The environmental justice implications of the Paris low emission zone: a health and economic impact assessment

Erika Moreno, Lara Schwarz, Sabine Host, Olivier Chanel, Tarik Benmarhnia

Air Quality, Atmosphere & Health
https://doi.org/10.1007/s11869-022-01243-7

The environmental justice implications of the Paris low emission zone: a health and economic impact assessment

Erika Moreno[1] · Lara Schwarz[2,3] · Sabine Host[4] · Olivier Chanel[5] · Tarik Benmarhnia[1]

Received: 13 February 2022 / Accepted: 25 August 2022

Abstract

Background Reducing the mortality burden associated with urban air pollution constitutes a public health priority, and evidence of unequal exposure and susceptibility across population subgroups is growing. Many European countries have implemented low emission zones (LEZs) in densely populated city centers. Although LEZs decrease air pollution exposure and health impacts, evidence is lacking on their impact across neighborhoods and socio-economic groups.

Objectives The aim of this study was to evaluate the most equitable approach to implementing the second phase of the LEZ in Paris, France. We also present a literature review of the studies evaluating the benefits associated with LEZs in Europe.

Methods A health impact assessment (HIA) was conducted to quantify changes in air pollution exposure and expected health benefits by socioeconomic group and neighborhood related to four hypothetical scenarios for the second phase of the LEZ based on French Deprivation Index scores. The study focused on NO_2 and $PM_{2.5}$ as air pollutants and evaluated the impact of the LEZ on the inequitable burden of childhood asthma and all-cause premature adult mortality. We also conducted an economic evaluation associated with the LEZ benefits on prevented deaths and asthma cases.

Results The scenario with the largest LEZ perimeter and the most stringent vehicle standards prevented the highest number of cases and produced the most equitable distribution of health benefits, especially childhood asthma. It is expected that 810 deaths and 3200 cases of asthma could be prevented from the LEZ extension in this scenario. These results were distributed heterogeneously across three socioeconomic (SES) groups, most noticeably with asthma cases as 230, 180, and 210 cases were avoided per 100,000 inhabitants in high, medium, and low SES groups, respectively. We found substantial economic benefits associated with LEZ, with estimates ranging from €0.76 billion to €2.36 billion for prevented deaths. The benefits associated with asthma reduction ranged from €2.3 million to €8.3 million.

Discussion Conducting HIAs with a focus on equity will further inform policy makers of the impact of LEZ models on air pollution, health, and environmental justice. Developing these systematic methods and applying them to future LEZs and other air pollution policies will increase their effectiveness to reduce the burden of ambient air pollution on society and the environment.

Keywords Low emission zones · Traffic-related air pollution · Air pollution · Air pollution policy · Health equity · Environmental justice

✉ Tarik Benmarhnia
tbenmarhnia@ucsd.edu

1 Scripps Institution of Oceanography, University of California, San Diego, CA, USA

2 Herbert Wertheim School of Public Health and Human Longevity Science, University of California San Diego, La Jolla, CA, USA

3 School of Public Health, San Diego State University, San Diego, CA, USA

4 Observatoire Régional de Santé, Île-de-France, Paris, France

5 Aix-Marseille Univ, CNRS, AMSE, Marseille, France

Introduction

Traffic-related air pollution (TRAP) is one of the largest sources of ambient air pollution in cities worldwide and plays a significant role in driving adverse human health outcomes (Cohen et al. 2017). Inhaling pollutants such as particulate matter (PM), ozone, and nitrogen dioxide (NO_2) can cause morbidities such as cardiovascular disease, respiratory disease, and cognitive decline (Schraufnagel et al. 2019a, b). In 2015, exposure to $PM_{2.5}$ ranked as the fifth leading cause of death worldwide with 4.2 million deaths (Cohen et al.

Published online: 31 August 2022

2017). Various policy measures across the world have been implemented on local and national scales in order to address this public health threat.

Low emission zones (LEZs) are a common traffic reduction strategy that aims to address TRAP and improve human and environmental health mostly implemented in European cities. Today, there are around 250 LEZs in operation across Europe and most of them were established since 2010 (Bernard et al. 2020a, b; Ezeah et al. 2015). In general, LEZs are designed around the perimeter of densely populated urban cities to regulate the entry of high-emitting vehicles. Typically, these zones prohibit older vehicle models (light-duty and heavy-duty vehicles), especially those with diesel engines, from entering the zone either 24 h a day 7 days a week, or between certain weekday hours. LEZs are also designed to become more restrictive as technology and air pollution research advance. Enforcement of LEZs is either subject to police monitoring or digital surveillance with cameras set up to read vehicle license plates (Bernard et al. 2020a, b). LEZ across Europe has been shown to have a beneficial effect at the population level (Bernard et al. 2020a, b; Jiang et al. 2017; Santos et al. 2019).

However, the expected health outcomes of major environmental policies are not always equitably distributed (Benmarhnia et al. 2014). It has been observed globally that vulnerability and exposure to high TRAP levels disproportionally affect low socio-economic groups (Deguen et al. 2015; Hajat et al. 2015; Tonne et al. 2018). This is an issue of environmental injustice, or the unequal subjugation to environmental hazards and their associated adverse health impacts based on race, color, national origin, or income (Charleux 2013; EPA 2020). Not only do populations from a low socio-economic status (SES) often face higher exposure to these environmental health risks, but they have also been found to have increased vulnerability. In other words, the same exposure can have a more harmful effect on these populations (Deguen and Zmirou-Navier 2010; Forastiere et al. 2007). This disproportionate burden on certain groups is usually not considered when evaluating the potential benefits of environmental policies on population health (Benmarhnia et al. 2014; Gehrsitz 2017; Host et al. 2020; Malina and Scheffler 2015; Mudway et al. 2019; Wang et al. 2016; Wood et al. 2015).

In 2015, the French State Council implemented a national framework for metropolitan Low Emission Zones (*Zone à faible émissions—ZFE*) in Paris. It is estimated that one out of every two Parisians is exposed to NO_2 levels that exceed annual limit values set by the European Parliament (GUAPO 2019). Moreover, around 6600 annual deaths are attributable to chronic air pollution in Paris and 60,000 deaths are recorded in all of France (Host 2019; MGP 2019). The Paris LEZ was drafted and introduced under a five-phase roll-out schedule that will restrict all exhaust-emitting vehicles from entering the *Metropole du Grand Paris* (MGP) by 2030. Each of the five phases of the Paris LEZ policy is linked to the restriction of a new category of a vehicle within the LEZ. There are four scenarios that policy makers in Paris can use to inform further action regarding the evolution and the strengthening of the LEZ (Host et al. 2020). Briefly, these scenarios are defined by two different perimeters for the LEZ—the Paris ring road and the extended LEZ that includes municipalities within the A86 roadway—and two different restriction levels, Crit'Air3 and Crit'Air4. A recent study by Host et al. applied a health impact assessment (HIA) to assess the health benefits associated with reductions in TRAP exposure attributable to the Paris LEZ (Host et al. 2020). The assessment was conducted for four different hypothetical scenarios for phase two of implementation and is unique in that it evaluates air quality improvements and calculates the benefits of several health outcomes on a fine scale for the Paris region.

