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Alexis Poulhès, Laurent Proulhac

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1 The Paris Region low emission zone, a benefit shared with residents 2 outside the zone.

3 Alexis Poulhès (corresponding author), Ecole des Ponts, Laboratoire Ville Mobilité Transport (UMR
4 Ecole des Ponts ParisTech, Université Gustave Eiffel), 14-20 boulevard Newton - Cité Descartes -
5 Champs-sur-Marne, 77447 Marne-la-Vallée Cedex 2, France. alexis.poulhes@enpc.fr

6 Laurent Proulhac, Université Gustave Eiffel, Laboratoire Ville Mobilité Transport (UMR Ecole des Ponts
7 ParisTech, Université Gustave Eiffel), 14-20 boulevard Newton - Cité Descartes - Champs-sur-Marne,
8 77447 Marne-la-Vallée Cedex 2, France. laurent.proulhac@enpc.fr

9 Abstract

10 This study proposes to assess the potential health benefits of LEZs for the population of the Paris region
11 by taking into account individual levels of exposure to air pollution during travel and activities during the
12 day. Dynamic maps of NO₂ concentration, a household travel survey and a road traffic model are used to
13 assess the population exposed to air exceeding 40 µg/m³ of NO₂. The impact of LEZ implementation in
14 the Paris region would be smallest for those populations that are most sensitive to pollution problems, the
15 youngest and oldest. The wealthiest would be the big winners from the LEZ, but were also the most
16 exposed. According to scenarios, between 13 and 43% of residents who were exposed to high NO₂
17 concentrations outside the LEZ perimeter fell below the critical threshold of 40 µg/m³.

18 Keywords

19 Pollution exposure; low emission zone; NO₂; air quality; transport policy; Paris region

20 1 Introduction

21 Despite a trend towards improved air quality, most major European cities still exceed the regulatory
22 thresholds and pollutant concentration recommendations set by the European Commission for health
23 protection (EEA, 2020). In order to meet air quality objectives, more and more European cities are setting
24 up systems to reduce pollutant emissions. Many tools exist to limit the use of cars and therefore car
25 pollution, including urban tolls, low-speed zones, HOV lanes or pedestrianization. One of them, Low
26 Emission Zones (LEZs), limits access within a defined perimeter, usually the city center, to the least
27 polluting vehicles. This traffic restriction tool has been adopted since the end of the 1990s in more than
28 210 European cities, including many Italian and German cities, as well as London, Amsterdam, Brussels
29 and Gothenburg (Pouponneau and Cape, 2017; Ademe et al., 2019). In the Paris region, the field of study
30 for this work, only newer vehicles properly marked with a sticker are allowed to circulate in the city center
31 since 2016.

32 However, although an increasing number of studies have estimated the benefit of LEZs for the health of
33 the population living within the perimeter (Gehrsitz, 2017; Mudway et al., 2019; Host et al., 2020), to our
34 knowledge, none of them have done so for the entire resident population concerned by the system, i.e. the
35 metropolitan residents present within the perimeter at a given time of day. Better knowledge of the
36 beneficiaries of LEZs should make it possible to boost acceptance and, above all, ensure better compliance
37 among certain groups of reluctant motorists (Pouponneau and Cape, 2017). The objective of this work is
38 to evaluate the populations benefiting from the implementation of an LEZ on the scale of the Paris
39 metropolitan area.

40 Modelling of pollutant concentrations before and after implementation of the LEZ in the study field served
41 as input data for calculating individual exposures. Their activity schedules and the modes of transport used
42 for each trip were taken from a household travel survey. Such a survey provides information for each
43 individual on the characteristics of all their weekday travel and their socio-demographic characteristics.
44 The calculation of the variable levels of exposure in space and time provided quantitative and qualitative

45 knowledge of the populations exceeding the maximum pollution exposure threshold. To this end, exposure
46 was measured for each individual surveyed (i) in the places where their daily activities took place, taking
47 into account the start and end times of their activities, and (ii) during daily journeys, taking into account
48 the hours of travel, origin-destination and modes of transport used. In particular, exposure during road
49 travel was measured after the road had been assigned to the network based on traffic modelling. The
50 comparison of differences in daily exposure to air pollution for each individual according to the LEZ
51 implementation scenarios therefore allowed a precise estimation of the benefits for each individual.

52 The main contributions of this work are: (i) Proposing a general method for estimating the spatial and
53 temporal exposure of a resident population, (ii) comparing the population's exposure to NO₂ according to
54 two approaches (static and spatio-temporal), and (iii) assessing the benefits of an LEZ for metropolitan
55 residents according to their places of activity and daily trips, and not only for residents within the LEZ
56 perimeter.

57 The document is organized as follows. After a first part which is a literature review, part 3 sets out the
58 general method for calculating individual exposure to a pollutant with a space-time approach. The
59 different steps of the method for measuring exposure to pollution during activities and travel are
60 described. Part 4 outlines the required data and the main assumptions and scenarios implementing LEZs in
61 the Paris region. Finally, part 5 presents the general results and more qualitative results with a socio-
62 demographic analysis of the residents benefiting the most.

63 2 Literature review

64 The assessment of exposure to local pollutants is generally approached by considering the residents of the
65 area being studied as staying at their residence all day long. Since census data provide information on
66 place of residence, this approach can be used at the country level (Brooks and Sethi 1997; Scoggings et al.
67 2004). This method is most often used today to estimate populations impacted by pollution from the main
68 air pollutants (EEA 2019; Host et al. 2018), and it seems to be sufficient for large territories such as

69 countries or regions, as shown by Dhondt et al. (2012) for Flanders and Brussels, where the difference in
70 average exposure between an approach based on residence and an approach based on activity was only
71 1.2% for NO₂. However, as they also pointed out, at a more local level or depending on socio-
72 demographic characteristics, the difference can be much greater. In 2008, De Ridder et al. (2008a) used
73 travel modelling to show the impact of urban sprawl on pollutant concentrations and population exposure
74 in the Ruhr area in Germany. Their scenario (De Ridder et al., 2008b) estimated that air quality would
75 decrease despite the increase in traffic volume. Residents who continue to live in the center are more
76 exposed to pollutants, unlike people who have relocated from the center to the periphery.

77 Based on the work of Beckx et al (2009), the activity approach has increasingly been studied and used in
78 research to highlight differences in exposure to air pollution between methods or to evaluate public
79 policies. As early as 1997, Krzyzanowski stressed the need to use these methods when dynamic data on
80 individual exposures to air pollution are available. A number of research studies have thus focused on the
81 exposure of residents of a territory according to their place of activity (Beckx et al., 2009; de Nazelle et
82 al., 2009; Dhondt et al., 2012; Kickhöfer and Kern, 2015; Vallamsundar et al., 2016). Beckx et al. (2009)
83 demonstrated the value of using activity models to improve the calculation of population exposure to air
84 pollution. Activity models are increasingly replacing traditional generation and distribution models in
85 conventional transport models. They are based on a synthetic population of the studied territory and the
86 activities are simulated according to the capacities of the transport networks and surveys available in the
87 territory. Since then, other studies have used this type of model to calculate exposures: for example De
88 Nazelle et al. (2009) to assess the impact of pedestrian-friendly designs on exposure, highlighting the great
89 uncertainty in the results due to the use of models to simulate the activities of each person in the
90 population. Kickhöfer and Kern (2015) compared the socio-economic impact of various public policies to
91 protect the city-center population in Munich, in particular two kinds of toll for private cars and freight
92 vehicles: the exposure-toll where the cost depends on exposure and the emission-toll dependent on the
93 pollutant emission level. They used a simplified exposure model approach around the MatSIM model,

94 which is a model that integrates activity modeling and assignment in transportation networks at an
95 individual level, and the HBEFA emission model. Vallamsundar et al, (2016) proposed an integrated
96 model for Arizona with a feedback loop with an activity model, a transport model, an emission model and
97 an exposure model.

98 The WHO underscored the interest in approaches calculating population exposure to air pollution
99 according to activity by introducing model and survey approaches in a report on the state of the art of
100 methods useful for assessing air quality and its impact on health (WHO, 2014), although without citing
101 studies using surveys. It should also be noted that some research targeting specific populations has used
102 instrumentation of a group in their trips to obtain an estimate of their exposure. One example was the work
103 by Duché (2015) on the exposure of tourists to air pollution in Paris using GPS data. A study in Lyon also
104 showed the difference between a residence approach and an activity approach, without considering
105 transport exposure and using a household travel survey (Golay et al. 2014) or work-related mobility data
106 from the population census (Maury et al. 2016), but did not evaluate public policy.

