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CO2 Emissions and Road Traffic in Paris: Study, Modelling and Visualisation for a Better Environmental Understanding

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The environmental impact of human activities is a major problem in today's society, attracting increasing attention in the world of research. Among these activities, road traffic stands out for its significant contribution to greenhouse gas emissions, particularly carbon dioxide (CO₂). These emissions play a crucial role in global warming, which is why it is so important to understand and quantify them. We have conducted an in-depth study to estimate CO₂ emissions from road traffic in the Paris metropolitan area and developed an intuitive visualization tool for these data. Our ultimate goal is to develop an eco-friendly navigation application guiding users along the most ecological routes. For this, we are planning to implement a hybrid deep learning (CNN-LSTM) model [16], whose architecture was outlined in our previous work. This model aims to use both historical and real-time traffic data for predictions. Yet, understanding the factors affecting CO₂ emissions on Paris streets, and how traffic reshapes these emissions, is an essential preliminary step. This article focuses on our algorithm for estimating CO₂ emissions in relation to road traffic in Paris. This in-house developed algorithm is used to generate data that we then analyse and visualise to derive meaningful information. We describe in detail the process of creating this algorithm: from the definition of the input parameters, through the various stages of calculation, to the management of the challenges associated with its construction.

However, the purpose of our prediction model is to provide more accurate interpretations of the data generated using our algorithm. Additionally, data visualization tools are crucial to make this information understandable and actionable. In order to better understand this data, we are using several types of visual representation. We will also show how these generated estimates are integrated into our visualisation application, providing users with an intuitive visual representation of the distribution of CO₂ emissions along the different roads in the city. Finally, we will discuss how our visualisation tool can be improved to enhance the user experience, improve understanding of the data and raise awareness of the environmental footprint of urban traffic.

Keywords: smart-city, environment, pollution, connected devices, data analysis, data visualisation

1. Introduction

The environmental impact of human activities is now a major issue in scientific research. Among these activities, road traffic stands out for its major role in the emission of greenhouse gases, mainly carbon dioxide (CO₂) [1]. These emissions make a significant contribution to the pollution of the air around us and to global warming, which is why we need to understand and quantify them better. More than 31% of greenhouse gas emissions in the Ile-de-France region are due to road traffic. [2].

In this context, we carried out research focused on estimating CO₂ emissions from road traffic in the Paris metropolitan area and on creating an intuitive visualisation of this data.

This article highlights two key aspects of our work:

- The development of our CO₂ estimation algorithm, in which we put forward the emissions factors and activity parameters of our calculation model.

- The design of our data visualization tool, in which we highlight the different visualization tools to offer a global perspective on CO₂ emissions.

With regard to the development of our CO₂ estimation algorithm, we first highlight the key factors in our dataset that enable us to design our CO₂ estimation model. We then compare our CO₂ estimation model linked to road traffic with the various CO₂ estimation calculation models available today [3,4,5,6]. Our comparison will focus initially on the input variables of our model. In this section, we set out the various road traffic metrics that enable us to obtain a static estimation of the CO₂ emission rate on the various roads, boulevards and avenues in the city of Paris.

Thus, we will detail all the parameters that have an influence on the estimation of CO₂ for each specific route. In addition, an in-depth comparison of our overall architecture with those of other applications performing similar tasks will be put forward. More specifically, we aim to juxtapose the approach adopted by our CO₂ estimation model with the approaches of various existing models in this field. This will enable us to analyse and understand the similarities, differences and potential opportunities for improvement.

Finally, we present the visualisation tool integrated into "GreenNav". This tool is equipped with precise functionalities such as interactive graphs, detailed maps, charts and explanatory tables, all designed to highlight and effectively monitor the rate of CO₂ emissions resulting from road traffic in Paris. We will also explore the improvements that have been made to these features, aimed at simplifying their use and providing users with a better understanding of the ecological impact of road traffic.

2. State of the art

With a view to gaining a better understanding of the impact of road traffic on CO₂ emissions, several applications and models have been developed and have proved their worth in their strategies for monitoring the rate of CO₂ emissions linked to road traffic.

- Copert [7] is an application developed by the European Environment Agency that is used to calculate greenhouse gas emissions and atmospheric pollutants from road transport. It takes into account various factors such as vehicle type, engine technology, ambient temperature, driving conditions, average speed and engine condition, i.e. whether the engine is cold or warm. All these factors are used to determine EF emissions factors such as road traffic, weather and the engine technology used. In this way, the COPERT model estimates the CO₂ emissions linked to road traffic by multiplying the level of activity by a specific emission factor. In summary, the method for calculating the CO₂ rate of the Copert model can be formulated more simply as follows [8]:

