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Spatial and Temporal Analysis of Road Transport Emissions in Colombia

Análisis espacial y temporal de las emisiones del transporte carretero en Colombia

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ABSTRACT

Road transport is a major contributor to climate change and the degradation of air quality, posing risks to human health. To effectively manage air quality, it is crucial to quantify emissions and understand their spatial and temporal distribution. In this study, we focused on estimating the annual exhaust emissions of NO_2, $PM_{2.5}$, SO_2, CO, CO_2, and BC from road transport in Colombia during 2019. To derive emission estimates, we employed a comprehensive approach. Vehicle activity data was obtained from car sales websites, and emission factors were obtained from COPERT, using vehicle registration data and other local variables. We distributed the total annual emissions using the road network and highway traffic flows to break down the emissions into a 10 x 10 km resolution. Similarly, we analyzed the temporal dimension, examining hourly emissions patterns. Our findings revealed that cargo vehicles are the primary contributors to emissions, significantly impacting BC, NO_2, and $PM_{2.5}$ levels. Meanwhile, motorcycles were identified as the main source of CO emissions. In terms of CO_2 and SO_2, passenger cars emerged as the most substantial mobile source. Concerning spatial and temporal disaggregation, the emissions were concentrated in metropolitan areas and exhibited a daily dispersion pattern, with three distinct peak hours. This study sheds light on the emissions profile of road transport in Colombia during 2019. By identifying the main culprits and understanding their spatial and temporal dynamics, policymakers can devise targeted strategies to mitigate the adverse impacts on air quality and human health, ultimately fostering a cleaner and healthier environment for all.

Keywords: road transport, air quality, spatial and temporal disaggregation, exhaust emissions, pollution source

RESUMEN

El transporte carretero contribuye en gran medida al cambio climático y a la degradación de la calidad del aire, lo que supone riesgos para la salud humana. Para gestionar eficazmente la calidad del aire, es crucial cuantificar las emisiones y comprender su distribución espacial y temporal. En este estudio nos centramos en estimar las emisiones anuales de escape de NO_2, $PM_{2.5}$, SO_2, CO, CO_2 y BC provenientes del transporte por carretera en Colombia durante el 2019. Para derivar las estimaciones de emisiones, empleamos un enfoque integral. Los datos de actividad de los vehículos se obtuvieron de sitios web de ventas de automóviles, y los factores de emisión se obtuvieron de COPERT utilizando datos de registro de vehículos y otras variables locales. Distribuimos las emisiones anuales totales utilizando la red de carreteras y los flujos de tráfico por carretera para desglosar las emisiones en una resolución de 10 x 10 km. Del mismo modo, analizamos la dimensión temporal, examinando los patrones de emisiones por hora. Nuestros resultados revelaron que los vehículos de carga son los principales contribuyentes a las emisiones, afectando significativamente los niveles de BC, NO_2 y $PM_{2.5}$. Entretanto, las motocicletas surgieron como la principal fuente de emisiones de CO. En cuanto al CO_2 y el SO_2, los automóviles resultaron ser la fuente móvil más importante. En cuanto a la desagregación espacial y temporal, las emisiones se concentraron en las áreas metropolitanas y presentaron un patrón de dispersión diaria, con tres picos horarios distintos. Este estudio arroja luz sobre el perfil de emisiones del transporte por carretera en Colombia durante 2019. Mediante la identificación de los principales culpables y la comprensión de su dinámica espacial y temporal, los formuladores de políticas pueden diseñar estrategias específicas para mitigar los impactos adversos sobre la calidad del aire y la salud humana, fomentando en última instancia un medio ambiente más limpio y saludable para todos.

Palabras clave: transporte carretero, calidad del aire, desagregación espacial y temporal, emisiones de escape, fuente de contaminación

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Highlights:

- Road transport-related emissions were assessed using spatial and temporal disaggregation.
- The study revealed cargo vehicles as major contributors in BC, NO_2, and $PM_{2.5}$ emissions.
- The findings highlight motorcycles as a CO pollution source in Colombia.
- Passenger cars are the primary mobile source of CO_2 and SO_2 emissions in Colombia.
- Concentrated emissions and daily dispersion patterns pose challenges to air quality management in metropolitan areas.

Introduction

Poor air quality has extensive detrimental effects. For example, it endangers community sustainability, compromises environmental preservation, and reduces residents' quality of life [1]-[7]. Surprisingly, almost 92% of the world's population lives in regions where pollution levels surpass the tolerable thresholds, as reported by the World Health Organization in 2005 [8]. According to the National Health Observatory in 2019 [9], poor air quality is responsible for 7% of Colombia's yearly mortality rate.

In order to successfully tackle and control air quality problems, it is crucial to compile a comprehensive record of air pollutant emissions. The Environmental Protection Agency (EPA) [10] states that it offers essential quantitative data regarding the amount of pollutants released by multiple sources in a certain area over a specified period of time. Emission inventories are crucial for the formulation and oversight of public programs that target emissions reduction. They allow researchers to perform comparative evaluations of pollutant emissions across time, aiding environmental authorities and decision-makers in formulating air pollution management plans.

When creating an emissions inventory, it is crucial to include both climate forcers and criteria air pollutants. Climate forcers affect the Earth's climate system by emitting or absorbing radiation, thus contributing to climate change, with greenhouse gases (GHGs) being a major component. Criteria air pollutants are common and pose risks to the environment and human health [11]. Emission inventories also play a vital role in raising public awareness about air pollution in specific areas [12].

A clear grasp of atmospheric emissions is essential to prevent misunderstandings. When creating an emissions inventory, prioritizing data accuracy is also crucial. This is achieved by comparing projected emissions values against documented energy consumption statistics from the assessed sources. For instance, in the context of road transport, projected emissions can be verified against gasoline sales data from official organizations and emissions inventory obtained through various methods. The goal is to adjust transport activity values (*e.g.*, annual kilometers traveled) in the inventory by consistently matching them with relevant statistical data for the region [13].

Spatial and temporal disaggregation of emissions is widely used in emissions inventories. This practice consists of dividing emissions into smaller areas (grids) and shorter time periods (weekly and hourly records). This information is crucial for environmental management models that evaluate pollutant concentrations and atmospheric deposition. The spatial distribution of emissions plays a crucial role in determining how they spread and the magnitude of their effects in a specific region [14]. Several authors have suggested several approaches and guidelines to help break down emissions into spatial and temporal components [15]-[18].

