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

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ABSTRACT

Low-emission zones (LEZs) aim to improve urban air quality and reduce emissions but often face public opposition due to their regressive impacts on accessibility. However, the causes of these regressive impacts remain poorly understood. This study investigates the factors driving inequalities in the impacts of LEZs on job accessibility across occupational categories in eight French cities. Using ex-ante open-source data, it computes expected job accessibility losses due to LEZs per occupational category. Additionally, it provides a counterfactual decomposition of the disparities in LEZs' impacts between six drivers: ownership of polluting vehicles, 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 LEZs are predominantly regressive in six out of the eight cities examined. Despite a higher concentration of high-income workers and jobs within LEZs, resulting in significant accessibility losses for this group, low-income workers bear a greater burden due to the limited availability of public transportation near their residences and workplaces, longer commutes to work, and higher shares of polluting vehicles. These findings help inform potential complementary policies to address the regressive effects of LEZs.

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 (Liotta et al., 2023). Low-emission 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.

The number of LEZs has increased rapidly across Europe in recent years. In 2019, 228 LEZs were implemented in the EU-27, UK, and Norway, and their number has increased up to 320 in 2022, corresponding to a +40% increase in 3 years. Their number is expected to reach 507 in 2025, for example, due to national policies in France, Spain, and Poland (Clean Cities Campaign and Transport & Environment, 2022). The French "Climate and Resilience" law makes LEZs mandatory for cities with more than 150,000 inhabitants that do not meet air quality standards, while the Spanish "Climate and Energy Transition" law makes them mandatory for cities with more than 50,000 inhabitants. Although less common, LEZs have also emerged beyond Europe's borders, notably in countries such as China and Indonesia.

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 (Moreno et al., 2022; Schittly, 2023): 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.

Spatial accessibility indicators offer a promising way to analyze accessibility losses due to LEZs. Indeed, spatial accessibility indicators measure the ease with which people can reach desired opportunities; they are computed based on the distribution of opportunities in space combined with the efficiency of the transport system. In particular, the commonly used gravity-based measures (Hansen, 1959) sum the weighted opportunities within reach for each person or origin. These measures are relevant to this study because LEZs may put some opportunities out of reach for some populations, as the use of polluting private cars is restricted, leading to increased vulnerability for the

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inhabitants who cannot easily switch transport modes (Mattioli et al., 2019).

These measures have already been used to analyze various transport policies, such as the extension of the transport network (Viguié et al., 2023). However, except for Soukhov et al. (2024), few studies have calculated them in the context of LEZs, so the extent of accessibility losses due to LEZs and their differences across occupational categories or income groups remain unknown. In addition, existing research suggests that several factors, namely non-compliant vehicle ownership (Morton et al., 2018; Verbeek and Hincks, 2022), public transport availability (Morton et al., 2018; Liu and Kontou, 2022), and the spatial distributions of jobs and workers (Verbeek and Hincks, 2022; Dodson and Sipe, 2007), may contribute to disparities in the LEZs' impacts across different income classes, but do not quantify the relative importance of these factors.

Using the example of LEZs in eight French cities, this study aims to better understand the impact of urban climate policies on transport justice. The main research questions are: Are the LEZs' impacts regressive? What drives the differential effect of LEZs across income classes, and how does it vary across cities? Using ex-ante data, this article calculates the expected impact of LEZs on job accessibility for the different occupational categories. It focuses on the direct, short-term impacts of the LEZ, i.e. the fact that workers owning polluting vehicles will not be able to use private cars anymore if they commute from or to the LEZ, and that they will have to use public transport or active modes instead. In addition, it proposes a counterfactual approach to decompose the difference in expected spatial accessibility losses due to LEZs across occupational categories between factors related to the distribution of workers, the distribution of jobs, and the transport system.

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 (Bastiaanssen et al., 2021; Korsu and Wenglenski, 2010). 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 (Ding and Cao, 2019; Pfertner et al., 2022).

This paper offers both methodological and practical contributions. Methodologically, it proposes a refinement of the gravity-based spatial accessibility measure by decomposing the difference in expected spatial accessibility losses due to LEZs across occupational categories into 6 drivers: presence of homes and jobs within the LEZ, ownership of polluting vehicles, accessibility of homes and jobs by public transport, and proximity between homes and jobs. To do so, it proposes several methodological refinements of job accessibility measures, building notably on Shen (1998) and Deboosere and El-Geneidy (2018): in particular, it distinguishes between owners of polluting and non-polluting vehicles, as well as between different categories of workers, matching workers and jobs by occupational categories and scaling the results to allow for comparisons of accessibility losses between groups.

However, the main contribution is applied: this paper presents an ex-ante public policy impact assessment to support decision-making. A counterfactual approach is particularly relevant for policymaking, as it provides a clear and transparent understanding of how various factors, such as polluting vehicle ownership or access to transport, affect different occupational groups. This paper allows to visualize the impact of LEZs across occupational categories, for different cities, and their decomposition in a synthetic way. This contrasts with regression or machine learning models, which can be more challenging to interpret due to spatial correlations between variables (Berrill et al., 2024; Viguié et al., 2023; Padeiro et al., 2019).

The counterfactual decomposition of the changes in job accessibility proposed in this paper avoids these issues by directly accounting for the factors of interest, rather than relying on statistical methods. This decomposition approach offers greater interpretability by explicitly breaking down the contribution of each factor – such as vehicle ownership or public transport access – across occupational groups, allowing to precisely identify the sources of inequality in job accessibility and offering actionable insights for policymakers.

2. Literature review

2.1. LEZs, emissions, pollution, and health

Numerous studies and reports have established the LEZs benefits in terms of air quality, health, and climate. At the European level, a 2019 review found that many LEZs have delivered strong reductions in air pollutant concentrations, with magnitudes ranging from no discernable effect to a 32% decrease in NO_2 pollution in Madrid Central (Transport and Environment, 2019). Another review from the French Agency for the Ecological Transition (ADEME, 2020) found that LEZs in Europe have accelerated the renewal of the vehicle fleet and thereby contributed to reducing air pollution. More recently, Bernardo et al. (2021) show that LEZs have curbed air pollution, studying a panel of large European cities between 2008 and 2016.

Such improved air quality resulted in health benefits, as demonstrated by two studies conducted on German cities (Malina and Scheffler, 2015; Pestel and Wozny, 2021). LEZs also bring climate benefits: CO_2 emissions from transport in London are estimated to have decreased by 13% after the first six months of its Ultra-Low Emission Zone, compared to a scenario without the measure (Mayor of London, 2019). Smaller reductions have been observed in other cities, including Amsterdam, Paris, and Berlin (Beedham, 2022).

2.2. Environmental and transport justice

A few studies investigated LEZs environmental justice impacts and tried to determine who might benefit from air quality improvements. In the Paris metropolitan area, Poulhès and Proulhac (2021) find that wealthier households would be the biggest winners of the LEZ in terms of improved air quality, but they were also more exposed in the first place. Analyzing different scenarios of LEZ implementation in the Paris metropolitan area, Host et al. (2020) and Moreno et al. (2022) found that the scenario with the largest LEZ perimeter and the most stringent standards prevents the highest number of deaths and asthma cases, and produces the most equitable distribution of health benefits.

