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Road transport exhaust emissions in Colombia. 1990–2020 trends and spatial disaggregation

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Highlights

- Colombia's on-road transportation emissions from 1990 to 2020 have been calculated.
- Total transport emissions and trends have been compared with international sources.
- High-resolution spatial distribution of transportation emissions has been computed.

Abstract

Road traffic-related air pollution costs society in terms of lost lives, health problems, and financial damages. For directing regulatory actions and enhancing air quality, governments require emission inventories and trends over time across all geographic areas. This study provides a high-resolution spatially disaggregated on-road transportation emissions inventory in Colombia from 1990 to 2020. Our estimates followed a top-down approach that accounted for local characteristics such as fleet technology, fuel consumption, road infrastructure, and activity factors at a national and state level. We report annual CO₂, CH₄, NO_x, VOCs, PM_{2.5}, and black carbon at a spatial resolution of 0.01° x 0.01°. Economic crises (1998-2001), stringent emission requirements (2011), and the most recent sanitary quarantine (2020) all have an impact on emissions patterns, which grow at a slower rate than vehicle activity. For the annual emissions of CH₄, CO, and PM_{2.5}, the growth of motorbikes in the vehicle fleet is particularly crucial.

Keywords: on-road transport, emission inventory, air pollution, transport emissions, energy consumption, vehicle obsolescence

1. Introduction

The design, implementation, and evaluation of public policies aimed at improving air quality as well as making and upholding international commitments in the fight against climate change can all benefit from the coordinated knowledge about the dynamics of criteria air pollutants (CAPs), greenhouse gases (GHGs), and short-lived climate pollutants (SLCPs) (Schmale et al., 2014; Stohl et al., 2015; Von Schneidemesser et al., 2015). This can be achieved by using both climate and atmospheric chemical transport models (CTMs). Emission inventories are considered the most critical and uncertain input to these models (Huneus et al., 2020; Thunis et al., 2021). Therefore, they need to be evaluated and continuously improved using different approaches and resolution levels, checking their consistency to address air quality and climate change in a coordinated manner (Alamos et al., 2022; Melamed et al., 2016).

Global emission inventories such as EDGAR (Emissions Database for Global Atmospheric Research), CAMS (Copernicus Atmosphere Monitoring Service), or CEDS (Community Emissions Data System) are commonly utilized in the application of CTMs in scientific research and the evaluation of public policy at the regional and local levels (Crippa et al., 2016; Granier et al., 2019; Hoesly et al., 2018; Janssens-Maenhout et al., 2017). In Europe, Thunis et al. showed that the main differences between CTM results and air quality observations occur when there are more significant discrepancies in emissions from different information sources, such as official reports and independent estimates (Thunis et al., 2021). On the other hand, CTM results can be improved by using detailed local information in addition to official national-level reports. For example, Castesana et al. built an emissions inventory for South America based on the global CAMS dataset, using local data for Argentina, Colombia, and Chile, and obtained air quality modeling results for carbon monoxide (CO) and nitrogen oxides (NO_x) over Buenos

Aires than using CAMS alone (Castesana et al., 2022). Similarly, Gonzalez et al. reported simulation results for tropospheric ozone (O₃) and particulate matter smaller than 10 micrometers (PM₁₀) concentrations with WRF-Chem in the city of Manizales, Colombia, while utilizing a combination of EDGAR with local bottom-up emission data when compared to using EDGAR only (González et al., 2018).

Comparing different emission inventories for specific sectors is crucial to reduce uncertainty and establish roadmaps to enhance information quality. The road transport sector has been of particular interest because it is responsible for a considerable fraction of urban air pollution (Gouveia et al., 2021; Forehead and Huynh, 2018). In Colombia, road transport accounted for 78.3% of GEI (CO₂-eq) emissions from transportation and 9.7% of the total CO₂-eq emissions of the country in 2018 (IDEAM et al., 2021). It also contributed to 3.3% of particulate matter (PM), 12.3% of black carbon (BC), 24.3% of carbon monoxide (CO), 45.3% of nitrogen oxide (NO_x), and 1.4% of sulfur dioxide (SO₂) emissions in 2014 (IDEAM, 2020). Osses et al. recently demonstrated that Chile's road transport CO₂ emission trends from national and global estimates were similar between 1990 and 2020, but the magnitudes and trends for other pollutants were noticeably different (Osses et al., 2022). They also produced high spatial resolution emission maps, a dataset that can be used as input to CTMs across the country, and an update to global emission models for the road transport sector. Their approaches were designed to be easily implemented in other Latin American nations to estimate and disaggregate road transport emissions.

Although many countries in the Latin America and the Caribbean (LAC) region have estimated and reported their emissions to meet their international commitments, only Argentina (Castesana et al., 2020, 2018; Puliafito et al., 2017, 2015) and Chile (Alamos et al., 2022; Osses

et al., 2022) have made their own developments of national emission inventories for different sectors with the spatial and temporal resolution required as inputs to CTMs. In addition, Alonso et al. developed a tool to estimate and disaggregate an urban emissions inventory for South America as an input to the Coupled Chemistry Aerosol-Tracer Transport model to the Brazilian developments on the Regional Atmospheric Modeling System (CCATT-BRAMS) air quality model (Alonso et al., 2010). Castesana et al. compiled and disaggregated a regional emissions dataset, including Argentina, Chile, and Colombia, to use it as an input to Weather Research and Forecasting model coupled with chemistry (WRF-Chem) (Castesana et al., 2022). Similar works have been performed for specific cities, such as Bogota (Pachón et al., 2018), Manizales (González et al., 2020), Medellín (Toro et al., 2022), Lima (Romero et al., 2020; Sánchez-Ccoyllo et al., 2018), Santiago (Mazzeo et al., 2018; USACH, 2014) and Rio de Janeiro (Gerência de Qualidade do Ar (GQA), 2016); or specific sectors such as transport (D'Angiola et al., 2010; Osses et al., 2022). However, most air quality modeling studies in the region use global datasets.

Colombia's emission inventories have been estimated at the national level for two reasons. The first has been to document National Communications to the United Nations Framework Convention on Climate Change (UNFCCC) and its commitments to cut GHG emissions. The 3rd national climate change communication report (IDEAM et al., 2016) provides a time series of GHG emissions and sinks between 1990 and 2012 that were estimated following the guidelines established by the Intergovernmental Panel on Climate Change (Intergovernmental panel on climate Change, 2008). Furthermore, it shows, for the first time, a disaggregation of inventories by the department. However, there was no disaggregation in grids that could be used for numerical modeling purposes.

The second reason has been to help air quality policies by lowering CAPs and BC, the latter of which is a significant short-lived climate pollutant (SLCP). The first national inventory of CAPs and BC provided national-level emissions time series between 2010 and 2014 (IDEAM, 2020). Unfortunately, it does not include spatial disaggregation, which requires chemical transport models. This kind of disaggregation has previously been conducted by the scientific community and, on occasion, by authorities from various environmental agencies in the country to investigate and prioritize measures to improve air quality in cities, or specific non-attainment areas (Carmona Aparicio et al., 2016; Pachón et al., 2018). Additionally, some tools have been locally developed to estimate and disaggregate emissions, particularly in the road transport sector, i.e., the Disaggregation of on-Road Vehicle Emissions algorithm – DROVE (González et al., 2020). Similar efforts have been made in Brazil, with the BRAZilian Vehicular Emissions inventory Software – BRAVES (Hoinaski et al., 2022; Vasques and Hoinaski, 2021), which has higher temporal, spatial, and chemical resolution than EDGAR. Also, the Vehicular Emissions Inventories package – VEIN (Ibarra-Espinosa et al., 2018), which provides vehicular emission outputs to be used in the WRF-Chem model. As a result of significant discrepancies in methods, emission factors, activity factors, and information sources among local agencies, consistent spatially disaggregated emission inventories at the national level are only available for some LAC countries, including Colombia.

Road transportation is the focus of most emission reduction efforts in urban areas. Latin American cities, which have among the highest urbanization rates, have recently invested in enhancing their transportation infrastructure and updating the technology of their fleet. They have also put in place infrastructure for non-motorized transportation and implemented restrictions on the use of passenger vehicles. However, motorcycles have significantly increased in several nations in the region. Since emission inventories are not calculated or

updated regularly enough to see historical patterns, the effects of these changes on emissions of CAPs, GHGs, and SLCPs have yet to be thoroughly documented at the national level.

Colombia is divided into 32 Administrative Departments, including the Capital District in Bogotá and San Andrés, Providencia, and Santa Catalina islands. Colombian departments have significant differences regarding social and economic development, i.e., provision of social services, infrastructure, and the concentration of manufacturing, mining, and agricultural activities (Núñez and Torres, 2000). Those diverse characteristics will play an essential role in traffic-related emission estimations and are considered in this analysis.

This study aimed to build an independent high-resolution spatially disaggregated dataset of road transport emissions in Colombia at a $0.01^\circ \times 0.01^\circ$ resolution and a national road transport emissions time series for the 1990-2020 timeframe. The study is part of PAPILA (Prediction of Air Pollution In Latin America and the Caribbean), a collaborative project funded by the Horizon 2020 Research and Innovation Staff Exchange (RISE) programme that aims to develop air quality modelling tools for the region. The emission inventories work package of the project has focused on improving emission estimates for several countries of the region using local information and developing methods that can be easily applied to different countries in the region, according to their data availability. Thus, we adopted the methods developed in Chile (Osses et al., 2022) and adapted them to the data available in Colombia. To the best of our knowledge, this is the first road transportation emission disaggregation for the whole country at this high resolution and the first time series of road transportation emissions for more than two decades.

2. Materials and Methods

Our research estimates exhaust emissions for on-road transportation for 1990 through 2020, e.g., cars traveling on public roads, countrywide, in urban and rural areas. We follow a top-down approach, estimating emissions based on an activity factor (number of active vehicles and average distance traveled by vehicle category) for each department and an emission factor for each pollutant, vehicle category, vehicle technology, and fuel type. These estimated emissions were disaggregated at a $0.01^\circ \times 0.01^\circ$ resolution for the country. The inputs, procedures, and results that went into our estimations are depicted in Figure 1.