$$E = A * EF$$
 - E represents the total amount of CO₂ emissions.
 - A is the level of activity, which can be measured by the amount of fuel consumed or the number of kilometres driven.
 - EF is the emission factor.
- AirParif [9] is an air quality monitoring organisation that has developed a graphical interface enabling users to view air pollution levels in Paris and the Ile-de-France region in real time. Airparif's system relies on a vast network of sensors deployed in Paris to measure a range of emissions, including fine particles (PM_{2.5}, PM₁₀), sulphur dioxide (SO₂), ozone (O₃) and nitrogen dioxide (NO₂). These data are then processed, and estimated concentrations are made available to users in the form of interactive maps and graphs. However, the emissions measured by Airparif take into account emissions from all sectors of activity: residential and tertiary, agriculture, manufacturing industry, road traffic, etc.
- On the initiative of Airparif, the HEAVEN project [10] aims to focus on a single sector of activity that accounts for more than 31%, namely road traffic. The aim of the HEAVEN project is to reduce the impact of road traffic on air quality. HEAVEN uses traffic data obtained in real time from counting loops, combined with meteorological information, to provide an hourly description of road traffic emissions. The model is based on the European COPERT methodology, which uses emission factors according to vehicle type, speed and ambient temperature.
- ADEME (Agence de la Transition Ecologique) [11] and CITEPA (Centre Interprofessionnel Technique d'Études de la Pollution Atmosphérique) [12] are two French institutions that play a significant role in monitoring and reducing greenhouse gas emissions, including CO₂ emissions from road traffic. It should

be emphasised that neither ADEME nor CITEPA have a specific model for estimating CO₂ emissions from road traffic in real time. Their estimates are therefore based on statistical data and standard emission factors that do not take into account real-time variations in factors such as vehicle speed, driving style or weather conditions.

- Our eco-friendly navigation application, GreenNav, is currently focused on visualising traffic data to estimate CO₂ emissions on Paris's roads. We collect crucial information such as traffic volume, occupancy rate, average vehicle speed and fuel consumption by vehicle type. This data is used as input for our emissions calculation model. Our model is largely based on the COPERT and MOVES model [reference]. Designed to estimate pollutant and greenhouse gas emissions from road vehicles, COPERT also uses factors such as vehicle type, engine technology, driving speed and fuel consumption. Based on these principles, we have adapted and refined our CO₂ estimation model to suit our specific dataset and requirements.

3. Research methodology

3.1 Defining data in context

On the Paris network, traffic is measured mainly by electromagnetic loops installed in the roadway [13]. The construction of the Open Data Paris dataset is therefore due to a whole infrastructure of sensors that have been set up in the city of Paris to produce raw data. Using these sensor stations, which feed a large volume of data, we can gain an overview of the occupancy rate and traffic flow on more than 3,000 stretches of road [13]. In order to predict the rate of CO₂ emissions on the map of Paris, we first need to identify the dataset we are going to use. In this dataset, three types of data are highlighted: occupancy rate, road traffic flow and the status of road traffic:

- **The occupancy rate**, which corresponds to the time spent by vehicles on the road in question. For example, if we retrieve a value of 25% occupancy on a road, this means that during a time interval of 15 minutes the registered group of cars was present on the same road [13].
- **Road traffic flow** corresponds to the number of vehicles passing a counting point during a one-hour interval. For example, over a time interval of one hour, a flow of 100 vehicles passed along the study road.
- **The status of road traffic** corresponds to the state of road traffic during a time interval of one hour. Traffic can be categorised into 4 states: saturated, pre-saturated, fluid and blocked. This data is important in the context of our analysis, because with the same flow rate fixed, it can correspond to two different situations, as follows: "Fluid" or "saturated". For example, let's consider a one-hour period with a flow of 100 vehicles. If the occupancy rate on the road examined is high, this indicates that the road is close to saturation. On the other hand, if the occupancy rate is low, this suggests that traffic is flowing smoothly on the road.

However, the question arises as to how this real-time road traffic data is collected. In fact, this dataset is constructed using electromagnetic sensors installed in the pavement, which measure the number of vehicles present on a given road. There are two types of sensor stations that facilitate this data collection on the Paris network: [13].

- **Stations with dual functions**, which both measure the occupancy rate of traffic lanes and count the number of vehicles on the road. These stations provide very precise information on traffic conditions.
- **Flow stations** which only count the number of vehicles on the road. These measuring stations are less numerous in the traffic organisation and are generally located at the main intersections in the city of Paris.

These sensor stations, spread across the Paris road network, generate a rich dataset that we will use for our study. However, we asked ourselves the following question: how is this dataset, which contains a variety of types of information, structured and organised on Open Data Paris?

Our aim will then be to break down this complex mass of raw data, understand its internal structure, and identify the elements that are relevant to our research into CO₂ emissions. This understanding will enable us to efficiently identify and extract the relevant data for assessing CO₂ emissions on each road in the city of Paris.

