ENVIRONMENTAL JUSTICE IMPLICATIONS FOR THE PARIS LOW EMISSION ZONE:

A Health Impact Assessment

June 2020

UC San Diego | SCRIPPS INSTITUTION OF OCEANOGRAPHY

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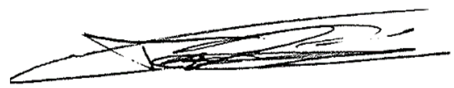

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Acknowledgments

This capstone project would not have been possible without the help of my Capstone Advisory Committee. First and foremost, I would like to thank my Committee Chair, Dr. Tarik Benmarhnia, for being an exceptional professor and advisor. He not only taught me everything I needed to know about health impact assessments but he also guided me towards this project and provided invaluable assistance throughout. The success of this project would not have been possible without Dr. Benmarhnia's support and encouragement during various setbacks. I also thank Sabine Host who graciously agreed to share her work with me and allowed this project to become my capstone project. It has been a privilege to take part in her research to help make Paris a more breathable city. I would also like to acknowledge, Dr. Rosana Aguilera Becker, who took the time to teach me all I needed to know about ArcMaps at the last hour.

Thank you as well to MAS Program Coordinator, Risa Farrell, and Program Director, Dr. Cory Gabriel who both provided valuable feedback, guidance, and encouragement when I needed it most. I am especially grateful for my cohort and the lifelong memories we have made together this year. I am inspired by everyone's achievements and I have no doubts that, in spite of our setbacks, we have come out of this program stronger and better equipped to take on the challenge of solving climate change from each of our unique perspectives.

I extend a special thank you to Dominick Mendola, without whom I would have never had the courage to pursue a master's education at Scripps.

Last but not least, my mom, dad, and closest friends deserve the highest recognition as I could not have persisted through this program amidst the chaos which has recently erupted in the world without their love and support.

Table of Contents

Project Motivation

The air pollution public health crisis has become the heart of my research since my atmospheric chemistry undergraduate course with Dr. Kim Prather, Director of the NSF Center for Aerosol Impacts on Chemistry of the Environment (CAICE). In an everyday livelihood sense, it is a tragic phenomenon that those who experience higher levels of poverty are often subject to the added physical toll of ambient air pollution, even though studies prove that these communities are the least responsible for the creation of such environmental burdens. As nations and governments attempt to reign in and regulate their emissions from all sectors, there is a consistent oversight in considering the environmental justice implications of such policies. This problem must be addressed because we as a society cannot continue to create environmental policies without incorporating provisions for equity. Without acknowledging the social injustices that exist across society and how they impact the nexus of climate change and human welfare, it is hard to imagine that any given clean air initiative will truly be effective in eliminating the burden of ambient air pollution. This is especially relevant in a time where respiratory diseases like COVID-19 have exacerbated the impact of morbidities associated with long and short-term exposures to the most dangerous known anthropogenic air pollutants.

Given these motives for a capstone project, it is with great privilege and fortune that, with the help of Dr. Tarik Benmarhnia, I was able to connect with Ms. Sabine Host from the Regional Health Observatory in Paris, France, who is dedicated to evaluating the effectiveness of air quality policies like France's first Low Emission Zone (LEZ). Known as *La Zone à Faibles Émissions*, the Paris LEZ has been studied according to its current and future effectiveness to lower traffic related air pollutants and its ability to ameliorate the health burden for which these emissions are responsible. This capstone project provides a novel analysis to the Paris LEZ in that it continues Host's work by aiming to shed light on the equity implications of this policy. More specifically, this project seeks to unveil which communities experience the most differential exposure and differential susceptibility – or both – to traffic related air pollutants and what can be done to better distribute this burden.

My partnership with Dr. Benmarhnia and Ms. Host to complete this evaluation is among the first of such endeavors and it is with great hopes that this report prompts more work in this area. The conversation of environmental justice and environmentalism must continue if the global community wishes to secure a pollution free future.

Part I: Background

Air Pollution: A Global Crisis

According to the World Health Organization (WHO), chronic exposure to ambient air pollution is a leading cause of global mortality with nearly 4.6 million attributable deaths in 2015 (Cohen et al., 2015). In fact, 91% of the world-wide population live in areas that do not meet WHO's air quality guidelines (WHO, n.d.). Since the beginning of the industrial era, ambient air across the world has been subject to increasing levels of industrial pollutants (Sherwin, 2017). Western entities such as Europe and the United States have led the world in technological progression since the 1800's. Unfortunately, the bulk of this progress has been powered by the combustion of natural resources like fossil-fuels, coal, and biomass (ie. wood, animal material). The gases associated with the burning of these resources are known to not only contribute to climate change, but their long and short-term residence in the lower atmosphere, where human activity occurs, negatively impacts human health. Air pollution is known to cause a large diversity of health effects such as cardiovascular disease, asthma, and cognitive decline. Moreover, studies have found that living in an urban environment increases an individual's risk of developing these adverse health outcomes (Rauh et al., 2008). As countries across the world catch up to western technology and become more industrialized, not only will industrial emissions increase, but rapid growth of urban populations is likely to follow. If air quality is left unchecked, deaths and morbidities linked to ambient air pollution will only get worse. In order to understand how to manage air quality across the world, it is important to know where these emissions are coming from and how they move about the environment.

Sources and Types of Pollutants

In the 5th assessment report from the Intergovernmental Panel on Climate Change, air pollutants are described as aerosols and are investigated to understand their impact on the environment and human welfare. Figure 1 provides a global look at seven major aerosols and their concentrations in various regions around the world. With this map it is important to recognize that while concentrations of industrial based aerosols are consistently higher in urban areas, these pollutants circulate across the world and impact rural or less populated areas at nearly equal rates.

Though natural sources of air pollution (i.e. minerals, sea spray, volcanic eruptions, decomposition of organic matter, etc.) exist, the primary sources that contribute to adverse outcomes on human health are man-made, known as anthropogenic air pollutants. Anthropogenic air pollution typically originates from sectors such as agriculture, energy, waste management, transportation, and households ("Air Pollution Sources", 2019). The specific types of anthropogenic pollutants that originate from these sources are referred to as criteria air pollutants. Criteria air pollutants are the most common compounds known to have adverse effects on human health and the environment. According to the U.S. Environmental Protection Agency, the following six compounds have been classified as criteria pollutants: ground-level ozone (O_3), particulate matter, nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and lead ("Criteria Air Pollutants", n.d.). Aerosols such as NO_2, SO_2, and PM are called primary pollutants because they are emitted directly from the source, while gases like ozone are secondary pollutants because they are derived from chemical reactions in the atmosphere. Each of these compounds are formed in the atmosphere due to the incomplete combustion of fossil fuels at high heat. As a result, most studies related to air pollution and it's impacts on human health are focused heavily on these six compounds.

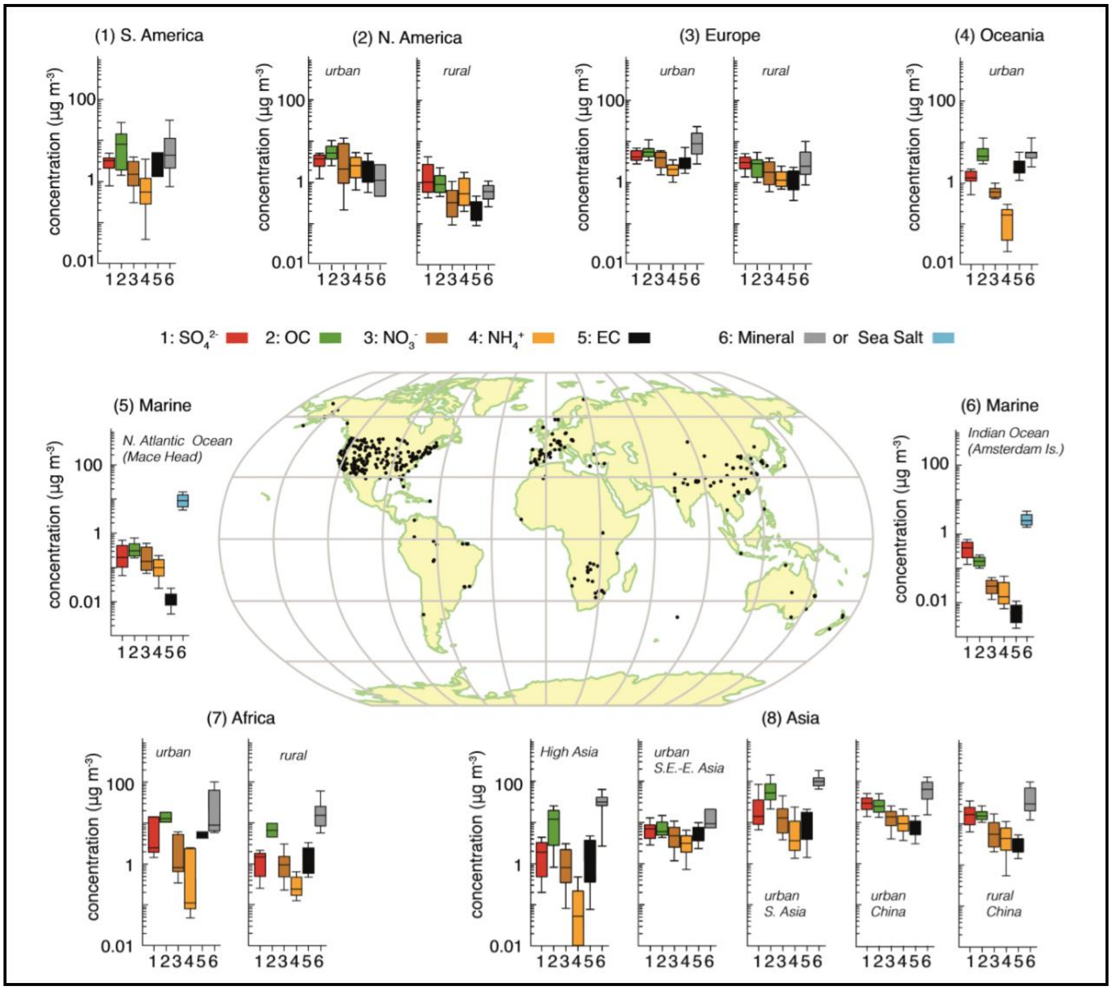

Figure 1. Aerosol concentration across six continents and two marine regions. Seven natural and anthropogenic aerosols are considered and both rural and urban sites are represented for each region. The black dots on the world map reflect where data was taken. The bar charts plot the mass concentrations (µg m−3) of each aerosol component from each region (Boucher et al., 2013)

Air Pollution Transport and Photochemical Smog

The impact that criteria air pollutants have on certain communities also depend on factors like local geography and weather. Geographic and weather-related air pollution transport includes proximity to mountain ranges and valleys, precipitation events, cloud cover, sunshine, wind speed, and atmospheric stability (Brusseau et al., 2019). Situations that lead to high concentrations of local air pollution, which then result in frequent photochemical smog events, are best exemplified by cities located near or in mountainous terrain and valleys, such as Mexico City and Los Angeles. While the generation of air pollution in large urban cities is due to traffic congestion, which exacerbates smog events, these cities are most often subjected to smog because they lie in regions where air can get trapped or become stagnant in the absence of strong winds or vertical mixing of the atmosphere (Brusseau et al., 2019). This type of event is known as an inversion layer. This occurs when high air pressure and surface temperature prevent turbulent mixing of the atmosphere, as depicted in Figure 2 ("Temperature inversion traps pollution", 2016). Sunny and urban regions of the world may also experience high local ozone levels as ozone is a product of compounds such as NO_2, CO, and CO_2 reacting with UV light in the ground-level layer of the atmosphere (Brusseau et al., 2019). On the positive side, pollutants can be removed from the atmosphere or prevented from reacting photochemically if they are rained out or if there is significant cloud cover, preventing UV rays from catalyzing any reactions (Brusseau et al., 2019). In regards to long-range transport, air pollution can travel and be dispersed, diluted, or re-concentrated in another region due to wind patterns.

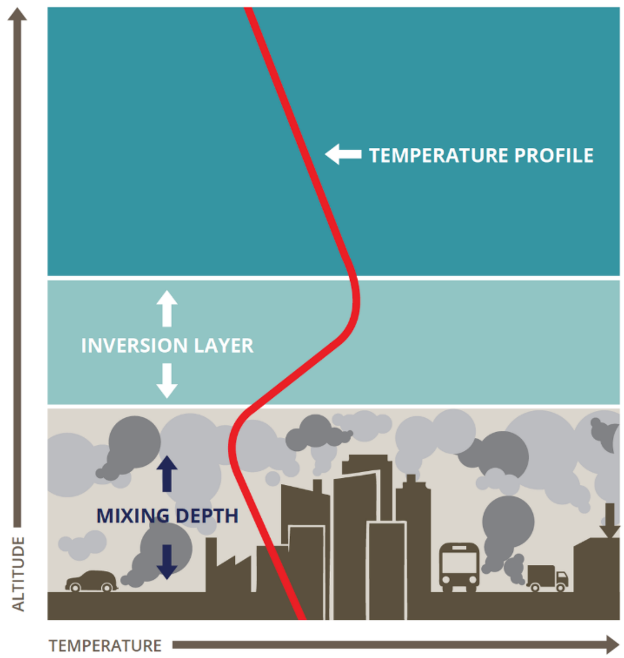

Figure 2. This image depicts a Temperature Inversion Layer which traps air pollutants at the surface ("Temperature inversion traps pollution", 2016)

Traffic Related Air Pollution

While geographical landscapes and weather patterns may vary drastically between each major city in the world, the one common denominator amongst them all is the transportation sector which is the primary anthropogenic source of urban air pollution. In some regions of the world, transportation accounts for up to 70% of ambient air pollution emissions (WHO, n.d.). These regions are typically large cities where people are highly concentrated. Each of the six criteria pollutants previously mentioned are also linked to vehicle exhaust. Lead is no longer as prominent in the atmosphere due to heavy regulation of petrol production world-wide, but NO_2, $PM_{2.5}$, and O_3 are still emitted and are known to be deadly. Nevertheless, the impact that exhaust emissions and traffic have on human health and low socio-economic communities is compelling.