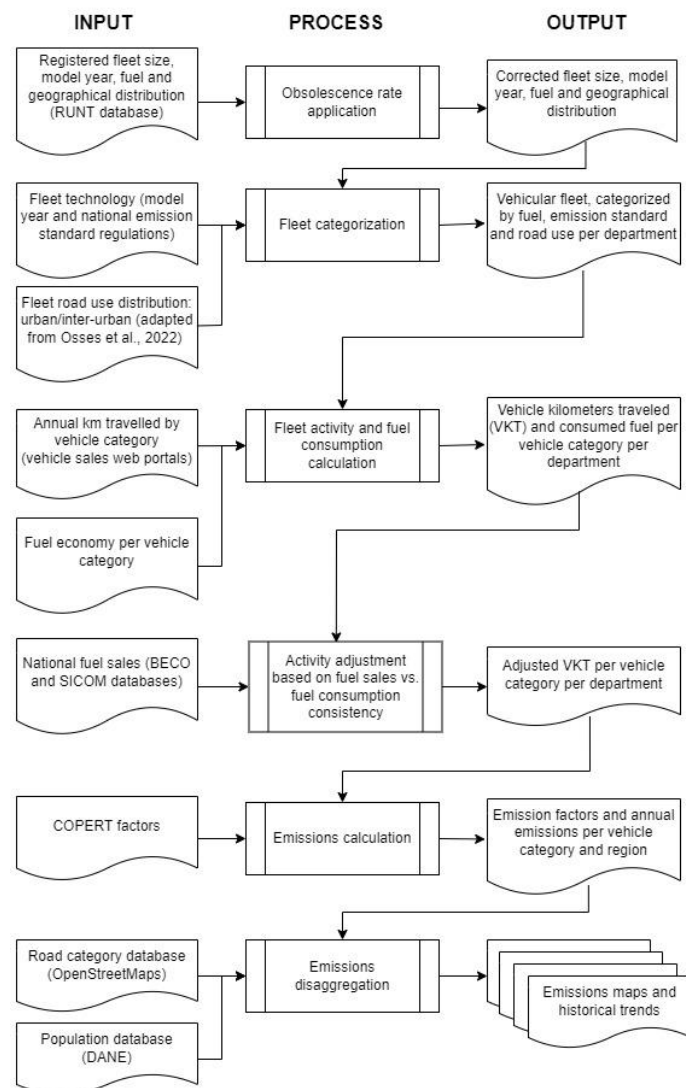


Figure 1. Estimation framework for on-road vehicle emission estimation

2.1. Vehicle activity and fuel consumption

We used spatial cluster analysis to define geographic clusters of similar departments based on the number of vehicle registrations, gasoline and diesel sales, roadways, and population (see Table 1). The total vehicle activity is expressed in vehicle kilometers traveled (VKT), which is computed as the sum of the vehicles in each class multiplied by the average annual mileage (Equation 1)

$$VKT = \sum_{i,j}^N N_{ij} \times KM_{ij} \quad (1)$$

where N_{ij} is the number of vehicles of type i in a geographic cluster j and KM_{ij} is the annual kilometers travelled by vehicles type i , in cluster j .

We combined sources in the lack of official datasets for active vehicles, N_{ij} , and vehicle activity, KM_{ij} , in Colombia. We used the National Single Transportation Registry (RUNT, as per its acronym in Spanish), a sizable, centralized database that stores data on all vehicles that have ever been operational and active in Colombia. For the period of interest, the RUNT database had 15,401,706 vehicles, each with information about their class, motor capacity, make, model, kind of service, fuel, department, and registration municipality. We used vehicle retirement and obsolescence rates to estimate the active vehicle fleet by year.

We classified Colombia's vehicle fleet according to the categorization of the Computer Programme to Calculate Emissions from Road Transport (COPERT) version 5.5, which consists of five categories: passenger cars (PC), motorcycles (MOT), light commercial vehicles (LCV), heavy-duty vehicles (HDV), and buses (BUSES). These categories are used to report

the results of our investigation. We utilized the National Vehicle Registration Database (RUNT) to assign each vehicle to a COPERT segment and Euro emission standard, based on factors such as vehicle class, model year, fuel type, capacity, engine size, and weight. A detailed explanation of the criteria employed can be found in (Alfonso A., 2022). Table 2 illustrates the categories and the correlation between COPERT 5.5 and RUNT categorization.

Table 1. Distribution of Departments by clusters

Cluster	Departments	Number of Departments
A	Caldas, Cauca, Casanare, Huila, La Guajira, Magdalena, Sucre, Nariño	8
B	Cundinamarca, Valle del Cauca	2
C	Amazonas, Arauca, San Andres, Caqueta, Choco, Guainía, Guaviare, Putumayo, Quindío, Risaralda, Vaupés, Vichada	12
D	Atlántico, Bolívar, Cesar, Norte de Santander	4
E	Antioquia, Bogota D.C.	2
F	Boyacá, Cordoba, Meta, Tolima, Santander	5

Table 2. Equivalence of Colombian vehicle categories RUNT to COPERT 5.5. categories and vehicle classes

COPERT	Colombia RUNT	Vehicle Class
Passenger cars (diesel, gasoline)	Automobile, SUV, jeep, taxi Small trucks	PC
Light commercial vehicles (gasoline)		LCV
Urban bus standard, Urban bus midi	Bus	BUSES
Urban articulated bus	Articulated buses	BUSES
Intercity (coach standard)	Bus	BUSES
Heavy-duty vehicles Rigid ≤ 7.5 t	Trucks	HDV
Heavy-duty vehicles Rigid 7.5 - 12 t	Trucks, dump trucks, trailer truck	HDV
Heavy-duty vehicles Rigid 12 - 14 t	Trucks, dump trucks, trailer truck	HDV
Heavy-duty vehicles Rigid 14 - 20 t	Trucks, dump trucks, trailer truck	HDV
Heavy-duty vehicles Rigid 20 - 26 t	Trucks, dump trucks, trailer truck	HDV
Heavy-duty vehicles Rigid 26 - 28 t	Trucks, dump trucks, trailer truck	HDV
L-Category (motorcycles)	Motorcycle, moped, quadricycle, four-wheeler	MOT

From the website tucarro.com, which displays used cars for sale and provides information on the vehicle's year and mileage, we retrieved data using web scraping (data extracted in Nov-2021). We collected 27.776 records and computed the annual average activity KM_{ij} of each vehicle as the reported mileage divided by the age of the vehicle. Then, we calculated the winsorized average of the annual mileage for each cluster by vehicle class. Table 3 shows the annual average activity obtained.

Tabla 3. Annual average activity in each cluster by vehicle class in Colombia ($km \cdot y^{-1}$)

Cluster	Vehicle Class				
	BUSES	HDV	MOT	LCV	PC
A	43521	41645	8084	35700	14277
B	45201	44058	9650	35095	13003
C	43568	42793	8880	36313	18464
D	45890	42579	7468	35813	15210
E	53240	46723	8299	35316	12767
F	46305	42579	7888	37185	13906

Based on the national regulations issued in Colombia to comply with international emission standards, and assuming every vehicle in the Colombian market complies with the norm, we classified the fleet using Table 4. This homologation process was used to assign corresponding emission factors found in COPERT 5 (EEA, 2019).

Table 4. Colombian regulation on vehicle emission standards

Vehicle category	Fuel/Service type	Before 1990	1991	1997	1998	1999	2000	2001	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020

PC / LCV*	Diesel / Private	PRE EURO		EURO II	EURO IV			
	Diesel / Public	PRE EURO		EURO IV				
	Gasoline	PRE EURO	EURO I	EURO II	EURO III	EURO IV		
HDV	Diesel	PRE EURO		EURO I	EURO II	EURO IV	EURO V	
	Gasoline	PRE EURO	EURO I		EURO II	EURO III	EURO IV	
BUSES	Diesel / Private	PRE EURO		EURO I	EURO II	EURO IV		EURO V
	Diesel / Public	PRE EURO		EURO I	EURO IV		EURO V	
	Gasoline	PRE EURO		EURO I	EURO IV		EURO V	
MOT	Gasoline	PRE EURO			EURO II			

Resolution 005 –1996: Regulates emissions of pollutants by gasoline or diesel-powered mobile sources, before 2000. Resolution 1048-1999: Regulates emissions of pollutants by gasoline or diesel-powered mobile sources starting from the 2001 model year for PC, LCV, HDV. Resolution 910-2008: Regulates emissions of pollutants by mobile sources starting in 2010. MOT (Euro II) LDV, HDV, BUSES (Euro II). Resolution 2604-2009: Regulates emissions of pollutants by mobile sources starting in 2010 for public LDV, HDV, BUSES (Euro IV) Resolution 1111-2013: Regulates emissions of pollutants by mobile sources starting in 201 for private LDV, HDV, BUSES (Euro IV)

We used COPERT’s estimated fuel consumption per vehicle category, together with fleet size, distribution, and activity, to estimate total fuel consumption at the department and national level per road class. From these data, fleet size has the highest uncertainty since it does not account for the number of active vehicles. We established the Colombian Energy Balance (BECO) fuel sales database as our gold standard to adjust fuel consumption and emissions estimates (Unidad de Planeación Minero Energética (UPME), n.d.). BECO is the basis for reporting consumption data per sector to the International Energy Agency (IEA).

We adjusted fleet activity by using a correction factor corresponding to the BECO fuel sales / estimated fuel consumption ratio. This adjustment is associated with the actual number of active vehicles, in contrast to the number of registered vehicles from RUNT. Once the fleet activity was adjusted, i.e., national fuel consumption was consistent with national BECO fuel sales, we used disaggregated data derived from the Fuel Marketing Information System (SICOM)

database, which we obtained for 2019, to calculate fuel consumption per vehicle category and road class at the department level (Ministerio de Minas y Energía, n.d.).

2.2. Emissions inventory

Vehicle emission standards in Colombia have been gradually introduced in national regulations, following Euro standards – or their EPA equivalents –, according to the timeline shown in [Table 4](#). We adopted the RUNT fleet distribution, based on vehicle model year, to produce a fleet distribution based on emission standards using this timeline. We used COPERT 5.5 and COPERT’s road transport emissions spreadsheet (EEA, n.d.) to estimate emission factors per category and, hence, emissions by multiplying emission factors by VKT. We calculated PM_{2.5} and BC emissions from COPERT’s PM emissions, by applying PM_{2.5}/PM and BC/PM_{2.5} ratios, according to each vehicle emission standard and fuel (Bond et al., 2004; Cai et al., 2013; Chow et al., 2010; Minjares et al., 2014; Ntziachristos et al., 2009; Payri and Desantes, 2011). For this study, we used the same ratios applied for Chile (Osses et al., 2022). Since CH₄ emission factors are not included in COPERT 5.5, we estimated them from previous studies (Ntziachristos et al., 2009). We used COPERT’s base values and corrections for the rest of the pollutants.

As a result, we produced an emissions database per vehicle category, department, and road class for CO₂, methane (CH₄), PM_{2.5}, BC, carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOCs) for the 1990-2020 period.

We also produced total national emissions time series between 1990-2020 for all pollutants. We compared them with data reported for road transportation in Colombia by global emissions datasets, namely EDGAR 4.3.2, EDGAR 6.1, CAMS-GLOB-ANT, and CEDS.