107 With regard to LEZs, ex-ante pollutant concentration and exposure studies would appear to be far too
108 optimistic about actual pollutant concentration reductions due to LEZs in Europe (Pouponneau and Cape,
109 2017). Holman et al. (2015) list the studies that evaluate LEZs in Europe with either a prospective
110 simulation method or a monitoring evaluation method. The main limitation identified with the first method
111 is the calculation of NO_x emissions and the limitations of the second method would come from the
112 difficulty in identifying the effects of the LEZ from the effects of other policy measures and
113 meteorological variation. Research studies have thus shown the relatively small gain in concentrations
114 after the implementation of a LEZ where the restriction concerns only HGV and LDVs. When LEZs
115 concern cars, in Germany (Holman et al., 2015) and Lisbon (Santos et al., 2019), pollutant concentration
116 reductions are more consistent. In London, a study showed the effect of LEZs on the composition of the
117 fleet after 5 years of application, with a 20% reduction for certain categories of polluting vehicles, but
118 showed little effect on PM₁₀ concentrations (-1%) and none on NO_x (Ellison et al., 2013) offset by the

119 increase in the number of heavy vehicles. On the other hand, air quality improved in Lisbon, with -16%
120 for PM10 and -6% on NO₂ (Silva et al., 2014) or between -12% and -22% for NO₂ depending on the
121 perimeter studied (Santos et al., 2019); the fleet was renewed with more recent vehicles (Ferreira et al.,
122 2015). For the German LEZs, Wolff (2014) estimated a 9% drop in fine particles and a gain in health that
123 was double the investment required to change the vehicle fleet. These large differences between gains are
124 in particular due to the use of rather theoretical pollutant emission models that may deviate from actual
125 emissions but also to the types of vehicle bans in the LEZ. On the other hand, the effect on fleet renewal
126 has been verified. Again for the LEZs, Malina and Scheffler (2015) showed a non-negligible effect of
127 their implementation on the PM10 concentrations in German cities, based on a regression model. They
128 also showed a gain via billions of euros in savings on health, by estimating the number of deaths avoided.
129 Despite this, few studies have yet looked at the gains for the population from reduced exposure to local
130 pollutants in LEZs. A study of a large cohort of children estimated the health benefit to children in the
131 London LEZ (Wood et al., 2015; Mudway et al., 2019). The gain appeared to be very small, despite the
132 significant reduction in exposure to NO₂, although not to other pollutants including fine and ultrafine
133 particles. Another study in Germany (Gehrsitz, 2017) showed that the LEZs resulted in a decrease of 3
134 days in threshold exceedance, but no significant gain in children's health.

135 3 Method

136 The method developed in this research is applicable in a territory where many individuals move daily
137 between some areas where thresholds are exceeded and others that are less concerned. This is the
138 dominant organizational model of large European cities and metropolitan areas where the center is the
139 focus of human activities (residences, jobs, equipment, etc.) and road infrastructures. For example, the
140 development of road and rail infrastructures and widespread use of the car over the last few decades have
141 allowed many workers living in peripheral areas that are less exposed to air pollution to come and work
142 every day in the center of the metropolitan area, where they are exposed to higher pollution. In order to
143 implement the space-time approach to calculating exposure, three types of data must be available in the

144 area under study: (i) the values of exposure to pollutants in space and time for an average or typical day,
145 (ii) the locations, times and durations of presence and trips of residents, and (iii) a traffic model that makes
146 it possible to estimate the path and travel times of people using motorized vehicles. The general
147 methodology and data used are described in more detail in the sub-sections below.

148 3.1 Principle

149 To evaluate the reductions in exposure to air pollution due to a public policy measure, we use the
150 thresholds of exposure to pollutants defined by the competent public authorities. In order to measure these
151 thresholds at the individual level, the method must allow the populations that are exposed above the
152 danger thresholds for human health to be quantified.

153 3.1.1 Exposure threshold

154 Although some studies show that there is no threshold value and that all exposure to pollutants is
155 dangerous (Brunekreef, 2002), the definition of exposure thresholds is of key importance in order to assess
156 trends in air pollution or compare public policies.

157 These thresholds are given on an annual basis to take account of the variability of pollution according to
158 the days and seasons. However, the trips of individuals are surveyed for a typical working day of the
159 week, excluding school holidays and weekends. In order to achieve a match between the annual exposure
160 thresholds and the daily presence/travel locations of individuals, we assume an equivalence between the
161 average annual threshold and a daily threshold. The value of the annual average exposure threshold
162 becomes a daily exposure threshold not to be exceeded. This strong assumption neglects days with high
163 pollution but also days with cleaner air. It would therefore be expected that the number of people above
164 the threshold will not be the same between a year-round approach and a day-round approach, but for a
165 public policy assessment, the most important is the differences between the scenarios applying an identical
166 method.

167 3.1.2 Calculation of daily exposure

168 The method measures the exposure of each individual throughout the day, taking account of the places
169 where they are and their daily trips. For each individual, an average daily exposure is calculated based on
170 the total exposure. If the value is below the exposure threshold defined as dangerous, then the individual is
171 not considered as being exposed to a health risk. Conversely, if the value is above the exposure threshold
172 defined as dangerous, then the individual is considered to be exposed to a health risk. Other, less common
173 indicators of urban air quality are based on an exposure time not to be exceeded above a certain threshold.
174 The advantage of our indicator is that it distinguishes between exposures with high values, compared to an
175 average exposure, which hides disparities in daily exposure.

176 In this method, the individual's day is divided into two distinct periods of exposure. The first corresponds
177 to periods of "activities" (home, work, study, leisure, shopping, administrative procedures, etc.) in precise
178 locations with a start time and an end time. The second corresponds to periods of travel between an origin
179 and a destination with a departure time and an arrival time. Subpart 3.3 explains in detail the calculation of
180 exposure in different places and subpart 3.4 the calculation of exposure during travel. **In the section 4 a**
181 **diagram resumes the method and the additional assumptions.**

182 3.2 Required Data

183 Our method requires 3 types of data widely available around the world: household travel surveys (Stopher
184 and Greaves, 2007), fine mapping of pollutant concentrations (Schmitz et al., 2019) and traffic models.

185 3.2.1 Exposure map of the studied pollutant

186 The agencies responsible for monitoring air quality use forecasting models to anticipate spells of
187 pollution. Among the results of these models are estimates of average exposure values for each pollutant
188 studied in steps of time and space. These maps of pollution concentration are produced by simulation
189 models that are consistent in time and space. They thus can be used to calculate exposures during travel.

190 3.2.2 Household travel survey

191 In order to find out about the daily travel practices of their residents, large cities regularly conduct surveys
192 of a sample of households that are representative of their population. Only residents are surveyed; this
193 excludes in particular tourists and workers who live outside the scope of the survey. These surveys
194 provide information for each individual in a household on the characteristics of all their travels, i.e. origins
195 and destinations, departure and arrival times, modes of transport, distances, durations, etc. All journeys are
196 explained and one journey is associated to a single mode of transport. These surveys also provide
197 information on the socio-demographic characteristics of individuals, i.e. location, income, age, gender,
198 activity, socio-professional category, etc.

199 3.2.3 Traffic assignment model

200 Large cities that have to manage an extensive transport network often have a traffic model at their
201 disposal, that allows them to make prospective assessments for infrastructure projects. In particular, these
202 models give an estimate of travel times on the main transport routes used for everyday purposes. For the
203 main modes of transport, these simulations provide a fairly accurate picture of the travel times and routes
204 taken by the individuals in the household-travel survey, in which itineraries are not informed.

