What drives inequalities in Low Emission Zones' impacts on job accessibility?

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Charlotte Liotta[1,2,3]

[1] CIRED, Nogent-sur-Marne, France
[2] Technische Universität Berlin, Berlin, Germany,
[3] Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany

Abstract. This study investigates the factors driving inequalities in the impacts of low-emissions zones (LEZs) on job accessibility across different occupational categories in 8 French cities. It analyzes six key drivers that may explain disparities in LEZ impacts: ownership of polluting vehicles, presence of workers' residences and workplaces within the LEZ, accessibility of workers' homes and workplaces via public transportation, and feasibility of active transportation modes for commuting between homes and workplaces. The findings reveal that the implementation of LEZs has predominantly regressive effects in 6 out of the 8 cities examined. Despite a higher concentration of skilled workers and jobs within the LEZ, resulting in significant accessibility losses for this group, low-skilled workers bear a greater burden due to the limited availability of public transportation near their residences and workplaces, longer distances between their homes and jobs, and a higher proportion of polluting vehicles. These results provide insights into the potential for implementing complementary policies to address the anti-redistributive impacts of LEZs.

Keywords: Low emission zones · Transport justice · Urban form.

1 Introduction

Urban climate policies have the potential to mitigate urban greenhouse gas (GHG) emissions while bringing local co-benefits and improved quality of life for inhabitants [8]. Low emissions zones (LEZs) are an example of such policies: LEZs are defined areas, generally in city centers, where access by polluting vehicles is restricted with the aim of improving air quality in the targeted area while incentivizing modal shifts and mitigating GHG emissions. 320 LEZs have already been implemented in the EU-27, UK, and Norway [3], and their number will keep increasing due for instance to the French "Climate and resilience" law which makes LEZs mandatory in cities of more than 150,000 inhabitants that are not compliant with air quality standards.

However, transportation mitigation policies might trigger public opposition. Regarding LEZs, key elements in the public and scientific debates are their transport and environmental justice impacts [10, 15]: who will be the most affected by

the accessibility losses due to the LEZ, and who will benefit from the improved air quality and the related health co-benefits? The former in particular is of concern, as LEZs may disproportionately affect low-income households and those living in suburban or rural areas with limited public transportation options. However, it has received limited attention in the scientific literature.

Existing research suggests that several factors, namely non-compliant vehicles' ownership [11, 16], public transport availability [11, 9], and the spatial distributions of jobs and workers [16, 5], may contribute to disparities in the LEZs' impacts across different income classes. Consequently, the effects of LEZs on inequalities vary among cities. For example, in Brussels, where low-income populations predominantly reside in the city center and have convenient access to public transportation, LEZs can improve environmental justice without encountering transport justice issues. Conversely, in London, the situation is more intricate due to the non-linear correlation between income and proximity to the city center [16]. Despite these studies successfully identifying the primary factors that result in unfair impacts of LEZs on low-income households, they predominantly offer descriptive analyses, leaving the relative importance of these factors unknown.

Taking the example of the implementation of LEZs in 8 French cities, this study aims to better understand the impacts of urban climate policies on transport justice. The main research question is the following: what drives the differences in LEZs' impacts between income classes, and how does it vary between cities? To answer this question, I decompose the difference in job accessibility losses due to the LEZs between occupational categories to understand the relative weights of different drivers: polluting vehicles ownership, homes and jobs accessibility by public transports, presence of homes and jobs within the LEZ, and potential for using active transport modes due to home-to-work proximity. An aim of this research is to understand how factors related to policy design, urban form, and vehicle ownership could help in mitigating the potential anti-redistributive impacts of LEZs.

In this study, the main outcome of interest is job accessibility, i.e. the opportunities of employment an individual has access to within reasonable transportation time. Poor job accessibility may have large welfare impacts, increasing, for instance, travel times and costs, or increasing unemployment probability [1]. One clear limitation of this study is that it does not study accessibility to schools, shops, services, or amenities. Still, the commuting patterns to one's place of employment wield significant influence over the ownership of automobiles within households, subsequently shaping their travel behaviors to other destinations [4, 13].

2 Methods

2.1 Job accessibility

Job accessibility of a worker of occupational category c living in location i is computed as:

$$A_{c,i} = \sum_j d_c(j) e^{-\beta min(t_{ij}^P, t_{ij}^A, t_{ij}^C)} \tag{1}$$

with $d_c(j)$ the share of jobs of category c in location j and t_{ij}^P, t_{ij}^A, and t_{ij}^C the transportation time between i and j using public transport, active transportation modes, and private cars respectively.

$A_{c,i}$ is a gravity-based measure of job accessibility [6], meaning that it considers travel time decay of job opportunities. It also accounts for the matching between people and jobs, i.e. it considers only the jobs that match the occupational category of the worker [17].

Therefore, denoting $n_c(i)$ the share of workers of category c living in i, the average accessibility of workers of occupational category c to jobs of the matching category is defined as:

$$A_c = \sum_i \sum_j n_c(i) d_c(j) e^{-\beta min(t_{ij}^P, t_{ij}^A, t_{ij}^C)} \tag{2}$$

A_c can be interpreted as the average share of jobs of his matching category a worker of occupational category c has access to.