In this paper, we propose to evaluate the impact of LEZs on health equity accounting for differential exposure and susceptibility. Applying this analysis to the next phase of the LEZ implemented in Paris, France, in 2015, we demonstrate its applicability in understanding the implications of these policies on health equity. While previous work has considered the health impacts of the LEZ in France, none has considered its impacts on equity, accounting for differences in both exposure and susceptibility. In this study, we considered differences in exposure–response functions by the socio-economic group to evaluate the potential equity implications of the extension of the Paris LEZ. We applied a HIA which considers equity-related modifiers regarding differential susceptibility coupled with an economic evaluation. Furthermore, we included an economic evaluation to emphasize the societal benefits related to the implementation of the Paris LEZ considering the environmental justice implications of TRAP health impacts. Such quantitative evidence will inform policymakers in Paris about the expected spatial and socio-economic distribution of the LEZ benefits and allow for some adaptation to consider the equity and economic implications.

Materials and methods

Review of the literature

We conducted a literature review of studies assessing LEZs in Europe (see details in Table 1). This involved searching databases like ScienceDirect, PubMed, NCBI, and Google Scholar. The keywords used included low emission zones, low emission zones and health, low emission zones and air pollution, low emission zones and equity, low emission zones and policy, LEZs, and traffic-related air pollution.

Table 1 Literature review of studies assessing the effects of low emission zones in Europe on air pollution and health

Study site (s)	Authors	Aim	Pollutants studied	Impacts considered		Results		Conclusion
				Health	Equity	Health	Equity	
Rome	Cesaroni et al. 2013	Assess LEZ effectiveness in terms of air quality and health effects and assess impacts on socioeconomic position	PM_{10} and NO_2	Years of Life Gained (YLG)	Socioeconomic position (SEP)	NO_2 reduction was associated with an average of 921 YLG per 1,000,000	Residents with a higher SEP saw a higher rate of YLG (1387 vs 340 YLG per 100,000)	LEZ was effective in reducing traffic-related air pollution but most health gains were skewed towards wealthier residents
Grenoble	Charleux 2013	How LEZ could affect individuals' mobility, specifically enquiring whether or not the impact would be socially differentiated and might constitute a social injustice	$PM_{2.5}$, PM_{10}, and NO_2		Socio-professional groups in relation to access to various mobility options			Implementing a LEZ would uphold already existing social inequalities
Germany	Morfeld et al. 2014	Large-scale analysis of LEZ impacts on NO_2, NO, and NOx concentrations	NO_2, NO, and NOx					There is a statistically significant reduction in NO_2, NO, and NOx but reductions are small
London	Wood et al. 2015	Assess the link between TRAP and respiratory or allergic symptoms among 8–9-year-olds living within the LEZ	NOx, NO_2, $PM_{2.5}$, PM_{10}	Respiratory/allergic symptoms in children		Only rhinitis was positively affected by reductions in NOx, NO_2, $PM_{2.5}$, PM_{10} exposure		The LEZ did not improve air quality or health during the first three years of operation
Germany (25 cities)**	Malina et al. 2015	LEZ impact on particulate matter and public health	PM_{10}	All-cause premature mortality (adults > 30 years old), monetized health benefit		Stage 1 would produce a savings of around 760 M euros. Stage 2 would save around 2.4B euros. Mortality is reduced by 5% in Germany as a result of Stage 1		Decrease in PM_{10} concentrations can be attributed to the LEZ, significant health benefits for the affected population

Table 1 (continued)

Study site (s)	Authors	Aim	Pollutants studied	Impacts considered		Results		Conclusion
				Health	Equity	Health	Equity	
5 EU countries (Denmark, Germany, Netherlands, Italy, and UK)	Holman et al. 2015	Review of the efficacy of LEZs to improve urban air quality	PM_{10} and NO_2					No clear reductions have been observed except for the German LEZs where concentrations were reduced by a few percent
London, Berlin, and Munich	Ezeah et al. 2015	LEZ effectiveness as an air quality management strategy	PM and NOx					PM reduction is minimal in spite of high compliance rates. Munich and Berlin report significant reductions likely due to differences in implementation
London and Berlin	Cruz, C. and Montenon, A. 2015	LEZ impact on freight activity in Europe: local schemes vs national schemes	PM and NOx					Local LEZ frameworks tend to not encourage vehicle replacement as much as national frameworks, but they do consider economically vulnerable firms more. The Paris LEZ sets a new precedent
Germany	Jiang et al. 2017	LEZ impact on air pollution levels	$PM_{2.5}$, PM_{10}, NO, NOx, and NO_2					Significant progress has been made to reduce particulate matter in the last 10 years. Further improvement is small given 89% vehicle compliance
Germany	Gehrsitz 2017	LEZ impact on air pollution and infant health	SO_2, PM_{10}, and NO_2	Birth weight (in g), birthweight (< 2500 g), still birth		No statistically significant effect on birthweight observed (increase of 0.26 g), 96 infant lives saved		Air pollution reductions are too small to produce significant improvements in infant health

Table 1 (continued)

Study site (s)	Authors	Aim	Pollutants studied	Impacts considered		Results		Conclusion
				Health	Equity	Health	Equity	
Île-de-France	Andre et al. 2018	LEZ impacts on the geographical variation in vehicle fleet composition	VOC, CO, CO_2, PM_{10} NOx					LEZ effectiveness is dependent on knowledge of the local fleet composition. Air pollution reduction measures should be targeted accordingly
Lisbon	Santos et al. 2019	LEZ impact on air quality	PM_{10} and NO_2					Annual reductions in PM_{10} and NO_2 between 2009 and 2016 were 29% and 12%, respectively, in Zone 1. For Zone 2, reductions were 23% and 22% annually
London	Mudway et al. 2019	LEZ impact on air quality and children's respiratory health	$PM_{2.5}$, PM_{10}, and NO_2	Respiratory Health in Children		Children's forced vital capacity (FVC) improved by 0.0023 L/µg per m^3 of NO_2		Air quality was improved during the study period but no improvements were observed in children's health
Paris	Host et al. 2020	Assess different LEZ implementation scenarios on a fine scale in terms of reduction in exposure and expected health benefits	$PM_{2.5}$ and NO_2	Mortality (adults > 35 years old), ischemic heart disease (IHD) (40–74 years old), asthma (0–17 years old), full-term low birth weight (newborns)	Socioeconomic deprivation	340 deaths prevented (114,300 YLG), cases avoided: 170 low-weight births, 130 new cases of IHD, and 2930 new cases of asthma	Possible increase of inequalities. Not specifically defined	The scenario that maximized health benefits and reduced inequalities involved using the most stringent vehicle standards and extending the LEZ perimeter to the Greater Paris Region
Paris	Bernard et al. 2020a, b	To quantify the discrepancy between exhaust emissions under testing conditions and real-world conditions	NOx					A substantial reduction in NO_2 emissions can be expected from 2024 and on

Table 2 Crit'air restrictions of types of vehicles allowed and banned according to the Paris low emission zone

Crit' air	Types of vehicles							Ban level	
	Motorcycles and mopeds	Passenger car		LDV		HDV's, buses, and coaches		Low	High
		Diesel	Petrol	Diesel	Petrol	Diesel	Petrol		
"Uncategorized"	Pre-Euro*	Pre-Euro or Euro 1		Pre-Euro or Euro 1		Euro I or Euro II		X	X
Crit'Air 5	–	Euro 2	–	Euro 2	–	Euro III	–	X	X
Crit'Air 4	Pre-Euro**	Euro 3	–	Euro 3	–	Euro IV	–	X	X
Crit'Air 3	Euro 2	Euro 4	Euro 2/3	Euro 4	Euro 2/3	Euro V	Euro III/IV		X

Most relevant articles that included an evaluation of the impacts of LEZs on air pollution or health outcomes in Europe were summarized in Table 1.