Still, such environmental justice impacts need to be put into perspective and compared with transport justice impacts: which population will experience the largest losses in spatial accessibility? 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 (Verbeek and Hincks, 2022).

Studies that focus specifically on transport justice remain scarce. Charleux (2014) demonstrates that a LEZ in Grenoble might have a different impact on people's mobility depending on their occupational category due to varying shares of polluting vehicle ownership, job locations, and transportation mode substitution possibility. Morton et al. (2018) built an index to identify vulnerable households with little capacity to adapt to the Edinburgh LEZ. Qualitative studies show the broader impacts of LEZs, for instance on shopping activities (Tarriño-Ortiz et al., 2022) or social relations (De Vrij and Vanoutrive, 2022). However, so far, few studies compute the impact of LEZ on accessibility measures specifically. An exception is Soukhov et al. (2024); however, they only consider inequalities in the effects of LEZs between users of different modes of transport and do not consider inequalities between different income classes or occupational categories.

Although the literature on LEZs and transport justice remains scarce, it can be connected to the wider literature that studies car dependency and social justice in the context of vulnerability to rising oil prices: indeed, car-dependent households are more likely to be unable to adapt to LEZs. This literature demonstrates that vulnerability to rising oil prices intersects with spatial socioeconomic patterns but may be mitigated by an efficient public transport system, anti-sprawl policies, or the existence of city subcenters (Dodson and Sipe, 2007; Nicolas et al., 2012; Cao and Hickman, 2018).

2.3. Drivers of job accessibility losses from the LEZ

Existing studies identify some key drivers that may explain inequalities in LEZs' impacts on job accessibility.

The first driver is polluting vehicle ownership, which might have consequences on LEZs' distributional impacts if polluting vehicle ownership depends on the occupational category. For instance, in Grenoble, Charleux (2014) showed that blue-collar workers are likelier to drive prohibited cars. This factor is often cited in the public debate to explain opposition to the introduction of LEZs (Floc'h, 2022).

Other drivers are the availability of public transport near homes and jobs: there might be large differences in the availability of public transport near high-income and low-income jobs or high and low-income workers' homes. The study by Verbeek and Hincks (2022) highlights access of low-income households to public transport as a key determinant of the differences in LEZs equity impacts between London and Brussels. In the broader literature on transport poverty, oil vulnerability indices (for instance, in Dodson and Sipe (2007) or Morton et al. (2018)) account for the availability of alternative transport modes near homes.

Similarly, the proximity between homes and jobs, and thus the possibility to commute by active mobility – i.e., forms of transportation that rely on human physical activity such as walking or cycling – is an important driver. For instance, comparing French cities, Nicolas et al. (2012) show that, in sprawled cities, low-income households living in the outer suburbs are largely car-dependent. However, within the urban area of Lille, two large subcenters allow to mitigate this car dependency of low-income households.

Finally, which type of workers or jobs are located within the LEZs matters to understand their distributional impacts. For instance, in Grenoble, Charleux (2014) finds that the LEZ largely impacts skilled workers due to the concentration of high-level jobs within the LEZ.

However, the relative contributions of these drivers to inequalities in LEZs impacts across occupational categories have never been quantitatively assessed. This study uses a counterfactual decomposition to understand to what extent each driver is responsible for the unequal LEZs' impacts across occupational categories.

2.4. Quantifying transport injustice using spatial accessibility methods

This study attempts to quantify the unequal impact of LEZs on job accessibility across occupational categories. To date, such accessibility measures have rarely been computed in the context of LEZs, with the exception of Soukhov et al. (2024), which proposes a spatial accessibility measure to assess inequalities in job accessibility losses due to LEZ implementation between users of different transport modes, with an application to Madrid, Spain. However, beyond the context of low-emission zones, accessibility measures have been extensively used to analyze inequalities in job accessibility.

First, job accessibility measures can be calculated at fine spatial resolutions, and allow comparing neighborhoods within cities. Recent examples include Slovic et al. (2019), in Sao Paulo, Hu (2015), in Los Angeles, and Kelobonye et al. (2019) in Perth. For instance, Kelobonye et al. (2019) show poor spatial equity in Perth, with outer suburbs having low levels of accessibility to jobs, but also education, shopping, and health care.

These measures are also useful for comparing accessibility among income groups. For instance, Viguié et al. (2023) compare the evolution of accessibility across income groups between 1968 and 2010 in the Paris metropolitan area, and Guzman et al. (2017) assess equity in accessibility to employment and education across low, medium, and high-income groups in Bogota, Colombia. In Fortaleza, Brazil, Pinto et al. (2023) compare accessibility to formal and informal jobs across socioeconomic groups. Similarly, job accessibility measures can compare ethnic groups (Yeganeh et al., 2018; Grengs, 2012). Job accessibility methods also allow to quantify inequalities between different transport mode users: Shen (1998) compares car owners and non-car owners, while Soukhov et al. (2024) analyzes the competition between bike users, pedestrians, car users, and transit users.

Many studies jointly consider several of these variables. For instance, Slovic et al. (2019) investigates the overlap between areas of low accessibility and those with disadvantaged populations, while Grengs (2012) analyzes both ethnic and socioeconomic inequalities in accessibility.

The goal of this study is to analyze the unequal impacts of LEZ on job accessibility across occupational categories. In doing so, it also decomposes these inequalities by considering key factors related to urban form and transport mode availability. This approach builds on the existing literature on spatial accessibility measures, which offers methods for assessing such inequalities.

3. Cities' sample and context

The first French LEZ was implemented in Paris in 2015, and the policy has been gradually extended to other cities. In 2021, the "Climate and Resilience" law mandated LEZs for cities with more than 150,000 inhabitants. These cities must progressively ban polluting vehicles, starting with "Non-Classified" and "Crit'Air 5" vehicles, which are the most polluting. This is followed by bans on "Crit'Air 4" and "Crit'Air 3" vehicles, while "Crit'Air 2", "Crit'Air 1" and "Crit'Air E" are the least polluting categories.

This study's sample includes eight mid-size French cities (Fig. 1, Table 1), targeted by the "Climate and Resilience" law, 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 design[1], including the geographical boundaries of their LEZ and the timetable for banning polluting vehicles. These cities cover 8.5 million inhabitants, corresponding to 13.5% of the population of mainland France, or 17.1% of the population of mainland France excluding the Paris metropolitan area.

Importantly, Paris, which is way more advanced than the other cities in its LEZ implementation, and where the LEZ might already have had impacts on residence and job locations or polluting vehicle ownership, is excluded. Instead, this paper focuses on mid-size cities, which is relevant in the context of increasing implementation of LEZ in mid-size cities, for instance as a response to the French "Climate and Resilience", or to the Spanish "Climate and Energy Transition" law that makes them mandatory for cities of more than 50,000 inhabitants.

Although cities must follow national guidelines – such as ensuring that the LEZ covers a minimum area and banning Crit'Air 3 vehicles by September 2025 – they retain considerable autonomy in designing their LEZs, including decisions on the perimeter, implementation timetable, and exemptions. For example, the banning dates for Crit'Air 3 vehicles vary between January 2024 and January 2029 (Table 1). Often,

[1] 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, accessed on 05/07/2023

Table 1
City sample.