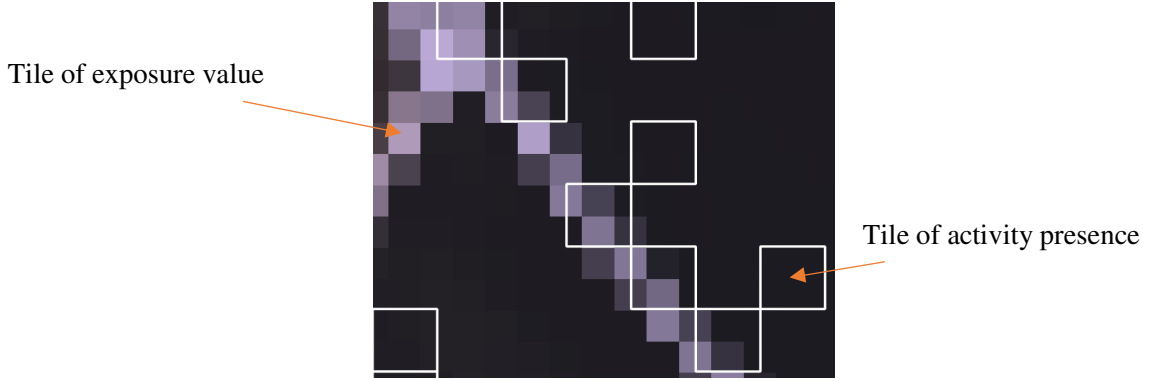
205 3.3 Exposure attribution method for activity places

206 Let us consider pollutant X whose concentration is calculated by simulation. On day D , the whole territory
207 being studied is divided into cells which form a grid $I \times J$. Each cell (i, j) has a corresponding exposure
208 $E_{ij}(h)$ at time h . This exposure is constant during time step t . The step values are named $\{h_1, \dots, h_n\}$

209 For each individual $k \in K$, the sample data from the household travel survey contains a list of trips with a
210 place of origin and a destination.

211 In a day, activity times supplement the individual's travel time. The activity start time is the arrival time of
212 the travel to get to that activity and the end time is the start time of the next travel to get to the next
213 activity. The list of activities for each individual is thus constructed and each activity is associated with a

214 place, a start time and an end time. Let us name a spatial place $s \in S_k$ for the surveyed day identifiable on
 215 a specific provided grid $M \times N$. The corresponding cell of place s is noted (m_s, n_s) .



216
 217 Figure 1: Superimposing the grids of exposure values and activity presence of the individuals surveyed in
 218 the household travel survey.

219 These two grids do not have the same institutional origin and therefore have no reason to have the same
 220 surface area and spatial reference points (Figure 1). A spatial join allows the correspondence between the
 221 two tables and gives for each cell (m_s, n_s) its average exposure for each time step available for the
 222 exposure values. As we do not know where the individual is exactly in the cell, we approximate the
 223 exposure in a cell (m_s, n_s) , which corresponds to activity d on time schedule h with the ratio of the
 224 surface shares S of each cell (i, j) by its exposure which belongs spatially to (m_s, n_s) . We then obtain:

$$225 \quad E_h(d) = \frac{1}{S_{(m_s, n_s)}} \sum_{(i, j) \cap (m_s, n_s)} S_{(i, j) \cap (m_s, n_s)} \cdot E_{ij}(h)$$

226 During activity d of individual k , which starts at time h and lasts for a time t_d , noted $h_i \in [h_1, h_n]$ the
 227 time discretization of the exposure maps, the average exposure is :

$$228 \quad E(d) = \frac{1}{t_d} \left((h_1 - h) \cdot E_{h_1}(d) + \sum_{h_1 < h_i < h_n} (h_i - h_{i-1}) \cdot E_{h_i}(d) + (h + t_d - h_n) \cdot E_{h_n}(d) \right)$$

229 3.4 Exposure attribution method for trips

230 A traffic model is used to estimate the exposure of individuals during their journey. Most traffic models
231 are not multimodal. For example, trips that are only on foot are rarely assigned. In this theoretical step, it
232 is assumed that the model is fully multimodal and that all trips in the household travel survey can be
233 assigned by the model. In the case study, we will use a traffic model with only road vehicle assignment.
234 Depending on the time of day, the average travel times are of course different depending on peak and off-
235 peak hours and congestion on the network. We therefore consider time periods, each with its own routes
236 per mode and travel time on the multimodal transport network. The network is a graph of V nodes and A
237 arcs.

238 Two general simplifications are made in this theoretical part. Firstly, exposure during journeys by rail,
239 both on platforms and in trains, is very difficult to estimate (Cepeda et al., 2017). To escape from this
240 complexity, which requires detailed knowledge of the network and exposure values in confined spaces,
241 the decision was made to remove the time spent in heavy transport from the daily exposure assessment.
242 For individuals who used rail transport, the final exposure time therefore corresponded to 24 hours minus
243 the time spent in rail transport. Secondly, exposures during car journeys are estimated from exposures
244 outside the vehicle, hence the maps of concentrations, and not in the cabin.

245 The method therefore consists in joining the paths of each journey given by the simulations and between
246 the values of exposure to the pollutant at each time. Let us consider a trip τ by individual k between 2 tiles
247 (o, d) in the $M \times N$ grid. A spatial analysis allows us to associate the center of gravity of the tile with the
248 nearest grid node. We thus obtain the path $p \subset A$ taken by individual k for trip τ which starts at time h_τ :
249 $p(o, d, h_\tau) = \{(a, h_{\tau,a}, t_a(h_\tau)), a \in p\}$ for which a is an arc, $h_{\tau,a}$ the arriving time on a , and $t_a(h_\tau)$ is the
250 travel time of arc a at the time of the travel. This time is a function of the time of departure and hence of
251 the traffic condition which varies throughout the day. The route chosen is considered to be the minimum
252 time between the origin and destination.

253 For each arc a of path p , the geographical coordinates of the arcs and arrival time $h_{\tau,a}$ are sufficient to
 254 obtain the values of exposures on the path.

255 Spatial representations of transport networks are often handmade and have an element of uncertainty.
 256 Thus, exposure values and networks do not necessarily overlap. In order to limit representation errors, the
 257 highest pollutant value is associated with each arc in a buffer of a distance θ m from each arc, which is
 258 called A_θ :

$$259 \quad E_a(h_{\tau,a}) = \max_{(i,j) \cap A_\theta} (E_{ij}(h_{\tau,a}))$$

260 We then obtain the average exposure of individual k for trip p with $t_p = \sum_{a \in p} t_a(h_\tau)$ the travel time:

$$261 \quad E(p) = \frac{1}{t_p} \sum_{a \in p} t_a(h_\tau) \cdot E_a(h_{\tau,a})$$

262 3.5 Daily exposure calculation

263 Parts 3.3 and 3.4 explain how individual exposures are calculated for each time of day, at each activity
 264 location, and during travel by all modes of transport except rail, which is too complex to consider. We
 265 calculate the average daily exposure \bar{E}_k for each individual as the sum of exposure during the activities
 266 $E(d)$ and during the trips $E(p)$:

$$267 \quad \bar{E}_k = \frac{1}{24 - t_{RT}} \left(\sum_d t_d \cdot E(d) + \sum_p t_p \cdot E(p) \right)$$

268 By noting $\mathbf{1}$, the indicator function which gives 1 if the inequality condition is met, otherwise 0, and the
 269 dangerousness threshold E_{LIM} , the number of individuals exposed $K_E \subset K$ to values considered to be
 270 hazardous to health by the competent agencies was therefore:

$$271 \quad K_E = \sum_{k \in K} \mathbf{1}_{\bar{E}_k > E_{LIM}}$$

272 4 Data and assumptions

273 The rest of the article illustrates the theoretical model presented in the previous section. The selected case
274 study is exposure to the NO₂ pollutant characteristic of diesel engine emissions. This part introduces NO₂
275 pollution, the dangerous exposure thresholds chosen for the study, the data necessary to produce the
276 results for the Paris region (Ile-de-France). Finally, we present in this part the principle of the LEZ and the
277 particularities of the LEZ in the Paris region and the scenarios to be evaluated with their main assumptions
278 especially the expected concentration of NO₂.

279 4.1 From threshold to exposed population

280 In order to go from exposure per individual to an indicator of danger to health, exposure thresholds have
281 been defined. In particular, two types of thresholds are monitored for NO₂. Exposure thresholds for very
282 high pollutant concentrations are used to measure the magnitude of pollution peaks. Not all organizations
283 in charge of setting these thresholds throughout the world have the same thresholds. It can be noted that
284 the WHO sets this threshold at 200 µg/m³. A second type of threshold aims to measure background
285 exposure, i.e. the average continuous exposure of individuals to pollution despite daily variations or
286 exceptional exposure of individuals. Several thresholds also coexist, but one threshold is more widely
287 accepted since it is used by the WHO and the European Union: the limit value of 40 µg/m³ as an annual
288 average exposure. In this research, this annual average value is used as an indicator for an average day.

