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► **To cite this version:**

Alexis Poulhès, Laurent Proulhac. Exposed to NO<sub>2</sub> in the center, NO<sub>x</sub> polluters in the periphery: Evidence from the Paris region. *Science of the Total Environment*, 2022, 821, pp.153476. 10.1016/j.scitotenv.2022.153476 . halshs-03578362

**HAL Id: halshs-03578362**

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Submitted on 1 Oct 2023

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# Exposed to NO<sub>2</sub> in the center, NO<sub>x</sub> 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<sub>2</sub> during an average working day and the average traffic NO<sub>x</sub> emitted during a day by the motorized trips for each resident surveyed. The dynamic exposure to NO<sub>2</sub> 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<sub>x</sub> emission; NO<sub>2</sub> 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/m<sup>3</sup> 24-hour mean for NO<sub>2</sub>)<sup>1</sup>. Most major European cities exceed the EU air quality thresholds, which correspond to the old WHO

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

26 thresholds ( $40\mu\text{g}/\text{m}^3$  for  $\text{NO}_2$ ). Road traffic plays a central role in pollutant emissions in all cities (Setton et al.,  
27 2011). The challenge of reducing the impact of road vehicles on air quality determines a number of public  
28 policies. However, many studies already point to certain social inequalities in exposure to air pollutants,  
29 demonstrating the need for better knowledge and information on environmental injustices. In particular, a  
30 focus on the populations exposed to air pollutants and the populations contributing to them, within a  
31 territorial approach, is a necessary step in knowledge. Thus, the targeting of certain populations should help  
32 in the drafting of coherent public policies to reduce air pollution that are accepted by the population.

33 A very rich literature has focused on inequalities in the exposure of populations to air quality. The term  
34 “environmental justice” can be used to define the adequate distribution of populations faced with  
35 environmental impacts such as air pollution. It can also define a rebalancing of an environmental injustice  
36 through compensation, often financial. The study of exposed populations and in particular exposure  
37 inequalities mostly follows a standard method that crosses Census data at the scale of a large territory and  
38 maps of pollutant concentrations (Clark et al., 2014; Li and Myint, 2021; Mikati et al., 2018; Miranda et al.,  
39 2011; Samoli et al., 2019; Verbeek, 2019). One example of research conducts analyses over multiple years  
40 (Buzzelli et al., 2003), cross-referencing multiple censuses with changes in air quality in a city in Canada. Also  
41 over a long period, Guak et al. study exposure in Seoul over a long period of time by differentiating  
42 seasonality; they use a time location method and try to see whether there is a correlation between types of  
43 population and exposure (Guak et al., 2021). All of this research highlights the dual inequalities in income and  
44  $\text{NO}_2$  exposure among certain disadvantaged populations. These inequalities are confirmed by a literature  
45 review of environmental justice studies (Mohai and Saha, 2015). These authors confirm environmental  
46 injustice in sociopolitical, racial and economic terms. They also defend longitudinal studies that investigate  
47 whether emission sources are growing in disadvantaged neighborhoods or whether other population  
48 categories are leaving polluted areas. Other research points to a spatial inequality according to population  
49 density, with air quality declining as population increases (Borck and Schrauth, 2021; Li and Myint, 2021).  
50 Solutions to improve air quality in polluted areas are being studied: implementation of Low Emissions Zones,  
51 implementation of Toxicity Loads, reductions in vehicle speed, etc. However, in order to ensure that these

52 measures are accepted and perhaps propose others, it is necessary to identify the contributors. Studies of the  
53 population of polluters are very uncommon in air quality research, which has only touched upon policy  
54 solutions to limit emissions at the origin, i.e., directed at the driver or at the planning policies that favor  
55 driving. Charging the pollution emitter, or at least redistributing some of the gains from air quality measures to  
56 those who do not benefit from them, is called distributional effects in economics. The topic of the link  
57 between air quality and industry has a long history (Gianessi et al., 1979) as the subsidy or tax policies on  
58 certain categories of vehicles (West, 2004). Economic reviews have also evaluated certain environmental  
59 policies with an impact on air quality, such as the diffusion of electric vehicles in the US (Holland et al., 2019).  
60 Inequalities in air quality purchases and gains are analyzed across population types. In the case of policy  
61 evaluation, the evaluation is performed against a current baseline situation. Our research is limited to an  
62 understanding of the current situation and a comparison between population profiles, and does not consider  
63 the temporal aspect. In the field of research on climate change prevention, studies are numerous (Fullerton,  
64 2011), in particular on the adoption of a carbon tax (Wang et al., 2016) and its impacts on the budgets of poor  
65 households without compensatory measures, an effect that has been observed in France with the "yellow  
66 vests" and the non-acceptance of the measure by the middle classes, who are car-dependent. Few research  
67 studies jointly investigate exposures to air pollutants by population types and those emitting the pollutants  
68 (Jephcote and Chen, 2012; Mitchell and Dorling, 2003; Sider et al., 2015). In their UK-wide research, Mitchell  
69 and Dorling do not assess exposure by activity locations and focus on exposed populations. By crossing  
70 exposure with emissions, they only show that the poorest populations are the most NO<sub>2</sub>-exposed populations  
71 and also the ones that emit the least NO<sub>x</sub>. In Leicester, Jephcote and Chen point to the relationship between  
72 PM10 emissions from road traffic and hospitalization rates among children. They also show the  
73 environmental inequity of a situation where the wealthier populations in the center contribute the most to  
74 road PM10 emissions and have the least exposure to PM10. Sider et al. use a model of simulations at the scale  
75 of the Montreal metropolitan area to compare values of exposure, emission and a socio-economic indicator.  
76 They analyze by area and not by individual, calculating a polluter-pays index that masks the specificities of the

77 territory. Their study shows that some socially disadvantaged areas are also more exposed to pollution, even  
78 though they emit little.

