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Analysis of $PM_{2.5}$ and PM_{10} emissions from road and port transport in the Metropolitan Region of Salvador in 2017

Katty Santos da Silva[1*], Anderson da Silva Palmeira[2], Davidson Martins Moreira[3]
[1] *Universidade Senai Cimatec, PPG-MCTI, Salvador, Bahia, Brasil*
[2] *Universidade Senai Cimatec, PPG-MCTI, Salvador, Bahia, Brasil*
[3] *Universidade Senai Cimatec, PPG-MCTI, Salvador, Bahia, Brasil*
**Corresponding author: Universidade Senai Cimatec;*
katty.silva@outlook.com;davidson.moreira@gmail.com;andersonpalmeira@icloud.com

Abstract: This study compares atmospheric emissions of fine particulate matter ($PM_{2.5}$) and coarse particulate matter (PM_{10}) from vehicles emissions and port emissions in the Salvador Metropolitan Region (RMS) in 2017. Using sectoral inventories prepared using IPCC, EPA, and international guidelines, emissions were estimated based on sector-specific activity data. The results indicate that vehicles emissions account for approximately 75% of total $PM_{2.5}$ emissions in RMS, far exceeding port sources. Although smaller in magnitude, port emissions have a significant impact because they occur in densely populated areas and are associated with the use of high-sulfur fuels. These results can inform public policies aimed at mitigating air pollution and the transition to a low-carbon economy.
Keywords: Vehicle emissions. Port emissions. Airport emissions. Particulate matter. Nitrogen oxides.

Abbreviations:
CO, carbon monoxide. NO_x, nitrogen oxides. $PM_{2.5}$ fine particulate matter. MP_{10}, coarse particulate matter. EPA, Environmental Protection Agency. IPCC, Intergovernmental Panel on Climate Change. RMS, Metropolitan Region of Salvador.

1. Introduction

The intensification of urban and industrial activities has increased concentrations of atmospheric pollutants, especially in coastal regions with high population density and complex logistical infrastructure [1]. In the RMS, the urban road system, the port of Salvador, Luís Eduardo Magalhães International Airport, and the Camaçari Industrial Complex stand out as significant emission sources [2].

Among the pollutants of greatest environmental and health concern are carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter ($PM_{2.5}$, and PM_{10}), all associated with impacts on human health, environmental degradation, and climate change [3].

Most studies on emissions in the RMS focus on isolated modes, making it difficult to prioritize mitigation actions [4]. The comparative approach between sectors (road and port) allows us to identify which activities have the greatest potential for reducing emissions and to allocate resources more efficiently.

This study provides a quantitative and comparative analysis of PM emissions from road transportation and port operations in the Metropolitan Region of Mato Grosso do Sul (RMS) in the 2017 baseline year. Estimates were made using internationally recognized methodologies (IPCC, EPA, IMO, CETESB), using activity data obtained from official agencies and institutional reports. The results contribute to urban and environmental planning in the Metropolitan Region, aligning with the national goals of the Paris Agreement.

2. Methodology

The methodology adopted was based on fleet data for the year under analysis and on information on the operation and activities of each sector, obtained from their respective official sources, with the aim of quantifying particulate matter (PM) emissions. The inventories were prepared based on emission factors from national and international technical agencies, such as the Intergovernmental Panel on Climate Change (IPCC) [5], the Environmental Protection Agency (EPA) [6], the International Maritime Organization (IMO) [7], CETESB [8], and the Ministry of the Environment (MMA) [9]. This study considered road transport and port operations.

2.1 Vehicles emissions

For the vehicles emissions [10,11], a top-down approach was applied according to guidelines from the Ministry of Transportation (MMA) and CETESB. The first step consisted of estimating the circulating fleet, calculated based on survival functions that describe the permanence of vehicles in use over time. For vehicles with Otto cycle engines, the modified exponential function was used. (Eq. 1):

$$S(t) = 1 - e^{-e(a+bt)} \tag{1}$$

And, for diesel cycle vehicles and motorcycles, the Gompertz function was applied (Eq. 2):

$$S(t) = \frac{1}{1+e^{[a(t-to)]}} + \frac{1}{1+e^{[a(t+to)]}} \tag{2}$$

The actual fleet in circulation was obtained by multiplying the number of registered vehicles by their respective survival rate. (Eq. 3):

$$F_{R_{i,k}} = V_{i,k} \cdot S_{i,k} \tag{3}$$

Next, the intensity of use was adjusted, estimating the theoretical fuel consumption (Eq. 4).

$$C_{est} = F_{R_{T,A}} I_{U_{ref}} Q_{l_{T,A}} \tag{4}$$

And then, the adjusted intensity was determined by the ratio between the actual consumption (ANP data) [12] and the estimated. (Eq. 5):

$$Iu_{ajusC,T,A} = Iu_{refT,A}\left(C_{real} / C_{estC,T,A}\right) \tag{5}$$

Vehicle emissions were then estimated by category and emission type:

