Impact of Low Emission Zones on Spatial and Economic Inequalities using a Dynamic Transport Simulator

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Abstract

Low Emission Zones (LEZs) are widely implemented in European cities to improve air quality by restricting access for the most polluting vehicles. However, their effects on air quality, travel behavior, road congestion, and social inequalities often remain difficult to predict due to the interdependence of travelers' decisions. This paper evaluates the LEZ implemented in the Greater Paris area using METROPOLIS2, a dynamic agent-based transport simulator. METROPOLIS2 models equilibrium travel decisions – mode, departure time and route choice – across large-scale road networks for millions of agents.

Our analysis quantifies the LEZ's impact on travel surplus and pollution exposure for individuals both inside and outside the zone. The findings suggest that while the LEZ significantly improves air quality and reduces CO_2 emissions, it also creates disparities: a small segment of the population bears most of the travel costs, while others benefit greatly from reduced congestion. Those most penalized are owners of banned cars living within the LEZ, particularly in areas with poor public-transit access, while owners of authorized cars in heavily congested areas see the greatest benefits. The negative impacts of the LEZ can be mitigated by offering affordable electric vehicle rentals the owners of non-compliant vehicles.

This study provides important insights into the wider effects of LEZs on urban mobility and offers a robust framework for evaluating transportation policies.

Keywords: transport simulation; low emission zone; road traffic emissions; air quality; policy evaluation; equity.

JEL Codes: C63; Q53; R4

1 Introduction

The transport sector remains one of the largest contributors to both global greenhouse-gas (GHG) emissions and local air pollution. According to the European Environment Agency (EEA): "The transport sector is the largest source of greenhouse gas emissions in the European Union and has shown little progress in emission reduction in recent decades. Despite efforts such as increasing the deployment of electric vehicles and promoting low-carbon fuels, transport emissions have only declined slightly since 2005, with a temporary reduction in 2020 due to COVID-19."

Addressing climate change is particularly challenging because transport emissions are structurally embedded in daily mobility patterns and economic organization (see e.g., Ben-Akiva et al. 2026; de Palma et al. 2025). Globally, transport accounts for roughly 15 % of total GHG emissions (Bashmakov et al., 2022). In the European Union, road transport alone represents around 73 % of all transport GHG emissions (EEA, 2025).[1]

At the local scale, an estimated 40 400 premature deaths in 2019 were attributed to chronic exposure to nitrogen dioxide in Europe (EEA, 2021).[2] Road transport alone accounts for 37 % of nitrogen oxides emissions (EEA, 2022),[3], underscoring the urgent need for targeted interventions to improve urban air quality and public health.

Cities have explored a variety of strategies to address this challenge, including expanding public-transit networks (see e.g., Tan et al. 2024), promoting active mobility (see e.g., Srivastava et al. 2025), and incentivizing the adoption of electric vehicles (see e.g., Kühlert et al. 2025). While these measures contribute to reducing pollution, their effectiveness often depends on local context, infrastructure, and public acceptance.

In this landscape of policy options, Low Emission Zones (LEZs) have emerged as a particularly effective tool. A LEZ is a designated area, mainly in or around a city center, where the most polluting vehicles are restricted from entry. By directly targeting high-emission road transport, LEZs aim to mitigate both the global climate impacts and the severe local health burdens associated with urban air pollution.

Initially implemented in Northern Europe in the late 1990s, LEZs now operate in several hundred European cities (e.g., London, Madrid, Amsterdam) and have been adopted in other world regions, including China and Indonesia. They have been shown to reduce ambient concentrations of particulate matter (PM_{10}, $PM_{2.5}$) and nitrogen oxides (NO_x), while

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[1] Source: `https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-transport` [accessed 2025/11/18]

[2] Source: `https://www.eea.europa.eu/publications/air-quality-in-europe-2021/health-impacts-of-air-pollution` [accessed 2025/09/22]

[3] Source: `https://www.eea.europa.eu/publications/air-quality-in-europe-2022/sources-and-emissions-of-air` [accessed 2025/09/22]

accelerating fleet renewal and supporting the uptake of electric and hybrid vehicles (Holman et al., 2015; Ellison et al., 2013).

However, empirical studies highlight distributional concerns, particularly for low-income and suburban households less able to switch vehicles or access robust public-transport alternatives (Tarriño-Ortiz et al., 2021; Player et al., 2023), suggesting that LEZ effectiveness depends on complementary policies such as targeted subsidies, scrappage schemes, and improvements in multimodal accessibility (Nieuwenhuijsen et al., 2024).

The immediate effect of a LEZ is that individuals with restricted vehicles may choose to reroute around the zone, switch to another mode of transportation, or buy a new vehicle. This can reduce road congestion and emissions within the LEZ, but it could also increase congestion and pollution outside the zone if some drivers take long detours. Furthermore, some individuals with authorized vehicles may switch from public transit to driving, taking advantage of reduced congestion inside the LEZ – a phenomenon known as "rebound effect".

Individual travel decisions – such as route choice, departure time, transportation mode, and vehicle ownership – are influenced by a complex interplay of factors, including time-dependent road congestion, scheduling constraints and the value of time. These factors are further complicated by the interdependence of individuals' travel decisions, which affect one another through transportation networks. As a result, estimating the impact of LEZs at both global and individual levels requires detailed transport simulations.

In this study, we use METROPOLIS2, a dynamic agent-based transport simulator developed by Javaudin and de Palma (2024), based on the original METROPOLIS simulator (de Palma et al., 1997). METROPOLIS2 simulates the equilibrium arising from the travel decisions of millions of individuals (referred to as *agents*) on large-scale road networks composed of up to hundreds of thousands of road segments. As an agent-based model, METROPOLIS2 provides detailed results into how each agent react to the LEZ policy (e.g., switching mode or route) and how they are affected (e.g., changes in travel surplus). METROPOLIS2 may also be coupled with METRO-TRACE (Le Frioux et al., 2024) to analyze the emissions of global and local air pollutants generated by road traffic and the exposure of the population to these pollutants, making it suitable for evaluating LEZs.

In this study, we evaluate the LEZ implemented in the Greater Paris area since 2018 and expanded in January 2025. This LEZ is substantial, covering 367 km^2, encompassing approximately 5 million inhabitants, and affecting 19.7 % of the region's predicted vehicle fleet for 2025. The policy is the subject of intense political debates.[4]

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[4] See e.g.`https://www.assemblee-nationale.fr/dyn/media/16/organes/commissions-permanentes-legislatives/developpement-durable/communication-miflash-zfem` [in French, accessed 2024/10/11] or `https://lcp.fr/actualites/zfe-la-suppression-des-zones-a-faibles-emissions-votee-en-commission-a-l-assemblee` [in French, accessed 2025/09/22].