3.2 Description of our data

After importing an 11-gigabyte segment of data from the Open Data Paris dataset into an xlsx file, we analysed the various elements of this data. To do this, we used data analysis and structural visualisation tools in Python, in particular the Pandas and Keras libraries. Analysis of this dataset revealed that the Open Data Paris dataset is structured as follows:



Figure 1 The data architecture of our dataset

By examining the various measures in the dataset, we were able to structure the information relating to road traffic, as illustrated in Figure 1. We then explained each element to describe its role and implication in the dataset, which we set out below.

- **Arc identifier:** A unique identifier representing a street or boulevard in Paris.
- **Arc name:** The name of the street or boulevard in question.
- **Count date and time:** The date on which counting of vehicles on the street or boulevard in question began. This date is in ISO format: YYYY-MM-DD HH-MM-SS.
- **Hourly throughput:** This is the number of cars present on a target street or boulevard in a one-hour interval.
- **Occupancy rate:** This is a percentage value that tells us how long the measurement station is occupied by vehicles over the course of an hour.
- **Traffic condition:** This value, represented by an integer, enables us to identify and classify the state of road traffic on the street or boulevard concerned. This value fluctuates between 0 and 4, with each number having a specific meaning relating to the state of the traffic: 0 for an unknown state, 1 for fluid traffic, 2 for a pre-saturated state, 3 for a saturated state and 4 for a return to fluid traffic.
- **Upstream node identifier:** A unique identifier representing an upstream road or boulevard.
- **Upstream node name:** The name of the upstream street or boulevard.
- **Downstream node identifier:** A unique identifier representing a downstream road or boulevard.
- **Downstream node name:** The name of the street or boulevard downstream.
- **Arc state:** This value, represented by an integer, provides us with information about the state of the arc in question. It varies between 0 and 3, each number having a precise meaning linked to the state of the arc: 0 for an unknown state, 1 for an open state, 2 for a closed state, and 3 for an invalid state.
- **Data availability start date:** This is a date that tells us when the data captured by the sensor stations will be made available.
- **End of data availability date:** This date tells us when the data captured by the sensor stations will no longer be available.
- **Geo_point_2d:** These are the 2d coordinates representing the road or boulevard in question.
- **Geo_shape:** These are the start and end coordinates of the target route we are analysing and describing.

3.3 Description of our co2 estimation algorithm

We have implemented our CO₂ estimation algorithm, based on a case study scenario (Figure 2). This scenario explicitly specifies the route and time interval to be studied. Having defined our experimental framework, in the next section we identify the data that our algorithm will use as a parameter to estimate the CO₂ emission rate. We have therefore developed our scenario using the following types of data:

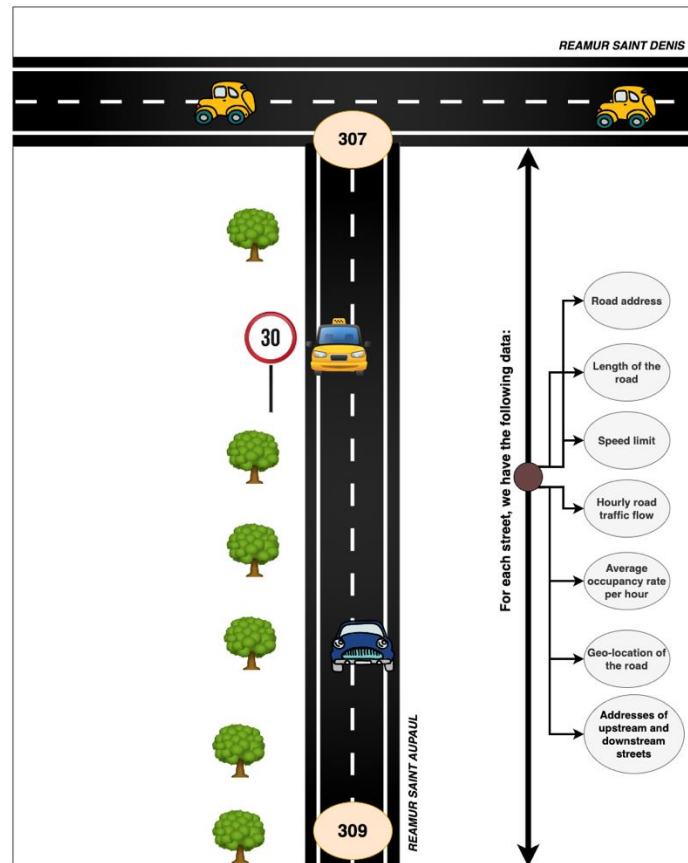


Figure 2. Experimental scenario on the REAMUR SAINT AUPAL road

- **Road address:** This parameter allows us to identify on a map the road that is the subject of our analysis.
- **Road length:** This is an essential parameter for estimating the distance that vehicles cover on a given stretch of road. The greater the distance, the greater the CO₂ emissions from vehicles. This measurement is obtained by calculating the distance between the start and end coordinates of the road.
- **Speed limit:** This parameter gives us a valuable indication of the average speed of vehicles on the road. By taking into account both the speed limit and the occupancy rate of the road, we can deduce the average speed of vehicles. This information is an important parameter in our co₂ estimation model, as speed has a significant influence on a vehicle's co₂ emissions [15].
According to the Barth and Boriboonsomsin study [14] this relationship can be summarised by a simple equation $E = f(v)$ where E is the CO₂ emission rate and v is the vehicle speed.
- **Road traffic flow:** This parameter is an important measure for estimating CO₂ emissions on a specific road [16]. Road traffic flow refers to the number of vehicles crossing a road over a given period. This measurement is obtained using electromagnetic sensors integrated into the road surface, which quantify the traffic flow [13]. This information provides us with an approximation of the number of vehicles contributing to CO₂ emissions on that road.
- **Average occupancy rate:** This parameter is also one of the strong metrics of our algorithm [16], as it describes the average percentage of car occupancy on the road being studied.
- **Geographical position of the road:** This parameter allows us to locate our study road on a geographical map. It can also be used as a means of generating other relevant parameters such as the length of the road and the speed limit.

- **Addresses of upstream and downstream streets:** This information allows us to determine the connections between the road under study and these adjacent streets. For example, for a vehicle to use street 'X', it must necessarily come from an upstream street 'A' and then head towards a downstream street 'B'. This information helps us to establish a network of streets, similar to a graph, where each node represents a street, and each edge represents a connection between two streets. It is important to highlight this parameter because the traffic on a given road is closely related to the traffic on adjacent streets, as demonstrated by Zhao et al. (2019) [17].

To sum up, by setting up our scenario for estimating the co₂ rate on a specific road, we were able to identify the data needed to develop our algorithm for calculating co₂ emissions from road traffic.

3.4 Models for calculating co₂ emissions

There are many complex models for estimating greenhouse gas emissions from road transport. According to the GPC [15,18], emission inventories for road transport can be carried out using two different methods:

- **The "bottom-up" approach** is based on calculating co₂ emissions from road traffic based on vehicle movements. This approach therefore requires richer data and offers finer spatial and temporal resolution. For example, the MOVES (Motor Vehicle Emission Simulator) software [18] uses different sources of data, such as odometer readings and scrap rates, to estimate CO₂ emissions for each class of vehicle.
- **The "top-down" approach** [15] is based on vehicle fuel consumption to calculate the rate of CO₂ emissions linked to road traffic. This approach uses large-scale aggregated data, such as total fuel sales for an entire region. It then makes assumptions to allocate these emissions according to the number of vehicles or the distance travelled.

Following this exploration of the different approaches to modelling CO₂ emissions, we will now further simplify our approach by focusing solely on the parameters related to road traffic. This focus will allow us to study the effects of these parameters on CO₂ emissions in a more specific and precise way.

- Simplified equation for the **MOVES** model [15, 19, 20, 21]:

$$TauxCo2 = \frac{Distance_{parcourue} \times Emission_{CO2}}{Taux_{occupation}}$$

Caption: *Distance parcourue* is the total distance travelled by the vehicle (expressed in km).

Emission CO₂ per kilometre is the vehicle's CO₂ emission rate per kilometre travelled (expressed in grams of CO₂ per kilometre). *Taux occupation* is the average number of people carried by the vehicle (expressed as people per vehicle).

- Simplified equation for the **NTM** (*National Transport Model*) [15,19,20,21]:

$$TauxCo2 = \frac{Distance_{parcourue} \times Emission_{CO2}}{Rendement_{\acute{e}nerg\acute{e}tique}}$$

Caption: *Distance parcourue* is the total distance travelled by the vehicle (expressed in km).

Emission CO₂ per kilometre is the vehicle's CO₂ emission rate per kilometre travelled (expressed in grams of CO₂ per kilometre). *Rendement \acute{e}nerg\acute{e}tique* is the fuel efficiency of the vehicle, i.e. the amount of energy used by the vehicle to cover a unit distance (expressed in MJ/km).

There may be a possible link between traffic volume, road occupancy and CO₂ emissions, particularly in busy urban areas. However, these connections are complex and can be affected by many other factors [15]. In densely trafficked areas, an increase in traffic flow and occupancy can lead to higher CO₂ emissions, notably due to traffic density and increased journey times. However, a high vehicle occupancy rate can reduce CO₂ emissions per passenger-kilometer. That said, the relationship between these variables is far from linear or direct, as many factors come into play, such as vehicle type, traffic speed, topography, CO₂ emissions per vehicle and weather conditions. To better understand these interactions, traffic and transport models can be used.

To construct our minimalist equation, we based ourselves on the main parameters that influence CO₂ emissions in road traffic. We will take a step-by-step approach to setting up our minimalist equation for estimating CO₂ levels using road traffic data.

First, the starting point is the relationship between the total CO₂ emission rate and the CO₂ emission rate per vehicle.

