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Exposed to NO_2 in the center, NO_x polluters in the periphery: evidence from the Paris region

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Abstract

Air pollution is the cause of many health problems. In cities, combustion vehicles are a major contributor to emissions of key air pollutants. While many studies have focused on populations exposed to pollutants and the resulting environmental and social inequalities, few compare exposures and contributions. In this research, the population of the Household Travel Survey of the Paris region is studied by confronting two elements: the average individual exposure to NO_2 during an average working day and the average traffic NO_x emitted during a day by the motorized trips for each resident surveyed. The dynamic exposure to NO_2 of each resident is estimated according to activities in an average working day. The results confirm an environmental inequality according to the place of residence: on average, the center residents contribute little to pollutant emissions but are highly exposed. Some categories of the population, including women and the socially disadvantaged, are the most affected by these inequalities.

Keywords: Urban Air quality; NO_x emission; NO_2 exposure; environmental justice; Paris Region; Air pollution

1. Introduction

The World Health Organization (WHO, 2018) estimates that 7 million people die each year due to poor air quality; according to recent research, globally this air quality is deteriorating (Shaddick et al., 2020). For this reason, the WHO has recently decided to lower its air quality thresholds (25µg/m³ 24-hour mean for NO_2)[1]. Most major European cities exceed the EU air quality thresholds, which correspond to the old WHO

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[1] https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health, visited on November 16, 2021

thresholds (40µg/m^3 for NO_2). Road traffic plays a central role in pollutant emissions in all cities (Setton et al., 2011). The challenge of reducing the impact of road vehicles on air quality determines a number of public policies. However, many studies already point to certain social inequalities in exposure to air pollutants, demonstrating the need for better knowledge and information on environmental injustices. In particular, a focus on the populations exposed to air pollutants and the populations contributing to them, within a territorial approach, is a necessary step in knowledge. Thus, the targeting of certain populations should help in the drafting of coherent public policies to reduce air pollution that are accepted by the population.

A very rich literature has focused on inequalities in the exposure of populations to air quality. The term "environmental justice" can be used to define the adequate distribution of populations faced with environmental impacts such as air pollution. It can also define a rebalancing of an environmental injustice through compensation, often financial. The study of exposed populations and in particular exposure inequalities mostly follows a standard method that crosses Census data at the scale of a large territory and maps of pollutant concentrations (Clark et al., 2014; Li and Myint, 2021; Mikati et al., 2018; Miranda et al., 2011; Samoli et al., 2019; Verbeek, 2019). One example of research conducts analyses over multiple years (Buzzelli et al., 2003), cross-referencing multiple censuses with changes in air quality in a city in Canada. Also over a long period, Guak et al. study exposure in Seoul over a long period of time by differentiating seasonality; they use a time location method and try to see whether there is a correlation between types of population and exposure (Guak et al., 2021). All of this research highlights the dual inequalities in income and NO_2 exposure among certain disadvantaged populations. These inequalities are confirmed by a literature review of environmental justice studies (Mohai and Saha, 2015). These authors confirm environmental injustice in sociopolitical, racial and economic terms. They also defend longitudinal studies that investigate whether emission sources are growing in disadvantaged neighborhoods or whether other population categories are leaving polluted areas. Other research points to a spatial inequality according to population density, with air quality declining as population increases (Borck and Schrauth, 2021; Li and Myint, 2021). Solutions to improve air quality in polluted areas are being studied: implementation of Low Emissions Zones, implementation of Toxicity Loads, reductions in vehicle speed, etc. However, in order to ensure that these measures are accepted and perhaps propose others, it is necessary to identify the contributors. Studies of the population of polluters are very uncommon in air quality research, which has only touched upon policy solutions to limit emissions at the origin, i.e., directed at the driver or at the planning policies that favor driving. Charging the pollution emitter, or at least redistributing some of the gains from air quality measures to those who do not benefit from them, is called distributional effects in economics. The topic of the link between air quality and industry has a long history (Gianessi et al., 1979) as the subsidy or tax policies on certain categories of vehicles (West, 2004). Economic reviews have also evaluated certain environmental policies with an impact on air quality, such as the diffusion of electric vehicles in the US (Holland et al., 2019). Inequalities in air quality purchases and gains are analyzed across population types. In the case of policy evaluation, the evaluation is performed against a current baseline situation. Our research is limited to an understanding of the current situation and a comparison between population profiles, and does not consider the temporal aspect. In the field of research on climate change prevention, studies are numerous (Fullerton, 2011), in particular on the adoption of a carbon tax (Wang et al., 2016) and its impacts on the budgets of poor households without compensatory measures, an effect that has been observed in France with the "yellow vests" and the non-acceptance of the measure by the middle classes, who are car-dependent. Few research studies jointly investigate exposures to air pollutants by population types and those emitting the pollutants (Jephcote and Chen, 2012; Mitchell and Dorling, 2003; Sider et al., 2015). In their UK-wide research, Mitchell and Dorling do not assess exposure by activity locations and focus on exposed populations. By crossing exposure with emissions, they only show that the poorest populations are the most NO_2-exposed populations and also the ones that emit the least NO_x. In Leicester, Jephcote and Chen point to the relationship between PM10 emissions from road traffic and hospitalization rates among children. They also show the environmental inequity of a situation where the wealthier populations in the center contribute the most to road PM10 emissions and have the least exposure to PM10. Sider et al. use a model of simulations at the scale of the Montreal metropolitan area to compare values of exposure, emission and a socio-economic indicator. They analyze by area and not by individual, calculating a polluter-pays index that masks the specificities of the territory. Their study shows that some socially disadvantaged areas are also more exposed to pollution, even though they emit little.

In conclusion, a large number of studies highlight the types of populations, often socially disadvantaged ones, that are most exposed to poor air quality. Some of them use a method of exposure assessment according to individual activities. In that research, pollution is seen as an exogenous negative factor that is not produced by the population itself. Few research studies attempt to compare the same population by its exposures but also by its emissions of pollutants in order to gain a new perspective on environmental injustices.

The objective of this research is to analyze and compare the socio-demographic characteristics of polluted populations and those of polluting populations on the same territory. We will focus on road traffic pollution with NO_2 exposure and NO_x emissions from private vehicles.