Study population

Residents of greater Paris living in municipalities within the A86 roadway (see supplemental materials for a map of these perimeters) is the study population of interest. For this study, census blocks were grouped into terciles in the LEZ_{Paris} and $LEZ_{Enlarged}$ perimeters based on their Fdep, or French deprivation index. The Fdep score is used to define socioeconomic status in France and is derived from four socioeconomic variables[1] using principal component analysis. Each tercile was further annotated as the T-Fdep score. This was done to evaluate differential exposure and susceptibility across the region by SES groups ($n=3$).

Health outcomes and characterization of differential susceptibility

Two health outcomes were considered to measure the benefits of LEZ-related air quality improvements. The first health outcome was deaths from nonaccidental causes avoided, in absolute numbers in adults over 30 years old. The second health outcome was childhood asthma in children between 0 and 17 years old (Host et al. 2020). New cases of childhood asthma were defined by three reimbursements for asthma treatment for children (0–17 years) in the year who did not receive treatment in the previous 3 years. The results related to childhood asthma are particularly important because children are more susceptible to the consequences of air pollution, specifically because they have smaller lung capacities (Schraufnagel et al. 2019a, b). They also have faster breathing and heart rates, so their levels of exposure have more of an impact on their developing bodies. Additionally, when children develop asthma or other respiratory diseases, these morbidities can impact the development of proper lung function into adulthood (Schraufnagel et al. 2019a, b).

Given the absence of published concentration response functions (CRF) between long-term exposure to NO_2 and mortality across different SES groups for Paris or any other French city, we relied on CRFs from other geographical contexts. We relied on CRFs for the effect of NO_2 on mortality from the Cesaroni et al. (2013) study in Rome that provided specific CRF across the high, medium, and low SES groups. We selected this study as it has been conducted in a European large city with similar patterns to Paris regarding differential exposure to NO_2 across SES subgroups. Using different CRF for each SES subgroup aims at quantifying the differential susceptibility to air pollution regarding a given health outcome. Such differential susceptibility can be explained by different underlying factors such as a differential distribution of pre-existing comorbidities or other social determinants of health across SES subgroups (Hajat et al. 2015). By using such CRF from a study conducted in a different geographical context, we make the assumption that the differential susceptibility across SES groups is similar between Rome and Paris. Such CRFs are estimated for the same exposure contrast (i.e., 10 units increase) and the differential exposure to air pollutants between SES subgroups is taken into account directly in the calculation of the attributable number of deaths by using census blocks specific exposures (see details below) (Table 2).

To the best of our knowledge, there are no published CRF in relation to the effect of NO_2 on asthma by the SES group. Therefore, to calculate concentration response values for childhood asthma and NO_2 exposure by the SES group, we applied the same differential CRF as for the mortality-NO_2 CRF from Cesaroni et al. (assuming that SES differential susceptibility is proportional between mortality and asthma risk). The CRFs (and 95% CI) of death and childhood asthma for a 10 $\mu g/m^3$ increase in exposure to NO_2 are summarized in Table 3.

For PM2.5 and mortality, we used the same approach and CRFs as proposed by Host et al. 2020 (see details in Table 3). For asthma, as no CRF for $PM_{2.5}$ were available

[1] Average household income, percentage of high-school graduates in the population aged 15 years and older, percentage of blue-collar workers in the active population, and unemployment rate.

Table 3 Concentration response functions of the effects of each pollutant on deaths and asthma for each socio-economic group and pollutant

Health outcome	Pollutant	High SES	Medium SES	Low SES
Death	NO_2	1.024 [1.012–1.036]	1.016 [1.002–1.03]	1.034 [1.024–1.045]
	$PM_{2.5}$	1.04 [1.02–1.06]	1.018 [0.99–1.04]	1.05 [1.03–1.07]
Asthma	NO_2	1.068 [1.056–1.08]	1.06 [1.046–1.074]	1.078 [1.068–1.089]
	-	-	-	-

from any European cities, we did not consider PM2.5 when estimating the asthma burden.

These values were then used in the HIA equations below to determine the attributable number (AN) of death and childhood asthma cases avoided by T-Fdep. Any CRF values below one, which would produce implausible negative AN estimates, were replaced by one.

Socioeconomic inequalities were evaluated based on three T-Fdep scores and their relation to mortality after 30 years of age and new cases of childhood asthma. These values were then translated into the number of cases prevented per 100,000 inhabitants by socio-economic group. The scenario with the lowest disparity between the case/population ratio amongst all three groups was defined as the most equitable.

Modelling reductions in emissions and population exposure

Each of the four LEZ scenarios was compared to a business as usual (BAU) scenario where there is an uninterrupted technological progression of the car fleet. Table 2 outlines the modeled LEZ-specific reduction in air pollution concentrations (see details below) across the two restriction levels, Ban_{low} and Ban_{high}. The inner and outer boundaries are labeled LEZ_{Paris} and $LEZ_{Enlarged}$, respectively. We refer to each scenario as $LEZ_{Paris}Ban_{low}$, $LEZ_{Paris}Ban_{high}$, $LEZ_{Enlarged}Ban_{low}$, and $LEZ_{Enlarged}Ban_{high}$.

For each of the four LEZ scenarios, reductions in NO_2 and PM2.5 emissions were the sole pollutants evaluated for years 2018 and 2019. In order to project emissions reductions for the Ban_{low} and Ban_{high} scenarios, a modeling chain was used to include road traffic modeling, traffic emissions modeling, and regional modeling which entailed mapping pollutant levels in urban and rural areas. Urban scale modeling allowed for visualizing concentrations closest to traffic with 50 m resolution (50 m × 50 m). Additionally, these projections were made under BAU conditions for both years. The smallest resolution possible for mapping population exposure was provided on the building level and data from the 2012 census was extrapolated to project population size and age groups at the census tract level (for more details, see (Host et al. 2020)).