We can therefore establish the following equation:

$$(1) \quad EmissionTotal_{CO_2} = Débit_{trafic} \times Emission_par_véhicule_{CO_2} \times Distance_{Parcourue}$$

Secondly, our aim is to assess the rate of CO₂ emissions per unit of distance travelled, in other words per road. This means that we need to relate total CO₂ emissions to the distance travelled. This leads us to the following equations:

$$(2) \quad TauxBrut_{CO_2} = EmissionTotal_{CO_2} / Distance_{Parcourue}$$

$$(3) \quad TauxBrut_{CO_2} = Débit_{trafic} \times Emission_par_véhicule_{CO_2}$$

Thirdly, at this stage of our equation, we do not take into account the average occupancy rate of vehicles or the average speed of vehicles. In order to include these two parameters in our equation, we make the following two assumptions:

- As far as the average occupancy rate is concerned, we assume that the lower it is, the lower the CO₂ emissions per kilometre, because the lower the occupancy rate, the less time cars spend on the road and thus pollute the road in question. We therefore divide the CO₂GrossRate by the average occupancy rate.
- The average speed of road traffic also has an impact on CO₂ emissions. However, it is important to note that both very high and very low speeds can lead to an increase in CO₂ levels. We therefore divide the Crude_CO₂_rate by the average speed. This leads us to the following equation:

$$(4) \quad Taux_{CO_2} = \frac{Débit_{trafic} \times Emission_par_véhicule_{CO_2}}{Taux_occupation_moyen \times Vitesse_moyenne}$$

Caption: *Débit_trafic* represents the traffic volume on the road, i.e., the number of vehicles passing a given road section over a specific period (expressed in vehicles per hour). *Emission_par_véhicule_CO2* is the CO₂ emission rate per vehicle, expressed in grams of CO₂ per kilometer. *Taux_occupation_moyen* refers to the average occupancy rate of vehicles on the road. It represents the average number of passengers per vehicle. *Vitesse_moyenne* is the average speed of all vehicles on the road, expressed in kilometers per hour.

4. Experiment

4.1 Scenario description: Analysis of CO2 emissions on Rue Réaumur

In the following scenario, we will apply our analysis methods and visualisation tools to a specific scenario to illustrate the impact of our work.

This scenario focuses on a single street, rue Réaumur in Paris, on 15 August 2023. The aim of this choice is twofold. Firstly, we want to know the rate of CO2 emissions on Rue Réaumur at a specific time, in this case 4pm. Secondly, we want to understand how CO2 emissions change over the course of the day.

In this scenario, we will use our GreenNav application to analyse and visualise the data collected by the city's sensor network. This includes information on road traffic flow, road occupancy, road length, speed limits, as well as upstream and downstream street addresses. As well as estimating CO2 emissions, our application provides tools for analysing changes in road traffic flow and occupancy levels over the course of the day. As well as being intrinsically interesting, these factors will enable us to highlight correlations between road traffic and CO2 emissions. This can help us to identify the periods of the day when CO2 emissions are particularly high, and can also give us clues as to the factors that contribute to these emissions.

The application also includes visualisation tools to make it easier to interpret the data. For example, we can visualise CO2 emissions, traffic flow and occupancy rates on a map of the city or in graphs over time.