Effects on the Human Body

Traffic related air pollution (TRAP) refers to the pollutants that are exposed in the environment as a result of motor vehicle emissions. The threat that TRAP poses on human health is the primary reason why intervention is critical. In fact, although WHO periodically proposes ambient air quality guidelines for nations to enforce at their discretion, there is no safe level of exposure to pollutants generated from fossil-fuel burning vehicles (HOST et al., 2020). One study goes so far as to claim that TRAP is so detrimental to one's health that chronic exposure is worse than smoking tobacco (Wang et al., 2019). When it comes to understanding the health impacts of air pollution, the pollutants that researchers primarily study are nitrogen dioxide (NO_2), particulate matter with a diameter of 10 μm (PM_{10}) or 2.5μm ($PM_{2.5}$), and Ozone. These three pollutants are the focus of many urban TRAP studies because NO_2 is the best known indicator of traffic emissions and is a precursor to ozone, while particulate matter is the most lethal of the toxins (Ezeah et al., 2015).

Morbidity and Mortality

After an extensive literature review on the adverse health events linked to air pollution, the three pollutants that are overwhelmingly used to identify health impacts are NO_2, PM, and Ozone. Both NO_2 and PM are known to be carcinogenic and acute ozone exposure harms both the lungs and heart (Ezeah et al. 2015). Overall, TRAP is known to negatively impact nearly every organ of the body and lead to higher incidences of disease and death, otherwise known as morbidity and mortality, respectively (Schraufnagel et al., 2019). Some health risks associated with chronic and acute TRAP exposure include an increased risk in cardiovascular disease, respiratory disease, neurological impairments, and adverse birth outcomes (Schraufnagel et al., 2019). The main cardiovascular disease related to air pollution is ischemic heart disease in adults (Schraufnagel et al., 2019). This essentially means that as pollutants enter the body through the lungs, the smaller particles will permeate into the blood stream and make their way to the heart where they have the potential to weaken heart muscles. Ultimately, this could eventually lead to a heart attack. It is estimated that 16% of cardiovascular deaths are attributable to air pollution (Schraufnagel et al., 2019). In regards to respiratory disease, TRAP is linked to higher incidences of asthma in children and chronic obstructive pulmonary disease (COPD) in adults. Mortality due to COPD as a result of TRAP accounts for 25% of worldwide deaths ("Mortality and burden of disease", n.d.). Dementia and strokes in adults are also attributable to long and short-term exposure to TRAP, respectively (Schraufnagel et al., 2019). In fact, air pollution may account for 21% of deaths caused by strokes (Schraufnagel et al., 2019).

Vulnerable populations

It is also important to note that vulnerability to adverse health impacts varies by age, socio-economic status, and pre-existing morbidities. Those who are most vulnerable age wise are children, the elderly, and fetuses (Schraufnagel et al., 2019). For children, TRAP exposure is especially dangerous due to their small lung capacities and fast heart and breathing rates (Watts et al., 2019). Long-term exposure leads to poorer lung function, higher rates of childhood asthma, and poorer cognitive development ("Air pollution and child health", 2019). TRAP also impacts pregnancy by increasing the risks of hypertensive disorders and miscarriages in mothers. Hypertensive disorders in mothers can then lead to a higher risk for preterm birth and/or low birth weight in infants (Schraufnagel et al., 2019). Lastly, while those with pre-existing health conditions may experience higher susceptibility to adverse health events related to TRAP, chronic exposure to such chemicals can cause severe morbidities in otherwise healthy individuals. For example, the most common morbidity associated with these pollutants and chronic exposure is lung cancer in adults. All in all, it is important to note that while these effects to the human body are known, there are likely other negative impacts that remain unknown simply because they have not yet been studied.

Environmental Justice Impacts on Low Socioeconomic Status Communities

The risk of developing such diseases also depends on the conditions of the places where people live, work, and recreate. These conditions are known as social determinants of health. This means that individuals and communities that are in close proximity to traffic on a daily basis may experience a differential exposure to air pollution than perhaps those that live further away. Or perhaps their socioeconomic status and access to healthcare make them more susceptible to developing more serious complications or other comorbidities. This is where equity and environmental justice become ingrained into the issue because communities that are subject to differential exposure AND differential susceptibility are often poorer communities and communities of color (Taylor, 2014).

When it comes to social determinants of health, SES is one of many factors that play a role in differential exposure and susceptibility to air pollution. In fact, this is the very definition of environmental injustice – the unequal subjugation to environmental hazards and their associated adverse health impacts based on race, color, national origin, or income (Charleux, 2013; EPA, n.d.) All around the world it is observed that vulnerability and exposure to high TRAP levels is not equally distributed among the public. This burden tends to fall disproportionately amongst low SES groups (Tonne et al., 2018; Hajat et al., 2015; Deguen et al., 2015). Moreover, of the 4.6 million annual deaths attributable to air pollution around the world, 90% of those deaths occurred in middle- to low- income countries ("Air Pollution", n.d.). Research also tells us that health inequalities tend to line up with social hierarchies (Benmarhnia, 2013). Access to sufficient health services, transportation services, and quality of life at home and at work are often defined by these hierarchies. However, public policy makes it possible to not only shift the burden of TRAP and health inequalities, but to reduce it all together.

Policy Interventions

Since the pollutants described above are known to inflict significant adverse health impacts, whether by short-term or long-term exposure, it is critical that more stringent emission standards are imposed on a global and local scale so as to improve the quality of life for the lives most directly affected by this public health crisis. Given the gravity of the TRAP public health issue, several interventions have been developed to target the transportation sector. By addressing TRAP in urban settings, significant strides can be made for improving human and environmental health (Rauh et al., 2008). Some approaches to policy that aim to reduce TRAP include the implementation of Low Emission Zones (LEZs) and congestion charging. In general, LEZ's are implemented around the perimeter of densely populated urban cities in order 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 hours a day 7 days a week, or between certain weekday hours. Enforcement of LEZ's is either manual (ie. subject to police monitoring of windshield stickers) or digital with cameras set up throughout the city that read vehicle license plates (Bernard et al., 2020). Congestion charging on the other hand is a policy method that charges all vehicles that wish to operate in the specified zone during certain hours. While the topic of congestion charging is not within the scope of this paper, its strength as an anti-pollution policy makes it worth mentioning. In regards to LEZ's, their implementation has been widely adopted across Europe and among a handful of Asian cities including Beijing, Shanghai, Tokyo, and Singapore (Malina et al.,2015; Mudway et al., 2019).

Other policy interventions to regulate air quality, such as the Clean Air Act in the United States, have also played a significant role in reducing ambient levels of criteria air pollutants. However, recognizing that it is not always easy to evaluate the effectiveness of policies aiming to improve air quality, there is a study that offers a set of guidelines that policy makers and other non-health experts can use to evaluate and improve such interventions (Cartier, Benmarhnia, and Brousselle, 2015). These guidelines require policy decision makers to consider six modifying factors that allow non-health experts to better understand what it takes to ensure that air quality policies have the intended impact on public health. These modifying factors include the sources, quantity and concentration of emissions and their spatial distribution, personal exposure to emissions, and individual variability (Cartier, Benmarhnia, and Brousselle, 2015). Any policy that wishes to address the issue of air pollution must act on at least one of these factors. More importantly this study emphasizes a way to ensure that the intended health benefits of any intervention are distributed equitably. Inequities in health are important to evaluate because they are health disparities that "systematically put groups of people who are already socially disadvantaged at further disadvantage with respect to their health" (Braveman and Gruskin, 2003). In the case for equity, spatial distribution and vulnerability are the key modifiers to consider, due to the fact that their differential nature generates such inequalities.

Part II: Low Emission Zones and Implementation in Paris

Low Emission Zones

History

In 1996, Sweden became the first country to implement a low emission zone. Stockholm, Gothenburg, and Malmoe each had what was known as an Environmental Zone (Müller and Le Petit, 2019). Since then, about 250 more zones have been implemented across the European Union (EU). While their popularity has grown, much of that growth began after 2010, making most LEZ's less than a decade old. Some of this growth may be attributed to the fact that in 2008, the European Parliament passed a directive mandating that all member states regulate their NO_2, SO_2, CO, Ozone, PM_{10}, and $PM_{2.5}$ concentrations ("La Qualité de l'air à Paris", n.d.). This directive provided a legislative means to punish countries for not meeting the value limits set by the European

Commission. As a result, in 2015 the European Commission exercised its right to pursue litigation by charging France for exceeding PM_{10} limits in 14 of its regions ("La Qualité de l'air à Paris", n.d.). Then, in 2018, the European Commission entered pre-litigation against France for exceeding NO_2 thresholds in the same regions ("La Qualité de l'air à Paris", n.d.). It is likely that the threat of legal sanctions for failing to comply with air quality directives has provided an added level of urgency for countries in Europe to gain control over their atmospheric pollutants. It has also paved the way for policies like LEZ's.

European Emissions Standards

In Europe, Low Emission Zones restrict vehicles based on their Euro Standard classification. The EU emission standard system was designed to regulate all new diesel and petrol vehicles sold in the EU and European Economic Area (EEA) member states (Nesbit et al., 2016). This system primarily identifies the limits for exhaust emissions of new cars (Nesbit et al., 2016). As time progresses and car fleets become more technologically advanced, these emissions standards will continue to become more stringent.

To date, six Euro Standard classifications have been implemented to label all diesel and petrol vehicles in Europe. The key factors that go into determining a vehicles Euro standard classification are the vehicles engine type (ie. petrol or diesel), first registration date and vehicle use type – passenger, light-duty vehicle (LDV), or heavy-duty vehicle (HDV) (Nesbit et al., 2016). Euro standard numbering for passenger cars and LDV's are based on Roman numerals (ie. Euro 1/2/3) while HDV Euro standards are differentiated by Arabic numerals (ie. Euro I/II/III). Table 1 details which directives passed by the EU led to the implementation of each round of restrictions, and Table 2 gives an example of EU emission standards for passenger cars. Table 2 also describes how CO (Carbon Monoxide), HC (Total Hydrocarbon), HC+NOx (Non-methane Hydrocarbons), NOx (Nitrous Oxides), PM, and PN (Particle Number) are the elements that are regulated under the Euro Standard directives and explains these emission limits. Appendix A contains two tables that detail the emission standards for LDVs and HDVs, respectively. These tables also describe how vehicles are categorized into different types of LDVs based on passenger or good capacity and weight, respectively.

Table 1. Regulations which lead to each Euro Standard (Host et al., 2020)

Standard(s)	Regulation(s)
pre-EURO	Directive 70/220/EEC (revised and updated multiple times)
EURO 1	Directive 91/441/EEC(passenger cars only) Directive 93/59/EEC* (PC and light trucks)
EURO 2	Directives 94/12/EC*96/44/EC96/69/EC*
EURO 3	Directive 98/69/EC*98/77/EC 1999/102/EC 2001/1/EC 2001/100/EC Directive 2000/80/EC Directive 2002/80/EC
EURO 4	2003/76/EC2006/96/EC
EURO 5	Regulation 715/2007"political" Regulation 692/2008 "implementing"
EURO 6	
*** Amendment to Directive 70/220/EEC**	

Table 2. EU Emissions Standards for Passenger Cars (Host et al., 2020)

EURO standards	Date	CO	HC	HC+NOx	NOx	PM	PN
				g/km			#/km
				Compression Ignition (Diesel)			
EURO 1	1992.07	2.72	–	0.97	–	0.14	–
EURO 2, IDI	1996.01	1.0	–	0.7	–	0.08	–
EURO 2, DI	1996.01[a]	1.0	–	0.9	–	0.10	–
EURO 3	2000.01	0.64	–	0.56	0.50	0.05	–
EURO 4	2005.01	0.50	–	0.30	0.25	0.025	–
EURO 5a	2009.09[b]	0.50	–	0.23	0.18	0.005[f]	–
EURO 5b	2011.09[c]	0.50	–	0.23	0.18	0.005[f]	6.0×10^{11}
EURO 6	2014.09	0.50	–	0.17	0.08	0.005[f]	6.0×10^{11}
				Positive Ignition (Petrol)			
EURO 1	1992.07	2.72 (3.16)	–	0.97 (1.13)	–	–	–
EURO 2	1996.01	2.2	–	0.5	–	–	–
EURO 3	2000.01	2.30	0.20	–	0.15	–	–
EURO 4	2005.01	1.0	0.10	–	0.08	–	–
EURO 5	2009.09[b]	1.0	0.10[d]	–	0.06	0.005[e,f]	–
EURO 6	2014.09	1.0	0.10[d]	–	0.06	0.005[e,f]	6.0×10^{11} [e,g]

Notes:
a. until 1999.09.30 (after that date DI engines must meet the IDI limits)
b. 2011.01 for all models
c. 2013.01 for all models
d. and NMHC = 0.068 g/km
e. applicable only to vehicles using DI engines
f. 0.0045 g/km using the PMP measurement procedure
g. 6.0×10^{12} 1/km within first three years from Euro 6 effective dates

Types of Frameworks

Current frameworks for LEZ policies differ between countries and cities, but as previously stated, the general principle is to restrict high emitting vehicles from driving within urban cities. Some countries have set up a national framework for LEZ's and have left it up to local officials to decide the implementation schedules and vehicle restrictions. France, for example, passed legislation in 2010 that opened a door for cities to adopt and implement LEZ's (Holman et al., 2015). This framework was later expounded upon by Paris, Grenoble, and five other major French cities. Other countries, like Italy on the other hand, have left adoption and implementation guidelines entirely up to individual cities (Holman et al., 2015). This means that within one country there may exist several different types of LEZ frameworks. This allows each municipality to tailor the rules and boundaries of its LEZ to best suit the needs of its residents. However, this becomes an issue when making multi-city trips within a short time period. Nevertheless, regardless of the initial framework, LEZs are typically structured to become more stringent over time. The ultimate goal is to empower citizens to adopt zero-emission vehicles and alter public behavior and perception to favor more breathable cities.

