Spatial distribution of non-exhaust particulate matter emissions from road traffic for the city of Bogota – Colombia

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ABSTRACT

Non-exhaust traffic emissions are an important source of particles in cities, however, current scientific knowledge on this source of pollution is scarce. Moreover, air quality modeling studies typically doesn't include these emissions mainly due to the difficulties associates with the estimation and the spatial distribution of such emissions for modeling.

In this work we used the US-EPA and the EEA methodologies to estimate the non-exhaust $PM_{2.5}$ and PM_{10} emissions for the city of Bogota (Colombia). These emissions included brake wear, tire wear and abrasion of paved and unpaved road surfaces. We also used traffic counts, activity data and a domain of 40x40 Km with cells of 1x1 Km to spatially distribute these emissions. The results show that near 54% of all the $PM_{2.5}$ emitted in the city comes from non-exhaust emissions (traffic exhaust emissions: 26%; industry: 20%), which agrees with results reported in other cities of the world. The results also reveal that near 80% of the non-exhaust PM emissions come from light-weight vehicles. Non-exhaust $PM_{2.5}$ and PM_{10} emissions are higher in the West of the city, an area with more deteriorated roads, higher volumes of vehicles, and with the highest levels of particles concentrations in the city.

This work underlines the importance of non-exhaust particulate emissions in cities from the developing world. It also urges the environmental authorities to control this source of pollution, and encourage the scientific community to improve existing methods to estimate and validate these emissions.

INTRODUCTION

Airborne particulate matter is one of the main environmental problems in most of the cities of the world[1] (WHO, 2005). Direct traffic exhaust emissions and industry have been considered as the main sources of particles in cities. However, recent studies show that non-exhaust particulate matter emissions from road traffic are also an important source of this air pollutant[2] (Thorpe, 2008). Non-exhaust particulate emissions involve abrasive processes such as tire wear, brake wear and road surface wear, these processes can lead to the deposition of particles on the road surface. The other process is the resuspension of road dust which is due to traffic induced turbulence, tire friction or the action of the wind.

Studies developed in different cities of the word show the importance of non-exhaust road traffic emissions. A study conducted in three European cities investigated the sources of road dust particles, it concluded that road dust resuspension is the dominant source of PM10 in Spain (60%), while in Zürich it only represents 30% of road dust loadings[3] (Amato, 2011). Another study conducted in Beijing investigated the characteristics of resuspended road dust and its impact on the urban air, this research concluded that resuspended road dust from traffic is one of the major sources of aerosols in Beijing[4]. The contribution of non-exhaust road traffic emissions to the total PM10 emissions can be as high as 90% in northern European countries.

Non-exhaust road traffic emissions represent a risk to human health [5] (Kupianinen, 2011). Road dust particles may contain toxic and carcinogenic compounds such as heavy metals, PAHs and other pollutants. A recent study conducted in Australia analyzed samples from road surfaces to identify their sources[6] (Gunawardana, 2012). It concluded that toxic pollutants represent 30% of the surface dust, which consist of break and tire wear, combustion emissions and fly ash from asphalt. Sadiktsis et al. (2012) found that automobile tires may be a potential source of carcinogenic dibenzopyrenes to the environment[7].

Despite the importance of non-.exhaust traffic emissions, current scientific knowledge on this source of pollution is scarce even in developed countries. In many cities from the developing world, this source of pollution has not been sufficiently study. Moreover, in most of the emissions inventories developed for such cities, non-exhaust emissions are not considered. The lack of this information and knowledge limit the correct implementation of abatement strategies to control airborne participles in cities.

In this work, we used the US-EPA and the EEA methodologies to estimate the non-exhaust $PM_{2.5}$ and PM_{10} emissions for the city of Bogota (Colombia). Bogota is among the most polluted cities from Latin America. PM10 concentrations show a high number of exceedance days of the annual air quality standard of 70 $\mu g/m^3$ and the 24-hour air quality standard of 150 $\mu g/m^3$, particularly in the Western stations such as Kennedy, Fontibón and Puente Aranda. Since it is a pollutant closely associated to morbidity and mortality indicators, PM10 emission reduction is the main goal of the 10-year air pollution-curbing plan designed for the city in 2010.