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

84 The objective of this research is to analyze and compare the socio-demographic characteristics of polluted  
85 populations and those of polluting populations on the same territory. We will focus on road traffic pollution  
86 with NO<sub>2</sub> exposure and NO<sub>x</sub> emissions from private vehicles.

87 Our method is based on individual daily evaluations of spatial and temporal exposure to NO<sub>2</sub> on the one hand  
88 and of NO<sub>x</sub> emissions from motor vehicles on the other. The individuals concerned are those from the  
89 Household Travel Survey (HTS), all of whose daily trips are provided, making it possible to reconstruct the  
90 detailed time use of the individuals and thus their exposure. These surveys also provide information on the  
91 technical characteristics of each household's vehicles and those used for each motorized trip. We also use  
92 pollutant emission models that simulate emissions per kilometer as a function of speed. This speed is  
93 estimated by a traffic model that gives us information on traffic conditions at different times of the day. Thus,  
94 we can reconstruct both the daily exposure of each individual to NO<sub>2</sub> but also these NO<sub>x</sub> emissions if the  
95 individual uses a motorized vehicle for their trips. Each individual, whose socio-economic characteristics are  
96 known, is then associated with their average NO<sub>2</sub> exposure values during an average working day and with  
97 their NO<sub>x</sub> emissions.

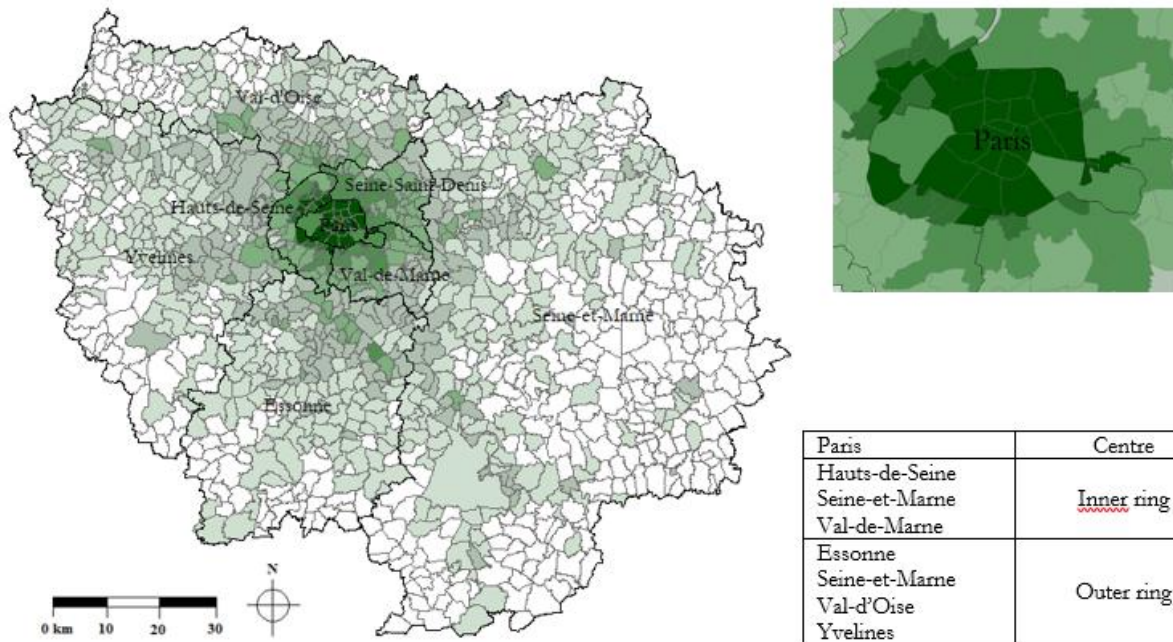
98 The rest of the article is divided into 3 parts. The first part presents the methodology in more detail with the  
99 exposure model and the emission model assigned to each individual applied to the Paris region. Part 2  
100 presents the general results on the territory and then by individual profile.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

## 102 2. Method and case study

### 103 2.1 The Paris Region

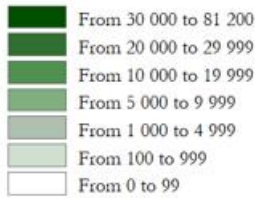
104 The Paris region (France) corresponds to the administrative region of Ile-de-France (Figure 1). 11.9 million  
105 people reside in the region. It is organized around the central city (Paris) and the inner ring (Hauts-de-Seine,  
106 Seine-Saint-Denis and Val-de-Marne), which form the center of the agglomeration in our study. This territory,  
107 which accounts for 6% of the total area of the region, concentrates 57% of inhabitants and 67% of jobs. The  
108 outer ring (Essonne, Seine-et-Marne, Val-d'Oise and Yvelines), accounting for the rest of the agglomeration,  
109 will be called the periphery in our study. Air pollution is an important issue in this area, with exceedances of  
110 the threshold of  $40\mu\text{g}/\text{m}^3$  for  $\text{NO}_2$  as an annual average for 1.3 million inhabitants (AirParif, 2018).