Colombia regularly participates in emissions estimation exercises and is included in global inventories such as EDGAR [19]. EDGAR is a global database that tracks greenhouse gas emissions and air pollution using international statistics and the methodology of the Intergovernmental Panel on Climate Change (IPCC). Two distinct methodologies have been employed to calculate the national emissions inventory from mobile sources in Colombia: [20] assessed the emissions of fine particulate matter ($PM_{2.5}$), black carbon (BC), carbon monoxide (CO), and sulfur dioxide (SO_2) between 2010 and 2014, and [21] evaluated carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x), volatile organic compounds (VOCs), $PM_{2.5}$, and BC emissions from 1990 to 2020 using 0.01 x 0.01° cells for high-resolution representation. These authors compared their results against national and global inventories to highlight emission trends and discrepancies.

Colombia is geographically, politically, and administratively separated into 32 departments, along with its capital city, Bogotá. These departments exhibit significant economic and demographic variety and demonstrate diverse patterns with regard to transportation [22]. Colombia's transportation system comprises 18 million vehicles, with automobiles accounting for nearly seven million and motorcycles making up the remaining 11 million [23]. The country possesses a vast road network that spans a significant portion of its land, measuring approximately 205 000 km in length. This network is categorized by the Ministry of Transportation into three distinct types: around 18 000 km are classified as *primary roads*, 45 000 km as *secondary roads*, and 142 000 km as *tertiary roads* [24].

The road transport sector is Colombia's primary source of pollution among several transportation subsectors, surpassing civil aviation, sea and river navigation, and railways [20]. In 2016, the transportation industry was responsible for 11% of the country's greenhouse gas emissions, with road transport accounting for 91% of that total [25]. In relation to criteria air pollutants, the transportation sector accounted for substantial portions of the yearly emissions, specifically 15.5, 4.5, 27.2, 70.7, and 9.7% of the annual emissions of BC, $PM_{2.5}$, CO, nitrogen dioxide (NO_2), and SO_2, respectively [20].

Although road transport emissions in Colombia significantly impact air quality and public health, there is a lack of studies developing robust methodologies to estimate and analyze them based on their spatial and temporal distribution. Prior research has predominantly concentrated on estimating pollution levels at the national level and has only examined a few types of pollutants. As a result, there is no comprehensive understanding of the unique contributions of different types of vehicles and their geographical distribution throughout the country. Moreover, the application of cutting-edge data sources and sophisticated techniques for estimating and breaking down emissions has been restricted. In light of the above, this study seeks to fill the existing research gap by conducting a thorough and meticulous examination of road transport emissions in Colombia. This analysis encompasses various criteria air pollutants and climate forcers and utilizes cutting-edge data sources and advanced spatial-temporal disaggregation techniques.

The aim of this study is to calculate and break down the yearly emissions of specific air pollutants (CO, NO_2, $PM_{2.5}$, SO_2) and climate-altering agents (BC, CO_2) produced by road transport in Colombia throughout 2019 while considering their spatial and temporal distribution. To this effect, a methodology is employed which integrates various transportation data sources to determine the average mileage by vehicle type, such as vehicles listed for sale on websites and data acquired from mechanical and technical inspections. Additionally, this study incorporates traffic volume data from vehicle counts and average operational speed data from Google's Roads API, among other sources.

Method

The inventory estimation of exhaust emissions from road transport employs a top-down technique, where emissions estimates for smaller geographical areas are derived from broader or macro-scale data. Eq. (1) [13] presents the primary formula for calculating the overall annual emissions originating from mobile sources.

$$E_{ij} = AF_j \;\; EF_{ij} \;\; N_j \tag{1}$$

Here, the variable E_{ij} represents the overall amount of pollutant i emitted by vehicles in category j, which is measured in grams per year. The activity factor (AF_j) represents the annual distance traveled by vehicles of type j, measured in kilometers per year per vehicle. The emissions factor (EF) is a measure of the amount of pollutants emitted by a certain source. In the case of road transport, EF_{ij} is the emissions factor of pollutant i for vehicle category j, measured in grams per kilometer per vehicle. N_j represents the quantity of vehicles of type j inside the region under study.

Our research methodology is organized into six distinct stages aimed at outlining the sequential methods employed to obtain full estimates of road transport emissions. These stages cover important aspects such as vehicle activity, fleet composition, EFs, fuel sales validations, and consumption statistics. Fig. 1 illustrates the input, process, and output of each of the following stages:

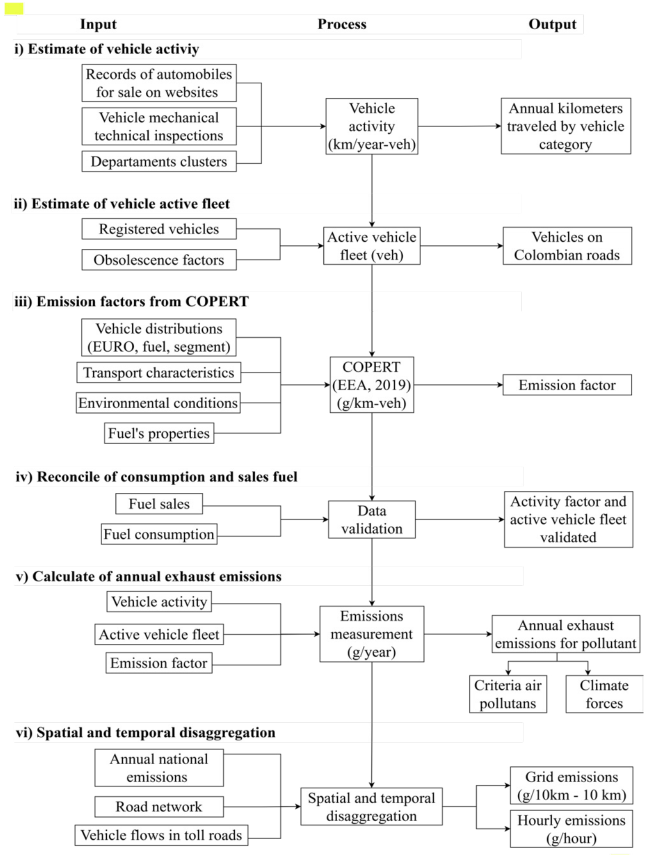


Figure 1. Method structure of the research
Source: Authors

Activity factor (AF)

The AF for road transport measures emissions intensity based on the total distance traveled by the active vehicles in a category over a year. This study used a clustering methodology to categorize departments with similar attributes, following [21]. We employed spatial cluster analysis to define six geographic clusters for 2019 while using data on the road network, registered vehicles, population, and gasoline sales. The annual mileage for each cluster was calculated using data from websites specializing in used vehicle sales (specifically www.tucarro.com.co), which included vehicle type and fuel information for passenger cars (excluding taxis) and motorbikes. Additionally, we incorporated data from the Ministry of Transport [24] and standardized inspections covering mechanical, environmental, and safety aspects from local environmental organizations and automobile diagnostic centers [26].

Regarding vehicle activity, motorbikes typically cover approximately 8000 km per year, whereas buses, tractor-trailers, and taxis often cover around 50 000 km. Table I presents the transportation activities for different vehicle classifications within each cluster.