	Population	Median income	LEZ area	Crit'air 3 vehicle ban
Marseille	2,189,779	22,050€	19.5 km^2	Sept. 2024[a]
Toulouse	1,425,256	23,660€	71 km^2	Jan. 2024[a]
Nice	1,091,877	22,050€	2.7 km^2	[a]
Strasbourg	945,215	22,990€	340 km^2	Jan. 2025
Rouen	865,281	21,780€	86 km^2	Jan. 2025[a]
Montpellier	814,267	21,600€	198 km^2	Jan. 2025
Grenoble	753,307	23,950€	270 km^2	Jan. 2025
Reims	406,238	21,910€	3.4 km^2	Jan. 2029

Incomes are declared income per unit of consumption from FiLoSoFi 2020. Population and LEZ area are computed by the author, using the data described in the data section. Polluting vehicle ban's date corresponds to Crit'Air 3 vehicle's ban date.

[a] Indicates that the measure has been suspended because the air quality is good enough.

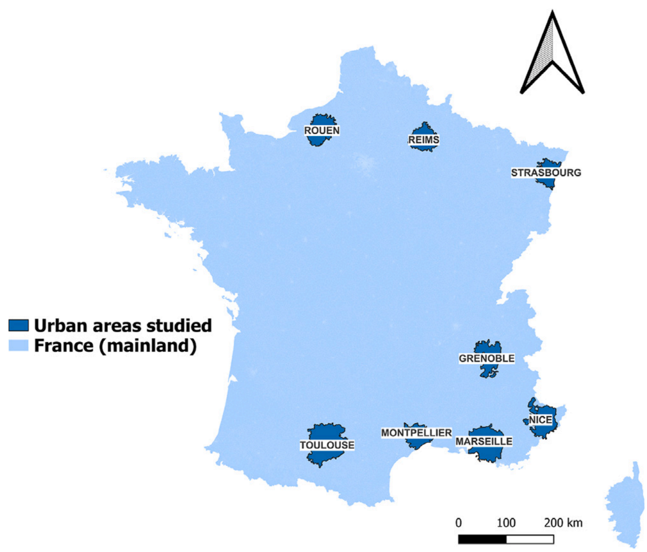

Fig. 1. Sample of cities studied. *The geographical boundaries of the urban areas studied are the Functional Urban Areas, as described in* Section 4.1.

these bans are preceded by a "trial period" during which vehicles are theoretically restricted, but violations result only in notices to drivers with no sanctions. In 2023, a national regulation stipulated that the implementation of LEZs can be suspended if air quality exceeds a certain threshold. For example, if Crit'Air 3 vehicles are not yet banned and air quality remains sufficiently good, the ban will not need to be enforced.

LEZ perimeters vary significantly among cities as well, ranging from 2.7 km^2 in Nice to 340 km^2 in Strasbourg (Table 1). Cities have some freedom in designing their LEZs, with some opting for minimal coverage while others include neighboring areas. Cities face a trade-off: larger LEZs may improve air quality more effectively, potentially suspending further restrictions, but they also cause greater spatial accessibility losses. Smaller LEZs affect fewer areas, but may not improve air quality sufficiently, necessitating the extension of restrictions to additional vehicle categories.

Finally, LEZ exemptions are set at both national and local levels. Section E.1 of Appendix A provides an overview of these exemptions. At the national level, five exemptions apply to all LEZs: priority general interest vehicles (e.g., police and fire trucks), Ministry of Defense vehicles, disabled parking permit holders, low-emission public transit vehicles, and public transit vehicles providing scheduled service. Additional city-specific exemptions may include specialty vehicles (e.g., refrigerated trucks), special use cases (e.g., moving operations), or a limited number of trips per year (e.g., up to 12, 24, or 52 days per year, depending on the city).

4. Data

This paper uses a collection of geographical urban boundaries data, socioeconomic data (Section 4.1), and transport data (Section 4.2), summarized in Table 2.

4.1. Geographical boundaries and socioeconomic data

OECD Functional Urban Areas (FUAs) are used as geographical boundaries of analysis. This approach ensures consistency across all eight cities, irrespective of urban administrative boundaries: FUAs encompass not only the central city but also its less densely populated outskirts that are part of the same labor market (Dijkstra et al., 2019). All the data have been aggregated on a 1 km resolution grid.

This paper considers six 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 3). CSP3, the occupational category with the highest average income, is used as a reference when needed.

The analysis in this paper focuses on occupational categories and does not consider income. While income data are available for France at a 1 km resolution, they are not integrated with occupational categories, which are crucial for understanding the types of jobs accessible to workers in this analysis. Still, as Table 3 shows, occupational categories are quite homogeneous in terms of income. For instance, the income decile 9 for "intermediate occupations" (CSP4) is roughly equivalent to the average income of "managers" (CSP3). Similarly, income decile 9 for "sales, services workers" (CSP5) or "blue-collar workers" (CSP6) is only approximately equal to the average income of "intermediate occupations" (CSP4). CSP1 and CSP2 appear heterogeneous in income, but this is partly due to the display of aggregated incomes for these two categories together.

Workers' spatial distributions per occupational category are taken from the 2017 census and are available at the IRIS[2] level. Jobs spatial distributions are taken from the 2018 "Emploi - Population Active" survey from INSEE and are available at the zip code level.

This research considers 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, two data sources are combined 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[3];
- "Mobilité des personnes" 2019 data on the share of polluting vehicles per occupational category, but at the NUTS2 level only. The survey, led by the French Ministry of Ecological Transition and Territorial Cohesion,[4] covers individuals aged 5 and over living in mainland France. It includes at least 12,000 persons, and the sample is stratified based on household types (rural or urban) and motorizations. Still, results are available at the NUTS2 level only and therefore do not distinguish between rural and urban locations within NUTS2.

2 Smallest census unit, corresponding to about 2000 inhabitants.
3 https://www.statistiques.developpement-durable.gouv.fr/donnees-sur-le-parc-de-vehicules-en-circulation-au-1er-janvier-2022
4 https://www.statistiques.developpement-durable.gouv.fr/enquete-sur-la-mobilite-des-personnes-2018-2019, accessed 12th February 2024

Table 2
Summary of the data. *More details can be found in sections 4.1 and 4.2.*

Category	Description	Source
Urban boundaries	Functional urban areas	OECD (Dijkstra et al., 2019)
Socioeconomic	Jobs spatial distribution	2018 “Emploi - Population Active” survey
	Workers spatial distribution	2017 INSEE Census
	Polluting vehicles ownership	2022 data per zip code
		“Mobilité des personnes” 2019 data
Transport	Travel time by public transport	*transport.data.gouv* (Table 4), retrieved in 2023
	Travel time by cars	OSM, data retrieved in 2023

Table 3
Occupational categories.
Source: Insee-DGFiP-Cnaf-Cnav-CCMSA, enquête Revenus fiscaux et sociaux 2018.

Category	Description	Average income	Income decile 1	Income decile 9	Share of workers
CSP1	Farmers	29,310 €	9,140 €	51,820 €	1.6%
CSP2	Executive directors				6.8%
CSP3	Managers	39,860 €	19,710 €	62,670 €	21.7%
CSP4	Intermediate occupations	27,000 €	15,330 €	39,730 €	24.6%
CSP5	Sales, services workers	21,480 €	11,680 €	31,500 €	26.0%
CSP6	Blue-collar workers	20,310 €	11,200 €	29,370 €	18.9%

Based on these two databases, the *scipy.optimize* package is used to estimate the shares of polluting vehicles per zip code and per occupational category. Specifically, the *scipy.optimize* package identifies the potential distributions of polluting vehicles that most closely match the distributions in these databases, minimizing the difference (in terms of absolute number of vehicles) with these two databases. Further details are provided in Appendix A.