HIA analysis

The following data was collected from the Host et al. study for the entire MGP region and used to conduct a HIA on the four hypothetical LEZ scenarios defined above. The difference in NO_2 and $PM_{2.5}$ exposure attributable to each LEZ scenario—Paris or enlarged and ban low or high—was derived from Airparif's road traffic emission modeling tools. The population of each age group was provided by INSEE, the national statistics bureau in France, and the rate of incidence for premature death and childhood asthma was taken from Sniiram and Santé Publique France (Host et al. 2020), the national health insurance database, and the national public health agency, respectively. Lastly, raw Fdep scores were pulled from Inserm, a public health research organization in France. The Fdep is a scale that runs from − 3.74 (low SES) to + 4.12 (high SES) and a value on this scale is assigned to each IRIS (French census track).

We first obtained (Eq. 1) the new CRF, or risk ratio (RR), RR_Δi, associated with the new level of NO_2 or PM2.5 exposure, denoted by Δ_i, for each IRIS. The base RR is given to be per 10 μg/m^3 increase of NO_2 or $PM_{2.5}$ and for each Fdep tercile in each IRIS as described above.

$$RR_{\Delta i} = e^{\ln(RR^{*}\Delta_i)} \tag{1}$$

Next, the attributable fraction (AF), given in Eq. 2, was calculated. The AF calculates the proportion of cases that are reduced or increased in each municipality according to the new RR ratio.

$$AF_i = \frac{(RR_{\Delta i} - 1)}{RR_{\Delta i}} \tag{2}$$

Finally, the AN was obtained; Eq. 3 describes this calculation. All three equations were then applied to each census block and for each scenario.

$$AN_i = AF_i * I * P_i \tag{3}$$

After calculating the four hypothetical LEZ scenarios, the data was mapped using ESRI ArcMap 10.7.1. Multiple maps (see supplemental material) were created which include the distribution of health outcomes and reductions in air pollution for each of the LEZ scenarios. We also considered the 95% confidence intervals (CI) of the CRF we used and estimated lower and upper limits for each estimate. Additionally, one map was made to depict the distribution of social deprivation (Fdep) by IRIS. Ethics approval and consent to participate were not required for this study.

Economic evaluation of the LEZ health benefits

Using such health benefits estimates, we also considered the health benefits of the LEZs from a societal perspective and expressed them through monetary estimates of the effects of premature mortality and new cases of childhood asthma in € 2018, based on the French national consumer price index ($1 = €0.85 on 1 July 2018). Details regarding the economic calculations including the evaluation of the value of a statistical life (for mortality) and cost-of-illness (for asthma) are provided in the appendix.

Results

In our review of the literature, we found LEZs to be effective in reducing atmospheric concentrations of NO_2 and $PM_{2.5}$ (Bernard et al. 2020a, b, Cesaroni et al. 2012; Cesaroni et al. 2013; Ezeah et al. 2015; Host et al. 2020; Jiang et al. 2017; Malina and Scheffler 2015; Mudway et al. 2019; Santos et al. 2019). However, most LEZs in operation require several years of implementation or systematically effective vehicle standards before observing the desired environmental and health impacts (André et al. 2018; Bernard et al. 2020a, b; Gehrsitz 2017; Mudway et al. 2019; Wood et al. 2015). There is some evidence that LEZs can be effective in reducing mortality and respiratory diseases (Host et al. 2020; Malina and Scheffler 2015). The impact of these policies on health equity, on the other hand, has only been fully assessed once by Cesaroni et al. 2013. Their findings revealed that health benefits were skewed towards higher income residents. Through the literature search, it was found that the impact of TRAP policy on health equity continues to be an area of research that needs more empirical evidence.

Table 4 shows the number of deaths and cases of asthma prevented in each LEZ scenario due to reductions in NO_2 with respect to three levels of social deprivation (Fdep terciles). We also present estimates using lower and upper limits for each pollutant-outcome CRF. By contrast, Host et al. (2020) that assumed the same CRF for all SES subgroups found lower estimates that in our study. In the $LEZ_{Enlarged}Ban_{High}$ scenario, a reduction of 730 deaths and 3200 childhood asthma cases were estimated, respectively. Additionally, implementation of either the $LEZ_{Paris}Ban_{High}$ or the $LEZ_{Enlarged}Ban_{Low}$ scenario yielded virtually the same health benefits. Table 4 also demonstrates that the distribution of expected health outcomes becomes more equitable as the LEZ perimeter expands and the restriction level increases. Figure 1 focuses on the raw value of cases reduced attributable to reductions in NO_2 and thus confirms that the most equitable implementation strategy is the $LEZ_{Enlarged}Ban_{High}$ scenario. This trend is most notable with asthma cases avoided, with only an 8% disparity in cases per capita between the low T-Fdep group and the high T-Fdep group in the $LEZ_{Enlarged}Ban_{High}$, compared to a 33% disparity in cases per capita in the least restrictive scenario. Deaths avoided due to reductions in PM2.5 demonstrated a similar trend across the different scenarios.

Figure 2 shows the general Fdep distribution across the whole study area. Figures 3 and 4 show the spatial distribution of death and asthma cases prevented from reduced NO_2 emissions in the $LEZ_{Paris}Ban_{High}$ and the $LEZ_{enlarged}Ban_{High}$ scenarios. These two map-sets represent the highest reductions in deaths and cases of childhood asthma for each LEZ perimeter based on three different CRFs. Figure 3 (a) shows that most deaths will be prevented along the Paris ring road, and Fig. 3 (b) shows that asthma cases are primarily reduced along the northern perimeter. Figure 4 demonstrates that there is a relatively even distribution of health outcomes as a result of the $LEZ_{Enlarged}Ban_{High}$ scenario. By comparing Fig. 4 to Figs. 2 and 3, one can conclude that health benefits will be distributed equitably with more benefits among low SES IRIS. Figures representing the other scenarios and the benefits attributable to $PM_{2.5}$ reductions can be found in the supplemental materials.

Finally, we also conducted an economic evaluation on the LEZ health benefits. Results in Table S1 show the monetary benefits for each of the health events (and upper and lower 95% CI bounds). Overall, mortality impacts dominate from €0.76 billion for LEZ_{Paris} Ban_{Low} to €2.36 billion for $LEZ_{enlarged}$ Ban_{High} for NO_2 (and about 10 times less for PM2.5). Asthma-related impact spreads from €2.3 million for LEZ_{Paris} Ban_{Low} to €8.3 million for $LEZ_{enlarged}$ Ban_{High}. We also show the spatial distribution of such economic benefits (see figures S5 and S6).