Several PM10 emission inventories exercises have been conducted in the last decade in order to determine the emissions share produced by different sources. The emission inventory developed for the city's air quality model in 2002[8] (Zárate et al., 2007) showed that industrial sources produced 64% of the total particulate matter (PM) emissions with 8 Ton/day or 2,920 Ton/yr. Mobile sources emitted the remaining 36% with 4,5 Ton/day or 1,640 Ton/yr. Diesel trucks and buses were found to emit 98% of PM10 from mobile sources. In a later study[9], Giraldo (2006) estimated that mobile-source PM emissions were much higher: 2,555 Ton/yr, diesel buses and trucks still being the main mobile source of this pollutant with 79% of total mobile PM emissions. Motorcycles, included for the first time in the emission inventory, were estimated to emit 14% of such emissions, becoming a very relevant source of mobile PM10, since most of the motorcycles were still powered by two-stroke engines. Behrentz et al. (2009) conducted an experimental emissions study[10] to determine both point- and mobile-source emission factors and estimate a new emission inventory, finding that point-source PM10 emissions were 1,440 Ton/yr and mobile-source PM10 emissions were 1,100 Ton/yr.

None of the emission inventories exercises included PM10 emitted by dust resuspension. However, PM10 chemical characterization studies have shown a significant fraction of crustal material and receptor modeling using such chemical composition identified resuspended dust as an important source of PM10. In residential sites, the contribution was found to be between 9% and 60%[11,12] (Rivera & Behrentz, 2009; Vargas et al, 2011). In sites with industrial influence, the contribution was found to be between 21% and 47% (Vargas et al, 2011; Rivera & Behrentz, 2009). Finally, in a sampling site near roads, the contribution was found to be 52% (Rivera & Behrentz, 2009). These results demonstrated that resuspended dust as a source of PM10 should be included in emission inventories, air quality models and air pollution-curbing plans.

Despite all the efforts made by the local environmental authorities and the scientific community, concentrations of particles in Bogota have not been reduced. The results of this study may be used to establish the importance of non-exhaust particulate matter in this Latin American city, to determine the policies needed to control airborne particulate matter, and as input information for future air quality modeling studies.

METHODOLOGY

Site description

Bogota, the capital of Colombia, is located in the Andes Mountains at 2600 m above sea level. With near 7.4 million inhabitants, it is the largest city in Colombia and one of the largest in Latin America. Bogota is one of the main industrial centers of the country; there are about 4000 industries and about 1.5 million vehicles in the city. All these activities have caused a decline in the city's air quality. Today air pollution is one of the main environmental problems in Bogota, been particulate matter the pollutant of most concern in the city.

Estimation of the non-exhaust particulate matter emissions

The non-exhaust particulate matter traffic emissions (E), are estimate from emission factors (EF) and vehicle activity data (A). The basic equation is:

$$E = EF * A \qquad (1)$$

Emission factors for resuspension

We used the US Environmental Protection Agency methodology to estimate resuspensión emission factors for paved and unpaved roads[14]. Briefly, the particulate emissions from resuspensión on a paved road surface are estimated from:

$$EF_{pr} = k * (sL)^{0.91} * (W)^{1.02} * (1 - \frac{P}{4*N}) \qquad (2)$$

Where

EF_{pr} = Particulate emission factor for a paved road (g/VKT)
k = Particule size multiplier (g/VKT ; from AP-42, table 13.2.1-1)
sL = Road surface silt loading (g/m^2)
W = Average weight of the vehicles traveling the road (ton)
P = Number of wet days with at least 0.254 mm of precipitation during the average period
N = Number of days in the average period (365 for annual)

The road surface silt loading is a key parameter for the estimation of particles resuspension emissions in a paved road. However, this parameter has not been estimated in Bogota. To determine this parameter we investigated the values used in similar cities of the world[15,16]. The road surface silt loading used in these cities vary from 0.03 to 0.2 g/m^2, thus we used the minimum and the maximum of these range with an average of 0.1 g/m^2 to estimated the particulate emission factor for a paved road. Furthermore, we used information from the local air quality monitoring network to estimate P. In this case, the number of wet days with at least 0.254 mm of precipitation during one year is 160.