4.2. 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 1 km-resolution grid encompassing the FUA of each city.

Transport times by private cars have been retrieved from OpenStreetMap using the *osmnx* python package (Boeing, 2017)[5]. It was not possible to collect transport data from each grid cell, so data were collected from a significant share of all cells[6], and then interpolated using the *interpolate.griddata* function from the python package *scipy*.

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 4. For each 1 km-resolution grid cell, it is assume that all jobs and inhabitants are located in the cell's centroid and have access to all the public transport stops within a 500 m walk. Then, for each origin–destination grid cell pair, the shortest transport time is retrieved using the GTFS data.

Travel times per walk between grid cells were estimated from the geographic distances between grid cells, assuming a walking speed of 4 km/h. Walking is the only active travel mode included, and cycling is excluded. Indeed, the modal share of cycling is low in most cities of the sample[7]: 1.4% in Nice and Rouen, 1.5% in Marseille, 2% in Reims, 3.6% in Montpellier and 3.9% in Toulouse. It exceeds 5% in only two cities, Grenoble (6.2%) and Strasbourg (7.1%). In addition, little is known about people's propensity to switch to bicycles, since

Table 4
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

it depends on several individual, social, and infrastructural factors including demographics, safety beliefs, social learning, and social influence, cycle lanes, amenities at destination (e.g. showers), or weather conditions (Javaid et al., 2020).

In the main specification, jobs are discounted based on their distance to workers using a decay parameter β (see Section 5.1). This parameter is assumed to be equal to 0.064, based on the estimation of Pfeiffer (2022) for the Paris metropolitan area, for a minimum between the transport time between private cars and public transport. Therefore, this paper makes the normative assumption that the decay parameter is the same for all transport modes, implying that travel time should discount opportunities in the same way, regardless of the transportation mode (Páez et al., 2012). A decay parameter of 0.064 means that a travel time of 25 mn, the French average (DARES, 2015), will lead to jobs being discounted by 80%. Other estimates of this parameter in the literature are 0.044 (Giannotti et al., 2022) and 0.05 (Ahlfeldt, 2013) for London, 0.07 for Berlin Ahlfeldt et al. (2015), 0.09 in Norway (Osland and Thorsen, 2008), 0.015 for Sao Paulo (Giannotti et al., 2022), and between 0.014 and 0.044 for Canadian cities (Kapatsila et al., 2023). Robustness checks for decay parameters of 0.015, 0.045, and 0.090 can be found in Section 6.3.

Exemptions, which allow certain vehicles or individuals to enter the LEZ without having to comply with the standard polluting vehicle ban, are not accounted for in the main analysis due to a lack of consistent data on the number of exemptions granted or precise household characteristics that might qualify for exemptions. Nonetheless, these exemptions minimally impact the results. For instance, exemptions granted to professional vehicles do not significantly alter workers' commutes. Exemptions for occasional use or limited distances per year are intentionally designed to exclude daily commuting. While exemptions are not accounted for in the main results of the paper, a robustness check is done for Grenoble, which is the city that grants the most significant exemption (see Section 6.3).

[5] Here, park-and-ride is not accounted for. However, park-and-ride corresponds to only 0.5% of local trips in France (Enquête Mobilité des Personnes 2019)

[6] With a method close to Saiz and Wang (2021) and Lepetit et al. (2023), a star shape with 8 branches centered on the city center has been defined for each city, and data from 100 grid cells per star branch were collected.

[7] Source: author's calculations based on the 2022 French census.

5. Methods

Section 5.1 shows how job accessibility by occupational category and the expected changes due to the LEZs are calculated. Then, Section 5.2 presents the decomposition between the different drivers.

5.1. Job accessibility

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

$$A_i^g = \sum_j d_j^g \max_{m\in\{P,A,C\}} f(t_{ij}^m) \tag{1}$$

with d_j^g the share of jobs of category g in location j and t_{ij}^m the transportation time between i and j using transportation mode $m \in \{P, A, C\}$ corresponding to public transport, active transportation modes, and private cars respectively. f is the transport time decay function, assumed as being an exponential function such that $f(t_{ij}^m) = e^{-\beta t_{ij}^m}$. For each destination j, the transportation mode that maximizes $f(t_{ij}^m)$ (i.e. the transportation mode that minimizes transportation time) is selected, as, for instance, in Viguié et al. (2023) or Kelobonye et al. (2019). Empirically, the combined accessibility of private cars and public transport, selecting the transport mode that minimizes travel time, has been shown to impact social outcomes such as unemployment duration (Korsu and Wenglenski, 2010).

A_i^g is a gravity-based measure of job accessibility (Hansen, 1959), meaning that it considers travel time decay of job opportunities. Based on Viguié et al. (2023), 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.

This accessibility measure is based on the share of jobs of category g in location j d_j^g, calculated by dividing the total number of category g jobs in location j by the overall number of category g jobs: this allows to standardize the measure across occupational groups in order to capture variations in accessibility due only to the LEZ, independent of initial differences between occupational categories. This method largely builds on Deboosere and El-Geneidy (2018), who proposes an attempt to match workers and jobs: they compute the job accessibility of low-income households only, and then scale it by the ratio of total jobs to low-income jobs, enabling comparison with the overall population job accessibility.

Denoting n_i^g the share of workers in category g living in census tract i, the weighted mean of A_i^g across the urban area is computed for each occupational category g:

$$A_g = \sum_i \sum_j n_i^g d_j^g \max_{m\in\{P,A,C\}} f(t_{ij}^m) \tag{2}$$

Therefore, A^g is an indicator that represents the average accessibility of workers in category g to jobs within the same occupational category.

Denoting s_i^g the share of polluting vehicles among workers of category g living in i, the average accessibility of workers in category g to jobs within the same occupational category, after LEZ implementation, is:

$$\begin{aligned} A_g^{LEZ} = & \sum_{(i\notin LEZ, j\notin LEZ)}\sum n_i^g d_j^g \max_{m\in\{P,A,C\}} f(t_{ij}^m) \\ & + \sum_{\substack{(i\in LEZ,j) \\ (i\notin LEZ,j\in LEZ)}}\sum n_i^g d_j^g (1-s_i^g) \max_{m\in\{P,A,C\}} f(t_{ij}^m) \\ & + \sum_{\substack{(i\in LEZ,j) \\ (i\notin LEZ,j\in LEZ)}}\sum n_i^g d_j^g s_i^g \max_{m\in\{P,A\}} f(t_{ij}^m) \end{aligned} \tag{3}$$

Eq. (3) highlights the fact that we consider that, for workers living and working out of the LEZ or for workers owning non-polluting vehicles (first and second term of the equation), the accessibility remains unchanged. However, for workers commuting from or to the LEZ and owning a polluting vehicle, the LEZ results in accessibility losses as workers cannot commute by private cars anymore.

