions, representing 63.7% of total emissions in 2010.

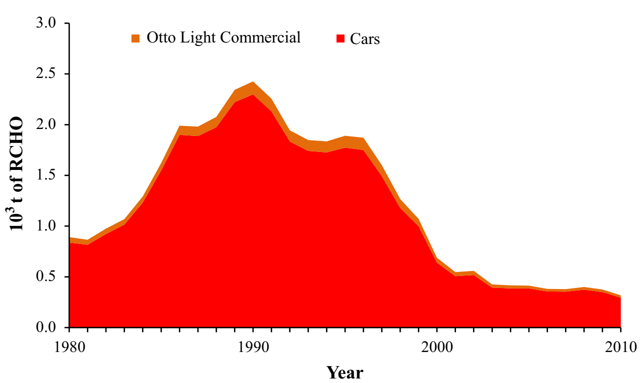

Fig. 4. Emissions of RCHO by road motor vehicle category in Rio de Janeiro. *Source*: Author's elaboration.

It can be noted that cars were the category that contributed most to RCHO emissions (92.7%). By analyzing the impact of fuel in relation to RCHO emissions, the results showed that in 2010 C gasoline and hydrated ethanol were the fuels that showed the highest contributions to RCHO emissions (47% and 39.1%, respectively). C gasoline has a high impact on RCHO emissions because it has up to 25% of anhydrous ethanol and it is by far the most used fuel for vehicles that use Otto cycle engines (Table 9). The decrease in RCHO emissions at the end of the 1990s reflects the removal of ethanol dedicated vehicles. With the introduction of flexible fuel vehicles after 2003, an increase in emissions from hydrated ethanol use was found.

The estimates of NO_x emissions show that emissions from vehicles with Diesel cycle engines are the dominant contributor, with urban buses and heavy trucks showing the highest contributions (in 2010, 39.7% and 29.4%, respectively). A sharp increase in emissions was noted at the end of the 1980s, which extended until the end of the 1990s, when the phase P4 of PROCONVE began (Table 2). When we analyzed the contribution of fuel types to the total estimated emissions of NO_x, diesel stands out, as it is responsible for 81.3% of NO_x emissions in 2010.

Heavy vehicles (buses and trucks) stand out in estimated emissions of PM. In 2010, urban buses contributed 41% and heavy trucks 35% to PM emissions. Analyzing the contribution of fuels in relation to PM emissions, we found that, in 2010, 91% of PM emitted by the road-transportation sector came from diesel fuel consumption.

Because of the initiatives to reduce the emissions of air pollutants (Tables 1 and 2), we found that even though the fleet in circulation increased by 359% and the total kilometers driven increased by 150% from 1980 to 2010, it was possible to reduce the emissions of all of the pollutants considered in this study (CO, THC, NO_x, PM, and RCHO), according to Table 10. In general, sharper reductions in emissions occurred at the end of the 1990s because of the introduction of the L3 and P4 phases of PROCONVE (Tables 1 and 2), when the regulated emission limits became stricter.

The situation shown in Table 10 highlights the effectiveness of implementing PROCONVE and PROMOT.

Once the kilometers traveled per vehicle by the fleet of Rio de Janeiro and Brazil are almost the same (Table 11) the fact that the state of Rio de Janeiro has reduced NO_x total emissions, a pollutant whose amount has increased in Brazil's total emissions, might be associated with the average age of Rio de Janeiro buses and trucks fleet (ranging between 9 and 13.5 years), that is lower than in Brazilian trucks and buses fleet (ranging between 17 and 21 years according to MMA, 2011). In terms of Brazil, the state of Rio de Janeiro shows a smaller quantity of emissions per vehicle and per km, as shown in Table 11.

