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CASE STUDY

Passenger car emissions in urban areas based on local vehicle fleet and environmental conditions

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ABSTRACT

BACKGROUND AND OBJECTIVES: For effective air quality management, suitable emission inventories must be classified for on-road mobile sources like cars, based on their usage, vehicle technology, and local environmental conditions. This study aims to estimate atmospheric pollutant emissions generated by passenger cars using the international vehicle emission model for the year 2023.

METHODS: To implement the international vehicle emission model and develop a baseline for an emissions inventory, vehicle technology in the study area was determined through surveys conducted at fuel filling stations in the two districts with the most significant traffic. The fleet was categorized based on criteria including emission control technology, fuel type, and engine displacement. Moreover, the research took into account geographic and environmental aspects, such as travel patterns on urban roads, fuel specifications, and elevation.

FINDINGS: In the province, 53 distinct vehicle categories were recognized and classified using the international vehicle emission model. Following the configuration of the fleet file detailing the distribution of vehicle categories and the location file outlining environmental conditions and representative characteristics, the model calculated atmospheric pollutant emissions for 2023 in metric tons. Passenger vehicles were the primary source of pollutant emissions, producing 1.78 million tons of carbon dioxide each year and 234.16 kilotons of carbon monoxide annually. Regarding emission factors, gasoline vehicles showed a proportional increase in carbon dioxide, nitrous oxide, nitrogen oxides, and sulfur oxides emissions per kilometer as vehicle size increased. A notable case was carbon monoxide emissions, where a medium-sized vehicle emitted approximately 41 grams per kilometer—twice the amount of a heavy car as 23 grams per kilometer, according to international vehicle emission model estimation. The majority of particulate matter emissions originated from heavy passenger vehicles, as opposed to light and medium cars, which contributed 90 percent and 83 percent of emissions, respectively.

CONCLUSION: This study developed an on-road mobile source emission inventory for 2023, focusing on passenger cars in Panama. A survey of 409 vehicles characterized a fleet of 534,322 cars, identifying 53 categories, with 94.8 percent running on gasoline and 5.12 percent on diesel. Over 45 percent of vehicles have traveled beyond 160,000 kilometers, leading to higher emissions. Medium-sized cars (1.5–3 liters) account for 61.1 percent of the fleet and are the largest emitters of carbon dioxide and nitrogen oxide. Although fewer in number, diesel vehicles produce nearly half of the particulate matter-10 emissions. Evaluations against national and international inventories affirm the impact of these vehicles on air pollution and the significance of each pollutant.

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NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
42	9	6

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INTRODUCTION

Air emission inventories are essential tools for environmental management. Air emission inventories provide a detailed record of the types and quantities of atmospheric pollutants emitted by various sources over a defined period according to the United States Environmental Protection Agency (EPA, 2022). Among these pollutants are greenhouse gases, which contribute to the warming of the Earth's surface (Jones *et al.,* 2023; Shevlyakov *et al.,* 2024).

Decarbonizing gas emissions from petrochemical production using microalgae along with criteria air pollutants that have health repercussions for at-risk populations (Fogelbach *et al.*, 2020) including respiratory ailments (Duan *et al.*, 2020; Parvin *et al.,* 2023). and nervous system diseases (Costa *et al.*, 2020). Air emission inventories are divided into three categories: point sources, area sources, and mobile sources (Almetwally *et al.,* 2020). The latter contribute the largest share of emissions of volatile organic compounds (VOCs), nitrogen oxides (NOx) and carbon monoxide (CO), generated by incomplete combustion (Zhang *et al.,* 2021) (Ministerio del Medio Ambiente Chile, 2022). Mobile sources consist of road vehicles, aircraft, railway transportation, maritime transport, among others. Studies reveal that private vehicles and taxis are the main sources of these emissions (Liliana and Pérez, 2015). Stationary emissions, like manufacturing facilities and production plants, are known as point sources. Conversely, area sources consist of emissions from multiple small sources that, when considered individually, do not fulfill the requirements to be classified as point sources. Their effects are evaluated as a whole since these emissions are released in small volumes and are widely distributed (EPA, 2001). Panama's economy is mainly based on service-related activities (Ministerio de Economía y Finanzas, 2017), supported by transportation as shown before (Valdes-Montenegro *et al.,* 2024). Transportation is essential for people's lives, as there is a need to move and commute to work or do other activities efficiently and promptly daily. Therefore, as the country's economy grows, so does the need for mobility and the emissions generated by these activities unless mitigation plans are implemented. There are two main measurement methods for vehicle emissions: laboratory measurements (idling or dynamometer) and real-world measurements (Lyu *et al.,* 2021). In Panama, the environmental emission standards for motor vehicles define acceptable emission limits based on the fuel type, the year of engine manufacture, or the vehicle weight. Although this regulation was established in 2009, it is not being enforced at this time. This regulation indicates that the permissible minimum emission limit for gasoline-fueled or alternative-fueled cars for carbon dioxide (CO_2) is 10.5 percent (%) for vehicles manufactured before 1999 and 12.5% for those manufactured after 1999. For CO emissions, a maximum of 4.5% is allowed for models before 1999 and 0.5% for those after 1999. Engines built before 1999 have a maximum unburned hydrocarbon emission limit of 500 parts per million (ppm), whereas for engines made after that year, the limit is reduced to 125 ppm. The only parameter evaluated in diesel-fueled cars is opacity. For lighter cars (3.5 tons), it is 60 Hartridge Smoke Units (HSU), and for heavier cars (3.5 tons), it is 70 HSU. Recently, an electric mobility mitigation plan (Gaceta Oficial, 2022) has passed that aims to reduce the internal combustion engine vehicle fleet by implementing electric mobility. A crucial first step in managing air quality effectively is to assess the emissions from internal combustion engine vehicles, considering their specific characteristics, technology, fuel efficiency, and consumption. In Panama, the Ministry of Environment reported for 2019 that greenhouse gas emissions originating from fuel combustion processes were represented by 99.9% CO_2, 0.03% methane (CH_4), and 0.002% nitrous oxide (N_2O). According to estimates, the transportation sector is responsible for 7,301.52 kilotons (kt) of CO_2 emissions, accounting for 46.9% of the total. Road transport emerges as the primary contributor, as depicted in Fig. 1, which details the subcategories of the transportation sector and their respective contributions (Ministerio de Ambiente, 2021).

The methodology for estimating emissions in this sector follows the Intergovernmental Panel for Climate Change (IPCC) Guidelines of 2006, applying the Tier 1 method, which calculates CO_2 emissions by multiplying the fuel sold by a default CO_2 emission factor by Intergovernmental Panel on Climate Change (IPCC, 2006). However, a better estimation of the emissions from on-road vehicles will be required to feed the inventory with characteristics of the vehicles, including the number of vehicles, vehicle year, mileage, and average travel speed (USEPA, 1992).