Denoting s_c^i the share of polluting vehicles among workers of category c living in i, the accessibility loss due to the LEZ is:

$$A_c^{LEZ} - A_c = \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum n_c(i) d_c(j) s_c(i) [e^{-\beta min(t_{ij}^P, t_{ij}^A)} - e^{-\beta min(t_{ij}^P, t_{ij}^A, t_{ij}^C)}] \tag{3}$$

2.2 Job accessibility losses decomposition

I aim at understanding the drivers of the differences in LEZ impacts between occupational groups c and c'. From A:

$$(A_c^{LEZ} - A_c) - (A_{c'}^{LEZ} - A_{c'}) = POL_{c,c'} + AM_{c,c'} + PT_{c,c'}^{POP} + LEZ_{c,c'}^{POP} + PT_{c,c'}^{JOB} + LEZ_{c,c'}^{JOB} \tag{4}$$

Therefore, differences in the LEZ impacts on occupational groups c and c' can be decomposed between 6 drivers:

(i) The impact of the difference in *polluting vehicles ownership* between occupational categories c and c':

$$POL_{c,c'} = \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum n_c(i) d_c(j) (s_c(i) - s_{c'}(i)) [e^{-\beta min(t_{ij}^P, t_{ij}^A)} - e^{-\beta min(t_{ij}^P, t_{ij}^A, t_{ij}^C)}]$$

(ii) The impact of the difference, between c and c', in the possibility of using *active transportation modes* to commute from home to jobs (i.e. the proximity between homes and matching jobs):

$$AM_{c,c'} = \sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum n_c(i)d_c(j)s_{c'}(i)e^{-\beta t^A_{ij}}\mathbb{1}_{t^C_{ij}\leq min(t^P_{ij},t^A_{ij})} - n_{c'}(i)d_{c'}(j)s_{c'}(i)e^{-\beta t^A_{ij}}\mathbb{1}_{t^C_{ij}\leq min(t^P_{ij},t^A_{ij})}$$

(iii) The impact of the difference in *public transport availability near homes* of workers of category c and category c':

$$PT^{POP}_{c,c'} = \sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum (n_c(i) - n_{c'}(i))d_c(j)s_{c'}(i)[e^{-\beta t^P_{ij}} - e^{-\beta t^A_{ij}}]\mathbb{1}_{t^C_{ij}\leq t^P_{ij}\leq t^A_{ij}}$$

(iv) The impact of the difference between the *shares of workers in the LEZ* of types c and c':

$$LEZ^{POP}_{c,c'} = -\sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum (n_c(i) - n_{c'}(i))d_c(j)s_{c'}(i)e^{-\beta t^C_{ij}}\mathbb{1}_{t^C_{ij}\leq min(t^P_{ij},t^A_{ij})}$$

(v) The impact of the difference in *public transports availability near jobs* of types c and c':

$$PT^{JOB}_{c,c'} = \sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum (d_c(j) - d_{c'}(j))n_{c'}(i)s_{c'}(i)[e^{-\beta t^P_{ij}} - e^{-\beta t^A_{ij}}]\mathbb{1}_{t^C_{ij}\leq t^P_{ij}\leq t^A_{ij}}$$

(vi) The impact of the difference between the *shares of jobs in the LEZ* of types c and c':

$$LEZ^{JOB}_{c,c'} = -\sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum (d_c(j) - d_{c'}(j))n_{c'}(i)s_{c'}(i)e^{-\beta t^C_{ij}}\mathbb{1}_{t^C_{ij}\leq min(t^P_{ij},t^A_{ij})}$$

3 Data

3.1 Cities' sample

The cities' sample consists of the French cities that had already implemented or were planning to implement a LEZ at the time this study was conducted, and that had made official their policy designs, including:

- The geographical boundaries of their LEZ;
- The timetable for banning polluting vehicles (indeed, cities do not ban all polluting vehicles at the same time, but ban vehicles from the more to the less polluting ones).

At the time the study was conducted, 11 cities met this requirement[4]. I exclude Paris, which is way more advanced than the other cities in its LEZ implementation, Lyon, for computational reasons, and Saint-Etienne, as its LEZ affects heavy vehicles only. Figure 1 shows the remaining 8 cities of the sample.

For all cities, I use the OECD Functional Urban Areas as urban boundaries and aggregate all data at the smaller unit level.

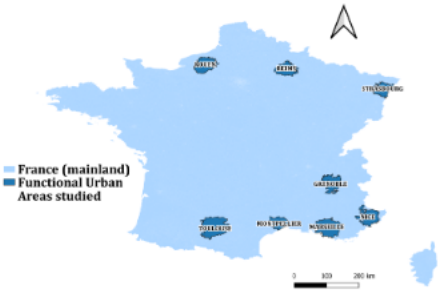

Fig. 1: Sample of cities studied.

3.2 Socioeconomic data

I consider 6 occupational categories, based on the French census institute (INSEE) definition. CSP1 corresponds to farmers, CSP2 and CSP3 overall correspond to high-income workers, CSP4 to middle-income workers, and CSP5 and CSP6 to low-income workers (Table 1). When needed, I use CSP3 as a reference, as it is the richest occupational category.