Therefore, the accessibility loss due to the LEZ, for workers of category g, is:

$$A_g^{LEZ} - A_g = \sum_{\substack{(i\in LEZ,j) \\ (i\notin LEZ,j\in LEZ)}}\sum n_i^g d_j^g s_i^g [\max_{m\in\{P,A\}} f(t_{ij}^m) - \max_{m\in\{P,A,C\}} f(t_{ij}^m)] \tag{4}$$

Eq. (4) highlights that accessibility losses from the LEZ are, in this framework, experienced by workers owning polluting vehicles and living in, or commuting to, the LEZ.

This approach considers polluting and non-polluting vehicles as distinct modes, each providing access to different job opportunities. Polluting vehicles provide access to jobs where both origin and destination are outside the LEZ, while non-polluting vehicles provide access to all jobs. Therefore, this paper considers two groups of car owners: those with polluting cars and those with non-polluting cars. This classification is inspired by the approach of Shen (1998), which distinguishes between workers who own a car and those who do not.

Ultimately, $A_g^{LEZ} - A_g$ is an indicator of the average accessibility losses due to the LEZ, by occupational category. It combines the approaches of Shen (1998), which proposes a method to distinguish the effect of location from the effect of workers' car ownership in accessibility measures, and of Deboosere and El-Geneidy (2018) or Pinto et al. (2023), which proposes a method allowing to compare accessibility across job types.

One major hypothesis is that travel times remain unchanged after the LEZ implementation, except for polluting car drivers who cannot commute by car due to the LEZ and who must switch to another transport mode. It means that it is assumed that commuters who start and end their trips out of the LEZs do not have to detour to avoid the LEZ: in practice, in most cities and most cases, such trips involve using ring roads outside the LEZ or exempted major routes within it, and therefore do not necessitate passage through the LEZ. It also means that it is assumed that the LEZ has no impact on congestion, leaving transport times by private cars unchanged. This hypothesis is supported by Bernardo et al. (2021), which finds, based on a panel of large European areas between 2008 and 2016, that LEZs can curb air pollution but are ineffective in mitigating congestion.

5.2. Job accessibility losses decomposition

This subsection proposes a method to decompose the difference in expected spatial accessibility losses due to LEZs across occupational categories between 6 drivers: presence of homes and jobs within the LEZ, ownership of polluting vehicles, accessibility of homes and jobs by public transport, and proximity between homes and jobs. This approach makes it possible to compare the relative importance of these different drivers in shaping the differential impacts of LEZs across occupational categories.

Comparing two occupational groups g and g' such that $g \neq g'$, a first step isolates the impact of the difference in the share of polluting vehicles for workers of categories g and g':

$$A_g^{LEZ} - A_g = \sum_{\substack{(i\in LEZ,j) \\ (i\notin LEZ,j\in LEZ)}}\sum n_i^g d_j^g s_i^{g'} [\max_{m\in\{P,A\}} f(t_{ij}^m) - \max_{m\in\{P,A,C\}} f(t_{ij}^m)] + POL_{g,g'} \tag{5}$$

with

$$POL_{g,g'} = \sum_{\substack{(i\in LEZ,j) \\ (i\notin LEZ,j\in LEZ)}}\sum n_i^g d_j^g (s_i^g - s_i^{g'}) [\max_{m\in\{P,A\}} f(t_{ij}^m) - \max_{m\in\{P,A,C\}} f(t_{ij}^m)]$$

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

Similarly, further decomposition accounts for the differences in spatial distributions of the workers of g and g':

$$A_g^{LEZ} - A_g = \sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum n_i^{g'} d_j^g s_i^{g'} [\max_{m\in\{P,A\}} f(t_{ij}^m) - \max_{m\in\{P,A,C\}} f(t_{ij}^m)] + \sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum (n_i^g - n_i^{g'}) d_j^g s_i^{g'} [\max_{m\in\{P,A\}} f(t_{ij}^m) - \max_{m\in\{P,A,C\}} f(t_{ij}^m)] + POL_{g,g'} \quad (6)$$

Finally, further decomposition accounts for the differences in spatial distributions of jobs of categories g and g':

$$A_g^{LEZ} - A_g = (A_{g'}^{LEZ} - A_{g'}) + \sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum n_i^{g'} (d_j^g - d_j^{g'}) s_i^{g'} [\max_{m\in\{P,A\}} f(t_{ij}^m) - \max_{m\in\{P,A,C\}} f(t_{ij}^m)] + \sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum (n_i^g - n_i^{g'}) d_j^g s_i^{g'} [\max_{m\in\{P,A\}} f(t_{ij}^m) - \max_{m\in\{P,A,C\}} f(t_{ij}^m)] + POL_{g,g'} \quad (7)$$

Then, the change in transport times are decomposed:

$$\begin{aligned}\max_{m\in\{P,A\}} f(t_{ij}^m) - \max_{m\in\{P,A,C\}} f(t_{ij}^m) &= (\max_{m\in\{P,A\}} f(t_{ij}^m) - f(t_{ij}^C)) \mathbb{1}_{t_{ij}^C \le min(t_{ij}^P, t_{ij}^A)} \\ &= (f(t_{ij}^P) - f(t_{ij}^C)) \mathbb{1}_{t_{ij}^C \le t_{ij}^P \le t_{ij}^A} \\ &\quad + (f(t_{ij}^P) - f(t_{ij}^A)) \mathbb{1}_{t_{ij}^C \le t_{ij}^A \le t_{ij}^P} \\ &= -f(t_{ij}^C) \mathbb{1}_{t_{ij}^C \le min(t_{ij}^P, t_{ij}^A)} \\ &\quad + (f(t_{ij}^P) - f(t_{ij}^A)) \mathbb{1}_{t_{ij}^C \le t_{ij}^P \le t_{ij}^A} \\ &\quad + f(t_{ij}^A) \mathbb{1}_{t_{ij}^C \le min(t_{ij}^P, t_{ij}^A)} \end{aligned} \quad (8)$$

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:

$$\begin{aligned}(A_g^{LEZ} - A_g) = &(A_{g'}^{LEZ} - A_{g'}) + PT_{g,g'}^{POP} + LEZ_{g,g'}^{POP} \\ &+ PT_{g,g'}^{JOB} + LEZ_{g,g'}^{JOB} + POL_{g,g'} \\ &+ \sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum (n_i^g - n_i^{g'}) d_j^g s_i^{g'} f(t_{ij}^A) \mathbb{1}_{t_{ij}^C \le min(t_{ij}^P, t_{ij}^A)} \\ &+ \sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum (d_i^g - d_i^{g'}) n_i^{g'} s_i^{g'} f(t_{ij}^A) \mathbb{1}_{t_{ij}^C \le min(t_{ij}^P, t_{ij}^A)} \end{aligned} \quad (9)$$

with

$$PT_{g,g'}^{POP} = \sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum (n_i^g - n_i^{g'}) d_j^g s_i^{g'} [f(t_{ij}^P) - f(t_{ij}^A)] \mathbb{1}_{t_{ij}^C \le t_{ij}^P \le t_{ij}^A}$$

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

$$LEZ_{g,g'}^{POP} = -\sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum (n_i^g - n_i^{g'}) d_j^g s_i^{g'} f(t_{ij}^C) \mathbb{1}_{t_{ij}^C \le min(t_{ij}^P, t_{ij}^A)}$$

