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Exposed to NO₂ 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 NO₂ 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 NO₂ 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; NO₂ 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 NO₂)¹. Most major European cities exceed the EU air quality thresholds, which correspond to the old WHO

¹ [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 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 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 NO₂-exposed populations
71 and also the ones that emit the least NO_x. 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 NO₂ exposure and NO_x emissions from private vehicles.

87 Our method is based on individual daily evaluations of spatial and temporal exposure to NO₂ on the one hand
88 and of NO_x 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 NO₂ but also these NO_x 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 NO₂ exposure values during an average working day and with
97 their NO_x emissions.

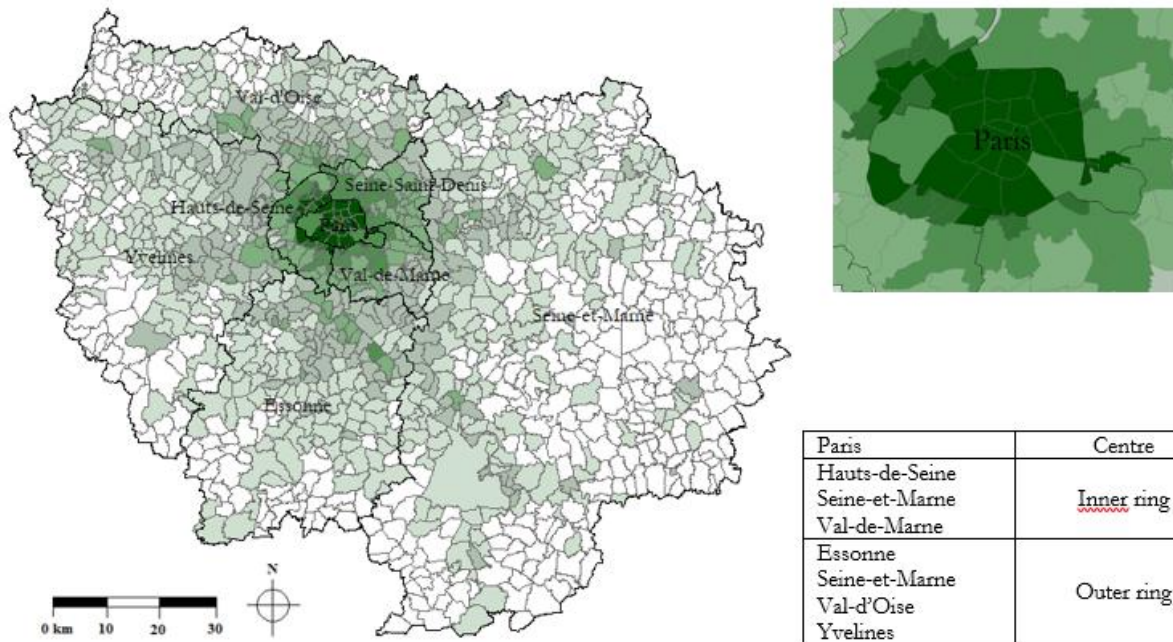
98 The rest of the article is divided into 3 parts. The first part presents the methodology in more detail with the
99 exposure model and the emission model assigned to each individual applied to the Paris region. Part 2
100 presents the general results on the territory and then by individual profile. 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

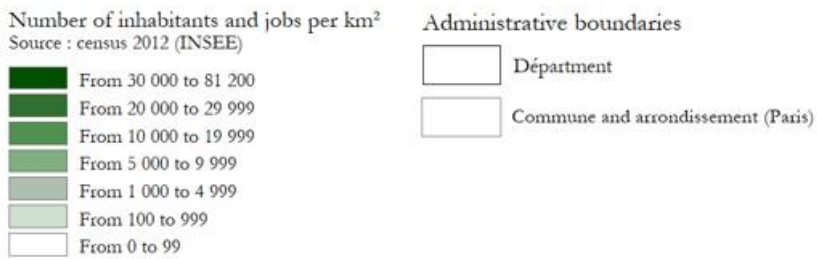
103 2.1 The Paris Region

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 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 |



112

113 **2.2 Why emission of NO_x and exposure to NO₂?**

114 This research aims to contextualize NO_x emissions from road transport with exposure to NO₂, 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_x emissions contribute to a significant portion of the NO₂ background concentration
 119 (Degraeuwe et al., 2017). To explain the NO₂ background concentration, emissions of all NO_x and not just
 120 NO₂ emissions need to be analyzed, due to the chemical reactions between NO and ozone that form NO₂
 121 (Keuken et al., 2009; Wild et al., 2017). This same NO₂ then enables the production of ozone, a pollutant that
 122 also has significant health impacts (Khaniabadi et al., 2017). The relevance of assessing NO_x emissions is

123 therefore obvious. We will focus on NO_x 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 NO₂ while the description of movements in individual vehicles allow the calculation of traffic
132 NO_x emissions. Thus, the exposed and contributing populations are analyzed in a consistent way.