For vehicles traveling an unpaved road at industrial sites, resuspension emissions are calculated from:

$$EF_{ur,industrial} = k * \left(\frac{s}{12}\right)^{a} * \left(\frac{W}{3}\right)^{b} * \left(\frac{365-P}{365}\right) \qquad (3)$$

And for vehicles traveling roads dominated by light duty vehicles, the emissions are estimated from:

$$EF_{ur,public\ roads} = \left[\frac{k*\left(\frac{s}{12}\right)^{a}*\left(\frac{S}{3}\right)^{d}}{\left(\frac{M}{0.5}\right)^{c}} - C\right]*\left(\frac{365-P}{365}\right) \quad (4)$$

Where

EF_{ur} = Particulate emission factor for a paved road (g/VKT)
k, a, b, c= Empirical constants (from AP-42, table 13.2.2-2)
s = Surface material silt content (4 - 6%, AP-42, table 13.2.2-3)
W = Average weight of the vehicles traveling the road (ton)
M = Surface material moisture content (7%, AP-42, table 13.2.2-3)
S = Average speed (mph) of the vehicles traveling the road
C = Emission factor for 1980's vehicle fleet exhaust, brake and tire wear (AP-42, table 13.2.2-4)
P = Number of wet days with at least 0.254 mm of precipitation

Emission factors for abrasion

We used the European Environmental Agency methodology to estimate particulate matter emission factors for abrasive processes[17]. Here the Tier 1 method was used to estimate these emissions. The processes included are road vehicle tire and brake wear, and road surface wear. In this case, particles are produced from the interaction between the vehicle's tires and the road surface, and when the brakes are used to decelerate the vehicle. This method also considers the evaporation of materials from the friction of surfaces.

Activity data and spatial distribution of the emissions

All the information needed to estimate the non-exhaust emissions in the entire road network of Bogota were obtained from a previous study in which vehicle exhaust emissions were computed and spatially distributed in the city[13]. Briefly, the total length of the road network used is near 10.000 Km, this road network was divided in 5 categories: main, secondary, rural, the bus rapid transit system - Transmilenio, and the Transmilenio feeders (Transmilenio secondary buses). The vehicle fleet was divided in 23 vehicle categories, which includes particular vehicles, taxis, motorcycles, public service vehicles and Transmilenio, etc. Vehicle kilometers traveled (VKT), for the different vehicle categories range from 37 Km/day for private vehicles, to near 200 Km/day for public service vehicles and Transmilenio.

The calculated non-exhaust emissions were then spatially distributed in a domain of 40x40 Km with grid cell of 1x1 Km. We used the geographical information system QuantumGIS for the spatial distribution of these emissions.

RESULTS

Estimated emissions of $PM_{2.5}$ and PM_{10} by road dust re-suspension and surface ware in Bogotá are shown in Table 1. Estimated $PM_{2.5}$ and PM_{10} emissions were 2,860 Ton/yr and 23,300 Ton/yr, respectively. Re-suspended $PM_{2.5}$ was roughly 30% of PM_{10} when emitted along paved roads and 8% when emitted along unpaved roads. Although the length of unpaved roads is significantly lower than that of paved roads, their emissions are somewhat higher, owing to the predominant presence of lose material. According to the model used, the uncertainty of this estimation was nearly 40% for $PM_{2.5}$ and 20% for PM_{10}. However, this uncertainty is not high enough to explain why the total estimated emission is higher than that of Mexico D.F., which is a much larger city (1,138 Ton $PM_{2.5}$/yr and 14,152 Ton PM_{10}/yr), or similar than that of Santiago de Chile, which is smaller (2,670 Ton $PM_{2.5}$/yr and 18,756 Ton PM_{10}/yr).