289 4.2 Paris region data

290 As explained in the general method, three types of data are used: the Ile de France household travel survey
291 (Île-de-France Mobilités, DRIEA¹), NO₂ concentrations estimated by modelling (Airparif) and the
292 MODUS travel simulation model (DRIEA). These data are all spatialized and have the same geographical
293 scope, i.e. the Ile-de-France region.

¹ Direction Régionale et Interdépartementale de l'Équipement et de l'Aménagement d'Ile de France.

294 4.2.1 The Ile de France household survey

295 The region's 2010 Household Travel Survey surveyed 32,241 individuals aged 5 years and older in 14,885
296 households. They correspond to a representative sample of resident households in Ile-de-France, which
297 has 12.2 million residents. A weighting system is applied to the individuals to adjust the results for all
298 residents. It provides information on the socio-economic characteristics of individuals and households.
299 The data also provides information on weekday travels by individuals. All spatial information, such as the
300 place of residence or the origin and destination of travel, is provided at the 100-metre tile scale. The
301 sample excluded individuals who travelled outside the region on the survey day. It should therefore be
302 borne in mind that the population studied in this research does not correspond exactly to the whole
303 resident population.

304 4.2.2 The space-time exposure simulation by Airparif

305 Airparif, the association for monitoring and controlling air quality in the Paris region, simulates the main
306 pollutants monitored for public health purposes using meteorological models, traffic models and maps of
307 emission sources. For this research, the NO₂ exposure maps for the day of 9 January 2019 are used. This
308 day was chosen because it is a working day out of school vacations and it is **a day with pollution**
309 **concentrations that are close to the annual averages (from 35 µg/m³ in the center to 10 µg/m³ in the**
310 **periphery, Airparif 2019)**. Exposure values are provided for each hour of the day with several spatial
311 discretizations. On the scale of the Paris region, a 50-metre tile grid covers the entire territory. The
312 exposures in the inner ring of suburbs are available in 25-metre tiles in the same orthonormed marker as
313 the 50-metre grid. Finally, a 12.5-meter grid covers the city of Paris.

314 4.2.3 The MODUS road assignment model

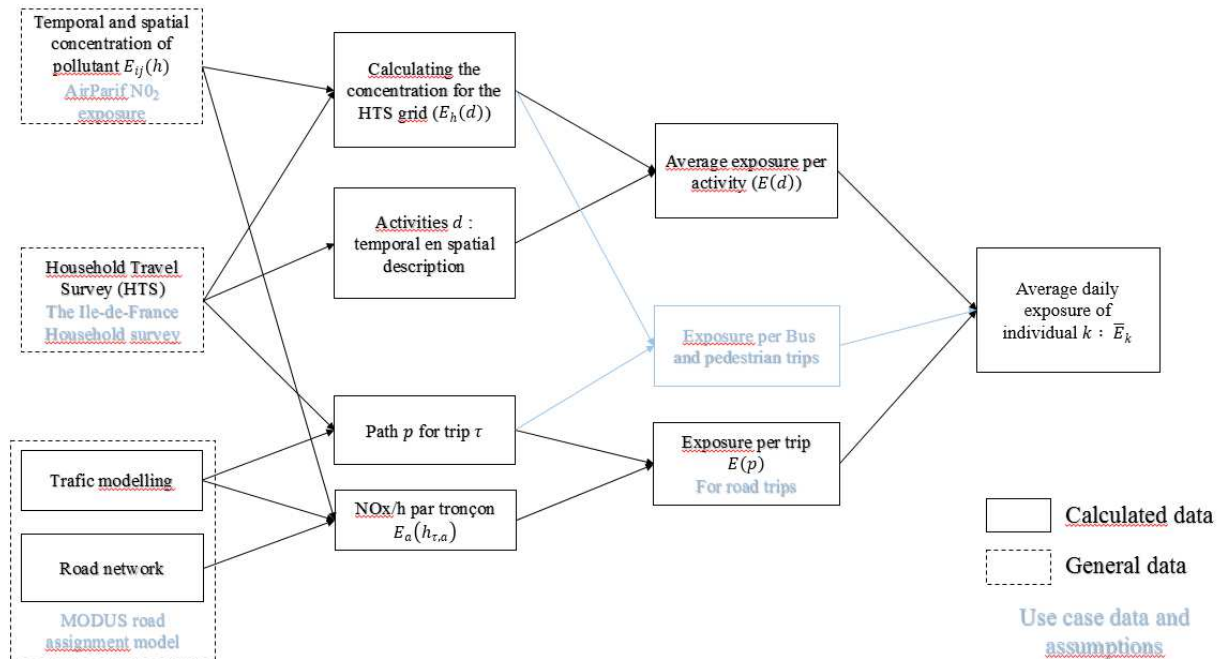
315 The DRIEA's MODUS traffic model simulates road travel on an average working day in the Ile de France
316 region. Three static simulations are made: one at morning peak hour (7-9am), one at evening peak hour (5-
317 7pm) and one representing off-peak hours. This time division only impacts traffic conditions and travel
318 times. For each hour of the day, the model estimates a travel time according to traffic conditions on each

319 section of the main road network in Ile de France. The nodes of the main network are not numerous
320 enough in sparsely populated areas to be able to estimate the routes of each journey precisely. Short trips
321 in peripheral areas that do not use the main network will be poorly estimated. However, the journeys that
322 will have an impact on exposures are those that are long and pass along main roads or through relatively
323 more polluted areas. These trips should be estimated well by the model.

324 4.2.4 Hypothesis for other trips

325 The MODUS model is a multimodal model. However, walking and cycling trips are not assigned to the
326 road network. Similarly, the public transport network is disconnected from the road network and the
327 network graph is only connections between successive stations. For all these trips, it is therefore not easy
328 to reconstruct a route on the metropolitan road network. In addition, pedestrian or bus travel is generally
329 over short distances (0.3km for pedestrians and 3.3km for buses, and bus travel encompasses pedestrian
330 access distances), while car distances have an average of 6.1km in the Paris region. Hence, the exposure
331 context varies relatively little between origin and destination. Moreover, the spatial resolution of NO₂
332 concentrations is not sufficient to cover certain streets. The simplifying hypothesis that was taken was to
333 estimate exposure during these trips as an average between the exposure at the points of origin and
334 destination over the entire duration of the travel. The average corresponds to a lower value than the
335 exposure close to road traffic, so the final value will tend to be lower than the average exposure of
336 individuals who choose these modes, but this assumption corresponds to less than 2% of daily time.

337 Finally, a diagram summarizes the method and data taken for the case study as well as the assumptions on
338 exposure during trips (Figure 2).



340

341 Figure 2: Diagram of the method for calculating individual exposure in the general cases and in blue font
342 for the Paris region use case.