To evaluate the LEZ's impact, we compare a calibrated baseline simulation (without the LEZ) to a counterfactual simulation (with the LEZ in its 2025 version). In both the baseline and LEZ simulations, five modes of transportation are considered: car driver, car passenger, public transit, bicycle and walking. We adopt a short-term perspective, assuming fixed household locations, activity locations, and vehicle ownership. In practice, the policy could lead to longer-term behavior changes, such as households relocating closer to transit hubs or purchasing authorized vehicles.

The aggregate results from the METROPOLIS2 simulations suggest that the LEZ will decrease the mode share of car trips by 1.9 percentage point (p.p.) – from 36.6 % to 34.7 % – reducing total vehicle-kilometers by 3.9 %. Pollution analysis indicates larger reductions in emissions: $-4.5\,\%$ for CO_2, $-9.2\,\%$ for NO_x, and $-7.6\,\%$ for $PM_{2.5}$, demonstrating the policy's effectiveness in targeting the most polluting vehicles. Additionally, the number of premature deaths due to NO_2 and $PM_{2.5}$ exposure is expected to decrease by 9.9 % and 13.0 %, respectively, due to the greatest air quality improvements occurring inside the LEZ, where population density is higher.

At the individual level, the health benefits of the LEZ are distributed relatively equitably, with changes in individual health exposure ranging from 0.00 € to +0.35 € daily. However, the distribution of travel surplus changes shows greater disparities, with 3.3 % of the population losing more than 1 € daily, while 1.2 % gain more than 1 €. These disparities may explain the LEZ's low public acceptance.

Further analysis reveals that the LEZ disproportionately impacts owners of banned vehicles living within the LEZ, who face longer travel times when switching to alternative modes. Conversely, the biggest beneficiaries are authorized vehicle owners living outside the LEZ and traveling in highly congested areas who gain from reduced congestion. However, no clear pattern emerges regarding the policy's effect on economic inequalities, as both winners and losers are spread across high- and low-income municipalities.

To assess the potential for adaptive responses, we extend the model to include an affordable electric vehicle (EV) rental program for owners of older, banned vehicles. This extension demonstrates that enabling flexible car-ownership choices can significantly mitigate the negative impacts of the LEZ. By providing access to EVs, the program not only reduces air pollution further but also increases average travel surplus, offering a practical way to improve social acceptability of the policy.

The paper is organized as follows. Section 2 provides a brief literature review. Section 3 describes the theoretical framework used to model travel decisions (demand side) and road congestion (supply side). Section 4 outlines the data sources and the preprocessing steps. Section 5 discusses the Paris LEZ policy. Section 6 presents the simulation results and analyzes the LEZ's impact. Finally, Section 7 summarizes the findings and suggests extensions for future research.

2 Literature Review

Evaluation of Low Emission Zones

Low Emission Zones have proved successful worldwide by cutting urban air pollution, accelerating fleet renewal, and improving public health in major cities (Delgado-Lindeman et al., 2025).

The environmental benefits of LEZs are well-documented. Chamberlain et al. (2023) conducted a systematic review of empirical studies, concluding that LEZs generally reduce air pollution and improve public health. Similarly, Holman et al. (2015) found that LEZs in Germany led to significant reductions in pollution. However, they note that isolating the effect of LEZs from other policies or from the natural renewal of the vehicle fleet can be challenging. This emphasizes the need for sophisticated tools, such as transport simulators, to assess LEZ impacts accurately.

In terms of costs – drivers having to adapt to the restrictions –, Börjesson et al. (2021) analyze the impact of Stockholm's LEZ using two methodologies: (i) measuring user cost increases related to the observed reduction in traffic volumes, and (ii) estimating driver losses based on price changes in the used car market. Their findings suggest that the costs of implementing Stockholm's LEZ outweigh its benefits, underlining the importance of a thorough cost-effectiveness evaluation when designing LEZ policies.

A central issue in LEZ design is the need to balance local and broader societal interests. De Borger and Proost (2013) develop an analytical model that compares the implementation of LEZs and other traffic policies by local versus federal governments. Their analysis shows that local governments, focusing primarily on the welfare of residents, tend to impose more stringent emission standards compared to federal governments, which must consider the welfare of non-resident commuters.

Evaluation of Paris' Low Emission Zone

Regarding the case of Paris, Poulhès and Proulhac (2021) propose a methodology to assess the health benefits of the LEZ at an individual level. By combining pollutant concentration data, a household travel survey, and a road traffic model, they estimate population exposure to pollution. While we adopt a similar approach to compute pollution exposure – by considering the spatial and temporal location of individuals over the course of a day – their methodology is limited to an *a priori* evaluation. This is because they rely on observed pollutant concentrations before and after the policy's implementation. In contrast, we employ an *ex-ante* approach, simulating the impact of the LEZ policy on trips, pollutant emissions, and concentrations, prior to its implementation.

Host et al. (2020) provide an *ex-ante* evaluation of Paris' LEZ using a complete chain of model to estimate pollutant emissions and population exposure, similar to the METRO-TRACE framework we employ (Le Frioux et al., 2024). However, unlike our work, which simulates how agents adapt their routes, departure times, and modes in response to the LEZ, their analysis relies on predefined assumptions about the share of agents who would switch to a newer vehicles, modify their itineraries, or shift to public transit.

Other Transport Policies Evaluated for Paris

Yin et al. (2024) present a socioeconomic evaluation of Paris' driving restriction zone using the MATSim transport simulator (for a comparison between METROPOLIS2 and MATSim, see Javaudin and de Palma, 2024). Their study evaluates a driving restriction that applies to all vehicles equally, unlike the LEZs, which target only the most polluting vehicles. They explore changes in traffic behaviors, including rerouting and mode shifts, and analyze emission variations inside and outside the restricted zone, with a particular focus on intermodality. While both policies share similarities, LEZs typically target only the most polluting vehicles and cover larger areas. Our study extends their work by considering vehicle heterogeneity, in terms of age and fuel type, which can have a significant impact on emissions. Additionally, we perform a more granular analysis at the agent level, evaluating individual travel surplus and pollution exposure.

Other recent evaluations of transport policies in Paris metropolitan area have been presented by Durrmeyer and Martinez (2022) and Bou Sleiman (2023). Durrmeyer and Martinez (2022) assess the impact of driving restrictions – banning a fraction of cars randomly – and road tolls using a structural model. This model allows them to compute the welfare consequences of the policy, including the impact on inequalities. Although this approach is more tractable than agent-based simulations, it simplifies the spatial analysis by dividing the region into only five zones and assuming homogeneous congestion within each zone. In contrast, transport simulators like METROPOLIS2, though computationally complex, allow for detailed simulations of traffic dynamics across extensive road networks, providing richer insights into traffic assignment and equilibrium.