2.3. Spatial disaggregation

The spatial disaggregation of road transport emissions entails distributing gigagrams of emissions annually across the entire national territory in cells with a latitude and longitude of $0.01^\circ \times 0.01^\circ$. The zones correspond to Colombia's territory divided into its 32 departments ("Departamento Nacional de Estadística (DANE)," n.d.). The population living in the various urban areas and the various roadway types present in each cell all affect how the annual emissions are distributed spatially, according to the road type, vehicle flow, and urban population.

OpenStreetMap has provided Colombia's road network, consisting of 171 800 km of rural and urban routes ("OpenStreetMap," 2021). This information has been processed using the open-source software QGIS and our own R script (Laengle, 2022). OpenStreetMaps has a road classification into 24 categories, such as highways, arterial roads, local roads, etc. To simplify calculations in this study, we selected four main road categories, namely Primary, Secondary, Tertiary, and Trunk. [Each road type is defined based on its characteristics, including whether it is a toll road or not, the speed limit, the level of traffic, and their respective roles in the transportation network. Detailed descriptions can be found in Laengle \(2022\).](#) In addition, we crossed land use maps from the Colombian Geographic Institute ("Instituto Geográfico Agustín Codazzi (IGAC)," n.d.) to assign road classes to urban and inter-urban roads. We used national average values for road weight factors to assign vehicle flows to road segments in each cell, as specific factors based on population and traffic counts for each department and road class were not available. Although it would have been preferable to use region-specific road weight factors, the lack of detailed local information made this approach unfeasible. Expressways account for

54% of the factors used, compared to 23% for principal roads, 16% for secondary routes, and 7% for tertiary routes (La tabla 2 (“Instituto Nacional de Vías (INVIAS),” n.d.). To divide each department's emissions among its main cities in urban areas, a further disaggregation factor based on population is used. The National Statistics Department (“Departamento Nacional de Estadística (DANE),” n.d.) has formally reported this data by department. We defined a disaggregation grid for the whole country and defined the cells corresponding to each department. In each cell of the department, we extracted length, category, and class of road segments, and applied the corresponding weight factors to allocate its fraction of total emissions. Finally, it is confirmed that the total emissions for each department and year match the aggregate of emissions from all cells.

3. Results and discussion

3.1. Vehicle technology and activity

Resolution 910 of 2008 (Ministerio de Ambiente Vivienda y Desarrollo Territorial (MAVDT), 2018) specifies emission standards for vehicles model year 2010 and later in Colombia. This Resolution applies to light-duty, medium-duty, and heavy-duty vehicles. Resolution 1111 of 2013 amended Resolution 2008 by introducing Euro 4/IV and US EPA Tier 2/2010 limits and regulating emissions from natural gas and liquified petroleum gas (LPG) heavy-duty engines. In 2019, Law 1972 was proposed to lower the limits for new diesel vehicles to Euro VI or equivalent. The technological and emission distribution of Colombia's vehicle fleet is uncertain, as outdated vehicles continue to remain in service beyond their reasonable lifetime, and the RUNT database, which is used to determine the emission standard distribution, does

not include information about the active status of vehicles. To account for these factors, we propose the use of vehicle obsolescence rates based on our analysis of top-down emissions using fuel sales. Specifically, we suggest an annual 3% obsolescence rate for buses, a 1% rate for heavy-duty vehicles, a 2% rate for passenger cars and light-commercial vehicles, and a 3% rate for motorcycles.

Buses, passenger cars, heavy-duty vehicles and motorcycles show an increasing trend during the three decades of analysis (see Figure 2). In contrast, the number of light-commercial vehicles decreased. Between 1990 and 2020, the entire fleet increased from 1.5 to 11.4 million units growing at an annual average of 6%. However, motorcycles have grown at 10% annual rate during the period of analysis going from representing 23% of the total fleet in 1990 to 58% in 2020. These growth and share are high even for the Latin American region, where motorcycles represent around 11% of the total fleet (Soares da Silva and Silveira Rodrigues, 2016). In contrast, in Colombia heavy-duty vehicles and light commercial show the lowest growth rate. Most of the increase in the bus fleet is observed during the first decade in 2000, which is aligned with the national policy to improve the public transportation service and implementation of BRT systems (Departamento Nacional de Planeación (DNP), 2002). Additionally, the total vehicle activity went from around 65 thousand million VKT to 150 thousand, growing at an average rate of 3% per year.

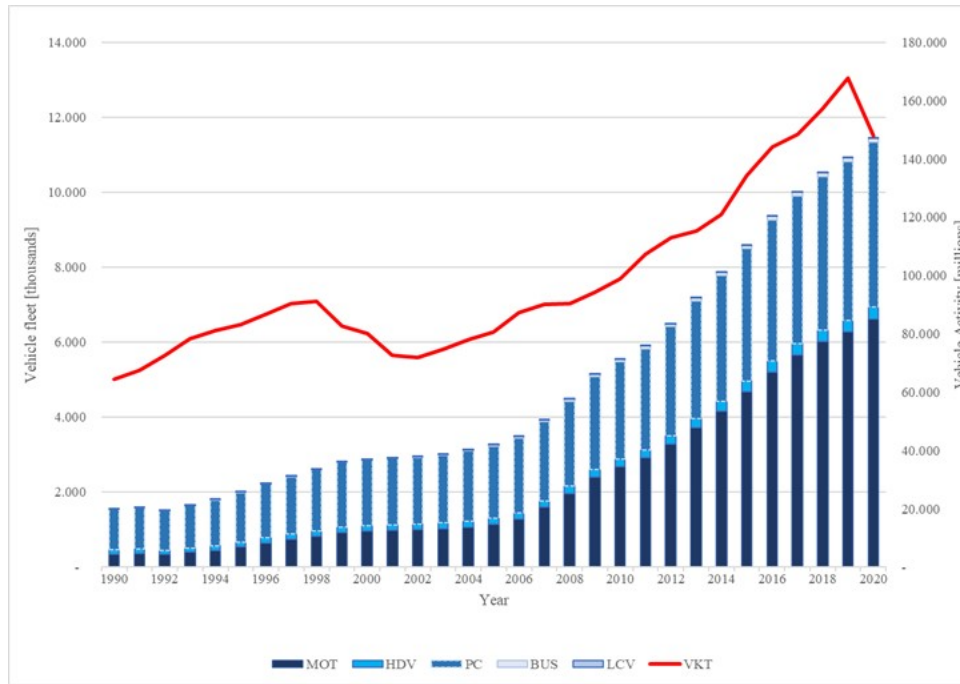


Figure 2. Vehicle fleet and VKT trends to 2020

Using the current norms and the homologation to the European vehicle standard condensed in Table 2 and 4, we display in Figure 3 the vehicle standard trend over time for buses (a), heavy-duty vehicles (b), light-commercial vehicles (c), motorcycles (d), and passenger cars (e). In general, during the three decades, we do not see a complete disappearance of pre-Euro (E0) technologies in any of the vehicle types. However, in passenger cars pre-Euro vehicle standards are gradually fading, giving way to a mix of standards Euro 1 to Euro 4 by 2020. We report a timid market penetration of Euro 5 and Euro 6 buses and passenger cars, accounting only for 1% of the total fleet by 2020 (Figure 3 a, e).

Two-wheel vehicles show an important change in growth rate after 2006, but only in 2010 did we start to see Euro 2 motorcycles in the market. In 2020, most of the motorcycles operating in

Colombia comply with the Euro 2 standard, even though less pollutant technology is already available in Europe and other developed countries (Figure 3 d).

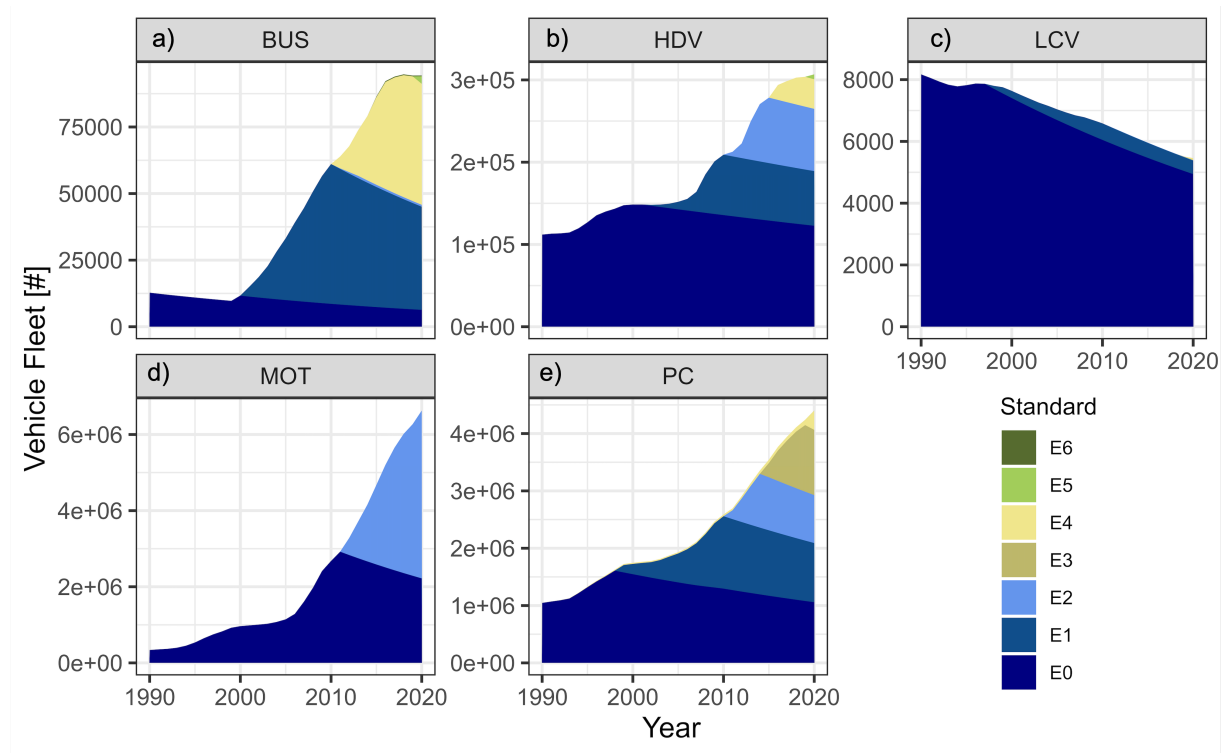


Figure 3. Trend Vehicle Fleet and standard 1990 to 2020

The number of heavy-duty vehicle units exhibits a consistent development, rising from 113.108 in 1990 to 306.815 in 2020. As stated before, pre-Euro and Euro I trucks did not cease to exist in 2020 and they still account for 61% of the heavy-duty fleet in Colombia. The adoption of newer emission standards has been gradual, leaving a mixed fleet dominated by Pre-Euro and Euro 1 and Euro II by 2020 (Figure 3 b). We report a decline in the number of light commercial vehicles, which represent gasoline-powered small trucks in Colombia (refer to Table 2). This vehicle technology is disappearing from the Colombian fleet and has been replaced by diesel trucks (Figure 3 b).

