Vehicular Emission Factor of Gases and Particulate Matter Measured in Two Road Tunnels in São Paulo, Brazil

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Abstract In this paper we show measurements of air pollutants for a mixed vehicle fleet, heavy and light duty vehicles (HDV, LDV), in the Rodoanel and Janio Quadros tunnels in the Metropolitan Region of Sao Paulo (MRSP) in May-July 2011. Measurements of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x) and Particle Matter (PM_{10}) were performed by the air quality monitoring net from CETESB (Environmental Agency of Sao Paulo State). High concentrations correlated with high density traffic (approximately 3,000 ± 1,000 vehicles per hour), especially during weekdays, and have a characteristic diurnal pattern with two peaks: at morning (06:00–9:00 h) and at afternoon (16:00–19:00 h).

The emission factors (EFs) of pollutant species were heavily influenced by the pollutant species loads, so the total vehicle traffic and the fraction of HDV. The EF values for HDV were 3.5 ± 1.5 g/km, 1,427 ± 1,178 g/km, 9.2 ± 2.7 g/km, 0.290 ± 0.248 g/km, for CO, CO_2, NO_x and PM_{10} respectively, and for a temperature inside the tunnel of 20–25 °C. These values could be directly applicable to outside tunnel conditions because they are derived from pollutant species mass concentrations that are roughly a factor of only 2.5–3.5 higher than São Paulo typical urban concentrations. EF values of 5.8 ± 3.8 g/km, 219 ± 165 g/km, 0.3 ± 0.2 g/km, 0.178 ± 0.143 g/km, for CO, CO_2, NO_x and PM_{10} respectively, were obtained for LDV, assuming constant ratios between concentration increments of pollutant species x and trace CO and considering than the $EF(CO)_{LDV}$ were 1.5 times higher than the $EF(CO)_{HDV}$. In the methodology used to determine inside tunnel EF estimates,

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parameters such as velocity of the air, cross section area and length of the tunnel and vehicles passing at one hour time interval were considered, and sensitivity analyses was done.

Introduction

The vehicle traffic is the major source of air pollution in megacities. It is the source of regulated pollutants majority of carbon monoxide (CO), nitrogen oxides (NO_x) and hydrocarbons (HC), and contributes to the formation of particulate matter (PM) as well as being most source of CO_2. 97 % of all HC emissions and 40 % of all inhalable particulate matter (PM_{10}) emissions come from mobile sources [2]. Measurements of air pollutants in road tunnels can be used to quantify on-road traffic emissions. Tunnel studies can provide information on in-use vehicles to describe actual traffic emissions [15]. Although it is possible to estimate Emission Factors (EFs) under real urban conditions inside tunnels, the accuracy of the calculations depends on the dispersion of the pollutants [1]. Tunnel studies assume that the contribution of sources other than the vehicle is negligible [10, 11]. Another important consideration is that the rate of occurrence of photochemical processes is small since there is no action of radiation. Road traffic emission factors are one of the main sources of uncertainties in emission inventories; it is necessary to reduce these uncertainties to manage air quality more efficiently [14].

Emissions from road vehicles are important to evaluate the contribution of road traffic to environmental pollution [4]. EF describes the emitted mass (g) of a compound per distance (km) or volume of fuel consumed and expresses the individual contribution of each pollutant [3]. The present study shows the results of PM_{10}, CO, CO_2 and NO_x emission factors estimated in two road tunnels in the metropolitan area of São Paulo (MASP), Brazil.