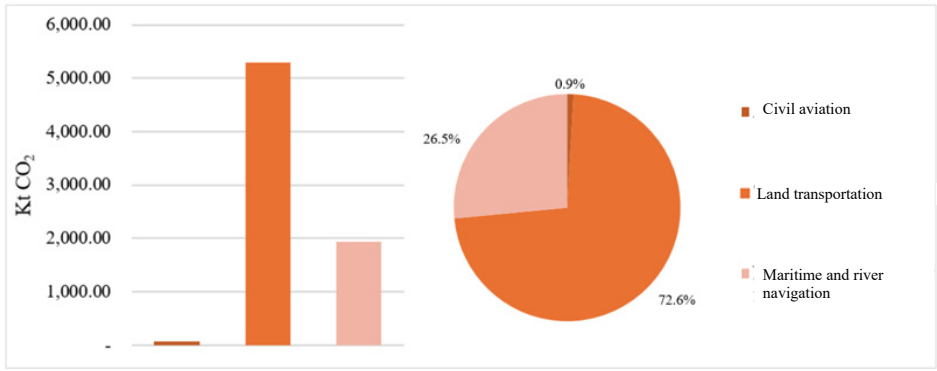

Fig. 1: Emissions from the transportation sector (2019) by activity (kt CO_2). From: Second Biennial Update Report: Learn About Climate Change Mitigation in Panama (Ministerio de Ambiente, 2021)

Tools for modeling that consider vehicle technology factors increase the accuracy of results (Tran *et al.,* 2024). The use of a vehicular emission estimation model, such as the international vehicle emissions (IVE) model, to to compile a mobile emissions inventory would greatly improve the decision-making process for formulating climate change mitigation strategies and preserving. These plans could include setting objectives for specific vehicle fleets and evaluating their progress. IVE model is able to estimate gases such as greenhouse gases (CO_2, N_2O, CH_4) and criteria air pollutants such as particulate matter (PM_{10}), CO, lead (Pb), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). Moreover, ammonia (NH_3) and VOCs are utilized to estimate the pollutants emitted by passenger cars in the IVE model. The Environmental Protection Agency (EPA) has defined air quality standards in the United States (Leland *et al.,* 2022) for the criteria for air pollutants. In 2023, in Panama, an executive order was passed to follow WHO guidelines regarding the short-term and long-term limits of fine particulate matter ($PM_{2.5}$), PM_{10}, CO, tropospheric ozone (O_3), sulfur dioxide (SO_2), and NO_2. Nonetheless, the absence of regulatory monitoring stations hinders the evaluation of how air pollutants behave. The IVE model is a multiscale model based on laboratory measurements, as it processes tens of thousands of datasets from tests conducted by the EPA, the California Air Resources Board (CARB), and the University of California, Riverside (UCR). This model further utilizes region-specific features, demonstrating a strong adaptability to developing countries (ISSRC, 2008) for estimating factors, greenhouse gases, and pollutant emissions of vehicles according to their technology (Outapa *et al.,* 2018). The emission factor is a measure of the mass of pollutant emissions relative to a unit of activity. The emissions are derived by multiplying this factor with the activity data (Fong *et al.,* 2022). Elements such as the travel distance of vehicles, the total number of vehicles, and emission factors significantly impact the amount of toxic emissions generated by vehicles (Outapa and Thepanondh, 2014). Although the IVE model has not seen significant updates in recent years, scientific publications using this model have been increasing compared to others with more recent updates (Cuba *et al.,* 2021). This is because the IVE model is a vehicular emissions estimation model developed for practical purposes, both for the United States and for developing countries (Marcela and Zapata, 2021). The IVE model would allow the establishment of a cost-effective method for evaluating vehicular air pollutants to develop a more representative emissions inventory for on-road mobile sources (Valdes-Montenegro *et al.,* 2024) and to evaluate the mitigation policies (Zhao *et al.,* 2021). Factors like traffic congestion are often seen in urban areas, producing harmful exhaust emissions that are discharged at breathing height and in crowded city environments, thus presenting a significant risk of human exposure (Trang *et al.,* 2015). Emissions can be calculated depending on the type of road (highway, avenue, or street), location (rural, urban) and population driving behaviors, all

these parameters differ by region. A study conducted in the city of Azogues, Ecuador, found that the highest emissions were recorded on highways, arterial roads, and commercial routes, respectively. Light gasoline vehicles equipped with a multi-point injection system largely represented the vehicle fleet (Peñafiel, 2019). In contrast, in the city of Guayaquil, a study using a high-resolution spatial breakdown of vehicle emissions indicated that the highest pollution rates were recorded in areas with high population density and an extensive network of secondary roads, rather than in areas with highways, which tend to have fewer connecting roads (Patiño-Aroca *et al.,* 2022This type of research, which assesses vehicle emissions using data like fuel type, daily or annual mileage, and vehicle weight, provides a crucial resource for government bodies in developing policies focused on enhancing air quality (Viteri *et al.,* 2023). Moreover, it enables the comparison with international contexts and allows for engagement in higher-level debates about air quality management. The objective of this study is to estimate the emissions of atmospheric pollutants generated by passenger cars, using the IVE model methodology to create an emissions inventory in the province of Panama in 2023.

MATERIALS AND METHODS

The information required to estimate the air emission inventory generated by passenger cars using the IVE model is shown in Table 1. The National Institute of Statistics and Census (INEC) of Panama defines a passenger car as one that is exclusively intended for the transportation of people, with a capacity of up to 13 people including SUVs, jeeps, coupes, and sedans. The methodology flowchart for estimating emissions from passenger cars is depicted in Fig. 2.

Passenger cars in circulation in the Republic of Panama are primarily found within the province of Panama, specifically in the Panama district, followed by the San Miguelito district. By 2022, 59.2% of the total vehicles in the country were in these districts. To determine the prevalent vehicle technologies in the country, various regions within these districts were studied. These areas are representative because they correspond to major high-traffic avenues in the Panama and San Miguelito districts, and they also cover areas of low, medium, and high incomes. Fig. 3 shows the chosen avenues; Centenario, Cincuentenario, Domingo Díaz, José Agustín Arango, and Simón Bolívar.

Data collection

In the process of data collection phase, drivers were interviewed at fuel stations found in the previously designated locations. The questionnaire was designed to obtain detailed information about vehicle characteristics and driving behavior. The questions included vehicle type, year of manufacture, type of car exhaust catalyst, engine size, type of fuel used, among others. In cases where the driver was unfamiliar with certain characteristics, the vehicle registration information was examined. Given that the

Table 1: Input parameters for the air emission inventory using the IVE Model

Report	Parameter	Description
Location	Environmental variables	Ambient temperature
		Ambient relative humidity
		Altitude
	Fuel specifications	Sulfur in gasoline and Diesel
		Lead in gasoline
		Benzene in gasoline
	Driving behavior	Driving patterns and Driving distance
		Slopes
		Use of air conditioning
		Cold start distribution
Fleet	Vehicle fleet fraction	Vehicle size
		Fuel type
		Vehicle use
		Fuel delivery system
		Evaporative emission control system
		Exhaust control system/Standard