Vehicle fleet

Data regarding the vehicle fleet in Colombia were obtained from the database of vehicles registered in the platform of the Single National Traffic Registry [27]. This information was not used for the direct estimation of emissions due to its substantial level of uncertainty, as the original database encompasses all vehicles that have been registered, regardless of their operational status.

To determine Colombia's vehicle fleet for 2019, several measures were implemented, including the exclusion of vehicles registered before 1990, the elimination of emissions-free vehicles (electric, hydrogen, ethanol, and LPG), and the application of an obsolescence factor for vehicles taken out of circulation due to accidents or poor conditions.

The obsolescence variables, unique to each vehicle category, were created via an iterative procedure aimed at attaining an optimal alignment between fuel consumption and sales data. The obsolescence factors used for the different vehicle categories in Colombia were as follows:

- buses: 3%
- heavy-duty vehicles: 1%
- L-Category vehicles: 3%
- passenger cars: 2%
- light commercial vehicles: 2%

The aforementioned parameters were employed to consider the proportion of vehicles that were no longer in active operation within each specific category, thereby yielding a more precise and detailed depiction of the active automobile fleet [21].

After conducting the necessary procedures, the initial count of 15 428 671 registered vehicles was adjusted to a refined estimate of 10 675 062, providing a more representative foundation for calculating emissions.

Emissions factor (EF)

Local EFs from fieldwork in Colombia are currently unavailable. The Colombian guide for estimating atmospheric emissions [12] recommends using reference EFs from international agencies like the EPA, the European Environment Agency (EEA), or the IPCC when representative EFs are not available for the study area. This study used the COPERT model [26] to calculate EFs based on vehicle segment, fuel type, EURO technology, and department.

COPERT requires multiple inputs to estimate an EF. The grouping of the fleet by EURO technology (Table A – supplementary information), fuel type, and vehicle segment (Table B – supplementary information) was based on data from the vehicle registration database [27], and the classification of the fleet by EURO standards presented

Table I. Annual activity by vehicle type and cluster (km)

Vehicle Category	Fuel	Cluster F*	Cluster E*	Cluster D*	Cluster C*	Cluster B*	Cluster A*
Motorcycle	Petrol	7 888	8 299	7 468	8 880	9 650	8 084
Passenger Cars	Diesel	17 708	16 227	15 995	18 382	15 957	17 181
Passenger Cars	Petrol / CNG	12 435	11 422	12 827	14 164	12 371	12 698
Taxi	Diesel	51 240	52 346	41 258	42 650	52 379	53 744
Taxi	Petrol / CNG	48 575	50 208	39 091	39 494	40 193	33 132
Bus	Diesel	46 305	53 240	45 890	43 568	45 201	43 521
Bus	Petrol / CNG	40 032	50 320	42 950	40 000	35 916	30 609
Truck	Diesel	38 588	47 667	38 588	39 231	45 210	42 130
Truck	Petrol / CNG	30 935	28 448	26 819	28 319	26 880	26 352
Rigid Truck	Diesel	40 396	42 500	40 396	40 396	38 210	35 301
Tractor-Trailer	Diesel	48 752	50 000	48 752	48 752	48 752	47 503

***Departments by cluster**
Cluster A: Caldas, Cauca, Casanare, Huila, La Guajira, Magdalena, Sucre, Nariño
Cluster B: Cundinamarca, Valle del Cauca
Cluster C: Amazonas, Arauca, Archipielago of San Andres, Caqueta, Choco, Guainia, Guaviare, Putumayo, Quindio, Risaralda, Vaupes, Vichada
Cluster D: Atlantico, Bolivar, Cesar, North of Santander
Cluster E: Antioquia, Bogota
Cluster F: Boyaca, Cordoba, Meta, Tolima, Santander

Source: Authors

in Table 2 was based on official vehicle registration data. However, studies such as that by [28] and reports from the ICCT (2023) indicate that gasoline-powered light-duty vehicles in Colombia were primarily meeting EURO 2/Tier 1 standards in practice, particularly in major cities. While EURO 4 standards were expected to be applied to new vehicles from 2023 onwards, the 2019 fleet comprised a mix of technologies, including older vehicles that remained in operation. This distinction is important when interpreting emissions estimates, as real-world values may differ from regulatory classifications.

The analysis considered various transport attributes, such as the mean operational velocity from historical data via Google Big Data, the total distance traveled by each vehicle category, the incline (estimated using accurate techniques), and the carrying capacity (for buses and freight vehicles) from BID data [29]. Environmental conditions, including temperature, relative humidity, and air conditioning consumption, were sourced from the Information System for the Management of Hydrological and Meteorological Data (DHIME-IDEAM) for each department and month of the reference year. Fuel characteristics were also taken into account.

Using the inputs in COPERT, we derived the EFs for each department, vehicle category, segment, motor technology, fuel type, and European emissions standard for four criteria air pollutants (CO, NO_2, $PM_{2.5}$, SO_2) and two climate forcers (BC, CO_2). Consequently, a total of 15 357 emission variables were acquired and utilized for estimating emissions.

Data validation via the reconciliation of fuel consumption and sales

To verify the estimated activity factor and the active vehicle fleet data, a comparison was made between the estimated fuel consumption and sales to road transport. Validating this data was crucial, as national statistics may not distinguish between on-road and off-road fuel use, affecting the accuracy of emissions estimation [30,31].

According to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, it is good practice to estimate fuel consumption using data on distances traveled and vehicle and fuel type.

The fuel sales were determined using the Colombian energy balance for 2019, as reported by UPME in 2021. According to [33], the road transport sector sold a total of 1 986 370 113 gallons of petrol and 1 584 403 079 gallons of diesel in 2019. The approach outlined in the fourth stage of the methodology, which involved reconciling fuel consumption and sales, yielded a total consumption of 1 872 107 705 gallons of petrol and 1 521 986 611 gallons of diesel. Therefore, there is a predetermined agreement between the amount of gasoline used and the amount of gasoline sold, with a difference of 5.8%. Similarly, for diesel, there is a predetermined agreement between consumption and sales, with a difference of 3.9%. This validates the projected activity of road transport and the approximation to the number of active vehicles, which in turn reduces uncertainty in quantifying emissions.

Estimated emissions

After validating data consistency, we estimated the exhaust emissions for each department using the methodological approximation outlined in Eq. (1). This computation considered the current number of vehicles in use, the yearly usage per kind of vehicle, and the emission rates specified by the category, segment, engine technology, and fuel type of each vehicle. The application of these elements allowed determining the departmental emissions related to criteria air pollutants and climate forcers, which in turn led to the estimation of national emissions associated with road transport.