Buses grew from 12,495 in 1990 to 94,343 in 2020 showing a significant change during the 2000 decade. We report a total of 290 Euro VI buses and 348 electric buses by 2020. The first low-emission buses for public transportation were running in the main cities, which is nearly undetectable in Figure 3 a).

3.2. Total emissions

For the entire country of Colombia, from 1990 to 2020, annual CO₂, CH₄, PM_{2.5}, BC, NO_x, and VOC emissions have been computed and broken down by vehicle type and technology. Figure 4 compares vehicular activity (represented as VKT) with a number of compounds using 1990 as the base year.

The VKT curve exhibits a period of initial, steady rise between 1990 and 1997, followed by a significant decline between 1998 and 2001, before returning to an upward trend from 2002 to 2019. Several sources (Torres, 2012; Uribe and Vargas, 2002) describe the decline in activity seen in the years between 1998 and 2001, when Colombia was badly impacted by the economic crisis. Due to the high cost of fuel, this led to a decrease in the purchase of new automobiles as well as a decrease in the use of current ones. Except for 2020, when the impact of the COVID-19 epidemic surfaced and motor vehicle trips across the nation were significantly curtailed, the economic reactivation following 2001 has been consistent (Seguel et al., 2022).

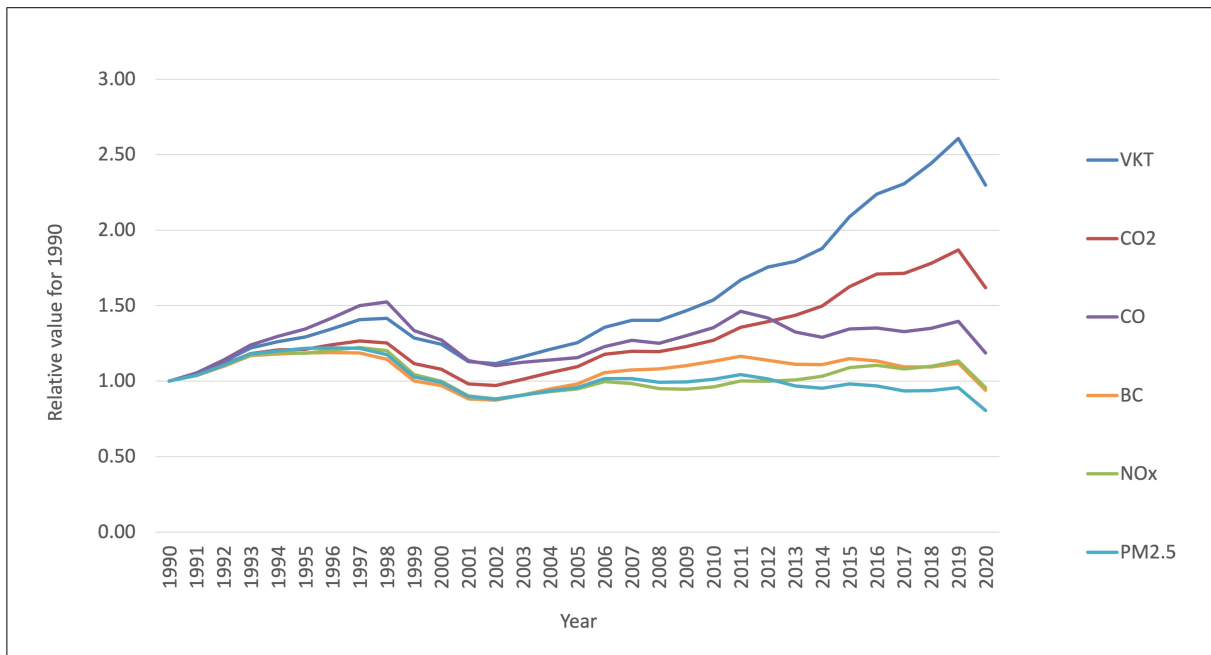


Figure 4. Normalized emission trends from 1990 to 2020

In the period under consideration, CO₂ emissions exhibit significant similarities to the vehicle activity curve, increasing by 3% between 1990 and 1998, declining by 6% between 1998 and 2001, and then increasing by 4% on average until 2019. Prior to 1998, there were rising trends in criterion pollutant emissions, which were also impacted by the economic crisis from 1998 to 2001. By implementing EURO standards nationwide, it becomes possible to distinguish the impact of vehicle activity from that of gas and particulate matter emissions.. This effect is most well-known in 2011, when emissions are clearly on the decline and have returned to 1990 levels for NO_x, PM_{2.5}, and BC.

Figure 5 breaks down the emissions of gases and particulate matter for the years 1990 to 2020 by color-coding the various types of land vehicles. A sizeable portion of CO₂, CO, and NO_x emissions come from passenger cars. Motorcycles dominate CH₄ and, in the last half of the

period, CO emissions, due to obsolete technology. Heavy trucks dominate PM_{2.5}, BC, and NO_x emissions, and while having fewer units, they have a similar impact on CO₂ emissions as passenger cars do.

Table 5. Annual exhaust emissions from on-road transportation in Colombia, 1990-2020 (Gg y⁻¹)

	Year							2020/1990 > 1 increase; < 1 decrease
	1990	1995	2000	2005	2010	2015	2020	
CO ₂	17544	21249	18906	19212	22292	28732	28612	1.63
NO _x	223	264	223	211	214	218	191	0.86
CO	603	812	767	697	817	810	714	1.18
PM _{2.5}	7.3	8.9	7.3	7.0	7.4	7.0	5.8	0.80
BC	3.2	3.8	3.1	3.1	3.6	3.3	2.7	0.85

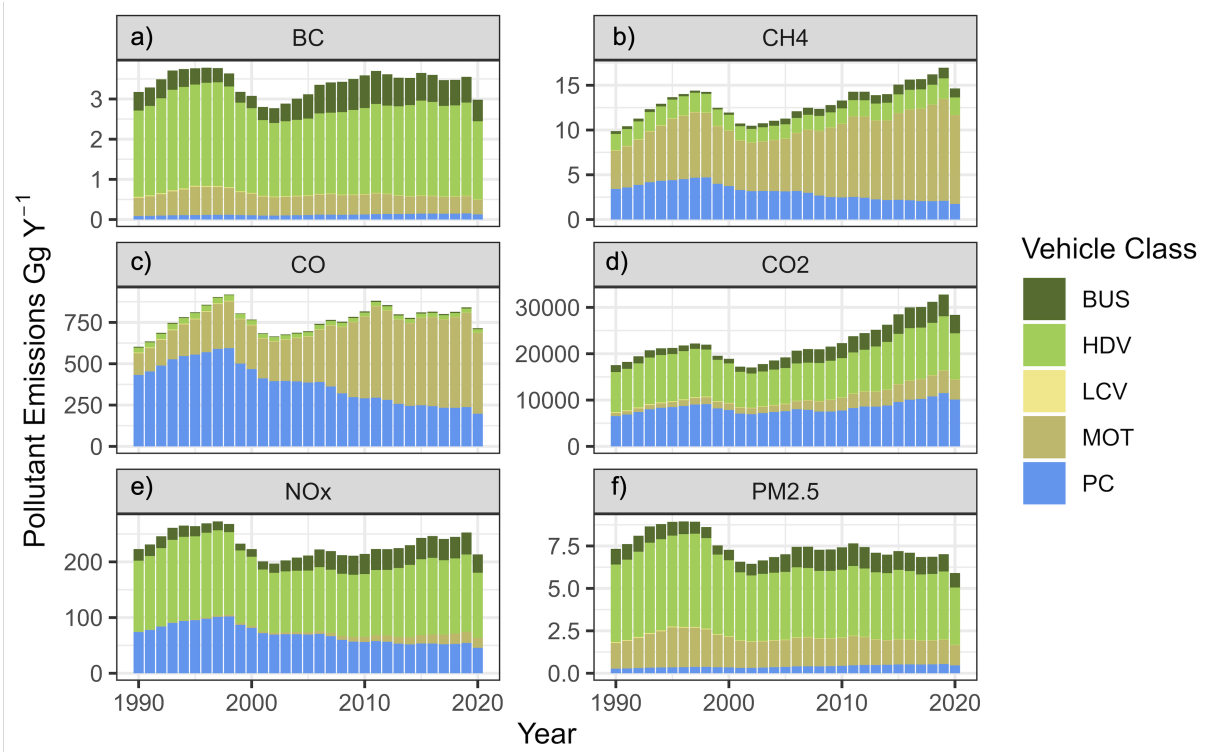


Figure 5. On-road transport emission trends from 1990 to 2020 per vehicle class

As of 2011, the nationwide trend for fine particulate matter emissions shows a minor but consistent trend of decline. This is consistent with assessments of this pollutant's air quality made in four Colombian cities (Casallas et al., 2022). The cities of Bogota, Medellin, Caldas, and Itagüi demonstrate declining trends in particulate matter concentrations between 2010 and 2020, according to Casallas et al.

3.3. Comparison with other inventories

We compared emission estimates from this study with the global emissions inventories EDGAR 4.3.2 (Janssens-Maenhout et al., 2017), EDGAR 6.1 (Crippa et al., 2021), CAMS (Granier et al., 2019), and CEDS (McDuffie et al., 2020; Smith et al., 2015), as well as national emissions inventories published by the Colombian government for greenhouse gases (INGEI, as per its acronym in Spanish) (IDEAM et al., 2016) –, and criteria air pollutants and black carbon – (INCCBC, as per its acronym in Spanish) (IDEAM, 2020). It is worth noticing that PM is not included in CAMS and CEDS, and CH₄ is not explicit in the official Colombian inventories. On the other hand, CAMS dataset was based on EDGAR 4.3.2. before 2015, and emissions were projected for later years. CEDS dataset is coincident with EDGAR 4.3.2. for some pollutants and part of the period (i.e. CO), but differ for other pollutants (i.e. BC). Therefore, our main reference for comparison is EDGAR 6.1.