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

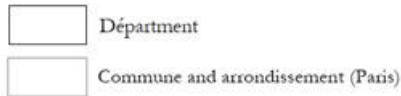


Paris	Centre
Hauts-de-Seine Seine-et-Marne Val-de-Marne	<u>Inner ring</u>
Essonne Seine-et-Marne Val-d'Oise Yvelines	Outer ring

Number of inhabitants and jobs per km<sup>2</sup>  
Source : census 2012 (INSEE)



Administrative boundaries



112

## 113 2.2 Why emission of NO<sub>x</sub> and exposure to NO<sub>2</sub>?

114 This research aims to contextualize NO<sub>x</sub> emissions from road transport with exposure to NO<sub>2</sub>, a pollutant  
 115 that still far exceeds regulatory thresholds in European cities (Guerreiro et al., 2014) and has a significant  
 116 impact on health and mortality in urban populations (Khomenko et al., 2021). One previous study has also  
 117 compared emissions of and exposures to the same pollutants (Mitchell and Dorling, 2003). Other research  
 118 confirms that NO<sub>x</sub> emissions contribute to a significant portion of the NO<sub>2</sub> background concentration  
 119 (Degraeuwe et al., 2017). To explain the NO<sub>2</sub> background concentration, emissions of all NO<sub>x</sub> and not just  
 120 NO<sub>2</sub> emissions need to be analyzed, due to the chemical reactions between NO and ozone that form NO<sub>2</sub>  
 121 (Keuken et al., 2009; Wild et al., 2017). This same NO<sub>2</sub> then enables the production of ozone, a pollutant that  
 122 also has significant health impacts (Khaniabadi et al., 2017). The relevance of assessing NO<sub>x</sub> emissions is

123 therefore obvious. We will focus on NO<sub>x</sub> emissions from road vehicles excluding heavy duty vehicles. Also  
124 excluded from the scope of the study are emissions from airports (9% of emissions in the Paris region) and  
125 other more marginal emission sources (AirParif, 2018). The studied contributions of road transport (56% of  
126 the total in the Paris region, Airparif) are mostly emitted in the central part of the study area, which is the  
127 densest area (Figure 1) and therefore the one with the most impact on population exposure.

### 128 2.3 General method

129 The method followed in this research is based on an HTS. The description of the movements and activities of  
130 the individuals in this database allow the construction of spatio-temporal profiles which are used to evaluate  
131 exposure to NO<sub>2</sub> while the description of movements in individual vehicles allow the calculation of traffic  
132 NO<sub>x</sub> emissions. Thus, the exposed and contributing populations are analyzed in a consistent way.

#### 133 ████████ NO<sub>2</sub> attribution method according to place of activity

134 The method for calculating NO<sub>2</sub> exposure focuses not only on residential locations in the assessment of  
135 average air pollution exposure but also on exposures at the place of activity, which may be in urban settings  
136 that are very different from the place of residence. These methods are increasingly applied using activity-based  
137 models (Beckx et al., 2009; Lu et al., 2019), but also survey data (Fenech and Aquilina, 2021; Park, 2020) or  
138 smartphone data (Li et al., 2021). Our methodology for calculating exposure is described in two previous  
139 studies (Poulhès and Proulhac, 2021; Proulhac and Poulhès, 2021). It consists in considering the exposure  
140 time spent on trips and those spent in activities, according to the time of the day. The method for calculating  
141 exposure during trips differs depending on the mode: (i) Because of the high uncertainty and the strong spatial  
142 variations of exposure, we do not consider the time spent in rail transport in the estimated average exposures  
143 (ii) In private motor vehicles, the exposures are calculated according to the itineraries simulated from traffic  
144 modelling (iii). For the other modes, namely buses, walking and cycling, we retain an average between the  
145 exposure at the place of origin and the exposure at the place of destination, since the accuracy of short-  
146 distance trips is not easy to obtain through modeling. For an individual  $i$ , the average daily exposure is  
147 therefore:



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

148 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  
 149 respectively the durations of activity  $A$  and trip  $T$  given in the HTS.  $E(h(T))$  and  $E(h(A))$  are the average  
 150 hourly exposures during trip  $T$  and activity  $A$ . Both can be expressed by discretizing them by the hourly  
 151 period corresponding to the concentration maps  $h$  over the entire duration of the activity/trip. Thus,  
 152  $E(h(T,A))$  can be expressed as the sums of the exposures over each of these periods:  $E(h(T,A)) =$   
 153  $\sum_{h \in h(T,A)} h \cdot E(h)$  where  $\sum_{h \in h(T,A)} h = t_{T,A}$ .