Spatial and temporal disaggregation

The spatial disaggregation of emissions enhances the local-scale resolution, aiding air quality models in assessing pollutant dispersion and deposition [14]. Geospatial tools effectively manage and visualize emissions, often using grids to standardize datasets and integrate emission sources [33]. The literature suggests a 0.1 x 0.1° grid (longitude/latitude) for national reporting. This is approximately comparable to cells that are 11 x 11 km in size [34]. This study employed a cell size of 10 x 10 km, as well as a more detailed resolution of 1 x 1 km to examine emissions in urban areas and local government units.

Different approaches have been suggested for breaking down emissions into smaller geographical units, typically relying on parameters like road hierarchy, vehicle flows, population density, or urbanized regions [35]. Building on the suggestions provided by earlier research works conducted by [36], [17], and [37], this study utilized a computational tool called *DROVE* [16]. This tool employs an algorithm to calculate disaggregation factors (DFs) for each grid cell. DFs are determined based on specific data, *e.g.*, road segment length, road types, and traffic flow. It should be noted that the accuracy of the disaggregated emissions inventory is contingent upon the quality of these data. The emission fluxes per grid cell are calculated by multiplying the DFs by the total emissions of each pollutant while ensuring the conservation of the total mass of emissions, as described by [16].

The DROVE algorithm provides three levels of disaggregation based on the given information. The primary level solely necessitates the road network, while the second level encompasses supplementary data such as road length, hierarchy types, and average flow based on road type. The highest level, which is the most sophisticated, employs a transportation model of the research region. In this analysis, we employed level two, as indicated by Eq. (2) [16].

$$DF_{I,J,K} = \left(\frac{L_j}{\sum_0^n L_j} \right) * fm_{i,k} \qquad (2)$$

The variables in this equation are defined as follows:

- DF represents the disaggregation factor
- L denotes the total length of the road segments within each grid cell
- j corresponds to the grid cell
- n represents the total number of cells in the domain
- k signifies the type of road
- the subscript I denotes the vehicle category
- fm represents the weight factor of the type of road

The data on the road network inside urban and interurban areas was acquired from OpenStreetMap's publicly available data. This data was then categorized into six distinct hierarchical groups, based on their functional features. The classification of roads includes interurban roads categorized as primary, secondary, and tertiary, and urban roads categorized as primary, local roads categorized as secondary, and residential roads categorized as tertiary. Fig. 2 depicts the layout of the road network, while Fig. 3 illustrates the process of geographical disaggregation for one of the 32 departments in Colombia.

We generated two temporal distribution curves to break down the annual emissions into hourly levels, using transportation demand as the basis. These curves distinguished between metropolitan regions and interurban roadways, offering

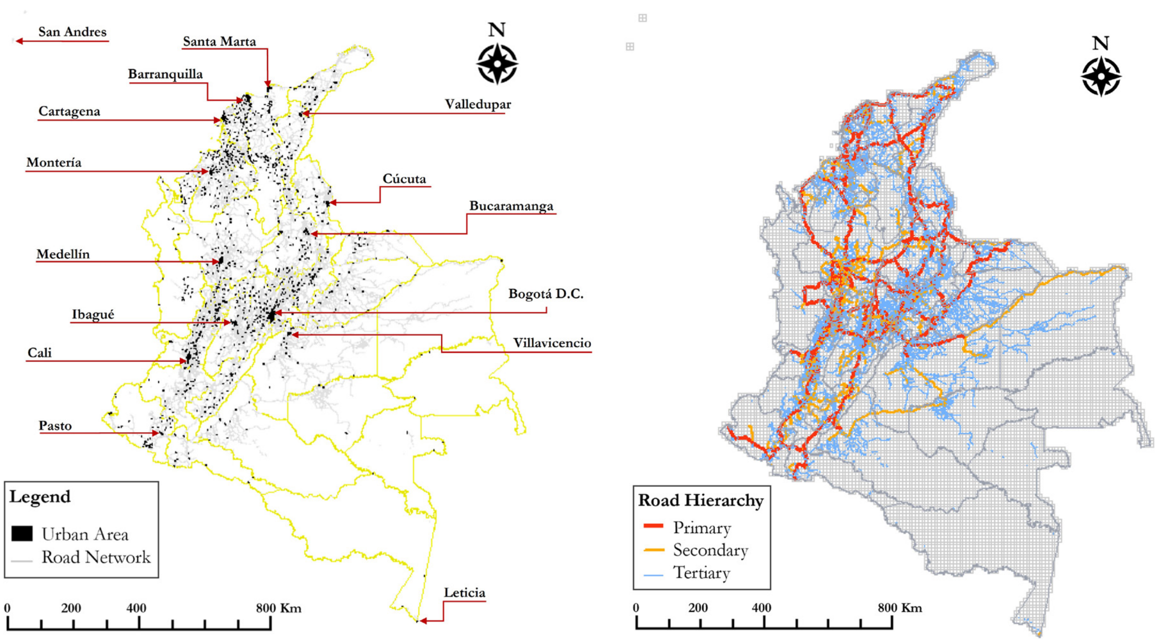


Figure 2. Urban area and road network configuration
Source: Authors

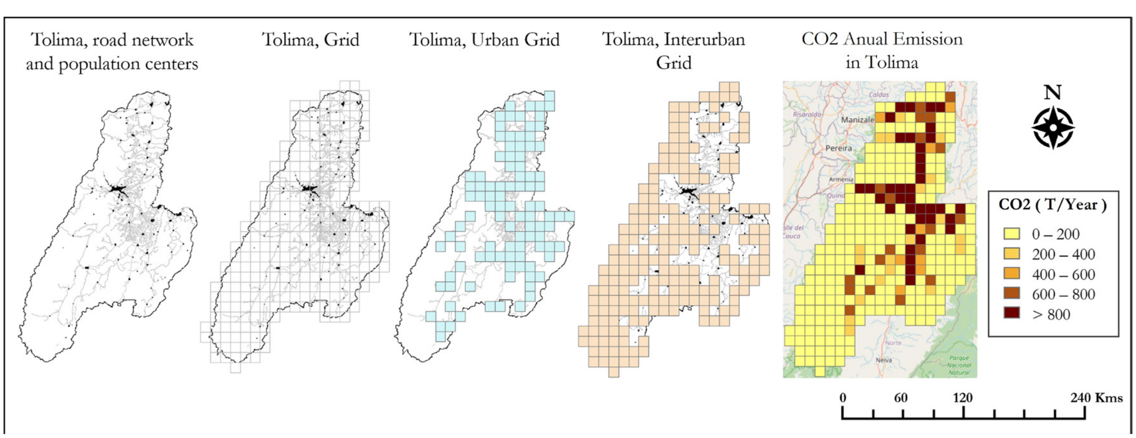


Figure 3. Tolima's emissions disaggregation using DROVE at a 10 x 10 km resolution
Source: Authors

valuable information about emission patterns throughout the day. The estimation of hourly profiles is limited by its use of a uniform factor. However, it was clearly established that the selected reference cities provide a representative sample. The urban curve was constructed using authoritative data obtained from mobility surveys carried out in the cities and regions included in our analysis, such as Bogotá [38], Valle de Aburrá [39,40], Cali [41], and Manizales [42].