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

$$PT_{g,g'}^{JOB} = \sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum (d_j^g - d_j^{g'}) n_i^{g'} s_i^{g'} [f(t_{ij}^P) - f(t_{ij}^A)] \mathbb{1}_{t_{ij}^C \le t_{ij}^P \le t_{ij}^A}$$

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

$$LEZ_{g,g'}^{JOB} = -\sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum (d_j^g - d_j^{g'}) n_i^{g'} s_i^{g'} f(t_{ij}^C) \mathbb{1}_{t_{ij}^C \le min(t_{ij}^P, t_{ij}^A)}$$

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

The two last terms correspond to the possibility of using 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 of commuting by active modes is largely determined by the joint location of homes and workplaces. Therefore, by rearranging these terms, the following final decomposition is obtained:

$$(A_g^{LEZ} - A_g) - (A_{g'}^{LEZ} - A_{g'}) = POLL_{g,g'} + AM_{g,g'} + PT_{g,g'}^{POP} + LEZ_{g,g'}^{POP} + PT_{g,g'}^{JOB} + LEZ_{g,g'}^{JOB} \quad (10)$$

with:

$$AM_{g,g'} = \sum_{\substack{(i\in LEZ,j)\\(i\notin LEZ,j\in LEZ)}}\sum n_i^g d_j^g s_i^{g'} f(t_{ij}^A) \mathbb{1}_{t_{ij}^C \le min(t_{ij}^P, t_{ij}^A)} - n_i^{g'} d_i^{g'} s_i^{g'} f(t_{ij}^A) \mathbb{1}_{t_{ij}^C \le min(t_{ij}^P, t_{ij}^A)}$$

Therefore, from Eq. (10), differences in the LEZ impacts on occupational groups g and g' can be decomposed between 6 drivers:

- the impact of the difference in *polluting vehicles ownership* between occupational categories g and g', $POL_{g,g'}$.
- the impact of the difference, between g and g', in the possibility of using *active transportation modes* to commute from home to jobs (i.e. the proximity between homes and matching jobs), $AM_{g,g'}$.
- the impact of the difference in *public transport availability near homes* of workers of category g and category g', $PT_{g,g'}^{POP}$.
- the impact of the difference between the *shares of workers living in the LEZ* of types g and g', $LEZ_{g,g'}^{POP}$.
- the impact of the difference in *public transports availability near jobs* of types g and g', $PT_{g,g'}^{JOB}$.
- the impact of the difference between the *shares of jobs in the LEZ* of types g and g', $LEZ_{g,g'}^{JOB}$.

These six drivers, as well as the left-hand side of the equation, can be calculated independently, using the data introduced in the previous section.

Focusing on job accessibility, this decomposition of LEZs' impacts does not account for drivers related e.g. to shopping patterns or social networks. Additionally, it does not account for specific working conditions, for instance, the possibility of remote work or night shifts, that might largely impact mobility patterns but for which detailed data were not available consistently for all cities. For the same reasons, it does not account for individual-level characteristics that might impact travel patterns such as disabilities.

6. Results

6.1. Accessibility losses from the LEZ

Fig. 2 shows the accessibility losses resulting from the implementation of LEZs, per city and occupational category, calculated from Eq. (4). For example, in Grenoble, it indicates that the ex-ante impact of the LEZ would be a 5% accessibility loss for CSP1 (farmers) and a 22% accessibility loss for CSP6 (workers).

The magnitude of the impact of LEZs varies across cities, with accessibility losses exceeding 20% for some occupational categories in Grenoble, Montpellier, Rouen, and Strasbourg, while accessibility losses remain small (below 5%) for all occupational categories in Marseille and Nice. This is largely due to differences in the LEZs' perimeters: as shown in Table 1, Marseille and Nice have relatively small LEZs, covering 19.5 km^2 and 2.7 km^2 respectively, while Grenoble, Montpellier,

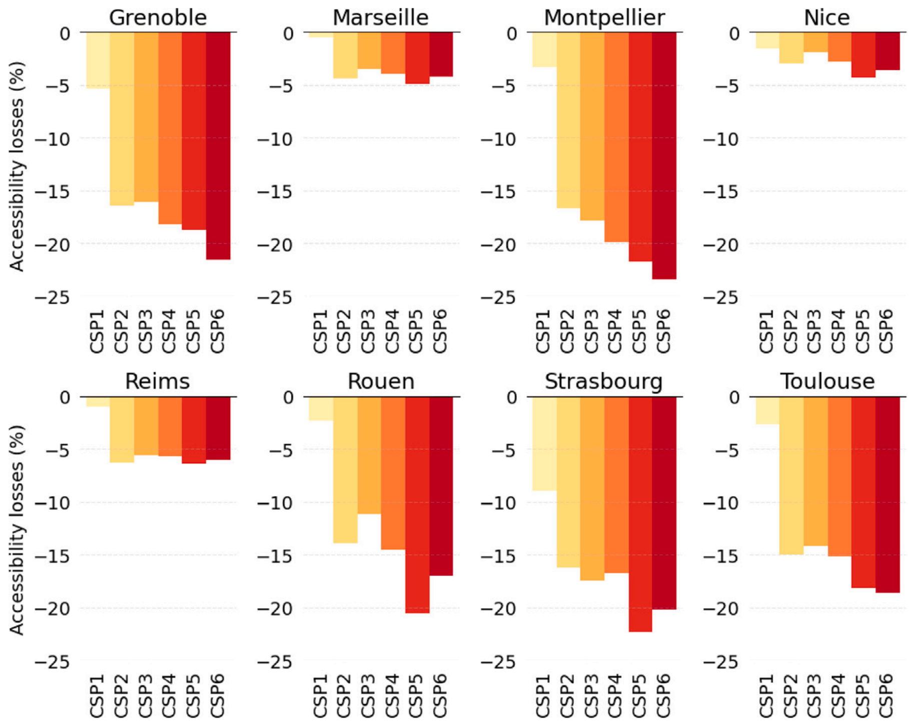

Fig. 2. Accessibility losses from the LEZ, by city and occupational group. *CSP2 and CSP3: high-income workers. CSP4: middle-income workers. CSP5 and CSP6: low-income workers. CSP1: farmers.*

Rouen, and Strasbourg have much larger LEZs, ranging from 86 to 340 km^2.

Based on the average income displayed in Table 3, CSP2 and CSP3 are labeled as high-income workers, CSP4 as medium-income workers, and CSP5 and CSP6 as low-income workers, even though such labeling is only an approximation that does not capture the heterogeneity within occupational groups and should be interpreted with cautious. Working with such categories does not allow computing the standard inequality indices; still, four out of the eight cities considered appear as clearly regressive. In Grenoble, Montpellier, Toulouse, and Rouen, the average accessibility loss of low-income groups (CSP5 and CSP6) is larger than the average accessibility loss of middle-income groups (CSP4), itself larger than the average accessibility loss of high-income groups (CSP2 and CSP3). For two additional cities, Strasbourg and Nice, the average accessibility loss of low-income groups (CSP5 and CSP6) is larger than the average accessibility loss of middle-income and high-income groups, but the ranking between middle-income and high-income groups themselves is unclear. Finally, the ranking of the impact of the LEZs is unclear in Marseille and Reims.