Bou Sleiman (2023) take an ex-post approach, using a difference-in-difference methodology to evaluate the impact of a road closure in Paris. While this technique efficiently isolates policy effects, it is limited to post-implementation analysis, whereas this study focuses on an ex-ante assessment of the LEZ policy.

Although the environmental benefits of LEZs are well-established, their broader impacts on road traffic, and spatial and socioeconomic inequalities require further investigations. By using agent-based simulations, and employing advanced modeling techniques, this study contributes to a more comprehensive evaluation of LEZ policies, shedding light on both their effectiveness and equity implications.

3 Definitions and Theoretical Foundations

The transport simulator METROPOLIS2 (Javaudin and de Palma, 2024) is a dynamic mesoscopic agent-based model designed to compute a Nash equilibrium of the interaction between supply (network infrastructure) and demand (agents traveling). While METROPOLIS2 is highly flexible, this paper focuses on a specific model specification described below.

3.1 Demand Side

The demand side of the model is characterized by a population of agents, indexed by n, who travel between various activities. These agents and their activities (including the activities' locations) are generated to be representative of an average weekday (see Section 4.2).

The activity purposes considered are *home*, *work*, *education*, *leisure*, *shopping* and *other*. All agents begin and end the day at home, with an arbitrary number of activities to be completed outside of home during the day. The location and duration of all outside activities are treated as exogenous.

To travel between activities, agents perform *trips*. Let $\mathcal{K} = \{1, \ldots, k, \ldots, K_n\}$ denote the set of trips performed by an agent to complete all their activities, where K_n is the number of trips.

An agent's trips are partitioned into one or more *tours*. Formally, $\mathcal{K}_q \subseteq \mathcal{K}$ denotes the set of trips for tour q, with $\cap_q \mathcal{K}_q = \mathcal{K}$. A tour q is defined as a sequence of successive trips where the purpose of the activity at the origin of the first trip and at the destination of the last trip is always *home*, with no *home* activity in between. Figure 1 illustrates an example agent with two tours. As shown in the figure, all activities have fixed duration, except for *home* activities, which serve as the default.

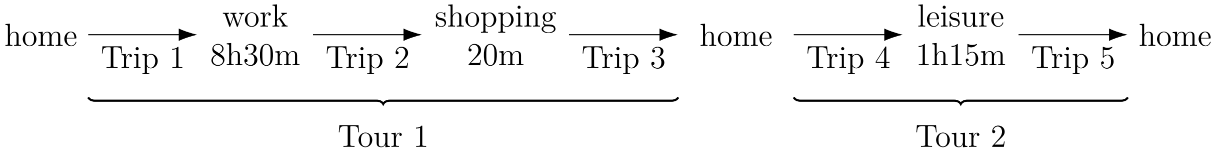

Figure 1: Example activity pattern of an agent with two tours

For each tour, the agent selects a transport mode and the departure time of the first trip, maximizing their utility. The utility of a tour is defined as the sum of utilities of its trips, where the utility of trip k with mode j, departure time t^{d} and arrival time t^{a} is given by (the agent index is omitted for readability)

$$V_{k|j}(t^{\mathrm{d}}, t^{\mathrm{a}}) = c_j - m_{k|j} \underbrace{-\alpha_j \cdot [t^{\mathrm{a}} - t^{\mathrm{d}}]}_{\text{travel utility}} \underbrace{-\beta_k [t_k^* - t^{\mathrm{a}}]_+ - \gamma_k [t^{\mathrm{a}} - t_k^*]_+}_{\text{schedule-delay utility}}, \tag{1}$$

where c_j is the mode-specific utility constant, $m_{k|j}$ are the monetary costs (fuel cost for car trips), α_j is the value of time, β_k is the penalty for early departure, γ_k is the penalty for late departure, t_k^* is the desired start time of the activity at destination of trip k – or equivalently, the desired arrival time at destination for trip k –, and $[x]_+ = \max(x, 0)$. The value of time depends on the selected mode, while the schedule-delay penalties depend on the purpose of the activity. These preference parameters are agent-specific. The activities' desired start times, t_k^*, are determined when generating the synthetic population (see Section 4.2). The utility function (1) is derived from the alpha-beta-gamma model (Vickrey, 1969; Arnott et al., 1990).

For a given tour q, with mode j and departure time for the first trip t, the departure times $(t_k^{\mathrm{d}})_k$ and arrival times $(t_k^{\mathrm{a}})_k$ for all tour trips $k \in \mathcal{K}_q$ can be inferred from the mode-specific travel-time function of each trip. The deterministic utility of tour q when selecting mode j and departure time t is given by the sum of the trips' utilities:

$$V_{q|j}(t) = \sum_{k \in \mathcal{K}_q} V_{k|j}(t_k^{\mathrm{d}}, t_k^{\mathrm{a}}). \tag{2}$$

Agents are assumed to choose their mode first and then their departure time. They can choose from five transport modes: car as a driver, car as a passenger, public transit, bicycle and walking.[5] All trips in a tour must be completed using the same mode but different tours can involve different modes for the same agent. The mode choice follows a Multinomial Logit model and the departure-time choice follows a Continuous Logit model (Ben-Akiva and Watanatada, 1981).

For each tour, the agent selects the departure time t for the first trip by maximizing their utility $V_{q|j}(t) + \varepsilon_q(t)$, where the deterministic utility $V_{q|j}(t)$ is given by Equation (2) and $\varepsilon_q(t)$ is an idiosyncratic random component. With the Continuous Logit formula, the probability

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[5] These five modes encompass more than 98 % of trips made in the study area.

that departure time t is chosen for tour q, given that mode j is selected, is

$$p^{\mathrm{d}}_{q|j}(t) = \frac{e^{V_{q|j}(t)/\mu_1}}{\displaystyle\int_{t^0}^{t^1} e^{V_{q|j}(\tau)/\mu_1}\,\mathrm{d}\,\tau},$$

where μ_1 is the scale parameter of the Continuous Logit model and $[t^0, t^1]$ is the feasible departure-time period. The expected utility that the agent derives from the departure-time choice is given by the "logsum" formula:

$$V_{q|j} = \mu_1 \ln \int_{t^0}^{t^1} e^{V_{q|j}(t)/\mu_1}\,\mathrm{d}\,t + \mu_1 \cdot \gamma, \tag{3}$$

where γ is Euler-Marscheroni constant.

The agent then selects the mode j that maximizes $V_{q|j} + \varepsilon_{q,j}$ where $V_{q|j}$ is the deterministic utility of choosing mode j, defined by Equation (3), and $\varepsilon_{q,j}$ is an idiosyncratic random component with Gumbel distribution of scale μ_2. The probability to choose mode j for tour q is then given by the Multinomial Logit formula:

$$p_{q|j} = \frac{e^{V_{q|j}/\mu_2}}{\displaystyle\sum_{j'} e^{V_{q|j'}/\mu_2}}.$$

Given the mode and departure time selected, agents choose the fastest route connecting origin to destination for all their trips.