Our method is based on individual daily evaluations of spatial and temporal exposure to NO_2 on the one hand and of NO_x emissions from motor vehicles on the other. The individuals concerned are those from the Household Travel Survey (HTS), all of whose daily trips are provided, making it possible to reconstruct the detailed time use of the individuals and thus their exposure. These surveys also provide information on the technical characteristics of each household's vehicles and those used for each motorized trip. We also use pollutant emission models that simulate emissions per kilometer as a function of speed. This speed is estimated by a traffic model that gives us information on traffic conditions at different times of the day. Thus, we can reconstruct both the daily exposure of each individual to NO_2 but also these NO_x emissions if the individual uses a motorized vehicle for their trips. Each individual, whose socio-economic characteristics are known, is then associated with their average NO_2 exposure values during an average working day and with their NO_x emissions.

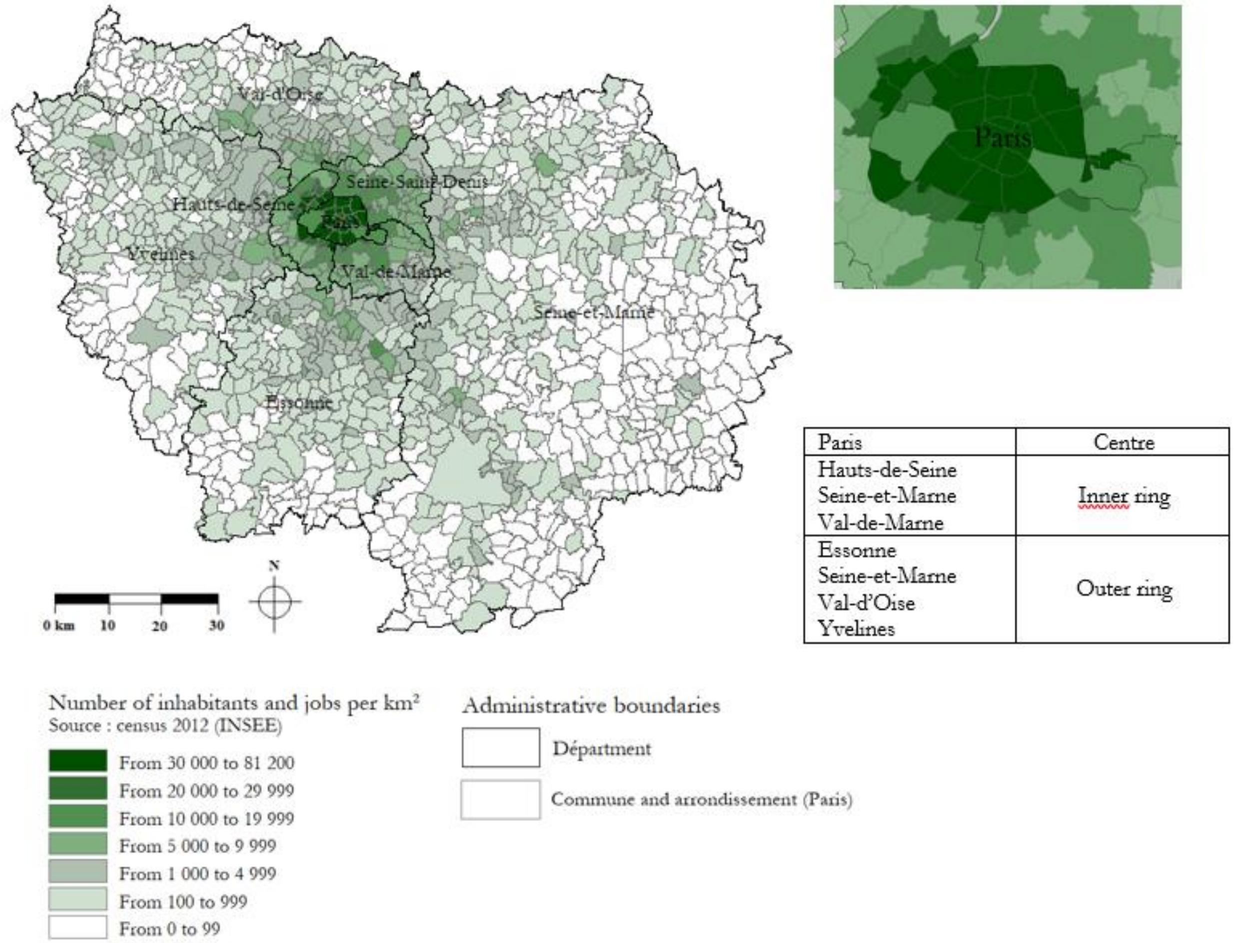
The rest of the article is divided into 3 parts. The first part presents the methodology in more detail with the exposure model and the emission model assigned to each individual applied to the Paris region. Part 2 presents the general results on the territory and then by individual profile. The last part outlines some of the limits of our approach and its possible perspectives for public policies.

2. Method and case study

2.1 The Paris Region

The Paris region (France) corresponds to the administrative region of Ile-de-France (Figure 1). 11.9 million people reside in the region. It is organized around the central city (Paris) and the inner ring (Hauts-de-Seine, Seine-Saint-Denis and Val-de-Marne), which form the center of the agglomeration in our study. This territory, which accounts for 6% of the total area of the region, concentrates 57% of inhabitants and 67% of jobs. The outer ring (Essonne, Seine-et-Marne, Val-d'Oise and Yvelines), accounting for the rest of the agglomeration, will be called the periphery in our study. Air pollution is an important issue in this area, with exceedances of the threshold of 40µg/m3 for NO_2 as an annual average for 1.3 million inhabitants (AirParif, 2018).

