Spatiotemporal modeling of CO2 Emissions in Casablanca, Morocco, with Integrated Web Mapping Application for Interactive Data Sharing

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ABSTRACT

As urbanization accelerates, cities is grappling with rising CO2 emissions, largely driven by road traffic and residential electricity consumption. this study delves into the heart of this environmental challenge in Casablanca, as the largest city in Morocco using advanced modeling techniques to estimate emissions from household electricity consumption in 2020, a year marked by the COVID-19 lockdown as well as emissions from private cars, buses, trams, taxis during a study period between 2019 and 2023. By integrating diverse data sources such as CO2 emission factors, transportation data, climate variables remote sensing data, and additional datasets such as population density and electricity consumption data, this research captures the full scope of emissions across the city, considering factors like temperature, precipitation, and travel time index. The findings show important emission hotspots, with districts like Sidi Bernoussi contributing the highest emissions, totaling over 124 million kg of CO2 in 2020. This surge, particularly during the COVID-19 lockdown, highlights the direct link between population density, residential energy use, and emissions. In the other hand Al Fida Mers Sultan wins the top spot as the most polluted district due to traffic intensity and the dominance of diesel cars with approximately 3.5 million tonnes CO2 in 2023. Simultaneously the study sheds light on the disparities in emissions across different modes of public transportation. While taxis are the largest emitter among public transport options, contributing 4.4 million tonnes of CO2 during the study period, tramways stand out as the most environmentally friendly choice with just 535,342 tonnes of CO2 for the reason that uses electricity and solar energy instead of fuel fossil as source of energy, this reinforces the need for sustainable transportation policies, particularly as the city works to reduce its overall carbon footprint.

A standout feature of this study is comparison of the transportation emission estimation using ODIAC satellite data, confirming its contribution to overall co2 fuel fossil emission in the city. The research also introduces the creation of an innovative web mapping tool that allows users to explore emissions data interactively, offering spatial and temporal visualizations of the results. By combining mathematical modeling, GIS, and user-friendly mapping, the research offers valuable insights for tackling urban air pollution and provides a replicable framework for other rapidly growing cities.

Keywords: CO2 Emissions, GIS and Remote Sensing, Urbanization, Transportation, Energy Consumption, Sustainable Policies

1. Introduction

Nowadays, air pollution and climate change are the greatest atmospheric challenges for societies, and they will continue in future decades. These environmental issues are highly connected, mainly through atmospheric processes and meteorological conditions (Afifa et al. 2024) . Air pollution is derived from local pollution sources but also affected by large-scale movement of air masses that contribute to regional background pollution and air pollution episodes (Khomsi et al. 2020). Since fossil fuels are the principal cause of the emissions, the majority of countries have already pledged to reduce or neutralise their carbon emissions in the coming years in response to the Paris Agreement (Gordic et al. 2023).The scientific consensus is clear human activities, particularly the burning of fossil fuels, are driving global warming, with road traffic being a major source of pollution in urban areas due to high traffic intensity and the prevalence of diesel vehicles (Inchaouh, Khomsi, and Tahiri 2018). Out of about 35 billion

tonnes of greenhouse gases (measured in tonnes of carbon dioxide equivalents – tCO_2e) that the world emits each year, the emissions resulting from the use of energy in residential buildings account for over 10% (Gordic et al. 2023) ,(Zen et al. 2022) .

The COVID-19 pandemic had a profound impact on global CO2 emissions, particularly in sectors such as residential electricity consumption and road traffic (Ray et al. 2022). During the initial phases of the pandemic, strict lockdowns and restrictions on movement led to a sharp decline in road traffic, as people stayed home and many businesses halted operations. This reduction in vehicular activity resulted in a temporary but significant drop in CO2 emissions, particularly in urban areas where road traffic is a major source of pollution (Taoufik, Laghlimi, and Fekri 2021). At the same time, residential electricity consumption surged, as more people worked from home and increased their use of household appliances and heating or cooling systems. This shift led to a rise in CO_2 emissions from the residential sector, particularly in countries reliant on fossil fuel-generated electricity. The increased demand for energy in homes partially offset the reductions in emissions from transportation and industry, highlighting the challenges in balancing energy consumption during a global crisis (Jing et al. 2022). The pandemic underscored the interconnections between human activity, energy consumption, and carbon emissions. While the short-term reductions in CO_2 due to decreased road traffic were significant, the overall impact on global emissions was mitigated by the rise in residential energy use.

In the context of Casablanca, a rapidly growing urban center, these global challenges are particularly pronounced due to its dense traffic, expanding vehicle fleet, and increasing energy demands from residential sectors. (Hasnaa et al. 2024), Furthermore, like many other cities, Casablanca experienced a temporary reduction in emissions during the COVID-19 pandemic, with road traffic plummeting due to lockdowns while residential energy consumption surged. However, the city's return to normalcy has once again elevated emission levels, underscoring the need for long-term solutions. Addressing air pollution and reducing CO_2 emissions in Casablanca will require integrated strategies that target both transportation and residential energy use, as well as the adoption of cleaner technologies to create a more sustainable and resilient urban environment.

To address the challenges posed by dynamic urban environments like Casablanca, our methodology employs emission factors a widely accepted approach in CO_2 emissions estimation.

Emission factors quantify pollutants emitted per unit of activity, such as kilometers traveled by vehicles or kilowatt-hours consumed by households (US EPA 2016). Studies like those by (Yao Wang et al. 2023) have demonstrated the importance of emission factors in calculating residential electricity consumption emissions. This approach allows for more precise calculations of emissions across different transport modes and residential sectors, providing a robust foundation for estimating the contributions of various activities to overall CO_2 emissions. Emissions from vehicles, for example, can be calculated using a formula that multiplies the distance traveled by the emission factor for each vehicle type, allowing for a granular understanding of pollution sources (Franco et al. 2013). However, emission factors alone may not capture the full complexity of urban emissions, especially when considering real-time changes in traffic patterns and environmental conditions.

To address this limitation, the integration of the spatiotemporal analysis with data from the Travel Time Index (TTI) from Waze Api and climate factors obtained from the ERA5 dataset. The TTI, which measures traffic congestion and its impact on travel times, is a key indicator of how urban mobility contributes to emissions. When combined with climate data, this approach enables a dynamic assessment of emissions, accounting for variations in weather and traffic congestion throughout the day (Rouky et al. 2024),(Khalis et al. 2022).

2. Study Area

Casablanca city has been chosen as the study area **(Fig.1)** for its significant air quality challenges which stem from rapid urbanization, and high vehicular traffic.

Spread on the Atlantic coast for nearly 50 km. Administratively, Casablanca is the capital of the Casablanca-Settat region, which encompasses a broader geographic area. The city of Casablanca covers 386.14 km2 and comprises 3,359,818 inhabitants (RGPH 2014.). It is also a major transport hub for the whole country, with a total road length of 5,693 km , which is well-distributed across national roads (451.83 km), regional roads (1,118.7 km), and provincial roads (4,121.6 km),('SIREDD Casablanca Settat', n.d.). According to the DRCR, light vehicles account for approximately 70% of this traffic, while heavy vehicles make up the remaining 30%. Additionally, the average daily traffic of both light and heavy vehicles is recorded by seven tollbooths along the Casablanca-Settat Highway and the Casablanca bypass. The DRCR's traffic counts cover around 334 km, representing 52% of the interurban road network within the region (Khadija and Bahi, n.d.).