Figure 6 shows the comparison of CO₂ (a) and CH₄ (b) emission estimates among this work and other emissions inventories. Magnitudes and temporal variations are very similar for all estimates of CO₂ emissions (Fig. 6a), with a mean difference of 1.4% and a range between –

23.3% and 13.9%. The highest negative and positive differences between PAPILA and EDGAR 6.1 occurred in 1994 (-22.1%), 2001 (8.7%), and 2012 (8.7%). Also, there's an important difference between CAMS and the rest of the inventories after 2012, because such values for CAMS correspond to projections, not to calculations from actual data. Our estimates show a 13.4% decline in CO₂ emissions between 2019 and 2020, caused by the reduction in mobility associated with COVID-19 lockdowns. Overall, this agreement shows that fleet activity and fuel consumption are consistent among inventories and are realistic for emission estimates of other pollutants included in this study.

Unlike CO₂, the magnitude of CH₄ emissions estimated in this work is much higher, roughly two-fold the values from global estimates. The reason of the difference can be attributed to a high proportion of motorcycles in the Colombian fleet, with a high emission factor for this pollutant (see Fig. 6b). Global emission inventories do not account for the share of motorcycles and, as a result, underestimate these emissions when compared with our calculations. We had estimated emissions from the Chilean fleet, and found a much better agreement with global estimates, since the share of motorcycles in the Chilean fleet is much lower than in Colombia (Osses et al., 2022). Although the magnitudes are different, temporal variations in CH₄ emissions are similar to those shown by EDGAR 4.3.2, EDGAR 6.1, and CAMS. CEDS shows a declining trend after 2004 that is not observed in the other inventories, likely attributable to assuming improvements in vehicle emission standards faster than other inventories. However, we do not have access to the CEDS source databases to confirm this.

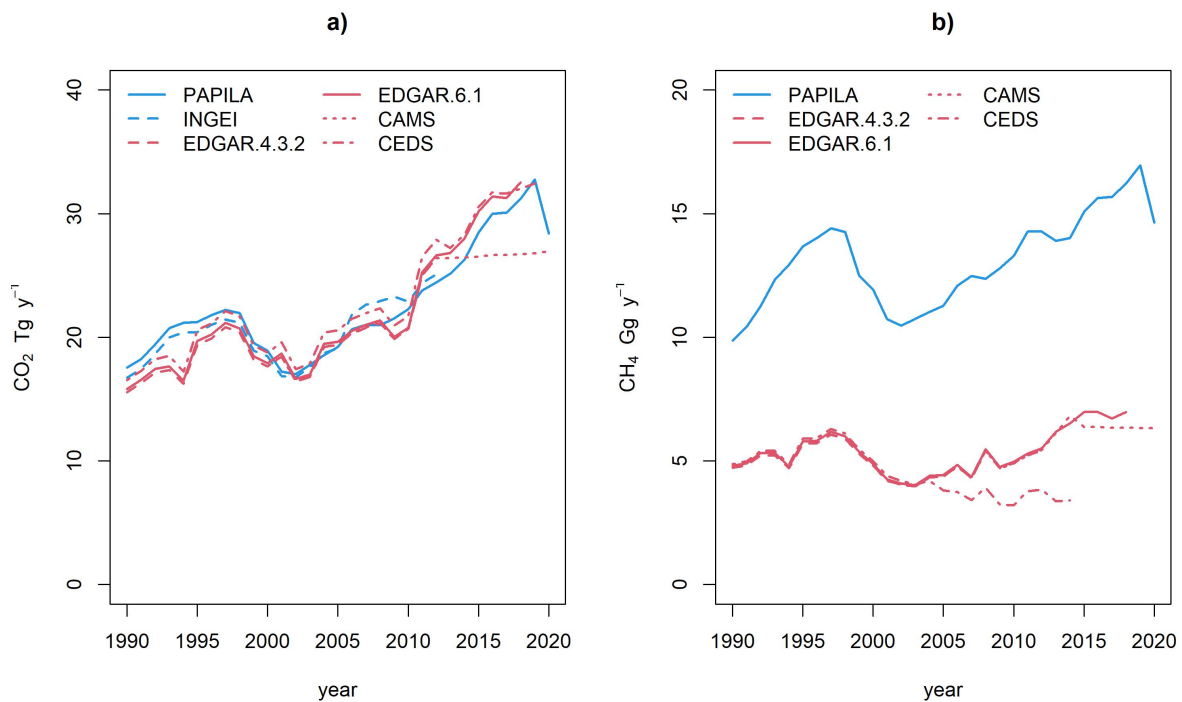


Figure 6. Comparison between this work (PAPILA) and other emissions inventories for a) CO₂ and b) CH₄.

Figure 7 shows the comparison of PM_{2.5} (a) and BC (b) emission estimates from this work and other emission estimates. For PM_{2.5} (Fig. 7a), local inventories and EDGAR 6.1 range between 4 and 10 Gg yr⁻¹, with a narrower range for local estimates. PM_{2.5} emissions from EDGAR 4.3.2 range roughly between 30 and 40 Gg yr⁻¹, much larger values. This suggests that the fleet composition, together with the corresponding emission factors, was adjusted between both versions of EDGAR, being EDGAR 6.1 more realistic. This study shows a net declining trend between 1997 and 2001, because of new regulations (Resolution 1048 –1999) that restricted automotive import or assembly without three-way catalytic converters, and after 2005, as a

result of fleet renewal with cleaner technologies (Pre-Euro to Euro 1). The trend is consistent, with 16% to 32% differences in magnitude with the local INCCBC inventory. The increasing trend shown by EDGAR 6.1 does not appear to include fleet renewal processes at the same rate as those used in this study until 2012. The underestimation before 2007 and overestimation of after 2008 in EDGAR 6.1 are likely to be associated to differences in emission factor and emission standard changes over time. While EDGAR 6.1 seems to use lower emission factors in the first part of the period, these factors did not improve before 2012. Using a detailed fleet composition and considering the introduction of technologies according to Colombian emission standards, this work shows a much earlier (1997) and faster change in trend, from a dirtier fleet and higher emission factors to a cleaner fleet and lower emission factors than those in EDGAR 6.1. The increasing trend from EDGAR 6.1 changes after 2012, showing a declining trend that is fairly consistent with local estimates. There is a 15% decline in PM emissions associated with the COVID-19 lockdowns in this study. As a result of opposite trends, EDGAR 6.1 PM_{2.5} emission estimates are lower than our estimates from 1990 to 2006 and higher afterwards. CAMS and CEDS inventories do not include PM_{2.5}.

For BC (Fig. 7b), there are important differences among inventories. Our estimates show emissions ranging between 2.7 and 3.8 Gg y⁻¹. They are roughly 30% higher than INCCBC between 2010 and 2014. EDGAR 4.3.2 and CAMS (derived from EDGAR 4.3.2) show values ranging between 1 and 4 Gg y⁻¹, 27% to 45% lower than EDGAR 6.1. CEDS shows higher values than all other estimates, ranging between 3.5 and 9.3 Gg y⁻¹, almost two-fold the values from EDGAR 6.1. Trends in BC emissions in our estimates show reductions between 1997 and 2002 and after 2011, as a result of regulations and fleet renewal, respectively. All global inventories show net increasing trends between 1990 and 2012. CAMS and CEDS show decreasing trends afterwards, somewhat consistent with our results. Differences in magnitudes

and, to a lesser extent, in trends suggest that fleet renewal processes do not occur at the same rate in global inventories as in this study, which consider the introduction of new vehicles with better emission standards. In our study, as for $PM_{2.5}$, the estimated decline in BC emissions caused by COVID-19 lockdowns was of 15%.

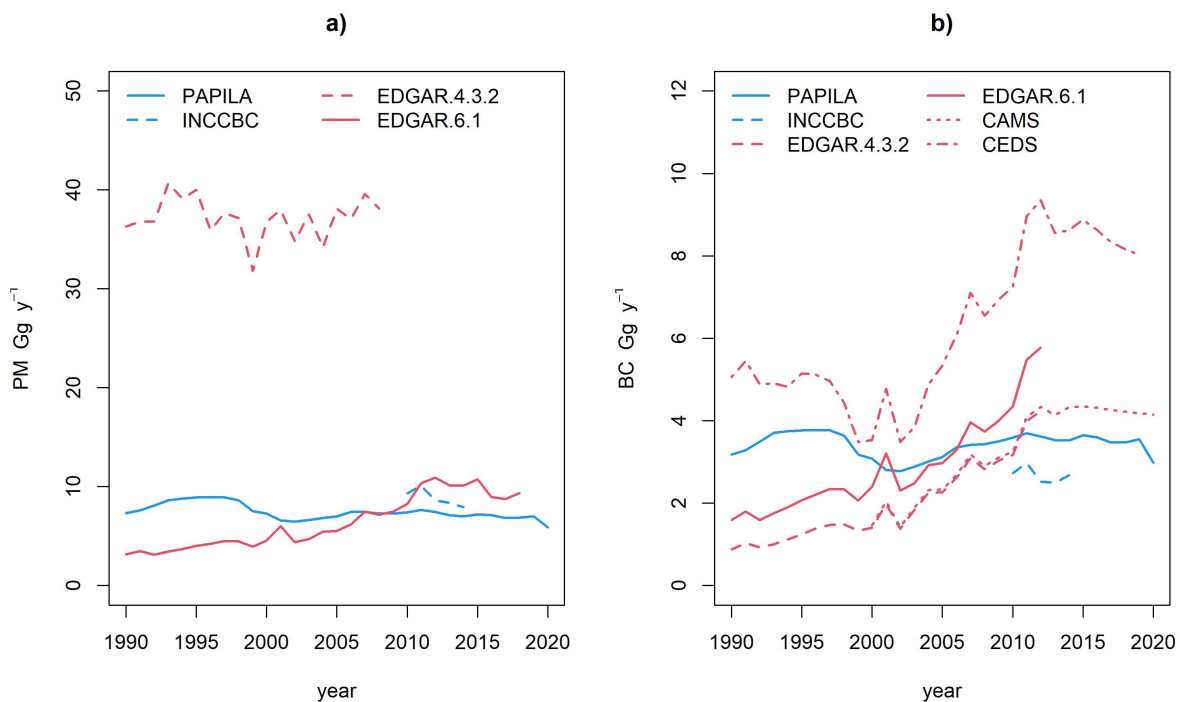


Figure 7. Comparison between this work (PAPILA) and other emissions inventories for a) PM and b) BC.

Figure 8 shows the comparison of CO (a) and NO_x (b) emission estimates from this study and other inventories. For CO (Fig 8a), the differences in magnitudes are similar to those described for PM, with EDGAR 4.3.2, CAMS and CEDS showing much higher values than this study and EDGAR 6.1. Emissions between 1990 and 2004 were higher in EDGAR 6.1 than in this

study, and lower afterwards. CO emissions in our study were roughly 20% higher than those in the INCCBC inventory between 2010 and 2014. Temporal changes are somewhat similar among all inventories, with an initial increase in the early 1990s, and a sharp decrease after 1997, attributable to the introduction of vehicles with better emission standards. Our study showed an increasing trend between 2002 and 2011, and a rather constant trend afterwards, which can be attributed to the increase in the number of motorcycles, as shown in Fig. 8a. Global inventories showed a second increase period starting later, in 2009.