Tunnel Experiments

Location, Traffic Volume and Sampling Analysis

Field measurements were performed in two experimental campaigns in the Janio Quadros Tunnel (TJQ), from 2 to 13 May 2011, and in the Rodoanel tunnel (TRA), from 4 to 19 July 2011. TJQ is located in the southwest area of São Paulo. It is a two-lane tunnel 850 m length with and the speed limit is 70 km h^{-1}. Inside tunnel, emissions are coming from gasohol and ethanol powered vehicles. TRA tunnel is located in the northeast area of São Paulo. It is a two-lane tunnel 1,150 m length. LDV and HDV vehicles burning gasohol, ethanol and diesel use TRA. Pollutant air concentrations were measured at the midpoint inside the tunnels (Fig. 1) and back-

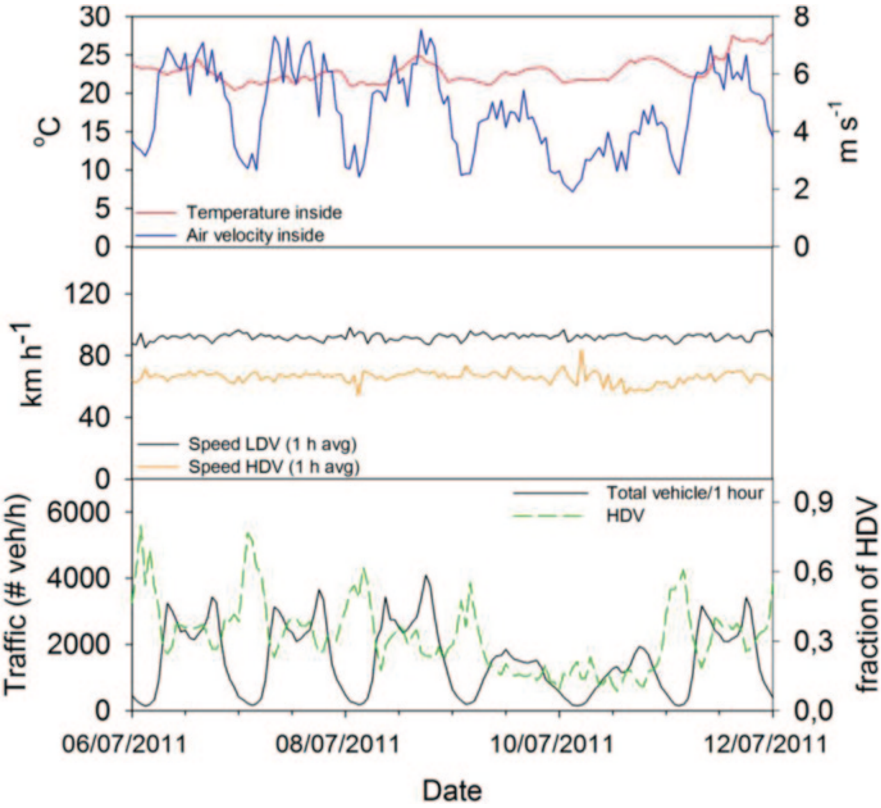

Fig. 1 Temperature, air speed, vehicle speed, traffic density and vehicle fleet composition (discrimination between LDV and HDV) during the measurements in the Rodoanel tunnel (TRA)

ground air concentrations were measured outside the tunnels. The sites outside the tunnels were located far from the tunnels in order to avoid their influence. Table 1 shows the assets of the two tunnels.

Cameras were installed in TJQ to obtain the traffic volume. In TRA an automatic system provided information of vehicle counts, type and average speed every 15 min. In TJQ vehicles were classified as motorcycles, light passenger vehicles, light-duty trucks/vans, and taxis whereas those using the TRA tunnel were classified as LDVs and HDVs.

Inside the tunnels and outside, air measurements were taken simultaneously to determine the concentrations of the species: Particulate Matter (PM_{10}), nitrogen oxide species (NO_x), carbon monoxide (CO) and carbon dioxide (CO_2). The monitoring was performed continuously by the CETESB [2]. The pollutants measured and methods are summarized in Table 2.