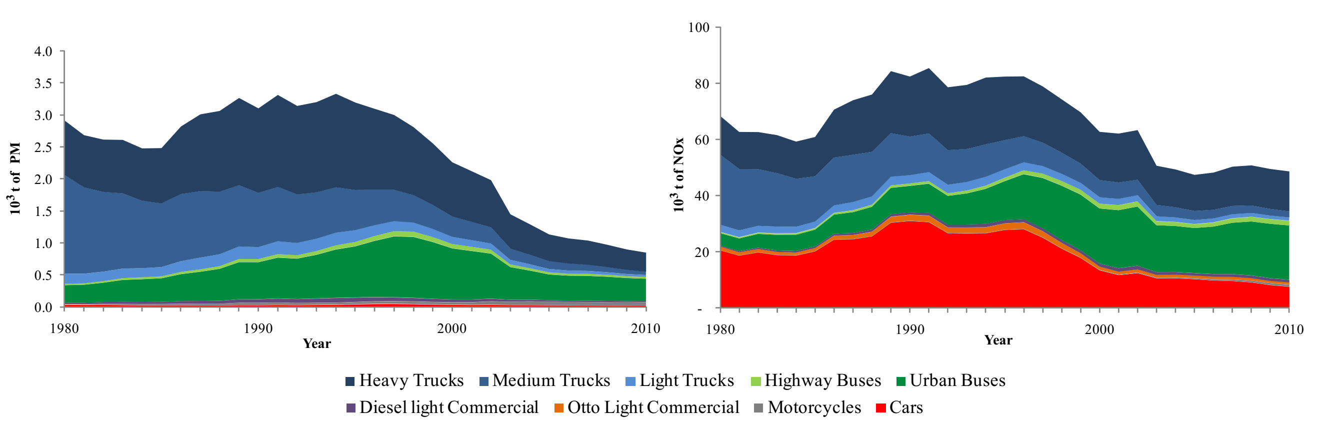

Fig. 5. Emissions of NO_x and PM by road motor vehicle category in Rio de Janeiro. *Source*: Author's elaboration.

5.2. Atmospheric emissions avoided due to the use of alternative non petroleum based fuels

Worldwide, the transportation sector mainly uses petroleum based fuels. Brazil and, consequently, the state of Rio de Janeiro share this same tendency. However, the country and Rio de Janeiro have sought to use alternative fuels to petroleum to not only minimize their dependence on petroleum but also to reduce emissions of conventional air pollutants and greenhouse gases.

The state of Rio de Janeiro has a fleet with vehicles that use hydrated ethanol and CNG as fuel (17% and 20% in 2010, respectively). To verify the reduction in air pollutant emissions from 1980 to 2010, we performed simulations that disregarded the use of hydrated ethanol and CNG as fuel. Later, the simulations were compared to the base situation to verify the amount of pollutants (CO, THC, NO_x, PM, and RCHO) avoided in each one of the situations (use of hydrated ethanol and CNG) (Table 12).

The quantity of atmospheric pollutant emissions that was avoided over 30 years (Table 12) suggests that the use of alternative fuels, instead of petroleum based fuels, was a positive approach to reduce most of air pollutant emissions and depending on the circumstances to improve air quality. In Table 12, it can be verified, for the total emissions of atmospheric pollutants, that the use of hydrated ethanol reduced emissions of CO, NO_x, PM and THC, with greater emphasis in CO (−10.90%) and THC (−13.08%). In addition, it should be considered that hydrated ethanol is a renewable fuel that positively impacts both the environment (reduces emissions of most of conventional pollutants and carbon dioxide that is a greenhouse gas) and society, by creating jobs and generating income outside the cities.

However, it is necessary to be aware of the fact that the use of ethanol increased RCHO emissions (37.15%), which are toxic and highly reactive precursors in forming ground-level ozone pollution (WHO, 1995). Besides that, many other environmental considerations should be evaluated to verify the environmental advantages and disadvantages of biofuels, such as efficient land use and biomass use (Cherubini and Strømman, 2011).

The use of CNG lightly reduced emissions of CO, PM, THC and RCHO, in small amount but with greater emphasis in CO (−1.7%) and RCHO (−1,9%).