343 4.3 The Paris metropolitan LEZ

344 4.3.1 The LEZ project

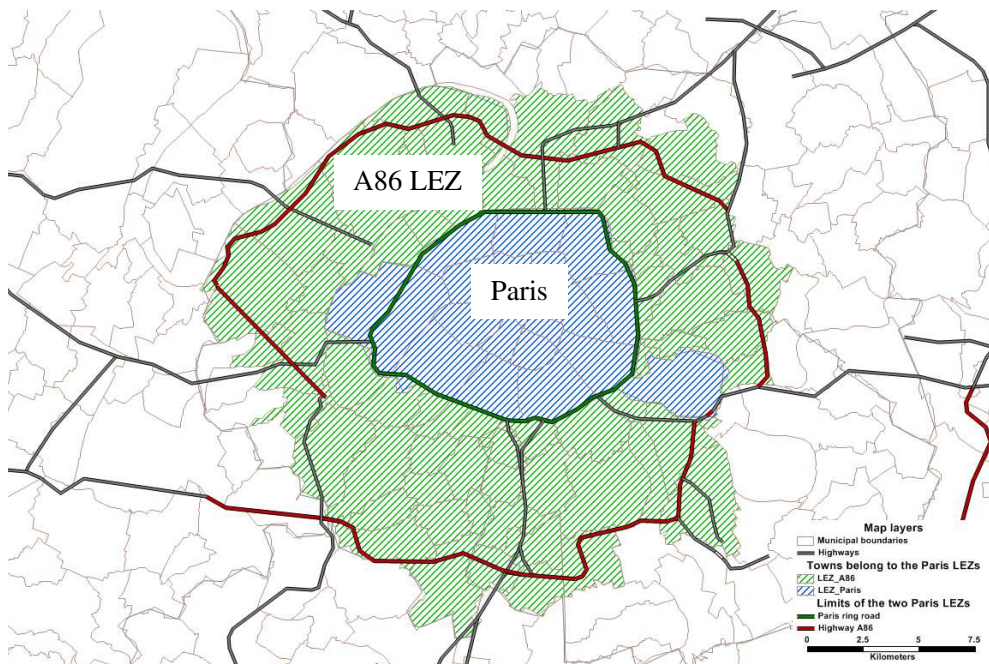
345 In 2015, the Greater Paris Metropolitan Authority, which manages a large part of the center of the Parisian
346 metropolitan area, won a call for projects from the French government to establish measures to improve
347 air quality by implementing an LEZ in particular. To accompany traffic restrictions, the Crit'Air sticker,
348 which is valid throughout France, was used to categorize all motorized vehicles according to the level of
349 atmospheric pollutant emissions from their engines based on the Euro standard (Table 1). Six classes of
350 vehicles were created in the Crit'Air classification (seven considering non-classified vehicles that do not
351 have a sticker). From 2016, vehicles without a sticker were no longer authorized to drive in Paris on
352 working days between 8am and 5pm. Since then, the oldest vehicles that theoretically emit the most
353 pollutants (Crit'Air 4 and 5 stickers) have been banned inside Paris. The metropolitan area has since

354 sought to limit pollutant emissions from road traffic over an area much larger than just the center of Paris.
 355 The perimeter inside the A86 bypass motorway has been defined for this purpose, and in July 2019 the
 356 most polluting vehicles are banned from travelling during the day within this large area (Figure 3).

357 Table 1: The 6 classes of the Crit'Air classification in Euro standard.

Crit'Air class	Green	1	2	3	4	5
passenger car or Gazoline		Euro 5-6	Euro 4	Euro 2-3		
light commercial vehicle (LCV)		(2011-)	(2006-2010)	(1997-2005)		
	Diesel		Euro 5-6	Euro 4	Euro 3	Euro 2
			(2011-)	(2006-2010)	(2000-2005)	(1997-2000)

358 The Green sticker corresponds to electric or hydrogen vehicles. Euro 1 or older vehicles cannot have
 359 stickers.



360
 361 Figure 3: Perimeters of the LEZs of the Paris metropolitan area.

362 Airparif and the Greater Paris Metropolitan Authority conducted an evaluation of the LEZ in Ile de France
 363 (Host et al., 2020). For this purpose, the reduction in emissions of each pollutant was estimated for each

364 tightening of traffic restrictions. The evaluation of the benefit in terms of population exposure was also
365 performed, but only on the basis of the place of residence of people living within the perimeter.

366 4.3.2 The LEZ scenarios

367 The two LEZ perimeters in the Ile de France region are studied. For the concentration scenarios and
368 average benefits from the LEZs, we use the study by (Host et al., 2020), which simulated several LEZ
369 scenarios in the Paris conurbation. They compared the concentration values obtained after simulation of
370 the implementation of LEZ with a scenario they called the “business-as-usual”, which in fact corresponds
371 to the years 2018/2019 prior to the date of the study and prior to implementation of some of the planned
372 LEZ scenarios. They justified this by the fact that trends in motor vehicle use are difficult to apprehend.
373 This allows us to consider the NO₂ concentrations for the day of January 9, 2019 as a reference in relation
374 to the concentrations estimated with the simulations for the various LEZs. In addition to the two
375 perimeters, two LEZ scenarios are considered: a “weak” scenario prohibiting stickers of Crit'Air category
376 4 and earlier (i.e. in particular diesel light vehicles manufactured before 2006, Table 1) and a “strict”
377 scenario prohibiting vehicles manufactured before 2011 and corresponding to the Euro 4 and earlier
378 standards. For the weak scenario limited to central Paris, they estimated a change in average value from
379 between 28 and 55µg/m³ in their baseline scenario to concentrations of between 24 and 51µg/m³. In their
380 “strict” scenario, the average values fell to 20-42µg/m³.

381 As we do not have the values for the extended LEZ, we will consider with regard to the NO_x gains (from
382 44% for Paris only to 51% for the extended LEZ (Airparif, 2018) and the gain maps presented in the
383 article by Host et al., that these gains were identical for the whole perimeter. We assume that new NO₂
384 exposures follow a linear decrease compared to exposures without LEZ and through the following
385 reference points:

- 386 (i) For the weak scenarios (Paris and A86): The range falls from 29µg/m³ to 24µg/m³ and from
387 58µg/m³ to 51µg/m³

388 (ii) For the strict scenarios (Paris and A86): from $28\mu\text{g}/\text{m}^3$ to $20\mu\text{g}/\text{m}^3$ and from $55\mu\text{g}/\text{m}^3$ to
389 $42\mu\text{g}/\text{m}^3$

390 4.3.3 LEZ assumptions

391 In addition to the assumptions already described about exposure in the transport modes, certain
392 assumptions are introduced in the scenarios: (i) Host et al (2020) specified that they could not distinguish
393 individuals who used the car entirely outside the 8am-8pm period in which the LEZ is active, meaning
394 that renewal of the vehicle fleet concerns those individuals who use their car during the working day. The
395 gains will therefore be assumed for the whole day and not just for the effective period of the LEZ. (ii) The
396 authors estimate a non-zero gain outside the perimeter due to the trip of individuals working within the
397 LEZ perimeter but residing outside. In the absence of precise values and spatial uncertainties in the
398 estimates, we will consider that the gains in concentrations relate only to the perimeters of the LEZs that
399 have been created.

400 To summarize, 4 scenarios are studied and compared to the reference day of 2019. A first group of
401 scenarios for a first objective of restricting motorized vehicles within the perimeters of Central Paris and
402 the A86 (Weak Paris LEZ, Weak A86 LEZ) and a second group for a second, more restrictive objective
403 that only authorizes vehicles with Crit'Air sticker number below 2 as described in Table 1 (Strict Paris
404 LEZ, Strict A86 LEZ).

405 5 Results

406 In this last part, original results will provide a fresh look at this type of assessment. Finally, a discussion
407 compares these results with more classical evaluation methods.

408 5.1 Who benefits from the Paris low emission zone?

409 In the appendix, the initial results justify the interest of the spatio-temporal method for population
410 exposure to NO_2 pollution by comparing exposed populations with our method and with a static
411 residential method.

412 By applying the spatio-temporal method for each of the 5 scenarios, the comparisons give us the results
 413 presented in this part. Since all residents are beneficiaries in terms of air quality but to different degrees, in
 414 our study we define as beneficiaries those who will benefit most from the implementation of the LEZ.