Discussion

In this study, we aimed at highlighting the important equity implications in relation to LEZ as policies to tackle TRAP and health benefits by considering both pre-existing inequalities in air pollution exposure and differential susceptibility. By approaching the Paris LEZ from this angle, this study is the first to quantify the spatial and SES distribution regarding expected health benefits. We conclude that the most equitable approaches (i.e., maximizing the health benefits among low SES communities) consist of incorporating as wide of a perimeter as possible and to restrict a wide variety

Table 4 Results of the health impact assessment showing prevented deaths and asthma cases* of the Paris low emission zone for each socio-economic group and pollutant

Health event (by pollutant)	*Socioeconomic status (SES)*	*Preventable cases*							
		LEZ_{Paris} Ban_{Low}	Per 100,000 inhabitants	LEZ_{Paris} Ban_{High}	Per 100,000 inhabitants	$LEZ_{enlarged}$ Ban_{Low}	Per 100,000 inhabitants	$LEZ_{enlarged}$ Ban_{High}	Per 100,000 inhabitants
Death (NO_2)	T-Fdep 1 (high)	100 (50,149)	8 (4, 12)	183 (92, 271)	14 (7, 21)	162 (82, 241)	12 (6, 18)	288 (146, 427)	21 (10, 31)
	T-Fdep 2	55 (7, 103)	4 (0.5, 7)	98 (12, 181)	7 (0.9, 13)	94 (12, 174)	7 (0.8, 12)	156 (20, 289)	11 (1, 21)
	T-Fdep 3 (low)	81 (57, 106)	5 (4, 7)	139 (99, 183)	9 (7, 12)	169 (120, 222)	11 (8, 15)	289 (206, 379)	20 (14, 26)
	All	236 (115, 358)	6 (3, 8)	420 (203, 635)	10 (5, 15)	425 (214, 637)	10 (5, 15)	734 (372, 1096)	17 (9, 26)
Death (PM2.5)	T-Fdep 1 (high)	10 (5, 14)	0.8 (0.4, 1)	16 (8, 24)	1 (0.7, 2)	13 (7, 20)	0.8 (0.5, 2)	31 (16, 46)	2 (1, 3)
	T-Fdep 2	4 (0, 10)	0.3 (0, 0.7)	16 (0, 24)	1 (0, 2)	6 (0, 13)	1 (0, 0.9)	13 (0, 29)	0.9 (0, 2)
	T-Fdep 3 (low)	11 (7, 15)	0.7 (0.4, 1)	14 (8, 19)	0.8 (0.5, 1)	14 (8, 19)	0.4 (0.6, 1)	33 (20, 46)	2 (1, 3)
	All	25 (12, 39)	0.6 (0.3, 0.9)	36 (16, 57)	0.9 (0.4, 1)	33 (15, 52)	0.8 (0.4, 1)	77 (36, 121)	2 (0.8, 3)
Asthma (NO_2)	T-Fdep 1 (high)	268 (222, 312)	78 (64, 90)	518 (431, 603)	130 (113, 158)	510 (424, 595)	140 (113, 159)	938 (781, 1092)	230 (192, 268)
	T-Fdep 2	262 (203, 320)	58 (45, 71)	490 (380, 597)	100 (80, 126)	501 (388, 611)	120 (84, 132)	866 (673, 1056)	180 (142, 223)
	T-Fdep 3 (low)	362 (317, 410)	52 (45, 59)	646 (567, 732)	90 (81, 105)	797 (699, 902)	120 (106, 137)	1398 (1229, 1581)	210 (183, 235)
	All	892 (743, 1043)	60 (49, 70)	1653 (1377, 1932)	110 (88, 124)	1808 (1511, 2109)	120 (101, 141)	3203 (2683, 3728)	210 (173, 240)

*Estimates presented in parentheses are based on the 95%CI of the CRF we used for each calculation

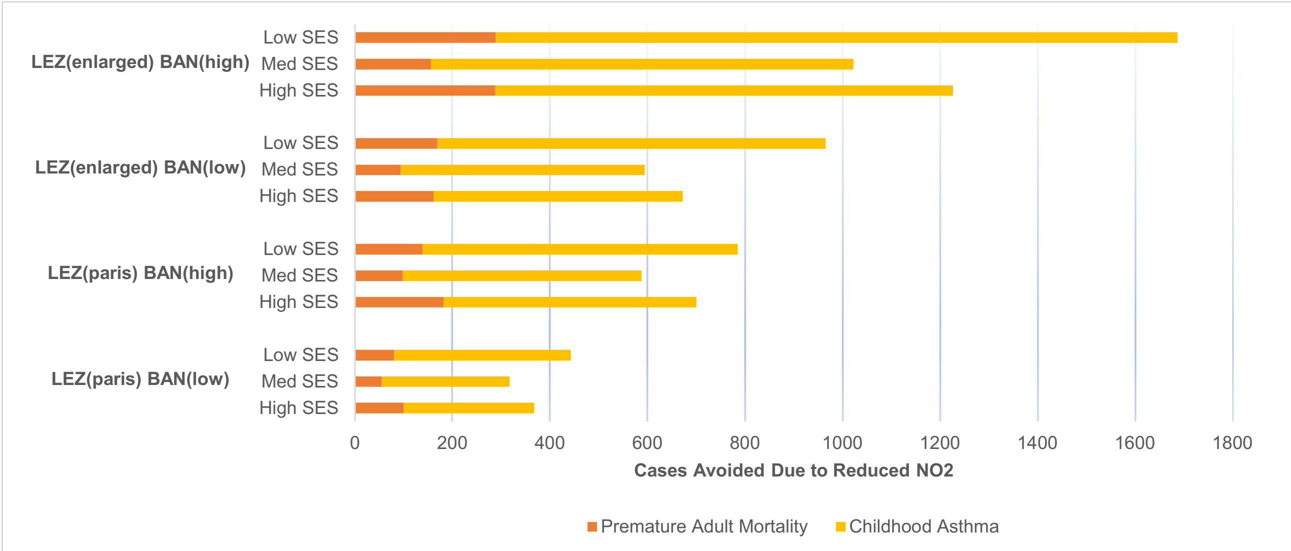

Fig. 1 Cases of all-cause premature adult mortality and childhood asthma avoided due to reductions in NO_2 broken down by low, medium, and high socio-economic status (SES) for each LEZ scenario

of high-polluting vehicles from entering the zone. Overall, we found that if the $LEZ_{Enlarged}Ban_{High}$ scenario is adopted for the next phase of implementation, it has the potential to prevent 811 premature deaths and 3203 cases of childhood asthma per year.

Low emission zones, compared to congestion charging and other traffic management schemes, are the most popular method of improving air quality in major cities across Europe. Studies have shown that this strategy is effective in reducing NO_2, PM_{10}, and $PM_{2.5}$ concentrations, given that the restrictions for entering the LEZ are stringent enough (Table 1). Moreover, LEZs are also capable of reducing the environmental burden traffic-related air pollutants pose on society. However, the literature review conducted for this study on European LEZs highlighted a need for additional research into how the benefits of any given LEZ might impact existing social inequalities.

Host et al. (2020) showed the health benefits associated with reductions in TRAP exposure attributable to the Paris LEZ (Host et al. 2020). Our study goes beyond to evaluate the impacts of this policy on health equity, accounting for differences in the effects of various air pollutants on incident childhood asthma cases and premature adult mortality by socio-economic groups, finding that the LEZ becomes more equitable as the perimeter expands and the policy becomes more restrictive. Other strengths of our study also include the consideration of small-scale variations in LEZ benefits for both NO2 and PM2.5 as well as multiple LEZ scenarios. We also implemented an economic evaluation of the different LEZ scenarios and quantified monetary estimates of prevented deaths and new cases of childhood asthma.