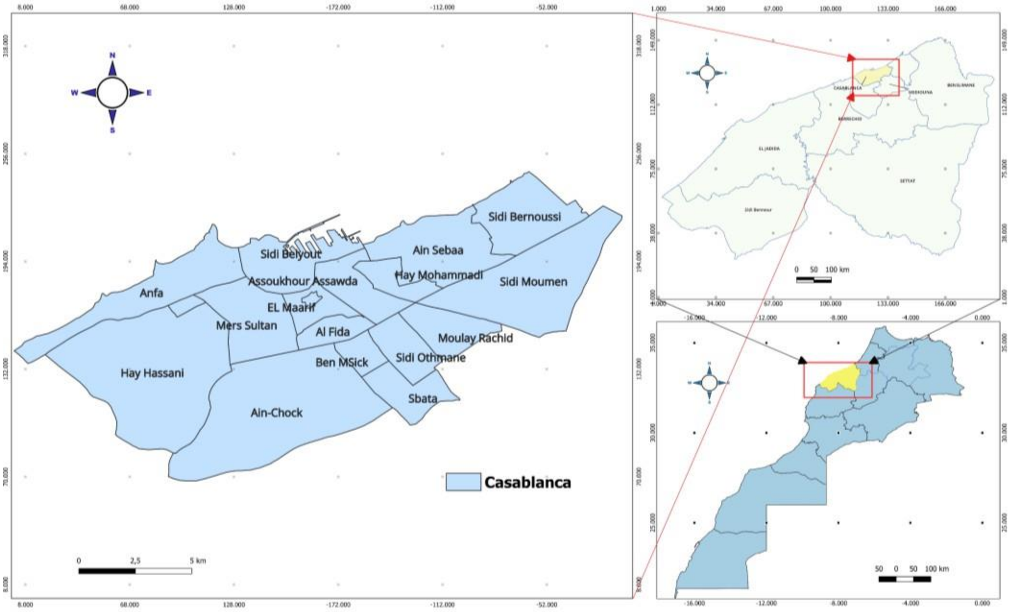

Figure 1 Geographical location of the study area

3. Methodology and Tools

This study employed a multidisciplinary approach to analyze CO_2 emissions in Casablanca, integrating spatial, temporal, and sector-specific datasets, advanced geospatial techniques, and mathematical modeling to deliver a robust, multidimensional assessment. The process began with comprehensive data collection, including CO_2 emission factors (specific to vehicle and fuel types), transportation statistics, electricity consumption, and climate variables (temperature and precipitation from 2019 to 2023, sourced from ERA5 via the Climate Engine platform). High-resolution spatial datasets such as GHS-BUILT-C and GHS-POP were also collected to characterize residential and non-residential built environments and population density at a 10-meter resolution. In addition, ODIAC satellite imagery on fossil fuel CO_2 emissions was utilized to obtain a fine-scale spatial distribution of emissions. Traffic congestion was assessed using the Travel Time Index (TTI) from the Waze API, enabling temporal and spatial characterization of vehicle flow.

Data preprocessing was conducted using Python and GIS tools to clean, reproject, and harmonize raster, vector, and tabular datasets. Emissions were then estimated for each transport mode cars, taxis, buses, and tramways based on vehicle counts, travel distances, fuel types, and emission factors. Climate adjustments were applied using temperature and precipitation data.

3.1. Residential Electricity Emissions

A Python-based geospatial pipeline was developed for household electricity emissions. Commune-level shapefiles containing demographic and energy data were aligned with household and population density rasters.
The emissions from households are determined by the number of households, their average energy consumption, and the specific emission factor associated with the energy source used **(1)**. The emission factor represents the amount of CO2 equivalent emitted per unit of energy consumed, varying based on the type of energy. By multiplying these factors, we obtain an estimation of the total emissions generated **(1)**, which allows for a detailed analysis of the environmental impact at the household level and can be used to inform strategies for reducing carbon footprints.

$$Emissions = HouseHold\ Pixel\ \times Avg\ Consumption\ \times EF \quad \textbf{(1)}$$

Where ***EF*** is an emission factor of **0.862 kg CO_2 /kWh** (Bastos, Monforti-Ferrario, and Melica 2024) and ***Avg Consumption*** is average energy consumption. The residential sector, in particular, is recognized as having substantial potential for emission reductions and plays a central role in strategies aimed at achieving carbon neutrality.

3.2. Vehicles emissions modeling

Emissions from cars and taxis were calculated using a mathematical model incorporating traffic volume, travel distance, fuel mix, and emission factors **(2)**. The daily emissions per location were computed as:

$$Emissions\ (\frac{Kg}{Co2}) = D \times N \times (P_{Diesel} \times EF_{Diesel} + P_{Gasoline} \times EF_{Gasoline}) \quad \textbf{(2)}$$

Where ***D*** represents the total distance traveled per day (in kilometers), and ***N*** denotes the total number of cars. The proportions of diesel and gasoline vehicles are indicated by P_{Diesel} and $P_{Gasoline}$, respectively. The associated CO_2 emission factors are

denoted as EF_{Diesel} and $EF_{Gasoline}$, expressed in kilograms of CO_2 per kilometer (kg CO_2 /km).
Specifically, **diesel cars** exhibit a CO_2 emission factor ***of 0.1875 kg/km***, which is slightly lower than that of **gasoline cars**, at ***0.2128***

kg/km (Zakaria, Mat Yazid, and Yaacob 2021) . This distinction is essential for modeling the overall environmental impact of transportation within the city, allowing for a more accurate understanding of each vehicle type's contribution to urban air pollution.
To account for environmental conditions, the emissions are adjusted based on the sensitivity of pollutants to temperature and precipitation **(3)**. This is achieved by applying a climate adjustment factor:

$$Adjusted\,Emissions = Emissions \times (1 + f(T,P)) \quad \textbf{(3)}$$

Where $f(T,P)$ is a function of temperature ***T*** and precipitation ***P***.

3.3. Buses emissions modeling

The analysis begins with the loading of geospatial data from a shapefile containing bus route information, alongside climate data sourced from a CSV file. Key operational assumptions, including the number of operating hours per day, downtime between trips, and the number of buses per line, are incorporated into the model. The script proceeds by iterating over each bus line to calculates the number of trips that a bus can make in one day **(4)**. It considers the total operating hours available in a day and accounts for the duration of each trip, including the downtime between trips. By dividing the total available time by the time required for each trip (including downtime), we can estimate how many trips a bus can complete in a single day.

$$Trips(Bus) = \frac{Operating\,Hours \times 60}{TD\,(minutes) + Downtime(minutes)} \quad (4)$$

Where ***TD*** stands to Trip Duration.
Next, the model calculates the daily distance traveled by each bus **(5)**. By multiplying the number of trips per day by the distance of each trip, the model provides an estimate of the total kilometers covered by each bus daily.

$$Distance(\frac{day}{Bus}) = Trips(Day/Bus) \times Distance\ per\ trips\ (km) \quad \textbf{(5)}$$

At this step the model calculates the daily emissions produced by each bus **(6)**. It takes into account the total distance traveled by the bus and applies the relevant emission factor to estimate the emissions in kilograms, which are then converted into tonnes.
In the case of Casablanca, the fleet predominantly consists of two Euro VI-compliant diesel bus models , the Irizar i3 and the Mercedes-Benz Conecto LF ('Casabus Opéré Par Alsa', n.d.), both characterized by a **CO_2 emission factor of 1.374 kg/km** (Ribeiro and Mendes 2022).

$$Emissions\,(tonne) = \frac{Total\,Distance\,(\frac{Day}{Bus}) \times EF\,(\frac{kg}{km})}{1000} \quad (6)$$

Where ***EF*** is the Emission Factor.
After that the model scales the daily emissions per bus to account for the entire fleet of buses operating on a particular line **(7)**. By multiplying the emissions per bus by the total number of buses, the model provides the total daily emissions for all buses on that line.

$$Total\,Emissions\,(tonnes) = Emissions\,(\frac{Day}{Bus}) \times Nr_{Buses} \quad \textbf{(7)}$$

Where Nr_{Buses} Stands for Number of buses.

The climate adjustment factor ***(CAF)*** modifies the emissions based on environmental conditions, specifically temperature and precipitation **(8)**. If the temperature or precipitation exceeds certain thresholds, the emissions are adjusted accordingly. This step ensures that the model accounts for the influence of weather on emission levels.

$$CAF = 1 + (0.002 \times T) + (0.05 \times P)\ if\ P > 0 \quad (8)$$

where ***T*** is temperature and ***P*** is precipitation. The adjusted emissions **(9)** are then calculated as:

$$AE(tonnes) = TE\,(Day, Tonnes) \times CAF \quad (9)$$

Where the ***CAF*** is the Climate Adjustment Factor, ***TE (Day, Tonnes)*** is Total Emissions per Day in tonnes and ***AE (tonnes)*** is Adjusted Emissions per Day (tonnes)
Emissions data are then aggregated on both daily and monthly across all bus lines to enable comprehensive temporal analysis. These aggregated results are stored in a yearly emissions **(10)** data frame and used to generate detailed temporal profiles. The final outputs, illustrating both spatial and temporal emission patterns, are exported as Excel files for further analysis and reporting.

$$AE\,(Year, tonne) = \sum(AE\,(tonne) For\ each\ day\ in\ the\ year) \quad \textbf{(10)}$$

Where the abbreviation ***AE (Year, tonne)*** stands for Annual Emissions per Bus Line, and ***AE*** stands for Adjusted Emissions per Day.