In contrast, the interurban curve was built using data obtained from national highway toll booths provided by the National Infrastructure Agency [43]. These data sources ensured the dependability and inclusiveness of the analysis of the temporal distribution in urban and interurban areas.

For a typical day, the three peaks observed in the urban environment can be explained by daily commuting patterns: morning trips to work, midday travel associated with work breaks, and evening returns home. Additionally, the selection of reference cities was justified by the fact that the four departments they belong to (Bogotá DC, Antioquia, Valle del Cauca, and Atlántico) account for more than half of the total vehicle fleet in the country. This substantial representation enhances the robustness and representativeness of the temporal distribution analysis. Fig. 4 depicts the curves obtained.

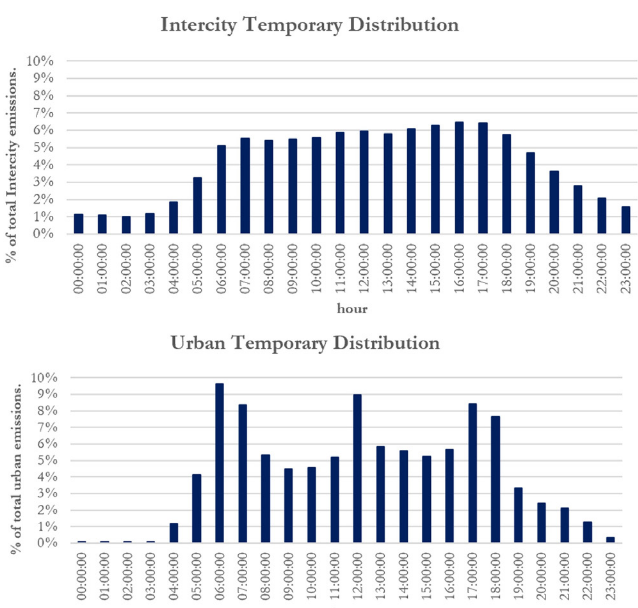


Figure 4. Urban and interurban profiles of the hourly vehicle flow intensities in Colombia
Source: Authors

Results and discussion

Our analysis of exhaust emissions from road transport in Colombia provides insights into the distribution of air pollutants and climate forcers. In 2019, road transport emitted approximately 34 184 853 metric tons (T) of CO_2 and 2 352 T of BC. The Colombian emissions inventory for 2018 reported 28 894 520 T of CO_2 emitted by road transport, accounting for 13.6% of the total national CO_2 emissions, 34.7% of the CO_2 energy emissions, and 78.6% of the CO_2 emissions in the transportation sector.

Our results for 2019 evidence an 18% increase in CO_2 emissions from road transport in comparison with the 2018 national emissions inventories. The annual emissions of criteria air pollutants show a significant coherence between our results and those of [20] for the 2010-2014 period (Fig. 5). Compared to 2010, SO_2 emissions decreased by 17.8%, $PM_{2.5}$ emissions by 51.5%, and BC emissions by 13.9%. These reductions can be attributed to the conversion of the private vehicle fleet to cleaner technologies, as demonstrated in Table A (supplementary information). Conversely, CO emissions increased by 14.5%, primarily due to motorcycle emissions, which have a high EF. This rise is linked to a significant increase in motorcycle registrations, making up 58% of all vehicles in 2019, and Colombia's lenient regulations, which only required EURO 2 technology in 2019, despite the advancement to EURO 5.

In terms of CO_2, we found that passenger cars represent the highest emissions, accounting for 33.3% of the total (Fig. 6). On the other hand, with regard to BC, freight vehicles make the largest contribution (54.8% of the emissions) (Fig. 6). Although BC is not a greenhouse gas, it can absorb light, leading to localized warming effects both in the atmosphere and on the Earth's surface. This warming effect becomes particularly significant in regions marked by high BC emissions, such as densely populated urban areas and transportation corridors.

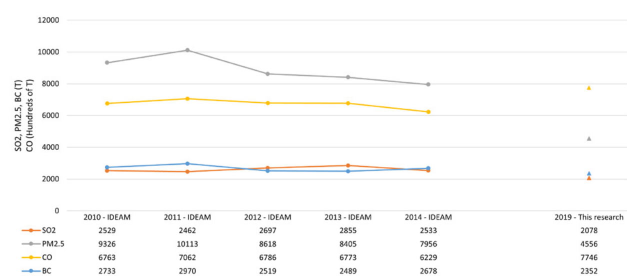
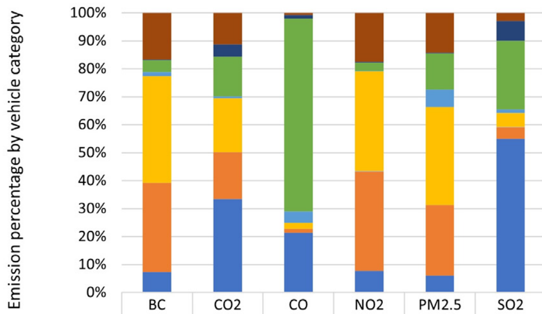


Figure 5. National emissions from road transport
Source: Authors

The emissions of criteria air pollutants resulting from road transport in Colombia for 2019 were estimated as follows: 2078 T of SO_2, 4556 T of $PM_{2.5}$, 774 637 T of CO, and 16 446 T of NO_2. The amount of SO_2 emitted is directly proportional to the sulfur content present in the fuel. In Colombia, gasoline contains a higher sulfur content compared to diesel fuel, leading to passenger cars and motorcycles contributing 54.9 and 25.9% of the SO_2 emissions, respectively. As for $PM_{2.5}$, which is known to be significantly associated with respiratory and cardiovascular diseases, it was found that freight vehicles and buses are the largest emitters, accounting for 49.3 and 25.3% of the emissions. Motorcycles, representing approximately 58% of the registered vehicle fleet, contribute the most to CO emissions, constituting 69.1% of the total.

As for NO_2, freight vehicles and buses emit 53.1 and 35.8% of the total emissions, respectively.

In 2019, freight vehicles contributed significantly to the national emissions in Colombia; they accounted for 54.8% of BC, 53.1% of NO_2, and 49.3% of $PM_{2.5}$. This finding aligns with the fact that Colombia has one of the oldest cargo transport fleets in the region, which translates into a higher proportion of less efficient vehicles [29]. The second most polluting vehicle category was passenger cars, accounting for 33.3% of CO_2 and 54.9% of SO_2. Lastly, motorcycles were the third most polluting category, with 69.1% of the CO emissions.