Figure 1: Human density (population and employment) of the Paris region by commune



Paris	Centre
Hauts-de-Seine Seine-et-Marne Val-de-Marne	Inner ring
Essonne Seine-et-Marne Val-d'Oise Yvelines	Outer ring

2.2 Why emission of NO_x and exposure to NO_2?

This research aims to contextualize NO_x emissions from road transport with exposure to NO_2, a pollutant that still far exceeds regulatory thresholds in European cities (Guerreiro et al., 2014) and has a significant impact on health and mortality in urban populations (Khomenko et al., 2021). One previous study has also compared emissions of and exposures to the same pollutants (Mitchell and Dorling, 2003). Other research confirms that NO_x emissions contribute to a significant portion of the NO_2 background concentration (Degraeuwe et al., 2017). To explain the NO_2 background concentration, emissions of all NO_X and not just NO_2 emissions need to be analyzed, due to the chemical reactions between NO and ozone that form NO_2 (Keuken et al., 2009; Wild et al., 2017). This same NO_2 then enables the production of ozone, a pollutant that also has significant health impacts (Khaniabadi et al., 2017). The relevance of assessing NO_x emissions is therefore obvious. We will focus on NO_x emissions from road vehicles excluding heavy duty vehicles. Also excluded from the scope of the study are emissions from airports (9% of emissions in the Paris region) and other more marginal emission sources (AirParif, 2018). The studied contributions of road transport (56% of the total in the Paris region, Airparif) are mostly emitted in the central part of the study area, which is the densest area (Figure 1) and therefore the one with the most impact on population exposure.

2.3 General method

The method followed in this research is based on an HTS. The description of the movements and activities of the individuals in this database allow the construction of spatio-temporal profiles which are used to evaluate exposure to NO_2 while the description of movements in individual vehicles allow the calculation of traffic NO_x emissions. Thus, the exposed and contributing populations are analyzed in a consistent way.

[redacted] NO_2 attribution method according to place of activity

The method for calculating NO_2 exposure focuses not only on residential locations in the assessment of average air pollution exposure but also on exposures at the place of activity, which may be in urban settings that are very different from the place of residence. These methods are increasingly applied using activity-based models (Beckx et al., 2009; Lu et al., 2019), but also survey data (Fenech and Aquilina, 2021; Park, 2020) or smartphone data (Li et al., 2021). Our methodology for calculating exposure is described in two previous studies (Poulhès and Proulhac, 2021; Proulhac and Poulhès, 2021). It consists in considering the exposure time spent on trips and those spent in activities, according to the time of the day. The method for calculating exposure during trips differs depending on the mode: (i) Because of the high uncertainty and the strong spatial variations of exposure, we do not consider the time spent in rail transport in the estimated average exposures (ii) In private motor vehicles, the exposures are calculated according to the itineraries simulated from traffic modelling (iii). For the other modes, namely buses, walking and cycling, we retain an average between the exposure at the place of origin and the exposure at the place of destination, since the accuracy of short-distance trips is not easy to obtain through modeling. For an individual i, the average daily exposure is therefore:

$$E_i = \frac{\left(\sum_{T \in D_{iT}} E(h(T)) + \sum_{A \in D_{iA}} E(h(A))\right)}{\left(\sum_{T \in D_{iT}} t_T + \sum_{A \in D_{iA}} t_A\right)}$$

Where D_{iT} is the set of trips of individual i during the survey day and D_{iA} the set of activities. t_A and t_T are respectively the durations of activity A and trip T given in the HTS. $E(h(T))$ and $E(h(A))$ are the average hourly exposures during trip T and activity A. Both can be expressed by discretizing them by the hourly period corresponding to the concentration maps h over the entire duration of the activity/trip. Thus, $E\big(h(T,A)\big)$ can be expressed as the sums of the exposures over each of these periods: $E\big(h(T,A)\big) = \sum_{h \in h(T,A)} h.E(h)$ where $\sum_{h(T,A)} h = t_{T,A}$.

[redacted] NO_x contribution method

To assess the contribution of individuals in the HTS, we draw on the Diagnostic Energy Emissions from Mobilities method (Hivert and Morchoine, 1998) which calculates pollutant emissions from individuals in a household travel survey, and on a previous study that performs the same pollutant quantity assessments but only from a transportation model. Average individual emissions are then calculated on area of residence or area of employment (Kotelnikova-Weiler et al., 2017).

The total individual daily emissions C_i are the sum of the emissions from each trip. If the mode used for this trip is one of passenger vehicles, motorized 2-wheelers, and light-duty vehicles, the emission ratio r_{NOX} will be non-zero and informed by specialized databases of pollutant emissions. For all other modes, emissions are considered to be zero.

This ratio depends on the speed and the engine type of the vehicle ϑ_{iT} used for the trip. The speed depends on the traffic conditions at the time of travel on the itinerary. The HTS does not provide information about the itinerary, so we use the itineraries reconstructed by the transportation model, as in the method that calculates the exposure. Thus, we can define the simulated itinerary as a succession of arcs $a \in T$ on which the simulated average speed $v_a(h(T))$ depends on the travel time $h(T)$. Denoting d_a the distance of arc a

($d_T = \sum_{a\in T} d_a$, the distance of the itinerary in the model), total emissions can be calculated. They are normalized by the distances provided in the HTS, d_{HTS}, which is more robust:

$$C_i = \sum_{T\in D_T} \left(\sum_{a\in T} d_a . r_{NOX}(v_a(h(T)), \vartheta_{iT}) \right) \frac{d_{HTS}}{d_T}$$

2.4 The databases and external traffic model

[redacted]Household travel survey

Household travel surveys describe precisely all the trips made by each individual surveyed on a given day. The survey day corresponds to one day of an average working week (from Monday to Friday) excluding school holidays. In France, a standard survey protocol is used to standardize the fields between the cities surveyed and thus provides information on a number of characteristics of the trip and of the individual. The time and place of origin and destination of each trip are described precisely. In this way, time schedules can be reconstructed with activity locations and time spent on-site. Similarly, the travel modes used between two activities are accurately described even in the event of multimodality. For individuals who own motorized vehicles, the age of the vehicles and the engine type are provided. In addition to these detailed trip descriptions, the socio-demographic characteristics of individuals are provided (age, gender, socio-professional category, salary category, etc.) as well as their place of residence.

In the Paris region, the EGT (Enquête Globale Transport, Ile-de-France Mobilités-OMNIL-DRIEA) dating from 2010 provides information on the trips of 43,000 individuals who are representative of the region's resident population.