Table 1 Estimation conditions for tunnels (one way, 2 lanes per direction)

	TRA (Normal/cong.)	TJQ (Normal/cong.)
Length, l (m)	1.150	850
Cross-sectional area, s (m^2)	100.5	80.6
Perimeter, P (m)	50.3	45.1
Natural flow velocity, u_0 ($m\ s^{-1}$)	4.9/1.0	6.1/1.0
Inlet ventilation rate, a_i (min^{-1})	0.3/0.2	0.3/0.2
Outlet ventilation rate, a_o (min^{-1})	0.3/0.2	0.3/0.2
Concentration in inlet air, C_i (μg CO m^{-3})	2.5/5.0	2.6/5.2
Concentration in outlet air, C_o (μg CO m^{-3})	3.9/7.6	3.7/7.4
Traffic volume, V (#vehicles h^{-1})	3.000/1.600	2.000/1.500
Vehicle speed, v (km h^{-1})	83/12	72/10
Percentage HDV, f_D (no units)	0.3/0.0	0.0/0.0
Vehicle emission factor (g NO_x kg^{-1})	12/48	8/32

Table 2 CO_2 and pollutants measured in the TJQ and TRA and methods

Pollutant	PM_{10}	NO_x	CO	CO_2
Method	Beta radiation	Chemi-luminescence	Non dispersive infrared analysis	Infrared analysis
Analyzer	5014i -Beta	Thermo electron (42i-HL)	Thermo electron (48B)	LI COR-6262 Picarro-G1301
Accuracy	±5%	±1.5%	±1–2.5%	±1%
Resolution	1 min	5 min	5 min	1 min
Units	μg m^{-3}	ppb	ppm/mg m^3	ppm

Emission Factors

To calculate the emission factors we used the following expression [11]:

$$E_p = 10^3 \left(\frac{\Delta[p]}{\Delta[CO_2] + \Delta[CO]} \right) \omega_c \tag{1}$$

where E_p is the emission factor of pollutant P (in g per kg of fuel burned), Δ[P] is the concentration of the pollutant (subtracted from the background value measured outside the tunnel, in μg m^{-3}), $\Delta[CO_2]$ and Δ[CO] are CO_2 and CO concentrations. The conversions of CO_2 and CO to mass units were done using a molecular weight of 12 g mol^{-1}, rather than 44 and 28 g mol^{-1}, and the concentrations were expressed in μg C m^{-3}. The weight fractions of fuel carbon ω_c were 0.85–0.87 g of carbon per gram of fuel, for gasohol and diesel respectively. The expression 1 can be used directly in TJQ since the tunnel has mainly LDVs. In the TRA, emissions from HDVs were obtained discounting the contribution of LDVs to the total emissions. Tunnel studies have shown that emissions from LDVs and HDVs have similar CO emission rates per kilometre [8, 9, 13]. CO_2 emissions were calculated from traffic data and fuel consumption parameters using the following equation:

$$\frac{\Delta[\mathrm{CO_2}]_\mathrm{D}}{\Delta[\mathrm{CO_2}]} = \frac{\mathrm{f_D U_D} \rho_\mathrm{D} \mathrm{w_D}}{(\mathrm{f_D U_D} \rho_\mathrm{D} \mathrm{w_D}) + ((1-\mathrm{f_D}) \cdot \mathrm{U_G} \rho_\mathrm{G} \mathrm{w_G})} \tag{2}$$

where $\Delta[CO_2]_D$ is the component of $\Delta[CO_2]$ emissions resulting from the diesel burned, f_D is the percentage of HDV, U is the average fuel consumption rate, ρ is the fuel density (740 and 840 g l^{-1} for gasohol and diesel fuel respectively), w is the fuel carbon fraction (0.85 g of C per g of fuel and 0.87 for gasohol and diesel respectively). The subscripts D and G denote diesel and gasohol. For the other pollutants, PM_{10} and NO_x, the share of HDV was expressed by:

$$\Delta[\mathrm{P}]_\mathrm{HDV} = \Delta[\mathrm{P}] - \Delta[\mathrm{CO}](1-\mathrm{f_D})\left(\frac{\Delta[\mathrm{P}]_\mathrm{LDV}}{\Delta[\mathrm{CO}]_\mathrm{LDV}}\right) \tag{3}$$

where $\Delta[P]_D$ is the component of $\Delta[P]$ in TRA related to HDV emissions and $\Delta[CO] \cdot (1-f_D)$ is the fraction of $\Delta[CO]$ emissions from LDV. The emission rates for LDV, $\Delta[P]_{LDV}/\Delta[CO]_{LDV}$, were measured in TJQ. These ratios were 0.025 and 0.054 for PM_{10} and NO_x respectively. Finally, the emission factor of pollutant P and vehicle type i (LDV and HDV), $E'_{P,i}$ (expressed in grams of pollutant per driven kilometre, g/km), was obtained using the following expression:

$$E'_{p,i} = E_{p,i} \cdot U_i \tag{4}$$

where U_i is the fuel consumption of vehicle i and $E_{P,i}$ comes from equation 1. U_i depends on the CO_2 emission factor (E_{CO2} in grams of CO_2 equivalent per driven kilometre, gCO_2/km), the density of fuel j (ρ_j, gasohol for LDV, 785 g l^{-1} of fuel, and diesel for HDV, 850 g l^{-1} of fuel) and the carbon intensity of fuel j (c_j, 2,331 g of CO_2 l^{-1} of gasohol and 2,772 g of CO_2 l^{-1} of diesel).

$$U_i = E_{CO2,i} \frac{\rho_j}{c_j} \tag{5}$$

The E_{CO2} for LDV and HDV was obtained using the following expression:

$$E_{CO2,LDV} = 10^{-6} \frac{\Delta[CO_2]_{LDV} \cdot s \cdot u_0 \cdot t}{V \cdot (1-f_D) \cdot l} \tag{6}$$

$$E_{CO2,HDV} = 10^{-6} \frac{\Delta[CO_2]_{HDV} \cdot s \cdot u_0 \cdot t}{V \cdot f_D \cdot l} \tag{7}$$

Table 3 Summary table including parameters used in equations 1–5

	$\Delta[PM10]_{LDV}/\Delta[CO]_{LDV}$ (no units)	$\Delta[NOx]_{LDV}/\Delta[CO]_{LDV}$ (no units)	$U_{G, D}$ (g km^{-1})	$\rho_{G, D}$ (g l^{-1})	$\omega_{G, D}$ (gC/g)	$c_{G, D}$ (gCO_2 l^{-1})
LDV (g)	0.025	0.054	75	785	0.85	2,331
HDV (d)	n.d.	n.d.	450	850	0.87	2,772

where $\Delta[CO_2]$ are the concentrations of CO_2 (μg m^{-3}), difference between the concentrations inside and outside of the tunnel, s is the cross section area of the tunnel (m^2), u_0 is the velocity of the air wind (m s^{-1}), t is the time interval corresponding to 1 h (3,600 s), V is the number of vehicles passing the tunnel at the time t, f_D is the percentage of HDV, and l is the tunnel length (km). The parameters used in the estimation of the emission factors are summarized in Table 3.

Results and Discussion

Hourly average concentrations are measured together with the number of vehicles inside and outside of the two tunnels. Figure 2 shows the variations of NO, NO_x, NO_2, CO, CO_2, VOCs, CH_4, PM_{10} and traffic for the second week of sampling in TRA. PM_{10} is correlated with vehicle traffic, especially at peak hours. NO_x emission shows higher concentrations in TRA compared to TJQ (TRA has large traffic of heavy vehicles).