Documented Impact on Air Quality, Health, and Equity

An extensive literature review was conducted in order to have a full view of the current understanding of the impacts LEZ policies have on urban centers. This literature review involved searching through databases like ScienceDirect, PubMed, NCBI, and Google Scholar. The key words used include: 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 3 summarizes these results which focus on LEZ implementation in Europe. This table includes studies published in English since 2012 and does not include studies that have already been assessed in previous literature reviews. In Table 3, each study discusses the observed or expected improvements to air quality. However, not all studies investigate the impact that air quality improvements attributable to LEZs have on health, much less equity. Appendix B contains another table that summarizes the specific details of LEZ interventions evaluated for each study mentioned in Table 3.

What this table tells us is that some LEZs require several years of implementation before reductions in air pollution or improvements in health outcomes can be observed. Furthermore, there are studies that prove the feasibility of designing LEZ policies that are effective in reducing atmospheric concentrations of NO_2, PM_{10}, and $PM_{2.5}$. Unfortunately, however, most frameworks are not strict enough to observe these results in the ideal timeframe. When it comes to observed health outcomes, substantial evidence pointing toward LEZ effectiveness on ameliorating health impacts is still lacking. Additionally, there is no uniformity in which health events are considered the most meaningful way to quantify an LEZs impact on health. The health events studied range from premature mortality, childhood asthma, and adverse birth outcomes. The Malina et al. study avoids morbidities all together and quantifies health benefits in terms of savings in healthcare spending. Equity, on the other hand, has only been fully assessed once since 2012 and continues to be an area of research that needs more support

Table 3. Summary of Literature Review on LEZ Impacts on Air Pollution Reduction, Health*, and Equity*

Study Site(s)	Authors	Aim	Pollutants Studied	Impacts Considered		Results		Conclusion
				Health	Equity	Health	Equity	
Rome	Cesaroni et al., 2012	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)	NO2 reduction was associated with an average of 921 YLG per 1000,000.	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 old's living within the LEZ	NOx, NO_2, $PM_{2.5}$, PM_{10}	Respiratory/allergic symptoms in children		Only rhinitis was positively effected 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 760M 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
5 EU countries (Denmark, Germany, Netherlands, Italy, and UK)	Holman et al., 2015	Review of 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 (<2500g), Still birth	No statistically significant effect on birthweight observed (increase of 0.26 grams), 96 infant lives saved	Air pollution reductions are too small to produce significant improvements in infant health
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. This is not statistically significant	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., 2020]	To quantify the discrepancy between exhaust emissions under testing conditions and real-world conditions.	NOx					A substantial reduction in NO2 emissions can be expected from 2024 and on.

*When assessed

**Morfeld et al., 2015 claim that the monetary health benefits calculated by Malina and Scheffler is probably too high and the uncertainty reported possibly too small.

Low Emission Zones and Equity

According to the literature review conducted and summarized in Table 3, there are causal relationships made and studied regarding the impacts of air and TRAP on health. The findings in these studies are clear, consistent, and well understood. Next, there are a hand full studies that investigate the correlation between air pollution and social deprivation. These studies have been conducted around the world and have mixed results depending on each city's values toward public transportation and other factors related to urban planning. The next two relevant causal relationships are how LEZ's impact concentrations of urban air pollution and how they improve health outcomes and mortality. However, only one study conducted in Rome incorporated an evaluation for equity.

Even though the scientific evidence for how LEZs directly impact equity is currently lacking, it is still possible to identify which existing social inequalities might play a role on this issue. For example, it is known that low SES groups contribute least to air pollution emissions due to the fact that they own less 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 NO2 concentrations than other well-off areas (Müller and Le Petit, 2019). Additionally, low-income households and small businesses often do not have the financial capacity to switch to a cleaner vehicle, making compliance to a LEZ difficult (Müller and Le Petit, 2019).

Discussing the health impacts of LEZ policies are important because a majority of these policies across the European Union are not yet a decade old. Before new norms are set and it becomes harder to make changes to the framework of LEZ policies, it is critical to answer the question of whether or not the health benefits are both significant and effective for everyone. Early evidence on equity can help to inform future modifications and implementation as LEZs become more stringent. If any given LEZ does not consider equity in its early framework it runs the risk of exacerbating already existing environmental injustices.

The Paris Low Emission Zone

Background

The city of Paris covers 105 km^2 and is home to approximately 2.21 million inhabitants. The Greater Metropolitan Region of Paris (MGP) extends further and covers 814 km^2, accommodating 7.02 million residents. This equates to 20,934 people/km^2 and 8,624 people/km^2, respectively ("La Qualité de l'air à Paris", n.d.). Infrastructurally, Paris is a dense, car-oriented city. This means that its inhabitants are subjected to significant health risks related to traffic related air pollution (Host et al., 2020). To date, 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. In the Greater Paris area, about 20% of inhabitants are exposed to these exceeded values ("La Qualité de l'air à Paris", n.d.). This is an improvement given that in 2007 100% of the population was at risk. However, further policy intervention is necessary to bring that risk to virtually zero. Additionally, around 6,600 annual deaths are attributable to chronic air pollution in Paris and 60,000 deaths are recorded in all of

France (Host, 2019; Métropole du Grand Paris, 2019). Evidence for specific health impacts of excessive rates of exposure include studies which show that about 16% of new cases of childhood asthma in Paris and in the Petite Couronne are attributable to traffic related air pollution ("La Qualité de l'air à Paris", n.d.). Moreover, it is estimated that if European limit values for $PM_{2.5}$ were respected, about 2,500 and 5,000 annual premature deaths could be avoided in Paris and in Greater Paris, respectively ("La Qualité de l'air à Paris", n.d.). From an economic perspective, measures to reduce air pollution could mean up to 2 million euros in savings annually for the French health system ("La Qualité de l'air à Paris", n.d.). As a result of this data, air quality control continues to be a high priority on the public policy agenda. Interventions that have proven successful in lowering emissions are car scrappage schemes and an increase in cycling and public transport incentives (Host et al., 2020). While both of these strategies are important for improving air quality and rates of alternative mobility, the most important scheme that Paris is interested in investigating is the success of the new LEZ.

In 2015, shortly after being put on notice by the EU Commission for exceeding PM limit values, the French State Council moved to prioritize all policy measures related to improving air quality (Métropole du Grand Paris, 2019). Therefore, that same year the MGP adopted the "Breathable Cities in 5 years" initiative as part of the Air Climate Energy Metropolitan Plan, which was set to be implemented November 12, 2018 (Metropolis of Greater Paris, 2019). Under this initiative was a plan to formally introduce a national framework for metropolitan Low Emission Zones (*Zone à faible émissions* – ZFE). At this time, it was determined that an LEZ would have the greatest and quickest impact on improving air quality (Metropolis of Greater Paris, 2019). As a result, that same year in 2015, the Paris LEZ was drafted and introduced under a five-phase roll-out schedule that will be complete by 2030. The end goal of this policy is to eventually restrict 100% of exhaust emitting vehicles from entering the MGP.

Each of the five phases of the Paris LEZ policy are linked to the restriction of a new category of vehicle within the LEZ. These categories are titled "Crit'Air" and are numbered from one to five, as demonstrated in Figure 3. The higher the number the more pollutants the vehicle emits. A sixth category is labeled "Crit'Air Vert" which refers to electric or hydrogen vehicles that emit zero exhaust related pollutants. There is also the "unclassified" category which refers to vehicles registered before 1997 and does not receive a Crit'Air designation. Factors that determine which category a vehicle falls into are the vehicles engine type and Euro standard. A table explaining the requirements for each Crit'Air can be found in Appendix C.

Figure 3. Crit'Air stickers that are used to identify the emissions standards that the vehicle meets (Metropolis of Greater Paris, 2019)

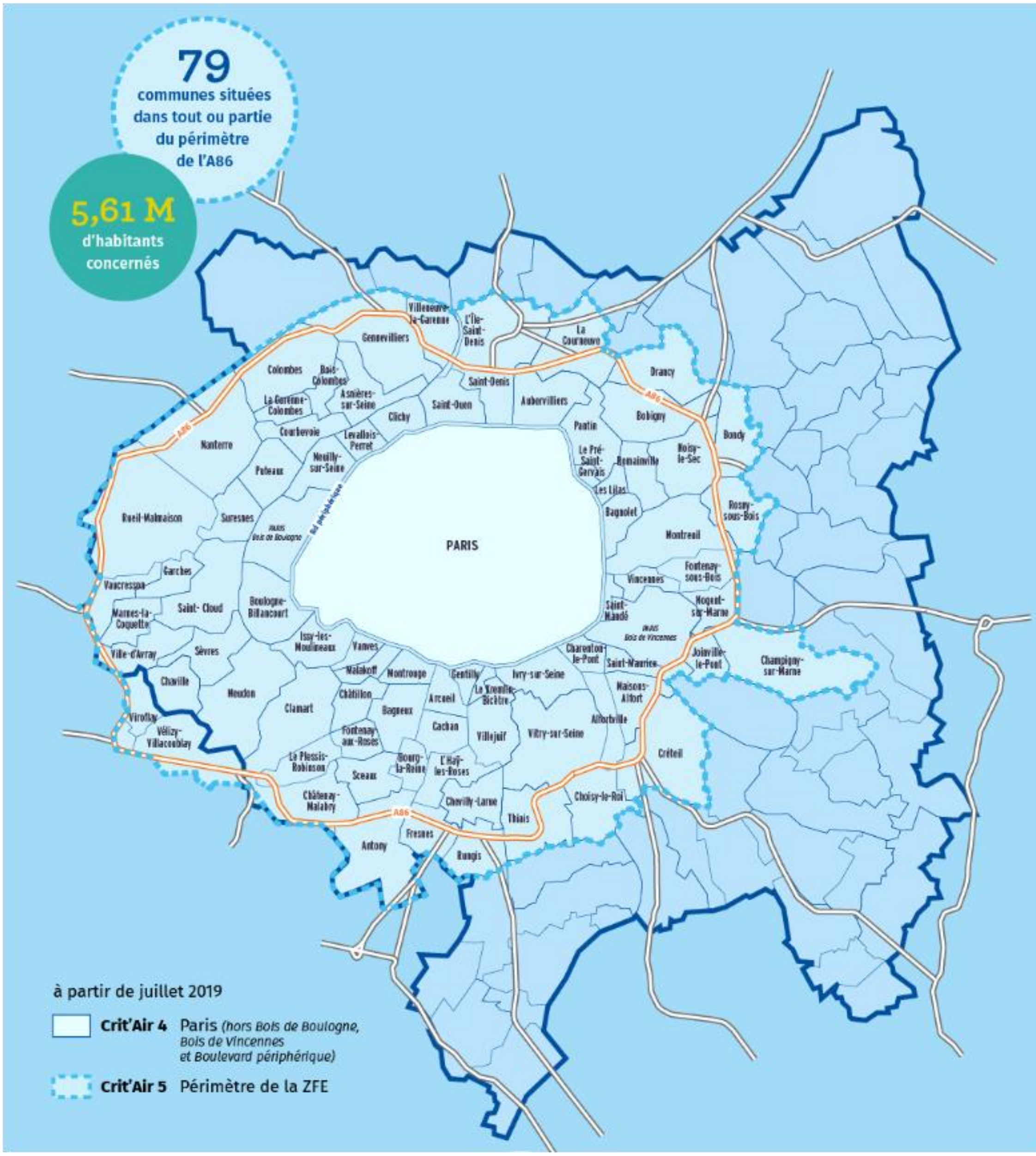

Figure 4. A map of the Paris Low Emission Zone limits. As of 2019, Crit'Air 5 vehicles are banned from the new LEZ perimeter which now includes municipalities within the A86 road way, denoted by the dashed line. Crit'Air 4 vehicles are banned from the Paris city limits, denoted by the lightest blue shaded area. The dark blue solid line is the perimeter for the MGP (Métropole du Grand Paris, 2019)

In 2017, phase one went into effect for the Paris inner city limit which restricted entry of "unclassified" and Crit'Air 5 vehicles (Host, 2019). As of July 2019, phase one was then extended to include municipalities of the MGP which lie inside the A-86 roadway. When this extension took place, Crit'Air 4 vehicles were simultaneously restricted from the Paris inner city limit, as demonstrated in Figure 4 ("La Qualité de l'air à Paris", n.d.). Not all municipalities were ready to comply at the time, but once the entire MGP is incorporated, it will be the largest LEZ initiative to date ("La Qualité de l'air à Paris", n.d.).

As this policy enters the beginning stages, many studies are keen to evaluate how effective this LEZ infrastructure is in reducing traffic related air pollutants. They also seek to determine how these reductions impact public health given that it is among the largest and most unique of its kind (Cruz and Montenon, 2015). However, an area of research that remains overlooked and understudied, especially in regards to this policy, is whether or not the LEZ will be equitable for all those living in and around the MGP. As with almost all LEZs currently in place around the world, there is still no sufficient research on environmental justice issues related to these policies, nor is there a framework within these policies to consider these needs.