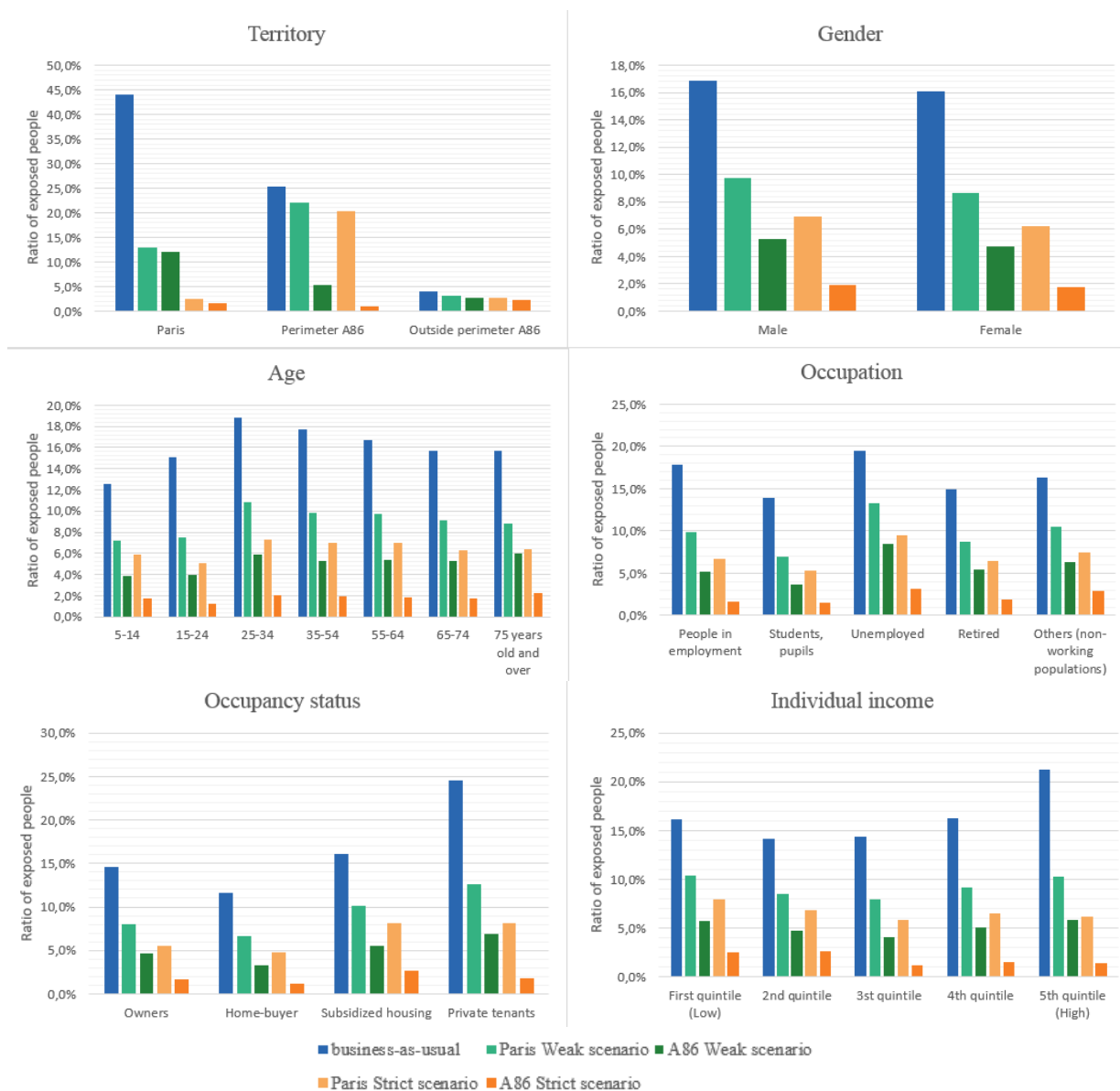
415 5.1.1 General results

416 Table 2 provides information on the number of people who remain above the dangerous exposure
 417 thresholds for each of the simulated scenarios, who are referred to as "polluted". The largest gains are for
 418 the simplest scenario to implement, the Paris perimeter and the least severe motorized vehicle restrictions,
 419 with nearly 45% of the population being removed from critical exposure levels. Extending the perimeter
 420 to the whole of the A86 reduces the number of polluted people by a further 45%. The strong scenario has
 421 less impact on the Paris perimeter than on the A86 perimeter, with the share of the number of polluted
 422 people balancing out between Paris and the rest of the dense conurbation with the implementation of the
 423 Paris LEZ. The strict scenario is therefore effective within the A86 perimeter within the framework of the
 424 assumptions made, with a drop of nearly 90% in the number of polluting vehicles. There would only be
 425 1.8% of the population above the critical thresholds for NO_x pollution. This result is of course open to
 426 criticism insofar as it depends on two very strong hypotheses, the first being strict compliance with the
 427 LEZ by motorists, and the second the fact that 70% of the owners of banned vehicles choose to buy a new
 428 car (Host et al. 2020).

		Weak		Strict	
		Paris LEZ	A86 LEZ	Paris LEZ	A86 LEZ
Total number of exposed people	1 722 000	963 000	529 000	688 000	190 000
Ratio of exposed population from total Paris Region	16,5%	9,2%	5,1%	6,6%	1,8%

429 Table 2: The number of people exposed to critical thresholds for all scenarios

430 Figure 4 shows the results per scenario as a function of the area of residence and the socio-demographic
431 characteristics of the population. For each characteristic or place of residence, a breakdown into categories
432 makes it possible to quantify the percentage of exposed persons out of the total for that category. This
433 indicator makes it possible to evaluate the benefits of each scenario for each category. For the territorial
434 breakdown, while 44% of Parisians were polluted in the reference scenario, the figure was only 13% in the
435 weak scenario limited to Paris and a little over than 3% for the strict Paris scenario. It is interesting to see
436 that the Paris LEZ scenarios also benefit residents inside and outside the A86. A decrease of 13% and 20%
437 in the number of polluted residents for each of these territories is found for the weak Paris scenario. For
438 the highest scenario, the drop in polluted residents outside the A86 perimeter is even 43%, showing the
439 importance of exposure to pollutants during travel, particularly for these areas far from the center and with
440 little NO₂ pollution. We note that men are more exposed than women, whatever the scenario. When
441 making calculations for residential exposure, the polluted populations are comparable between men and
442 women, so it can be deduced that men's choice of transport mode and more polluted places of activity
443 explain these differences. The age distribution also shows that while 5-14 year-olds are the least polluted,
444 the most polluted are 25-34 year-olds in the reference scenario. Whatever the scenario, the under-25s
445 represent the smallest portion of polluted residents. Unemployed and employed workers are the most
446 polluted at present, while students and pensioners are the least. Quite logically, residential first-time
447 buyers and owners, mainly located in the periphery, are those who are least exposed to the most severe
448 NO₂ pollution, unlike tenants in the very many private housing estates in Paris and in the densely-
449 populated areas of the conurbation. The richest and poorest categories of population are the most polluted,
450 and it is these categories that are over-represented in Central Paris, unlike the middle class who live in
451 areas far from the center, that are therefore less polluted.



452

453

454

455 Figure 4: Characteristics of populations with exposure exceeding danger thresholds, by LEZ scenario.

456 5.1.2 The beneficiaries

457 Finally, the characteristics of the beneficiaries are specified in the following table (Table 3). While the
 458 previous figure detailed the distribution of the number of people polluted according to each characteristic
 459 studied, this table shows the dynamic aspect of the distribution of the population with the changes in
 460 distribution by category according to the scenarios. The percentages are therefore the relative differences

461 for each category in the population leaving the initial group of those exposed to pollution, and the
 462 remaining population. The reference population is therefore the whole polluted population in the reference
 463 scenario, and the variations in relation to this population are then observed according to the different
 464 scenarios.

	Weak				Strict			
	Paris LEZ		A86 LEZ		Paris LEZ		A86 LEZ	
	Those leaving the >40µg/m ³	Those remaining in the >40µg/m ³	Those leaving the >40µg/m ³	Those remaining in the >40µg/m ³	Those leaving the >40µg/m ³	Those remaining in the >40µg/m ³	Those leaving the >40µg/m ³	Those remaining in the >40µg/m ³
Area of location								
Paris	38%	-91%	16%	-13%	37%	-596%	69%	-192%
Perimeter A86	-236%	36%	41%	-47%	-197%	50%	70%	-210%
Outside perimeter A86	-113%	30%	-382%	55%	-101%	43%	-953%	81%
Gender								
Men	-3%	3%	-1%	1%	-1%	3%	-2%	2%
Women	5%	-4%	6%	-4%	3%	-3%	4%	-3%
Age group (in years)								
5-14	-2%	2%	-1%	1%	-13%	15%	-26%	18%
15-24	13%	-13%	20%	-17%	11%	-20%	27%	-32%
25-34	-3%	3%	-1%	1%	3%	-3%	4%	-4%
35-54	2%	-1%	5%	-3%	1%	-1%	2%	-2%
55-64	-4%	3%	-5%	4%	-2%	4%	4%	-4%
65-74	-4%	3%	-14%	9%	1%	0%	0%	1%
Over 75	0%	1%	-38%	19%	0%	2%	-34%	23%
Occupation								
People in employment	3%	-1%	7%	-5%	5%	-7%	16%	-16%