6. Strategies to reduce air pollutant emissions from road motor vehicles

The emissions of conventional air pollutants are affected by the vehicle fleet, emission factors, and intensity of use. Because this last parameter is the most uncertain in Rio de Janeiro, to verify the impact of vehicle use on emissions of cumulative air pollutions, the emissions were estimated by considering a reduction of 5% and 10% in the reference intensity of use, which led to a proportional reduction in emissions, as shown in Table 13.

A reduction in the intensity of vehicle use can be achieved through an incentive to use public transportation, beginning a shift in usage and regulatory measures for individual transportation (car and motorcycle).

The type of fuel used is another factor that impacts emissions of atmospheric pollutants. In this context, the consumption of biodiesel has increased 1679% from 2006 (60×10^3 m^3) to 2009 (1228×10^3 m^3), due to the fact that this fuel was introduced in 2006 and that was the growth stage of consumption. Considering both the consumption of biodiesel and ethanol it was possible to reach 18.8% of the energy consumed in 2009 in Brazil by the transportation sector. The state of Rio de Janeiro has followed the national trend; however, it can be assumed that initiatives can expand the use of biofuels even further.

Therefore, for 2010, an increase in the use of biodiesel (mixture of 80% petroleum diesel and 20% biodiesel-B20) was estimated considering an energy-content-based substitution, according to Table 13.

The use of ethanol from 1980 to 2010 has provided the reduction of all air pollutants but RCHO due to the smaller emission factors ethanol Otto cycle engine showed before 1996

Table 11
Selected results of air pollutant inventory for comparison between the state of Rio de Janeiro and Brazil (2010).
Source: Authors' elaboration based on MMA (2011).

Items analyzed		Regions analyzed		
		Rio de Janeiro[a]	Brazil[b]	(%) RJ/Brazil
Fleet	(Vehicles)	2,979,317	41,055,938	7
Fuel consumption	(10^6 m^3)	4,647,597	82,850,070	6
	(10^6 m^3/ vehicle)	1.56	2.02	77
Energy consumption	(10^6 MJ)	176,801	2,591,891	7
	(MJ/vehicles)	3.68	3.86	95
km/year[c]	(10^6 km)	48,102	672,075	7
km/vehicle	(km)	16,145	16,370	99
CO	(10^6 g)	87,390	1,372,103	6
	(g/km)	1.817	2.042	89
	(g/vehicle)	29,332	33,420	88
THC[d]	(10^6 g)	17,015	257,709	7
	(g/km)	0.354	0.383	92
	(g/vehicle)	5,711	6,277	91
RCHO	(10^6 g)	318	7,103	4
	(g/km)	0.007	0.011	63
	(g/vehicle)	107	173	62
NO_x	(10^6 g)	48,613	966,578	5
	(g/km)	1.011	1.438	70
	(g/vehicle)	16,317	23,543	69
MP	(10^6 g)	852	28,807	3
	(g/km)	0.018	0.043	41
	(g/vehicle)	286	702	41

Note:
[a] Data elaborated by the authors.
[b] Data taken by MMA (2011);
[c] The Brazilian average (km/year) was estimate considering the fuel consumption and the average of fuel economy informed by MMA (2011);
[d] Equals $NMHC_{exhaust}+NMHC_{evaporative}+CH_4$.

Table 10
Motor vehicle fleet size, air pollutant emissions and distance traveled by year for 1980 and 2010 in Rio de Janeiro.
Source: Author's elaboration.

Year	Total fleet (number of vehicles)	Emissions (t)					km/year
		CO	THC[a]	NO_x	PM	RCHO	
1980	649,397	583,667	69,689	68,400	2917	892	$19,256\times10^6$
2010	2,979,320	87,390	17,013	48,613	852	318	$48,102\times10^6$
% Change	359%	−85%	−76%	−29%	−71%	−64%	150%

Note:
[a] Equals $NMHC_{exhaust}+NMHC_{evaporative}+CH_4$.

Table 12
Estimated emissions avoided due to hydrated ethanol and CNG use—1980 to 2010 in Rio de Janeiro.
Source: Author's elaboration.