[4] https://www.gouvernement.fr/politiques-prioritaires/planifier-et-accelerer-la-transition-ecologique/zones-a-faibles-emissions-accelerer-collectivement-lamelioration-de-la-qualite-de-lair-pour-preserver-la-sante-des-francais: :text=Pourquoi%20mettre%20en%20place%20des,(ZFE)%20avant%20fin%202024., accessed on 05/07/2203

Table 1: Occupational categories.

Category	Description	Average yearly income	Share of workers
CSP1	Farmers		1.6%
CSP2	Executive directors	29,250 euros	6.8%
CSP3	Managers	39,990 euros	21.7%
CSP4	Intermediate occupations	27,720 euros	24.6%
CSP5	Sales, services workers	22,510 euros	26.0%
CSP6	Blue-collar workers	21,130 euros	18.9%

Source: Insee-DGFiP-Cnaf-Cnav-CCMSA, enquête Revenus fiscaux et sociaux 2019.

Workers' spatial distributions per occupational category are taken from the 2017 census and are available at the IRIS[5] level. Jobs spatial distributions are taken from the 2018 "Emploi - Population Active" survey from INSEE, and are available at the zip code level.

I consider vehicles of categories NC, Crit'Air 5, Crit'Air 4, and Crit'Air 3 as polluting vehicles, and those belonging to the categories Crit'Air 1, Crit'Air 2, and Crit'Air E as non-polluting, given that none of the cities in the sample plan implementing bans on the latter set of vehicles for the moment. As no detailed data on the shares of polluting vehicles per location and per occupational category exist, I combine two data sources to estimate them:

- Data on the share of polluting vehicles per zip code in 2022, but without any information on the distribution per occupational category[6];
- "Mobilité des personnes" 2019 data on the share of polluting vehicles per occupational category, but at the NUTS2 level only.

Using the python *scipy.optimize* package, I estimate the shares of polluting vehicles per zip code and per occupational category by minimizing the difference (in terms of absolute number of vehicles) with the two databases (see Appendix C).

3.3 Transport data

LEZ boundaries for each city are retrieved from the transport open data website of the French government, transport.data.gouv.fr. Transport times data are collected for three transportation modes: private cars, public transport, and walking, over a 1km-resolution grid encompassing the Functional Urban Area of each city.

Transport times by private cars have been retrieved from OpenStreetMap using the *osmnx* python package [2]. It was not possible to collect transport

[5] Smallest census unit, corresponding to about 2000 inhabitants.

[6] https://www.statistiques.developpement-durable.gouv.fr/donnees-sur-le-parc-de-vehicules-en-circulation-au-1er-janvier-2022

data from each grid cell, so I collected data from a significant share of all cells[7], and then interpolated them using the *interpolate.griddata* function from the python package *scipy*. Maps of transport times by private cars to the city center for each city can be found in Appendix B.

Transport times by public transport are taken from the GTFS data provided by local transport companies on the transport open data website of the French government, transport.data.gouv.fr. A detailed list of the sources is provided in table 2. For each 1km-resolution grid cell, we assume that all jobs and inhabitants are located in the cell's centroid and have access to all the public transport stops within a 500m walk. Then, for each origin-destination grid cell pair, we retrieve the shortest transport time using the GTFS data.

Table 2: Public transport data sources per city.

City	Public transport data sources
Reims	CITURA, Fluo Grand Est
Strasbourg	CTS
Nice	Lignes d'Azur
Marseille	RTM
Montpellier	TAM, Transp'Or
Toulouse	TISSEO
Rouen	Astuce
Grenoble	TAG, TPV, TouGo

Finally, transport times per walking between grid cells have been estimated from the geographical distances between grid cells, assuming a walking speed of 4km/h, and the decay parameter β is assumed as being equal to 0.064 [12].

4 Results

4.1 Accessibility losses from the LEZ

Figure 2 shows the accessibility losses resulting from the LEZs implementations, per city and occupational category, computed from equation 3. For instance, in Grenoble, the LEZ will result in accessibility losses of about 5% for CSP1 (farmers) and of 22% for CSP6 (blue-collar workers), meaning that, given the current distribution of jobs, workers, public transports and polluting vehicles, farmers will have access to 5% fewer jobs and blue-collar workers to 22% fewer jobs.

The magnitudes of the LEZs' impacts differ between cities, with accessibility losses exceeding 20% for some occupational categories in Grenoble, Montpellier,

[7] With a method close to [14] and [7], I defined a star shape with 8 branches, centered on the city center, and I collected data from 100 grid cells per star branch

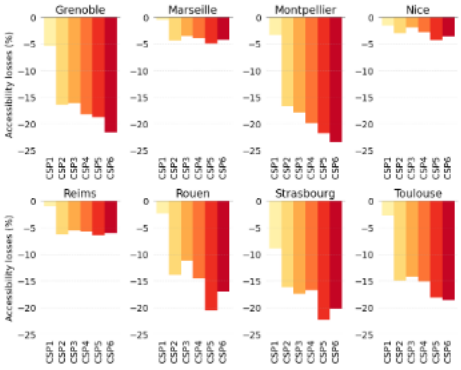

Fig. 2: Accessibility losses from the LEZ, by city and occupational group. *CSP2 and CSP3: high-income workers. CSP4: middle-income workers. CSP5 and CSP6: low-income workers. CSP1: farmers.*

Rouen, and Strasbourg, whereas accessibility losses remain small (below 5%) for all occupational categories in Marseille and Nice. This is largely due to differences in the LEZs' perimeters.