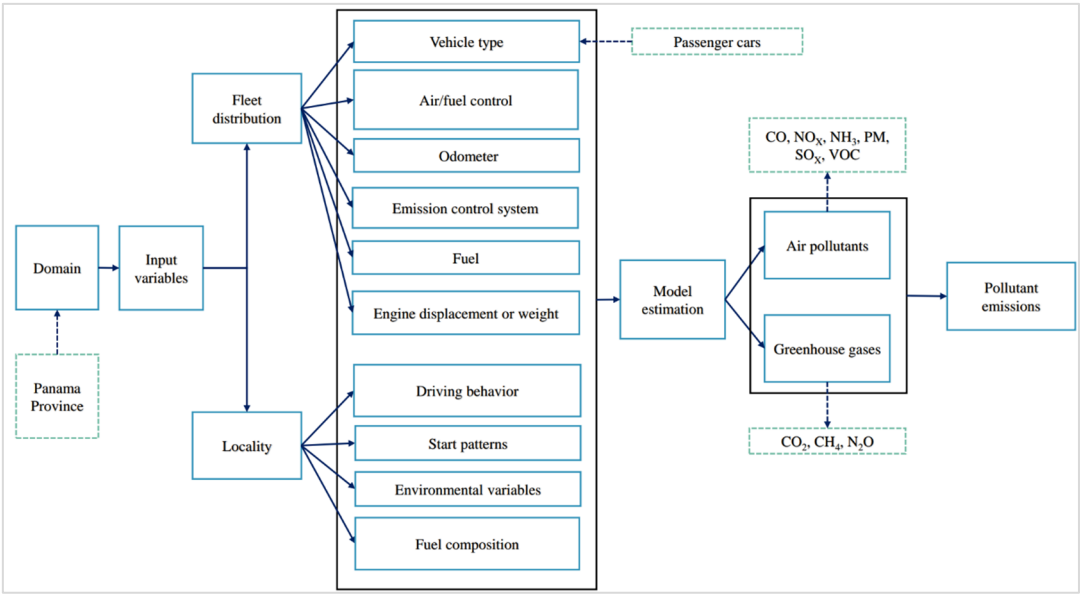

Fig. 2: Flowchart of the input variables in the IVE model

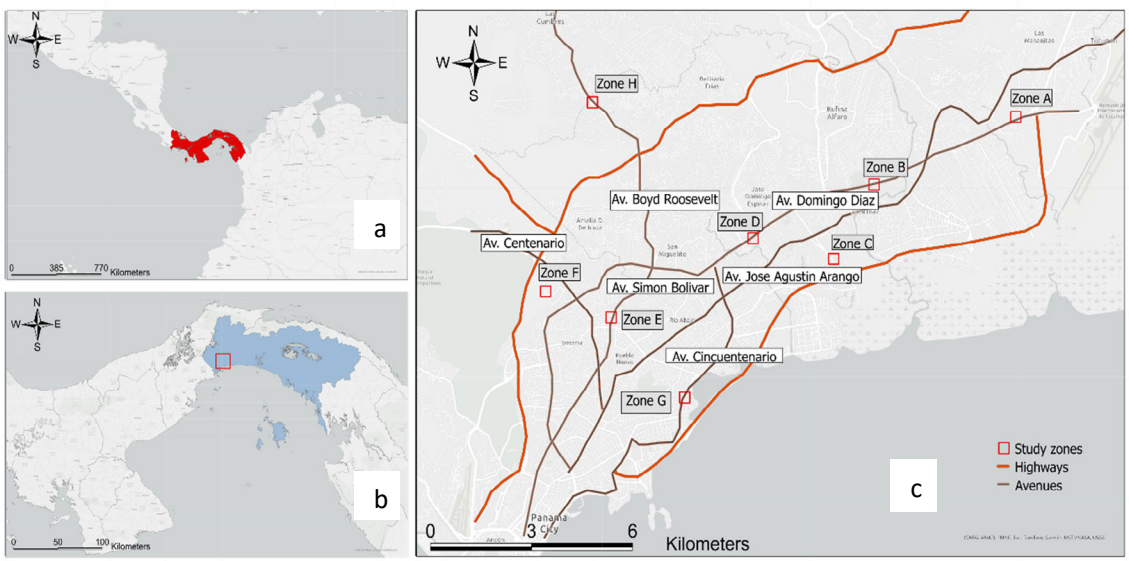

Fig. 3: Geographical location of the Republic of Panamá in Central America (a), location of the province of Panama in the Republic of Panamá (b), location of the study area in the main avenues within the districts of Panamá and San Miguelito (c)

survey concentrated on passenger vehicles, therefore, the inclusion of hatchbacks and pickup trucks was due to drivers reporting their personal usage rather than for business purposes. To represent a fleet of 534,322 passenger cars, a sample of 409 vehicles was surveyed. A convenience sampling (a non-probabilistic approach) method was applied to define the sample size. This technique was picked to evaluate the number of vehicle users to be surveyed, owing to its capability in pinpointing the qualitative features of the vehicle fleet in Panama province. It enables quick and easy access to participants, which is crucial for data collection

Table 2: Distribution of surveyed vehicle fleet by location

Avenue	Location of filling stations		No. of vehicles surveyed	Distribution (%)
	Zone	Coordinates		
Domingo Díaz	A	9° 4' 6.5" N 79° 24' 34.1" W	107	26.2 %
	B	9° 3' 6.0" N 79° 26' 50.1" W		
	D	9° 2' 17.9" N 79° 28' 46.2" W		
José Agustín Arango	C	9° 1' 59.5" N 79° 27' 28.9" W	25	6.1 %
Simón Bolívar	E	9° 1' 7.2" N 79° 31' 2.4" W	44	10.8 %
Centenario	F	9° 1' 30.4" N 79° 32' 5.3" W	102	24.9 %
Cincuentenario	G	8° 59' 55.5" N 79° 29' 51.8" W	82	20 %
Boyd Roosevelt	H	9° 4' 19.4" N 79° 31' 20.3" W	49	12 %
Total			409	100 %

in areas with high traffic density. The distribution by location is shown in Table 2.

Vehicle technology distribution

The pollutant emissions generated by vehicles are influenced by their mechanical characteristics and incorporated technology. The IVE Model includes a database with the most common characteristics of passenger cars, which was used for vehicle classification. Despite this, the IVE Model has not undergone recent updates, thereby limiting its effectiveness in characterizing vehicles that utilize more advanced technologies compliant with Euro 5 and Euro 6 standards. Consequently, spark-ignition vehicles that comply with these international standards have been categorized under the most stringent standard in the IVE model, which is European (Euro)- 4.

Geographic and environmental profile

Meteorological conditions have a significant impact on traffic behavior and vehicle performance. These parameters were established for the baseline year using data from weather monitoring stations at two locations within the province of Panama: Albrook "Marcos A. Gelabert" International Airport (8° 58' 00" N, 79° 34' 00" W) and Tocumen International Airport (9° 03' 56" N, 79° 23' 31" W), both near the study areas in the Panama district. The database was obtained using the OpenAir and worldmet (Carslaw, 2023) libraries in R (John Chambers, 2024). This dataset includes an hourly historical record of air temperature and relative humidity for the year 2023. To correlate these variables with peak traffic hours, values were limited to the period between 6:00 a.m. when traffic congestion is highest in the city (Banco Interamericano de Desarrollo and Alcaldía de Panamá, 2016) and 8:00 p.m., when vehicle flow begins to decrease on the city's main roads (Velasco Soldevila, 2014). In Table 3, the air temperature results derived from the software were evaluated against daily meteorological data from Institute of Meteorology and Hydrology of Panama (IMHPA), evaluating the percentage error between both values.