[redacted]Trafic model

In addition to the HTS, which provides detailed information on travel modes and schedules, a traffic model on the same spatial scale as the survey is used to simulate the expected itineraries of individuals using an individual motorized mode. These forecasting tools have the benefit of being calibrated with data from household travel surveys and also with observed traffic conditions on major roads. However, these large-scale models have the drawback of having limited network description data. For example, secondary roads are not described in the model. For long-distance trips, the itineraries are therefore fairly well represented. For short distances, however, the uncertainty is higher, so we use the survey distances in our emission calculations.

We use the DRIEA MODUS model from 2012, which simulates the daily trips made in the Paris region. We then estimate the traffic conditions on the road network that allow us to simulate the itineraries and speeds on the road sections represented in the model.

[redacted] Exposure map

In order to calculate average exposure levels, our method requires spatially detailed and dynamic exposure maps. The maps used are the results of simulations made by Airparif, the air quality agency of Ile-de-France which uses a suite of models to calculate pollutant emissions, a meteorological model, pollutant diffusion models and sensor data to calibrate their models. The calculated exposures correspond to the day of January 9, 2019, a working day which is a day excluding school vacations and with NO_2 pollution levels that are neither low nor high compared to the references over the region. This day chosen by Airparif corresponding to an average working day in 2019. Thus, apart from the date inconsistency due to a survey not yet updated, the exposure day is consistent with the typical day of the HTS. The spatial resolution of the grid is 10m in the center (around Paris), 25m in the inner ring and 50m in the outer ring. The temporal resolution is 1h for the whole day with a beginning time of 4 AM and an end time of 3h59 AM.

[redacted] External emission model

To calculate NO_x emissions from motorized vehicles, the emission factors of the European Copert 4 database are used (Ntziachristos et al., 2009). The focus is on the private road modes reported in the HTS. Thus, three categories of vehicle are considered (Table 1): passenger cars, light commercial vehicles and motorized two-wheelers. For each of these categories, emission ratios are distinguished according to the engine and the age of the vehicle. The emission levels are given according to the corresponding Euro standard. Thus, from Copert 4, the emissions per kilometer of an average vehicle in each of these subcategories are estimated as a function of vehicle speed. Studies have shown that the emission ratios in Copert are underestimated for average speed conditions with acceleration and deceleration and in cases of congestion. For example, over Paris, estimates made by Copert 4 are -16% lower compared to congested cases (Lejri et al., 2018). Other studies confirm the underestimation of Copert 4 in terms of NO_x emissions (Kousoulidou et al., 2013; O'Driscoll et al., 2016), whatever the Euro standard. However, uncertainties and variations between vehicles and traffic conditions render estimates very difficult. made also decided not to consider emissions from public transport, which cannot be estimated in an acceptable way at the individual scale.

Table 1: Vehicle categories for which NO_x emissions are calculated and their characteristics per vehicle

Type of vehicle	**Engine type**	**Date of purchase**	**Euro norm**
Private Car	Diesel/Gasoline/Hybrid/Liquid Gas		1/2/3/4/5
Light commercial vehicle	Diesel		1/2/3/4/5
Two-wheeler	Gasoline		1/2/3/4/5

3. Results

The attribution of daily average NO_2 exposure and NO_x emissions to each individual in a representative sample of the population of the Paris region can produce a large number of results. We will focus our efforts on the comparison between exposures and emissions, which is the least discussed topic in the literature. We will first present two maps that clearly show the spatial opposition between exposed and emitting populations.

3.1 Spatial mismatch exposed – polluter populations

Figure 2: (a) Left, map of average NO_2 per capita exposure levels by HTS draw area (b) Right, map of average traffic NOx per capita emissions by HTS draw area.