The impact of LEZs is anti-redistributive in most cities, including Grenoble, Montpellier, Rouen, Strasbourg, and Toulouse, meaning that the LEZs result in higher accessibility losses for low-income occupational categories. It is also anti-redistributive in Nice, even though the magnitude of the effect is smaller. The impact of the LEZs on inequalities is unclear in Marseille and Reims.

Still, there is no direct link between accessibility loss and income. For instance, accessibility losses are low for CSP1 (farmers), as, due to the nature of their job, farmers often live and work out of the city center, and are not impacted by the LEZ. In some cities, LEZ has a larger impact on CSP5 (sales or services workers), while in others, it has a larger impact on CSP6 (blue-collar workers), even though those two occupational categories have similar average incomes (Table 1): this might be due to the distributions of jobs of these two categories.

4.2 Decomposition of the differences between occupational categories

What drives differences in LEZ impacts between occupational categories? This section decomposes the differences in accessibility losses between occupational categories between different drivers, using equation 4. Figure 3 shows the results for CSP6 (blue-collar workers) only, while Figure 4 shows the results for all drivers and occupational categories.

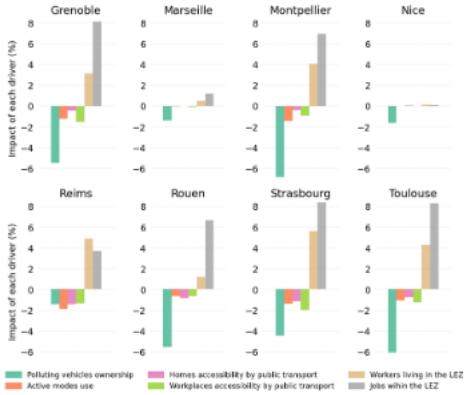

Fig. 3: Impact of different drivers on the differences in LEZ impacts between CSP3 (high-income) and CSP6 (low-income), in % of the pre-LEZ accessibility of CSP6. For instance, distributions of polluting vehicles and active modes and public transport use opportunities worsen the impact of the LEZ on CSP6, compared with CSP3. But presence of workers and jobs in the LEZ mitigates the impact of the LEZ on CSP6, compared with CSP3. *Similar figures for the others occupational categories can be found in Appendix E.*

In most cities, the 4 first drivers (polluting vehicles' ownership, active mode use, and homes and workplaces accessibility by public transport) make the im-

pact of the LEZ worst for low-income workers than for high-income workers. Indeed, low-income workers are more likely to own polluting vehicles than high-income workers (Appendix D); they also live further away from public transport, and their jobs are also located further away from public transport. Finally, they don't live close to their jobs, and therefore cannot use active transport modes.

In contrast, the last two drivers—namely, the shares of workers and jobs within the LEZ—tend to mitigate the adverse effects of the LEZ on low-income workers in comparison to their high-income counterparts. Indeed, there are fewer low-qualified jobs and workers than high-qualified ones in city centers.

In terms of magnitude, the two main drivers of the unequal impacts of LEZ are the shares of jobs in the LEZ and polluting vehicles' ownership. Polluting vehicles' ownership, in particular, plays a key role in Toulouse, Grenoble, Rouen, Montpellier, and Strasbourg. Shares of jobs in the LEZ also play a key role in most cities, except in Nice, where the LEZ is very small, so that the impact of this driver is also small and not clearly redistributive or anti-redistributive.

The share of workers of each occupational category living in the LEZ is also an important driver, although it plays a different role between cities. This result was not fully expected given that there is no clear pattern in who lives in city centers in French cities, with descriptive statistics showing that in most cities, the average income is decreasing when we get further away from the city center, apart from the inner center where the average income is generally low (Appendix D). Rouen is an exception, as the shares of workers in the LEZ play a low or even anti-redistributive impact.

The three remaining drivers, i.e. jobs accessibility by public transport, home accessibility by public transport, and home-work proximity (conditioning the possibility to commute by walking), play a role of a lower magnitude. Middle-income or low-income jobs tend to be less accessible by public transport, except in Nice. Similarly, middle- or low-income workers live in places that are less accessible via public transport: although this paper does not investigates causal mechanisms, explanations might be the fact that low-income households often live far from city centers, or that public transport availability might cause gentrification. Finally, in almost all cities, households have fewer opportunities to switch from private cars to active modes as they live far from their jobs.