#### 154 ████████ $\text{NO}_x$ contribution method

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

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

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

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

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

## 171 2.4 The databases and external traffic model

### 172 Household travel survey

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

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

### 186 Traffic model

187 In addition to the HTS, which provides detailed information on travel modes and schedules, a traffic model  
188 on the same spatial scale as the survey is used to simulate the expected itineraries of individuals using an  
189 individual motorized mode. These forecasting tools have the benefit of being calibrated with data from  
190 household travel surveys and also with observed traffic conditions on major roads. However, these large-scale

191 models have the drawback of having limited network description data. For example, secondary roads are not  
192 described in the model. For long-distance trips, the itineraries are therefore fairly well represented. For short  
193 distances, however, the uncertainty is higher, so we use the survey distances in our emission calculations.

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

#### 197 Exposure map

198 In order to calculate average exposure levels, our method requires spatially detailed and dynamic exposure  
199 maps. The maps used are the results of simulations made by Airparif, the air quality agency of Ile-de-France  
200 which uses a suite of models to calculate pollutant emissions, a meteorological model, pollutant diffusion  
201 models and sensor data to calibrate their models. The calculated exposures correspond to the day of January  
202 9, 2019, a working day which is a day excluding school vacations and with NO<sub>2</sub> pollution levels that are  
203 neither low nor high compared to the references over the region. This day chosen by Airparif corresponding  
204 to an average working day in 2019. Thus, apart from the date inconsistency due to a survey not yet updated,  
205 the exposure day is consistent with the typical day of the HTS. The spatial resolution of the grid is 10m in the  
206 center (around Paris), 25m in the inner ring and 50m in the outer ring. The temporal resolution is 1h for the  
207 whole day with a beginning time of 4 AM and an end time of 3h59 AM.

#### 208 External emission model

209 To calculate NO<sub>x</sub> emissions from motorized vehicles, the emission factors of the European Copert 4 database  
210 are used (Ntziachristos et al., 2009). The focus is on the private road modes reported in the HTS. Thus, three  
211 categories of vehicle are considered (Table 1): passenger cars, light commercial vehicles and motorized two-  
212 wheelers. For each of these categories, emission ratios are distinguished according to the engine and the age of  
213 the vehicle. The emission levels are given according to the corresponding Euro standard. Thus, from Copert  
214 4, the emissions per kilometer of an average vehicle in each of these subcategories are estimated as a function  
215 of vehicle speed. Studies have shown that the emission ratios in Copert are underestimated for average speed

216 conditions with acceleration and deceleration and in cases of congestion. For example, over Paris, estimates  
 217 made by Copert 4 are -16% lower compared to congested cases (Lejri et al., 2018). Other studies confirm the  
 218 underestimation of Copert 4 in terms of NO<sub>x</sub> emissions (Kousoulidou et al., 2013; O’Driscoll et al., 2016),  
 219 whatever the Euro standard. However, uncertainties and variations between vehicles and traffic conditions  
 220 render estimates very difficult. made also decided not to consider emissions from public transport, which  
 221 cannot be estimated in an acceptable way at the individual scale.

222 Table 1: Vehicle categories for which NO<sub>x</sub> emissions are calculated and their characteristics per vehicle

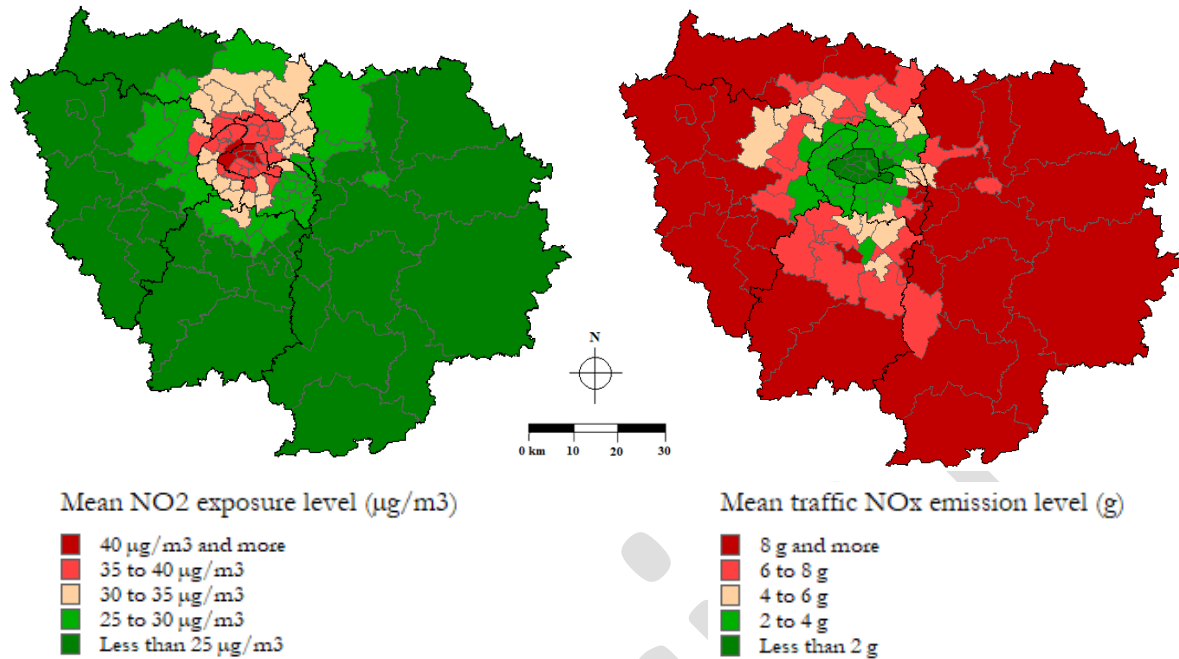
Type of vehicle	Engine type	Date of purchase	Euro norm
Private Car	Diesel/Gasoline/Hybrid/Liquid		1/2/3/4/5
	Gas		
Light commercial vehicle	Diesel		1/2/3/4/5
Two-wheeler	Gasoline		1/2/3/4/5