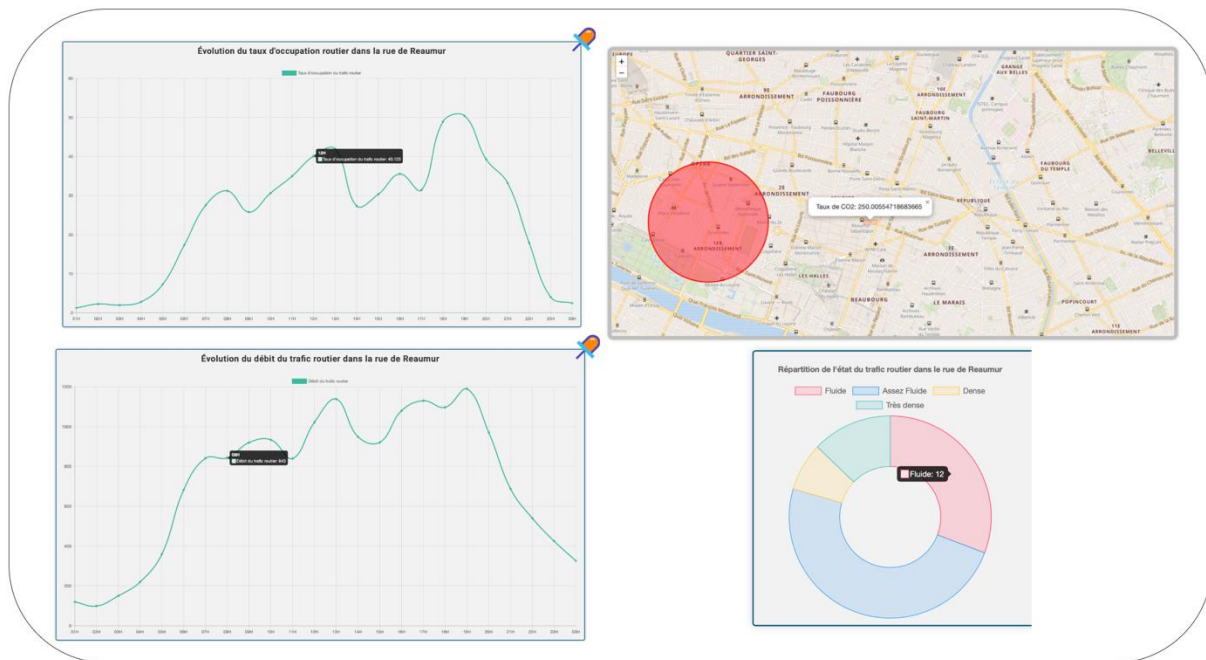


Figure 3. Data visualisation tools

In addition, our GreenNav web application includes a data filtering tool that is essential for the analysis of CO2 emissions. This tool uses algorithms to navigate efficiently through the large datasets provided by the Open Data Paris platform. It can filter this data according to a number of parameters such as: traffic status (fluid, non-fluid, saturated, blocked), CO2 emission levels, the name of the arc representing a specific street, the date of recording, road traffic flow and occupancy rate. This makes road traffic information such as traffic flow and occupancy rate particularly useful. It can be correlated with CO2 emission levels to identify trends or specific patterns. For example, we could investigate whether high levels of CO2 emissions are often associated with congested traffic or high occupancy rates. For example, if we are specifically interested in Rue Réaumur on 15 August 2023 at 4pm, where traffic is not flowing and CO2 levels are high, we can configure the filter to extract only the data that corresponds to this scenario. Filters can also be modified to allow comparisons between different traffic states, CO2 levels, or streets at different times or days.

In short, GreenNav's data filtering tool provides a personalised and accurate approach to analysing and understanding CO2 emissions in specific urban contexts.

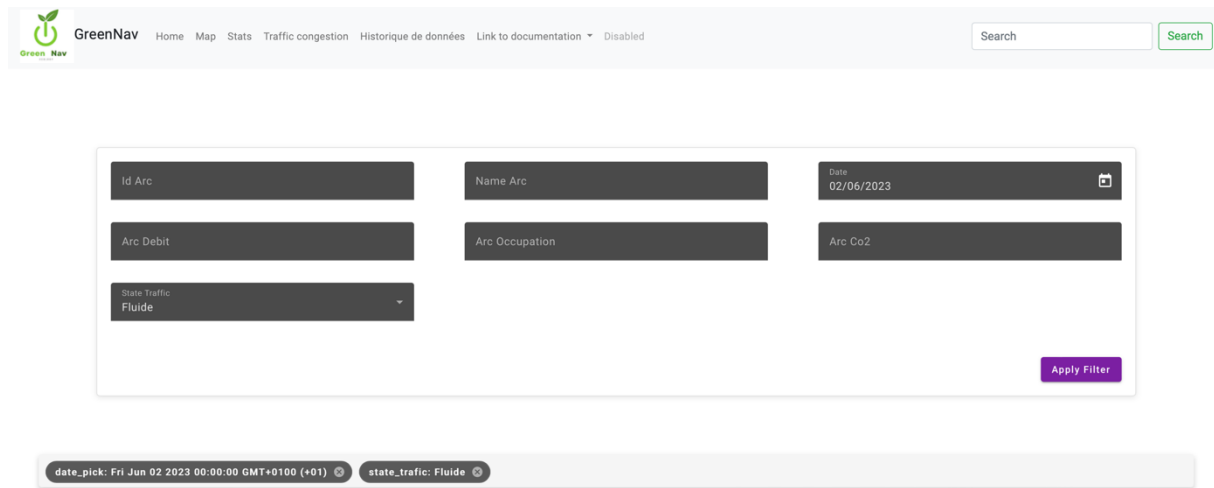


Figure 4. Filtering tool

In summary, this scenario aims to illustrate how our work can be applied to study CO2 emissions in a specific street, and how it can help to understand the links between road traffic and CO2 emissions. We believe that this knowledge could be very useful for efforts to reduce the environmental impact of urban traffic.

4.2 Interactive visualisation of road data: a tool for understanding the impact of traffic between different routes.

We have developed an interactive road data visualisation tool that provides an in-depth understanding of how traffic on one road can influence traffic on other adjacent or connected roads. This can be crucial in determining the most effective strategies for minimising CO2 emissions without unduly disrupting the flow of traffic in the city.