3.4. Tramways emissions modeling

Tramway-related CO_2 emissions were estimated based on electricity consumption, with adjustments to account for climatic variability **(11).** The adjusted electricity consumption was calculated using the formula:

$$Adjusted\,Consumption = Consumption \times (1 + f(T,P)) \quad (11)$$

Where $f(T,\ P)$ represents the climate adjustment factor as a function of temperature ***(T)*** and precipitation ***(P)***.
Daily and monthly emissions for each tramway line are calculated by iterating through the climate data and applying emission factors to the adjusted consumption values **(12).** The results are aggregated, annual emissions are computed for each line, and the data are exported to Excel files for further use.

$$Emission\,(tonne) = Adjusted\,consumption \times EF_{electricity} \quad \textbf{(12)}$$

Where $EF_{electricity}$ denotes the emission factor for electricity.
The Casablanca tramway uses the Alstom Citadis model ('Casatramway', n.d.), an electric tram that forms part of the city's sustainable transport system, with a CO2 emission factor of just **0.003 kg/km**, it reflects the low environmental impact of electric mobility ('Calculation of CO2 Emissions | Transilien', n.d.).

3.5. Aggregation, Output & Validation

The final phase involved aggregating results into daily, monthly, and yearly emissions profiles.

Validation was conducted by comparing modeled transport emissions with monthly ODIAC satellite-derived CO_2 rasters. Emission layers were clipped using city boundaries, and both total and peak emissions were extracted to quantify the transport sector's share in overall urban emissions. This cross-validation provided a quantitative assessment of urban mobility's environmental impact and served as a basis for evaluating urban policy effectiveness.

3.6. Web mapping application development

The Web-Mapping Application is meticulously designed with a multi-layered architecture to effectively manage a wide range of functionalities, including advanced map rendering, comprehensive user management, and sophisticated data analytics. This flowchart clearly delineates each phase of the development process **(Fig.2)**,

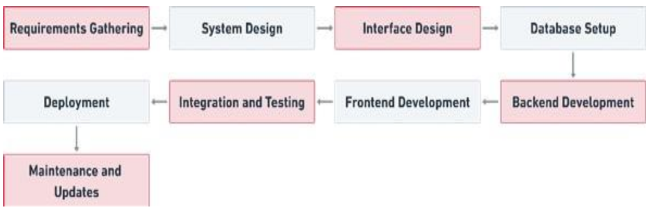

Figure 2 Development process of the web mapping application

starting from requirements gathering and culminating in maintenance and updates. The linear flow ensures that the progression of tasks is easy to follow, and it highlights the importance of each stage in contributing to the overall success of the project. By breaking down the process into these distinct phases, the methodology emphasizes thorough planning, development, and quality assurance, ensuring that the final product is robust and well-maintained.

It begins with comprehensive stakeholder interviews to gather detailed requirements for key components, including the homepage, emission calculator, login page, heatmaps, user management, data visualization, and real-time updates. Building upon these requirements, a modular system design is implemented, integrating components like the CO_2 emission calculator, user authentication, and interactive maps. Technologies such as PHP, MySQL, and Leaflet.js are employed to ensure robust functionality and responsive design. The user interface is crafted with a user-centric approach, emphasizing intuitive navigation and accessibility across all devices. Simultaneously, the database is structured to efficiently handle user data, emission calculations, and geospatial information. Backend development focuses on secure user authentication and accurate emission computations, while the frontend ensures a seamless user experience with real-time data updates. To validate system reliability, rigorous testing including unit, integration, and user acceptance tests is conducted. Deployment involves configuring the server environment, implementing security measures, and establishing continuous integration and delivery pipelines. Post-deployment, ongoing maintenance encompasses performance monitoring, regular updates, and incorporating user feedback to enhance features like heatmaps and emission calculators.

4. Results and Discussions

The results of this study provide a comprehensive overview of CO_2 emissions from various transportation mode in Casablanca over a five-year period, from 2019 to 2023 and residential electricity consumption for 2020. The analysis offers both monthly and yearly emissions data, allowing for a detailed temporal examination of emission patterns. Additionally, the study presents annual CO_2 maps of the study area, visually representing the spatial distribution of emissions across different areas within Casablanca providing a holistic view of the city's carbon footprint.

The Web-Mapping Application is developed to provide detailed insights into urban air quality by mapping emissions across various prefectures. It integrates advanced data visualization techniques with robust user and admin management features. The interface is designed to be intuitive, responsive, and highly functional, allowing users to easily explore spatial data, while administrators have detailed control over the application's functionalities.

4.1. Residential electricity emissions

This part presents a spatial analysis of carbon emissions resulting from household electricity consumption across different districts and prefectures of Casablanca, Morocco, during the year 2020 using the Moroccan provincial data. The analysis highlights the impact of population density and residential patterns on carbon emissions, providing crucial insights into the city's environmental footprint during a year marked by widespread home confinement due to the global COVID-19 pandemic. In 2014, the prefecture of Casablanca recorded 819954 households, with an average household size of 4.1 persons. This represents a significant increase from the previous census, which reported 639,201 households, indicating an average annual increase of 18,075 households ('Monographie de La Prefecture de Casablanca.Pdf',2018.) .

The map illustrates CO_2 emissions across Casablanca at a spatial resolution of 10 x 10 meters, offering a detailed view of emission patterns in the city **(Fig.3)**. A color gradient ranging from green to red is used to represent varying levels of CO_2 emissions: green indicates low emissions, yellow represents moderate levels, and red signifies high emissions. This high-resolution mapping enables precise identification of emission hotspots, revealing localized patterns at the level of individual city blocks or neighborhoods.

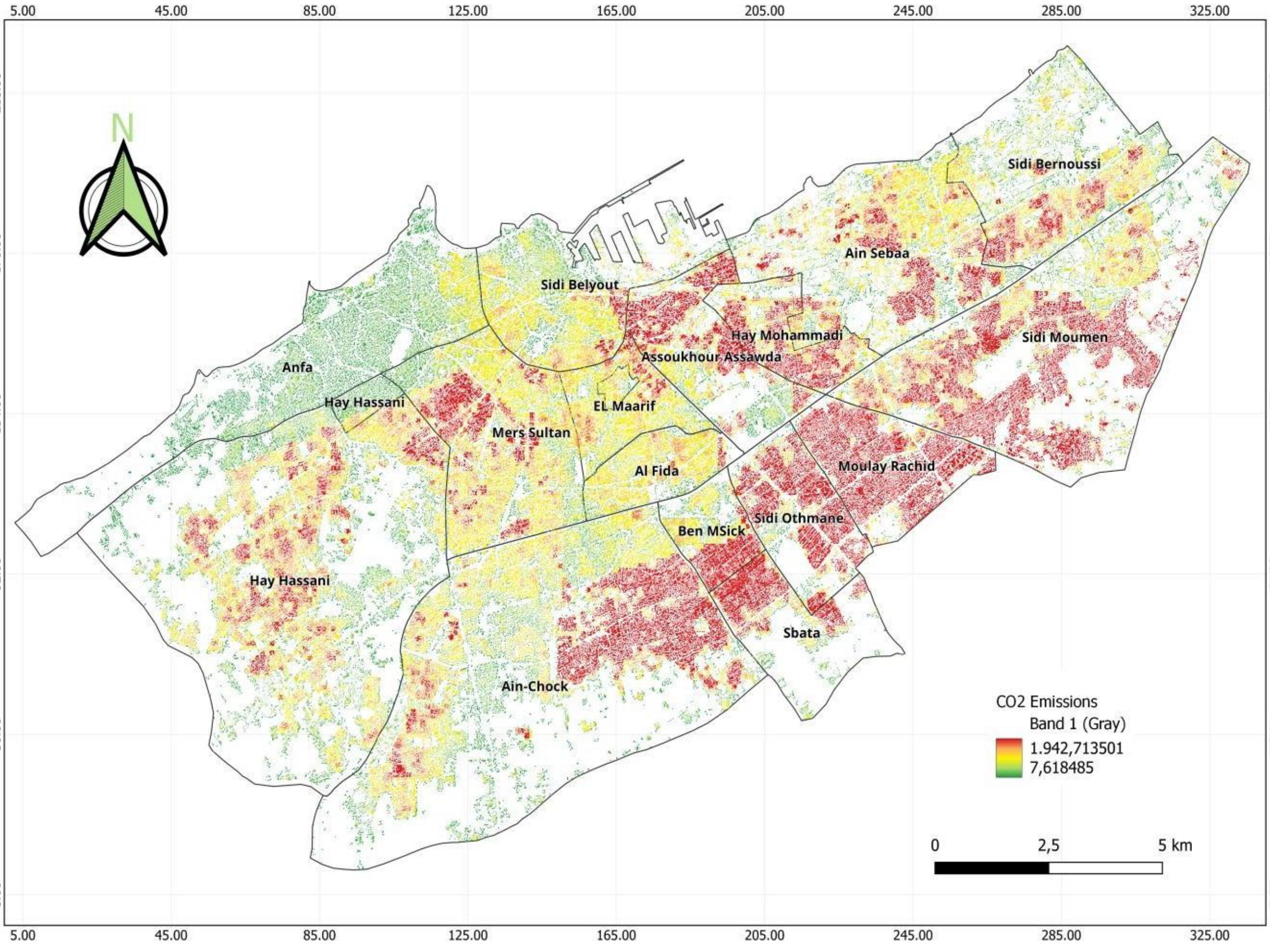

Figure 3 Spatial Distribution of CO2 Emissions in Casablanca

CO, emissions in the map range from ***1.942,713501 kg CO2/kWh*** to ***7,618485 kg CO2/kWh***. The Anfa district appears predominantly green, indicating lower emissions, likely due to its lower residential density and fewer energy-intensive activities. Similar low-emission zones are observed in parts of Hay Hassani, as well as around El Maarif and Sidi Belyout, suggesting a smaller contribution to the city's overall carbon footprint. In contrast, districts such as Moulay Rachid, Sidi Bernoussi, Sidi Othmane, and Hay Mohammadi are marked in red, indicating high emissions likely resulting from dense residential areas and elevated energy consumption. Several districts, including Hay Hassani, Ain Sebaa, El Fida-Mers Sultan, Ain Chock, and Sbata, show a mix of red and yellow, reflecting moderate to high emission levels. The yellow zones may correspond to a balanced mix of residential and commercial activities, while the red zones indicate areas with more intense energy use.