For vehicle exhaust emissions, the general equation used was. (Eq. 6):

$$E_{P,T,C} = \left(Fr_{T,C,A}.Iu_{T,C,A}.Fe_{P,T,C,A}\right)10^{-6} \tag{6}$$

Evaporative emissions included daytime losses. (Eq. 7):

$$E_{NMHC,d,T,C,A} = \frac{Fr_{T,C,A}.ed_{T,C,A,F}.D_f}{10^6} \tag{7}$$

Hot soak (Eqt. 8) and losses during operation (Eq. 9):

$$E_{NMHC,s,T,C,A} = \frac{Fr_{T,C,A} * Iu_{T,C,A} * \left(\frac{es_{T,C,A,F}}{9,48}\right) * Df(\%)}{10^6} \tag{8}$$

$$E_{NMHC,r,T,C,A} = \frac{Fr_{T,C,A} * Iu_{T,C,A} * \left(\frac{er_{T,C,A,F}}{9,48}\right) * Df(\%)}{10^6} \tag{9}$$

And the emissions associated with the supply were calculated by (Eq. 10):

$$E_{NMHC,abastC} = \left(Te_c - C_{real,c}\right)10^{-6} \tag{10}$$

Emissions from tires, brake, and road wear followed the same logic as combustion (Eq. 6). The emission factors used were taken from official CETESB tables and European literature (EEA, 2023), covering both new and deteriorated vehicles.

2.2 Port emissions

For the port emissions, the methodology followed a bottom-up approach, adapted from Entec UK [13] and the IMO. Emissions were calculated for three ship operating modes: berthing, approach, and cruising [14]. During berthing, auxiliary engines remain on. During approach, the reduced load of the main and auxiliary engines is considered. During cruising, emissions were calculated considering the distance sailed, the average speed, and the engine load. Thus, the calculation of emissions from ships in the port of Salvador at the time of berth in 2017, considering the sulfur content in the fuel oil used at 3%, was performed as (Eq. 11):

$$E_{atr} = T_{atr}\left[\left(MP.FC_{MP_{atr}}.FE\right)+\left(MA.FC_{MA_{atr}}.FE\right)\right] \quad (11)$$

During port maneuvers, the main engine (MP) is used for ship movement and maneuvering, and the auxiliary engine (MA) is kept running during berth and/or port waiting periods to keep support and maintenance systems operational. Emission factors were differentiated by fuel type and operational phase, based on the bottom-up approach adapted from Entec UK and the IMO. All variables used in the equations presented are described, with their respective units and definitions, in Table 1.

Table 1. Variable Definitions (Equations used).

Symbol	Description	Unit
S(t)	Vehicle survival rate at age "t"	-
t	Vehicle age	year
a, b, t_0	Survival function tuning parameters	-
$Fr_{i,k}$	Effective fleet of category "i" and technology/fuel "k"	unit
$V_{i,k}$	Total registered fleet	unit
Iu_{ref}	Reference usage intensity	km·year⁻¹
Iu_{ajus}	Adjusted intensity of use	km·year⁻¹
C_{real}	Actual fuel consumption	L
C_{est}	Estimated theoretical consumption	L
$Ql_{T,A}$	Average specific consumption by category	$L \cdot km^{-1}$
$E_{P,T,C}$	Pollutant emission rate "P" for category "T" and fuel "C"	$t \cdot year^{-1}$
FE	Emission factor	$g \cdot km^{-1}$ and $g \cdot kWh^{-1}$
DF	Number or percentage of days to choose the emission factor	day / %
9,48	Average distance per trip in the RMS	km
TE_c	Evaporation rate in supply	$g \cdot L^{-1}$
MP, MA	Power of main and auxiliary engines	kW
FC	Motor load percentage	%
T_{atr}	Time spent at berth	h

3. Results and discussions

In the land vehicles sector, total emissions were 523.21 t/year of TSP, 334.16 t/year of PM_{10}, and 179.99 t/year of $PM_{2.5}$. Automobiles were the main source, accounting for 48.3% of total TSP, 48.5% of PM_{10}, and 48.6% of $PM_{2.5}$. Next, heavy trucks (15.5% TSP; 15.3% PM_{10}; 15.3% $PM_{2.5}$) and semi-heavy trucks (11.2% TSP; 11.1% PM_{10}; 11.1% $PM_{2.5}$) stood out. These three categories together represented approximately 75% of road emissions of $PM_{2.5}$. Figure 1 and Table 2 represent these emissions by vehicle category, highlighting the predominance of cars and large cargo vehicles.