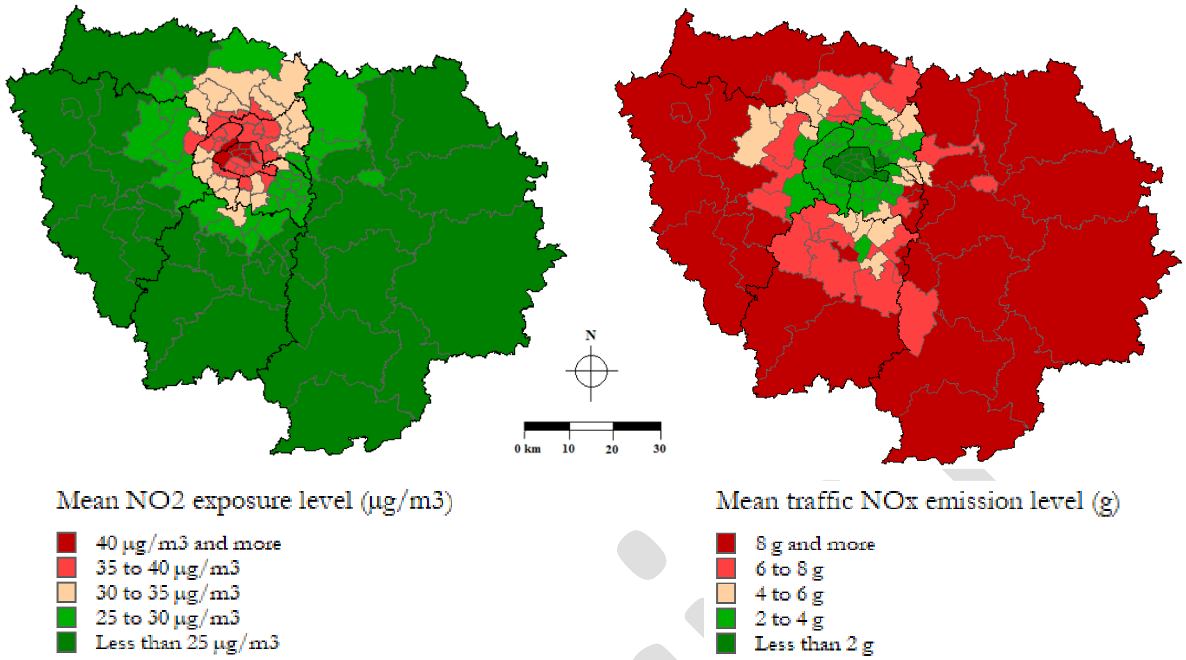


Figure 2a illustrates the spatial disparities of average exposure and the obvious gap between the center of the region with the densest districts of Paris (20,000 hab./m^2) and the more rural areas with rather low densities (500 hab./m^2?). The daily average exposure values increase from less than 25µg/m3 in the rural areas to more than 40µg/m3 in the center. It can be noted that this latter value exceeds the old annual thresholds of danger defined by the WHO (>40µg/m^3) but that all the territories in the region exceed the new annual thresholds (>10µg/m^3). As already confirmed by extensive research, populations in the densest areas are the most impacted by air pollution (Borck and Schrauth, 2021; Li and Myint, 2021). The map of individual emissions attributed to the place of residence (Figure 2b) mirrors average exposures. A ratio of 1 to 4 differentiates the center of the agglomeration where few residents use their car (15% only in Paris) from the outer territories which are highly dependent on the private car. These results are consistent with the double inequality of exposure of central populations to pollution that is mostly not their own, as pointed out by previous research (Singh et al., 2020). While the two maps have often been presented in different research papers either on exposure (Host et al., 2020) or on contributions (Bouzouina et al., 2013), to our knowledge they have never been presented at the same time from a common population.

3.2 Socio-economic results per profile

[redacted] Profile presentation

In this second part of the results, we propose to compare different profiles of the population that we characterize in relation to their use of the car, their place of residence and their place of activity. Four main profiles seemed to us to be the most relevant to compare. Table 2 presents these profiles. “Urban” is defined as a resident of the center of the agglomeration (Paris and inner ring) and “Peri-urban” as a resident of the outer ring, as shown in Figure 1.

Table 2: presentation of the population profiles studied

Name	**Description**	**Share of the total population**
Urban Pedestrian (UP)	Parisians and residents of the inner ring who did not use a car (or motorized two-wheelers) and who travelled only in Paris and the inner ring	33.6%
Urban Driver (UD)	Parisians and residents of the inner suburbs who made at least one trip by car (or motorized two-wheelers) and who travelled only in Paris and the inner ring	14.9%
Peri-urban Driver in Centre (PDC)	Residents of the outer ring who have made at least one trip by car (or motorized two-wheelers) between the outer ring and the center (Paris and inner ring)	5.0%
Peri-urban Driver in Periphery (PDP)	Residents of the outer ring who have made at least one trip by car (or motorized two-wheelers) and who have only travelled within the outer ring	20.5%

The objective is to be able to better differentiate the socio-demographic characteristics of the population, not only with respect to their place of residence but also with respect to their places of activity, and especially their mobility behavior. The main interest is to compare the populations in the center, who are the most exposed and who do not travel by car (UP), with the other types of populations who travel by car, namely those who also live in the center (UD) but also those who live in the periphery. Among the latter population, we differentiate between those who travel to the center of the agglomeration for activities (PDC), who have the highest impact on air pollution, and those who stay in the periphery (PDP). We have chosen to aggregate the populations of Paris and the inner ring for a better representation of the profiles. Even though the density is lower than in Paris, the urbanism of the inner ring is closer to that of Paris than to the periphery. Thus, through our profiles, 74% of the population of Ile-de-France is studied.

[redacted] Disparities between profiles

In 2021, the WHO defined a new threshold of dangerousness threshold of danger corresponding to daily thresholds not to be exceeded: 25µg/m³ in daily average (WHO, 2021). Then the population exposed to thresholds higher than 25µg/m³ of NO_2, will be referred, in the following article to as “the polluted”.

The profiles studied have very heterogeneous mean values of NO_x emissions and NO_2 exposure (Table 3). By definition, UPs do not emit NO_x in their daily trips. While UDs have a contribution to emissions almost proportional to their proportion in the total population, peri-urban residents contribute 2 times more emissions than their representation in the total population; additionally, their level of emissions is 2 times higher than the Ile-de-France average for PDP and 5 times higher for PDC. Conversely, the proportion of the population exposed above the thresholds is logically much higher in the population of the center than in the peripheral population (Borck and Schrauth, 2021), while it is also much higher for the population that does not travel by car than for the driving population. This overrepresentation is mainly due to the distribution of the demotorized population in the urban area. 30% of non-motorized trips are made by Parisians who are the most exposed (56% of the most exposed are Parisians, (Poulhès and Proulhac, 2021)) for 20% of the whole population. 80% of the Paris region residents are exposed to thresholds higher than the WHO of 2021 (25 µg/m³) and almost all the residents of the center (UP or UD).

Table 3: General results of average NO_2 exposure and average NO_x emissions by population profile

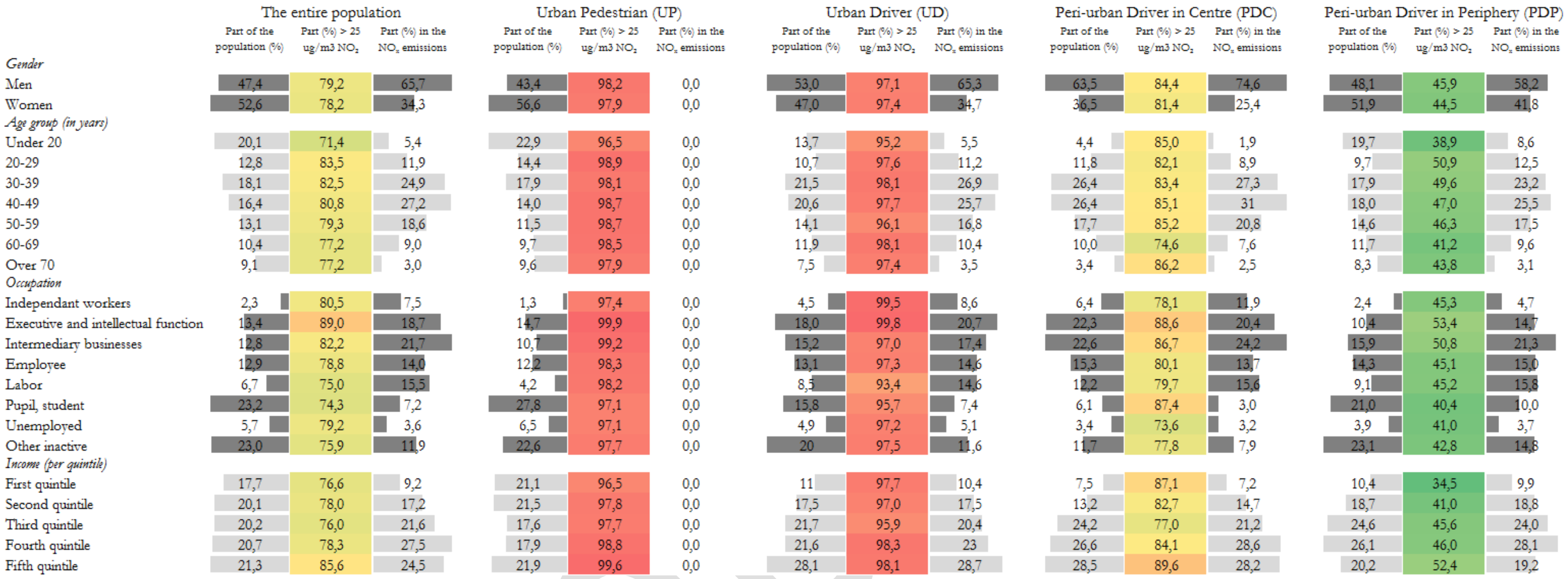
	UP	UD	PDC	PDP	Entire population
Average level exposure of NO_2 (ug/m3)	37.1	35.8	30.9	25.2	32.1
Population part (%) > 25 µg/m³ of NO_2	98.0%	97.3%	83.3%	45.2%	78.7%
Average emission level of NO_x (g/cap/j)	-	6.0	27.6	10.2	5.0
Part (%) in the total emissions	-	18%	27%	42%	100%
Distance/j/cap. By car and two wheelers	-	12.3 km	47.0 km	18.7 km	9.3 km