For NO_x (Fig 8b), this study shows higher emissions than all other inventories between 1990 and 2010, and lower emissions than EDGAR 6.1 and CEDS after 2011. EDGAR 4.3.2 and CAMS emissions remained lower than this study after 2011. Temporal variations followed a similar behaviour, with an initial increase between 1990 and 1997, followed by a sharp decline between 1997 and 2003, associated with the variations in fuel consumption. However, while our study suggests a stabilization in emissions after 2005, with some oscillations, global inventories show a net increase, except for CAMS projection after 2012, that shows a slow reduction. This difference in trends suggest that EDGAR and CEDS consider a slower rate in the introduction of new vehicles with better emission standards. Our study shows 15% to 30% higher emissions of NO_x than the INCCBC local inventory between 2010 and 2014, but the INCCBC series is not long enough to infer if the difference would be attributable to emission factors or fleet composition. The estimated reduction in NO_x emissions associated with COVID-19 lockdowns was 15.5%.

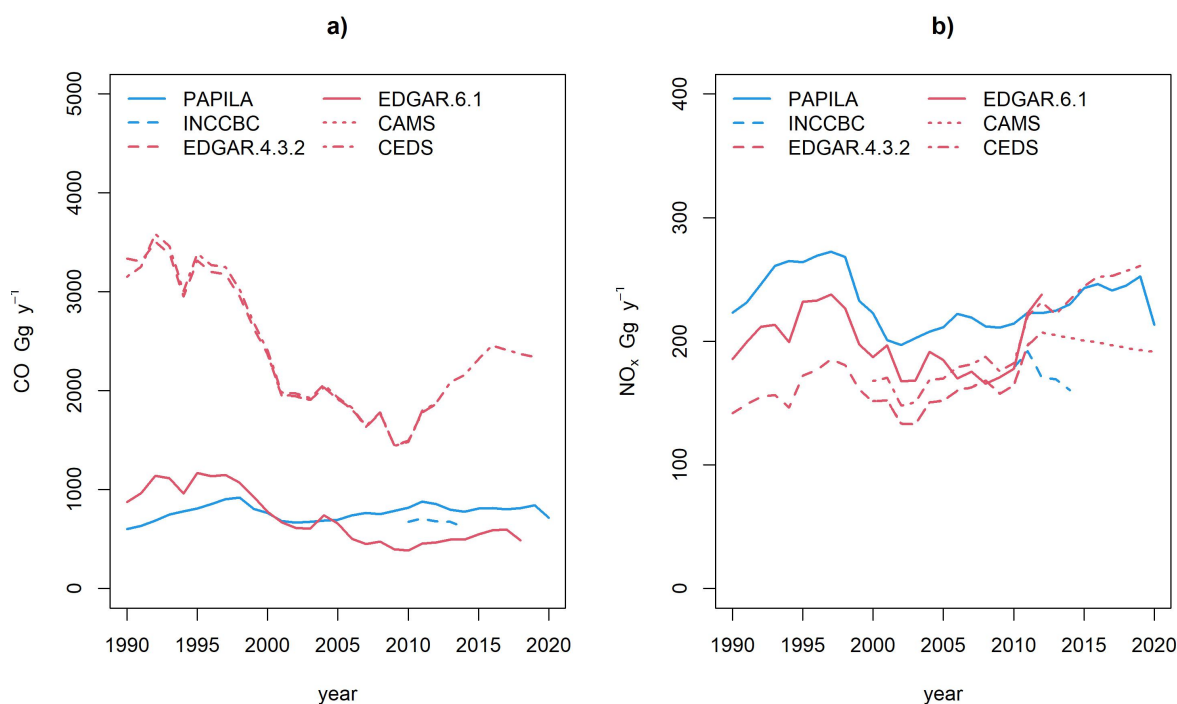


Figure 8. Comparison between this work (PAPILA) and other emissions inventories for a) CO and b) NO_x.

CO/NO_x ratio refers to the ratio of the concentration of carbon monoxide (CO) to that of nitrogen oxides (NO_x) in a given mixture or combustion process. This ratio is frequently used as an indicator of combustion efficiency in vehicle engines, which is associated with their technology and emission standard. Figure 9 shows the comparison of the CO/NO_x ratio between this study and other inventories. This study, INCCBC and EDGAR 6.1 show ratios ranging between 1.8 and 5.4, much lower than those in EDGAR 4.3.2, CAMS and CEDS, which are very closely related. This study shows an increasing trend between 1990 and 2012, followed by a decreasing trend afterwards. In contrast, EDGAR 6.1 shows a net decreasing trend during the

same period. The large change between EDGAR 4.3.2 and its updated version, EDGAR 6.1, makes this global inventory much more consistent with local estimates, suggesting more realistic emission factors. Lower ratios from EDGAR 6.1 than from our study are likely attributable to the share of motorcycles.

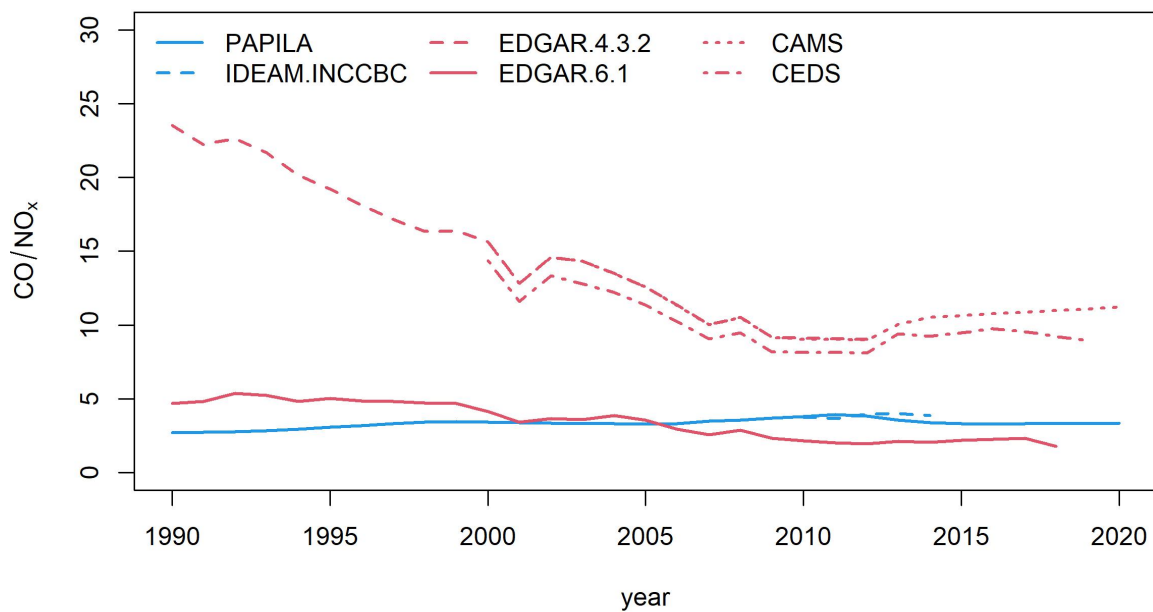


Figure 9. Comparison between this work (PAPILA) and other emissions inventories for the CO/NO_x ratio.

We have conducted a comparative analysis with local emission inventories for road transport in various cities around Colombia in addition to comparing the results of annual emissions with worldwide databases. The five locations where recent inventories similar to those in this study have been recorded are listed in Table 6. These areas correlate to the towns of Medellín, Itagü, Sabaneta, La Estrella, Bello, Copacabana, Envigado, Girardota, Barbosa, and Caldas in the Vallé de Aburrá and the cities of Barranquilla, Bogotá, Cali, and Manizales. Based on our

projection for the year 2017, the values provided by pollutant and the fraction between the external studies and the current study are shown in each case. Bogotá and Cali both have two inventories that are published in the same year. This is due to the fact that in these investigations, the emissions were calculated using a bottom-up (BU) or top-down (TD) methodology, respectively.

Table 6. Comparison of on-road transportation emission inventories for several studies in Colombia (Gg y⁻¹)

Row	Author	Location & year	CO	NOx	VOC	CO ₂	PM _{2.5}
A	This study	Barranquilla 2017	37756	6163	7970	892653	293
B	Méndez, 2018	Barranquilla 2018	16878	10639	3720	N/A	N/A
		B/A ratio	0,45	1,73	0,47	-	-
C	This study	Bogota 2017	207788	45254	30662	6786667	1563
D	SDA, 2018	Bogota 2018 TD	595441	84032	109942	N/A	1676
E	SDA, 2018	Bogota 2018 BU	393953	88094	31522	N/A	1907
		D/C ratio	2,87	1,86	3,59	-	1,07
		E/C ratio	1,90	1,95	1,03	-	1,22
F	This study	Calí 2017	166033	11114	44320	2647410	923
G	UNAL 2022	Cali 2022 TD	60215	7516	10824	1346355	639
H	UNAL 2022	Cali 2022 BU	84950	11368	21696	2087924	812
		G/F ratio	0,36	0,68	0,24	0,51	0,69
		H/F ratio	0,51	1,02	0,49	0,79	0,88
I	This study	Manizales 2017	23843	1961	7460	392147	184
J	Valencia, 2019	Manizales 2017	27955	4580	5137	486281	624
		J/I ratio	1,17	2,34	0,69	1,24	3,39
K	This study	Valle Aburrá 2017	202739	30905	48468	4530744	1668
L	Toro, 2019	Valle Aburrá 2018	562557	16522	32736	N/A	2625
		L/K ratio	2,77	0,53	0,68	-	1,57

The greatest disparity for VOC is found in Bogota, where the top-down methodology is 3.59 times greater than our study. However, the same study conducted in Bogota using bottom-up methodology is nearly identical to ours. The study by Valencia (2019) for the city of Manizales also reports higher values than our inventory, which is explained in part by a higher estimate of

CO₂, which is proportional to activity level. Lower values reported by external references are observed in the city of Cali, compared to our results, which are explained by the lower CO₂ value and the difference between the years considered in each case. Given the foregoing, it is reasonable to conclude that the current study does not differ significantly from the external results reported in Table 3.