Figure 1. PM emissions (TSP, $PM_{2.5}$ and PM_{10}) by vehicles in the RMS 2017 (t/year)

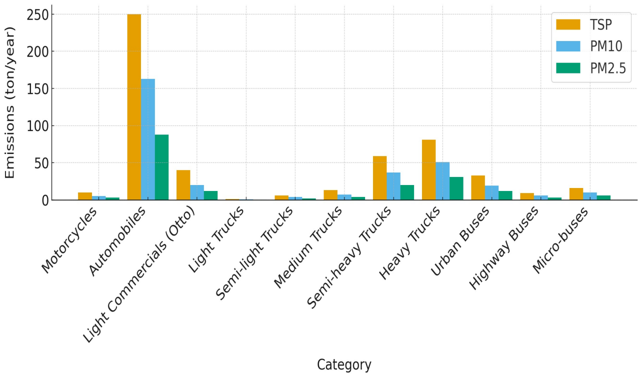

Table 2. PM emissions (TSP, PM_{10} and $PM_{2.5}$) by vehicles (tons/year) - RMS 2017

Category	TSP	PM_{10}	$PM_{2,5}$
Motorcycles	12.873	8.462	4.501
Cars	252.59	162.1	87.492
Light commercial vehicles (Otto)	37.479	24.05	12.982
Semi-light trucks	0.889	0.593	0.322
Light trucks	5.932	3.959	2.15
Medium trucks	14.511	9.158	4.918
Semi-heavy trucks	58.813	37.12	19.936
Heavy trucks	81.192	51.24	27.522
Urban buses	34.153	21.55	11.577
Intercity buses	8.379	5.287	2.841
Minibus	16.948	10.7	5.744

In the port sector, total PM emissions were 254.8 t/year, with a strong concentration in two vessel types: tankers (46.3%) and container ships (45.7%), which together accounted for 92% of port PM emissions. The other vessels (general cargo, Ro-Ro, bulk carriers, passenger, and others) combinedly accounted for only 8% of the total. Furthermore, these two dominant classes also led port emissions of volatile organic compounds (VOCs), accounting for approximately 65% of the sector's total. Figure 2 and Table 3 represent these emissions by ship category, highlighting the predominance of tankers and container ships.

Figure 2. Port emissions of PM and VOC – 2017

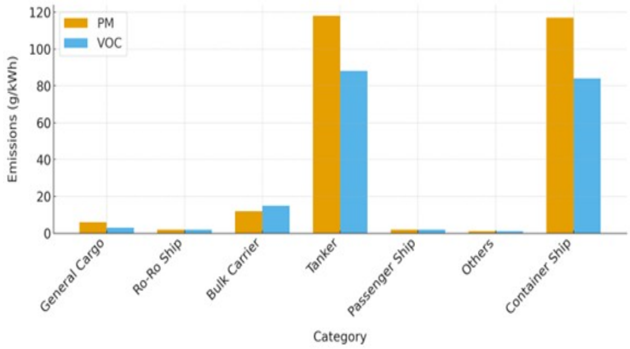

Table 3. Port emissions (tons/year) - RMS 2017

Ships	NO_x	CO_2	COV	PM
General Cargo	19.5* 16.2**	1237.2	2.3	3.7
Ro-Ro Ship	22.9* 19.0**	1480.2	2.9	2.3
Bulk Carrier	127.5* 105.9**	8142.9	15.8	12.6
Tanker ship	766.8* 634.7**	34458.5	83.7	117.9
Passenger ship	12.8* 10.6**	829.6	1.7	1.3
Other ships	6.0* 5.0 **	380.7	0.7	0.6
Container carrier	742.2* 614.3**	33755.1	83.9	116.4

**Before the year 2000; **After the year 2000.*

A direct comparison between sectors shows that road transportation emitted approximately 2.05 times more $PM_{2.5}$ and 1.31 times more total PM (TSP) than the port sector. Despite the lower absolute volume, port emissions have a significant local impact, as they are concentrated in densely populated urban areas and result from the use of high-sulfur fuels, potentially negatively impacting the health of the surrounding population.

These results reinforce the need for mitigation policies to be differentiated by sector. In road transportation, fleet renewal, expansion of low-emission public transportation, and promotion of cleaner fuels are priorities. In the port sector, the need to reduce sulfur fuel content, modernize auxiliary engines, and implement shore power systems stands out, reducing emissions directly in the urban port area.

4. Final consideration

The study showed that, although road transport leads to the volume of particulate matter emissions in the RMS, the port impact cannot be underestimated due to the spatial concentration of operations. The predominance of automobiles and heavy vehicles in road emissions indicates that actions targeted at a few segments can generate significant reductions. In the port, the high share of only two classes of ships in PM emissions suggests that specific measures for these vessels would have a significant effect. Therefore, the priority should be twofold: in road transport, accelerating fleet renewal and expanding clean public transport; in ports, modernizing engines and implementing shore power. Furthermore, integrated air quality management, with continuous monitoring and updated inventories, is essential to monitor the effectiveness of policies and ensure that reduction targets are met. The coordinated adoption of these measures will not only reduce PM emissions but also contribute to public health, environmental sustainability, and the fulfillment of Brazil's climate commitments.

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