With respect to the monthly relative humidity for 2023, the data displayed in Table 4 was gathered exclusively from the R source.

Geographical elevation

The avenues above mentioned primarily extend within watershed 144 (Juan Díaz River and between Juan Díaz and Pacora) and watershed 142 (Rivers between El Caimito and Juan Díaz) of the country. The average elevation of watershed 144 is 90 meters above sea level (masl), in contrast to watershed 142, which has an average elevation of 67 masl.

Fuel composition

The fuel composition is subject to regional regulations according to the Central American

Table 3: Average monthly temperature for the year 2023

Months	Weather monitoring stations					
	Albrook "Marcos A. Gelabert" International Airport			Tocumen International Airport		
	Temp. R (°C) (6 a.m.-8 p.m.)	Temp. IMHPA (°C)	Error (%)	Temp. R (°C) (6 a.m.-8 p.m.)	Temp. IMHPA (°C)	Error (%)
January	27.8	27.3	1.9 %	27.9	27.8	0.3 %
February	28.8	28.1	2.4 %	28.6	27	6.1 %
March	28.8	27.9	3.2 %	28.7	27.1	5.9 %
April	29.7	29	2.4 %	29.6	27.9	5.9 %
May	29.5	29.3	0.5 %	29.6	28.8	2.8 %
June	28.7	28.2	1.7 %	28.5	27.9	2.0 %
July	28.5	28.5	0.0 %	28.4	28.1	1.1 %
August	28.5	28.4	0.5 %	28.3	27.9	1.3 %
September	28.7	28.5	0.6 %	28.3	27.8	1.9 %
October	28.2	28	0.8 %	27.5	27.3	0.8 %
November	28.1	27.9	0.6 %	27.9	27.5	1.5 %
December	29.2	28.9	1.2 %	28.9	27.9	3.5 %

Table 4: Monthly average relative humidity (RH) for the year 2023

Months	Weather monitoring stations	
	Albrook "Marcos A. Gelabert" International Airport	Tocumen International Airport
	RH (%)	RH (%)
January	73.38	68.55
February	64.74	64.11
March	66.54	65.45
April	63.29	63.23
May	74.47	72.49
June	80.59	81.93
July	81.50	82.74
August	81.60	83.14
September	80.84	83.04
October	82.67	87.73
November	83.28	84.99
December	75.00	76.70

Technical Regulation 75.01.20:19 for Petroleum products, where it is established the physical and chemical characteristics that automotive-grade premium gasoline must comply with, effective from February 2021 (Ministerio de Comercio e Industrias de la República de Panamá, 2022). For diesel, the specifications established in regulation RTCA 75.02.17:19 for automotive-grade diesel fuel have been in effect since October 2021 (Ministerio de Comercio e Industrias, 2021). The national regulations concerning fuel quality in vehicles are illustrated in Table 5. Fuel adulteration and unauthorized vehicle modifications were excluded from the input in the IVE model.

Driving patterns

In establishing the driving pattern for passenger cars in Panama province, the country lacks previous studies or available information on vehicle travel behavior. Upon examining vehicle travel behaviors and the implementation of the IVE model, it was determined to employ reference data obtained from Thailand (Outapa *et al.*, 2018). The similarities between the two countries allow these values to be used as a baseline, since both share urban congestion and similar weather conditions, notably a humid tropical climate. The driving patterns are mainly defined to establish a specific velocity profile. The input in the software requires non-discrete data. The data was derived sourced from driving behaviors in Thailand, yet in the current study, the profile was corroborated with the speed limits on the roads adjacent to the filling station where the survey occurred. The emission factors (EF) were calculated

using the results obtained.

Methodology for emission factors

The emission factors (EF) (g/km) were calculated by dividing the total emissions by the fleet size and the annual mileage, adjusting the emissions to a basis of grams per kilometer per vehicle. The emission factors are determined using Eq. 1 modified from (ISSRC, 2008):

$$EF_{i,j} = \frac{E_{i,j} \times 1,000,000}{NV_j \times (kma)} \quad (1)$$

Where;

Eij = Total fleet emissions for pollutant *i* and technology *j* (tons/year)

NVj = Number of vehicles corresponding to technology *j*

kma = Annual mileage (km/year)

RESULTS AND DISCUSSION

Driving distance

Concerning the kilometers driven by the vehicle fleet during a designated period, estimating the fleet's mileage annually is vital for compiling an emissions inventory for the year. This parameter was determined by using odometer reading collected from the vehicles during the survey, where the daily kilometers traveled (Daily km) of the vehicles were calculated in this study, using Eq. 2:

$$\text{Daily km} = \frac{\text{Odometer Lecture}}{(\text{Inventory year} - \text{manufacturing year}) * \left(365 - \frac{\text{holidays}}{2}\right)} \quad (2)$$

In Eq. 2, half of the holidays in the year were subtracted. This adjustment was made because vehicles are used less on holidays, and it improves accuracy by considering population behavior. The formula takes into account the inventory year, which aligns with the base year of the study, 2023, as well as the vehicle's manufacturing year. Fig. 4 presents a histogram showing the distribution of daily kilometers traveled by private passenger cars, representing 71% of the fleet identified in the sample. The figure indicates that 91% of private passenger cars travel less than 87 kilometers per day (km/d). The histogram illustrates a right-skewed distribution, revealing that the number of vehicles that travel longer daily distances diminishes considerably. This right-skewed pattern suggests that less than 87 km per day trips are the most common among private passenger cars. Consequently, vehicles with daily distances greater than 87 km were left out to prevent incorporating outliers. Fig. 5 presents a box-and-whisker plot representing the annual kilometers traveled by private passenger cars with daily distances of less than 157 km (1) and 87 km (2). Case 2 shows less dispersion; therefore, this data will represent the annual kilometers traveled, averaging 14,611 km/year, which accounts for 65.2% of the surveyed sample of 409 cars.

Throughout the Panama and San Miguelito districts, a total of 53 distinct vehicle categories were identified during the field campaign. The findings from the survey reveal that 94.80% of cars were powered by gasoline (known as petrol), and 5.12% ran on diesel. The cars have accumulative mileage greater than 160,000 km, representing 45.19%, followed by vehicles with odometer readings of less than 79,000 km (23.22%). Concerning the engine displacement, 61.1% of the fleet's passenger cars have an engine displacement between 1.5 and 3 liters (classified as medium size), followed by 34.7% with a displacement of less than 1.5 liters (light size) and 4.2% possess a displacement exceeding 3 liters (designated as heavy size). Fig. 6 shows that light and medium cars have a higher proportion of vehicles with mileage exceeding 160,000 km.

According to the survey results, the average age of the car fleet was 9. This compares with neighboring countries such as Costa Rica, where the average age is 16 (Arias-Arguedas *et al.*, 2023), and 13 in Colombia (Alejandra Rico, 2025). In this study, the vehicle's origin was not questioned (imported or second-hand owner), and there are no official statistics with this information. A law was proposed in Panama in 2017 to ban the importation of cars that are classified as total loss or scrap, or having reached the end of their useful life in the country of origin. However, this law did not pass the legislative chamber. Even without a specific incentive to lower emissions from older vehicles, a financial inclination is observed in the country. Loans for newer cars generally offer lower interest rates, approximately 5.5% per year, and longer repayment periods of up to 96 months.