	BC	CO2	CO	NO2	PM2.5	SO2
Tractor-Trailers	16,64%	11,29%	0,83%	17,45%	14,28%	2,89%
Taxi	0,27%	4,44%	1,17%	0,33%	0,31%	7,04%
Motorcycles 4-stroke	4,33%	14,07%	69,05%	3,01%	12,87%	24,55%
Motorcycles 2-stroke	1,30%	0,78%	4,04%	0,06%	6,28%	1,37%
Trucks - Rigid trucks	38,15%	19,22%	2,16%	35,65%	34,98%	4,98%
Articulated buses	0,06%	0,12%	0,01%	0,23%	0,04%	0,03%
Two-axle buses	31,96%	16,73%	1,38%	35,60%	25,23%	4,24%
Passengers cars	7,27%	33,35%	21,36%	7,68%	6,01%	54,91%

Figure 6. Emissions of each pollutant by vehicle category
Source: Authors

Spatial distribution of pollutant emissions in the regions of Colombia

Upon completion of the annual emission calculations, it became evident how various pollutants are distributed across different regions. Notably, the departments characterized by larger populations, extensive road networks, and substantial registered vehicle fleets, such as Bogotá, Cundinamarca, Antioquia, and Valle del Cauca, exhibit the highest emission loads.

Fig. 7 provides insights into the spatial distribution of emissions across departments and highlights the relative magnitudes of each pollutant. Notably, the annual CO_2 emissions exhibit a significantly higher load compared to other pollutants. Nationally, road transport reports a total annual CO_2 emission of 34.18 million T, while the emissions of SO_2 amount to only 2.08 T.

Our analysis of the spatial distribution of pollutant emissions from mobile sources revealed a strong correlation between economic activity and pollutant emissions at the departmental level. The disaggregation into 10 × 10 and 1 × 1 km grids allowed for an accurate representation at both the national and urban levels (Figs. 8 and 9). Consistent with the study by [44] in India, the statistical analysis shows high correlation coefficients between emissions and the departmental GDP, reaching values of 0.98 for SO_2, 0.9 for CO, 0.87 for CO_2, 0.67 for $PM_{2.5}$, 0.66 for BC, and 0.64 for NO_2, indicating a significant relationship. This supports the trend observed in previous studies, such as that by [45], which highlighted the link between economic growth and increased emissions from the transport sector. However,

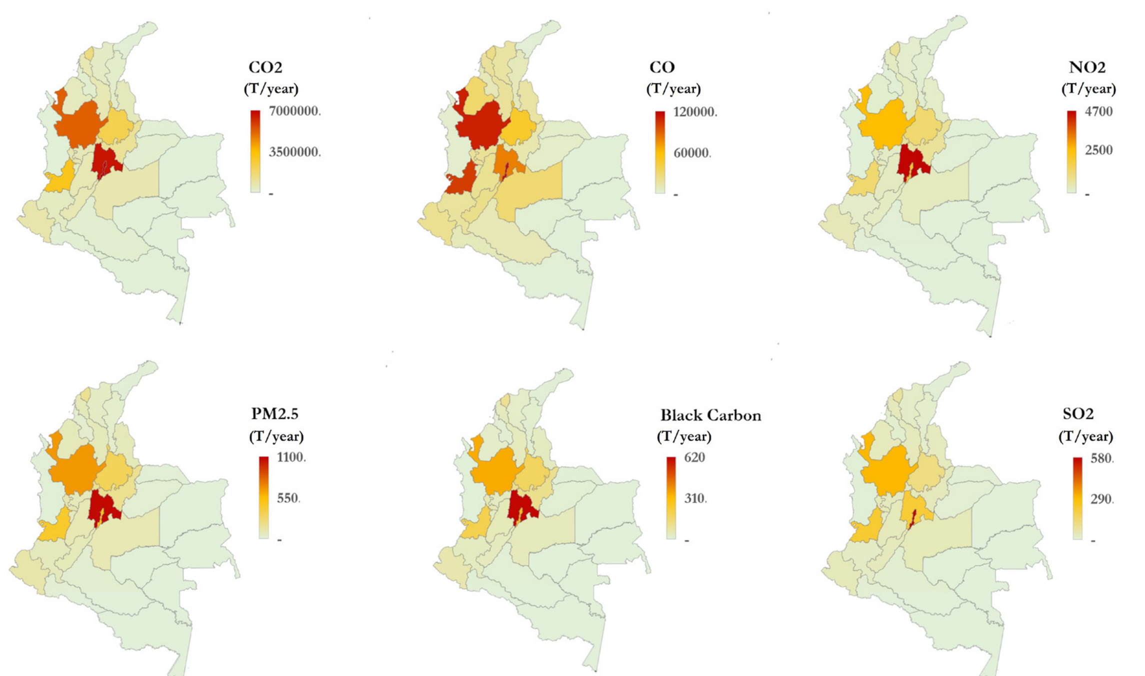


Figure 7. Annual road exhaust emissions by department
Source: Authors

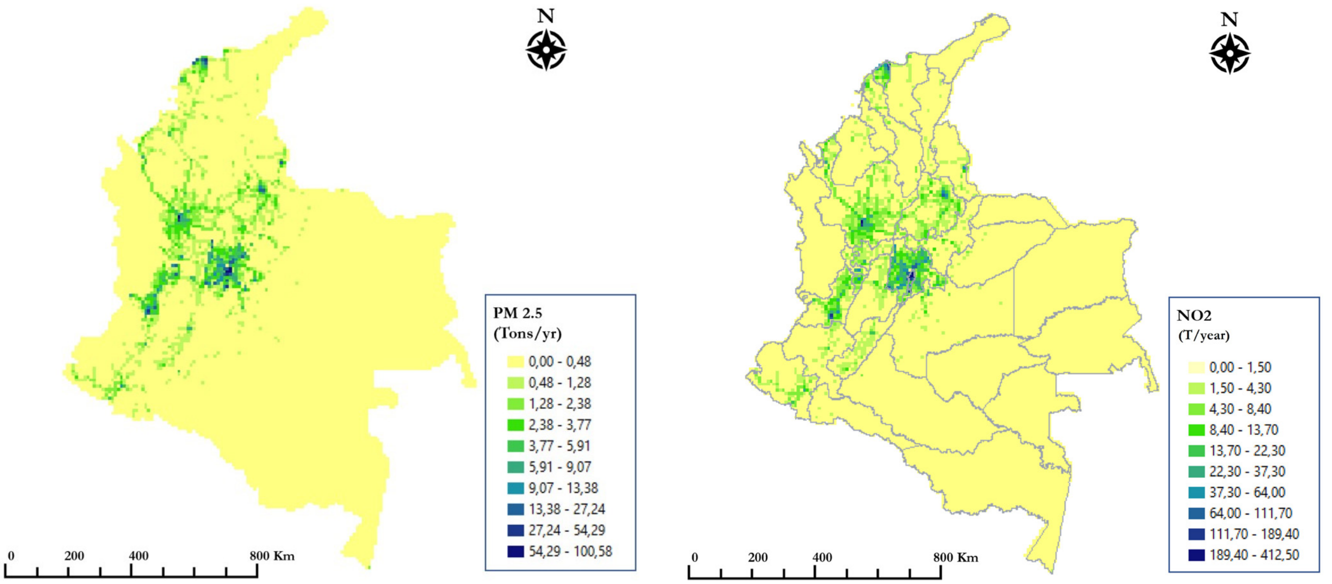


Figure 8. Spatial distribution of mobile source emissions by pollutant ($PM_{2.5}$ and CO_2) at the national level (10 × 10 km grid)
Source: Authors