Alternatives analyzed	Cumulative emissions–1980 to 2010									
	CO		NO_x		PM		THC[1]		RCHO	
	(t)	(%)	(t)	(%)	(t)	(%)	(t)	(%)	(t)	(%)
Base situation	11,963,781	–	2,059,296	–	73,858	–	1,625,058	–	38,023	–
Without using hydrated ethanol	13,268,397	10.90	2,100,026	1.98	74,199	0.46%	1,837,614	13.08%	23,897	−37.15
Emissions avoided due to hydrated ethanol use	1,304,616	–	40,729	–	341	–	212,556	–	−14,126	–
Without using CNG	12,166,612	1.70	2,056,559	0.13	73,945	0.12	1,640,418	0.95	38,737	1.88
Emissions avoided due to CNG use	202,831	–	2,738	–	87	–	15,360	–	715	–

Note:
[1] Equals $NMHC_{exhaust}+NMHC_{evaporative}+CH_4$.

Table 13
Sensitivity analysis for intensity of use and renewable fuels use—year 2010-Rio de Janeiro.
Source: Author's elaboration.

Alternatives analyzed	CO		NO_x		PM		THC[a]		RCHO	
	(t)	(%)	(t)	(%)	(t)	(%)	(t)	(%)	(t)	(%)
Base situation	87,390		48,613		852		17,013		318	
5% reduction in intensity of use	83,020	−5	46,182	−5	809	−5	16,162	−5	302	−5
10% reduction in intensity of use	78,651	−10	43,751	−10	7668	−10	15,311	−10	286.2	−10
15% increase biodiesel in B5[b] mixture	87,333	−0.07	48,613	0.00	839	−1.57	17,013	0.00	318	0.00

Notes:
[a] Equals $NMHC_{exhaust}+NMHC_{evaporative}+CH_4$,
[b] Equals 95% diesel oil and 5% biodiesel.

if compared to C gasoline Otto cycle engines. However, nowadays the use of this fuel does not necessarily result in a significant net reduction in conventional air pollutants over C gasoline (see Table 8).

In the case of B20, a light reduction in emissions of CO (0.07%) and PM (1.57%) was verified. For the other pollutants, (NO_x, THC, and RCHO) variations were not observed.

To promote the replacement of petroleum based fuels, such as diesel, with renewable fuels, such as biodiesel, incentives to use biofuels should be aligned with policies to ensure a price and supply that guarantee benefits to the customer.

7. Final considerations, limitations, and suggestions for future studies

Completing an inventory of air pollutant emissions from road transportation constitutes an important task that enables the evaluation of the great challenge the state of Rio de Janeiro will face: to promote development while improving transportation infrastructure, reducing air pollutant emissions, and improving air quality.

The significance of this model and its results, as a way to illustrate how increased substitution of certain fuels and vehicles result in quantifiable changes to the total regional emission inventory can help to improve transportation planning in a sustainable way.

To complete this inventory, a bottom-up approach was used to verify which categories of vehicles showed the greatest contribution to emissions of conventional air pollutants with local impacts. It was estimated that in 2010 cars were responsible for 55% of CO emissions, 61% of THC emissions, and 93% of RCHO emissions. Heavy trucks and urban buses were responsible for 69% of total NO_x emissions and 76% of PM emissions. These results enable the government of Rio de Janeiro to make relations between motor vehicle category and air pollutant emission by factor and to establish guidelines to promote the reduction of such air pollutant in order to reduce the environmental impact of road transportation.

Compared to Brazil, the state of Rio de Janeiro has a circulating fleet that represented, in 2010, approximately 7% of the country's total fleet and consumed approximately 6% of total fuel in the country. As a result, the state of Rio de Janeiro was responsible for 6% of total atmospheric emissions (CO, THC, PM, NO_x, and RCHO) in the country, with this percentage reflecting 6% of CO emissions, 5% of NO_x and THC emissions, 4% of RCHO emissions, and 3% of PM emissions.