Num arc	Name arc	Date	Débit du trafic	Taux d'occupation	Taux de co2	État du trafic
553	Reaumur	2023-06-02T22:00:00+00:00	739	11.21333	262.0770695829577	Fluide
553	Reaumur	2023-06-02T21:00:00+00:00	617	9.88056	248.32634317623024	Fluide
553	Reaumur	2023-06-02T12:00:00+00:00	733	13.17889	221.1792242492855	Fluide
553	Reaumur	2023-06-02T11:00:00+00:00	656	11.36889	229.4589298808708	Fluide
553	Reaumur	2023-06-02T10:00:00+00:00	685	12.74167	213.788040866438	Fluide
553	Reaumur	2023-06-02T09:00:00+00:00	565	12.11611	185.44043151363485	Fluide
553	Reaumur	2023-06-02T08:00:00+00:00	554	12.00778	183.47049440723706	Fluide
553	Reaumur	2023-06-02T07:00:00+00:00	538	13.46556	158.88285869036764	Fluide
553	Reaumur	2023-06-02T06:00:00+00:00	343	12.42	109.82259796027911	Fluide
553	Reaumur	2023-06-02T05:00:00+00:00	170	3.21056	210.56555035051	Fluide
553	Reaumur	2023-06-02T04:00:00+00:00	103	1.82	225.05311355311355	Fluide
553	Reaumur	2023-06-02T03:00:00+00:00	107	1.71889	247.5454120585572	Fluide
553	Reaumur	2023-06-02T02:00:00+00:00	170	2.53667	266.5042490088712	Fluide
553	Reaumur	2023-06-02T01:00:00+00:00	279	3.71945	298.29410262269954	Fluide
553	Reaumur	2023-06-02T00:00:00+00:00	459	6.355	287.22108575924466	Fluide

Figure 5. Results of the Filtered Analysis of CO2 Emissions and Road Traffic

The visualisation is presented in the form of an interactive graphic. It includes a map of the city on which roads are represented by lines. Data relating to each road, such as traffic flow, occupancy rate and CO2 emissions, can be viewed by hovering over or clicking on the corresponding lines. In figure 6 we have based our example on three roads: rue Réaumur, boulevard saint germain and rue Réaumur st Denis. In this scenario, our visualisation would display these three roads on the map of Paris. By selecting one of these roads, for example boulevard saint germain, we would be able to see at a glance the traffic situation on this road and its CO2 emissions at a given moment.

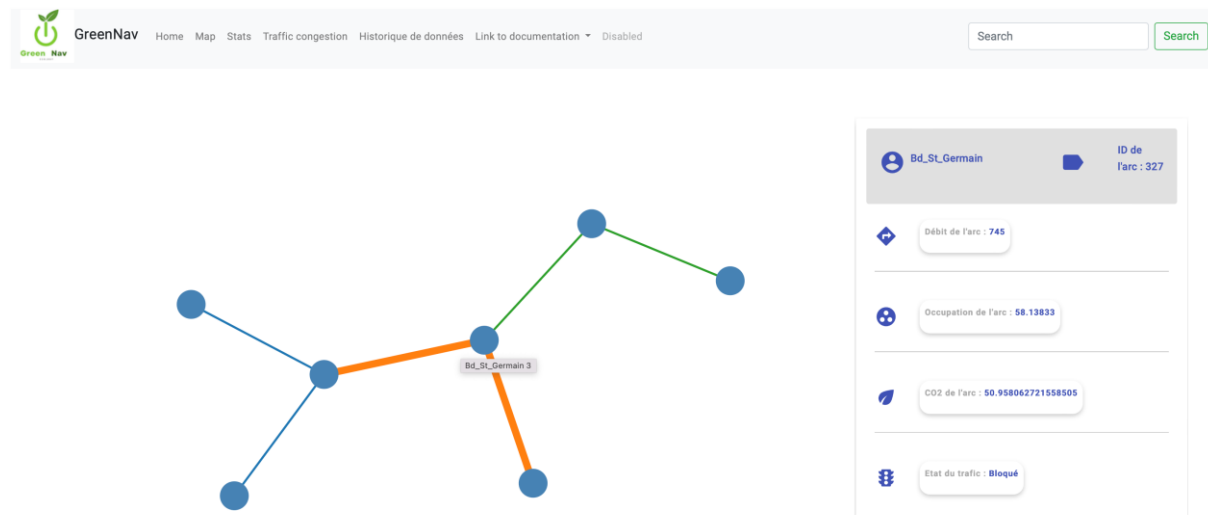


Figure 1. Interactive visualisation of road data: a tool for analysing traffic and CO₂ emissions

The advantage of this approach is that it makes it possible to understand the impact of traffic on one road on other connected roads. For example, if rue Réaumur is congested, this could have an impact on traffic on boulevard saint germain and rue Réaumur st Denis. Similarly, if traffic flows smoothly on rue Réaumur, this could reduce congestion on other roads. Our interactive visualisation is therefore a tool for understanding the interaction between the different roads in a city. By providing a clear picture of how traffic on one road can influence traffic on other roads, it can play a crucial role in planning strategies to reduce CO₂ emissions that are both effective and practical.