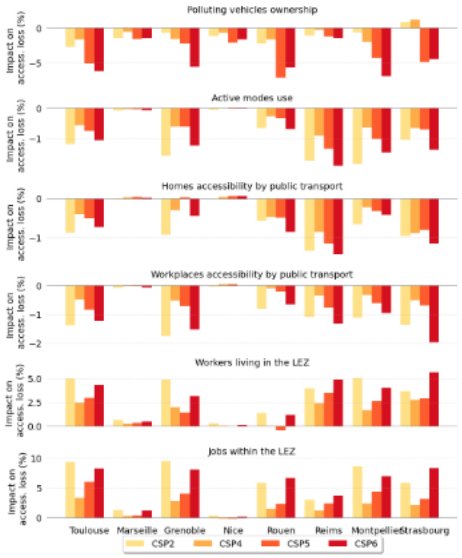

Fig. 4: Impact of different drivers on the accessibility losses of each occupational group, compared with CSP3 (in % of the pre-LEZ accessibility of each occupational group). For instance, compared with CSP3, the other occupational categories tend to have more polluting vehicles and fewer opportunities to go to work using active modes or public transports, resulting in larger accessibility losses from the LEZ. But they also have fewer workers and jobs in the LEZ, resulting in smaller accessibility losses from the LEZ.
CSP2 and CSP3: high-income workers. CSP4: middle-income workers. CSP5 and CSP6: low-income workers. CSP1: farmers.

5 Discussion

Overall, the implementation of LEZs has clear anti-redistributive impacts in six out of the eight cities studied, the two exceptions being Marseille and Reims. In Marseille, the overall impact of the LEZ is limited due to its small perimeter, and public transport is relatively accessible to low-income groups compared to high-income groups. In Reims, the ownership of polluting vehicles by low-income households is limited, and fewer low-income workers are living within the LEZ. Nevertheless, it is important to note that even in cases where the theoretical impact of the LEZ is distributed fairly among occupational categories, it remains more challenging for low-income workers to adapt to the LEZ by purchasing a new car as the cost of new cars weighs heavily on their budgets.

The high ownership of polluting vehicles among low-income households is a crucial factor in the debate on LEZs and inequalities in France. Does this ownership significantly contribute to the anti-redistributive impact of LEZs? The findings of this study indicate that it does, although other factors such as specific policy design and urban characteristics also play a role. Notably, limited access to public transportation for low-income populations and limited accessibility to low-income jobs by public transport, as well as the greater distance between homes and workplaces for low-income workers (which hinders active mobility), contribute to the anti-redistributive effects of LEZs. Conversely, low-income workers and jobs are less frequently located within the LEZ compared to high-income workers and jobs, thereby mitigating the anti-redistributive effects of the LEZ.

These findings offer insights into potential policy measures for mitigating the effects of LEZs on workers' accessibility. Firstly, numerous subsidies available at national and local levels are designed to incentivize the acquisition of newer, less environmentally harmful vehicles. It is worth noting that lower-income households tend to own more polluting vehicles; however, they are also less likely to reside or work within LEZs. As a result, the distributional consequences of this policy hinge on its specific design. Presently, some subsidies, such as the "Prime à la conversion" or "Bonus écologique", offer higher benefits to low-income households.

Secondly, exemptions permitting the entry of polluting vehicles into LEZs may be granted based on job type. For instance, Reims has introduced a specialized exemption pass allowing the transportation of grapes during the harvest to presses situated within the LEZ. However, except for Lyon, where low-income households can temporarily benefit from an exemption, income is not the primary consideration for these passes.

Thirdly, in conjunction with implementing LEZs, many cities are concurrently developing public transportation systems as well as shared and active mobility options. Montpellier, for instance, plans to progressively introduce free public transport for all metropolitan area residents, while simultaneously expanding and enhancing these services. However, it should be noted that low-income households often encounter limited access to public transportation. Therefore, the free public transport policy may have anti-redistributive impacts and

the development of new public transport lines might be more efficient for equity purposes if measures are taken to ensure that these developments specifically benefit low-income households and cater to their transportation needs, which may prove challenging in practice [17]. Specifically, improving access to job locations for low-income workers could contribute to mitigating inequalities in LEZ impacts.

Lastly, long-term policies such as the establishment of employment subcenters, aimed at reducing commuting distances between residences and workplaces, offer a solution to enhance the fairness of LEZs. However, it is important to strike a balance between short-term policies, including subsidies for clean vehicle purchases, and medium- to long-term policies related to urban planning and improving public transportation efficiency. This balance is crucial to ensure equitable outcomes in the impacts of LEZs at all times.

In this study, the analysis is static, whereas, in the medium and long run, we can expect changes in populations and job distributions that will affect the conclusions of this study. For instance, gentrification may happen around public transport stations due to the increasing importance of public transport to mitigate the impact of LEZs on accessibility. The social composition of the city center might also change due to two mechanisms playing in opposite directions: housing prices might rise because living in the city center will be healthier, but they might also decrease as the city center will be less accessible. Consequences in terms of equity impacts of LEZs are unclear and could be investigated using a dynamic urban economics model.

6 Conclusion

In summary, this study finds that LEZs predominantly yield regressive effects in six out of the eight cities examined. This means that LEZs disproportionately impact the accessibility of low-skilled workers compared to their high-skilled counterparts.