Overall, the fleet of motor vehicles in the state of Rio de Janeiro emits less conventional air pollutants per vehicle and per km than the Brazilian fleet. In addition, in 2010, reductions per vehicle of 12% less CO emissions, 26% THC emissions, 38% RCHO emissions, 31% NO_x emissions, and 59% PM emissions were observed. Once the kilometers traveled per vehicle by the fleet of Rio de Janeiro and Brazil are almost the same, this situation could be related to the fact that a part of the fleet of vehicles of Rio de Janeiro has a lower average age if compared to the fleet of Brazil. This newer fleet of road motor vehicles has smaller emissions factor for all pollutants due to the emission limits established by PROCONVE (Tables 1 and 2) and PROMOT (Table 1).

Based on the results of this study, potential strategies to reduce emissions of conventional air pollutants, such as reducing the intensity of use and increasing the use of biofuel (biodiesel), were analyzed.

It was found that reducing the intensity of use leads to proportional reductions in emissions of all of the conventional air pollutants. An increase in the use of biodiesel showed a marginal reduction in only CO and PM emissions.

One should also consider that the state of Rio de Janeiro has encouraged the use of alternative fuels instead of petroleum based products by using ethanol since the 1970s and CNG since the 1990s. During the period studied (1980 to 2010), the use of alternative fuels avoided the emission of 1507,446 t of CO, 37,992 t of NO_x, 428 t of PM, and 227,915 t of THC, with RCHO increasing by 13,411 t.

The main limitation in this study was the difficulty in obtaining reliable data on the state's vehicle fleet and the intensity of use. Because of this limitation it was also not possible to include the results of Inspection and Maintenance (I&M) programs in the model (Eq. (1)).

As a complement to this study, we suggest a projection to the years 2020 and 2030 of atmospheric air pollutants to predict future trends. Strategies to reduce emissions can be simulated to provide support in decision making.

In addition, we suggest that future studies estimate emissions of greenhouse gases (GHG) from road transportation. It is also possible to estimate and thereby compare emissions of GHG from other forms of transportation.

References

(ANTT) Agência Nacional de Transportes Terrestres, 2010. Relatório Anual [Annual Report.] 2010, Brasília, DF. Brazil.

Baidya, S., Borken-Kleefeld, J., 2009. Atmospheric emissions from road transportation in India. Energy Policy 37, 3812–3822.

Borba, B.S.M.C., 2008. Metodologia de regionalização do mercado de combustíveis automotivos no Brasil. Dissertação de mestrado–Planejamento Energético [Methodology of Regionalization in the Market for Automobile Fuel in Brazil. Master's thesis—Energetic Planning], Universidade Federal do Rio de Janeiro, COPPE/UFRJ, Rio de Janeiro, RJ.

Cachiolo, A., 2011. Dados sobre rendimento e intensidade de uso de caminhões. [Data on the Performance and Intensity of Use of Trucks.] Diretor da Replace Transportadora Ltda, Rio de Janeiro, RJ.

(CETESB), Companhia Ambiental do Estado de São Paulo, 2011a. Inventário de emissão dos gases de efeito estufa associada ao transporte rodoviário no Estado de São Paulo, 1990 a 2008. [Inventory of Greenhouse Gas Emissions Associated with Road Transportation in the State of São Paulo, 1990 to 2008.] São Paulo, SP, Brasil.

(CETESB),Companhia Ambiental do Estado de São Paulo, 2011b. Qualidade do ar no estado de São Paulo 2010. [Air Quality in the State of São Paulo 2010.] São Paulo, SP, Brasil.

Cherubini, F., Strømman, A.H., 2011. Life cycle assessment of bioenergy systems: state of the art and future challenges. Bioresource Technology 102 (2), 437–451.

Colvile, R.N., Hutchinson, E.J., Mindell, J.S., Warren, R.F., 2001. The transport sector as a source of air pollution. Atmospheric Environment 35, 1537–1565.