For each tour performed, the agent obtains a *travel surplus*, $\bar{V}_q$, defined as the expected utility that they will get from the combined mode and departure-time choice. It is defined as the "logsum" of the upper-level decision (the mode choice):

$$\bar{V}_q = \mu_2 \ln \sum_j e^{V_{q|j}/\mu_2} + \mu_2 \cdot \gamma, \tag{4}$$

where γ is Euler-Marscheroni constant. The travel surplus of the agent is defined as the sum of the travel surplus for all their tours.

In addition to the trips performed by agents, truck trips are also simulated. For these trips, mode choice is irrelevant and the departure times are exogenously determined, making route choice the only decision. The primary reason for including truck trips in the simulation is to account for the road congestion they generate, and the impact it has on car trips.

3.2 Supply Side

Car and truck trips take place on a road network, represented as a directed graph of nodes (intersections) and edges (road segments).

Road congestion occurs in two ways. First, road-level *bottlenecks* limit vehicle entry and exit flows based on a predefined road-level capacity. If two vehicles arrive within a time interval shorter than allowed by the capacity, the second vehicle is delayed at the bottleneck. If a vehicle arrives and there is already a queue, it must wait at the end of the queue. Capacity is measured in passenger car equivalent (PCE), where we assume, following the *Highway Capacity Manual* (2016), that cars are equal to 1 PCE and trucks are equal to 2 PCE.

Second, the number of vehicles on a road segment is limited by the segment's total length (actual length multiplied by the number of lanes). If a vehicle reaches a full road, it must wait on its current road segment until space becomes available. This phenomenon is known as *spillback*. The length a vehicle occupies while on a road segment is assumed to be 8 m for cars and 16 m for trucks.

Additionally, speed is limited to 90 km/h for trucks in the simulations.

For public transit, bicycle, and walking, travel times are assumed to be constant, independent of departure time or traffic congestion. Details on how travel times are computed for these modes can be found in Section 4.3.

4 Data Input

This section outlines the data collection and preprocessing steps necessary to generate the inputs for the simulation. The preprocessing tasks are divided into three categories: (i) generating the supply side (road and public-transit networks), (ii) generating the demand side (synthetic population), and (iii) additional mode-specific processing. The study area for the simulation is Île-de-France, a $12\,011\,\mathrm{km}^2$ administrative region centered on Paris.

4.1 Supply Side

We use OpenStreetMap (OSM) data to generate the road network (used by cars and trucks) and the walking network (used by pedestrian and bicycles). The data is obtained from Geofabrik for the Île-de-France region, using a snapshot of January 1st, 2024. Various preprocessing steps are undertaken to refine the data. For instance, bus-only roads are excluded from the road network, and bidirectional roads are represented as two directed edges. The final output consists in two directed graphs representing the road and walking networks.

For the road network, edge-level data includes length, speed limit, number of lanes and additional attributes used for calibration, such as indicators for urban area and the presence of traffic lights. The imported road network includes 294 706 nodes and 610 629 edges, for a total of 72 962 kilometers. A chunk of the road network is shown in Figure 2, illustrating the various road types.

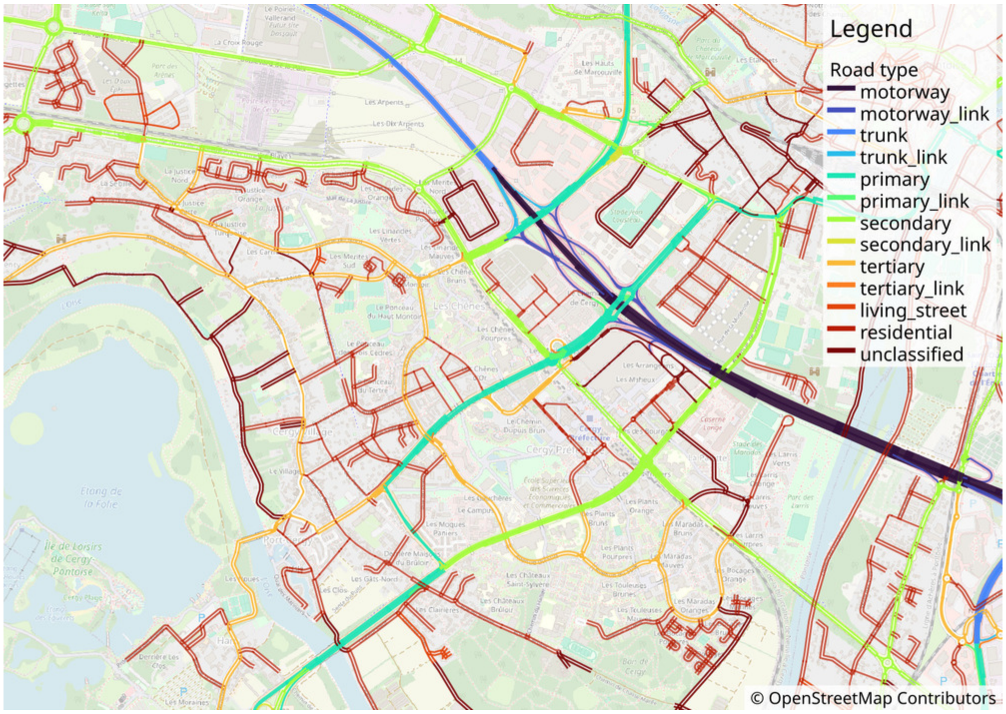

Figure 2: Road segments imported from OpenStreetMap, near Cergy

The walking network stores only the length of the edges. It includes 1 003 920 nodes and 2 704 016 edges, for a total of 189 803 kilometers.

Public-transit trip data is provided by *Île-de-France Mobilités* and based on the General Transit Feed Specification (GTFS), which includes schedules for all public-transit lines in the region. Additionally, OSM data is used for the walking legs of the trips.

4.2 Demand Side

The demand side of our simulation relies on a synthetic population: a statistically representative population of households, individuals, and their daily trips in Île-de-France. This population is generated using the methodology of Hörl and Balac (2021), which integrates open datasets such as census data, the 2010 Enquête Globale Transport regional travel survey, and information on buildings and firms. We extend this approach in two key ways: first, by assigning vehicle characteristics (fuel type and age) to each household's cars using a Markov Chain model applied to French Ministry of Ecology data, allowing us to estimate fuel consumption, emissions, and LEZ eligibility; and second, by simulating desired start times and durations for all activities, drawing on regional travel survey data and accounting for socio-professional and geographic differences.