The results of the spatiotemporal analysis was as follow, Casablanca's CO, emissions varied significantly across its prefectures, with **Sidi Bernoussi** emerging as the highest contributor, accounting for **20.7%** of the city's total emissions equivalent to **124,492,864 kg CO, /kWh** due to its dense population of 452,863 and high household concentration of *103,310* ('Monographie de La Prefecture de Casablanca.Pdf',2018.).

Similarly, **Aïn Sbaa–Hay Mohammadi**, encompassing districts like Roches-Noires and Hay Mohammadi, contributed **18.1% (108,982,824 kg CO, /kWh)**, driven by a population density of *16,009* inhabitants/km² and over 56,000 households ('CasablancaCity.Ma - Portail Officiel de La Ville de Casablanca', n.d.).

Aïn Chock followed with **16.7% (100,603,440 kg CO, /kWh)**, spurred by rapid residential growth households surged by 64.3% from 2004 to 2014 (HCP, n.d.).

Hay Hassani, with 467,880 residents and 118,700 households ('Monographie de La Prefecture de Casablanca.Pdf', n.d.), contributed **14.4% (86,544,528 kg CO, /kWh),** reflecting the impact of both large household numbers and moderate density.

Moulay Rachid, one of the most densely populated prefectures at 22,890 inhabitants/km²('Monographie de La Prefecture de Casablanca.Pdf', n.d.), added **12.9% (77,454,872 kg CO, /kWh)**, while **Ben M'Sick,** with 131,883 residents and a staggering density of over 54,000/km² ('Monographie de La Prefecture de Casablanca.Pdf', n.d.-a), produced **37,197,580 kgCO, /kWh**.

Interestingly, **Al Fida–Mers** Sultan, despite being the second most densely populated area (41,800 inhabitants/km²)('Monographie de La Préfecture Des Arrondissements Al Fida Mers Sultan (Version Française).Pdf', n.d.), recorded comparatively lower emissions at ***33,517,262 kg*** ***CO_2 /kWh***, showing the complexity of the population-energy relationship.

Casablanca-Anfa, although a central and economically vibrant zone with 454,908 inhabitants across 37.5 km²('Monographie de La Prefecture de Casablanca.Pdf', n.d.-b), only contributed **5.3% (31,758,807 kg CO_2 /kWh)**, due to a focus on commercial rather than residential energy use. **Méchouar de Casablanca**, the royal and historical enclave with just 4,000 inhabitants('Monographie de La Prefecture de Casablanca.Pdf',n.d.-b), emitted the least **1,626,424.5 kg CO_2 /kWh** representing only **0.3%** of the city's emissions. These figures underscore how household growth, density, and urban structure collectively influence the spatial distribution of carbon emissions across Casablanca.

4.2. Private car's emissions

By applying a mathematical model to five years of private car usage data in Casablanca, this analysis captures the evolution of CO_2 emissions over time while uncovering spatial contrasts shaped by traffic intensity, urban form, and economic activity. In **2019**, emissions ranged from **1,271,234 tonnes in** february to **1,589,654 tonnes in** August. In **2020**, a sharp drop occurred, with values falling from **1,342,987 tonnes** in March to **264,312 tonnes** in April, before gradually rising again to **1,139,855 tonnes** in December. In 2021, emissions fluctuated between **891,234 tonnes** in April and **1,504,121 tonnes** in August, reflecting an uneven recovery. In 2022, values stabilized between a full return to normal, ranging from **1,299,845 tonnes** in January to **1,578,334** tonnes in August. These results highlight the combined effects of socio-economic dynamics and climatic conditions on urban carbon emissions. **1,314,654** tonnes in February and **1,589,763 tonnes** in August, approaching pre-pandemic levels. In 2023, emissions confirmed

In 2023, **Al Fida Mers Sultan** emitted approximately **3.5 million tonnes (Fig.4)** of CO2 with an average TTI of 2.63, reflecting the dense urban structure and persistent traffic congestion. Similarly, **Casablanca Anfa**, including **Sidi Belyout** and **Anfa**, recorded high emissions of around **3.5 million tonnes** and the highest TTI average of 3.30, due to intense economic activity and heavy traffic in central business areas. Moving to the northeastern side, **Sidi Bernoussi** known for its industrial character emitted over **2.8 million tonnes** with moderate TTI of 2.12, where emissions are largely driven by industrial sources rather than congestion alone. This industrial influence is also evident in **Hay Mohammadi - Ain Sebaa**, which followed closely with **2.7 million tonnes** and a higher TTI of 2.65, mainly due to industrial traffic and congestion hotspots.

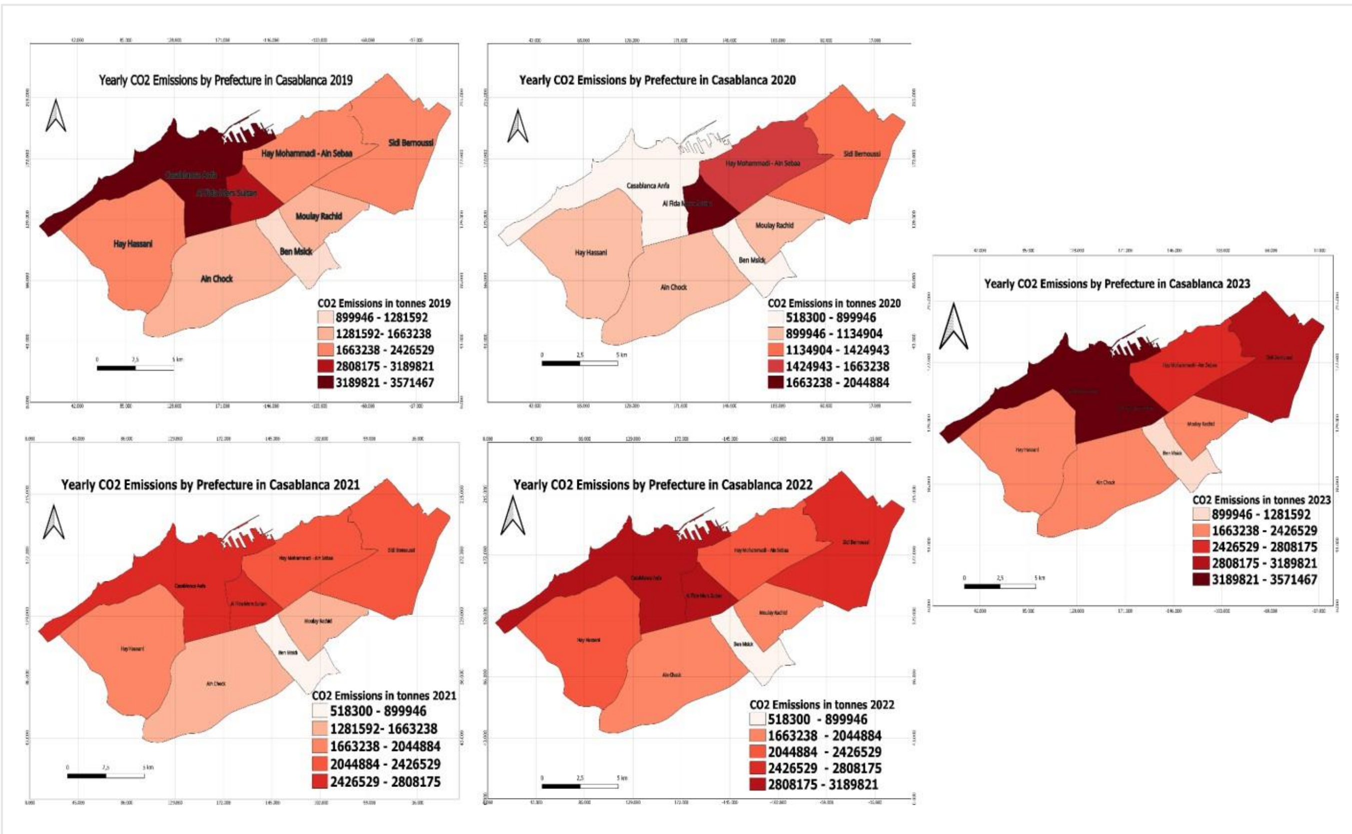

Figure 4 Spatial analysis of co2 emissions from cars (2019-2023)

Heading south, **Hay Hassani** reached **2.4 million tonnes** and a high TTI of 2.77, driven by its residential density and peak-hour commuting. Not far from there, **Moulay Rachid** emitted just over **2.2 million tonnes**, with a TTI of 2.12, reflecting a balance between residential and commercial activity. Continuing on to **Ain Chock,** the emissions reached around **1.9 million tonnes**, with a TTI of 2.14, impacted by traffic from schools and daily commuting.