### 223 3. Results

224 The attribution of daily average NO<sub>2</sub> exposure and NO<sub>x</sub> emissions to each individual in a representative  
 225 sample of the population of the Paris region can produce a large number of results. We will focus our efforts  
 226 on the comparison between exposures and emissions, which is the least discussed topic in the literature. We  
 227 will first present two maps that clearly show the spatial opposition between exposed and emitting populations.

#### 228 3.1 Spatial mismatch exposed – polluter populations

229 Figure 2: (a) Left, map of average NO<sub>2</sub> per capita exposure levels by HTS draw area (b) Right, map of average  
 230 traffic NO<sub>x</sub> per capita emissions by HTS draw area.



231

232 Figure 2a illustrates the spatial disparities of average exposure and the obvious gap between the center of the

233 region with the densest districts of Paris (20,000 hab./m<sup>2</sup>) and the more rural areas with rather low densities

234 (500 hab./m<sup>2</sup>). The daily average exposure values increase from less than 25µg/m<sup>3</sup> in the rural areas to more

235 than 40µg/m<sup>3</sup> in the center. It can be noted that this latter value exceeds the old annual thresholds of danger

236 defined by the WHO (>40µg/m<sup>3</sup>) but that all the territories in the region exceed the new annual thresholds

237 (>10µg/m<sup>3</sup>). As already confirmed by extensive research, populations in the densest areas are the most

238 impacted by air pollution (Borek and Schrauth, 2021; Li and Myint, 2021). The map of individual emissions

239 attributed to the place of residence (Figure 2b) mirrors average exposures. A ratio of 1 to 4 differentiates the

240 center of the agglomeration where few residents use their car (15% only in Paris) from the outer territories

241 which are highly dependent on the private car. These results are consistent with the double inequality of

242 exposure of central populations to pollution that is mostly not their own, as pointed out by previous research

243 (Singh et al., 2020). While the two maps have often been presented in different research papers either on

244 exposure (Host et al., 2020) or on contributions (Bouzouina et al., 2013), to our knowledge they have never

245 been presented at the same time from a common population.

## 246 3.2 Socio-economic results per profile

### 247 ██████████ Profile presentation

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

253 Table 2: presentation of the population profiles studied

Name	Description	Share of the total population
<b>Urban</b>	Parisians and residents of the inner ring who did not use a car (or	33.6%
<b>Pedestrian (UP)</b>	motorized two-wheelers) and who travelled only in Paris and the inner ring	
<b>Urban Driver (UD)</b>	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%
<b>Peri-urban Driver in Centre (PDC)</b>	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%
<b>Peri-urban Driver in Periphery (PDP)</b>	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%

254

255 The objective is to be able to better differentiate the socio-demographic characteristics of the population, not  
256 only with respect to their place of residence but also with respect to their places of activity, and especially their

257 mobility behavior. The main interest is to compare the populations in the center, who are the most exposed  
258 and who do not travel by car (UP), with the other types of populations who travel by car, namely those who  
259 also live in the center (UD) but also those who live in the periphery. Among the latter population, we  
260 differentiate between those who travel to the center of the agglomeration for activities (PDC), who have the  
261 highest impact on air pollution, and those who stay in the periphery (PDP). We have chosen to aggregate the  
262 populations of Paris and the inner ring for a better representation of the profiles. Even though the density is  
263 lower than in Paris, the urbanism of the inner ring is closer to that of Paris than to the periphery. Thus,  
264 through our profiles, 74% of the population of Ile-de-France is studied.

### 265 [REDACTED] Disparities between profiles

266 In 2021, the WHO defined a new threshold of dangerousness threshold of danger corresponding to daily  
267 thresholds not to be exceeded:  $25\mu\text{g}/\text{m}^3$  in daily average (WHO, 2021). Then the population exposed to  
268 thresholds higher than  $25\mu\text{g}/\text{m}^3$  of  $\text{NO}_2$ , will be referred, in the following article to as “the polluted”.