Nevertheless, accessibility losses seem to depend largely on the nature of each occupational category. For instance, accessibility losses are small for CSP1 (farmers). In some cities, the LEZ has a larger impact on CSP5 (sales or service workers), while in others, it has a larger impact on CSP6 (blue-collar workers), even though these two occupational categories share similar characteristics in terms of income (see average incomes and income deciles 1 and 9 in Table 3): this may be due to the distribution of jobs of these two categories (see Table 6 in Section F of Appendix A which shows the share of jobs of each category in the LEZs).

Although the aim of this paper is to present descriptive statistics on the expected average accessibility losses due to the LEZs by occupational category (and on the drivers of such losses) in order to give a synthetic overview of the impact of LEZs that is relevant for policymaking, maps of the changes in accessibility losses can also be found in Section G of Appendix A. For all cities, there is heterogeneity in the impact of LEZs across occupational categories and census units. The most affected are those living at medium distances from the LEZ and far from public transport. Indeed, they had good accessibility to jobs located within the LEZ before the LEZ was introduced; they are affected by the LEZ and cannot switch to public transport. People living within the LEZ are also largely affected, as they cannot commute by polluting cars after the policy is implemented.

6.2. Decomposition of the differences between occupational categories

What drives differences in LEZ impacts across occupational categories? This section decomposes the differences in accessibility losses between occupational categories into different drivers, using Eq. (10).

Specifically, Fig. 3 shows the impact of different drivers on the differences in LEZ impacts between CSP3 (high-income) and CSP6 (blue-collar workers); similar figures for the other occupational categories can be found in Section C of Appendix A. Negative values for a driver mean that it contributes to reducing $(A^{LEZ}_{CSP6} - A_{CSP6}) - (A^{LEZ}_{CSP3} - A_{CSP3})$, i.e. worsening the impact of the LEZ on CSP6 $(A^{LEZ}_{CSP6} - A_{CSP6})$ compared to CSP3 $(A^{LEZ}_{CSP3} - A_{CSP3})$. Fig. 3 shows that in most cities, the distribution of polluting vehicles, opportunities for active transport use, and the availability of public transport worsen the impact of the LEZ on CSP6 compared to CSP3. However, the presence of workers and jobs in the LEZ mitigates the impact of the LEZ on CSP6 compared to CSP3.

Fig. 4 displays the same results for all drivers and occupational categories. In most cities, the first four drivers (ownership of polluting vehicles, use of active transport, and accessibility of home and work by public transport) make the impact of the LEZ worse for low-income workers than for high-income workers. Indeed, low-income workers are more likely to own polluting vehicles than high-income workers (Section B of Appendix A); they also live farther from public transit, and their jobs are farther from public transit. Finally, they do not live near their jobs and therefore cannot use active transportation.

In contrast, the last two drivers – namely, the shares of workers' homes and jobs within the LEZ – tend to mitigate the adverse effects of

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.

the LEZ on low-income workers in comparison to their richer counterparts. Indeed, there are fewer low-income than high-income jobs in the city center, and fewer low-income workers than high-income workers living in city centers.

In terms of magnitude, the two main drivers of the unequal impact of LEZs are the share of jobs in the LEZ and the share of polluting vehicle ownership. In particular, the ownership of polluting vehicles plays a key role in Toulouse, Grenoble, Rouen, Montpellier, and Strasbourg. The share of jobs in the LEZ also plays a key role in most cities, except Nice, where the LEZ is very small, so the impact of this driver is also small and not clearly progressive or regressive.

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 decreases when we get further away from the city center, apart from the inner center where the average income is generally low (Section B of Appendix A). Rouen is an exception, as the shares of workers in the LEZ play a low or even regressive impact.

The three remaining drivers, i.e. job 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. Medium or low-income jobs tend to be less accessible by public transport, except in Nice. Similarly, medium or low-income workers live in places that are less accessible via public transport: although this paper does not investigate 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.

Farmers (CSP1) exhibit different characteristics from other categories; therefore, they are not displayed in Fig. 4 but in Figure 11 in Section C of Appendix A. Farmers tend to have fewer homes and jobs within the LEZ, mitigating the impact of the LEZ on them, but they also have jobs that are way less accessible by public transport than other categories.

6.3. Robustness checks

Several robustness checks complement this analysis. The first is a robustness check for the decay parameter, using decay parameters of 0.015, 0.045, and 0.090, in line with the literature (see Section 4.2). Results can be found in Section D of Appendix A: the qualitative results of the paper remain unchanged. The effects of the LEZs on job accessibility remain regressive for most cities, with accessibility exceeding 20% for some occupational categories in Grenoble, Montpellier, Rouen, and Strasbourg. In most cities, polluting vehicle ownership, active mode use, and home and workplace accessibility by public transport make the impact of the LEZ worst for low-income workers than for high-income workers. In contrast, the last two drivers – namely, the shares of workers' homes and jobs within the LEZ – tend to mitigate the adverse effects of the LEZ on low-income workers in comparison to their richer counterparts.

The second robustness check is for Grenoble. Indeed, Grenoble is one of the cities that grants the most significant exemptions: one of them is the "Workers outside the LEZ" exemption, which benefits individuals residing within the LEZ, working outside of it, and lacking access to public transport for their commute. Results can be found in Section E.2 of Appendix A: accounting for this exemption does not alter the main qualitative findings for Grenoble. The effect of the LEZ remains regressive, and the impacts of the different drivers for each occupational group remain similar with and without the exemption.

In addition, a robustness check is performed by aggregating the results at the "Commune" census unit level instead of the 1 km2 resolution grid (Section D of Appendix A). The effects of LEZs remain largely regressive, but their magnitudes appear to be less important,