Finally, **Ben Msick** though less congested still registered **1.9 million tonnes** of CO2 with a TTI of 2.00, consistent with its quieter residential layout and moderate traffic levels.

4.3. Taxi's emissions analysis

From 2019 to 2023, CO_2 emissions from taxis in Casablanca showed clear shifts influenced by major events and seasonal patterns. In 2019, emissions were steady, starting at around **99,000 kg** in January, peaking near **100,000 kg** in summer, then slightly dropping to **93,000 kg** in November and ending at **98,000 kg** in December. In 2020, due to COVID-19, emissions dropped sharply from **85,000 kg** in February to just **15,000 kg** in April during the lockdown. Summer levels stayed low, between **45,000** and **55,000 kg**, ending the year at around **60,000 kg**. Emissions gradually recovered in 2021, starting at **67,000 kg** and stabilizing around **80,000** to **83,000 kg** by mid-year. In 2022, levels neared normal, ranging from **55,000** to **59,000 kg** throughout the year. By 2023, emissions exceeded all previous years, with monthly values consistently around **98,000** and **100,000 kg** and peaking at **101,000 kg** in December, driven by increased travel and year-end activities.

The mathematical modeling results indicate a steady increase in CO2 emissions from taxis across different areas **(Fig.5)**, with a clear correlation to traffic congestion, urban density, and seasonal variations. In **Al Fida Mers Sultan**, emissions from taxis rose progressively from **120,000 tonnes** in **2019** to **175,000 tonnes** by **2023**. This upward trend aligns with a high TTI of 2.63, indicating frequent delays due to significant traffic congestion. The modeled data suggests that the dense urban environment of this area plays a crucial role in elevating emissions, with limited reductions despite attempts at congestion management.

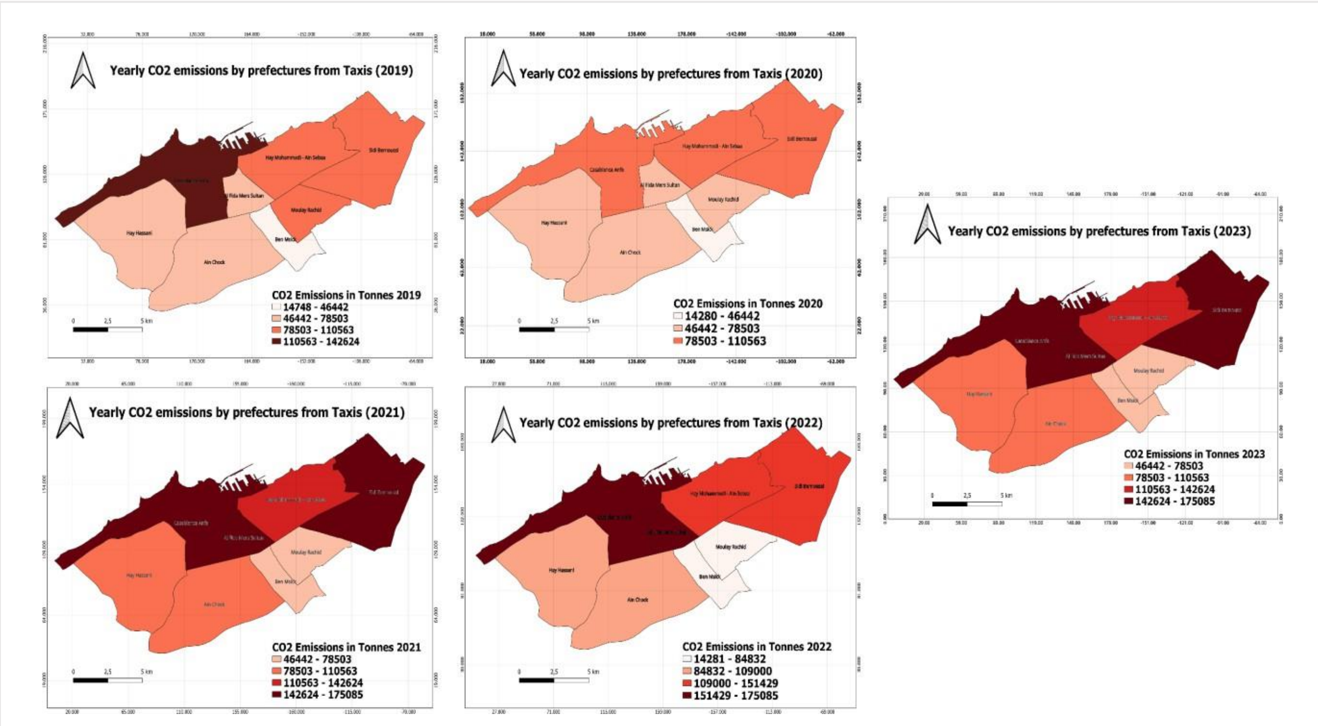

Figure 5 Yearly CO2 by prefecture from taxis

For Ain Chock, the emissions also followed a gradual increase from **100,000 tonnes** in **2019** to **140,000 tonnes** by **2023**.With a moderate TTI, the area's mixed residential and commercial profile contributes to moderate congestion. The model suggests that enhancing public transport options in **Ain Chock** could lead to a reduction in taxi emissions, as the current emissions are driven by the steady demand for taxis despite moderate traffic delays.

Sidi Bernoussi displayed the most significant emissions increase, from **150,000 tonnes** in **2019** to **175,000 tonnes** by **2023**. The area's industrial activities and a TTI of 2.12 suggest that both industrial transport and commuter traffic contribute substantially to the emissions. The model predicts that stricter industrial regulations and improved traffic management could significantly reduce emissions in this area. In Casablanca Anfa, the highest levels of emissions were recorded, reaching over **190,000 tonnes** in **2023**, up from **160,000 tonnes** in **2019**. The area's extremely high TTI of 3.30 reflects severe congestion, exacerbated by intensive commercial and business activity.

Modeling predicts that reducing congestion and improving traffic flow would be key to curbing emissions in this highly congested area. **Moulay Rachid** showed relatively stable emissions, with a gradual increase from **100,000 tonnes** in **2019** to **120,000 tonnes** in **2023**. The model attributes these emissions to residential and light industrial activities, with a moderate TTI of 2.12, suggesting less severe congestion compared to more central areas. The emissions in this area are expected to remain moderate unless significant urban expansion occurs. **Ben Msick** exhibited the lowest emissions profile, under **50,000 tonnes**, due to its lower TTI and relatively low traffic congestion. The model suggests that this trend will continue unless there are substantial increases in industrial activity or a rise in taxi usage. **Hay Hassani** saw emissions rise from **130,000 tonnes** in **2019** to nearly **170,000 tonnes** by **2023**. The high TTI of 2.77 reflects significant traffic congestion, and the model indicates that expanding public transport options could alleviate some of the pressure on taxis, reducing emissions in this densely populated area. Finally, **Hay Mohammadi - Ain Sebaa**, an industrial hub, recorded the highest emissions among all regions, increasing from **160,000 tonnes** in **2019** to nearly **200,000 tonnes** in **2023**. A high TTI of 2.65 reflects severe traffic congestion due to industrial and vehicular traffic. The model indicates that addressing both industrial emissions and congestion would be crucial in mitigating further increases in CO2 emissions in this area. Overall, these results underscore the need for targeted interventions to reduce emissions, such as improving public transport infrastructure, managing traffic congestion, and regulating industrial emissions.

With **10,600 taxis** operating in the city, the taxi sector remains a significant contributor to CO2 emissions, particularly in congested urban areas.