269 The profiles studied have very heterogeneous mean values of  $\text{NO}_x$  emissions and  $\text{NO}_2$  exposure (Table 3). By  
270 definition, UPs do not emit  $\text{NO}_x$  in their daily trips. While UD's have a contribution to emissions almost  
271 proportional to their proportion in the total population, peri-urban residents contribute 2 times more  
272 emissions than their representation in the total population; additionally, their level of emissions is 2 times  
273 higher than the Ile-de-France average for PDP and 5 times higher for PDC. Conversely, the proportion of the  
274 population exposed above the thresholds is logically much higher in the population of the center than in the  
275 peripheral population (Borck and Schrauth, 2021), while it is also much higher for the population that does  
276 not travel by car than for the driving population. This overrepresentation is mainly due to the distribution of  
277 the demotorized population in the urban area. 30% of non-motorized trips are made by Parisians who are the  
278 most exposed (56% of the most exposed are Parisians, (Pouilhès and Proulhac, 2021)) for 20% of the whole  
279 population. 80% of the Paris region residents are exposed to thresholds higher than the WHO of 2021 ( $25$   
280  $\mu\text{g}/\text{m}^3$ ) and almost all the residents of the center (UP or UD).

281 Table 3: General results of average  $\text{NO}_2$  exposure and average  $\text{NO}_x$  emissions by population profile

	UP	UD	PDC	PDP	Entire population
Average level exposure of NO <sub>2</sub> (ug/m <sup>3</sup> )	37.1	35.8	30.9	25.2	32.1
Population part (%) > 25 µg/m <sup>3</sup> of NO <sub>2</sub>	98.0%	97.3%	83.3%	45.2%	78.7%
Average emission level of NO <sub>x</sub> (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

282

283 **Evidence of environmental inequality**

284 The breakdown of the population of each profile into socio-demographic characteristics provides a more  
 285 accurate view of environmental inequalities (Table 4). Overall, while the average exposure or the proportion  
 286 of people exposed to hazardous values is quite homogeneous in each of the profiles studied, the NO<sub>x</sub>  
 287 contributions are very heterogeneous between the categories of population within the same profile. In this  
 288 section, we propose to present the main results.

289 Among the population of the same territory, the differences in exposure and pollutant rates by population  
 290 category are quite small. Conversely, individual contributions to NO<sub>x</sub> are very unequally distributed from one  
 291 individual to another, even within the same profile. Thus, there are strong inequalities. To begin with, the  
 292 question of gender. Men emit twice as much NO<sub>x</sub> as women and are just as likely to be polluted. In particular,  
 293 among the PDC profile, we even obtain an emission factor of 3 between women and men, for a slightly



294 higher rate of polluted for men. On the other hand, the proportion of polluted women in the UD profile is  
295 higher. By age group, the rates of polluted young and old people are the lowest in the total population, and  
296 their contribution to NO<sub>x</sub> pollution is also very low: 5% for young people while they represent 20% of the  
297 population and 3% of old people for 9% of the population. Among the UP, the highest rates of polluted  
298 people are in the 50-70 years age group. Finally, the ratio of emissions by age group is roughly the same for  
299 each motorized profile studied. By occupation, working people obviously emit more than other categories, but  
300 there are heterogeneities between the categories of active people. The unemployed emit only 3.6% of NO<sub>x</sub> for  
301 5.7% of the total population and are 79.2% polluted. Conversely, workers emit a lot (15.5% of emissions for  
302 6.7% of the population) and are less polluted (75%). Among the less unequal findings, the highest rates of  
303 polluted people are found among the upper social categories, which are also those who emit the most. By  
304 profile, the rates of unemployed and executives in the UP are the highest and the gap with the rest of the  
305 population of the profile is even higher for the UD. The over-representation of active people in the  
306 populations that travel by car confirms their predominant place among the emitters. Executives are  
307 particularly numerous in the profiles commuting by car in the center (UD and PDC), and less so in the  
308 suburbs. They therefore contribute even more to the high concentration of NO<sub>2</sub> in the center, while being less  
309 impacted by pollution (between 86 and 89% of PDC executives are polluted compared with 99% of UP).  
310 Finally, an analysis by income group confirms that the wealthiest populations are the biggest emitters (2/5 of  
311 the population for more than 50% of emissions). They have the highest average polluted rates, especially the  
312 wealthiest 1/5 of the population, with 85,6% compared to 77% on average for the rest of the population. This  
313 is logical because they represent a larger proportion of the population in the center of the agglomeration,  
314 which is more polluted. While the distribution of UDs is homogeneous among the income categories, the  
315 wealthy UDs are over-represented in the profile (50% for 2/5 of the population), in contrast to the poorest  
316 quintile which represents only 11% and contributes to only 10% of the emissions of the profile. Similarly, the  
317 peri-urbans who use their car to travel to the center (PDC) are in a large minority the poorest (20% of the  
318 population for the first two quintiles and also 20% of the emissions of the profile).