[redacted] Evidence of environmental inequality

The breakdown of the population of each profile into socio-demographic characteristics provides a more accurate view of environmental inequalities (Table 4). Overall, while the average exposure or the proportion of people exposed to hazardous values is quite homogeneous in each of the profiles studied, the NO_x contributions are very heterogeneous between the categories of population within the same profile. In this section, we propose to present the main results.

Among the population of the same territory, the differences in exposure and pollutant rates by population category are quite small. Conversely, individual contributions to NO_x are very unequally distributed from one individual to another, even within the same profile. Thus, there are strong inequalities. To begin with, the question of gender. Men emit twice as much NO_x as women and are just as likely to be polluted. In particular, among the PDC profile, we even obtain an emission factor of 3 between women and men, for a slightly higher rate of polluted for men. On the other hand, the proportion of polluted women in the UD profile is higher. By age group, the rates of polluted young and old people are the lowest in the total population, and their contribution to NO_x pollution is also very low: 5% for young people while they represent 20% of the population and 3% of old people for 9% of the population. Among the UP, the highest rates of polluted people are in the 50-70 years age group. Finally, the ratio of emissions by age group is roughly the same for each motorized profile studied. By occupation, working people obviously emit more than other categories, but there are heterogeneities between the categories of active people. The unemployed emit only 3.6% of NO_x for 5.7% of the total population and are 79.2% polluted. Conversely, workers emit a lot (15.5% of emissions for 6.7% of the population) and are less polluted (75%). Among the less unequal findings, the highest rates of polluted people are found among the upper social categories, which are also those who emit the most. By profile, the rates of unemployed and executives in the UP are the highest and the gap with the rest of the population of the profile is even higher for the UD. The over-representation of active people in the populations that travel by car confirms their predominant place among the emitters. Executives are particularly numerous in the profiles commuting by car in the center (UD and PDC), and less so in the suburbs. They therefore contribute even more to the high concentration of NO_2 in the center, while being less impacted by pollution (between 86 and 89% of PDC executives are polluted compared with 99% of UP). Finally, an analysis by income group confirms that the wealthiest populations are the biggest emitters (2/5 of the population for more than 50% of emissions). They have the highest average polluted rates, especially the wealthiest 1/5 of the population, with 85,6% compared to 77% on average for the rest of the population. This is logical because they represent a larger proportion of the population in the center of the agglomeration, which is more polluted. While the distribution of UDs is homogeneous among the income categories, the wealthy UDs are over-represented in the profile (50% for 2/5 of the population), in contrast to the poorest quintile which represents only 11% and contributes to only 10% of the emissions of the profile. Similarly, the peri-urbans who use their car to travel to the center (PDC) are in a large minority the poorest (20% of the population for the first two quintiles and also 20% of the emissions of the profile).