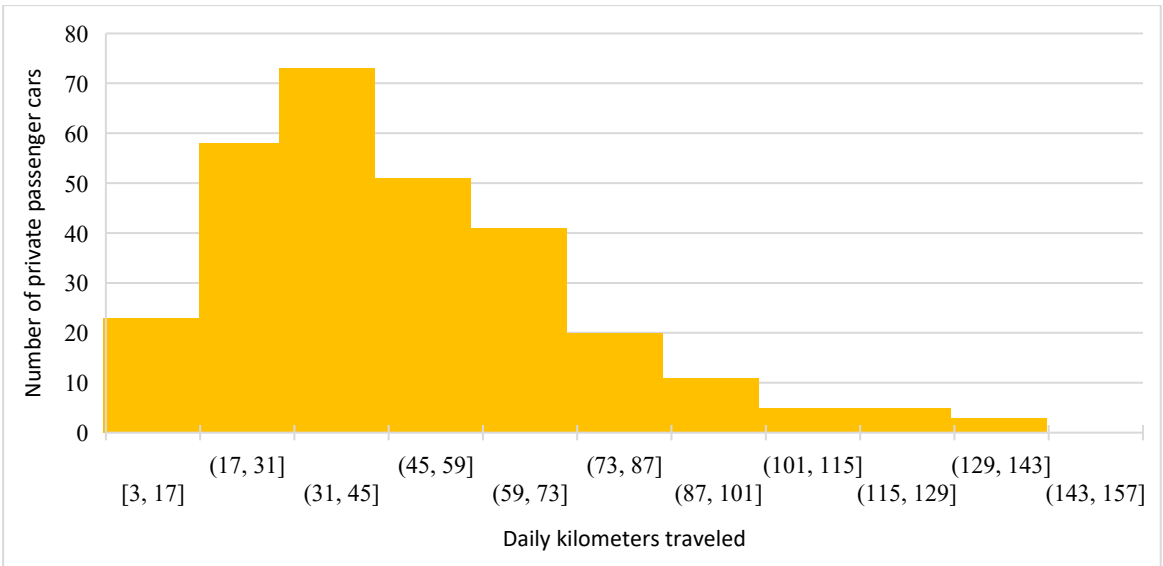

Fig. 4: Histogram of daily kilometers traveled by the passenger car fleet

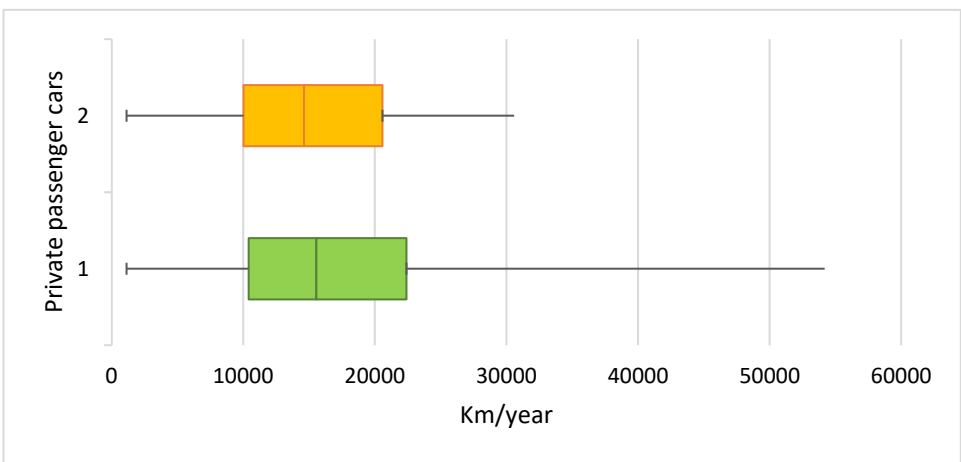

Fig. 5: Box-and-whisker plot of the annual kilometers traveled by passenger vehicles with daily ranges of up to 157 km (1) and up to 87 km (2)

In contrast, used vehicles typically have interest rates starting from approximately 7.75% annually.

Methodology for emission factors

The emissions of greenhouse gases and other atmospheric pollutants (in metric tons) generated by passenger cars in the province of Panamá in 2023, based on fuel type and vehicle, are displayed in Table 5. The results were obtained after setting the vehicle categories, the environmental conditions and the local profile in the IVE model.

The contribution of GHG pollutants from passenger vehicles is as follow: 1.78 Mt (Megatonnes) per year of CO_2, 1111.7 t per year of CH_4 and 58.3 t per year of N_2O. Regarding air pollutants, CO was the main pollutant emitted reaching 234.16 kt in the year of analysis, followed by VOCs (5.40 kt), NOx (4.95 kt), NH_3 (1.17 kt), PM_{10} (0.16 kt), and SOx (0.031 kt) (Fig 7.). With increasing vehicle mileage, there is a corresponding rise in engine wear, which affects the efficiency of combustion and leads to incomplete combustion. Also, the degradation of the emission control system occurs. Vehicles use lubricants to

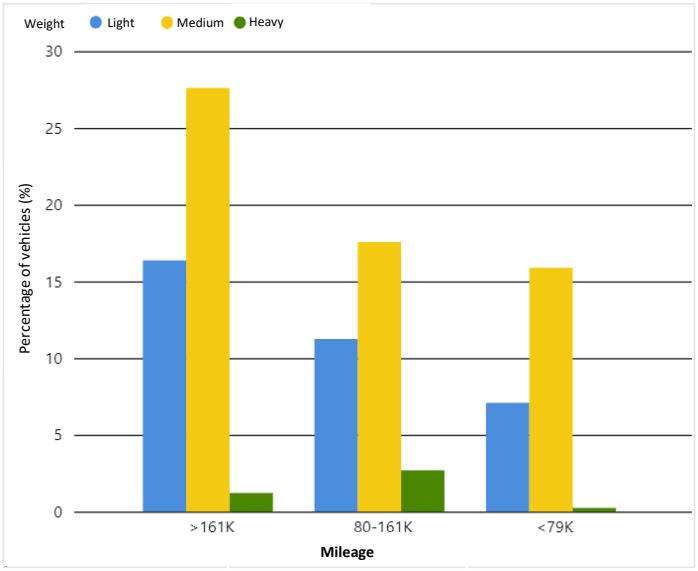

Fig. 6: Percentage of vehicles based on their weight (size) and accumulated mileage

Table 5: Physicochemical specs of fuels according to national regulations and the input in the IVE Model

Fuel	Physicochemical properties	Unit	Regulatory limit	Value employed in the IVE model
Gasoline	Sulfur	mg/kg (% mass)	150 (0.015) max.	50 (0.0050)
	Lead Content	g Pb/L	0.013 max.	0
	Benzene	% volume	1.5 max.	1.5
	Oxygenates	% volume	0.7 max.	0
Diesel	Sulfur	mg/kg (% mass)	15 (0.0015) max.	15 (0.0015)

reduce friction between engine components, which minimizes wear and improves engine efficiency. Furthermore, with the passage of time and continuous use, the oil breaks down and its efficiency diminishes, causing incomplete combustion in the vehicle and increasing emissions of VOCs and CO.