NO_x concentrations were evaluated in both tunnels. The marked difference between the two tunnels indicates the significant emissions of NO_x by HDVs. On average, concentration values in TRA were about ten times greater than in TJQ. Important relationship between CO emissions and number of vehicles was found in the two tunnels. At the investigated period, morning peak was observed in TJQ due to traffic congestion. A significant reduction of CO emissions from LDVs was observed in TJQ [12]. Reductions of CO emissions can be explained by the improved combustion of gasoline and ethanol use. Ethanol has higher oxygen content resulting in lower particle and CO emissions [5].

All pollutants showed higher concentration values inside the tunnel than outside, expressed as ratios. In TJQ these ratios were: 3.3, 1.6 and 7.1 for CO, NO_x, and PM_{10} respectively. In TRA the differences between concentrations were: 3.1, 9.0, and 2.2.

Emission Factors

Emission factors were calculated for LDVs and HDVs according to the methodology proposed. The vehicles using TJQ had cleaner technology than in other parts of the city and, on the other hand, HDVs using TRA were old trucks. Thus the emission factors presented in this paper may underestimate the emission of LDVs and

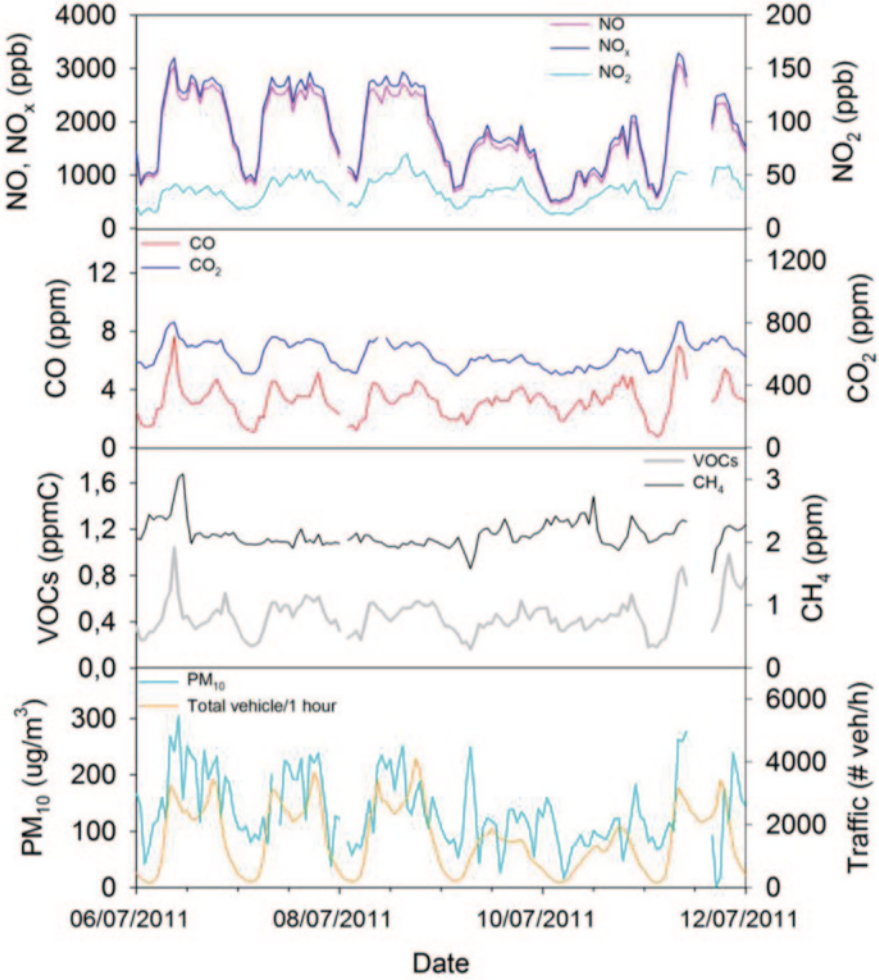

Fig. 2 Time variation of the researched gas and particulate associated compounds inside the Rodoanel tunnel (TRA)

overestimate the emission of HDV. The emission factors are presented in g km^{-1} in Table 4.