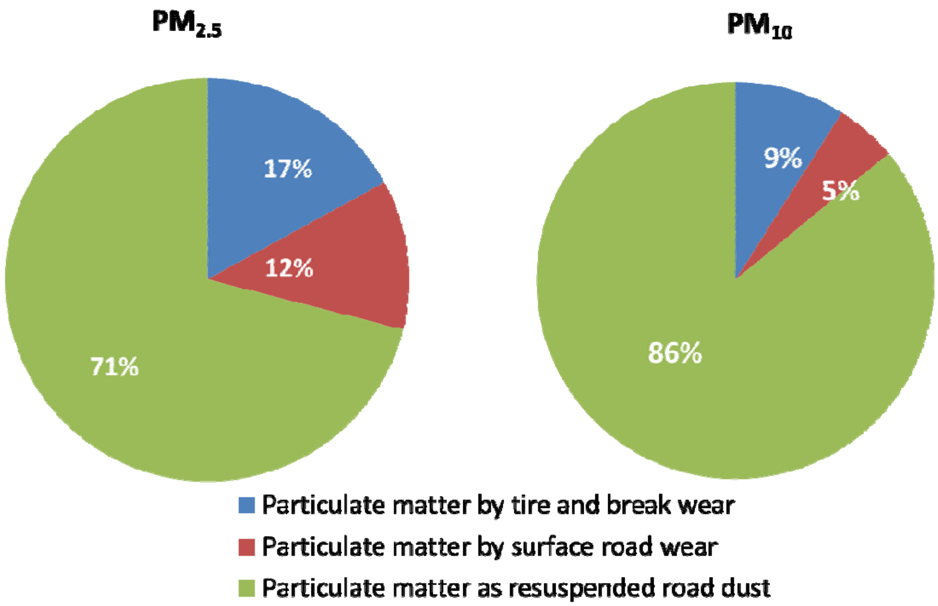
Table 1. Estimated $PM_{2.5}$ and PM_{10} emissions by road dust re-suspension and surface wear in Bogotá.

		PM2.5 (Ton/yr)	PM10 (Ton/yr)
Paved Road	Re-suspension	1160 ± 750	4830 ± 1,700
	Wear surface	320 ± 50	570 ± 150
Unpaved Road	Re-suspension (industrial)	1,140 ± 250	11,600 ± 1,600
	Re-suspension (public road)	240 ± 150	6,300 ± 1,700
TOTAL		2,860 ± 1,200	23,300 ± 5,000

When adding the estimated $PM_{2.5}$ emissions by dust re-suspension to combustion emissions by point and mobile sources, it was found that dust re-suspension accounted for 54% of total PM2.5 emissions in Bogotá, which is a slightly lower fraction than that in Santiago de Chile (57%) and a much higher fraction than that in Mexico D.F. (24%). According to these results, road dust re-suspension and surface wear would be the main source of PM2.5 and PM10 in the city. The contribution of this source is fairly consistent with receptor modeling results by Rivera & Behrentz (2009)[11], but higher than the fraction found by Vargas et al (2012)[12], which could suggest an overestimation of re-suspended PM.

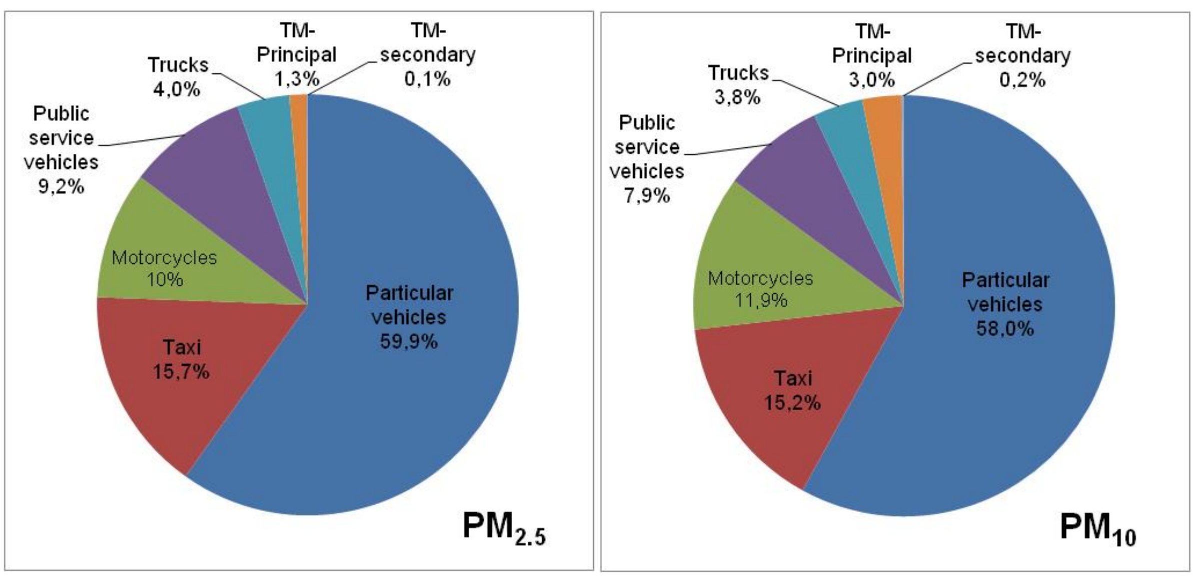
The estimated contribution of different source types of re-suspended dust to $PM_{2.5}$ and PM_{10} is shown in Figure 1. Most of the PM, roughly 70% of $PM_{2.5}$ and 86% of PM_{10}, comes from lose dust deposits over the roads. The second contribution comes from tire and brake wear, which accounts for 17% of $PM_{2.5}$ and 9% of PM_{10}. The remaining fraction is contributed by the road surface ware.