When it comes to understanding how exposure to air pollution is distributed among social groups, there are only a handful of known studies conducted in Europe that investigate possible inequalities based on socioeconomic deprivation. In Paris, only three studies are known to have investigated this relationship. Two of these studies will be discussed in further detail. The first study by Deguen et al. considers the impact of short-term exposure to ambient NO_2 on areas that already experience higher than average levels of chronic air pollution and are considered socially deprived (Deguen et al., 2015). The health outcome that was used to determine the impact on health was all-cause mortality on individuals over 35 years old. What they found was that low socioeconomic groups do experience higher rates of long-term NO_2 exposure and as a result are subject to a higher risk of all-cause mortality during short-term peaks of NO_2 exposure (Deguen et al., 2015). Appendix D presents figures that demonstrate the areas most impacted by NO_2 concentrations and social deprivation by census block, respectively. Based on these two maps, there is a clear overlap along the ring road of Paris where NO_2 exposure by census block is concentrated unequally over lower socioeconomic groups. Figure 5 below is from another study that hypothesized the effect of air pollution reduction policies on health and equity by conducting a health impact assessment using spatial analysis methods (Kihal-Talantikite et al., 2018). The results here demonstrate that premature deaths of individuals over 30 years old are clustered primarily in the northeastern census blocks which experience the most social deprivation and are attributable to NO_2 exposure. Not only are these deaths clustered in these census blocks, but these deaths account for 80% of Paris' total number of premature deaths.

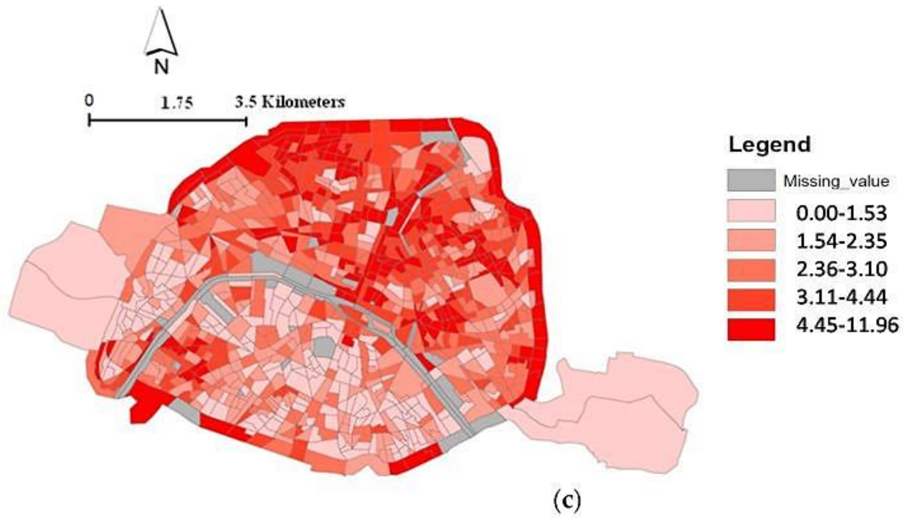

Figure 5. Spatial variability of NO2 and socio-economic status level according to census blocks (Kihal-Talantikite et al., 2018)

A third study was conducted in Grenoble, France prior to the implementation of France's first LEZ and discussed the impact such a policy might have on environmental injustices (Charleux, 2013). The result of this study declared that social groups indeed play a role in the efficiency of transitioning to other modes of transportation or replacing older vehicles. This study revealed that LEZ's are more often implemented around wealthier urban regions which defeats the purpose of reducing inequalities (Charleux, 2013). The suggested resolution was that congestion charging schemes might have a more egalitarian result. As a result, LEZ policy was removed from consideration until 2015 when improvements to the LEZ framework were developed (Holman et al., 2015).

Therefore, the remainder of the paper will address how the implementation of an LEZ around both the City of Paris and the Greater Paris Metropolis perimeters will impact the distribution of health benefits. Will these benefits be distributed equitably, or will they reinforce already existing gradients between higher and lower SES groups? One validated approach to answer such a timely question is to conduct a health impact assessment.

Conducting a Health Impact Assessment

In order to determine whether or not the Paris LEZ policy will further exacerbate any environmental injustices that some citizens may already be facing, conducting a health impact assessment (HIA) will be the most efficient method of evaluation. In general, HIA's are useful in aiding decision makers who seek to create public policies or projects that improve public health in a manner that is evidence based (Center for Disease Control, 2016). With the same relative structure as an Environmental Impact Assessment, an HIA is capable of determining the health benefits and adverse health outcomes of any given policy or project (Center for Disease Control, 2016). HIAs are especially useful when it comes to urban planning projects, such as transportation initiatives, or land use development (Center for Disease Control, 2016).

In this scenario, the current HIA for the Paris LEZ was led by a group of experts affiliated with the Île-de-France Regional Health Observatory, Airparif, and Santé Publique France. Each of these organizations are scientific, governmental and non-profit entities that conduct research related to public health and air pollution monitoring in France. The focus of this study was to assess reductions in TRAP exposure on a fine-scale attributable to the Paris LEZ and determine the expected health benefits (Host et al., 2020). Additionally, this assessment was conducted for four different hypothetical implantation scenarios (Host et al., 2020). The HIA conducted by Host et al. 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. This level of analysis for a specific policy measure that is being implemented on a large-scale has never been done in neither Paris nor in France (Host et al., 2020). This project intends to extend the results of this study to include more explicit factors related to differential susceptibility to TRAP and identify which areas and SES groups are most disproportionately left out of the proposed health benefits.

Methods

Before beginning to evaluate the environmental justice implications of the Paris LEZ, it is necessary to first understand how the current HIA was conducted. The following section outlines the steps taken to determine how reductions in exposure for four different hypothetical scenarios are likely to produce reduced incidences of mortality and reduced incidences of four morbidity outcomes.

Four scenarios

The Host et al. study evaluates four scenarios that policy makers can use to inform further action regarding the evolution and the strengthening of the LEZ. 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 (Figure 6 demonstrates where these perimeters lie) - and two different restriction levels, Crit'Air3 and Crit'Air4. Each of these four scenarios are then compared to a Business as Usual (BAU) scenario where there is an uninterrupted technological progression of the car fleet. Table 4 outlines the difference between the two restriction levels, Ban_{low} and Ban_{high},. The inner and outer boundaries are labeled LEZ_{Paris} and $LEZ_{Enlarged}$, respectively. As a result, the following chart details how each of the four scenarios will be referred:

$LEZ_{Paris}Ban_{Low}$	$LEZ_{Enlarged}Ban_{Low}$
$LEZ_{Paris}Ban_{High}$	$LEZ_{Enlarged}Ban_{High}$

Table 4. Type of vehicles concerned by the restriction according to the two stages of implementation (Host et al., 2020).

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

* first registered before 5/31/00

** first registered between 06/01/00 and 06/30/04

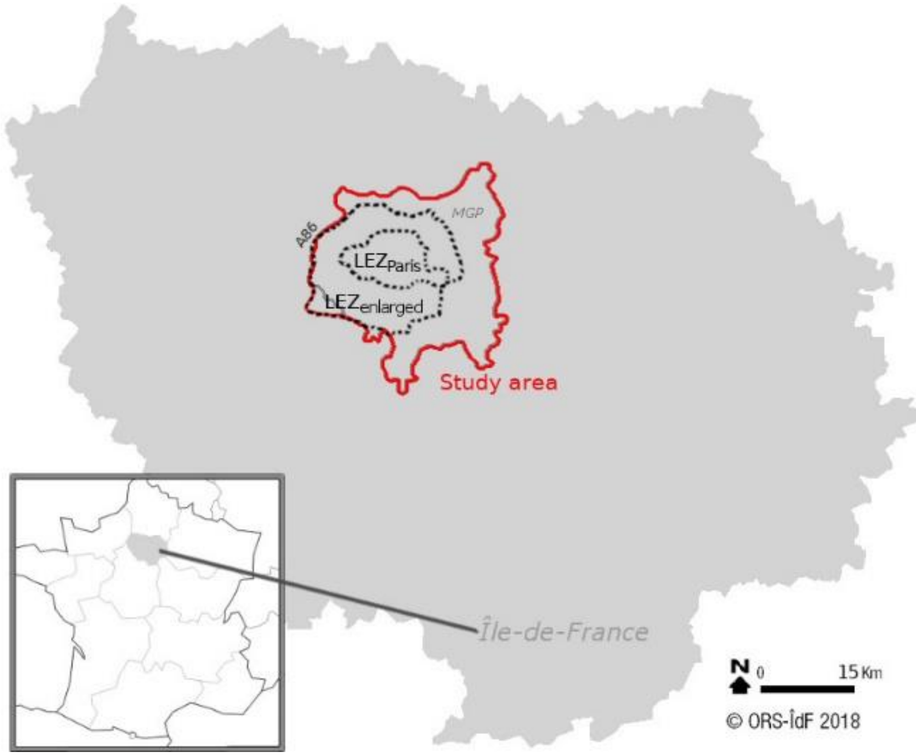

Figure 6. From inside out, this image depicts the LEZ defined by the Paris ring road, the expanded LEZ defined by the A86 roadway, the perimeter of the MGP region, the Francilienne perimeter which is defined by the dark grey shading, and the entire Ile-de-France region which is defined by the lighter grey shading (Host et al., 2020)

Modelling Reductions in Emissions and Population Exposure

For each of the four LEZ scenarios, reductions in NO_2 and $PM_{2.5}$ emissions were the sole pollutants evaluated for years 2018 and 2019. However, for the sake of mapping, only NO_2 reductions were modelled in Host et al.'s study due to the fact that NO_2 is the most useful indicator for traffic related emissions (Host et al., 2020). On the other hand, $PM_{2.5}$ is primarily derived from other non-exhaust related sources, such as breaking tires and road surface wear, and also tends to be transported from other areas (Host et al., 2020). However, given the impact PM has on health and other politically motivated factors, it is still relevant to ultimately assess the associated health benefits due to reductions in $PM_{2.5}$. In order to project emissions reductions for the Ban_{low} and Ban_{high} scenarios, a modelling chain was used to include road traffic modelling, traffic emissions modeling, and regional modelling which entailed mapping pollutant levels in urban and rural areas. Urban scale modelling allowed for visualizing concentrations closest to traffic with 50m resolution. Additionally, these projections were made under BAU conditions for both years. As a result, maps like Figure 7(c) were created for each hypothetical scenario to combine NO_2 concentrations at background levels and the impacts of roadside levels.

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 this level.

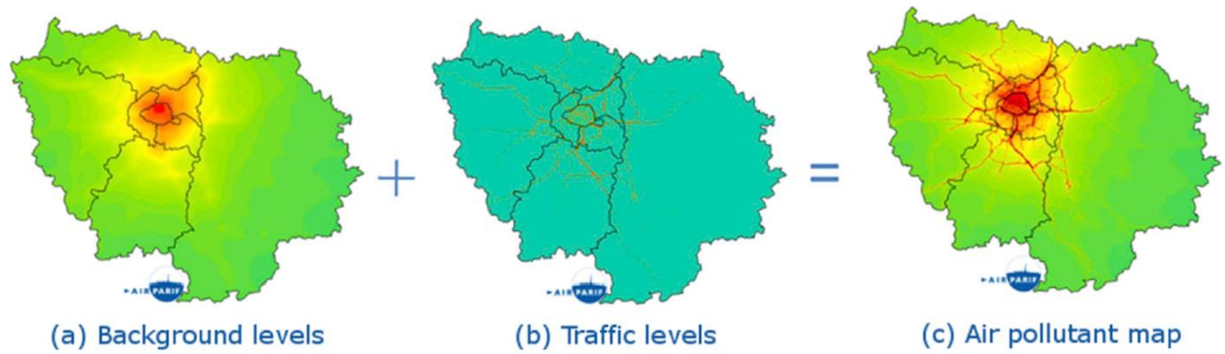

Figure 7. (a) A map of background levels of NO2 pollution, (b) a map of the impact of roadside levels, and combined in one map (c) is an example of an NO2 concentration map. All of these images represent the entire Ile-de-France region (Host et al., 2020)

Identifying Health Benefits

With the aim of measuring the benefits of air quality improvements, four health outcomes were considered. The first outcome was deaths avoided, in absolute numbers and in terms of Life Years Gained (LYG), in adults over 30 years old. Due to the fact that public records do not specify an individual's cause of mortality, deaths under 30 years old were not considered because this age group experiences more accidental deaths. Therefore, deaths were evaluated on an all-cause basis. The next health event considered was reduced incidences of ischemic heart disease (IHD) in adults between 40-74 years old. Incidence rates of IHD were defined by hospitalizations of individuals for IHD who did not have any previous IHD hospitalizations within the past 10 years. Third was childhood asthma in children between 0-17 years old. New cases of childhood asthma were defined by three reimbursements for asthma treatment in children who did not receive treatment in the previous 3 years. The last morbidity considered was low birthweight in full term newborns. Full-term birth was defined as gestation lasting 37 weeks or more and low birth weight was determined to be less than 2.5 kg. In order to quantify these outcomes, the Population Attributable Fraction (PAF) was used to assess the attributable risk of any given health event. The equations used to calculate the PAF and the Attributable Number (AN) of cases avoided due to the implementation of the LEZ scenario can be found in Part III of this document.