With respect to the fuel type used in vehicles, Fig. 8a. illustrates that diesel-powered vehicles, which constitute under 6% of the fleet, are accountable for almost 50% of the PM10 emissions, precisely 47% of the total emissions. In contrast, each gasoline vehicle emits approximately 169 grams of PM_{10} per year, while diesel vehicles emit significantly more, with 2779 grams of PM_{10} per year. In the analysis of emissions by vehicle size, Fig. 8b demonstrates that medium-sized cars are the largest sources of all gaseous emissions. Heavy vehicles, with engine displacements over 3000 cc (cubic centimeters), have the greatest impact on particulate matter emissions, contributing 15%. These data reflect the impact of diesel vehicles on air quality. Unlike CO_2, which primarily affects the atmosphere temperature, pollutants such as SOx, NOx, and particulate matter present a direct risk to human health. The contribution of vehicles to GHG emissions and air pollutants is depicted in Fig. 8c, which is based on the total mileage of the fleet. Vehicles with mileage over 160,000 km are the main contributors to emissions, with significant impacts on CO (79%), PM_{10} (80%), VOC (78%), and CH_4 (76%) emissions. In contrast, vehicles with mileage under 79,000 km, which have a lower travel distance, contribute relatively little to the emissions of CH_4 (4%), CO (3%), and VOC (4%). According to national statistics, hybrid vehicles represent less than 0.24% of the total cars in the study area. Consequently, hybrid and electric vehicles were excluded from the emission model. Current information about the passenger car fleet indicates that alternative fuels

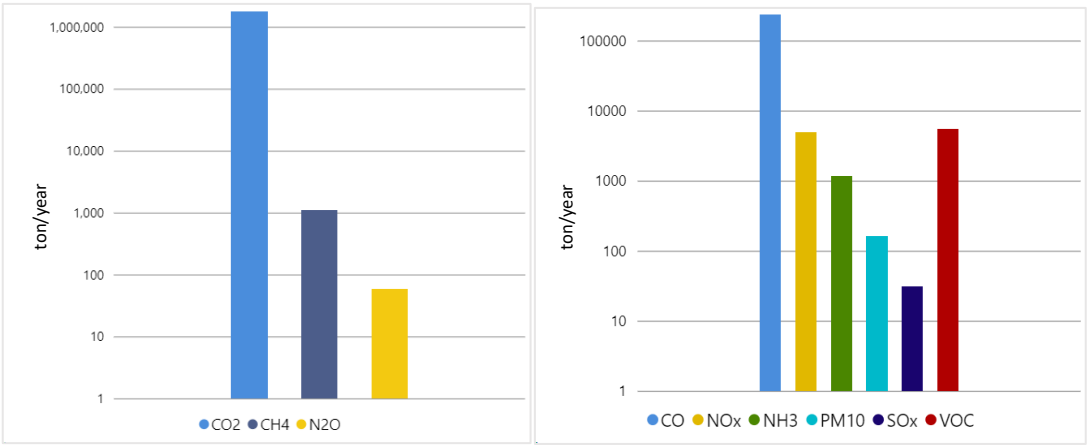

Fig. 7: Greenhouse Gas and Air Pollutant Emissions (ton/y)

were not employed in 2023. The assumptions made in the current model reflect the existing distribution of the vehicle fleet. However, it is understood that modifications will be essential as hybrid, electric, and various low-emission technologies become increasingly common in the region.

Performing a linear regression with a coefficient of determination of 95% on the emissions reported by the Ministry of Environment in the country to date, 5.78 Mt of CO_2 emissions generated by land transportation (cars, motorcycles, buses, trucks, machinery, etc.) are estimated for the year 2023. According to the IPCC methodology, these emissions have been calculated, revealing that 31% of the produced emissions associated with land transportation stem from passenger cars within the Province of Panama.

Emission factors

IVE model facilitates the determination of emission factors for future estimates, measured in grams of pollutants per kilometer. This calculation considers the emission control technology implemented in the fleet. Table 6 shows the emission factors calculated based on the 2023 emissions inventory, taking into account the fuel type and vehicle size (engine displacement). For gasoline-powered vehicles, emissions of CO_2, N_2O, NOx, and SOx per kilometer increase proportionally with vehicle size. However, this behavior varies for other air pollutants. Regarding CH4, light-duty vehicles release the least amount of this gas, in contrast to the higher and comparable emissions from medium and heavy vehicles. Diesel vehicles of medium size generate approximately 0.19 g/km of PM_{10}, whereas heavy vehicles emit 0.25 g/km. Although diesel vehicles without emission control systems belong only to the medium-size category, vehicle size remains a key parameter in determining emissions. When compared, heavy vehicles emit 31% more PM10 per kilometer than medium-sized vehicles, underscoring the influence of vehicle size on pollutant emissions.

Comparative analysis of the estimated emissions inventory versus other localities

The aim of this section is to present a comparative analysis of atmospheric pollutant emissions of CO, NOx, and VOCs generated by passenger cars in different cities or regions, alongside the results obtained in this study for the province of Panama. To achieve a proportional comparison, emissions were examined on a per capita basis, acknowledging the population disparities across different regions. These per capita emissions are shown in Fig. 9. CO is the primary pollutant emitted in all the analyzed locations, with the province of Panama reporting the highest emissions (446 g/d/per capita), three times higher than Guayaquil, Ecuador (138 g/d/capita). In Guayaquil, the IVE model was applied using 2018 dataA significant contrast between Panama and Guayaquil is evident in their vehicle counts: Panama had 371 cars for every 1,000 inhabitants, while