The final validation of an emissions inventory is usually performed by applying a chemical transport model to obtain air pollutant concentrations that can be compared with air quality observations. The application of a chemical transport model with the emission inventories estimated in this work, however, is out of the scope of this manuscript. As a qualitative validation, figure 10 compares our emission inventory time series with those from Bogota's air quality monitoring data for CO, NO_x and PM_{2.5} between 2010 and 2020, which is the period with the most reliable observations. In all cases, both pollutant concentrations and emissions show net decreasing trends in this 11-year period. CO concentrations decreased between 2010 and 2015, then increased between until 2018, and decreased again until 2020. These variations are similar to those estimated in the emission inventories. NO_x concentrations showed more variability, but similar decrease and increase trends as its emissions. PM_{2.5} concentrations showed a more continuous, monotonous trend for the whole period when compared with CO and NO_x, as occurred also with its emissions. Similar trends in PM_{2.5} concentrations were also

observed by Casallas et al. (2022) for the cities of Bogota (2011-2020), Caldas (2013-2020), Itagüi (2014-2020), and Medellin (2009-2020).

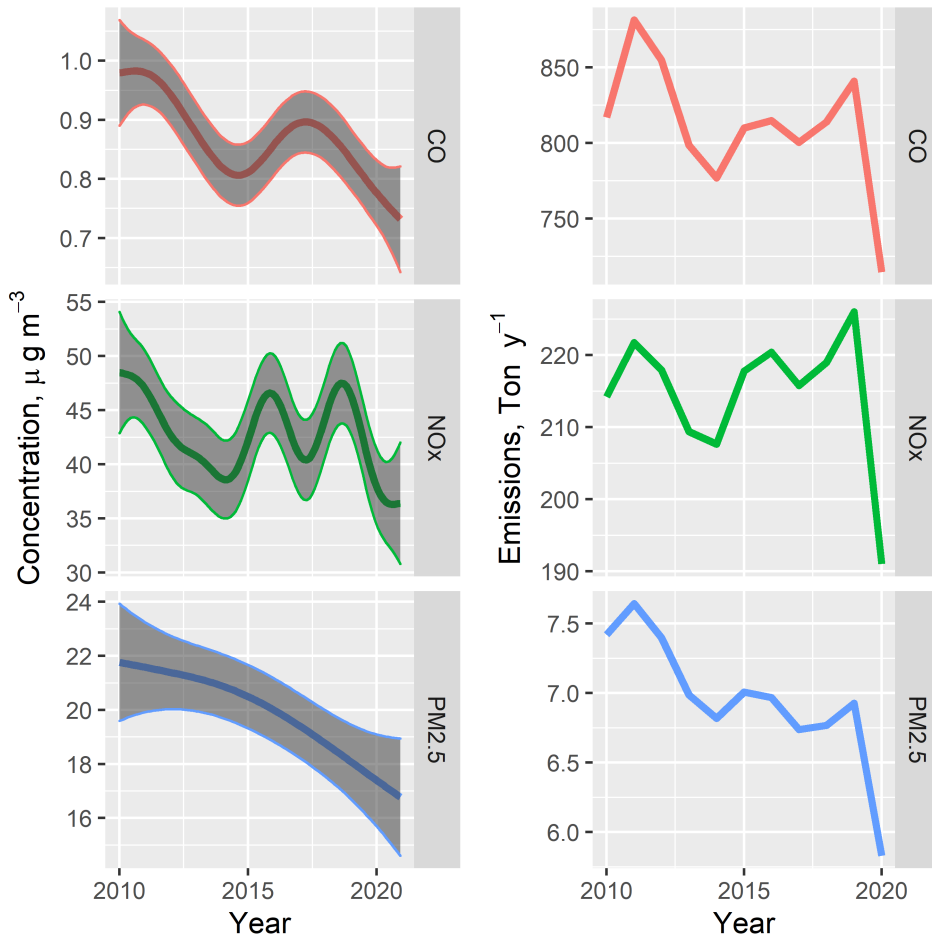


Figure 10. Air quality observations vs. Emissions estimated in this work for CO, NO_x and PM_{2.5} between 2010 and 2020.

3.4. Spatial disaggregation

The spatial distribution of transport emissions per region consists of allocating Gg of emissions per year to each cell in a grid, with cells of 0.01 x 0.01 degrees of latitude and longitude covering the 33 departments in the country. The departments correspond to the political administrative division of the territory. The distribution depends on the types of roads in each cell, the vehicle flow, and the presence of urban population. Average road weight factors, which translate to

54% for trunk, 23% on primary, 16% for secondary, and 7% on tertiary roads, were taken from Chile (Laengle, 2022).

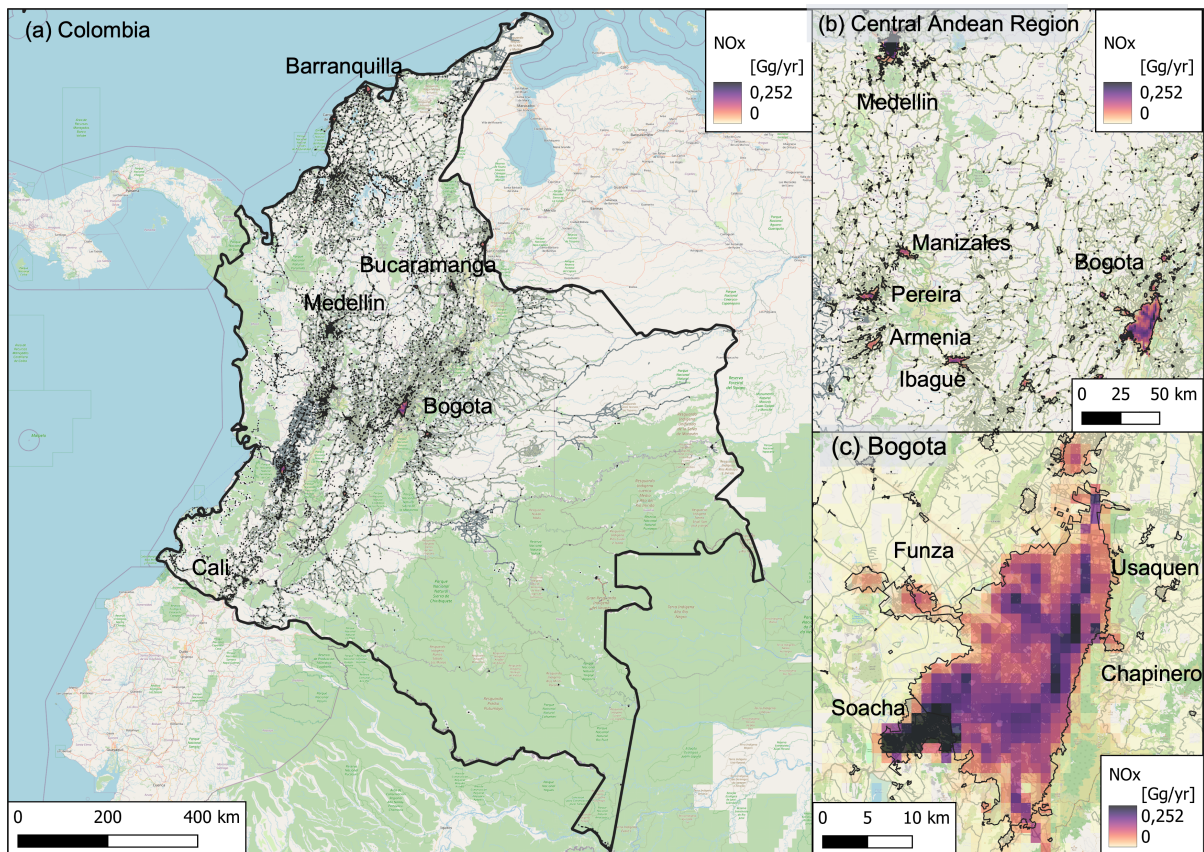


Figure 11. Spatially distributed NOx on-road vehicle emissions, year 2020. (a) Colombia and main cities, (b) Central Andean region, (c) City of Bogota.

The large concentration of emissions in the nation's urban centers and on major roadways is demonstrated by the spatial disaggregation of emissions at the national level. Figure 11 depicts the fraction of NOx emissions over cells that are 0.01 x 0.01 degrees in latitude and longitude, or around 1.11 x 1.11 kilometers, for the year 2020. Four significant cities stand out with higher emissions (Bogota, Bucaramanga, Cali, Medellin). Figure 10b provides a more thorough illustration of Colombia's central Andean region, which includes the Coffee Cultural Zone.

Figure 10c depicts Bogotá, where the Soacha industrial zone in the southwest has the highest NO_x emissions.