Ultimately, the synthetic population data includes a list of *households*, with their car characteristics and income; a list of *persons*, including their household affiliations and socio-demographic attributes (e.g., age, gender, socio-professional category); and a list of *trips / activities* for each person, including activities' desired start times and duration, as well as their purpose and precise coordinates.

To reduce simulation runtime, the synthetic population is generated to represent 20 % of the total population of Île-de-France. During calibration, road capacities are adjusted to ensure that the road congestion observed with the 20 % synthetic population replicates the congestion of the full population. Aggregate results are subsequently scaled up to represent 100 % of the population, meaning that vehicle-kilometers traveled, for example, are multiplied by five.

The resulting synthetic population consists of 1 095 819 households, 2 451 841 persons and 8 774 929 trips.

The truck trips are generated based on an origin-destination matrix provided by DRIEAT, the regional public authority responsible for transport (DRIEAT Île-de-France, 2021). The trips' origin and destination zones are mapped to actual road intersections in order to spread the departure and arrival points over the zones. A total of 599 669 truck trips are simulated.

4.3 Mode-specific Processing

The simulation considers five transport modes: car driver, car passenger, public transit, bicycle and walking. For car drivers and passengers, travel times are computed dynamically within the simulation based on traffic conditions at the time of departure. For all other modes, travel times are assumed to be constant, independent of departure time or traffic congestion.

Car driver and Car passenger The car driver and car passenger modes are available only to agents whose households own at least one car. Additionally, only agents with a driving license can select the car driver alternative. However, the model does not enforce the constraint that each car in the household can only be used simultaneously by a single agent. Furthermore, any agent can choose the car passenger alternative even if no other agent in the household – or even in the entire simulation – is making the same trip as a car driver. These limitations could be addressed in future research.

Fuel consumption for car trips is calculated based on the fastest route under free-flow conditions, using the EMISENS model (Ho et al., 2014). The value appears as a factor in the trip utility function (1). Computing fuel consumption based on the actual route taken would require running the EMISENS model at each iteration of the simulator, considerably increasing computation time. However, an *a priori* analysis reveals a strong correlation (99 %) between fuel consumption under free-flow conditions and actual fuel consumption, justifying the use of free-flow estimates in the simulation.

While both car drivers and passengers are impacted by road congestion, only car drivers contribute to the generation of congestion in the simulator.

Public Transit For public-transit, travel time is determined by the least-cost itinerary among all itineraries arriving within 30 minutes of the desired arrival time. Public-transit itineraries are computed using the open-source software OpenTripPlanner. The cost of an itinerary accounts for the in-vehicle time, walking time and waiting time. The public-transit alternative is not available at the tour level if one of the trips is not feasible (e.g., when the origin is too far away from a bus stop or train station). Moreover, the public-transit alternative is omitted from the choice set of the agent if it is faster to walk than to take public transit for all trips of a tour.

Public-transit pricing is not modeled in this paper and thus is captured by the public-transit utility constant.

The current model does not account for crowding in public transit, meaning that agents do not face additional costs when boarding crowded vehicles, and that vehicles can exceed their capacity. This limitation may introduce a bias towards public transit in the simulation, as crowding is a major issue in the Paris area (e.g., Haywood and Koning 2015). However, this bias is likely limited, as the results show a small increase of public-transit use, especially on the most congestion lines (e.g., only a 1.2 % rise in passenger-kilometers on the main transit line, RER A). In a future version of METROPOLIS2, public-transit vehicles could be modeled explicitly which would allow for more detailed considerations of waiting time, number of transfers, in-vehicle congestion and reliability.

Bicycle and Walking For both bicycle and walking trips, travel time is assumed to be proportional to the distance of the shortest path on the walking network. Similarly to the car modes, the origin and destination coordinates are mapped to the nearest segment of the walking network to compute the shortest path. Average speeds are assumed to be 10 km/h for bicycles and 4 km/h for walking. These two modes are always included in the choice set of the agents (bicycle ownership is not explicitly modeled).

5 Low Emission Zone Policy

The methodology outlined so far allows us to build and calibrate[6] a baseline simulation for the Île-de-France region, replicating a typical working day under current conditions. This baseline can then be compared to counterfactual simulations to evaluate the impact of specific policies or exogenous shocks. In this paper, we evaluate the Low Emission Zone (LEZ) policy being implemented in the Greater Paris area.

The Paris LEZ restricts entry for the most polluting vehicles in an area covering Paris and 76 surrounding municipalities. As shown on Figure 3, the LEZ is bordered by the A86 highway, providing an alternative route around the zone. The LEZ covers an area of 367 km^2, which accounts for only 3.04 % of the Île-de-France region. However, approximately 40 % of the population resides within the LEZ, and 49 % of all trips either originate or terminate inside the LEZ. Additionally, roads within the LEZ represent 9 % of the total road network of Île-de-France.

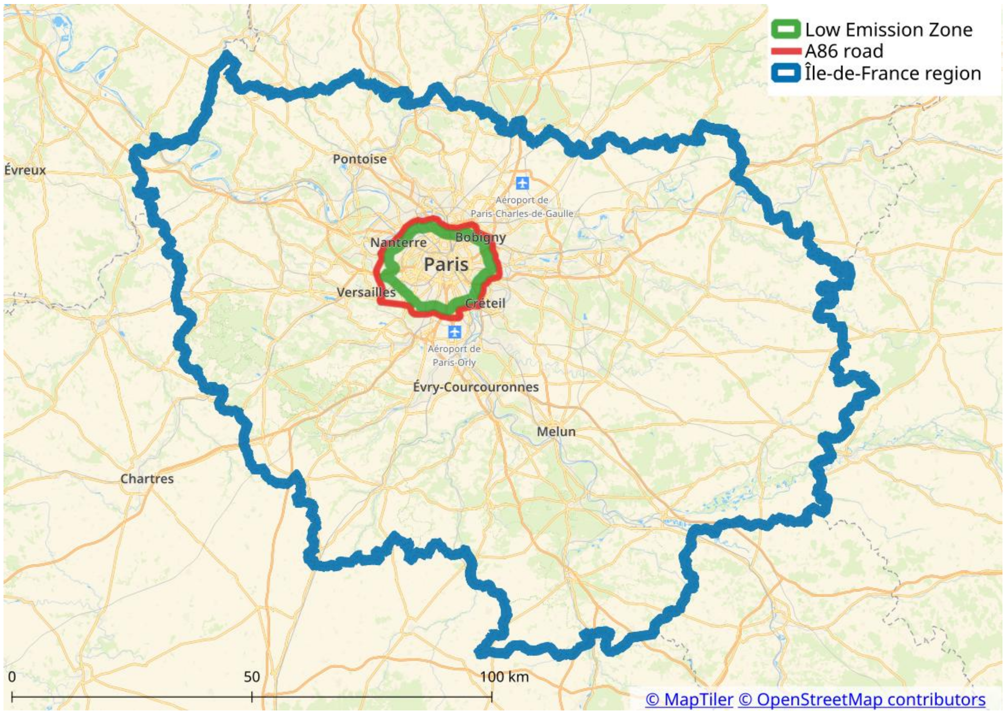

Figure 3: Area of the Low Emission Zone within Île-de-France

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[6] See Javaudin (2024, Chapter 3) for more details on the calibration process.