319 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 <sub>2</sub>	Part (%) in the NO <sub>x</sub> emissions	Part of the population (%)	Part (%) > 25 ug/m3 NO <sub>2</sub>	Part (%) in the NO <sub>x</sub> emissions	Part of the population (%)	Part (%) > 25 ug/m3 NO <sub>2</sub>	Part (%) in the NO <sub>x</sub> emissions	Part of the population (%)	Part (%) > 25 ug/m3 NO <sub>2</sub>	Part (%) in the NO <sub>x</sub> emissions	Part of the population (%)	Part (%) > 25 ug/m3 NO <sub>2</sub>	Part (%) in the NO <sub>x</sub> emissions
<i>Gender</i>															
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
<i>Age group (in years)</i>															
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
<i>Occupation</i>															
Independent 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
<i>Income (per quintile)</i>															
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

320

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## 321 4. Discussion

322 The specificity of Paris, with its overrepresentation of affluent people in the center, explains why the  
323 wealthiest populations are the most exposed to NO<sub>2</sub> pollution, in contradiction with certain previous studies  
324 on cities with different urban characteristics (Clark et al., 2014; Sider et al., 2015). In contrast, analysis of NO<sub>x</sub>  
325 emissions confirms that the lowest emitters are the poorest populations (Jephcote and Chen, 2012; Mitchell  
326 and Dorling, 2003; Sider et al., 2015). Analysis of population profiles by mode used and by trip reveals  
327 specificities that are diluted in the average values. In particular, two profiles are particularly interesting:  
328 residents of the periphery who drive to the center on a daily basis, and those who live in the center and do not  
329 use a private car on a daily basis. The first group is polluting while being moderately exposed and the second  
330 group (33.6% of the total population) is highly exposed without contributing directly to their exposure.

331 This result leads to a first discussion on the gap in the study between the NO<sub>2</sub> exposure and NO<sub>x</sub> emission  
332 calculations. Several methodological distinctions should be highlighted. The date difference between the 2011  
333 HTS and the 2019 exposures should be noted, but living and activity locations as well as mobility practices  
334 have changed only slightly since 2011 as shown by the preliminary results of the new HTS (Omnil and Ile-de-  
335 France Mobilités, 2019). NO<sub>2</sub> exposure and NO<sub>x</sub> emission calculations. Several methodological distinctions  
336 should be highlighted. Secondly, the HTS and the concentration map are based on a typical average working  
337 day, which is therefore consistent with each other, but poses difficulties with regard to the use of exposure  
338 thresholds as health risk indicators. Since 2021, the WHO considers a threshold of 25 µg/m<sup>3</sup> as a daily  
339 average, which must be compared with its annual average ambitious threshold of 10 µg/m<sup>3</sup>. Thus, in the Paris  
340 region, 9 out of 10 residents are exposed beyond these annual thresholds (Airparif, 2021) and 8 out of 10 in  
341 our daily approach. This very low threshold makes it difficult to compare populations in the Paris region  
342 where concentrations are very often above 25 µg/m<sup>3</sup> in the center and in the periphery. To confirm our  
343 results on exposure, we also tested a threshold of 40 µg/m<sup>3</sup> which corresponds to the old WHO threshold in  
344 annual average. On the one hand, even if only 16% of the population exceeds this threshold, the populations  
345 that exceed the two thresholds the most remain the same with very few exceptions. On the other hand, the

346 differences between the parts of the most polluted populations are more significant especially for the  
347 populations of the center.

348 NO<sub>x</sub> emission values consider all sources of pollution without extracting the part corresponding to daily  
349 traffic while NO<sub>2</sub> concentrations by definition consider all emission sources, wherever they come from. In  
350 particular, the emissions of residents are considered in the study as non-emitters. Without emitting directly  
351 from the modes and trips under study, many indirect sources of emissions should be considered: (i) Emissions  
352 from other modes of transport such as buses, whose emissions are the responsibility of the community and  
353 the transport authority which is in charge of fleet renewal; (ii) Long-distance trips which are not part of the  
354 HTS perimeter and which contribute a significant proportion of NO<sub>x</sub> emissions (37% of total driving distance  
355 in France (Nicolas et al., 2012)). However, they are mostly made in low-density areas and therefore have less  
356 impact on the population; (iii) Emissions due to heavy vehicle traffic, estimated at 30% by a study on NO<sub>x</sub> in  
357 the Paris region (Coulombel et al., 2018), even if only part of the traffic is for local consumption; (iv) Air  
358 travel: according to Airparif, 9% of NO<sub>x</sub> emissions come from airport hubs in the Paris region, of which only  
359 a portion is for resident travel. These important gaps in our method, which for the most part also relate to the  
360 way of life of the populations, are also present in other studies that associate NO<sub>x</sub> emissions with a population  
361 (Bouzouina et al., 2013). If we consider that the rich consume more goods (Nielsen et al., 2021), fly more  
362 often and make more long-distance trips (Nicolas and David, 2009), adding these emissions into the balance  
363 sheet would further increase environmental inequalities between social classes.

364 Another important limitation is that emissions are not weighted according to where they occur. In the average  
365 balance, the emission does not depend on the population density, and a trip in the center can have as much  
366 impact as a trip in the periphery, whereas this is not the case in reality. The analysis by population profile  
367 makes it possible to distinguish between populations that make at least one trip to the center and populations  
368 that make no trips to the central area. This also raises questions about the urban dynamics and the future of  
369 these populations, who are highly dependent on private cars and who emit more than 40% of the region's  
370 NO<sub>x</sub> emissions in our study. Beyond the obvious contribution to CO<sub>2</sub> emissions, NO<sub>x</sub> emissions in the peri-

371 urban area contribute to the diffusion of ozone, a pollutant that is also harmful to the health and predominant  
372 in rural areas (Betancourt-Odio et al., 2021).