The values of EFs estimated for CO and NO$_x$ for LDVs in the present work show significant reduction when compared the values of EFs calculated in the experiment conducted in 2004 [12]. The reduction ratio was 2.2 times for CO and 3.2 for NO$_x$. In recent decades, control of NO$_x$ emissions from gasoline burning cars has been experienced by use of catalytic converters in the exhaust system of vehicles. Modern three way catalysts use platinum and rhodium surfaces, changing the nitrogen oxides back to nitrogen and oxygen elemental [6]. Similarly, for HDVs the values of EFs showed significantly reduction for CO and NO$_x$.

Table 4 Emission factors (g km^{-1}, g/kg of fuel burned) from 2011 in comparison with values calculated in 2004 study (mean ± standard deviation)

Veh.	Local measured	Fuel	CO	NO_x	PM_{10}	CO_2
		(km kg^{-1})	(g km^{-1})	(g km^{-1})	(g km^{-1})	(g km^{-1})
			(g kg^{-1})	(g kg^{-1})	(µg kg^{-1})	(g kg^{-1})
LDV	TJQ (2011)	13.7 ± 18.4	5.8 ± 3.8	0.3 ± 0.2	0.178 ± 0.143	219 ± 165
			78.9 ± 25.3	4.2 ± 2.6	2,441 ± 44	3,001 ± 85
HDV	TRA (2011)	2.24 ± 2.71	3.5 ± 1.5	9.2 ± 2.7	0.290 ± 0.248	1,427 ± 1,178
			7.8 ± 4.3	25.5 ± 8.1	692 ± 663	3,177 ± 90
LDV	TJQ (2004) [12]	n.d.	14.6 ± 2.3	1.6 ± 0.3	n.d.	n.d.
			n.d.	n.d.	n.d.	n.d.
HDV	TMM[1] (2004) [12]	n.d.	20.6 ± 4.7	22.3 ± 9.8	n.d.	n.d.
			n.d.	n.d.	n.d.	n.d.

Comparing the EFs of LDVs and HDVs we observed the highest contribution of light vehicles to CO emissions; this was expected since CO emissions originate from gasoline vehicles are higher than for diesel vehicles [7]. The marked difference between the two tunnels in terms of the concentration of NO_x and PM_{10}, indicates the significant emissions of such pollutants by HDVs. The emission factors for these two pollutants were shown to be higher for HDVs.

Conclusions

PM_{10} and inorganic gas species (CO, NO_x, CO_2) were measured in the TJQ and TRA tunnels during two weeks in May and July 2011. Concentrations had a typical diurnal profile with two concentration peaks related to vehicle traffic in the morning peak hour (6:00–9:00) and in the afternoon peak hour (16:00–19:00) on working days. The PM_{10} concentrations were higher on working days, when the percentage of HDVs (p) was 38.7 ± 4.3 %, while on weekends with p 20.1 %, the concentrations dropped by a factor of 2 (while the traffic did substantially decrease on weekends). The PM_{10} and NO_x concentrations were normalized to the CO_2 concentration, to account for the fuel consumption in the tunnels and were higher when the NO_x/PM_{10} and NO_x/CO had maximum values. High NO_x/PM_{10} and NO_x/CO ratios are usually associated to diesel vehicle emissions.

The EFs estimated for CO_2, CO, NO_x and PM_{10} and the NO_x/CO and PM_{10}/CO ratios were strongly affected by the traffic and proportion of HDVs. EFs for HDVs and LDVs were calculated in the TRA and TJQ tunnels. The $EF(PM_{10})_{LDV}$ was 0.178 ± 0.143 g km^{-1} and the $EF(PM_{10})_{HDV}$ was 0.290 ± 0.248 mg km^{-1} for a temperature of 20–25 °C inside the tunnels. Driving conditions and traffic composition were quite different in the two measurement tunnels.

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