The literature review conducted on equity dimensions of LEZ demonstrated that, since the creation of the first LEZ in 1996, only one European study had evaluated the impact of LEZs on equity (Müller and Le Petit 2019). However, several previous studies have considered equity dimensions in their research. A recent study by Kihal-Talantikite et al. concluded that avoided premature adult deaths would mostly be clustered in poor communities, regardless of the hypothetical reduction of NO_2, PM_{10}, and $PM_{2.5}$ (Kihal-Talantikite et al. 2018). We find that health equity can be strategically achieved with regard to the existing Paris LEZ and future extensions. With respect to other LEZ evaluations across Europe, such as those in Germany and the UK, the estimated reductions in deaths and asthma cases are also significant. Should policy makers implement the LEZ at a faster pace, these results may be even greater and achieved sooner (Bernard et al. 2020a, b).

While it is important to highlight the potential distribution of LEZ benefits across SES groups, it is also important to consider how this policy will economically impact low SES individuals who will likely have a harder time complying with the most stringent requirements of the $LEZ_{Enlarged}Ban_{High}$ scenario. It is known that low SES groups contribute the least to TRAP emissions as they own fewer cars (Bannon 2019; Müller and Le Petit 2019). In Austria, it was found that about 44% of low-income households did not own a car but were exposed to higher than average levels of TRAP (Müller and Le Petit 2019). In fact, the most socially deprived areas saw 50% higher ambient NO_2 concentrations than other well-off areas (Müller and Le Petit 2019). Low-income households and small businesses often do not have the financial capacity to switch to a cleaner vehicle, making

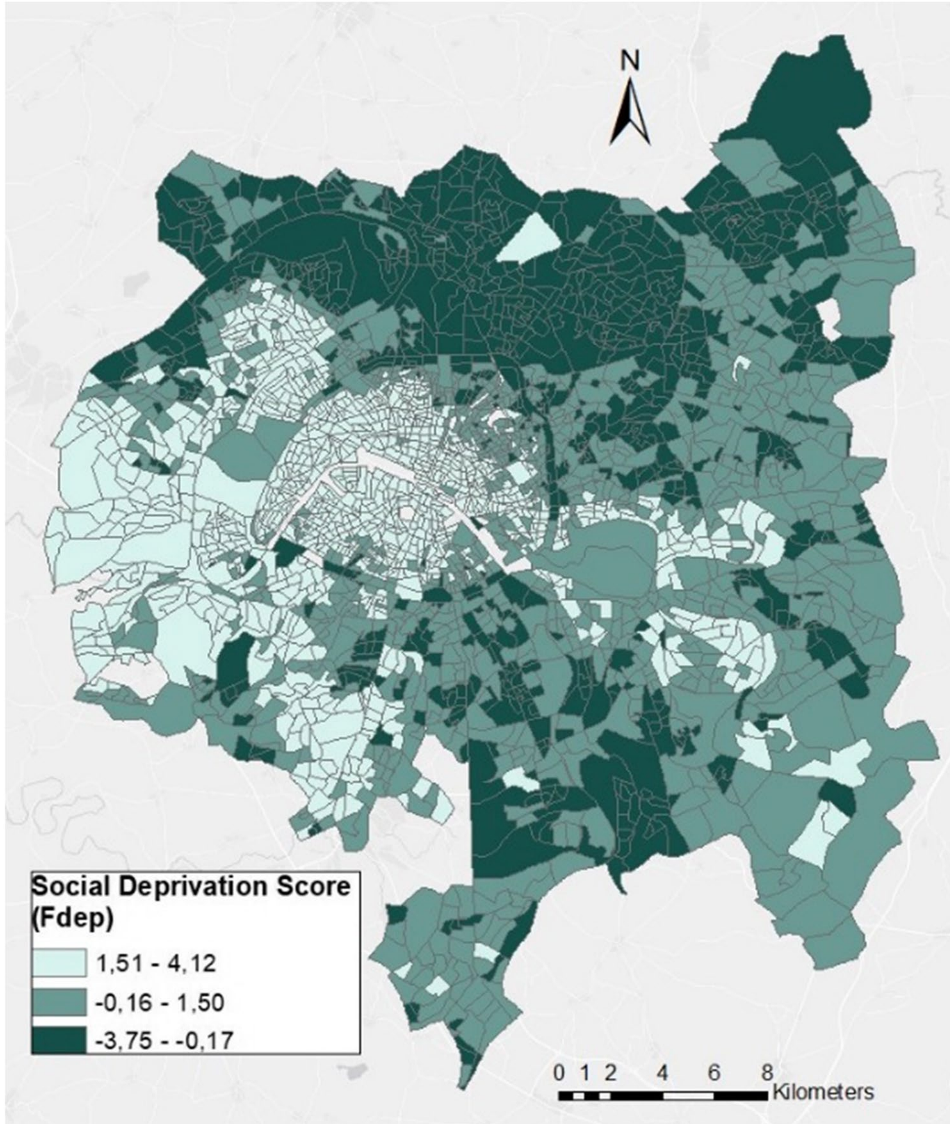

Fig. 2 Distribution of social deprivation for the entire Metropolis of Greater Paris

compliance with a LEZ difficult (Müller and Le Petit 2019). In fact, these individuals and households are most likely to own a high-polluting vehicle and may not have the resources to switch to an alternative vehicle that meets the Crit'Air 3 requirements. Other equity considerations include the impacts of gentrification, access to public transportation, and employment mobility which could result from LEZs. These factors are intertwined with an individual or households' access to low-emission vehicles. In light of these concerns, LEZ implementation to date is accompanied by targeted incentives for vehicle replacement that take into account different levels of income and is part of a larger action plan which aims at widening access to collective transport and other alternative mobilities. This holistic approach, which considers the results of the health impact assessment alongside other socio-economic factors, should continue when implementing the following phases of the Paris LEZ.

We also included an assessment of the economic benefits attributable to the LEZ implementation. We found that the LEZ may lead to substantial economic benefits that took into account both costs related to premature mortality and prevented costs of asthma related to medical costs and lost productivity. Yet, some limitations of such an approach need to be acknowledged. While both components (mortality and asthma) underestimate the actual total health benefits, combining the two methods could lead to a possible overlap. Such overlap is likely to be limited in countries like France, with high coverage for health and sick leave (Soguel and Griethuysen 2003; Ortiz et al. 2011).