Identifying Socio-economic Inequalities

Lastly, socioeconomic inequalities were also evaluated based on five Fdep (French Deprivation Index) scores and their relation to mortality after 30 years of age and new cases of childhood asthma. An Fdep score of five refers to the most socially deprived SES group, while a score of one is assigned to most affluent groups. However, the results for this data in regards to equity are not very specific due to the lack of information like an explicit concentration response function (CRF). By evaluating factors related to environmental justice on a fine-scale and mapping these effects onto existing data, it will be possible to provide further insight to policy makers on how to improve LEZ policy for all Parisians.

Incorporating Equity

Now, for the purpose of evaluating whether or not the social inequalities reinforced by the LEZ are due to differential exposures, differential susceptibilities, or both, we must turn to another study by Kihal-Talantikite et al. which does exactly this for the City of Paris, but for a hypothetical change in air pollution. This means that hypothetical emissions reductions were used to model changes in excess NO_2 exposure. As previously mentioned, this study conducted an HIA on a hypothetical policy and mapped the health and equity impacts of air pollution reduction at a small spatial scale. Where this study is different is that we used the same method, but applied it to the modeled emissions reductions of the Paris LEZ. The health outcome Kihal-Talantikite et al. focused on was premature deaths among adults over 30 years old. The pollutants modelled were PM_{10}, $PM_{2.5}$, and NO_2. With the aim of quantifying the number of premature deaths by deprivation level, a clustering approach was used to map these results on a fine-scale. Similar to the Host et al. study, fine-scale here is defined as population size and age group by building level in each census block. However, in this study, social deprivation was categorized into ten groups in order to document spatial variability, ten (Cat 10) being the most socially deprived and one (Cat 1) being the least socially deprived.

The results obtained from this study stated that for each pollutant considered, Cat 10 census blocks were consistently the most impacted by air pollution. Not entirely unsurprising however, Cat 3 and 4 census blocks also appeared to be highly impacted by air pollution. By using a statistical spatial approach, it was confirmed that there is a significant spatial aggregation of "premature" deaths in the northeast region of Paris. The cluster most likely to be adversely impacted by air pollution includes an area of 459 census blocks and is associated with a health risk that is 1.12 times higher than the rest of the study area. Out of the 3,455 premature deaths calculated that were attributable to excess NO_2 exposure, 80% of them were found to be in the most at-risk cluster. No statistically significant aggregation of deaths was found to be attributable to PM_{10} or $PM_{2.5}$ in this study. For the results that follow, a similar approach will be applied to the data collected regarding reductions in air pollution emissions and for all four hypothetical implementation scenarios.

Part III: Assessing Equity for the Paris Low Emission Zone

Methodology

By incorporating the alternative dose response functions associated with changes in NO_2 and $PM_{2.5}$ exposure given by the Kihal-Talantikite et al. study, it will be possible to build on Host et al. and extend the results of the HIA. This will then make it possible to map the distribution of health benefits according to SES on a fine-scale. For this assessment, only the impacts of reduced NO_2 and $PM_{2.5}$ emissions will be evaluated. Furthermore, the health benefits observed will be limited to premature deaths avoided for those over the age of 30 and to childhood asthma cases avoided for all children under the age of 17. As in the Host et al. study, all four hypothetical scenarios will be evaluated so as to observe which strategy will produce the most equitable results. The following is the procedure for attaining this new data.

HIA Analysis

In order to first estimate the total number of death and asthma cases avoided as a result of each scenario, the following data was extracted from the Host et al. study for each census block within both of the LEZ_{Paris} and $LEZ_{Enlarged}$ perimeters.

1. Difference in NO_2 and $PM_{2.5}$ exposure attributable to each LEZ scenario – Paris or Enlarged and Ban Low or High
2. The population of each age group
3. The rate of incidence of either premature death or childhood asthma
4. The Relative Risk ratio of NO_2 exposure for both premature death and childhood asthma
5. The Relative Risk ratio of $PM_{2.5}$ exposure for premature death
6. Raw Fdep scores which indicate the level of social deprivation for each census block

With this data, the first equation used was Equation 1 which calculates the new Relative Risk (RR) ratio, $RR_{\Delta i}$, associated with the new level of NO_2 or $PM_{2.5}$ exposure, denoted by Δ_i, for the specified municipality. Here, RR, is the base RR per 10 μg/m^3 increase of NO_2 or $PM_{2.5}$.

Equation 1

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

Next, the Attributable Fraction (AF) was calculated. This calculation tells us the proportion of cases that are reduced or increased in each municipality according to the new RR ratio.

Equation 2

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

Finally, the Attributable Number (AN) was obtained by multiplying the AF by the incidence rate of the health outcome and the population of the specific age group. This procedure was then repeated for each census block and for each scenario.

Equation 3

$$AN_i = AF_i * I * P_i$$

Concentration Response Functions

The equations used above are how Host et al.'s study acquired overall values for preventable cases of death and asthma by LEZ scenario and fdep quantile. However, only one dose response function was used for all census blocks and only differentiations based on health outcomes and pollutants were made. For this study, I divided the census blocks in the LEZ_{Paris} and $LEZ_{Enlarged}$ perimeters into tertials based on their Fdep score and denoted this new classification as the T-Fdep score. This was done in order to use the three different dose responses identified by Kihal-Talantikite to evaluate differential exposure and susceptibility across the region. These three dose responses are taken from the Cesaroni et al., 2012 study and are used to associate long-term NO_2 or $PM_{2.5}$ exposures and all-cause mortality to high, medium, and low SES groups. The Kihal-Talantikite et al. study also discusses dose responses based on a Dutch study with five separate RR ratios for five SES groups. However, these ratios were not used because they only provided data for NO_2 and PM_{10}. Given that this study is focused on NO_2 and $PM_{2.5}$, we decided to use the ratios from the Italian study instead. As such, the RR ratios of death (for a 10 μg/m^3 increase in exposure to NO_2) used in this evaluation are 1.024, 1.016, and 1.034 for high, medium, and low SES groups, respectively. The RR ratios of death for a 10 μg/m^3 increase in exposure to $PM_{2.5}$ are 1,04, 1.018, and 1.05 for high, medium, and low SES groups, respectively.

At this time there is no data available to tell us the dose response to childhood asthma for increases in long-term $PM_{2.5}$ exposure, therefore this pollutant was not assessed. However, Host et al. conducted a meta-analysis and determined the dose response for a 10 μg/m^3 increase in long-term NO_2 exposure to be 1.054. In order to calculate three dose response values for childhood asthma and NO_2 exposure by SES group for use in this study, I took the difference between the all-cause mortality dose response for NO_2 used in the Host et al. study and each of the three RR ratios found in the Kihal-Talantikite et al. study. I then added this difference to the 1.054 value found in the meta-analysis. This gave me RR ratios of 1.068, 1.06, and 1.078 for high, medium, low SES groups, respectively. These nine values were then used in the equations above to determine the AN of death and childhood asthma cases avoided by T-Fdep.

Mapping

After calculating the four hypothetical LEZ scenarios, the data was then mapped using ArcMaps. IRIS[1] data and shapefiles for the Île-de-France region were pulled from an open data platform provided by Région Île-de-France. A total of 21 maps were created which include the distribution of health outcomes and reductions in air pollution for each of the LEZ scenarios. Additionally, one map was made to depict the distribution of social deprivation (Fdep) by IRIS.

Results

Air Pollution

To begin our assessment on equity, this study will first take a look at the results found in the Host et al. study. Table 5 displays the study's results on the reductions in air pollution based on the criteria for each hypothetical scenario. The first outcome, titled Car Fleet Advancement refers to the new level of car fleet modernization attained due to the LEZ. This means that for the $LEZ_{Paris}Ban_{high}$ scenario, the resulting car fleet would resemble the fleet expected by year 2028, under a BAU scenario. The second outcome, % of kilometers driven, refers to the reduction in kilometers driven

[1] IRIS contours roughly equate to census tracks and are the smallest geographical division in France. Each IRIS contains an average of 2,000 inhabitants and municipalities with more than 5,000 inhabitants are further divided into multiple IRIS (Host et al., 2020).

by the oldest vehicles on the road in Paris. This table demonstrates that the most ideal implementation scenario is $LEZ_{Enlarged}Ban_{high}$. This framework has the potential to reduce NO_x and $PM_{2.5}$ emissions by almost half and reduce the kilometers driven by the highest polluting vehicles by a quarter. In addition, further evaluation suggests that all four scenarios would lead to decreased exposure to NO_x and PM in areas lying outside of the designated LEZ. This is depicted by Figure 8 which further demonstrates the distribution of reduced NO_2 exposure by IRIS. The data for Figure 8 is derived from the findings of Host et al. From these maps we can conclude that due to LEZ implementation, most NO_2 exposure reductions can be found along the northern ring of the Paris city limits and across the northern region of the MGP. Appendix E contains another figure which includes maps showing the distribution of reduced $PM_{2.5}$ exposure by IRIS.

Table 5. Estimated Emissions Reductions for all Four Scenarios

	$LEZ_{Paris}Ban_{low}$	$LEZ_{Paris}Ban_{high}$	$LEZ_{Enlarged}Ban_{low}$	$LEZ_{Enlarged}Ban_{high}$
Car Fleet Advancement (years)	5	9	--	--
% of km driven	7%	21%	9%	25%
Decrease in NOx emissions	23%	44%	28%	51%
Decrease in PM10 emissions	12%	25%	13%	37%
Decrease in PM2.5 emissions	17%	36%	19%	47%

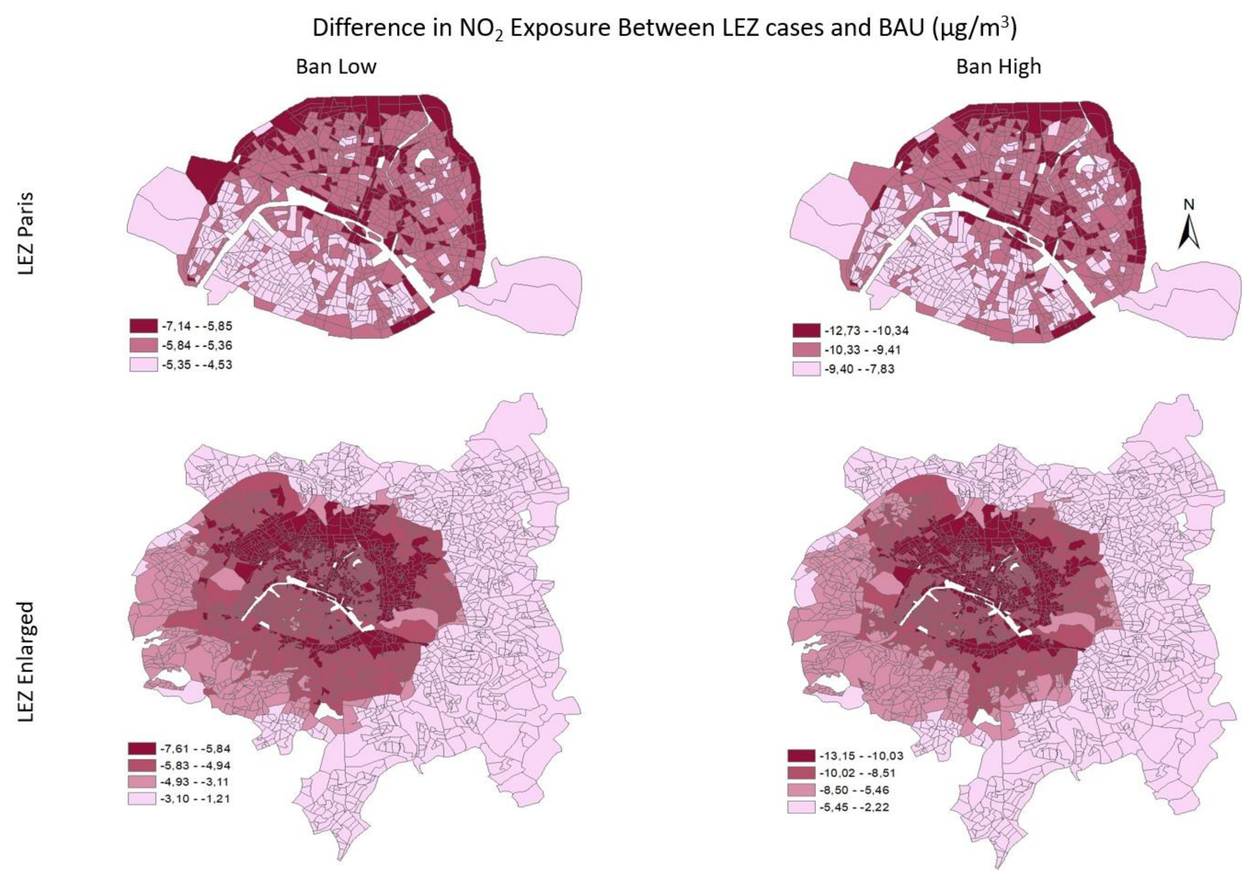

Figure 8. Difference in NO2 concentrations by IRIS between all four LEZ cases and the BAU scenario.

Air Pollution and Health

The results produced by Host et al. directly relate to the continued health impact evaluation of equity. In terms of health, overall, they found that the $LEZ_{enlarged}Ban_{High}$ scenario produced three times as many preventable cases as the LEZ_{Paris} Ban_{Low} scenario. For this best case scenario the mortality benefits observed were 340 deaths prevented (114,300 YLG). The expected preventable cases for the other three morbidities were 170 low-weight births avoided, 130 new cases of IHD avoided, and 2930 new cases of asthma prevented.

The health impacts observed for decreased exposure to $PM_{2.5}$ were not explicitly stated in this study, but overall, it appeared that the health benefits were lower than those observed for NOx, except in the LEZ_{Paris} Ban_{Low} and $LEZ_{enlarged}Ban_{High}$ scenarios. Nevertheless, the $LEZ_{enlarged}Ban_{High}$ scenario proved to be the most ideal implementation strategy.