5.1 Crit'Air Classification System

Entry restrictions for the LEZ are based on the *Crit'Air* classification system, which categorizes vehicles into six groups depending on engine type (electric, hydrogen, petrol or diesel) and European emission standards. Figure 4 shows the evolution of Crit'Air shares within the Île-de-France vehicle fleet between 2011 and 2025, with the last three years being interpolated.

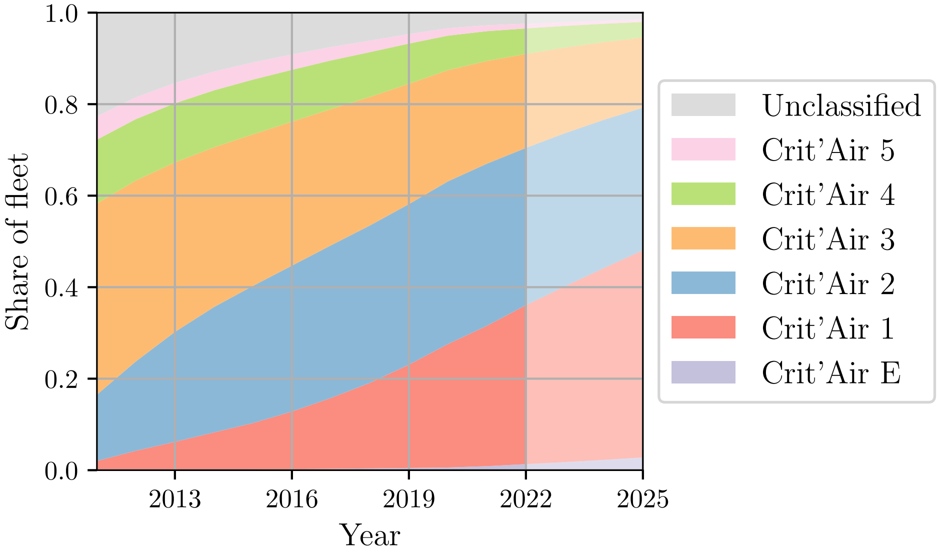

Figure 4: Evolution of Crit'Air category shares in the Île-de-France vehicle fleet
Note. Values after 2022 are interpolated using a basic Markov Chain model based on the preceding three years.
Source: French Ministry of Ecology.

As of June 2021, vehicles in the lowest two Crit'Air categories (4 and 5) as well as unclassified vehicles are banned from entering the LEZ. These vehicles represent 5.4 % of the 2025 Île-de-France vehicle fleet (interpolated). In January 2025, the ban will be extended to Crit'Air 3 vehicles, raising the total share of banned vehicles to 20.8 %. Table 1 summarizes the Crit'Air categories, their fleet shares and the dates of the corresponding bans.

Figure 5 shows the spatial distribution of banned vehicle shares for the January 2025 policy. The highest shares of banned vehicles are found in municipalities outside the LEZ, especially in the north of Paris, while the lowest shares are in municipalities in the west and southwest of Paris – inside and outside the LEZ. Interestingly, these shares are negatively correlated with the municipality's income level, with a Pearson correlation coefficient of −29.7 %.

Table 1: Crit'Air categories

Category	Vehicles	Share	Cum. share	Ban date
Unclassified	N/A	1.4 %	1.4 %	July 2019
Crit'Air 5	Diesel cars registered before 2000	0.6 %	2.0 %	July 2019
Crit'Air 4	Diesel cars registered between 2001 and 2005	3.4 %	5.4 %	June 2021
Crit'Air 3	Petrol cars registered before 2005 or diesel cars registered between 2006 and 2010	15.3 %	20.8 %	January 2025
Crit'Air 2	Petrol cars registered between 2006 and 2010 or diesel cars registered after 2011	31.2 %	51.9 %	N/A
Crit'Air 1	Rechargeable gas and hybrid vehicles or petrol cars registered after 2011	45.3 %	97.2 %	N/A
Crit'Air E	Electric and hydrogen	2.8 %	100.0 %	N/A

Note. Shares and cumulative shares are computed from the interpolated 2025 Île-de-France vehicle fleet, using data from the French Ministry of Ecology.

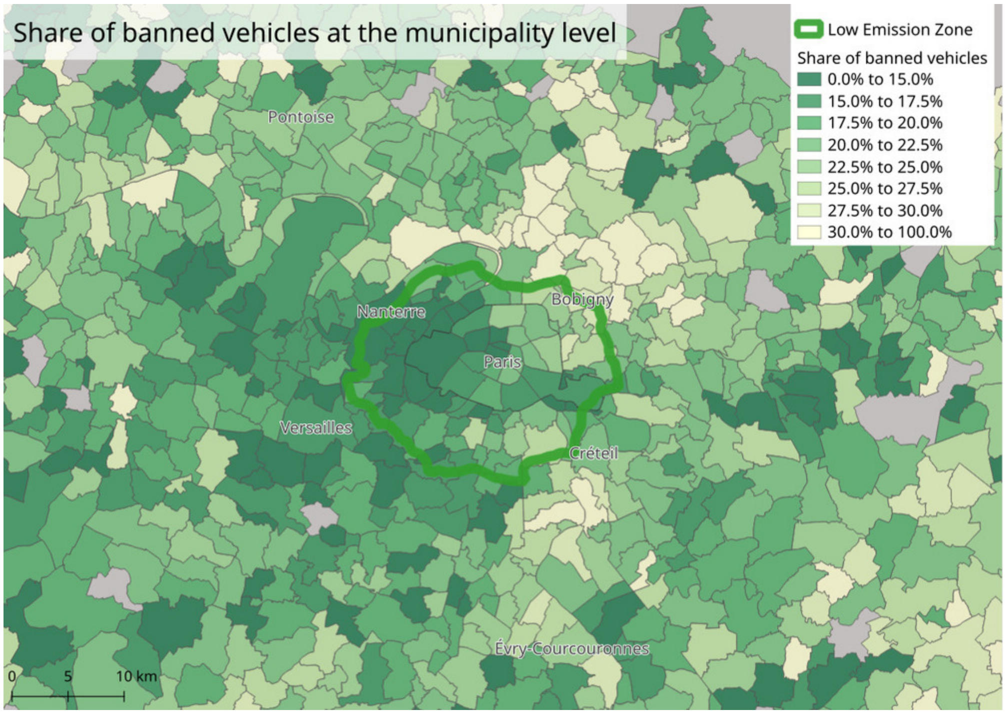

Figure 5: Share of cars with Crit'Air 3 or worse at the municipality level for the 2025 vehicle fleet

5.2 Simulating the LEZ

To simulate the LEZ, we use METROPOLIS2's road restriction feature, defining two vehicle types: authorized vehicles (Crit'Air 2 or better), which have unrestricted access to all roads, and banned vehicles (Crit'Air 3 or worse), which are prohibited from accessing any road within the LEZ. Agents are assigned to these vehicle types based on the car characteristics generated in the synthetic population (see Section 4.2).[7] Owners of banned vehicles may be required to reroute around the LEZ to reach their destination.