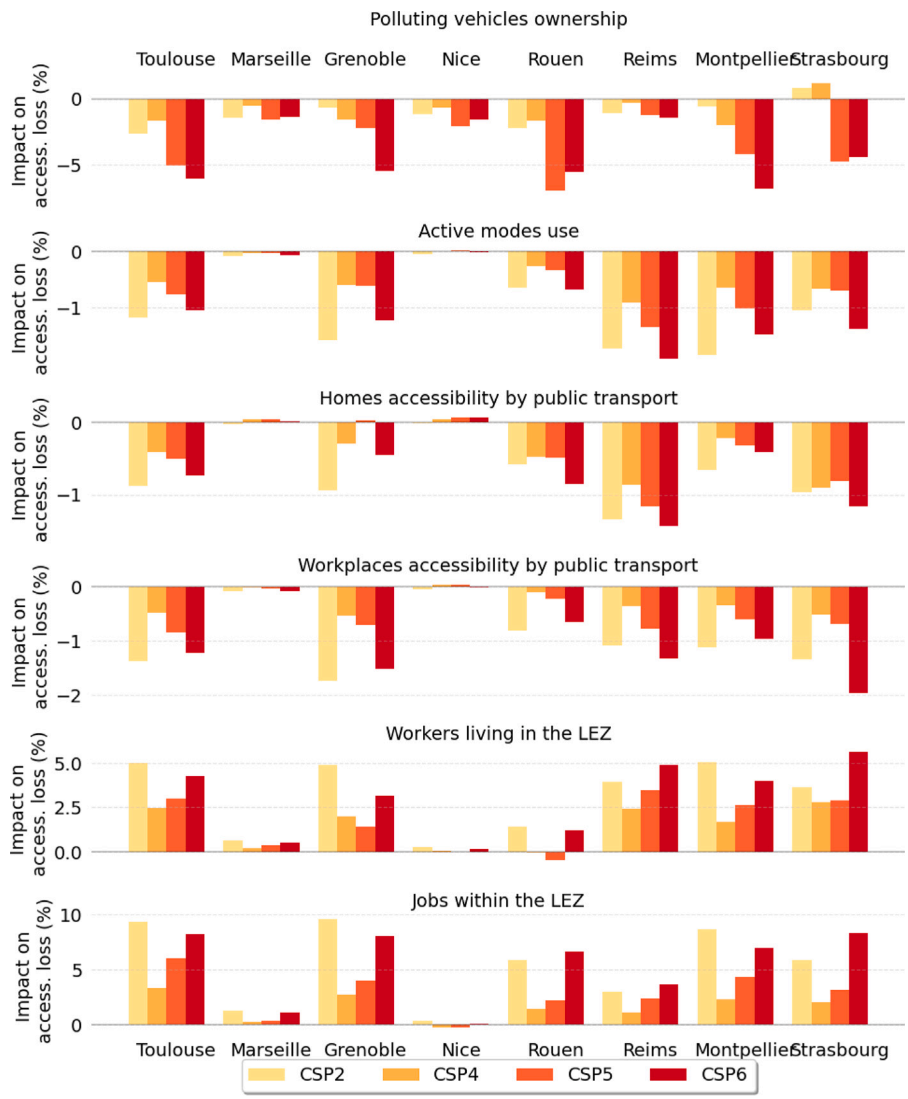

Fig. 4. Impact of different drivers on the accessibility losses of each occupational group, compared with CSP3 (in % of the pre-LEZ accessibility of each occupational group). *CSP2 and CSP3: high-income workers. CSP4: middle-income workers. CSP5 and CSP6: low-income workers. A figure that includes CSP1 can be found in* Section C of Appendix A.

which can be explained by the fact that the coarser spatial resolution does not allow to capture all the regressive effects of LEZs

7. Discussion

Overall, the implementation of LEZs has clear regressive 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 (Chiroleu-Assouline, 2022).

The high ownership of polluting vehicles among low-income households is a crucial factor in the debate on LEZs and inequalities in France (see for instance Laurent (2022)). Does this ownership significantly contribute to the regressive 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 regressive effects of LEZs (Section 6.2, Fig. 4). Conversely, low-income workers and jobs are less frequently located within the LEZ compared to high-income workers and jobs, thereby mitigating the regressive effects of the LEZ (Fig. 4, Section F of Appendix A).

These results shed light on the potential pitfalls of existing public policies aimed at reducing the effects of LEZs on workers' accessibility, particularly in terms of distributional impacts. First, many subsidies available at the national and local levels are designed to encourage the purchase of newer, less polluting vehicles (Jullien, 2023; Weppelhorst et al., 2023). 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, some cities grant exemptions permitting the entry of polluting vehicles into LEZs (ADEME, 2020). 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, ensuring access to public transport and active mobility for all is a way to mitigate the LEZ's regressive impacts. Several cities are already developing public transportation systems and active mobility options in conjunction with implementing LEZs. Montpellier, for instance, plans to progressively introduce free public transport for all metropolitan area residents while simultaneously expanding and enhancing these services (Delevoye et al., 2022). However, low-income households often encounter limited access to public transportation. Therefore, the free public transport policy may have regressive 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 (Viguié et al., 2023). 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 (Hu and Schneider, 2017; Park et al., 2020), 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 the efficiency of public transport. This balance is crucial to ensure equitable outcomes in the impacts of LEZs at all times. In summary, policy instruments already in place may help address the distributional impacts of LEZs; however, their effectiveness in doing so largely hinges on their specific design, which could be enhanced.

8. Conclusion

8.1. Summary of the results

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

Low-income 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-income 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-income workers within LEZs, as well as the fewer instances of low-income 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. However, other factors, such as urban form through the distance between home and work and the use of active transportation, also play a role.

8.2. Limitations and avenues for further research

This article focuses solely on analyzing inequalities between occupational categories due to the unavailability of detailed income data integrated with occupational categories. Still, occupational categories are relevant as they shed light on job competition and are commonly employed in accessibility research (see recent examples by Papaix et al. (2022) or Viguié et al. (2023)). Occupational categories are also relevant as they share common characteristics in terms of political mobilization, as exemplified by the farmers' protests in France in 2024 or by the Yellow Vest protests, mostly led by CSP5 and CSP6 (Les Gilets Jaunes et al., 2019). Occupational categories, also called "socio-professional categories", are extensively used in social science research in France to examine living standards and inequalities, particularly in areas such as education and property (Penissat et al., 2018).

The accessibility measure used in this analysis is simple; further research could replicate this work using more complex accessibility measures that account, for instance, for competition for jobs (Shen, 1998; van Wee et al., 2001; Merlin and Hu, 2017). Further research could also study the sensitivity of the results to alternative spatial accessibility measures, as other types of accessibility measures, including cumulative, gaussian gravity-based, or log–logistic gravity-based, have been shown to be relevant (Kapatsila et al., 2023). Finally, further research could try to account for the monetary cost of travel (van Heerden et al., 2022), time, or chain trip constraints (Jonsson et al., 2014).

This article does not account for detailed worker characteristics, such as disability, or job characteristics, such as the ability to work remotely or night shifts. This could bias the results if, for example, low-income workers are more likely to work night shifts and therefore not be able to use public transport. This also biases the results because special exemptions are not accounted for, and therefore accessibility losses are overstated. Further research could refine this analysis with more detailed data on workers and jobs, and combine this with data on specific LEZ designs and exemptions.

In this research, changes in congestion and changes in transport times for trips that start and end out of the LEZ, but cross the LEZ and therefore may have to make a diversion, have not been taken into account, leading to an underestimation of the accessibility losses from the LEZ, in particular for low-income groups that are more likely to live and work out of the LEZ. Further research could use better transport data, for instance by systematically gathering private car transport times for all grid cells, and better transport models, allowing to account for congestion and changes in transport times because of the LEZ. Additionally, supplementary modes like cycling could be integrated into the analysis.

This analysis is a static, ex-ante analysis. It does not aim to predict the impact of the LEZs, but only to explain why, in the current condition of the city, the LEZ has a different impact on different occupational groups. In the medium and long run, we can expect changes in populations and job distributions or vehicle ownership 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. Finally, the LEZ might also change the number of jobs per occupational category; evidence on the impact of LEZs on the composition of employment remains limited, but studies on car use restrictions suggest that they have a limited impact on the accessibility of shops and restaurants (Szarata et al., 2017) and that shop owners largely value being located in a pedestrian zone (Tinessa et al., 2021). Further analyses could empirically assess the impacts of existing LEZs on employment, incomes, or transportation times, and costs.

The sample of cities analyzed is limited, comprising 8 French mid-size cities. Still, even though the results might not be directly generalizable to other cities, the methodology presented herein offers a replicable framework for conducting similar analyses in diverse contexts and facilitating inter-city comparisons.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.tranpol.2024.10.029.

Data availability

Data will be made available on request.

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