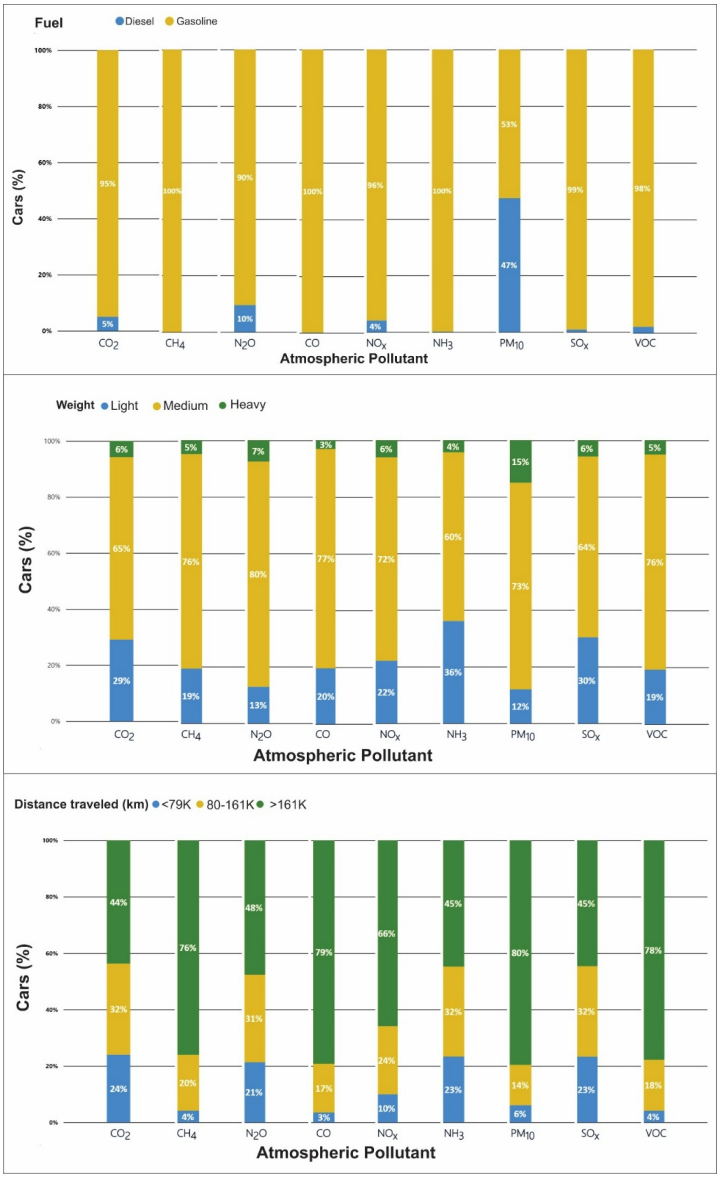

Fig. 8: Atmospheric pollutant emissions of CO_2, CH_4, N_2O, CO, NOx, NH_3, PM_{10}, SOx, and VOC (a) by fuel type (b) by vehicle size (c) by mileage (distance travel)

Guayaquil only had 114 in the same year of the study. The lowest CO emissions were found in Manizales, Colombia, based on a 2017 study using the COPERT model, which showed emissions 69% lower than those estimated by the IVE model for the same year—differences largely due to varying emission factors and calculation methods. Additionally, vehicle activity in Panama is higher (41 km/car/d) compared to Manizales (25 km/car/d). The second most significant pollutant is VOC, Guayaquil leading (15 g/day/per/ habitant), followed by Bogotá (13 g/d/capita) (Alcaldía Mayor de Bogotá D.C. and Secretaría de Ambiente, 2021) and Panama (10 g/d/capita). In Bogotá, there are 240 cars for every 1,000 people—twice as many as in Guayaquil, even though both cities demonstrate comparable levels of VOC

Table 6: Passenger vehicle emissions by vehicle category (ton/year)

Vehicle characteristics		%	CO_2	Methane (CH_4)	N_2O	CO	NO_x	Ammonia (NH_3)	PM_{10}	Sulfur oxides (SO_x)	VOC
Fuel	Weight			ton/y				ton/y			
Gasoline	Light	34.7	518430.7	214.8	7.5	45954.0	1094.6	424.4	19.4	9.3	1036.7
	Medium	56.2	1074562.6	842.9	40.9	180859.8	3375.6	699.2	46.1	19.4	3982.3
	Heavy	3.9	98011.3	54.0	4.3	7062.3	282.1	49.3	19.6	1.7	264.0
Diesel	Medium	4.9	84081.8	0.0	5.5	268.9	187.2	1.2	72.0	0.3	112.2
	Heavy	0.2	4947.8	0.0	0.0	13.4	14.3	0.1	4.7	0.0	5.4
Total		100	1780034.2	1111.7	58.3	234158.3	4953.9	1174.1	161.7	30.8	5400.6

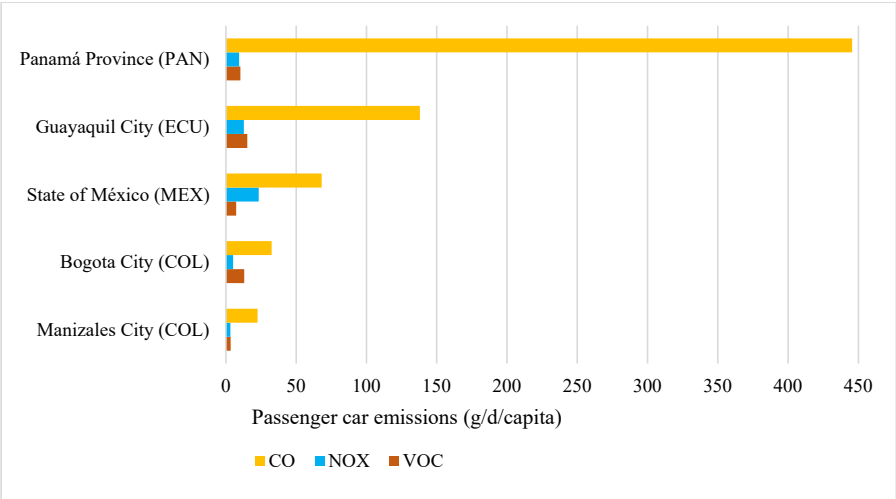

Fig. 9: Daily per capita emissions by location

emissions. NOx emissions were highest in the State of Mexico (23 g/d/capita in 2018) (Secretaría de Medio Ambiente y Recursos Naturales, 2024), 155% higher than in Panama, which ranks third. In 2018, the State of Mexico report 320 cars per 1,000 inhabitants (Dirección General de Estadística, 2024), while Panama had 16% more cars in 2023. PM_{10} emissions are below 1 g/d/capita and were not analyzed in detail. This study highlights the significance of local elements like the size of the vehicle fleet, vehicle activity, and the emission models employed to ensure accurate and representative emission estimates. Moreover, it indicates the situation in comparison to countries in the region and it will help as a reference to propose policies to improve air quality management at the district or provincial level in Panamá. In a study conducted in the city of Manizales, Caldas Department in Colombia (Cifuentes *et al.*, 2021), a comparison of COPERT/Top-down and IVE/Top-down shows that the IVE performed better than the COPERT because information about vehicle-specific power, which accounts not only for average speed, but for acceleration, vehicle weight, road slopes, among other variables. Nonetheless, future studies of this kind will offer enhanced information concerning the effectiveness of the IVE model in this context.

Uncertainty analysis

An uncertainty analysis was performed using error propagation method, as recommended by the IPCC. This method allows for quantifying the level of uncertainty associated with the product of the quantities involved in the emissions estimation. This approach for merging uncertainties was employed to determine the uncertainty percentage for the

Table 7: Emission factors for passenger vehicles per kilometer (g/km)

Vehicle characteristics		CO_2	CH_4	N_2O	CO	NO_x	NH_3	PM_{10}	SO_x	VOC
Fuel type	Weight	g/km					g/km			
Gasoline	Light	191.317	0.079	0.003	16.958	0.404	0.157	0.007	0.003	0.383
	Medium	244.957	0.192	0.009	41.229	0.770	0.159	0.011	0.004	0.908
	Heavy	321.906	0.177	0.014	23.195	0.927	0.162	0.064	0.006	0.867
Diesel	Medium	220.699	0.000	0.014	0.706	0.491	0.003	0.189	0.001	0.295
	Heavy	264.070	0.000	0.002	0.715	0.765	0.004	0.248	0.001	0.289

numerical input data in the IVE Model, taking into account the statistical variability of the associated variables. A method utilizing qualitative evaluation of the origin and characteristics of the data was employed for qualitative variables. The outcome revealed a roughly 14% uncertainty associated with the input data. On the other hand, the Second Biennial Update Report: Learn About Climate Change Mitigation in Panama in 2021 has an uncertainty of ±58.0 %, and the national inventory in 2024 indicates an uncertainty of ±194.5 % due to the use of Tier 1 methodology in both cases.