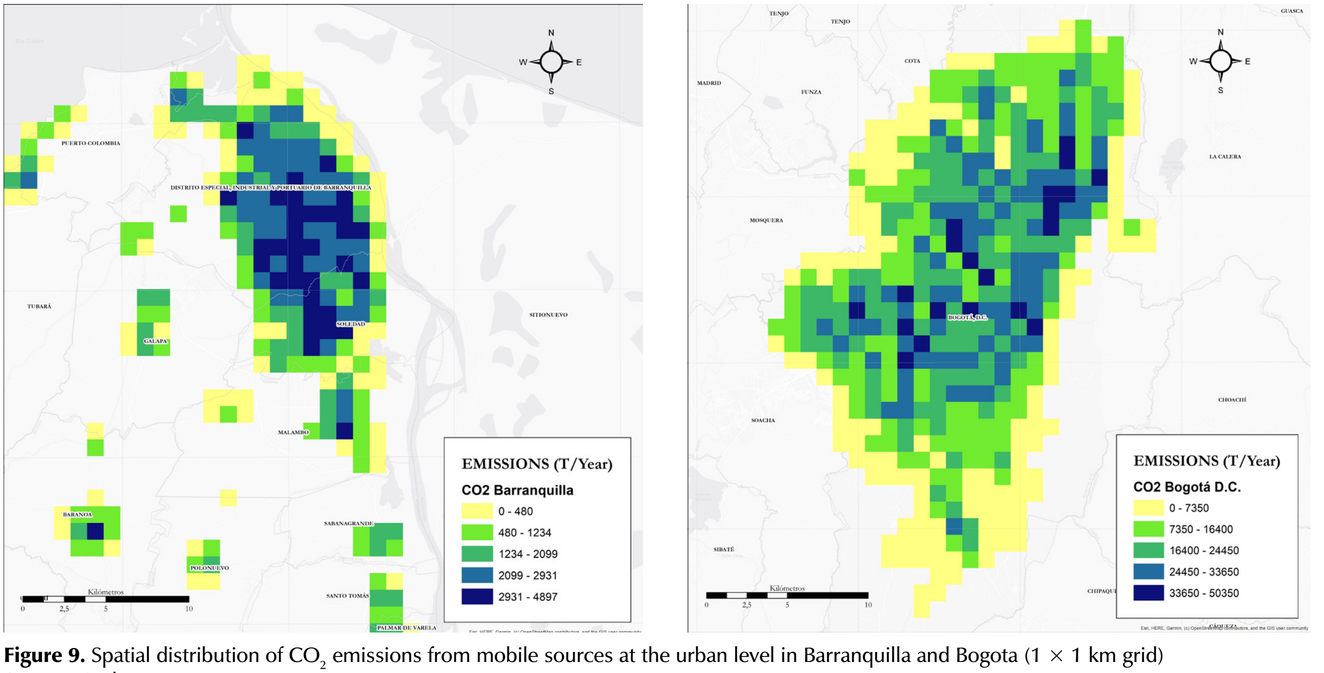


Figure 9. Spatial distribution of CO_2 emissions from mobile sources at the urban level in Barranquilla and Bogota (1 × 1 km grid)
Source: Authors

a particular case is Cundinamarca, where emissions are disproportionately high compared to its GDP, potentially due to the relocation of economic and logistical activities from Bogotá to this department.

Conclusions

Utilizing various tools and data sources, this study estimated and spatially and temporally disaggregated the exhaust emissions from road transport in Colombia for the year 2019. With the purpose of enhancing the coherence and representativeness of the estimates, alternative techniques were employed to determine activity factors for mobile sources. These techniques included data from mechanical and technical inspections provided by local environmental agencies and automotive diagnostic centers, as well as records of vehicles for sale on online platforms. Additionally, vehicle obsolescence factors were identified, and the active fleet was assessed, thereby reducing uncertainty, reconciling fuel consumption and sales, and achieving a more accurate emissions estimation. The analysis indicated that road transport significantly contributes to climate forcing and air pollution by criteria pollutants.

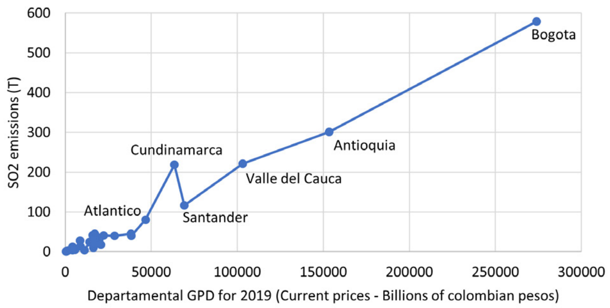


Figure 10. Relationship between SO_2 emissions and departmental GDP in 2019 (correlation coefficient of 0.98)
Source: Authors

The spatial distribution of the annual emissions was analyzed using a weighting method based on the road network. The areas with the highest emissions were identified at a resolution of 10 × 10 km while considering temporal variability. It was established that the highest emissions occur in urban regions and are distributed throughout the day, with three peak hours identified.

The estimates of this study confirm that passenger cars and freight vehicles were the primary sources of emissions in 2019, with the former contributing 33.3% of CO_2 emissions and the latter accounting for 54.8% of BC emissions. Additionally, the main sources of criteria pollutant emissions were identified: passenger cars and motorcycles were responsible for the majority of SO_2 emissions, while freight vehicles and buses were the leading emitters of $PM_{2.5}$ and NO_2. Motorcycles represented the largest share of CO emissions.

Departmental estimates indicate that Bogotá, Antioquia, Cundinamarca, and Valle del Cauca account for the majority of road transport emissions in Colombia, with impacts ranging from 52 to 64% depending on the pollutant. A direct relationship was identified between pollutant emissions and economic activity in these regions, demonstrating that GDP growth drives increased transport demand and, consequently, elevated emissions. Without effective regulations, the impact of transport on air quality and the environment will likely continue to rise.