(DETRAN-RJ),Departamento estadual de Trânsito do Estado do Rio de Janeiro, 2011 Dados sobre veículos cadastrados no Estado do Rio de Janeiro. [Data on Registered Vehicles in the State of Rio de Janeiro. Database.] Banco de dados, Rio de Janeiro, RJ.

(EPA), Environmental Protection Agency, 2010. Effects of Air Pollutants—Health Effects. U.S. Available at: 〈http://www.epa.gov/apti/course422/ap7a.html〉 (accessed on Feb./02/2012).

(EPA) Environmental Protection Agency, 2012. What Are the Six Common Air Pollutants? Available at: 〈http://www.epa.gov/air/urbanair/〉 (accessed on jul./23/2012).

Faiz, A., 1993. Automotive emissions in developing countries-relative implications for global warming, acidification and urban air quality. Transportation Research: Part A: Policy and Practice 27 (3), 167–186.

Faiz, A., Weaver, C.S., Walsh, M.P., 1996. Air pollution from motor vehicles. Standards and Technologies for Controlling Emissions. The Word Bank, Washington, DC, USA.

Freitas, F.A., 2011. Dados sobre rendimento e intensidade de uso de caminhões. [Data on the Performance and Intensity of Use of Trucks.] Administração central da AMBEV (American Beverage Company), São Paulo, SP.

GASNET, 2011. Informação sobre número de veículos convertidos por ano. [Information on the Number of Vehicles Converted per Year.] Available at 〈http://www.gasnet.com.br/novo_gnv/〉 perfil_gnv_brasil.asp. (accessed on Sep/30/2011).

Heywood, J.R., 1988. Pollutant Formation and Control in Internal Combustion Engine Fundamentals. McGraw-Hill Inc., Science/engineering/math, pp 567–597.

Huo, H., Zang, Q., He, K., Yao, Z., Wang, X., Zheng, B., Streets, D.G., Wang, Q., Ding, Y., 2011. Modeling vehicle emissions in different types of Chinese cities: importance of vehicle fleet and local features. Environmental Pollution 159, 2954–2960.

(INMET) Instituto Nacional de Metereologia [National Institute of Meteorology], (2011). Normais Climatológicas do Brasil 1961–1990. [Climatological Norms in Brazil 1961–1990.] Brasília, DF. Brazil.

(IPEA), Instituto de Pesquisa Econômica Aplicada [Institute of Applied Economic Research], 2011. PIB estadual a preços constantes. [State GDP at constant rates] Available at 〈www.ipeadata.gov.br〉, (accessed on Feb/02/2012).

Lin, C.A., Pereira, L.A.A., Conceição, G.M., Kishi, H.S., Milani Jr, R., Braga, A.L.F., Saldiva, P.H.N., 2003. Association between air pollution and ischemic cardiovascular emergency room visits. Environmental Research. 92 (1), 57–63.

(MMA), Ministério do Meio Ambiente [Ministry of the Environment], 1993. Resolution CONAMA n° 8, 31/08/1993, Conselho Nacional do Meio Ambiente [National Council of the Environment], Brasília, DF, Brazil.

(MMA), Ministério do Meio Ambiente [Ministry of the Environment], 2002a. Resolution CONAMA n° 297, 26/02/2002, Conselho Nacional do Meio Ambiente [National Council of the Environment], Brasília, DF, Brazil.

(MMA), Ministério do Meio Ambiente [Ministry of the Environment] 2002b. Resolution CONAMA n° 315, 29/10/2002, Conselho Nacional do Meio Ambiente [National Council of the Environment], Brasília, DF, Brazil.

(MMA), Ministério do Meio Ambiente [Ministry of the Environment], 2003. Resolution CONAMA no 342, 25/09/2003, Conselho Nacional do Meio Ambiente [National Council of the Environment], Brasília, DF, Brazil.

(MMA), Ministério do Meio Ambiente [Ministry of the Environment], 2008. Resolution CONAMA n° 403, 11/11/2008, Conselho Nacional do Meio Ambiente [National Council of the Environment], Ministério do Maio Ambiente, Brasília, DF, Brasil.