RECOMMENDATION

This study proposed the following recommendations: 1) *To disclose information about the emission standard and the emission control system in the vehicle registration*. Currently, there is no obligated for manufacturers to disclose information concerning the vehicle emission standard or the type of emission control system in the user manual. 2) *To update the emission test*. Environmental policies in other countries require tests on dynamometers that allow manufacturers to share information about the vehicle's emissions versus fuel consumption or kilometers travel. 3) *To continue implementing the recently approved electric mobility law*. As indicated, the government must replace the fleet with electric cars by 10% by 2025, 25% by 2027, and 40% by 2023. Establishments must reserve at least 15% of the parking lots for electric cars. Electric vehicles are exempt from paying for car plates for five years. 4) *To invest in public transportation*. The inaugural Metro line was launched in 2014 to reduce congestion between San Miguelito and Panama Districts. Later in 2019, Metro Line 2 was inaugurated with 18 stations, connecting the east side of Panama City. In 2023 (Quiñones, 2023), 255000 people commute daily on line 1 and 157000 on line 2. A Monorail is envisioned as Line 3 for 2025, aimed at connecting West Panama Province to Panama City. The original plan was to construct a bridge over the Panama Canal waterway by a bridge, but the proposal has recently shifted to a tunnel situated 60 meters beneath it. In Panama City, the metro line is supplied by the public transportation services provided by the buses known as "MiBus". However, users complain about frequency, schedules, security, and capacity. 5) *To allow greater transparency in government public data on vehicles registered nationwide, and to facilitate more effective collaboration among public institutions*. Making this data accessible and regularly updated would allow better air emission inventories estimations. 6) *To expand vehicle registration information.* Vehicle registration should encompass details regarding technological specifications, odometer mileage, maintenance schedule, type of fuel used, vehicle efficiency, and the categorization of vehicles (passenger, commercial, heavy-duty vehicle, L-category, etc.). 7) *To require car registration in the driver's residency municipality.* Currently, cars can be registered in any municipality in the country. However, this does not help with urban planning and local governments environmental policies. 8) *To initiate public awareness campaigns*. Clarify how fuel usage correlates with emissions and the subsequent health consequences for the community. 9) *To discourage the use of diesel-powered cars.* Currently, three types of fuel for vehicles are sold in Panama: Ultra-Low Sulfur Diesel (ULSD), 95-octane gasoline, and 91-octane gasoline. The prices vary depending on the province, but diesel per liter is lower than gasoline. In July 2022, following significant strikes throughout the country, a fuel price subsidy was approved for 91-octane gasoline and ULSD valid until January 2024. Policies aimed at reducing the use

of diesel-powered vehicles should start by raising public awareness about the impact of air pollution on community health to prevent social unres. 10) *To verify authorized car workshops*. The Land Transit and Transportation Authority (in Spanish: La Autoridad de Tránsito y Transporte Terrestre (ATTT)) is supposed to enforce the current vehicle emission regulation law. They must inspect authorized car workshops and verify that they have the certified equipment to conduct the annual emission inspection. 11) *To evaluate long-term strategies regarding phasing out or retrofit*. It is essential to consider these policies since they may not be suitable for the social context and might predominantly benefit vehicle dealers. Moreover, they could facilitate the second-hand black-market business. Retrofitting an internal combustion engine to an electric vehicle will require trained labor.

CONCLUSION

This study estimated the air emission inventory of on-road mobile sources in 2023 for passenger cars in the province of Panama. A field investigation was performed to recognize the technologies that characterize passenger vehicles within the designated study area. Fifty-three vehicle categories were identified, with gasoline-powered cars making up 94.8% of the fleet, while diesel vehicles represented only 5.12%. Results indicate that more than 45% of the vehicles exceed 160,000 km. The distribution by size shows that medium-sized vehicles (with an engine displacement between 1.5 and 3 liters) constitute the majority (61.1%) and are the highest emitters in all pollutant categories, particularly in CO_2 and N_2O. Although diesel vehicles are fewer, they account for nearly half of the PM_{10} emissions, especially those with engine displacements greater than 3 liters. CO_2 was identified as the main pollutant emitted by passenger cars. With the increase in vehicle mileage, a significant uptick in the emissions of pollutants including CO, NOx, and VOC is observed. Diesel vehicles are notable for their high NOx and PM_{10} emissions, which pose a considerable risk to human health. Additionally, reducing sulfur content in diesel has significantly contributed to decreasing NOx, PM_{10}, and SOx emissions, underscoring the importance of fuel quality regulations. Examining emission factors for passenger vehicles has uncovered trends that are influenced by the size of the vehicle and the type of fuel used. In gasoline-fueled vehicles, emissions of pollutants such as CO_2, N_2O, NOx, and SOx increase proportionally with vehicle size, while other gases such as CH_4 show more variable behavior. Ultimately, the comparative analysis with other regions emphasizes the variations in per capita emissions, which are affected by elements like vehicle density, distance traveled, and the software used. This analysis demonstrates that, although estimates may vary, the size and use of the vehicle fleet play a crucial role in determining atmospheric emissions. Moreover, the survey revealed that the public lacks awareness of the connection between air pollution and their car usage.

AUTHOR CONTRIBUTIONS

A. Valdés-Montenegro has analyzed the data, written the manuscript, prepared all the figures, and interpreted the results. F. González-Olivardía, the corresponding author, has contributed by supervising the work, interpreting the results, and writing the manuscript. C. Pinzón-Acosta participated in the interpretation of the results and manuscript revision. All the authors participated in the data collection process.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
°C	Degree Celsius
a.m.	ante meridiem or before noon.
CARB	California Air Resources Board
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
EPA	United States Environmental Protection Agency
g/km	Grams per kilometer
HSU	Hartridge Smoke Units
IMHPA	Panama Institute of Meteorology and Hydrology
INEC	National Institute of Statistics and Census
IPCC	The Intergovernmental Panel for Climate Change
IVE	International vehicle emissions
km	Kilometer
kma	Annual mileage (km/vehicle)
Km/d	kilometers per day
km/kWh	electricity consumption
km/lt	fuel consumption
km/y	kilometers per year
kt	Kilotons
kt CO_2	Kilo-tonnes of carbon dioxide emissions
Mt	Megatons
masl	Meters above sea level
N	North
NH_3	Ammonia
N_2O	Nitrous oxide
No.	Number
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
O_3	Tropospheric ozone
p.m.	post meridiem or after noon
Pb	Lead
$PM_{2.5}$	Fine inhalable particles, with diameters that are generally 2.5 micrometers and smaller.
PM_{10}	Inhalable particles, with diameters that are generally 10 micrometers and smaller
ppm	parts per million

RH	Relative humidity
SO_2	Sulfur dioxide
SOx	Sulfur oxides
SUV	Sport Utility Vehicle
Temp.	Temperature
Ton/y	Tonnes per year
UCR	University of California, Riverside
ULSD	Ultra-low sulfur diesel
VOC	Volatile organic compounds
W	West

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