For trips that either start or end inside the LEZ, owners of banned vehicles lose access to the car driver or car passenger modes, as the trip becomes infeasible. In total, we identified 91 270 agents (0.88 % of the population) who no longer have access to a car, with at least one trip which cannot be completed by public transit and requires more than 1 h of walking (or over 24 min by bicycle). Given that it is not practically feasible for these "trapped" agents to avoid car use, we assume they can still travel within the LEZ by car, despite the restriction. This assumption accounts for possible exceptions, such as exemptions for disabled individuals, classic cars, or instances where some drivers may disregard the LEZ regulations.

5.3 Air Quality Impact

Improving air quality is the primary goal of the LEZ. To evaluate its effectiveness, we assess road-traffic emissions and the related health impacts using the methodology developed by Le Frioux et al. (2024) for METROPOLIS2. This methodology computes emissions of nitrogen oxides ($\mathrm{NO_x}$) and particulate matter ($\mathrm{PM_{2.5}}$) due to road traffic, and estimates population exposure to these pollutants. The process includes five steps. Road-traffic *emissions* are calculated based on vehicle characteristics and simulated speeds at the road level, using the EMISENS model (Ho et al., 2014). These emissions are *dispersed* in the atmosphere using a Gaussian plume dispersion model, which generates average daily pollutant concentrations on a grid of resolution 500 m × 500 m, assuming a west-to-east wind with speed 10 km/h. *Population density* is computed from METROPOLIS2's output, showing the location of each agent over the simulation day. Then, *exposure* can be calculated by multiplying pollutant concentrations with population density on the grid. Finally, the *health costs* of pollution exposure are obtained by first computing the relative risks due to pollution exposure (the increase in mortality that can be attributed to pollution), then multiplying the result with the mortality rate (1 %), the average number of years lost when dying from

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[7] Since vehicle ownership is defined at the household level, we assign a random vehicle from the household fleet to each agent.

air pollution (10.4 years), and the price of a year of life lost (106 985 €). See Le Frioux et al. (2024) for additional details.

This methodology allows us to compute exposure at the agent level, which is critical for evaluating spatial and economic disparities resulting from the LEZ. Additionally, CO_2 emissions are computed from the EMISENS model (Step 1).

5.4 Expected Results

The primary expected outcome of the LEZ is a reduction in air pollutants within the zone. Additional benefits include reducing CO_2 emissions, road congestion and noise pollution.[8] The most direct expected effect of the LEZ is that the most polluting vehicles will no longer circulate within the LEZ, leading to a reduction in both air pollutants and road congestion within the area. Owners of banned vehicles who used to drive in the LEZ have several potential responses: (i) buying an authorized vehicle, (ii) switching to another transport mode (e.g., public transit), or (iii) rerouting around the LEZ, provided that both their origin and destination are outside the zone. The first option, buying a new vehicle, is typically not feasible in the short term.

Second order effects may also arise. For instance, the number of vehicles driving in the LEZ could increase if owners of authorized vehicles change their routes or modes due to decreased congestion (rebound effect). Additionally, air pollutant emissions and road congestion may increase in areas surrounding the LEZ if many drivers choose to reroute around the zone. Verifying these predictions and measuring the magnitude of the effects require running METROPOLIS2 simulations and comparing the results with and without the LEZ.

5.5 Limits of the Methodology

Our evaluation focuses on the short-term impacts of the LEZ, where agents can adjust their mode, departure time, and route, but other variables such as car ownership, activity plans, and residential locations are assumed to remain fixed. In the medium term, agents could respond to the LEZ by purchasing authorized vehicles, changing shopping or other activity locations, or moving closer to public transit, among other adjustments.

Additionally, the study assumes that agents have not anticipated the LEZ policy. This is reflected in the assumption that the vehicle fleet follows the same evolution trend between 2020–2022 and 2023–2025. To account for such medium-term adjustments, more complex

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[8] The analysis of the impact of LEZs on noise pollution, albeit important, is outside of the scope of this paper.

models would be required, including car ownership models, activity-based models, and land-use models, all of which fall outside the scope of this paper.

Another potential adjustment not modeled in this study is the use of park-and-ride strategies, where agents drive their unauthorized vehicles to the LEZ boundaries, park near a train station, and complete their trip using public transit. Such behaviors are unlikely to represent a significant response to the policy, as they represent only 1.4 % of the trips in the region according to the travel survey (0.8 % when excluding trips by car passengers). In a related case study, Yin et al. (2024) find that park-and-ride trips would not increase substantially when implementing a driving restriction zone in Paris. Nevertheless, park-and-ride trips could be incorporated into the model in future research, as long as the locations of the park-and-ride facilities chosen by agents are well defined (e.g., selecting the facility closest to home, as in Yin et al. 2024).

Despite these limitations, the results provide valuable insights into the short-term effects of the LEZ, representing upper-bound estimates of the policy's impact if agents do not anticipate it.

Furthermore, the LEZ is modeled as an absolute restriction, with banned vehicles prohibited from entering at any time within the LEZ, while, in reality, the LEZ operates only between 8 a.m. and 8 p.m., on weekdays. There are also several exceptions to the LEZ. Exemptions exist for disabled individuals, classic cars, and certain professional vehicles. Additionally, enforcement is currently not fully automated, and some individuals may evade compliance. Owners of Crit'Air 3 vehicles are also allowed 12 exceptions per year, granting them temporary access to the LEZ for up to 24 hours. All these cases are not accounted for in the simulations.

6 Results

We run two simulations of METROPOLIS2, one for the baseline scenario and another for the LEZ scenario, each running for 100 iterations. These iterations are necessary for road congestion and travel decisions to adjust to each other, allowing the simulator to approximate an equilibrium.[9]

6.1 Aggregate results

Before comparing the results between the baseline and LEZ simulations, we first aim to understand how many agents are directly impacted by the LEZ by examining the character-

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[9] See Javaudin (2024, Chapter 3) for details on the convergence of the simulations.

istics of their tours. Table 2 summarizes the share of tours based on car ownership status (authorized car, banned car, or no car) and specific tour characteristics, such as whether a trip occurs inside the LEZ or if public transit is available.