(MMA), Ministério do Meio Ambiente [Ministry of the Environment], 2011. Primeiro Inventário Nacional de Emissões Atmosféricas por Veículos Automotores Rodoviários. [First National Inventory of Atmospheric Emissions by Motor Vehicles. Final report] Relatório Final, Brasília, DF, Brazil.

(MME), Ministério de Minas e Energia [Ministry of Mines and Energy], 2011. Balanço Energético Nacional — Relatório Final, [National Energy Balance — Final Report]. Brasília, DF, Brazil.

(MMA), Ministério do Meio Ambiente [Ministry of the Environment], 2011. Balanço Energético Nacional –.

Öner, C., Altun, S., 2009. Biodiesel production from inedible animal tallow and an experimental investigation of its use as alternative fuel in a direct injection diesel engine. Applied Energy 86, 2114–2120.

Progiou, A.G., Ziomas, I.C., 2011. Road traffic emissions impact on air quality of the Athens Area based on a 20 year emissions inventory. Science of the Environment 410–411, 1–7.

Rechder, H. e Fonseca, W., 2003. Como evoluíram os caminhões. [How Trucks Evolved] Transporte Moderno, ano 40, n. 403, abril/maio [April/May], OTM Editora, Ltda, São Paulo, SP, pp.: 30–31.

Ribeiro, G.S.R.B., 2011. Dados sobre rendimento, intensidade de uso e frota ônibus no Estado do Rio de Janeiro. [Data on Performance, Intensity of Use, and Bus Fleets in the State of Rio de Janeiro.] Engenheira de meio ambiente, Departamento de Mobilidade Urbana da Federação das Empresas de Transportes de Passageiros do Estado do Rio de Janeiro [Environmental Engineering, Department of Urban mobility of the Federation of Passengers Transport Companies] (FETRANSPOR), Rio de Janeiro, RJ.

Ribeiro, H., Cardoso, M.R.,.A., 2003. Air pollution and children's health in São Paulo (1986–1998). Social Science & Medicine 57, 2013–2022.

Saija, S., Romano, D., 2002. A methodology for the estimation of road transport air emissions in urban areas of Italy. Atmospheric Environment 36, 5377–5383.

Szwarcfiter, L., 2004. Opções para o aprimoramento do controle de emissões veiculares de poluentes atmosféricos no Brasil–uma avaliação do potencial de programas de inspeção e manutenção e de renovação acelerada da frota. [Options for Improving the Control of Vehicle Emissions of Atmospheric Pollutants in Brazil–an Evaluation of the Potential of Inspection and Maintenance Programs and Accelerated Renovation of the Fleet.] Tese de doutorado—Planejamento Energético [Ph.D. Dissertation—Energetic Planning], Universidade Federal do Rio de Janeiro, COPPE/UFRJ, Rio de Janeiro, RJ.

Szwarcfiter, L., Mendes, F.E., La Rovere, E.L., 2005. Enhancing the effects of the Brazilian program to reduce atmospheric pollutant emissions from vehicles. Transportation Research: Part D 10, 153–160.

Thambiran, T., Diab, R.D., 2011. Air pollution and climate change co-benefit opportunities in the road transportation sector in Durban, South Africa. Atmospheric Environment 45, 2683–2689.

Uherek, E., Halenka, T., Borken-Kleefeld, J., Balkanski, Y., Berntsen, T., Borrego, C., 2010. Transport impacts on atmosphere and climate: land transport. Atmospheric Environment 44, 4772–4816.

Vieira, C., 2011. Dados sobre venda de gás e total de veículos convertidos. [Data on the Sale of Gas and Total Vehicles Converted.] Diretoria Geral do Grupo Gás Natural Fenosa, Rio de Janeiro, RJ.

WHO, World Health Organization, 1995. International Programme on Chemical: Safety Environmental Health Criteria, 167. Acetaldehyde. Geneva.