4.4. Buse's emissions analysis

The analysis of monthly CO2 emissions from buses in Casablanca from 2019 to 2023 **(Fig.6)**, reveals how operational practices, seasonal temperature fluctuations, and broader climate trends significantly influence urban emissions. In 2019, emissions were relatively stable, reflecting consistent bus operations across **700** buses and **53 lines**, with minor variations likely due to normal seasonal changes. However, the year 2020 marked a sharp departure from this pattern, driven by the COVID-19 pandemic. The drastic reduction in public transport usage, combined with milder weather that reduced the need for heating and cooling, led to a significant decline in emissions, particularly during the spring and early summer months when lockdowns were most stringent. As restrictions eased in **2021**, bus operations gradually resumed, resulting in a partial recovery of CO2 emissions. However, this recovery was uneven, with emissions fluctuating throughout the year.

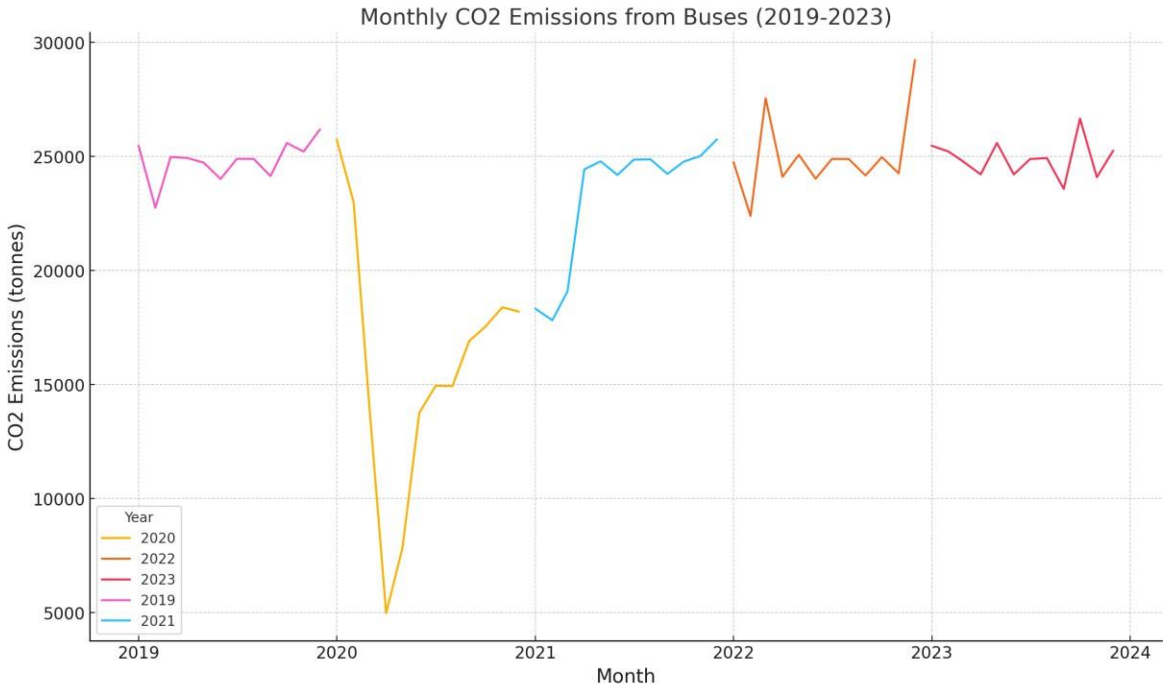

Figure 6 Monthly CO2 emissions from buses (2019-2023)

This variability can be attributed not only to the staggered return of public transport services but also to climatic factors, such as warmer-than-usual summer temperatures, which increased the demand for air conditioning on buses, traffic congestion, passenger demand and, consequently, fuel consumption and emissions. By 2022 and 2023, emissions data showed a return to more consistent levels, though still below the peaks observed in 2019. This suggests that while bus operations had largely returned to normal, there were potentially lasting changes in public transport usage patterns or improvements in the bus fleet's efficiency. Moreover, the analysis underscores the importance of considering both seasonal and longer-term climate trends in urban emissions studies. Rising summer temperatures and extended warm periods into autumn are likely contributing to a higher baseline energy need for cooling, which impacts fuel consumption across the fleet, Additionally, variations in precipitation, affecting road conditions and driving efficiency, also contribute to the variability in monthly emissions. In conclusion, the CO2 emissions from buses in Casablanca during this period are shaped by a complex interplay of operational dynamics, public health responses, and climatic conditions. As the climate continues to warm, the need for more climate-resilient and energy-efficient public transport systems becomes increasingly critical for controlling urban emissions and ensuring sustainable development in cities like Casablanca.

In **2019** the CO2 emissions across Casablanca's bus lines were indicative of the early stages of urban mobility expansion. For instance, bus line **L014**, which traverses **15.87 km** with **38 stops**, produced roughly **1150 tonnes** of CO2. This figure reflects the early challenges of managing emissions on medium-length routes in areas prone to moderate congestion. Line **L018,** stretching **13.23 km** and comprising **29 stops**, recorded emissions of around **1050 tonnes,** highlighting that even routes of moderate length and fewer stops can contribute significantly to the city's carbon footprint. The data from 2019 paints a picture of a city grappling with the balance between expanding its public transport network and managing the environmental consequences of increased bus activity.

The year **2020**, heavily influenced by global events, saw a distinct shift in CO2 emissions across the bus network. With mobility restrictions in place for much of the year, lines like **L008**, which typically spans **14.42 km** with **34 stops**, saw emissions decrease to approximately **900 tonnes**, reflecting reduced usage. However, the reduction was not uniform across all lines. For example, **L017**, covering **12.95 km** with **32 stops**, recorded emissions of about **950 tonnes**, suggesting that while overall mobility was down, certain routes remained heavily utilized due to their critical role in connecting essential services. Line **L019**, with a route length of **16.27** km and **36 stops**, produced around **1150 tonnes** of CO2, showing that longer routes maintained higher emissions even during restricted periods.

In **2021**, as the city began to recover from the disruptions of the previous year, CO2 emissions from bus lines surged in response to the resumption of regular activities. Line **L010**, with its **14.77 km** route and **35 stops**, saw emissions rise to approximately **1300 tonnes**, marking a significant increase as buses returned to full operation. Similarly, **L012**, stretching **17.82 km** and comprising **40 stops**, emitted around **1400 tonnes**, reflecting the combined effects of distance and an uptick in passenger numbers as public transportation returned to normalcy. By **2022**, the bus network in Casablanca was fully operational, with emissions reflecting a return to pre- pandemic levels. Line **L005**, emitted approximately **1350 tonnes** of CO2, underscoring the sustained impact of medium-length routes in congested areas. **L013**, recorded emissions around **1450 tonnes**, showing that routes with frequent stops continue to be significant contributors to urban emissions. On the other hand, **L024**, emitted approximately **1650 tonnes**, illustrating the ongoing challenge of managing emissions on routes that traverse extensive and densely populated areas. Shorter routes like **L031**, still managed to produce around **1150 tonnes** of CO2. Finally, **L035** emitted around **1600 tonnes**, reaffirming the pattern observed in previous years where longer, stop-heavy routes generate higher emissions. In **2023**, CO2 emissions for these lines varied significantly, with line **L006**, for instance, emitting approximately **1837 tonnes** of CO2, this bus line, demonstrates how an increased number of stops can lead to higher fuel consumption due to the frequent need for acceleration and deceleration, especially in dense urban areas where traffic congestion is common. The interaction between stops and traffic further exacerbates fuel consumption, as buses often spend more time idling or moving slowly, which is less efficient and results in higher emissions. Similarly, line **L007**, covering **11.73 km** with **26 stops**, recorded CO2 emissions of around **1635 tonnes**.

4.5. Tramway's CO2 emissions

The results illustrate the monthly CO2 emissions from tramways in Casablanca over a five-year period from 2019 to 2023 **(Fig.7).** The data is plotted as a continuous time series, enabling a comprehensive analysis of trends and fluctuations across these years. The tramway CO2 emissions remained relatively stable throughout most of the period, with notable fluctuations during 2020 due to the COVID-19 pandemic. In 2019, emissions ranged between **9.4** and **10.3 tonnes** per month, reflecting consistent operations. However, in **2020**, emissions dropped sharply, falling from 9.8 tonnes in February to just **1.8 tonnes** in April, coinciding with global lockdowns and reduced public transportation usage. As restrictions eased, emissions gradually recovered, reaching **6.3 tonnes** by December **2020**. The years **2021** and **2022** saw a progressive return to pre-pandemic levels, stabilizing between **6.2** and **9.5 tonnes** in **2021** and **9.5 to 10.2 tonnes** in **2022**, indicating growing public transport demand. By 2023, emissions closely resembled pre-pandemic patterns, ranging from **9.6** to **10.3 tonnes** per month, though slight variations suggest ongoing operational adjustments or shifts in ridership. This overall trend highlights the significant impact of the pandemic on public transport emissions and the subsequent recovery phase.