Students, pupils	13%	-12%	21%	-18%	4%	-4%	4%	-3%
Unemployed	-36%	18%	-71%	29%	-15%	17%	-57%	33%
Retired	-5%	4%	-27%	15%	-4%	7%	-17%	13%
Others (non-working populations)	-22%	13%	-41%	21%	-9%	12%	-71%	37%
Income (per consumption unit)								
First quintile	-22%	13%	-22%	13%	-18%	19%	-45%	28%
Second quintile	-10%	7%	-15%	9%	-16%	18%	-85%	41%
Third quintile	2%	-1%	12%	-9%	0%	1%	28%	-33%
Fourth quintile	-1%	1%	-1%	1%	1%	0%	17%	-18%
Fifth quintile	15%	-16%	15%	-12%	16%	-37%	43%	-66%
Housing occupancy status								
Owners	3%	-2%	-6%	4%	4%	-5%	-2%	2%
Home-buyer	-2%	2%	11%	-8%	-1%	3%	7%	-6%
Subsidized housing	-17%	11%	-16%	10%	-20%	21%	-55%	32%
Private tenants	10%	-9%	12%	-9%	11%	-19%	35%	-46%

465 Table 3: Relative differences in population distribution

466 While the study of values by place of residence confirms that LEZ perimeter residents are the primary
467 beneficiaries, and variations by gender are quite small, the other characteristics do highlight categories of
468 the population that benefit more from LEZs than others. In particular, with regard to age, 15-24 year-olds
469 seem to benefit most from the LEZs, regardless of the geographical perimeter. For the A86 perimeter,
470 among the people who would remain the most polluted, the elderly would be over-represented compared
471 to other age groups, particularly those aged 75 and over. The 5-14 year-olds, in contrast to 15-24 year-
472 olds, will be over-represented among the people who will remain among the most exposed to pollution in
473 the strict scenarios. In principle, these two categories of population are those who remain closest to home,
474 travelling an average of less than 6 km per day, whereas the other age groups do between 14 and 25 km

475 per day on average. We can thus deduce that if they live in a very polluted neighborhood, they do not
476 benefit from concentration values below the danger threshold by travelling to other neighborhoods. This
477 trend is confirmed by studying the occupation of individuals. The unemployed, inactive people at home
478 and those who have retired, who are the least likely to go to another place for a long time during the day,
479 are quite significantly the categories of population that will benefit least from the LEZ in all the scenarios
480 studied. The Parisian strict scenario would be the least inegalitarian from the point of view of occupation,
481 in contrast to the A86 perimeter scenarios which, for the weak scenario, benefit mainly students and, for
482 the strict scenario, rather employed workers. The distribution by income clearly shows that the biggest
483 beneficiaries of the LEZ would be the individuals with the highest incomes. This would confirm the
484 results obtained by Holz et al. (2020) from the population census with a static approach. Social housing
485 tenants are the least advantaged by the LEZ, in contrast to tenants in private housing stock.

486 This analysis clearly shows that the most mobile people are the big winners of the LEZs, be they students,
487 managers or the wealthiest individuals. Changing location during the day allows them statistically to
488 optimize their chances of having an average daily exposure below the $40 \mu\text{g}/\text{m}^3$ threshold. The places of
489 residence of the poorest, unemployed or retired people may also be in the most polluted areas. Lowering
490 average NO_2 exposures would not be enough to bring them below the danger thresholds.

491 Cross-referencing with the previous results, the poorest populations and the unemployed, who are the
492 biggest polluted populations at present, benefit least from the different LEZs studied here. There is
493 therefore no evening out between the populations but, on the contrary, a widening of inequalities.
494 Similarly, for the populations at risk (the youngest and oldest), although they are the least numerous
495 among the polluted population, more of them would remain at average concentrations above the danger
496 thresholds.

497 5.2 Discussion

498 A number of uncertainties in the results arising from the many assumptions made in the method need to be
499 discussed. Two types of assumptions can be grouped together, those directly related to the method and
500 those intrinsic to the tools or values chosen in the literature.

501 For the first group of hypotheses, one uncertainty comes from the use of the exposure map, which is the
502 most precise available for the Paris region for only one particular day of average NO₂ pollution
503 concentration, and not for all the days of a whole year. It would have been possible to use an average
504 exposure day that includes weekend days or school holidays that are very different from other working
505 days in terms of automobile traffic and therefore NO₂ exposure. But it would have been just as
506 questionable for our method, which cross-references concentrations with the activities of individuals on a
507 working day. However, apart from days with high NO₂ pollution or weather conditions favorable to good
508 air quality, the low dispersion of NO₂ around sources of pollution limits the variations in concentrations
509 between two average days. Moreover, the estimates of the drop in concentration taken for the LEZ
510 resulting from simulation are sufficiently large to limit the impact of uncertainties on the initial
511 concentrations chosen.

512 A second classic uncertainty in this type of method concerns the transition from average concentration on
513 a spatial tile to individual exposure. Studies have shown the bias in the use of outdoor concentrations for
514 personal exposure, regardless of indoor or outdoor location (Evangelopoulos et al., 2020; Shaw et al.,
515 2020). They also point to the decorrelation between outdoor and indoor pollution. The lower values of
516 exposure to NO₂ inside buildings would have a fairly homogeneous relative impact on the entire urban
517 population, which spends most of its time in a building and more rarely outdoors, with the exception of
518 certain trades or tourists who could be the subject of specific research studies (Duché, 2015).

519 Exposure during travel by different modes of transport is also very difficult to assess (Cepeda et al., 2017).
520 If exposure during motorized travel is assessed fairly accurately on tiles corresponding to road
521 infrastructure, the NO₂ concentration in the passenger compartment is likely to be much higher than

522 outdoor concentrations, but the dispersion of values is very high and an important parameter that emerges
523 from the study is the distance from the vehicle in front and the pollution it emits (Airparif, 2009). In the
524 Hamburg conurbation, a city where public transport is widely used, as in the Ile de France region, only
525 10% of total annual exposure during travel is by public transport (Ramacher and Karl, 2020). In the Paris
526 region, only 24% of residents travel by heavy transit mode and in this mode, the average travel time by
527 day is 27min i.e. 2% of a day. The average exposure would be between $40 \mu\text{g}/\text{m}^3$ and $60 \mu\text{g}/\text{m}^3$ depending
528 on the mode in the Paris region (Delaunay et al. 2012). This relativizes the importance of having removed
529 public transport trips by rail from the study. Another study also showed the preponderance of exposure
530 during car trips over other modes of travel (Žak et al., 2017), between 33% and 60% higher than a bus trip
531 and between 60% and 80% higher than a walk. A meta-study also put these results into perspective by
532 studying the differences between exposure and inhaled concentrations (Cepeda et al., 2017). Inhaled
533 concentrations are higher for pedestrians and cyclists, but physical activity outweighs the health harms.

534 To better assess the impact of these uncertainties in our method, we performed an analysis of sensitivity to
535 different exposures during trips. The chosen method clearly minimizes exposure to pollutants. We
536 compare the averages obtained by our model with those available in the literature (Delaunay et al. 2012),
537 which gives references of exposures for Parisian trips. We choose to test an increase in exposure to this
538 high limit for the following modes: car, bus and walking. A 100% increase in exposure during car and
539 motorized two-wheeler travel increases the share of the polluted population from 16.5% to 21.0%, +50%
540 for pedestrian trips or +100% for the bus, a share of 17.8%. Finally, the combination of a degraded
541 exposure in the three modes provides a share of 23.7%. However, for the LEZ, with these high values of
542 exposure in travel, a decrease in exposure through the LEZ will always benefit those who make the most
543 trips, i.e., workers.

544 The second group of uncertainties concerns the adapted hypotheses of studies on the same territory with
545 different LEZ simulations (Host et al., 2020). A hypothesis of a homogeneous concentration gain over all
546 the LEZ perimeters was taken. However, the gains would be greater in the vicinity of major road

547 infrastructures. Motorists who spend the most time in their vehicles, as well as residents or workers in
548 areas adjacent to busy roads, would thus benefit the most from LEZ. A more precise study based on a gain
549 map of the territory would make it possible to take into account these variations in concentration around
550 the main road infrastructures. The average gain values that were applied are certainly too optimistic. Host
551 et al (2020) considered a strict respect of access restrictions and very optimistic hypotheses for the
552 renewal of the fleet towards a new fleet. As shown by studies (Holman et al., 2015) comparing the
553 concentrations estimated by simulations and sensor readings in several large cities, there is a very large
554 difference and the gains could be 10% lower. The advantage of large gains is to show what can be
555 achieved by accompanying the LEZ with other measures, such as support for the purchase of clean cars or
556 a strict control of entry into the LEZ. This also makes it possible to achieve significant results and not
557 remain within the margins of error. It is shown that the beneficiaries vary relatively little according to the
558 gain values. The assumption of zero NO₂ concentration gain outside the LEZ limits the number of
559 beneficiaries outside the LEZ. Therefore, it can be assumed that this number is much higher than the one
560 evaluated only with those who enter the LEZ during their activities.