Other limitations of this study need to be highlighted and could be addressed in future work. One limitation is how the reductions in NO_2 and $PM_{2.5}$ exposures were derived from theoretical models and not real-world observations. Given that the Paris LEZ entered the beginning phases of

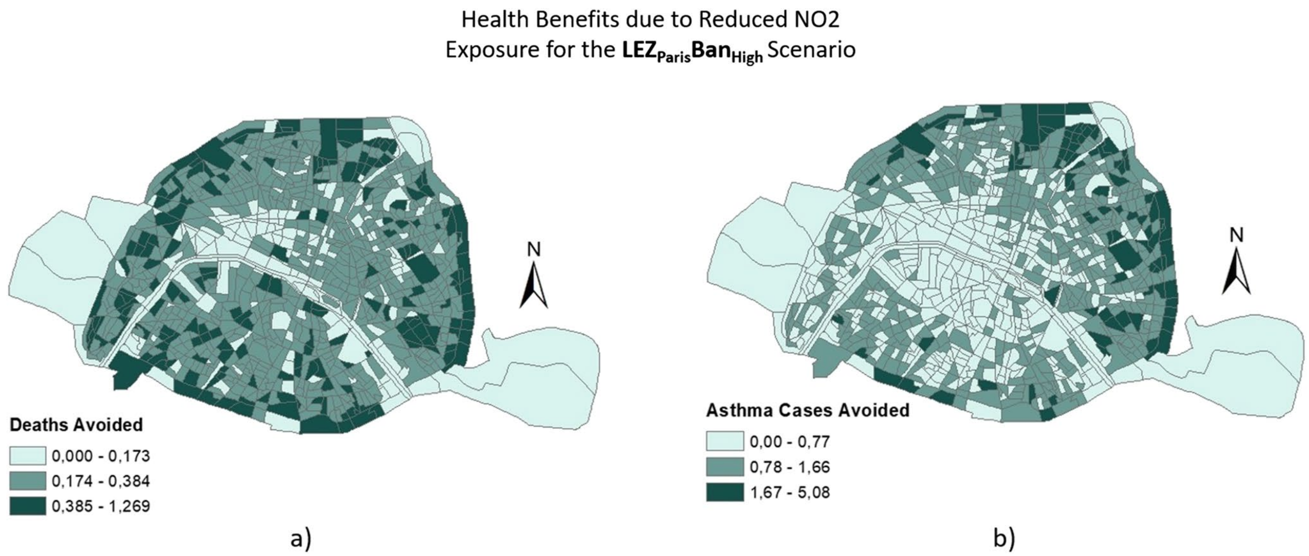

Fig. 3 Number of deaths **(a)** and childhood asthma **(b)** cases prevented from reduced NO_2 emissions, based on the T-Fdep score, for the $LEZ_{Paris}Ban_{High}$ scenario

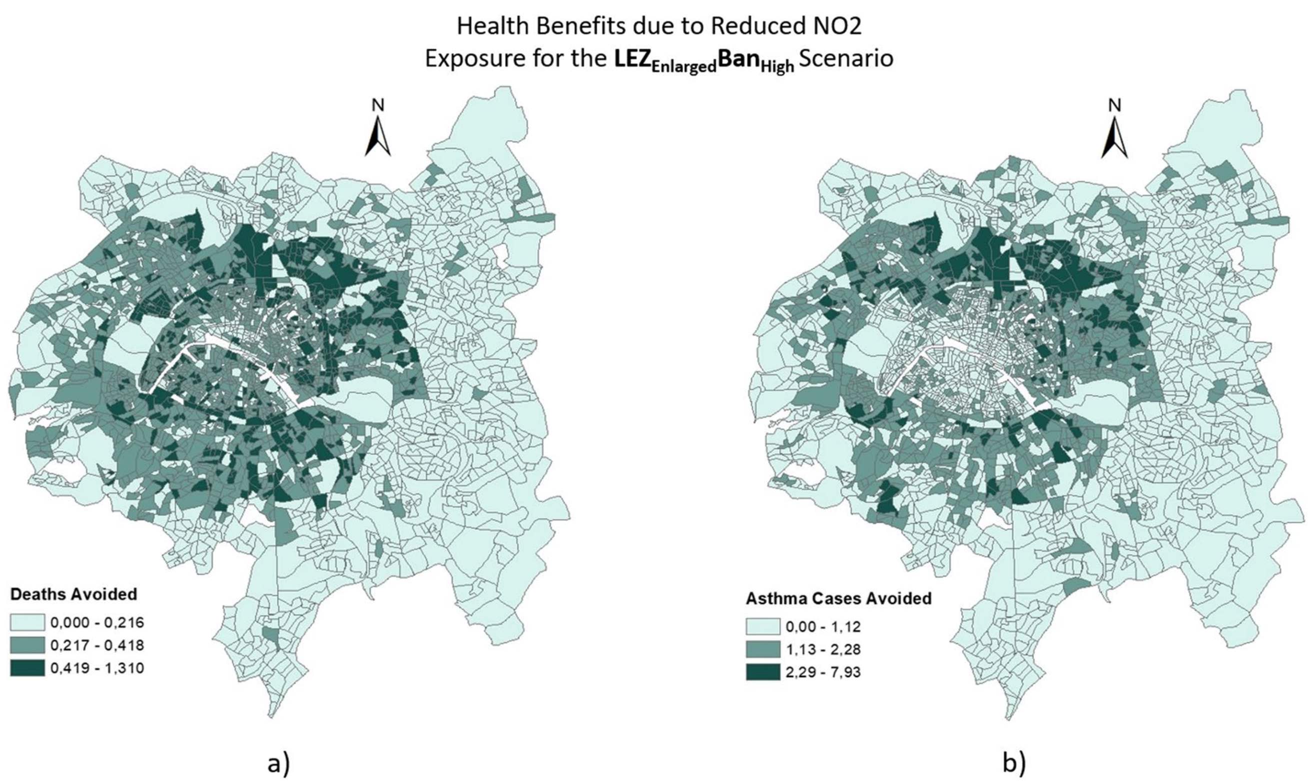

Fig. 4 Number of deaths **(a)** and childhood asthma **(b)** cases prevented due to reduced NO_2 emissions,based on the T-Fdep score, for the $LEZ_{Enlarged}Ban_{High}$ scenario

implementation in 2017, modeling is the only means to currently evaluate LEZ effectiveness. However, as time progresses, it will be important to compare how these models fared against real-world observations. Another limitation is that the three concentration responses used were pulled from a study in Italy, which surely poses a different socioeconomic landscape than that of Paris. In order to produce data that is more in line with the conditions in Paris, further studies must be conducted for the MGP region to determine the appropriate concentration responses for at least five socioeconomic levels. Lastly, it would be pertinent to gather more data on other health events such as strokes or other adverse birth outcomes in order to paint a bigger picture of the benefits society could expect from reduced traffic pollutants.

Conclusion

Our study shows that the most equitable approach to LEZs includes the incorporation of as wide of a perimeter as possible and restricting a wide variety of high-polluting vehicles from entering the zone. Overall, we found that the most restrictive scenario for the next phase of Paris low emission zone has the potential to prevent over 800 premature deaths and over 3000 cases of childhood asthma per year. Results of this study show that low emission zones can have important equity implications that should be considered when designing and implementing these types of policies.

These results show the importance of performing evaluations to ensure that LEZ plays a positive role in easing the environmental burden of ambient air pollution considering health equity. The transportation sector is the largest contributor to urban air pollution so if taken into account, it has the potential to significantly reduce the health disparities between socioeconomic groups. Additionally, these methods to assess health equity should be applied to any type of intervention that seeks to improve air quality, whether in an urban or rural setting. With the purpose of continuing this work, it is encouraged that these methods be applied to LEZ implementation to ensure equity is a core component of future evaluations and to other forms of interventions related to improving air quality in urban settings.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11869-022-01243-7.