4.3 Comparison of Estimation Models and Visualisation Applications for CO₂ Emissions

4.3.1 Comparison of CO₂ estimation models:

In the table below, we compare our approach with three models that are widely recognised in the field of CO₂ emissions estimation: Copert [6], Moves [6] and NTM [5]. This comparison is based on various criteria such as accuracy, estimation scale, input data requirements and a brief description of the model. It should be noted that the accuracy and scope of GreenNav have yet to be confirmed by a large-scale test.

Model	Precision	Estimate scale	Input data	Brief description and comparison of the model.
Copert	High	National / Regional	<ul style="list-style-type: none"> - Number and type of vehicles. - Fuel consumption. - Engine technology. - Number of km/year 	This approach is based on the rate of emissions per kilometre travelled, which is suitable for large-scale analyses but may lack precision on a local scale.
Moves	Very high	Local / Specific vehicle	<ul style="list-style-type: none"> - Type and age of vehicle. - Driving style. - Fuel used. - Data on vehicle routes. 	Approach based on emissions per second of driving, requires very detailed data and can be complex to implement.
NTM	Medium to High	National / Regional	<ul style="list-style-type: none"> - Number of vehicles. - Distances covered. - Type of vehicle and fuel. 	May lack precision for small-scale or short-term analyses, but provides a good overview of large-scale traffic and emissions.
GreenNav	Still to be proven by a large-scale test.	Our study is based on a single city, Paris. Our analysis therefore covers every street and every arrondissement in the city.	<ul style="list-style-type: none"> - Road traffic flow - Occupancy rate - Average speed - Road traffic conditions - Fuel consumption per vehicle. 	Our approach is based on calculating the CO ₂ emission rate for each route. This means that we use the data for each route to estimate the rate of CO ₂ emitted on the route in question.

Table 1. Comparison of CO₂ estimation models

4.3.2 Comparison of CO₂ estimation visualisation applications

The table below compares our GreenNav application with two recognised visualisation tools: Airparif [10] and ADEME's Bilan Carbone [11]. This comparison includes criteria such as description, scale of use, type of tool and available visualisations. This will enable us to better understand the strengths and areas for improvement of our application compared with existing tools.

Application	Description	Scale	Type of tool	Visualisations available
Airparif	Airparif is an association approved by the French Ministry for Ecological Transition to monitor air quality in the Île-de-France region, including CO2 levels.	Île-de-France Region	Website/Web application	AirParif offers : <ul style="list-style-type: none"> - Interactive maps showing levels of CO2 and other pollutants. - Graphs of CO2 concentration over time. - Detailed data tables.
Bilan Carbone ADME tools	Bilan Carbone® is a methodology developed by ADEME to help organisations quantify their greenhouse gas emissions.	Organisation, sector, region, country	Software tool/ Methodology	ADME offers : <ul style="list-style-type: none"> - Dashboards with various emissions indicators. - Trend graphs and comparisons - Maps showing the geographical distribution of emissions.
GreenNav	GreenNav is a web application designed to enable users to observe the CO2 emissions linked to road traffic that are emitted on every boulevard and avenue in the city of Paris.	Île-de-France Region	Website/Web application	GreenNav offers : <ul style="list-style-type: none"> - Graphs over time, showing changes in the co2 emissions rate for each road in the city of Paris. - An interactive map showing the co2 emissions from the road. - This graph shows the link between CO2 emissions from upstream and downstream routes. - A dashboard showing various road traffic parameters, giving a better understanding of the relationship between road traffic values and co2 emissions.

Table 2. Comparison of CO2 estimation visualisation applications

5. Conclusion

As part of our research, we analysed the impact of CO2 emissions generated by road traffic in Paris conurbation using algorithms inspired by the MOVE, NTM and COPERT models. These models, which take into account various factors such as the type of vehicle, the fuel used, traffic speed and weather conditions, enabled us to establish relevant estimates of emissions. The visualisation tools we have developed have contributed to a better understanding of the dynamics of these emissions. These interactive representations of CO2 flows on different roads have highlighted the interactions between roads, as well as the impact of road traffic on the profile of CO2 emissions. Our work highlights the importance of modelling and data visualisation for analysing the environmental impact of urban traffic. By combining proven emission models with visualisation tools, we offer new perspectives for understanding and managing CO2 emissions from road traffic.

In addition, we want to enhance these visualisations by integrating real-time and historical data from APIs such as Airparif. In the long term, we plan to improve the accuracy of our forecasts by adopting a hybrid CNN-LSTM model [16]. This will enable our model to be trained with these historical and real-time data. Initially, this will give us a more accurate estimate of CO2, and at a later stage, it will contribute to the creation of a more accurate and reliable ecological navigation route.

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