In particular, low-skilled workers are particularly harmed by LEZs due to the limited availability of public transportation options near their residences and workplaces. In addition, the commuting patterns of low-skilled workers often involve longer distances, and a higher proportion of them own polluting vehicles, thereby exacerbating the impact of LEZs. In contrast, the relatively lower presence of low-skilled workers within LEZs, as well as the fewer instances of low-skilled jobs being situated within these zones, serves as a mitigating factor, resulting in a comparatively smaller effect of LEZs on this group.

In terms of magnitude, the shares of jobs of each occupational category in the LEZs and the share of polluting vehicle ownership per occupational category play key roles, explaining the difference in LEZs' impacts between occupational categories and cities. Still, other factors such as urban form, through residence-workplace distances and active transport mode use, also play a role.

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A Job accessibility losses decomposition

In a first step, I isolate the impact of the difference in the share of polluting vehicles for workers of categories c and c':

$$A_c^{LEZ} - A_c = \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum n_c(i) d_c(j) s_{c'}(i) [e^{-\beta min(t_{ij}^P, t_{ij}^A)} - e^{-\beta min(t_{ij}^P, t_{ij}^A, t_{ij}^C)}] + POL_{c,c'} \tag{5}$$

with

$$POL_{c,c'} = \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum n_c(i) d_c(j) (s_c(i) - s_{c'}(i)) [e^{-\beta min(t_{ij}^P, t_{ij}^A)} - e^{-\beta min(t_{ij}^P, t_{ij}^A, t_{ij}^C)}]$$

corresponding to the impact of the difference in polluting vehicles' ownership between occupational categories.

Similarly, I decompose further to account for the differences in spatial distributions of the workers of c and c':

$$\begin{aligned} A_c^{LEZ} - A_c = & \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum n_{c'}(i) d_c(j) s_{c'}(i) [e^{-\beta min(t_{ij}^P, t_{ij}^A)} - e^{-\beta min(t_{ij}^P, t_{ij}^A, t_{ij}^C)}] + \\ & \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum (n_c - n_{c'})(i) d_c(j) s_{c'}(i) [e^{-\beta min(t_{ij}^P, t_{ij}^A)} \\ & - e^{-\beta min(t_{ij}^P, t_{ij}^A, t_{ij}^C)}] \\ & + POL_{c,c'} \end{aligned} \tag{6}$$

Finally, I decompose further to account for the differences in spatial distributions of jobs of categories c and c':

$$\begin{aligned} A_c^{LEZ} - A_c = & (A_{c'}^{LEZ} - A_{c'}) + \\ & \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum n_{c'}(i) (d_c - d_{c'})(j) s_{c'}(i) [e^{-\beta min(t_{ij}^P, t_{ij}^A)} \\ & - e^{-\beta min(t_{ij}^P, t_{ij}^A, t_{ij}^C)}] + \\ & \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum (n_c - n_{c'})(i) d_c(j) s_{c'}(i) [e^{-\beta min(t_{ij}^P, t_{ij}^A)} \\ & - e^{-\beta min(t_{ij}^P, t_{ij}^A, t_{ij}^C)}] \\ & + POL_{c,c'} \end{aligned} \tag{7}$$

Then, I decompose further the change in transport times:

$$\begin{aligned} e^{-\beta min(t_{ij}^P, t_{ij}^A)} - e^{-\beta min(t_{ij}^P, t_{ij}^A, t_{ij}^C)} &= (e^{-\beta min(t_{ij}^P, t_{ij}^A)} - e^{-\beta t_{ij}^C}) \mathbb{1}_{t_{ij}^C \leq min(t_{ij}^P, t_{ij}^A)} \\ &= (e^{-\beta t_{ij}^P} - e^{-\beta t_{ij}^C}) \mathbb{1}_{t_{ij}^C \leq t_{ij}^P \leq t_{ij}^A} \\ &\quad + (e^{-\beta t_{ij}^P} - e^{-\beta t_{ij}^A}) \mathbb{1}_{t_{ij}^C \leq t_{ij}^A \leq t_{ij}^P} \\ &= -e^{-\beta t_{ij}^C} \mathbb{1}_{t_{ij}^C \leq min(t_{ij}^P, t_{ij}^A)} \\ &\quad + (e^{-\beta t_{ij}^P} - e^{-\beta t_{ij}^C}) \mathbb{1}_{t_{ij}^C \leq t_{ij}^P \leq t_{ij}^A} \\ &\quad + e^{-\beta t_{ij}^A} \mathbb{1}_{t_{ij}^C \leq min(t_{ij}^P, t_{ij}^A)} \end{aligned} \tag{8}$$

The first term corresponds to the transport times decay of job accessibility by private cars, when private cars are the faster mode, the second to the difference between the transport time decay by public transports and private cars, when public transports are faster than active modes and slower than private cars, and the last one to the transport times decay by active modes.