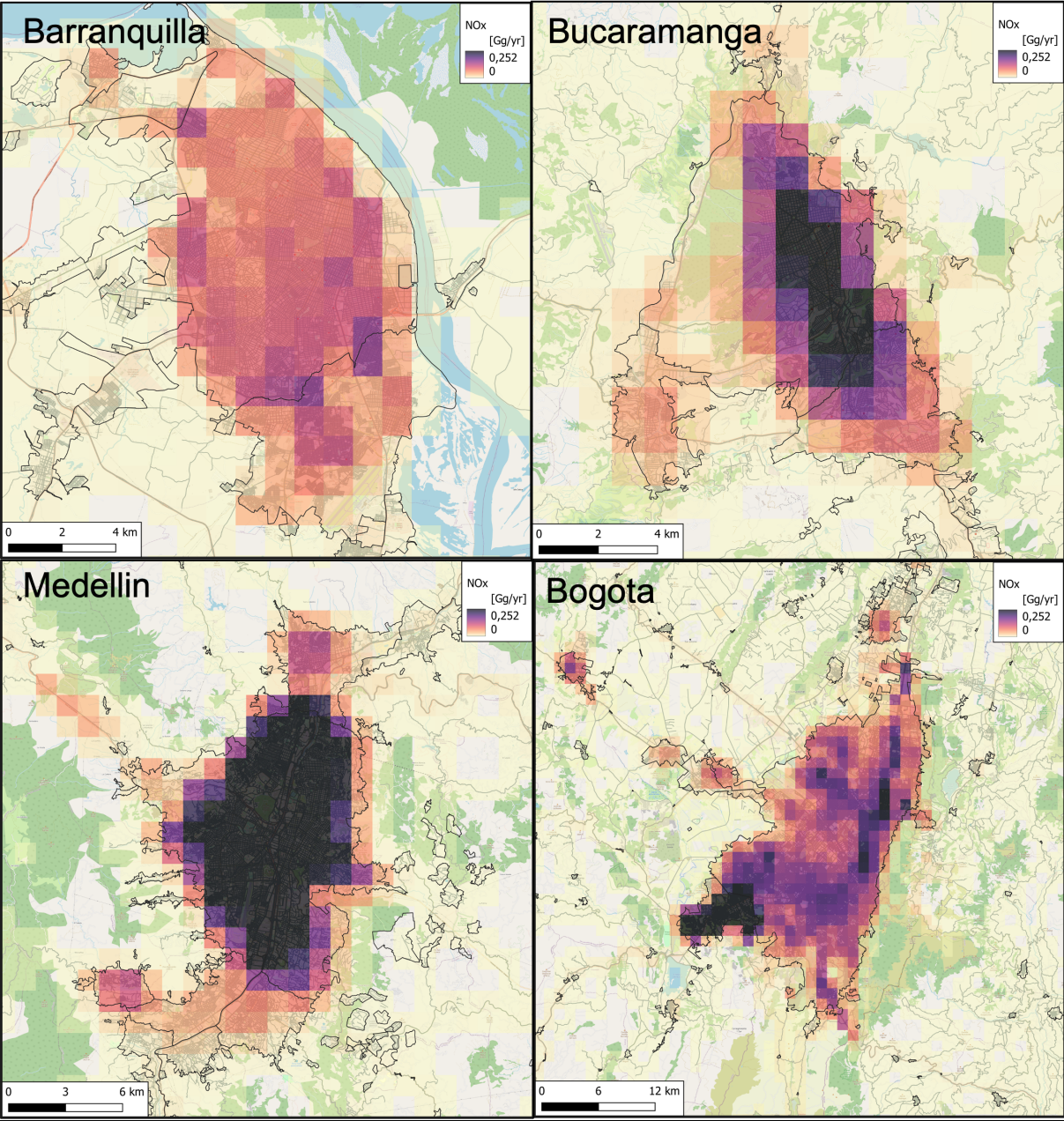


Figure 12. Spatially distributed NO_x on-road vehicle emissions, year 2020. (a) Barranquilla, (b) Bucaramanga, (c) Medellín, (d) Bogotá.

Figure 12 displays the NO_x emissions for 2020 for four significant cities in Colombia, allowing for the identification of the urban form and road system in each metropolitan core. The identical color palette and size scale are used throughout, making it possible to see the high amount of emissions present in Medellín. These high values are comparable to Soacha's in Bogotá and Bucaramanga's city center. NO_x emissions are at lower levels in Cali and Barranquilla.

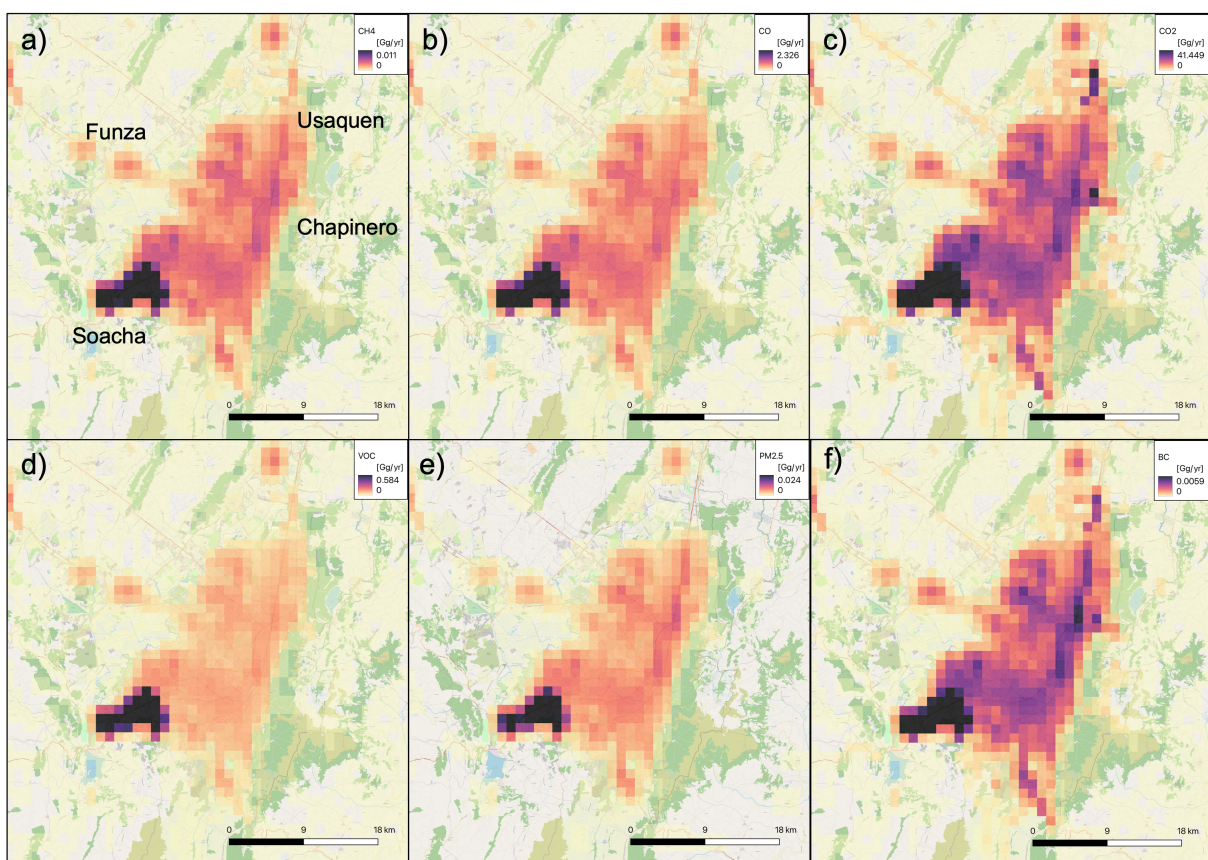


Figure 13. Spatial distribution of different compounds over Bogotá, a) CH₄, b) CO, c) CO₂, d) VOC, e) PM_{2.5}, f) BC

Figure 13 depicts the spatial variability of six different compounds across the city of Bogotá. The tonal differences correspond to the scales used for each compound's different emission ranges. In any case, the spatial distribution varies slightly depending on whether gasoline or

diesel vehicles are present in different areas of the city. For all compounds, the Soacha industrial area has the highest concentration of emissions. Further north, Chapucero and Usaquen have the lowest concentrations of VOC, whereas CO₂ is prevalent throughout the city, followed by BC.

4. Conclusions

In this study, we estimated a time series of road transport emissions of greenhouse gases (CO₂, CH₄), air pollutants (PM, NO_x, and CO), and a short-lived climate pollutant (BC) in Colombia between 1990 and 2020 and disaggregated such emissions in a grid with a 0.01° x 0.01° cell resolution. We considered the vehicle fleet size, composition, technology distribution, deterioration, and activity, as well as the national road infrastructure's capacity and traffic flow characteristics. We contrasted our results with estimates of the Colombian government and global estimates such as CAMS, EDGAR 4.3.2 and 6.1, and CEDS.

While our study provides valuable insights into road transport emissions in Colombia, there are some limitations that should be considered. For instance, the lack of detailed data on local emission factors and road-use distribution factors may result in some inaccuracies in our estimates. Additionally, the use of national average values, while necessary due to data limitations, may not fully capture the complexity of the road class and traffic counts that can have a significant effect on pollution. Moreover, as non-exhaust emissions for different vehicle technologies and ages were not included, our estimates may potentially underestimate overall emissions. Lastly, the absence of projections related to policy-making scenarios in sustainability and decarbonized economy contexts may limit the practical application of our

results for policymakers. Finally, while we used a grid with a $0.01^\circ \times 0.01^\circ$ cell resolution, it is important to note that this resolution may not be sufficient to capture emissions hotspots and variations at a more local level.

There was a nearly eightfold increase in the fleet size between 1990 and 2020, at a much faster pace in the second half of the period. The fleet's activity decreased in the late 1990s and early 2000s because of the economic crisis but recovered its growth trend after 2002. CO₂ emissions showed a similar, yet slower growth trend than vehicle activity because of the higher fuel economy of the newer fleet introduced after 2007. The impact of improved vehicle technology and better fuel quality is also seen in the trend toward declining air pollutant emissions, especially after 2011. Nevertheless, there is a significant lag in the adoption of the best available technologies in Colombia. The contribution of motorcycles to the vehicle fleet, activity, and emissions is striking and should be addressed by policy makers.

Our results also show that the impact of the COVID-19 pandemic lockdowns was a 13% reduction in vehicle activity and emissions in 2020 with respect to 2021.

Our CO₂ emissions estimates were consistent with the Colombian government inventory and with the CAMS, CEDS, and EDGAR 6.1 global datasets. We achieved similar magnitudes, with some differences in trends, for PM, BC, CO, and NO_x. CH₄ emissions from this study were remarkably higher than those in global datasets. This is due to the high contribution of motorcycles, which is only considered in our estimates. On the other hand, the agreement between our estimates and EDGAR 6.1 was remarkably better than with EDGAR 4.3.2. This reflects an effort of EDGAR developers to improve the representation of technology distribution, and therefore emission factors.

The spatial disaggregation of emissions identified large emission gradients and emission hotspots within cities. This kind of visualization can be used by city governments to design and prioritize emission reduction measures such as low-emission zones. Our dataset can also be used as an input to air quality or climate models. Further work to enhance the accuracy of these emission estimates can focus on i) measuring local emission factors, ii) improving road-use distribution factors, iii) including non-exhaust emissions for different vehicle technologies and ages, and iv) projecting emissions related to different policy-making scenarios in sustainability and decarbonized economy contexts.

Recent developments in fuel quality have led to significant reductions in emissions generated during combustion. In Colombia, the sulfur content in gasoline has seen a commendable decrease of 95% over the past fifteen years, from 1000 ppm in 2005 to 300 ppm in 2011, and currently to 50 ppm. Similarly, diesel has undergone a reduction of over 99% in 20 years, from 4000 ppm in 1998 to 3000 ppm in 2008, and currently to 20 ppm. Furthermore, the government has taken steps to oxygenate fuels by introducing biofuel additions since 2005. Presently, gasoline contains between 8% to 10% of bioethanol (from sugarcane), and diesel contains 10% of biodiesel (extracted from palm oil), as established by the Ministry of Mines and Energy in 2017. These advancements in fuel quality have played a crucial role in reducing emissions and promoting sustainable practices in the energy sector. The effect of these fuels on emissions is yet to be evaluated, and we encourage further research in this area.

Author contributions

Néstor Y. Rojas: Conceptualization, investigation and formal analysis, writing - original draft and editing. **Mauricio Osses:** Funding acquisition, conceptualization, investigation and formal analysis, writing - original draft and editing. **Sonia C. Mangones:** Funding acquisition, conceptualization, investigation and formal analysis, writing - original draft and editing. **Claire Granier:** Funding acquisition, validation. **Ignacio Laengle:** Data curation, investigation, software, visualization. **Julieth V. Alfonso:** Data curation, investigation, **Johann A. Méndez:** Data curation, investigation, visualization.

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