Table 4: Socio-demographic results per profile



	The entire population			Urban Pedestrian (UP)			Urban Driver (UD)			Peri-urban Driver in Centre (PDC)			Peri-urban Driver in Periphery (PDP)		
	Part of the population (%)	Part (%) > 25 ug/m3 NO$_2$	Part (%) in the NO$_x$ emissions	Part of the population (%)	Part (%) > 25 ug/m3 NO$_2$	Part (%) in the NO$_x$ emissions	Part of the population (%)	Part (%) > 25 ug/m3 NO$_2$	Part (%) in the NO$_x$ emissions	Part of the population (%)	Part (%) > 25 ug/m3 NO$_2$	Part (%) in the NO$_x$ emissions	Part of the population (%)	Part (%) > 25 ug/m3 NO$_2$	Part (%) in the NO$_x$ emissions
Gender															
Men	47,4	79,2	65,7	43,4	98,2	0,0	53,0	97,1	65,3	63,5	84,4	74,6	48,1	45,9	58,2
Women	52,6	78,2	34,3	56,6	97,9	0,0	47,0	97,4	34,7	36,5	81,4	25,4	51,9	44,5	41,8
Age group (in years)															
Under 20	20,1	71,4	5,4	22,9	96,5	0,0	13,7	95,2	5,5	4,4	85,0	1,9	19,7	38,9	8,6
20-29	12,8	83,5	11,9	14,4	98,9	0,0	10,7	97,6	11,2	11,8	82,1	8,9	9,7	50,9	12,5
30-39	18,1	82,5	24,9	17,9	98,1	0,0	21,5	98,1	26,9	26,4	83,4	27,3	17,9	49,6	23,2
40-49	16,4	80,8	27,2	14,0	98,7	0,0	20,6	97,7	25,7	26,4	85,1	31	18,0	47,0	25,5
50-59	13,1	79,3	18,6	11,5	98,7	0,0	14,1	96,1	16,8	17,7	85,2	20,8	14,6	46,3	17,5
60-69	10,4	77,2	9,0	9,7	98,5	0,0	11,9	98,1	10,4	10,0	74,6	7,6	11,7	41,2	9,6
Over 70	9,1	77,2	3,0	9,6	97,9	0,0	7,5	97,4	3,5	3,4	86,2	2,5	8,3	43,8	3,1
Occupation															
Independant workers	2,3	80,5	7,5	1,3	97,4	0,0	4,5	99,5	8,6	6,4	78,1	11,9	2,4	45,3	4,7
Executive and intellectual function	13,4	89,0	18,7	14,7	99,9	0,0	18,0	99,8	20,7	22,3	88,6	20,4	10,4	53,4	14,7
Intermediary businesses	12,8	82,2	21,7	10,7	99,2	0,0	15,2	97,0	17,4	22,6	86,7	24,2	15,9	50,8	21,3
Employee	12,9	78,8	14,0	12,2	98,3	0,0	13,1	97,3	14,6	15,3	80,1	13,7	14,3	45,1	15,0
Labor	6,7	75,0	15,5	4,2	98,2	0,0	8,5	93,4	14,6	12,2	79,7	15,6	9,1	45,2	15,8
Pupil, student	23,2	74,3	7,2	27,8	97,1	0,0	15,8	95,7	7,4	6,1	87,4	3,0	21,0	40,4	10,0
Unemployed	5,7	79,2	3,6	6,5	97,1	0,0	4,9	97,2	5,1	3,4	73,6	3,2	3,9	41,0	3,7
Other inactive	23,0	75,9	11,9	22,6	97,7	0,0	20	97,5	11,6	11,7	77,8	7,9	23,1	42,8	14,8
Income (per quintile)															
First quintile	17,7	76,6	9,2	21,1	96,5	0,0	11	97,7	10,4	7,5	87,1	7,2	10,4	34,5	9,9
Second quintile	20,1	78,0	17,2	21,5	97,8	0,0	17,5	97,0	17,5	13,2	82,7	14,7	18,7	41,0	18,8
Third quintile	20,2	76,0	21,6	17,6	97,7	0,0	21,7	95,9	20,4	24,2	77,0	21,2	24,6	45,6	24,0
Fourth quintile	20,7	78,3	27,5	17,9	98,8	0,0	21,6	98,3	23	26,6	84,1	28,6	26,1	46,0	28,1
Fifth quintile	21,3	85,6	24,5	21,9	99,6	0,0	28,1	98,1	28,7	28,5	89,6	28,2	20,2	52,4	19,2

4. Discussion

The specificity of Paris, with its overrepresentation of affluent people in the center, explains why the wealthiest populations are the most exposed to NO_2 pollution, in contradiction with certain previous studies on cities with different urban characteristics (Clark et al., 2014; Sider et al., 2015). In contrast, analysis of NO_x emissions confirms that the lowest emitters are the poorest populations (Jephcote and Chen, 2012; Mitchell and Dorling, 2003; Sider et al., 2015). Analysis of population profiles by mode used and by trip reveals specificities that are diluted in the average values. In particular, two profiles are particularly interesting: residents of the periphery who drive to the center on a daily basis, and those who live in the center and do not use a private car on a daily basis. The first group is polluting while being moderately exposed and the second group (33.6% of the total population) is highly exposed without contributing directly to their exposure.

This result leads to a first discussion on the gap in the study between the NO_2 exposure and NO_x emission calculations. Several methodological distinctions should be highlighted. The date difference between the 2011 HTS and the 2019 exposures should be noted, but living and activity locations as well as mobility practices have changed only slightly since 2011 as shown by the preliminary results of the new HTS (Omnil and Ile-de-France Mobilités, 2019). NO2 exposure and NOx emission calculations. Several methodological distinctions should be highlighted. Secondly, the HTS and the concentration map are based on a typical average working day, which is therefore consistent with each other, but poses difficulties with regard to the use of exposure thresholds as health risk indicators. Since 2021, the WHO considers a threshold of 25 μg/m^3 as a daily average, which must be compared with its annual average ambitious threshold of 10 μg/m^3. Thus, in the Paris region, 9 out of 10 residents are exposed beyond these annual thresholds (Airparif, 2021) and 8 out of 10 in our daily approach. This very low threshold makes it difficult to compare populations in the Paris region where concentrations are very often above 25 μg/m^3 in the center and in the periphery. To confirm our results on exposure, we also tested a threshold of 40 μg/m^3 which corresponds to the old WHO threshold in annual average. On the one hand, even if only 16% of the population exceeds this threshold, the populations that exceed the two thresholds the most remain the same with very few exceptions. On the other hand, the differences between the parts of the most polluted populations are more significant especially for the populations of the center.

NO_x emission values consider all sources of pollution without extracting the part corresponding to daily traffic while NO_2 concentrations by definition consider all emission sources, wherever they come from. In particular, the emissions of residents are considered in the study as non-emitters. Without emitting directly from the modes and trips under study, many indirect sources of emissions should be considered: (i) Emissions from other modes of transport such as buses, whose emissions are the responsibility of the community and the transport authority which is in charge of fleet renewal; (ii) Long-distance trips which are not part of the HTS perimeter and which contribute a significant proportion of NO_x emissions (37% of total driving distance in France (Nicolas et al., 2012)). However, they are mostly made in low-density areas and therefore have less impact on the population; (iii) Emissions due to heavy vehicle traffic, estimated at 30% by a study on NO_x in the Paris region (Coulombel et al., 2018), even if only part of the traffic is for local consumption; (iv) Air travel: according to Airparif, 9% of NO_x emissions come from airport hubs in the Paris region, of which only a portion is for resident travel. These important gaps in our method, which for the most part also relate to the way of life of the populations, are also present in other studies that associate NO_X emissions with a population (Bouzouina et al., 2013). If we consider that the rich consume more goods (Nielsen et al., 2021), fly more often and make more long-distance trips (Nicolas and David, 2009), adding these emissions into the balance sheet would further increase environmental inequalities between social classes.