Combined with the previous equation, this leads to:

$$\begin{aligned} (A_c^{LEZ} - A_c) = (A_{c'}^{LEZ} - A_{c'}) &+ PT_{c,c'}^{POP} + LEZ_{c,c'}^{POP} \\ &+ PT_{c,c'}^{JOB} + LEZ_{c,c'}^{JOB} + POL_{c,c'} \\ &+ \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum (n_c(i) - n_{c'}(i)) d_c(j) s_{c'}(i) e^{-\beta t_{ij}^A} \mathbb{1}_{t_{ij}^C \leq min(t_{ij}^P, t_{ij}^A)} \\ &+ \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum (d_c(j) - d_{c'}(j)) n_{c'}(i) s_{c'}(i) e^{-\beta t_{ij}^A} \mathbb{1}_{t_{ij}^C \leq min(t_{ij}^P, t_{ij}^A)} \end{aligned} \tag{9}$$

with

$$PT_{c,c'}^{POP} = \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum (n_c(i) - n_{c'}(i)) d_c(j) s_{c'}(i) [e^{-\beta t_{ij}^P} - e^{-\beta t_{ij}^A}] \mathbb{1}_{t_{ij}^C \leq t_{ij}^P \leq t_{ij}^A}$$

which corresponds to the impact of the difference in public transport availability near homes of workers of category c and category c';

$$LEZ_{c,c'}^{POP} = - \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum (n_c(i) - n_{c'}(i)) d_c(j) s_{c'}(i) e^{-\beta t_{ij}^C} \mathbb{1}_{t_{ij}^C \leq min(t_{ij}^P, t_{ij}^A)}$$

which corresponds to the impact of the difference between the shares of workers in the LEZ of category c and category c';

$$PT_{c,c'}^{JOB} = \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum (d_c(j) - d_{c'}(j)) n_{c'}(i) s_{c'}(i) [e^{-\beta t_{ij}^P} - e^{-\beta t_{ij}^A}] \mathbb{1}_{t_{ij}^C \leq t_{ij}^P \leq t_{ij}^A}$$

which corresponds to the impact of the difference in public transports availability near jobs of category c and category c';

$$LEZ_{c,c'}^{JOB} = - \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum (d_c(j) - d_{c'}(j)) n_{c'}(i) s_{c'}(i) e^{-\beta t_{ij}^C} \mathbb{1}_{t_{ij}^C \leq min(t_{ij}^P, t_{ij}^A)}$$

which corresponds to the impact of the difference between the shares of jobs in the LEZ of category c and category c'.

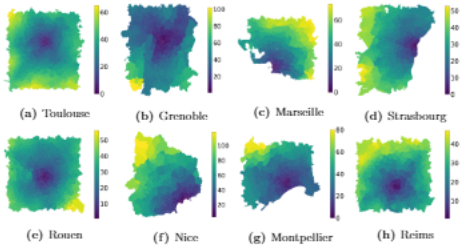
The two last terms correspond to the possibility to use active modes for commuting, which depends on the proximity between homes and workplaces. Separating these last two terms would make little sense, as the possibility to commute by active modes is largely determined by the joint location of homes and workplaces. Therefore, by rearranging these terms, I obtain the following final decomposition:

$$\begin{aligned} (A_c^{LEZ} - A_c) - (A_{c'}^{LEZ} - A_{c'}) = POLL_{c,c'} + AM_{c,c'} + PT_{c,c'}^{POP} \\ + LEZ_{c,c'}^{POP} + PT_{c,c'}^{JOB} + LEZ_{c,c'}^{JOB} \end{aligned} \tag{10}$$

with:

$$AM_{c,c'} = \sum_{\substack{(i \in LEZ, j) \\ (i \notin LEZ, j \in LEZ)}} \sum n_c(i) d_c(j) s_{c'}(i) e^{-\beta t_{ij}^A} \mathbb{1}_{t_{ij}^C \leq min(t_{ij}^P, t_{ij}^A)} - n_{c'}(i) d_{c'}(j) s_{c'}(i) e^{-\beta t_{ij}^A} \mathbb{1}_{t_{ij}^C \leq min(t_{ij}^P, t_{ij}^A)}$$

B Transport times by private cars to the city center



(a) Toulouse (b) Grenoble (c) Marseille (d) Strasbourg

(e) Rouen (f) Nice (g) Montpellier (h) Reims

Fig. 5: Transport times (in mn) to the city center by private cars.
Results have been aggregated at the IRIS level for readability purposes.

C Share of polluting vehicles

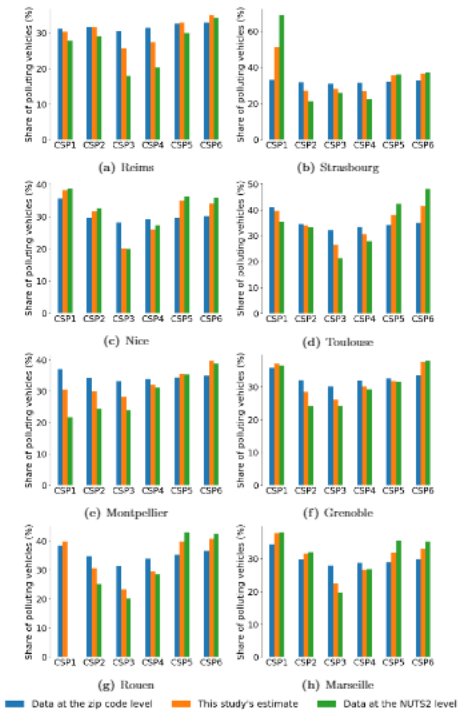
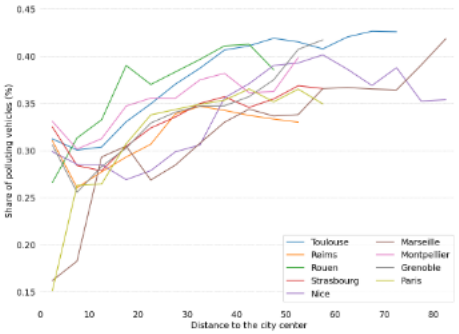