373 For the calculation of the NO<sub>x</sub> emissions, some assumptions were made. In the Copert database, the unit  
374 emissions depend only on speed and engine type, but other important factors are taken into account. The  
375 weight of the vehicle, as well as the cold start phases during which emissions are much higher (Suarez-Bertoa  
376 and Astorga, 2018) and the acceleration and deceleration phases are taken into account, although aggregated  
377 by an average value in the Copert emission factors. Thus, emissions from short and urban trips are  
378 underestimated in our results. Regarding NO<sub>2</sub> exposure, the accuracy of the exposure locations, limited by the  
379 size of the tiles of the exposure maps, but also that of the locations of presence in the HTS, only allows one to  
380 calculate exposure potentials. Our macroscopic approach does not enable use of street level diffusion models  
381 (Zhang et al., 2020). Similarly, during travel, the concentration of pollutants in the vehicle cabin is higher than  
382 outside, but the effort involved in walking and cycling causes pedestrians and cyclists to inhale more polluted  
383 air (Matthaios et al., 2020). A literature review confirms these results (Singh et al., 2021). Mass transit  
384 exposures, not considered in our study, are rather limited, according to other studies (Delaunay et al., 2012;  
385 Ramacher and Karl, 2020). The higher inhalation of pollutants by pedestrians and cyclists would be  
386 counterbalanced by physical activity in the overall impact on health (Cepeda et al., 2017).

387 Another important limitation in the quantification of exposure to air pollution among the population of an  
388 agglomeration with our method concerns the HTS in France. Household travel surveys in France do not  
389 survey children under 5 years of age, who are the most at risk from air pollution (Citerne et al., 2021). In the  
390 poorest populations, among the most vulnerable children, environmental inequalities are multiplied tenfold  
391 (Unicef and Réseau Action Climat, 2021). The effects of air pollution would also be multiplied by negative  
392 living conditions. Other sources of pollution should be considered in order to give a complete overview of the  
393 damage generated and suffered by the populations and to introduce the concept of exposome (Rappaport,  
394 2011). In addition to other atmospheric pollutants such as fine particles, whose emissions and concentration  
395 levels are fairly well correlated with NO<sub>2</sub> (Samoli et al., 2019), noise is also a nuisance closely linked to road  
396 traffic with a strong impact on health (Münzel et al., 2021).

## 397 5. Conclusion and policy implications

398 This research has enabled us to relate exposure to an urban air pollutant which is hazardous to health, NO<sub>2</sub>, to  
399 a proportion of the contributors of this pollutant: a large proportion of NO<sub>x</sub> traffic emitters. A coherency  
400 between the two analyses is achieved by means of a HTS to finely evaluate NO<sub>2</sub> exposure with a spatio-  
401 temporal approach that considers travel and exposure at activity locations. Each motorized individual in the  
402 HTS contributes to NO<sub>x</sub> emissions through his or her motorized trips as described in the survey. A spatial and  
403 socio-economic analysis then allows for an analysis of environmental inequalities.

404 The results confirm that the environmental injustice of exposure to air pollution is first of all a territorial  
405 injustice, with a large proportion of the population in the center of the Paris Region that does not emit NO<sub>x</sub>  
406 and is particularly exposed to NO<sub>2</sub> pollution (Sider et al., 2015). Conversely, the populations of the periphery  
407 are very little exposed and very contributive to NO<sub>x</sub>. Another social injustice is the fact that the unemployed  
408 and the lowest-income populations are the lowest contributors and are sometimes more exposed than other  
409 populations. Finally, the study of this pollution highlights a gender injustice, with women being over-exposed  
410 relative to their contribution.

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

419 Our results also allow us to discuss the urban planning policies that still favor urban sprawl. They are often  
420 criticized in terms of land artificialization, the carbon impact of motorized mobility, or the strong dependence  
421 on cars among modest households (Belton Chevallier et al., 2018). They are rarely analyzed in terms of impact

422 on air quality or the opposition between residents in the center, who are demotorized, live in cramped  
423 conditions, and whose living conditions are degraded, and motorized households living in large spaces who  
424 cause the damage. We can thus understand the vicious circle of the exodus of residents from the center to the  
425 peripheries in search of better-quality air. Consequently, car use and pollution in the center of the  
426 agglomeration are further exacerbated by a favorable peripheral urban context. Thus, policies to restrict car  
427 use in urban centers may be more acceptable but still reinforce the opposition between the center and the  
428 periphery. Only policies that are consistent between urban planning and transport and between center and  
429 periphery can resolve the escalation of territorial and social tensions due to environmental nuisances. Giving  
430 more authority to citizens, especially the poorest, to participate in the construction and improvement of their  
431 urban environment would limit the disaffection in certain urban areas (Faburel, 2008). In particular,  
432 renaturation projects and developing access to nature would limit inequalities with respect to air pollution  
433 (Jennings et al., 2021).

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

## 442 Acknowledgements

443 We would like to thank AirParif in particular for providing us with their NO<sub>2</sub> concentration maps. Thanks  
444 also to the DRIEA for allowing us to use its MODUS transport model. Finally, we would like to thank Cyrille  
445 François for his help in accessing the Copert emission ratios.

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