Air Pollution, Health, and Equity

Figure 9 combines the total number of deaths and cases of asthma prevented in each LEZ scenario due to reductions in NO_2 and $PM_{2.5}$, taking into account three levels of social deprivation. As a reminder, asthma cases avoided due to reductions in $PM_{2.5}$ could not be calculated due to the absence of a base relative risk value. Scenario 1 refers to LEZ_{Paris} Ban_{Low} and resulted in 90 and 30 total deaths prevented due to reduced NO_2 and $PM_{2.5}$ exposure, respectively, as well as 890 asthma cases prevented due to reduced NO_2 exposure. Scenario 2 refers to LEZ_{Paris} Ban_{High} which resulted in 420 and 40 deaths due to reduced NO_2 and $PM_{2.5}$ exposure, respectively, and 1890 asthma cases prevented. Scenarios 3 and 4 refer to $LEZ_{enlarged}Ban_{Low}$ and $LEZ_{enlarged}Ban_{High}$. For scenario 3 there is an expected reduction in deaths by 420 and 30 for reduced NO_2 and $PM_{2.5}$ exposure, respectively and 1,810 asthma prevented as a result of reduced NO_2 exposure. Lastly, scenario 4 is expected to reduces deaths by 730 and 80, and asthma cases by 3200. Each of these values were rounded to the nearest tenth. Figure 10 breaks each of these numbers down further by high, medium, and low SES. Figure 9 confirms what Host et al discovered which is that the $LEZ_{enlarged}Ban_{High}$ scenario produces the most health benefits overall. Additionally, implementation of either the LEZ_{Paris} Ban_{High} or the $LEZ_{enlarged}Ban_{Low}$ scenario yields virtually the same health benefits. Figure 10. however, demonstrates that the distribution of expected health outcomes becomes more equitable as the LEZ perimeter expands and the restriction level increases. This trend is most notable with asthma cases avoided.

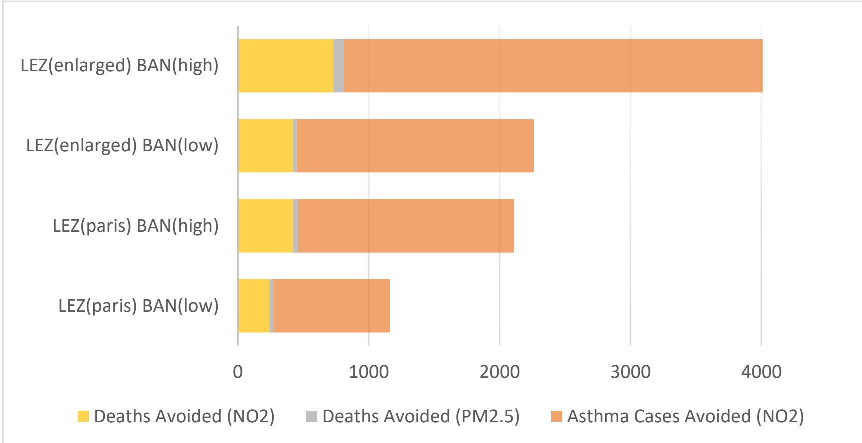

Figure 9. Total cases of death and childhood asthma avoided for each LEZ scenario taking three levels of socio-economic status into consideration.

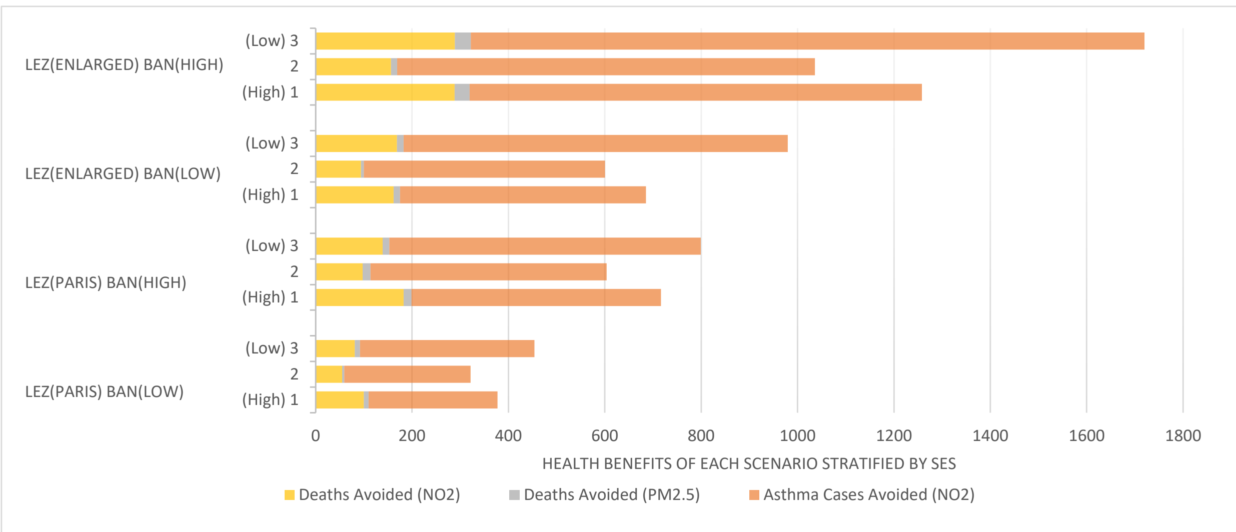

Figure 10. Cases of death and childhood asthma avoided broken down by low (3), medium (2), and high (1) socio-economic status for each LEZ scenario.

Table 7 represents the data behind Figures 9 and 10. Here one can further observe the extent to which each scenario does or does not distribute the expected health benefits equitably. The column labeled "% of Pop" is acquired by comparing the attributable number of cases for each SES group to their respective population sizes. This information confirms that the most equitable implementation strategy is the $LEZ_{enlarged}$ Ban_{High} scenario. The percent of each population receiving the expected health benefits is approximately equal for all three health outcomes.

Table 6. Health benefits by socio-economic group and scenario.

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 (NO2)	T-Fdep 1 (High)	100	8	183	14	162	12	288	21
	T-Fdep 2	55	3.9	98	7	94	7	156	11
	T-Fdep 3 (Low)	81	5.1	139	9	169	11	289	20
	All	236	5.6	420	10	425	10	734	17
Death (PM2.5)	T-Fdep 1 (High)	10	0.8	16	1.3	13	0.8	31	2.3
	T-Fdep 2	4	0.3	16	1.3	6	1	13	0.9
	T-Fdep 3 (Low)	11	0.7	14	0.8	14	0.4	33	1.8
	All	25	0.6	36	0.9	33	0.8	77	1.8
Asthma (NO2)	T-Fdep 1 (High)	268	78.	518	130	510	140	938	230
	T-Fdep 2	262	58	490	100	501	120	866	180
	T-Fdep 3 (Low)	362	52	646	90	797	120	1398	210
	All	892	60	1653	110	1808	120	3203	210

Mapping the LEZ_{Paris} Ban_{High} and the $LEZ_{enlarged}$ Ban_{High} scenarios via ArcMaps produced Figures 11 and 12. Maps of LEZ_{Paris} Ban_{Low} and the $LEZ_{enlarged}$ Ban_{Low} scenarios can be found in Appendix E. These two map-sets below represent the highest reductions in deaths and cases of childhood asthma for each LEZ perimeter based on three different dose response functions. Figures 11(a) and (b) show that most deaths will be prevented along the Paris ring road and Figure 11(c) shows that asthma cases are primarily reduced along the northern perimeter. Figure 12 demonstrates that there is a relatively even distribution of health outcomes as a result of the $LEZ_{enlarged}Ban_{High}$ scenario. Figure 13 shows the distribution of social deprivation based on each IRIS's Fdep score. Comparing this map to Figure 12, one can conclude that health benefits will distributed equitably amongst low, medium, and high SES groups.

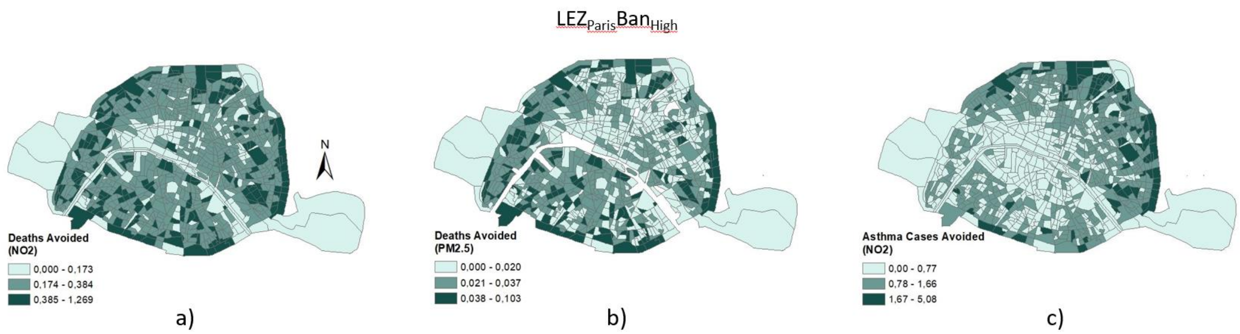

Figure 11. Number of deaths prevented by reducing NO_2 (a) and $PM_{2.5}$ (b) emissions as well as the number of childhood asthma cases prevented from reduced NO_2 (c) emissions, based on the T-Fdep score, for the $LEZ_{Paris}Ban_{High}$ scenario.

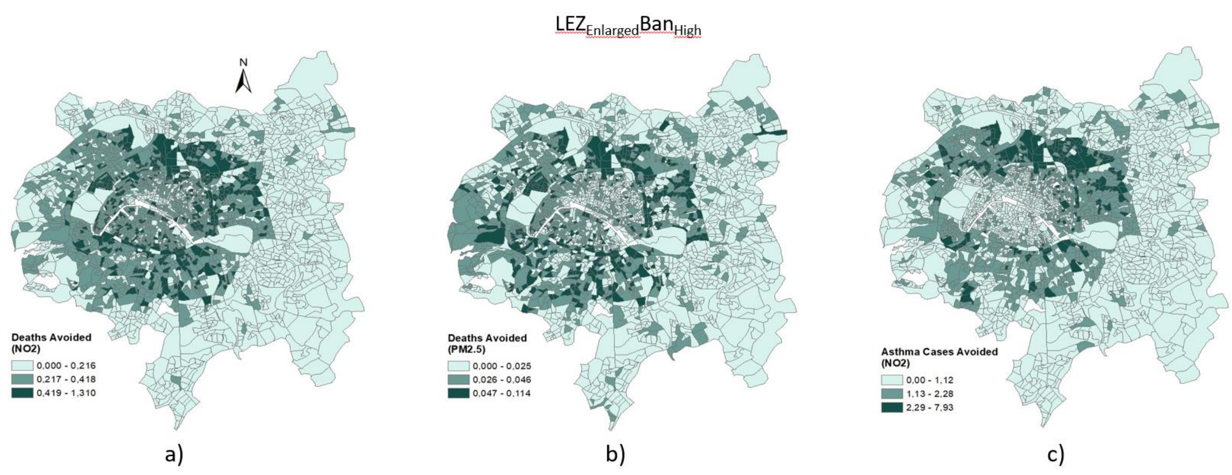

Figure 12. Number of deaths prevented by reducing NO_2 (a) and $PM_{2.5}$ (b) emissions as well as the number of childhood asthma cases prevented from reduced NO_2 (c) emissions, based on the T-Fdep score, for the $LEZ_{Enlarged}Ban_{High}$ scenario.

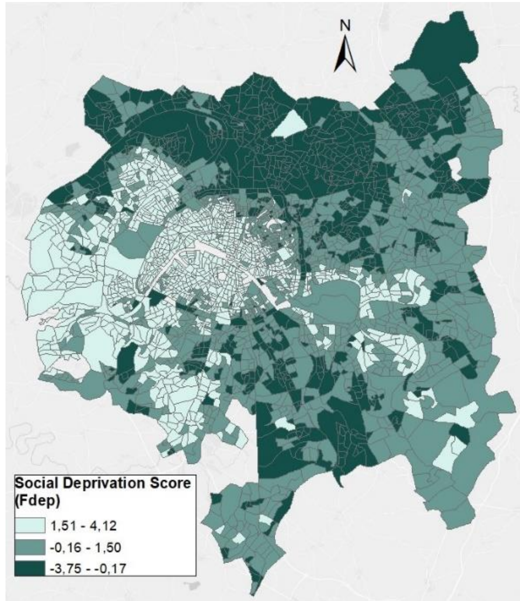

Figure 13. Distribution of social deprivation for the entire Metropolis of Greater Paris.

Discussion

Low emission zones are the most popular method of improving air quality in major cities across Europe. The goal of this type of traffic related air pollution policy is to slowly phase out the use of polluting vehicles within a specified boundary. To date, studies show that this strategy is effective in reducing emissions such as NO_2, PM_{10}, and $PM_{2.5}$, given that the restrictions for entering the LEZ are stringent enough. Moreover, LEZs are also capable of reducing the environmental burden traffic related air pollutants pose on society. However, the literature review this study conducted on European LEZs highlighted a need for additional research into how the benefits of any given LEZ might impact existing social inequalities. Furthermore, it demonstrated that no other study in Europe has considered an LEZs impact on equity.