Cundinamarca's case highlights the need to consider the relocation of productive activities in emissions reduction policies. Its emissions are disproportionately high relative to its GDP, likely due to operations shifting from Bogotá, which has concentrated economic activity and transport. These findings underscore the necessity of targeted measures to ensure sustainable development in areas where economic growth leads to excessive emissions.

While studies like that by [21] offer valuable insights into long-term trends and the effects of environmental policies, our analysis delivers a comprehensive assessment of the current situation. Additionally, the identification of daily dispersion patterns with specific hourly peaks underscores the necessity of implementing control and regulatory measures tailored to each vehicle type and its operational context. This approach will enable the formulation of effective strategies aimed at mitigating road transport emissions in Colombia. We conclude that the country should mandate the exclusive commercialization of new vehicles equipped with the most advanced EURO technology available for each segment. Furthermore, it is essential to establish a maximum lifespan for freight vehicles in order to prevent the circulation of obsolete trucks with poor environmental performance, which adversely affects transportation efficiency and air quality. Lastly, stricter regulations on engine technology for motorcycles are recommended, as its rapid growth has significantly increased CO emissions.

One of the key uncertainties in emissions estimation is the real-world application of EURO standards in the Colombian fleet. While official records classify new gasoline vehicles under EURO 4, studies (*e.g.*, [28], ICCT, 2023) suggest that a significant portion of the vehicles in circulation in major cities were still operating under EURO 2 or Tier 1 standards in 2019. This discrepancy may affect emissions estimates, particularly for pollutants sensitive to technological advancements in emissions control. Based on the results obtained in this study, the team's future work will focus on projecting road transport emissions under different technological advancement scenarios and evaluating compliance with national emissions reduction targets.

The scientific community is encouraged to utilize local EFs in future studies (UPME is already working on this) and to estimate all vehicle emissions, as this study only calculated exhaust emissions.

CRediT author statement

Julieth V. Alfonso A.: Conceptualization, methodology, data analysis, formal analysis, writing (original draft).
Sonia C. Mangones, Néstor Y. Rojas: Conceptualization, methodology, validation, writing (review and editing).
Mauricio Osses: Validation, writing (review and editing).
Dayron Bermúdez: Data curation, writing (original draft).
Carlos Rivera, Aquiles Darghan: Data curation.

All authors have read and agreed to the published version of the text.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available upon request from the corresponding author.

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Supplementary Information

Table A. Mapping the Colombian automobile fleet to EURO vehicle technologies

Vehicle Category	Fuel / Service type	1996 and earlier	Since 1997	Since 1998	Since 2000	Since 2001	Since 2010	Since 2011	Since 2013	Since 2014	Since 2015	Since 2019
Cars and taxis	Diesel / Private	Conventional					Euro 2				Euro 4	
	Diesel / Public	Conventional					Euro 4					
	Petrol	ECE 15/04		Euro 1			Euro 2			Euro 3		Euro 4
	Vehicular natural gas	Euro 4										
	Gasoline electric	Euro 6										
Cargo transportation vehicles	Diesel / Private	Conventional				Euro I	Euro II				Euro IV	Euro V
	Diesel / Public	Conventional				Euro I	Euro V					
	Petrol	Conventional	Euro I				Euro II			Euro III		Euro IV
Buses	Diesel / Private	Conventional			Euro I		Euro II		Euro IV			Euro V
	Diesel / Public	Conventional			Euro I		Euro IV					Euro V
	Vehicular natural gas / Private	Euro I					Euro II				Euro IV	
	Vehicular natural gas / Public	Euro I					Euro IV					
	Electric diesel	Euro VI										
Motorcycle	Petrol	Conventional						Euro 2				

Source: Authors

Table B. Vehicle segment and category rules

RUNT Class	Category	Segment	Classification rules
Car, van, camper	Passenger cars	Mini Small Medium Large-SUV-Executive	Cylinder capacity ≤ 1200 cm^3 Cylinder capacity ≤ 1600 cm^3 Cylinder capacity ≤ 2000 cm^3 Cylinder capacity > 2000 cm^3
Tricycle motorcycle, motorcar, moped, quadricycle, four-wheeler	L-Category	Quad & ATVs	–
Motorcycles	L-Category	Mopeds 2-stroke < 50 cm^3	Cylinder capacity ≤ 50 cm^3 2-stroke engine
		Mopeds 4-stroke < 50 cm^3	Cylinder capacity ≤ 50 cm^3 4-stroke engine
		Motorcycles 2-stroke > 50 cm^3	Cylinder capacity > 50 cm^3 2-stroke engine
		Motorcycles 4-stroke < 250 cm^3	50 cc < Cylinder capacity ≤ 250 cm^3 4-stroke engine
		Motorcycles 4-stroke 250 - 750 cm^3	250 cc < Cylinder capacity ≤ 750 cm^3 4-stroke engine
		Motorcycles 4-stroke > 750 cm^3	Cylinder capacity > 750 cm^3 4-stroke engine
Minibus, bus	Buses	Urban CNG Buses	Vehicular natural gas
		Urban Buses Diesel Hybrid	Diesel electric
		Urban Buses Midi <= 15 T	Diesel Cylinder capacity < 3000 cm^3
		Urban Buses Standard 15–18 T	Diesel 3,000 cm^3 < Cylinder capacity ≤ 6000 cm^3
		Coaches Standard <= 18 T	Diesel Cylinder capacity > 6000 cm^3 Less than or equal to 3 axes
		Coaches Articulated > 18 T	Diesel Cylinder capacity > 6000 cm^3 More than 3 axes
Trucks	Light commercial vehicles	N1-III	Petrol Cylinder capacity < 2200 cm^3
Trucks, Rigid Truck	Heavy Duty Vehicles (Diesel)	Rigid <= 7.5 T	2 200 cm^3 ≤ Cylinder capacity ≤ 5000 cm^3
		Rigid 7.5 - 12 T	5 001 cm^3 ≤ Cylinder capacity ≤ 6400 cm^3
		Rigid 12 - 14 T	6 401 cm^3 ≤ Cylinder capacity ≤ 7300 cm^3
		Rigid 14 - 20 T	7 301 cm^3 ≤ Cylinder capacity ≤ 8200 cm^3
		Rigid 20 - 26 T	8 201 cm^3 ≤ Cylinder capacity ≤ 11000 cm^3
		Rigid 26 - 28 T	Cylinder capacity ≥ 11001 cm^3
Tractor-Trailer	Heavy Duty Vehicles (Diesel)	Articulated 28 - 34 T	Cylinder capacity ≤ 14000 cm^3
		Articulated 50 - 60 T	Cylinder capacity ≥ 14001 cm^3

Source: Authors