133 [REDACTED] NO₂ attribution method according to place of activity

134 The method for calculating NO₂ 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 ████████ 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 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 ϑ_{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 XXXXXXXXXX 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 XXXXXXXXXX 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 NO₂ 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_x 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_x 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_x emissions are calculated and their characteristics per vehicle

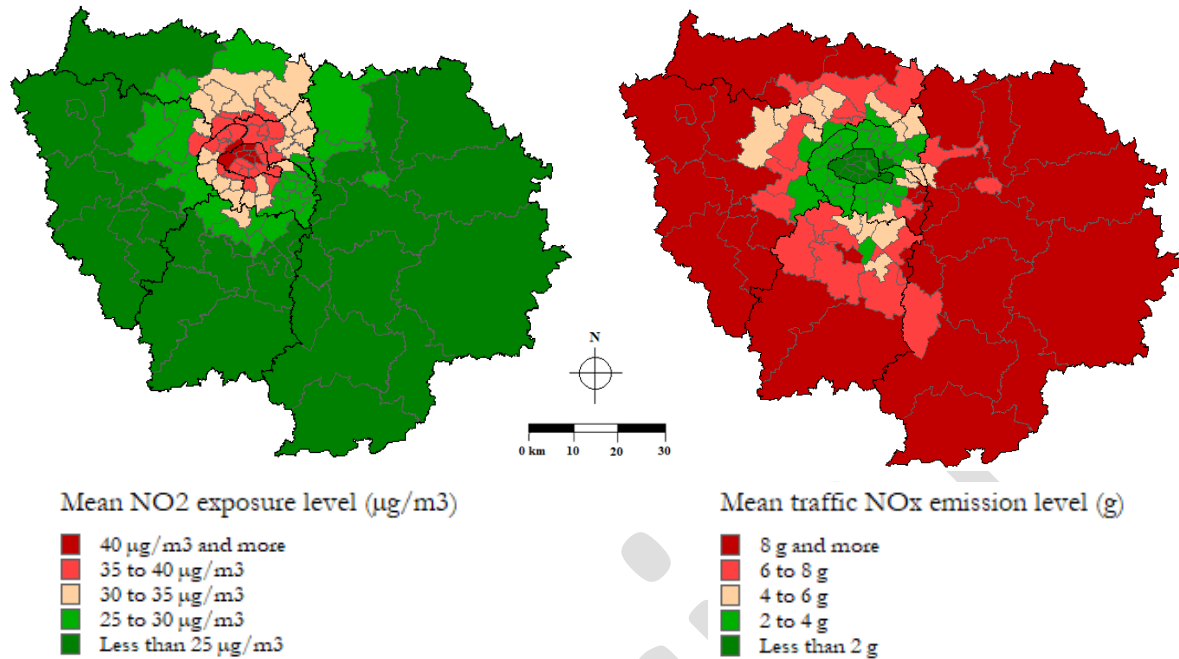
| Type of vehicle | Engine type | Date of purchase | Euro norm |
|--------------------------|-------------------------------|------------------|-----------|
| Private Car | Diesel/Gasoline/Hybrid/Liquid | | 1/2/3/4/5 |
| | Gas | | |
| Light commercial vehicle | Diesel | | 1/2/3/4/5 |
| Two-wheeler |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

223 3. Results

224 The attribution of daily average NO₂ exposure and NO_x 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 NO₂ per capita exposure levels by HTS draw area (b) Right, map of average
 230 traffic NO_x 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./m²) and the more rural areas with rather low densities

234 (500 hab./m²). The daily average exposure values increase from less than 25µg/m³ in the rural areas to more

235 than 40µg/m³ in the center. It can be noted that this latter value exceeds the old annual thresholds of danger

236 defined by the WHO (>40µg/m³) but that all the territories in the region exceed the new annual thresholds

237 (>10µg/m³). 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 |
|---|---|-------------------------------|
| Urban | Parisians and residents of the inner ring who did not use a car (or | 33.6% |
| Pedestrian (UP) | motorized two-wheelers) and who travelled only in Paris and the inner ring | |
| 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% |

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 ████████ 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 NO_2 , will be referred, in the following article to as “the polluted”.

269 The profiles studied have very heterogeneous mean values of NO_x emissions and NO_2 exposure (Table 3). By
270 definition, UPs do not emit NO_x in their daily trips. While UD has 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, (Poullès 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 NO_2 exposure and average NO_x emissions by population profile

| | UP | UD | PDC | PDP | Entire population |
|--|-------|---------|---------|---------|-------------------|
| Average level exposure of NO ₂ (ug/m ³) | 37.1 | 35.8 | 30.9 | 25.2 | 32.1 |
| Population part (%) > 25 µg/m ³ 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 |

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_x
 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_x 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_x 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_x 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_x 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 NO₂ 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 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 |
| <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 |

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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 NO₂ 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_x
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 NO₂ exposure and NO_x 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). NO₂ exposure and NO_x 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/m³ as a daily
339 average, which must be compared with its annual average ambitious threshold of 10 µg/m³. 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/m³ in the center and in the periphery. To confirm our
343 results on exposure, we also tested a threshold of 40 µg/m³ 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_x emission values consider all sources of pollution without extracting the part corresponding to daily
349 traffic while NO₂ 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_x 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_x 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_x 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_x 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_x emissions in our study. Beyond the obvious contribution to CO₂ emissions, NO_x 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_x 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 NO₂ 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 NO₂ (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, NO₂, to
399 a proportion of the contributors of this pollutant: a large proportion of NO_x traffic emitters. A coherency
400 between the two analyses is achieved by means of a HTS to finely evaluate NO₂ 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_x 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_x
406 and is particularly exposed to NO₂ pollution (Sider et al., 2015). Conversely, the populations of the periphery
407 are very little exposed and very contributive to NO_x. 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.

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