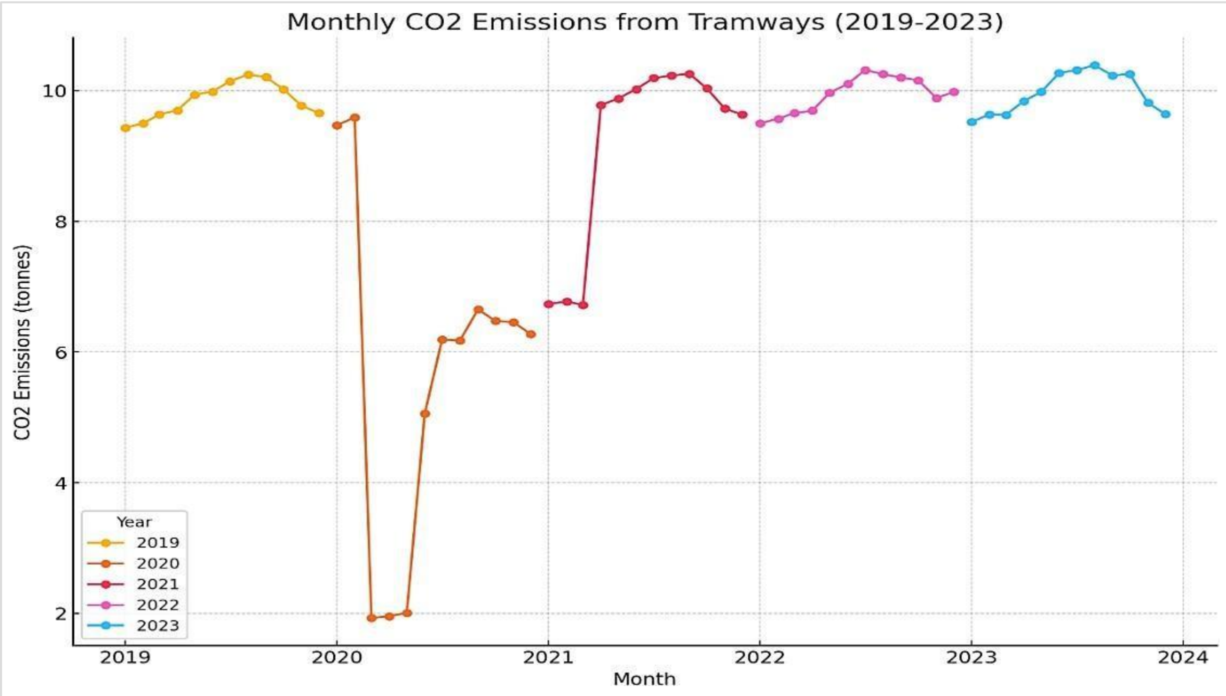

Figure 7 Monthly CO2 Emissions from Tramways (2019-2023)

The city's tramway network, specifically Lines **T1** and **T2**, contributes to the overall carbon footprint through its electricity consumption and resulting CO2 emissions.

Line T2 (Sidi Bernoussi - Ain Diab Plage), has a trip duration of **72 minutes** and operates with a frequency of **12 minutes** across **33 stations**, covering a distance of **22.5 km** at a speed of **19 km/h** (‘Casatramway', n.d.) **,** requires **20,929,692 kWh annually**, translating to a daily usage of approximately **57,333 kWh**. This leads to daily CO2 emissions between **0.172** and **0.218 tonnes (218 kg)**.

Line **T1** (Lissasfa - Sidi Moumen) spans **23.5** km, with **38 stations** and a travel time of **77 minutes**, offering **17 trips** per day(‘Casatramway', n.d.), has a higher electricity demand of **32,200,000 kWh** per year, equating to a daily consumption of about **88,219 kWh**, resulting in **0.265 tonnes (265 kg)** of CO2 emissions each day.

The variations in energy consumption and emission levels between these lines highlight their respective environmental impacts within the city's transportation system. These emission values, though reflective of the environmental impact of tramway operations, are considerably lower compared to emissions from other urban transportation modes, particularly those powered by fossil fuels such as cars and buses. According to the International Association of Public Transport (UITP), tramways significantly contribute to sustainable urban mobility by efficiently transporting large numbers of passengers with relatively low energy consumption per capita, thus serving as an eco- friendly alternative (‘UITP’, 2024). Furthermore, the European Environment Agency (EEA) emphasizes that electric public transport systems, such as tramways, can play a critical role in reducing urban CO2 emissions, especially when powered by renewable energy sources(‘Transport and Mobility’ 2025).

4.6. Transportation modes comparison

One of the most powerful insights from the past five years of CO_2 emission analysis in Casablanca is the massive gap between private car use and public transportation. While both contribute to the city’s carbon footprint, the numbers speak volumes:

Private cars emitted approximately **24,475,750.6 tonnes** of CO_2 , compared to just **5,591,221.1 tonnes** from all forms of **public transport** combined nearly five times more. This stark contrast highlights the crucial role public transportation plays in reducing urban emissions.

Despite serving thousands of passengers daily, public transit systems like buses, trams, and taxis operate with far greater energy efficiency. They produce significantly fewer emissions per person compared to private vehicles. According to the Victoria Transport Policy Institute, public transit modes such as buses and tramways emit far less greenhouse gas per passenger-mile than cars, making them a more sustainable choice for urban mobility (Litman, n.d.).

Moreover, when cities support public transportation with smart planning like transit-oriented development that encourages denser, mixed-use neighborhoods they can further cut down on the need for long commutes and reduce per capita emissions even more. This approach not only lowers CO_2 output but also helps combat traffic congestion and improves overall quality of life.

Encouraging a shift from car dependency to clean, efficient public transport, backed by supportive urban policies, is one of the most effective strategies for reducing a city's carbon footprint and building a greener, healthier future (Li et al. 2025).

4.7. Comparative analysis and validation

In contrast to laboratory-based studies which show that CO_2 emissions increase at lower ambient temperatures due to factors such as higher internal resistance and inefficient engine warm-up (as demonstrated in the WLTC tests across −10 °C to 40 °C) (Yachao Wang et al. 2022), the findings in this study reveal a positive correlation between temperature and CO_2 emissions in Casablanca from 2019 to 2023. This apparent contradiction can be attributed to the contextual differences between controlled experiments and real-world urban environments. While cold-start effects dominate in test cycles, urban-scale emissions are influenced by behavioral and operational factors, such as increased private vehicle usage during warmer months, higher air-conditioning demand, and elevated economic and social activity, particularly in summer.

The referenced study confirms that air conditioner usage alone can elevate CO_2 emissions by over 22% (Yachao Wang et al. 2022), aligning with the observed peaks in emissions during the hotter months in Casablanca. Moreover, for temperatures above 75°F (~24°C), studies have shown that emission increases are no longer related to engine start conditions but rather to air-conditioning loads and evaporative emissions (Choi et al., n.d.). These mechanisms likely contributed to the consistently high emissions observed in August of each year. Furthermore, while precipitation is known to influence traffic speeds, the literature suggests that its impact on emissions is limited and inconsistent(Hooper, Chapman, and Quinn 2014), explaining why no clear correlation was found between rainfall and CO_2 levels in this study. These findings underscore the importance of considering localized urban activity patterns and climatic context when interpreting emission trends beyond controlled vehicle testing environments.

To validate and contextualize our calculated annual transport emissions from private cars, taxis, buses, we will conduct a comparative analysis with satellite data extracted from the OCO- 2 Open-Source Data Inventory for Anthropogenic CO2 (ODIAC). This global high-resolution emission data product provides estimates of fossil fuel carbon dioxide (CO2) emissions in tonnes, offering a valuable external benchmark.

This comparison is crucial for understanding the contribution of mobility to the total CO2 emissions in the city and serves as a validation step to ensure the accuracy of our transport emissions calculations.

The charts **(Fig.8)** demonstrate a consistent pattern where fossil fuel emissions remain high across all months, with transport emissions constituting a notable portion of these totals. In this pre-pandemic year 2019, fossil fuel emissions were relatively stable, but transport emissions, while lower, followed a similar trend, reflecting steady usage of vehicles and public transport.

The year 2020, however, marked a significant reduction in emissions, particularly from March to June, coinciding with the COVID-19 pandemic lockdowns. This period saw a dramatic drop in transport emissions underscoring the sector's contribution to the overall emission levels under normal circumstances.