561 The level of detail of the results obtained by socio-demographic category and territory is limited by the
562 very coarse assumptions of gain, but above all by the statistical sampling of the survey, which does not
563 allow for too fine a disaggregation of the results. The use of the population census allows for finer
564 analyses of residence but does not provide enough information on individual trips and activities. The
565 activity models often used in research (Dhondt et al., 2012; Vallamsundar et al., 2016) allow the results to
566 be disaggregated very finely, but the uncertainty about what activities are actually carried out for different
567 types of individuals is much greater than the direct use of a household travel survey. Another limitation of
568 these surveys is that mobility behaviors are stable before and after measurement. No evaluation today uses
569 an activity model to assess LEZs because behavior change surveys are lacking to be able to reallocate
570 travel after the restriction.

571 An important discussion concerns the threshold used to define so-called polluted populations. This
572 threshold of $40 \mu\text{g}/\text{m}^3$ annual average concentration used by the main public health agencies remains very
573 arbitrary in defining which populations are at risk and which are not. A sensitivity analysis on this
574 threshold, as well as a finer analysis of the time spent by populations at very high NO_2 concentrations,
575 would be relevant to characterize the benefits more effectively.

576 Finally, those who benefit the most from the LEZ in terms of air quality are perhaps also those who
577 already have the most recent cars and therefore will not have the difficulties faced by certain
578 underprivileged populations in having to demotorize or buy a newer car. For this and other reasons, some
579 municipalities within the LEZ perimeter have not yet decided to apply the measure in their perimeter.

580 Conclusion

581 This article shows the main beneficiaries of the LEZ in the Paris region. To do this, an original method
582 was used, cross-referencing NO_2 exposure data with a household travel survey and an allocation model to
583 find out where individuals were in the course of the day. The results show that depending on the LEZ
584 scenario, between 13 and 43% of residents who were exposed to high NO_2 concentrations outside the LEZ
585 perimeter fell below the critical threshold of $40 \mu\text{g}/\text{m}^3$. The wealthy and working people who were
586 exposed to the highest concentrations represent the largest proportion of those who benefit from the LEZ,
587 while the unemployed, retired people and the very young, who remain close to their residence, are the
588 least numerous among the beneficiaries. This public policy evaluation provides decision-makers with
589 original and more precise results by showing that the beneficiaries are not necessarily residents within the
590 perimeter of the measure, but also that the most vulnerable categories of people, and those who emit the
591 least NO_2 , are the least advantaged by this type of environmental policy in a large conurbation such as
592 Paris. We can also question the effectiveness of this type of policy in reducing the impact on human
593 health. We can see that at least one strict LEZ over a very wide geographical area is needed to see a
594 substantial reduction in the population exposed to critical NO_2 concentrations. Supporting LEZ systems

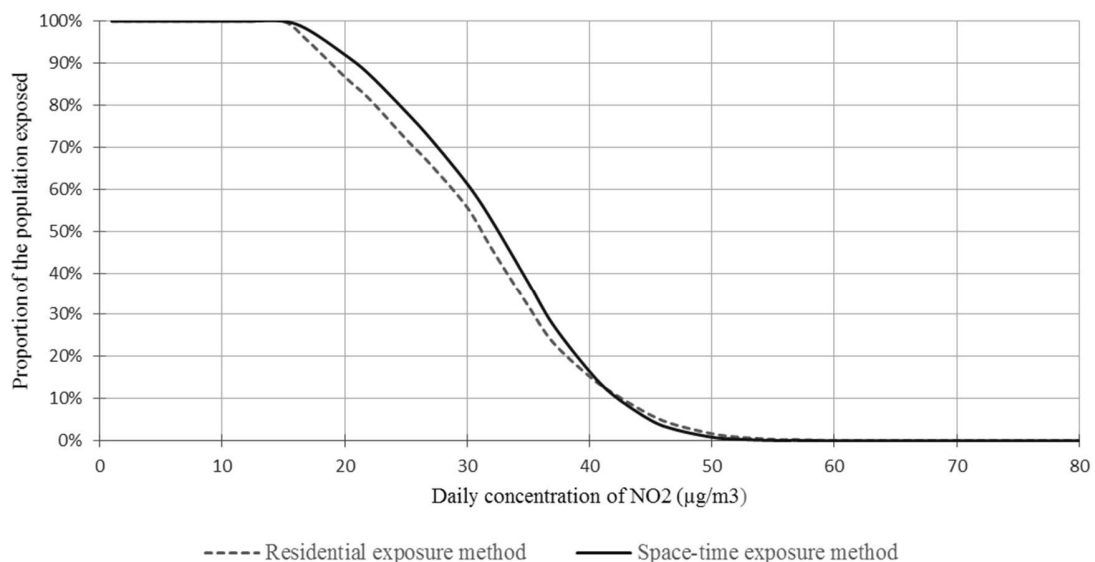
595 with strict control of entries and financial aid to get rid of the most polluting vehicles would provide an
596 effective complement to the LEZ system.

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599 We would also like to thank DRIEA for letting us use their MODUS model for our research. Thanks also
600 to Laurence Debrinka of IDFM for coming up with this idea.

601 Appendix

602 This appendix presents the results of daily NO₂ exposure for the population of Île-de-France according to
603 the residence approach and the spatio-temporal approach. The average daily exposure values are thus 31.0
604 µg/m³ and 32.1 µg/m³ respectively. The difference between the averages from these approaches does not
605 appear to be very high. This difference between the two approaches (+4%) is similar to that observed by
606 Dhondt et al (2012) in Flanders, who estimated an average daily exposure of 20.98 µg/m³ with the
607 residential approach and 21.6 µg/m³ with the spatio-temporal approach (+3%). Figure 2 shows the
608 breakdown of the population of Île-de-France by daily average NO₂ exposure value, between 0 µg/m³ and
609 80 µg/m³. The first result is that no individual is exposed to daily average levels below 15 µg/m³ and none
610 to levels exceeding 60 µg/m³. Then, the figure reveals that with the space-time exposure method, 16.5% of
611 the population is exposed to daily average values above the NO₂ concentration threshold (40 µg/m³)



612 compared to 15.3% of the population with the residential exposure approach (+7%). These results are
613 consistent with those of Airparif (2017) which calculates that about 10% of the Paris region population is
614 exposed to levels above $40 \mu\text{g}/\text{m}^3$. They use an annual average day that takes weekend days and less
615 polluted holiday days into account, which partly explains this difference.

616 Figure 5: Share of the population exposed according to the NO_2 concentration threshold

617 As shown by Dhondt et al (2012), the average daily exposure initially varies widely depending on the
618 place of residence in the metropolitan area. 44.0% of the residents of Paris are thus exposed to a daily
619 average exposure value exceeding $40 \mu\text{g}/\text{m}^3$ according to the spatio-temporal method. The result is
620 identical to that with the residential exposure method. This means that the daily mobility of Paris residents
621 does not take them to spaces that are less exposed to air pollution, or not for long enough. This is the case
622 for the occupied working population of Paris, which represents almost half of the resident population, who
623 are the individuals most likely to regularly spend time in spaces that are far from the polluted center for
624 their work. However, when working Parisians have a job outside the city center (around 35%), many of
625 them work in municipalities in the inner suburbs which also have high NO_2 concentration thresholds. On
626 the other hand, 25.3% of residents within the perimeter of the A86 motorway (outside Paris) exceed the
627 maximum NO_2 exposure threshold using the space-time exposure method, against 22.4% using the
628 residential exposure method, i.e. an increase of 13%. This difference can be explained by the fact that
629 many people living in the municipalities within the A86 motorway work in Paris (around 30%), in a space
630 where exposure to pollutants is often higher than in their place of residence at every moment of the day.
631 By comparison, Ramacher and Karl (2020) obtained a difference of 12% between the two approaches in
632 the Hamburg conurbation.

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