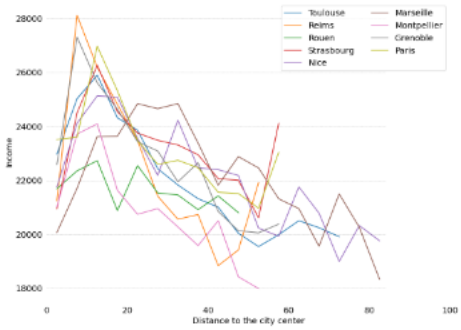
Fig. 6: Comparison between the different databases and this study's estimates for the share of polluting vehicles (Crit'air 3, Crit'air 4, Crit'air 5 and Non-Categorized vehicles).

D Descriptive statistics

(a) Share of polluting vehicles and income.



(b) Share of polluting vehicles and distance to the city center.



(c) Incomes and distance to the city center.

Fig. 7: Descriptive statistics: share of polluting vehicles, incomes and distance to the city center.
Data are aggregated per 1000 euros or 5km bins.
Sources: https://www.statistiques.developpement-durable.gouv.fr/donnees-sur-le-parc-de-vehicules-en-circulation-au-1er-janvier-2022 and Filosofi 2015. City centers are defined as 1km-grid cells with the highest density within the main city of the Functional Urban Area.

E Impact of different drivers on the differences in LEZ impacts between occupational categories - CSP1, CSP2, CSP4, and CSP5

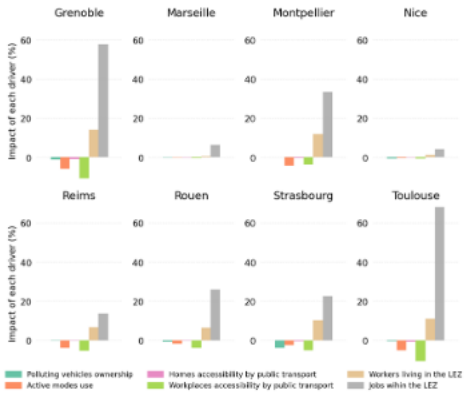


Fig. 8: Impact of different drivers on the differences in LEZ impacts between CSP3 (high-income) and CSP1 (farmers), in % of the pre-LEZ accessibility of CSP1).

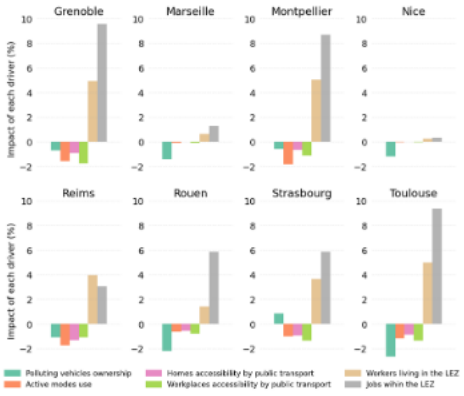


Fig. 9: Impact of different drivers on the differences in LEZ impacts between CSP3 (high-income) and CSP2 (high-income), in % of the pre-LEZ accessibility of CSP2).

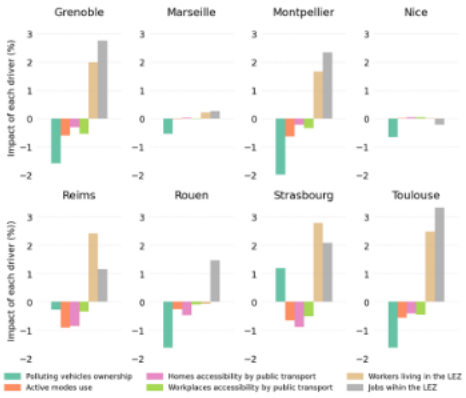


Fig. 10: Impact of different drivers on the differences in LEZ impacts between CSP3 (high-income) and CSP4 (middle-income), in % of the pre-LEZ accessibility of CSP4).

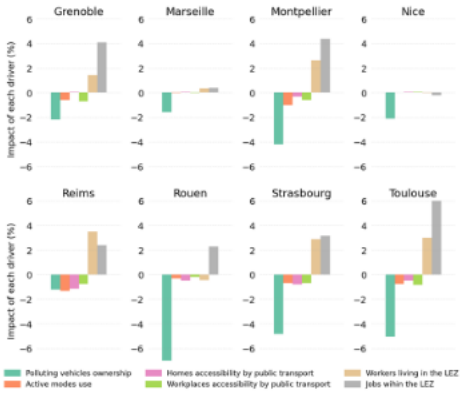


Fig. 11: Impact of different drivers on the differences in LEZ impacts between CSP3 (high-income) and CSP5 (low-income), in % of the pre-LEZ accessibility of CSP5).