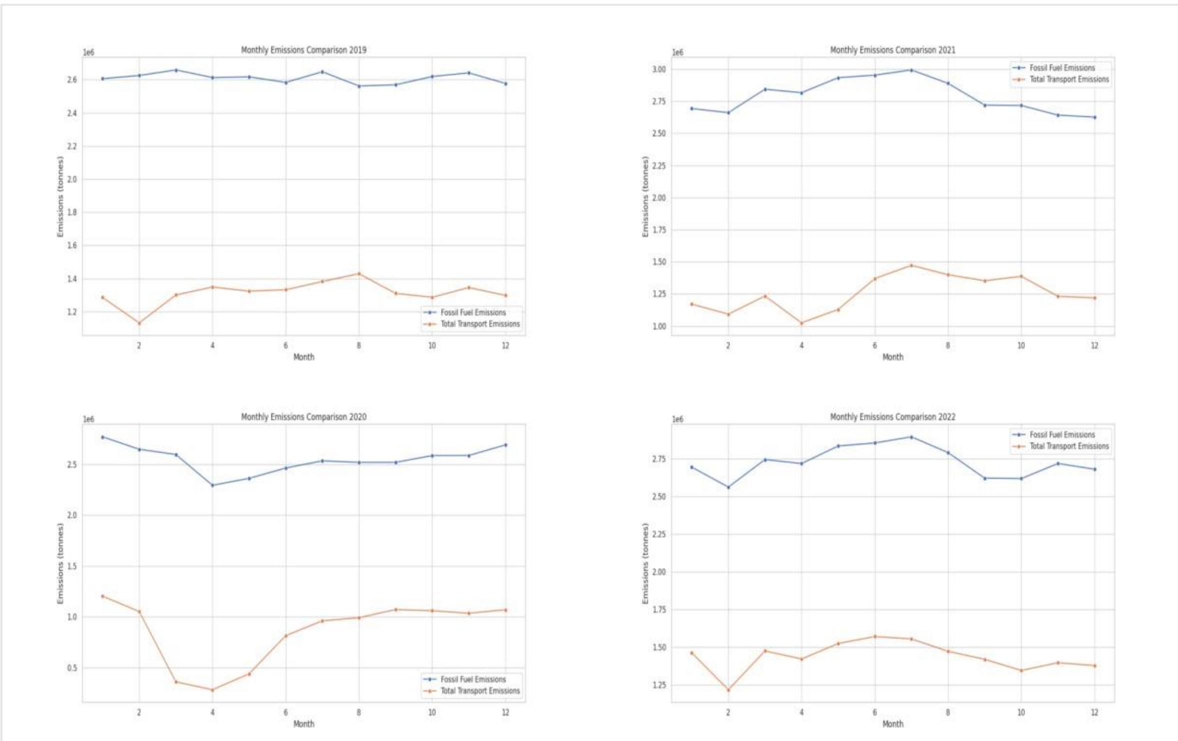

Figure 8 Comparison between transport and fossil fuel emissions

Fossil fuel emissions experienced a notable recovery in 2021, particularly during the mid-year period, as industries and economies gradually reopened following pandemic-related restrictions.

However, the chart also reveals some fluctuations, suggesting that the recovery process was not entirely smooth or consistent. Despite a significant increase from 2020 levels, total transport emissions remained below pre-pandemic figures, indicating a gradual return to normal transportation activities.

The persistent high levels of fossil fuel emissions in 2022, particularly during the middle of the year, indicate a return to typical urban activity and a continued reliance on road transport, which exacerbates CO2 emissions. This outcome aligns with the industrial profile of Casablanca, which, although a major urban center, is not heavily industrialized within the city boundaries themselves.

Casablanca's administrative division, comprising eight prefectures (Casablanca Anfa, Sidi Bernoussi, Ain Sbaa Hay Mohammedi, Al Fida Mers Sultan, Moulay Rachid, Ain Chock, Ben M'Sick Sidi Othmane, and Hay Hassani), does include some industrial areas, particularly in Ain Sbaa Hay Mohammedi. However, most heavy industrial activities, along with agriculture and forestry , are situated outside the city in areas like Mohammedia, Nouaceur, Médionna, Settat, and Benslimane, there is also large-scale industrial activities such as mining extraction and phosphate processing, particularly in areas like Jorf Lasfar These regions host significant industrial zones that contribute more prominently to regional emissions, while the city itself, being more focused on commercial , residential , heating and colling activities and sectors, sees transport as one of the major sources of emissions.

The data for Casablanca shows that transport emissions are a key contributor to the city's CO2 footprint, but they do not dominate the total emissions profile. This is consistent with the city's economic activities, which are centered more on services, commerce, and light industry, rather than the heavy industry or large-scale agriculture that would drive higher emissions elsewhere in the region.

4.8. Web mapping application

The results of the application demonstrate its effectiveness in providing an interactive and data-driven solution for assessing urban air quality and CO2 emissions in Casablanca. By integrating data from multiple sources, including traffic, climate, and energy consumption, the application allows users to analyze emissions across different sectors, such as transportation (taxis, buses, and trams) and other urban activities.

One of the key features is the **CO2 Emissions Dashboard**, which presents visual insights into emission levels by location and time, enabling users to easily identify high-emission areas in the city. Through **interactive heatmaps**, users can view the geographical distribution of emissions, which is crucial for urban planning and targeting specific zones for intervention.

The **Emissions Calculator** is another significant result of the application, which offers users the ability to input specific vehicle types, energy consumption, and other parameters to calculate real-time emissions. This tool helps users better understand the impact of various activities on the city's overall emissions. Additionally, the platform's **admin panel** allows for secure management of content and user access, providing a robust structure for administrators to monitor, update, and control data.

The **user panel**, on the other hand, ensures a personalized experience by offering tailored insights based on user preferences and inputs. The integration of **data security features**, such as user authentication and role-based access control, ensures that sensitive data is protected and that only authorized personnel can make updates or access specific information. Overall, the application not only serves as an informative tool for the general public but also provides valuable support to policymakers, urban planners, and environmental agencies in their efforts to reduce CO2 emissions and improve urban air quality in Casablanca.

5. Conclusion

The research presents an intricate and detailed study of CO2 emissions in Casablanca, with the most significant and challenging component being the mathematical modeling and calculation of these emissions. This element of the research is pivotal, as it involves the rigorous application of mathematical formulas and models to accurately estimate emissions from various sources, including private cars, buses, tramways, taxis, and residential electricity consumption. The complexity of this task is heightened by the need to integrate multiple data sources, such as traffic intensity, climate variables, and remote sensing data, into a cohesive framework that can accurately reflect the dynamic nature of urban air pollution. The mathematical models developed in this study are not merely academic exercises but practical tools that can predict CO2 emissions with high precision. For instance, the use of emission factors differentiated by fuel type, coupled with detailed transportation, climate data and travel time index, allows for the creation of models that can simulate real-world scenarios with remarkable accuracy.

The research meticulously calculates emissions on daily, monthly, and annual bases, taking into account the varying impacts of temperature, precipitation, and traffic congestion factors that are often overlooked in simpler models. One of the standout achievements of this study is the successful validation of the calculated emissions against ODIAC satellite data, which adds a significant layer of credibility to the results. This validation process demonstrates that the mathematical models developed are not only theoretically sound but also practical and reliable when applied to real-world data. The results of these analysis are presented in a variety of formats, including detailed maps and visualizations using GIS technics, which make the data accessible and actionable for stakeholders.

In conclusion, this study serves as a foundational framework for ongoing monitoring and future scenario modeling of CO, emissions in urban environments. Its methodologies and findings can be adapted to other cities facing similar challenges, making it a replicable model for sustainable urban development. By bridging the gap between scientific analysis and practical application, the research not only contributes to academic knowledge but also plays a pivotal role in guiding efforts to reduce emissions, enhance environmental resilience, and pave the way toward a low-carbon future for Casablanca and beyond.
In addition to the mathematical modeling, the development of an integrated web mapping application stands out as a major innovation of this research. This application is designed to facilitate interactive data sharing and visualization, making the complex results of the study accessible and actionable for a wide range of stakeholders. By incorporating the results of the mathematical models, the web mapping tool enables users to explore the spatial and temporal distribution of CO2 emissions across Casablanca, identify hotspots, and assess trends over time. The inclusion of a smart calculator within the application further enhances its utility, allowing users to estimate emissions from

various vehicle types and household activities, thus supporting more informed decision-making. The successful integration of these advanced mathematical models into a user-friendly web application demonstrates the practical application of the research, offering a powerful tool for the public to engage with and address the pressing issue of urban air pollution. This study not only advances scientific understanding but also provides practical solutions that can be adapted and applied in other rapidly urbanizing cities around the world.

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