Figure 1. Contribution of different source types to re-suspended PM emissions.



Regarding the vehicle type that produce the PM non-exhaust emissions, most of the contribution comes from light weight vehicles, represented by conventional vehicles (60%), taxis (15%) and motorcycles (10%) (Figure 2). Heavy weight vehicles such as the BRT system (Transmilenio - TM) has much fewer buses (1,800) than the conventional public system – consisting on low-capacity buses and minibuses – (16,000), although the weight of articulated buses is much higher (26 Ton vs. <15 Ton), activity factor is less than light weight vehicles, which explains their low contribution to re-suspended PM, as also the contribution of cargo trucks.

Figure 2. Contribution of different vehicle categories to PM non-exhaust emissions (includes resuspensión, surface ware, tire, and break ware)



The spatially disaggregated $PM_{2.5}$ and PM_{10} emissions are shown in Figure 4. Most of the cells with the highest PM_{10} emissions were found to occur precisely in the localities with the highest observed concentrations of PM10, located in the West of the city and the highest emissions from stationary and mobile combustion sources[13]. This area has a strong industrial activity but also a high population density, together with heavy traffic of particular vehicles, cargo trucks and buses of the conventional collective transport system. There is a high density of high-emission cells in the South, where a significant fraction of the roads are still unpaved or paved roads are in poor maintenance conditions. The air quality monitoring station located in this area show relatively high PM_{10} concentrations that have been related to mining and industrial activities such as brick manufacturing. High concentration cells in the East and the North are associated to roads with heavy traffic, roads with the highest activity of the BRT system and commuting roads that connect the city with dormitory towns or suburbs.

Figure 4. Spatial disaggregation of $PM_{2.5}$ and PM_{10} emissions by road dust re-suspension brake, tire and surface wear.

CONCLUSIONS

Non-exhaust $PM_{2.5}$ and PM_{10} emissions were estimated for Bogota using the US-EPA and the EEA methodologies. Emissions from dust resuspension, brake wear, tire wear and abrasion of paved and unpaved road surfaces were also disaggregated in a domain of 40x40 Km with cells of 1x1 Km using traffic activity data. Nearly 50% of all the $PM_{2.5}$ emitted in the city was found to come from non-exhaust emissions, in agreement with results reported elsewhere. Light-duty vehicles account for 80% of the non-exhaust PM emissions. The spatial disaggregation showed that non-exhaust $PM_{2.5}$ and PM_{10} emissions are higher in the south-west of the city, an area with poorly maintained roads, higher volumes of vehicles, and with the highest levels of particles concentrations in the city. These areas also have the highest concentrations of PM_{10} observed at the air quality monitoring stations, but also the highest emissions from stationary and mobile combustion sources. The contribution of dust re-suspension to total PM was in agreement with results from receptor modeling studies.

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KEYWORDS
Non-exhaust traffic emissions; particulate matter; emission inventory; mobile sources