Funding This research was partially supported by ADEME (Primequal, #1862C0011), the French National Research Agency Grant ANR-17-EURE-0020, by the Excellence Initiative of Aix-Marseille University—A*MIDEX, and by the University of California Multicampus Research Programs and Initiatives (MRP-17–446315).

Data availability The data that support the findings of this study are openly available from the corresponding author upon request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication All authors read and approved this version of the manuscript and gave their consent for publication.

Competing interests The authors declare no competing interests.

References

André M, Pasquier A, Carteret M (2018) Experimental determination of the geographical variations in vehicle fleet composition and consequences for assessing low-emission zones. Transp Res Part d: Transp Environ 65:750–760

Bannon E (2019) Low-emission zones are a success – but they must now move to zero-emission mobility. Transport and Environment. https://www.transportenvironment.org/wp-content/uploads/2021/07/2019_09_Briefing_LEZ-ZEZ_final-1.pdf

Benmarhnia T, Rey L, Cartier Y, Clary CM, Deguen S, Brousselle A (2014) Addressing equity in interventions to reduce air pollution in urban areas: a systematic review. Int J Public Health 59:933–944

Bernard Y, Miller J, Wappelhorst S, Braun C (2020) Impacts of the Paris low-emission zone and implications for other cities. True Real Urban Emiss Initiat 3–17

Cesaroni G, Boogaard H, Jonkers S, Porta D, Badaloni C, Cattani G et al (2012) Health benefits of traffic-related air pollution reduction in different socioeconomic groups: the effect of low-emission zoning in rome. Occup Environ Med 69:133

Cesaroni G, Badaloni C, Gariazzo C, Stafoggia M, Sozzi R, Davoli M et al (2013) Long-term exposure to urban air pollution and mortality in a cohort of more than a million adults in Rome. Environ Health Perspect 121:324–331

Charleux L (2013) Contingencies of environmental justice: the case of individual mobility and Grenoble's low-emission zone. Urban Geogr 35:197–218

Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K et al (2017) Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the global burden of diseases study 2015. The Lancet 389:1907–1918

Deguen S, Zmirou-Navier D (2010) Social inequalities resulting from health risks related to ambient air quality—a European review. Eur J Pub Health 20:27–35

Deguen S, Petit C, Delbarre A, Kihal W, Padilla C, Benmarhnia T et al (2015) Neighbourhood characteristics and long-term air pollution levels modify the association between the short-term nitrogen dioxide concentrations and all-cause mortality in Paris. PLoS ONE 10:e0131463

EPA (2017) Clean air act overview: benefits and costs of the clean air act 1990–2020, the second prospective study. https://www.epa.gov/clean-air-act-overview/benefits-and-costs-clean-air-act-1990-2020-second-prospective-study

EPA (2020) Environmental justice. Environmental Protection Agency. https://www.epa.gov/environmentaljustice

Ezeah C, Finney K, Nnajide C (2015) A critical review of the effectiveness of low emission zones (lez) as a strategy for the management of air quality in major European cities. J Multidiscipl Eng Sci Technol 2(7):1860–1868

Forastiere F, Stafoggia M, Tasco C, Picciotto S, Agabiti N, Cesaroni G et al (2007) Socioeconomic status, particulate air pollution, and daily mortality: differential exposure or differential susceptibility. Am J Ind Med 50:208–216

Gehrsitz M (2017) The effect of low emission zones on air pollution and infant health. J Environ Econ Manag 83:121–144

GUAPO (2019) La qualité de l'air à paris et dans la métropole du grand paris: État des lieux et enjeux.Guapo. https://www.airparif.asso.fr/sites/default/files/documents/2021-10/Bilan_MGP_2020.pdf

Hajat A, Hsia C, O'Neill MS (2015) Socioeconomic disparities and air pollution exposure: a global review. Curr Environ Health Rep 2:440–450

Host S, Saunal A, Honoré C, Joly F, Le Tertre A, Medina S (2018) Bénéfices sanitaires attendus d'une zone à faibles émissions : évaluation quantitative d'impact sanitaire prospective pour l'agglomération parisienne (106 p). Paris: Observatoire régional de santé Île-de-France. www.ors-idf.org/nos-travaux/publications/benefices-sanitaires-attendus-dune-zone-a-faible-emissions.html

Host S, Honore C, Joly F, Saunal A, Le Tertre A, Medina S (2020) Implementation of various hypothetical low emission zone scenarios in greater Paris: assessment of fine-scale reduction in exposure and expected health benefits. Environmental Research 185:109405

Jiang W, Boltze M, Groer S, Scheuvens D (2017) Impacts of low emission zones in Germany on air pollution levels. Transport Res Proc 25:3370–3382

Kihal-Talantikite W, Legendre P, Le Nouveau P, Deguen S (2018) Premature adult death and equity impact of a reduction of no2, pm(10), and pm(2.5) levels in Paris-a health impact assessment study conducted at the census block level. Int J Environ Res Public Health 16:38

MGP (2019) Mieux respirer pour mieux vivre. Metropole du Grand Paris. https://www.zonefaiblesemissionsmetropolitaine.fr/

Mudway IS, Dundas I, Wood HE, Marlin N, Jamaludin JB, Bremner SA et al (2019) Impact of London's low emission zone on air quality and children's respiratory health: a sequential annual cross-sectional study. Lancet Public Health 4:e28–e40

Ortiz RA, Hunt A, da Motta RS, MacKnight V (2011) Morbidity costs associated with ambient air pollution exposure in Sao Paulo Brazil. Atmos Pollut Res 2(4):520–529

Santos FM, Gómez-Losada Á, Pires JCM (2019) Impact of the implementation of Lisbon low emission zone on air quality. J Hazard Mater 365:632–641

Schraufnagel DE, Balmes JR, Cowl CT, De Matteis S, Jung S-H, Mortimer K et al (2019a) Air pollution and noncommunicable diseases: a review by the forum of international respiratory societies' environmental committee, part 1: the damaging effects of air pollution. Chest 155:409–416

Schraufnagel DE, Balmes JR, Cowl CT, De Matteis S, Jung S-H, Mortimer K et al (2019b) Air pollution and noncommunicable diseases: a review by the forum of international respiratory societies' environmental committee, part 2: air pollution and organ systems. Chest 155:417–426

Soguel N, Griethuysen PV (2003) Cost of illness and contingent valuation: controlling for the motivations of expressed preferences in an attempt to avoid double-counting. Économie Publique/Public Econ 12:179–200

Tonne C, Milà C, Fecht D, Alvarez M, Gulliver J, Smith J et al (2018) Socioeconomic and ethnic inequalities in exposure to air and noise pollution in London. Environ Int 115:170–179

Wang L, Zhong B, Vardoulakis S, Zhang F, Pilot E, Li Y et al (2016) Air quality strategies on public health and health equity in Europe—a systematic review. Int J Environ Res Public Health 13(12):1196

Wood HE, Marlin N, Mudway IS, Bremner SA, Cross L, Dundas I et al (2015) Effects of air pollution and the introduction of the London low emission zone on the prevalence of respiratory and allergic symptoms in schoolchildren in east London: a sequential cross-sectional study. PLoS ONE 10:e0109121–e0109121

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.