Another important limitation is that emissions are not weighted according to where they occur. In the average balance, the emission does not depend on the population density, and a trip in the center can have as much impact as a trip in the periphery, whereas this is not the case in reality. The analysis by population profile makes it possible to distinguish between populations that make at least one trip to the center and populations that make no trips to the central area. This also raises questions about the urban dynamics and the future of these populations, who are highly dependent on private cars and who emit more than 40% of the region's NO_x emissions in our study. Beyond the obvious contribution to CO_2 emissions, NO_x emissions in the peri-urban area contribute to the diffusion of ozone, a pollutant that is also harmful to the health and predominant in rural areas (Betancourt-Odio et al., 2021).

For the calculation of the NO_x emissions, some assumptions were made. In the Copert database, the unit emissions depend only on speed and engine type, but other important factors are taken into account. The weight of the vehicle, as well as the cold start phases during which emissions are much higher (Suarez-Bertoa and Astorga, 2018) and the acceleration and deceleration phases are taken into account, although aggregated by an average value in the Copert emission factors. Thus, emissions from short and urban trips are underestimated in our results. Regarding NO_2 exposure, the accuracy of the exposure locations, limited by the size of the tiles of the exposure maps, but also that of the locations of presence in the HTS, only allows one to calculate exposure potentials. Our macroscopic approach does not enable use of street level diffusion models (Zhang et al., 2020). Similarly, during travel, the concentration of pollutants in the vehicle cabin is higher than outside, but the effort involved in walking and cycling causes pedestrians and cyclists to inhale more polluted air (Matthaios et al., 2020). A literature review confirms these results (Singh et al., 2021). Mass transit exposures, not considered in our study, are rather limited, according to other studies (Delaunay et al., 2012; Ramacher and Karl, 2020). The higher inhalation of pollutants by pedestrians and cyclists would be counterbalanced by physical activity in the overall impact on health (Cepeda et al., 2017).

Another important limitation in the quantification of exposure to air pollution among the population of an agglomeration with our method concerns the HTS in France. Household travel surveys in France do not survey children under 5 years of age, who are the most at risk from air pollution (Citerne et al., 2021). In the poorest populations, among the most vulnerable children, environmental inequalities are multiplied tenfold (Unicef and Réseau Action Climat, 2021). The effects of air pollution would also be multiplied by negative living conditions. Other sources of pollution should be considered in order to give a complete overview of the damage generated and suffered by the populations and to introduce the concept of exposome (Rappaport, 2011). In addition to other atmospheric pollutants such as fine particles, whose emissions and concentration levels are fairly well correlated with NO_2 (Samoli et al., 2019), noise is also a nuisance closely linked to road traffic with a strong impact on health (Münzel et al., 2021).

5. Conclusion and policy implications

This research has enabled us to relate exposure to an urban air pollutant which is hazardous to health, NO_2, to a proportion of the contributors of this pollutant: a large proportion of NO_x traffic emitters. A coherency between the two analyses is achieved by means of a HTS to finely evaluate NO_2 exposure with a spatio-temporal approach that considers travel and exposure at activity locations. Each motorized individual in the HTS contributes to NO_x emissions through his or her motorized trips as described in the survey. A spatial and socio-economic analysis then allows for an analysis of environmental inequalities.

The results confirm that the environmental injustice of exposure to air pollution is first of all a territorial injustice, with a large proportion of the population in the center of the Paris Region that does not emit NO_x and is particularly exposed to NO_2 pollution (Sider et al., 2015). Conversely, the populations of the periphery are very little exposed and very contributive to NO_x. Another social injustice is the fact that the unemployed and the lowest-income populations are the lowest contributors and are sometimes more exposed than other populations. Finally, the study of this pollution highlights a gender injustice, with women being over-exposed relative to their contribution.

These conclusions raise questions about two types of policies. Public mobility policies aim to restrict access to central areas by the most polluting vehicles with the deployment of a Low Emissions Zone, which can have an effect in terms of air quality (Holman et al., 2015) but which still present social inequalities (Poulhès and Proulhac, 2021). Other types of enforcement measures are also possible. A tax on the heaviest vehicles would be a more socially equitable solution than a carbon tax (West, 2004) or a subsidy for the purchase of less polluting vehicles (Tovar Reaños and Sommerfeld, 2018), as has already been done in many countries, but at a cost that remains high for the poorest households. It should be noted that the most readily accepted policies are those that address social justice (Boyce and Pastor, 2013; Zachmann et al., 2018).

Our results also allow us to discuss the urban planning policies that still favor urban sprawl. They are often criticized in terms of land artificialization, the carbon impact of motorized mobility, or the strong dependence on cars among modest households (Belton Chevallier et al., 2018). They are rarely analyzed in terms of impact on air quality or the opposition between residents in the center, who are demotorized, live in cramped conditions, and whose living conditions are degraded, and motorized households living in large spaces who cause the damage,. We can thus understand the vicious circle of the exodus of residents from the center to the peripheries in search of better-quality air. Consequently, car use and pollution in the center of the agglomeration are further exacerbated by a favorable peripheral urban context. Thus, policies to restrict car use in urban centers may be more acceptable but still reinforce the opposition between the center and the periphery. Only policies that are consistent between urban planning and transport and between center and periphery can resolve the escalation of territorial and social tensions due to environmental nuisances. Giving more authority to citizens, especially the poorest, to participate in the construction and improvement of their urban environment would limit the disaffection in certain urban areas (Faburel, 2008). In particular, renaturation projects and developing access to nature would limit inequalities with respect to air pollution (Jennings et al., 2021).

The recent context of the coronavirus epidemic and the constraint of having to work remotely, which has turned into an opportunity for many, may accelerate the abandonment of the center and its environmental nuisances in favor of peripheral or rural areas (Fijalkow, 2020). Will the reduction in motorized travel afforded by remote working be enough to reduce car use in areas where car dependency has never been questioned? Or will the need for motorized travel in these areas increase pollution and thus exposure among residents who remain in the center and who often cannot work remotely, and have precarious jobs? Beyond the research on the impact of remote working on exposure to air pollution, the question of its impact on pollutant emissions remains.

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