The objective of this study was to evaluate LEZ impacts on equity for the first time in the context of the Paris LEZ. Doing so meant extending the health impact assessment conducted by Host et al. and determine which of four hypothetical implementation scenarios would produce the most equitable results in regards to distribution of health benefits. The four scenarios discussed looked at two different perimeters of implementation and two different levels of vehicle restrictions. The most pessimistic scenario was LEZ_{Paris} Ban_{Low} and the most optimistic scenario was $LEZ_{enlarged}$ Ban_{High}. The health benefits that this study focused on were premature deaths avoided in adults over 30 years old and cases of childhood asthma prevented in children aged 0-17. The pollutants studied in relation to these health benefits were NO_2 and $PM_{2.5}$. In order to evaluate the distribution of health benefits across three socioeconomic groups, three different dose responses were needed for high, medium, and low SES municipalities. This key piece of data was pulled from a study conducted by Cesaroni et al. and used in the Kihal-Talantikite et al. study which evaluated the impacts of hypothetical emissions reductions on differential exposure and differential susceptibility in Paris. As a result of these methods, it was determined that the $LEZ_{enlarged}$ Ban_{High} scenario was the most effective in distributing the observed health effects equitably, while the LEZ_{Paris} Ban_{Low} scenario was most likely to uphold existing inequities. This is most clearly observed with cases in childhood asthma prevented given that the distribution of cases across SES groups according to their population sizes all turned out to be near 0.2%. Overall, moving from the most pessimistic case to the most optimistic case, the total expected health benefits increased with each scenario. Therefore, if the $LEZ_{enlarged}$ Ban_{High} scenario were to be adopted for Phase 2 of the Paris LEZ implementation schedule, one could expect a total reduction of 811 premature deaths and 3,203 cases of childhood asthma.

Now that it is evident which strategy will be the most effective in producing the highest reductions in emissions, the most health benefits, and the most equitable spread of these benefits, the next step is to consider how this policy will impact low SES individuals who will likely have a harder time complying with most stringent requirements of the $LEZ_{enlarged}$ Ban_{High} scenario. As previously stated, these individuals and households are most likely to own a high polluting vehicle and the least capable of switching to an alternative vehicle that meets the Crit'Air 3 requirements. Other equity considerations that should be considered alongside this evaluation are the impacts of gentrification, access to public transportation, and employment mobility. These factors are intertwined with an individual or households' access to low-emission vehicles. However, future equity evaluations are at the discretion of policy makers responsible for deciding the next phase of implementation for the Paris LEZ.

In a larger context, it is critical that other cities begin to perform similar evaluations such as this to ensure that their LEZ framework plays a positive role in easing the environmental burden of ambient air pollution. This is important because if the transportation sector is the largest contributor to urban air pollution then the health disparities between socioeconomic groups have the potential to be reduced significantly. Additionally, these methods should be applied to any type of intervention the seeks to improve air quality, whether in an urban or rural setting. Research that aims to understand how to equitably redistribute or eliminate the health burden of any anthropogenic source must continue because recent events like the COVID-19 pandemic have tragically proven how long and short-term exposure to ambient air pollutants increase the risk of dying or ending up in intensive care when faced with a powerful respiratory disease (Conticini et al., 2020; Wu et al., 2020). Such examples make this work all the more relevant because polluted air reduces the likelihood that marginalized racial and income groups will be able to survive extreme events like a pandemic.

Lastly, there are several limitations of this study that can 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 implementation three years ago (as of this writing), 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 dose 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 dose responses for at least five different socioeconomic levels. Additionally, 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

This study found that, to date, no research study has evaluated the environmental justice impact of a low emission zone on a fine-scale. In order to study these impacts on the Paris low emission zone for this first time, a health impact assessment was used to quantify the expected health benefits stratified by socioeconomic status. By approaching the Paris low emission zone from this angle this study is one the first to discover that the most effective way to equitably distribute the expected health benefits of such a policy is to incorporate as wide of a perimeter as possible and to restrict a wide variety of high-polluting vehicles from entering the zone. 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 3,203 cases of childhood asthma. Additionally, these cases are stratified equitable among high, medium, and low socioeconomic groups. With the purpose of continuing this work, it is encouraged that these methods be applied to future phases of LEZ implementation to ensure equity is maintained, and to other forms of interventions related to improving air quality in urban settings. Without such work, it will not be possible to achieve true environmental justice with respect to ambient air pollution.

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Appendix

Appendix A

Table 7. EU Emission Standards for Light Commercial Vehicles (Host et al., 2020)

Category†	Stage	Date	CO	HC	HC+NOx	NOx	PM	PN
			g/km					#/km
			Compression Ignition (Diesel)					
N_1, Class I ≤1305 kg	EURO 1	1994.10	2.72	–	0.97	–	0.14	–
	EURO 2 IDI	1998.01	1.0	–	0.70	–	0.08	–
	EURO 2 DI	1998.01[a]	1.0	–	0.90	–	0.10	–
	EURO 3	2000.01	0.64	–	0.56	0.50	0.05	–
	EURO 4	2005.01	0.50	–	0.30	0.25	0.025	–
	EURO 5a	2009.09[b]	0.50	–	0.23	0.18	0.005[f]	–
	EURO 5b	2011.09[d]	0.50	–	0.23	0.18	0.005[f]	6.0×10^{11}
	EURO 6	2014.09	0.50	–	0.17	0.08	0.005[f]	6.0×10^{11}
N_1, Class II 1305-1760 kg	EURO 1	1994.10	5.17	–	1.40	–	0.19	–
	EURO 2 IDI	1998.01	1.25	–	1.0	–	0.12	–
	EURO 2 DI	1998.01[a]	1.25	–	1.30	–	0.14	–
	EURO 3	2001.01	0.80	–	0.72	0.65	0.07	–
	EURO 4	2006.01	0.63	–	0.39	0.33	0.04	–
	EURO 5a	2010.09[c]	0.63	–	0.295	0.235	0.005[f]	–
	EURO 5b	2011.09[d]	0.63	–	0.295	0.235	0.005[f]	6.0×10^{11}
	EURO 6	2015.09	0.63	–	0.195	0.105	0.005[f]	6.0×10^{11}
N_1, Class III >1760 kg	EURO 1	1994.10	6.90	–	1.70	–	0.25	–
	EURO 2 IDI	1998.01	1.5	–	1.20	–	0.17	–
	EURO 2 DI	1998.01[a]	1.5	–	1.60	–	0.20	–
	EURO 3	2001.01	0.95	–	0.86	0.78	0.10	–
	EURO 4	2006.01	0.74	–	0.46	0.39	0.06	–
	EURO 5a	2010.09[c]	0.74	–	0.350	0.280	0.005[f]	–
	EURO 5b	2011.09[d]	0.74	–	0.350	0.280	0.005[f]	6.0×10^{11}
	EURO 6	2015.09	0.74	–	0.215	0.125	0.005[f]	6.0×10^{11}
N_2	EURO 5a	2010.09[c]	0.74	–	0.350	0.280	0.005[f]	–
	EURO 5b	2011.09[d]	0.74	–	0.350	0.280	0.005[f]	6.0×10^{11}
	EURO 6	2015.09	0.74	–	0.215	0.125	0.005[f]	6.0×10^{11}
			Positive Ignition (Petrol)					
N_1, Class I ≤1305 kg	EURO 1	1994.10	2.72	–	0.97	–	–	–
	EURO 2	1998.01	2.2	–	0.50	–	–	–
	EURO 3	2000.01	2.3	0.20	–	0.15	–	–
	EURO 4	2005.01	1.0	0.1	–	0.08	–	–
	EURO 5	2009.09[b]	1.0	0.10[g]	–	0.06	0.005[e,f]	–
	EURO 6	2014.09	1.0	0.10[g]	–	0.06	0.005[e,f]	6.0×10^{11} [e,j]
N_1, Class II 1305-1760 kg	EURO 1	1994.10	5.17	–	1.40	–	–	–
	EURO 2	1998.01	4.0	–	0.65	–	–	–
	EURO 3	2001.01	4.17	0.25	–	0.18	–	–
	EURO 4	2006.01	1.81	0.13	–	0.10	–	–
	EURO 5	2010.09[c]	1.81	0.13[h]	–	0.075	0.005[e,f]	–
	EURO 6	2015.09	1.81	0.13[h]	–	0.075	0.005[e,f]	6.0×10^{11} [e,j]
N_1, Class III >1760 kg	EURO 1	1994.10	6.90	–	1.70	–	–	–
	EURO 2	1998.01	5.0	–	0.80	–	–	–
	EURO 3	2001.01	5.22	0.29	–	0.21	–	–
	EURO 4	2006.01	2.27	0.16	–	0.11	–	–
	EURO 5	2010.09[c]	2.27	0.16[i]	–	0.082	0.005[e,f]	–
	EURO 6	2015.09	2.27	0.16[i]	–	0.082	0.005[e,f]	6.0×10^{11} [e,j]
N_2	EURO 5	2010.09[c]	2.27	0.16[i]	–	0.082	0.005[e,f]	–
	EURO 6	2015.09	2.27	0.16[i]	–	0.082	0.005[e,f]	6.0×10^{11} [e,j]

Notes:
† For EURO 1/2 the Category N_1 reference mass classes were Class I ≤ 1250 kg, Class II 1250-1700 kg, Class III > 1700 kg
a. until 1999.09.30 (after that date DI engines must meet the IDI limits)
b. 2011.01 for all models
c. 2012.01 for all models
d. 2013.01 for all models
e. applicable only to vehicles using DI engines
f. 0.0045 g/km using the PMP measurement procedure
g. and NMHC = 0.068 g/km
h. and NMHC = 0.090 g/km
i. and NMHC = 0.108 g/km
j. 6.0×10^{12} 1/km within first three years from EURO 6 effective dates

Table 8. EU Emission Standards for Heavy Duty Vehicles

EURO standards	Regulation	Date	CO	HC	NOx	PM
			g/kWh			
EURO 0	1988/77/EEC	1990.10	11.2	2.4	14.4	-
EURO I	1991/542/CEC	1993.10	4.5	1.1	8.0	0.36
EURO II		1996.10	4.0	1.1	7.0	0.25
		1998.10	4.0	1.1	7.0	0.15
EURO III	1999/96/EC	2001.10	2.1	0.66	5.0	0.13
EURO IV		2006.10	1.5	0.46	3.5	0.02
EURO V		2009.10	1.5	0.46	2.0	0.02
EURO VI	2009/595/EC	2013.12	1.5	0.13	0.4	0.01

Table 9. Description of Light- and Heavy- Duty Vehicle Categories (Dieselnet, n.d.)

Category	Description
M	Motor vehicles with at least four wheels designed and constructed for the carriage of passengers
M_1	Vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat
M_2	Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass ("technically permissible maximum laden mass") not exceeding 5 tonnes
M_3	Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes
N	Motor vehicles with at least four wheels designed and constructed for the carriage of goods
N_1	Vehicles designed and constructed for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes
N_2	Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes
N_3	Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 12 tonnes
O	Trailers (including semi-trailers)
O_1	Trailers with a maximum mass not exceeding 0.75 tonnes
O_2	Trailers with a maximum mass exceeding 0.75 tonnes but not exceeding 3.5 tonnes
O_3	Trailers with a maximum mass exceeding 3.5 tonnes but not exceeding 10 tonnes
O_4	Trailers with a maximum mass exceeding 10 tonnes
G*	Off-Road Vehicles
* Combined designation—Symbol G is combined with either symbol M or N. For example, a vehicle of category N_1 which is suited for off-road use is designated as N_1G.	

Table 10. Description of Vehicle Classes Based on Weight (Dieselnet, n.d.)

Class	Reference Mass, RW	
	Euro 1-2	Euro 3+
I	RW ≤ 1250 kg	RW ≤ 1305 kg
II	1250 kg < RW ≤ 1700 kg	1305 kg < RW ≤ 1760 kg
III	1700 kg < RW	1760 kg < RW

https://dieselnet.com/standards/eu/index.php#vcat

Appendix B

Table 11. Details of LEZ frameworks evaluated by study and city

Study Site(s)	*Authors*	*LEZ Frameworks Discussed*
Rome	Cesaroni et al., 2012	Limited Traffic Zone (LTZ): Implemented Oct. 2001 and revised to include more communities and stricter standards in 2002 and 2003. Restricts all vehicles (unless authorized*) from 6:30am-6:00pm, Monday-Friday and 2:30pm-6:00pm on Saturdays. Cameras monitor enforcement. Primary objectives include reducing traffic, encouraging public transit use, and replacing older vehicles. Incentives include discounts to purchase low-emission vehicles.
Grenoble	Charleux, 2013	Zone d'Actions Prioritaires pour l'Air (ZAPA): Two perimeters considered and two levels of restriction (EURO 1/EURO2). Vehicles would be restricted all day. This study evaluated the potential effectiveness of implementing this policy. It never went into effect
Germany	Morfeld et al., 2014	All German Low Emission Zones which restrict EURO 1 cars from entering were studied (34 total). This means only diesel vehicles marked as having exhaust emissions which meet EURO 2 standards or higher, or vehicles with the appropriate retrofitting systems, could enter the zone.
London	Wood et al., 2015	The London Low Emission Zone: Introduced in 2008. In 2012, the final phase was implemented. The largest zone in the world at 1,600km^2. Restricts all heavy-duty diesel vehicles from entering the zone. There is currently no national framework for LEZs in the UK.
*Germany (25 cities)***	Malina et al., 2015	The Ordinance of Marking Vehicles with Low Emissions: Uses a 3-sticker classification system (green, yellow, red) to identify vehicles and the emissions standards they prescribe to. Those with no sticker are assumed to be pre-EURO 1 vehicles (diesel) or vehicles without a catalytic converter (gasoline). Exemptions for emergency vehicles apply.
5 EU countries	Holman et al., 2015	A literature review of all 200 LEZs in the EU as of 2015. Emphasis is given to LEZs in Denmark, Germany, The Netherlands, Italy, and the UK.
London, Berlin, and Munich	Ezeah et al., 2015	A study focused on LEZ implementation in London, Berlin, and Munich as of 2015. The Berlin Umweltzone is part of a national framework which entered phase 1 in 2008 and phase 4 in 2015. Phase 4 prohibits all vehicles not classified by a green sticker. Green stickers indicate that the vehicle meets EURO 4 emissions standards or are fitted with catalytic converters (gasoline). The Munich LEZ operates similarly. German LEZs are enforced manually.
London and Berlin	Cruz, C. and Montenon, A., 2015	A study focused on LEZ implementation in London and Berlin as of 2015.
Germany	Jiang et al., 2017	This study discusses the variability between frameworks across Germany which are founded on one national framework. Implementation has not been temporally uniform across German cities.
Germany	Gehrsitz, 2017	This study discusses the variability between frameworks across Germany which are founded on one national framework. Implementation has not been temporally uniform across German cities.
Île-de-France	Andre et al., 2018	Since LEZ implementation for the Paris region was still new, changes in vehicle fleet composition were evaluated in order to determine future LEZ effectiveness
Lisbon	Santos et al., 2019	The Lisbon LEZ was introduced in 2011 and was expanded to include 2 sub-zones in 2012. Since 2014, EURO 3 vehicles are prohibited in the city center and EURO 2 vehicles are prohibited in the outer layer of the zone. This LEZ is poorly enforced.
London	Mudway et al., 2019	The London LEZ is discussed.
Paris	Host et al., 2020	The Paris Zone à Faibles Émissions (ZFE), first introduced in 2015, entered Phase 1 in 2017 for the inner LEZ perimeter. The second perimeter, which includes more municipalities within the Greater Paris Metropolis, entered phase 1 in 2019. This study evaluates the effectiveness of the next phases of implementation according to 4 hypothetical scenarios. The Paris ZFE was the first such zone in France.
Paris	Bernard et al., 2020	This paper looks at the Paris ZFE and the impacts of current an accelerated implementation

*Authorizations are only given to residents, commercial vehicles, and public transit

**Morfeld et al., 2015 claim that the monetary health benefits calculated by Malina and Scheffler is probably too high and the uncertainty reported possibly too small.

Appendix C

Table 12. Requirments for each Crit'Air air quality certificate

CRIT'Air Class	Sticker	Eligible cars
Green		• **Battery-electric vehicles** • **Hydrogen fuel cell vehicles**
1		• **Gas-powered vehicles** including liquified petroleum gas vehicles (LPGs) and compressed natural gas vehicles (CNGs) • **Plug-in hybrid-electric vehicles** (PHEVs, petrol and diesel) • **Petrol and hybrids Euro 5 and 6**
2		• **Petrol and hybrids Euro 4** • **Diesel Euro 5 and 6**
3		• **Petrol and hybrids Euro 2 and 3** • **Diesel Euro 4**
4		• **Diesel Euro 3**
5		• **Diesel Euro 2**
Unclassified	No sticker	• **Petrol and diesel Euro 1 and earlier**

Appendix D

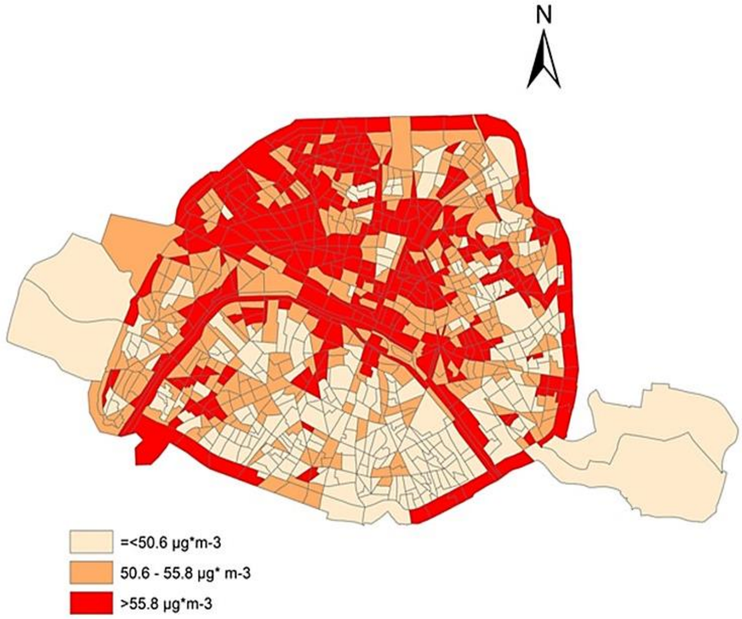

Figure 14. NO_2 concentrations by census block within the Paris ring-road (2002-2009) (Deguen et al. 2015)

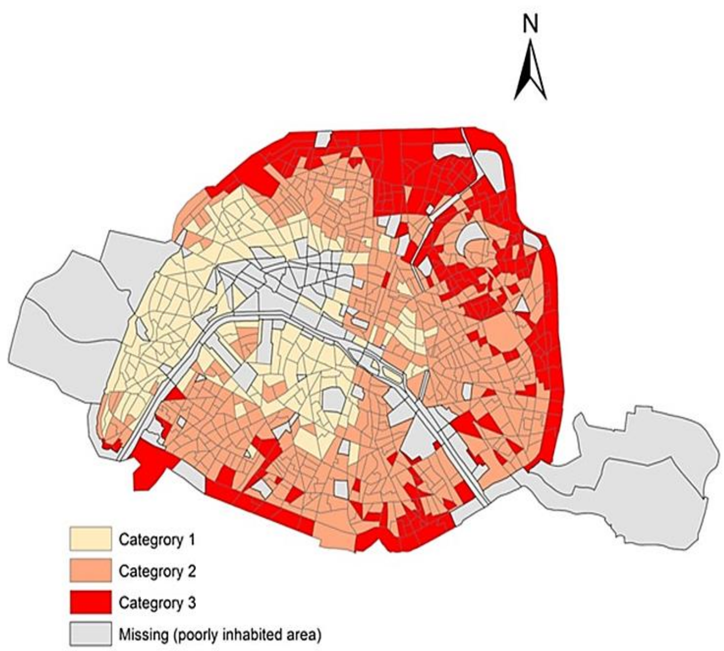

Figure 15. Socio-economic categories by census block within the Paris ring-road (Deguen et al. 2015)

Appendix E

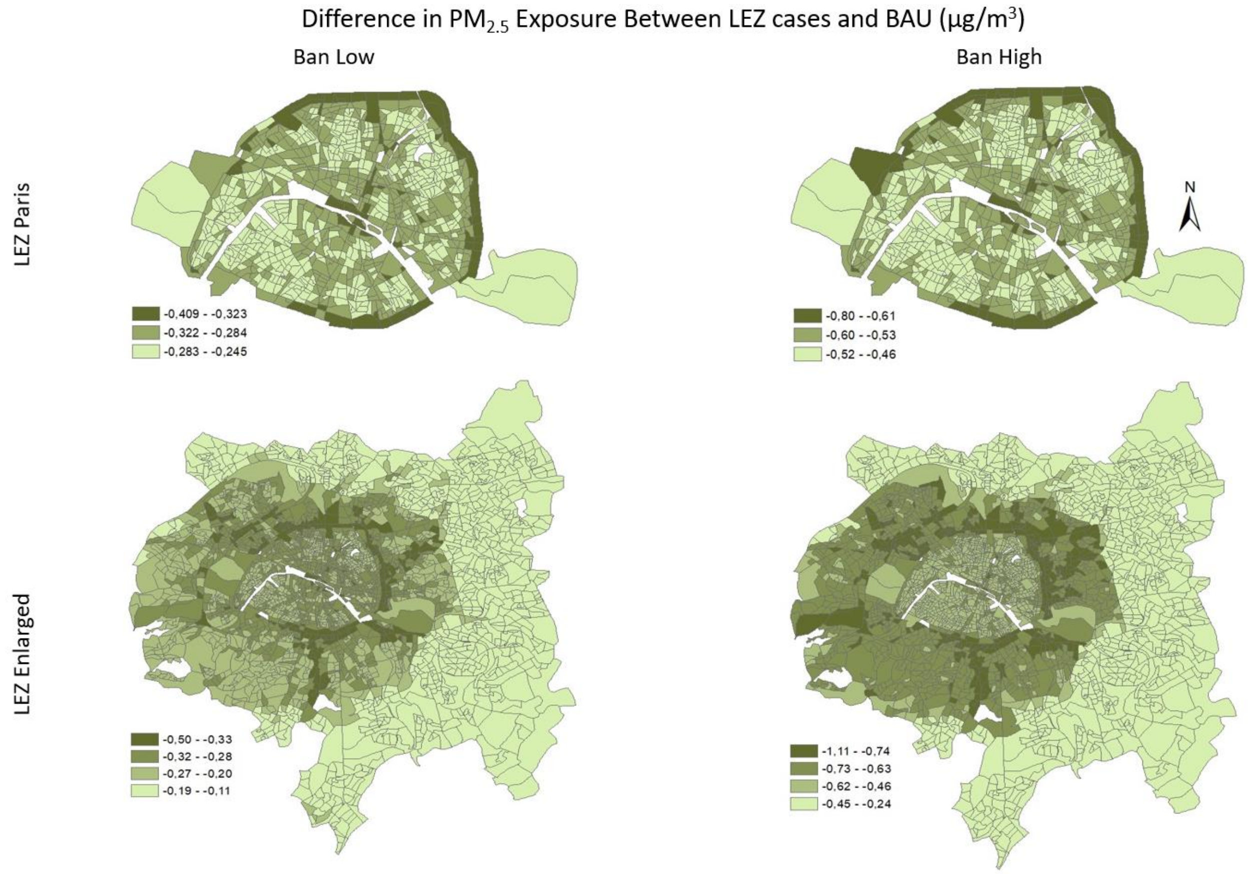

Figure 16. Difference in $PM_{2.5}$ emissions by IRIS between all four LEZ cases and the BAU scenario.

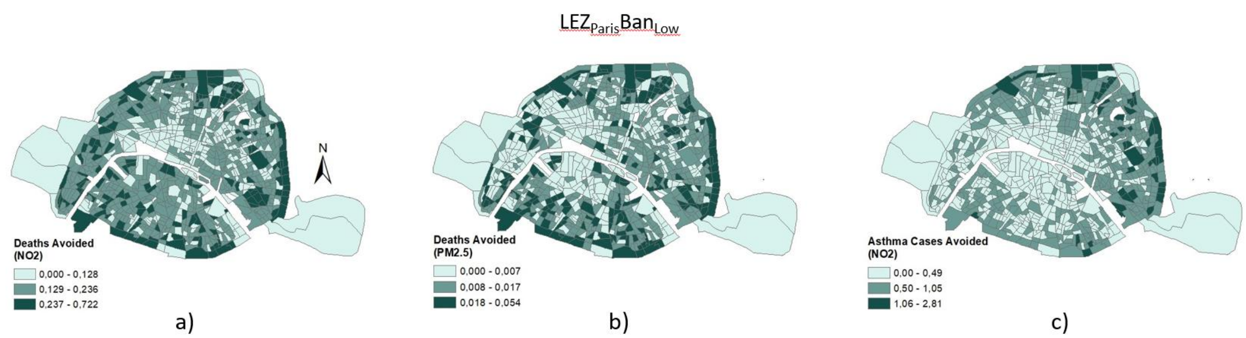

Figure 17. LEZ_{Paris} Ban_{Low} scenario. The number of deaths prevented by reducing NO2 (a) and PM2.5 (b) emissions as well as the number of childhood asthma cases prevented from reduced NO2 (c) emissions, based on the T-Fdep score.

$LEZ_{Enlarged}Ban_{Low}$

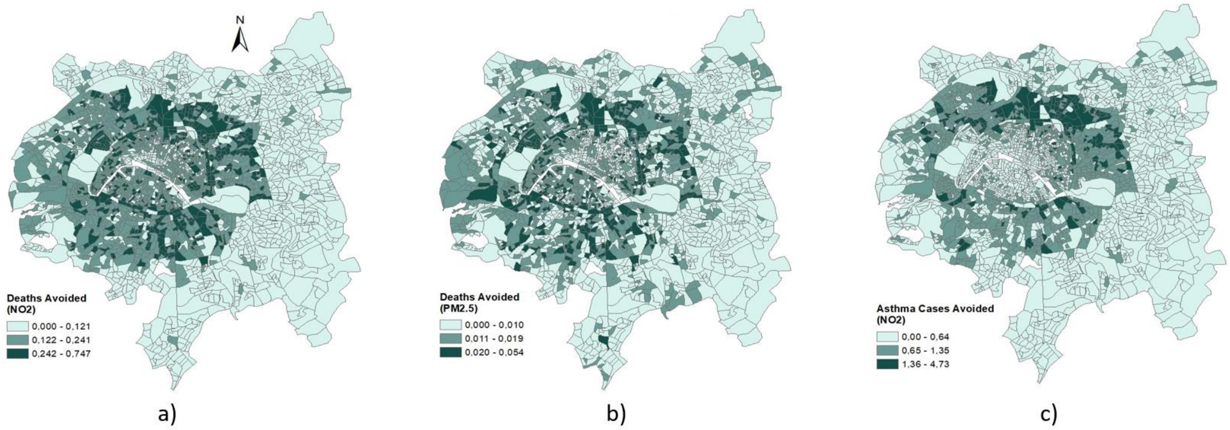

Figure 18. $LEZ_{Enlarged}Ban_{Low}$ scenario. The number of deaths prevented by reducing NO2 (a) and PM2.5 (b) emissions as well as the number of childhood asthma cases prevented from reduced NO2 (c) emissions, based on the T-Fdep score