Table 2: Tour characteristics by car ownership

	Authorized car	Banned car	No car
Overall	58 %	15.9 %	26.1 %
Agent has driving license (yes / no)	72.4 % / 27.6 %	71.5 % / 28.5 %	49.5 % / 50.5 %
Any trip start / end inside LEZ (yes / no)	48.3 % / 51.7 %	43.1 % / 56.9 %	73.4 % / 26.6 %
Selected mode in baseline scenario (car / other)	48.1 % / 51.9 %	48.9 % / 51.1 %	0.0 % / 100.0 %
Public-transit access (yes / no)	87.6 % / 12.4 %	87.5 % / 12.5 %	93.4 % / 6.6 %

Although 20.8 % of the vehicle fleet is classified as banned under the LEZ, the share of tours directly impacted by the policy is significantly smaller. Specifically, 26.1 % of all tours are conducted by agents without a car, leaving 15.9 % of tours conducted by agents who own a banned vehicle. Nevertheless, not all these 15.9 % of tours are directly affected by the LEZ. For example, only 71.5 % of them are performed by agents with a driving license, meaning the remaining 28.5 % of tours are performed by agents who do not have the option of driving. Furthermore, 43.1 % of the tours conducted by banned car owners have a trip that actually starts or ends inside the LEZ. For the remaining 56.9 % of tours, the banned car can still be used because the tour does not require entering the LEZ, although detours may be required. In the baseline scenario, fewer than half of the tours conducted by banned car owners are made using their car (48.9 %), while the rest (51.1 %) are done using alternative modes. This suggest that, in the LEZ scenario, even if agents could still use their banned car, they would often choose not to. Additionally, public-transit access is relatively high for tours involving banned cars, with only 12.5 % of them having no feasible public transit option for at least part of the trip.

A comparison of the aggregate results for the two simulations is presented in Table 3. The travel surplus of agents, representing the utility they expected to derive from their trips, is computed using the logsum formula, described in Equation (4).

The results show that, on average, the agent travel surplus decreases by 0.13 € when the LEZ is implemented, while the average daily travel time increases by 1 minute and 55 seconds. These outcomes reflect the added constraint of the LEZ, which forces some agents to reroute or switch to modes that provide lower utility.

The LEZ policy leads to a notable reduction in car usage, with the share of tours per-

Table 3: Measures of effectiveness for the simulated average day

	Baseline	LEZ	Variation	Observed value
Global output (agent level)				
Average travel surplus	−28.81 €	−28.94 €	−0.13 €	
Average daily travel time	01:09:14	01:11:09	+115 s	01:36:13 (2010)[a]
Mode shares (tour-level)				
Car driver share	31.1 %	29.3 %	−1.8 p.p.	30.7 % (2010)[a]
Car passenger share	5.5 %	5.4 %	−0.1 p.p.	8.8 % (2010)[a]
Public transit share	18.4 %	19.7 %	+1.3 p.p.	24.6 % (2010)[a]
Bicycle share	1.1 %	1.4 %	+0.3 p.p.	1.9 % (2010)[a]
Walking share	43.9 %	44.2 %	+0.3 p.p.	33.9 % (2010)[a]
Mode shares (weighted by Euclidean distance)				
Car driver share	53.3 %	51.2 %	−2.1 p.p.	47.2 % (2010)[a]
Car passenger share	7.8 %	7.7 %	−0.1 p.p.	7.5 % (2010)[a]
Public transit share	33.1 %	34.9 %	+1.8 p.p.	41.6 % (2010)[a]
Bicycle share	1.0 %	1.2 %	+0.2 p.p.	0.8 % (2010)[a]
Walking share	4.8 %	4.9 %	+0.1 p.p.	3.0 % (2010)[a]
Road-traffic output (excluding truck trips)				
Travel time (10^3 hours)	3502	3307	−5.6 %	5153 (2010)[a]
Time lost to congestion (10^3 hours)	379	348	−8.2 %	
Vehicle-kilometers (10^6 km)	126.28	121.40	−3.9 %	
Passenger-kilometers (10^6 km)	144.59	139.49	−3.5 %	

Note. All results are for an average working day.

[a] Source: Regional travel survey *Enquête Global Transport*.

formed by car (as either driver or passenger) dropping by 1.9 p.p.. Almost two-thirds of this shift is absorbed by public transit (+1.3 p.p.), while the remaining portion is distributed between bicycle and walking tours (+0.3 p.p. each). This trend holds when mode shares are weighted by Euclidean distance.

The decrease in car usage translates into a significant reduction in road usage: total travel time spent on roads by car drivers and passengers decreases by 5.6 %, time lost to congestion drops by 8.2 %, and vehicle-kilometers fall by 3.9 %.

While the aggregate mode share analysis shows a shift away from car use, it is important to investigate the possibility of a rebound effect, where owners of authorized vehicles switch back to using cars due to reduced congestion. To assess this, Table 4 presents the transition matrix of modes between the baseline and LEZ scenarios.

Mode shifts from car to non-car options represent 2.2 % of all tours. The most significant shifts are from car driver to public transit (1.4 p.p.). These changes are likely due to owners

Table 4: Transition matrix of modes from baseline to LEZ

	Car driver	Car passenger	Public transit	Bicycle	Walking	**Total**
Car driver	29.1 %	0.0 %	1.4 %	0.2 %	0.3 %	31.1 %
Car passenger	0.0 %	5.3 %	0.1 %	0.0 %	0.0 %	5.5 %
Public transit	0.2 %	0.0 %	18.1 %	0.0 %	0.0 %	18.4 %
Bicycle	0.0 %	0.0 %	0.0 %	1.1 %	0.0 %	1.1 %
Walking	0.0 %	0.0 %	0.0 %	0.0 %	43.9 %	43.9 %
Total	29.3 %	5.4 %	19.7 %	1.4 %	44.2 %	100.0 %

Reading example: 0.2 % of tours have mode *public transit* in the baseline scenario and mode *car driver* in the LEZ scenario.

of banned vehicles being forced to switch to alternative modes.

Conversely, the rebound effect manifests in 0.3 % of all tours switching from non-car to car options, with public transit to car driver (0.2 p.p.) representing the most important shifts. These shifts, involving roughly 48 000 tours, likely reflect the behavior of authorized vehicle owners who prefer to drive when congestion is reduced due to the LEZ.

To better understand how the LEZ impacts road congestion, we visualize the variation in daily average travel times at the road-segment level in Figure 6. The results indicate that congestion mostly decreases on roads near the LEZ boundaries.

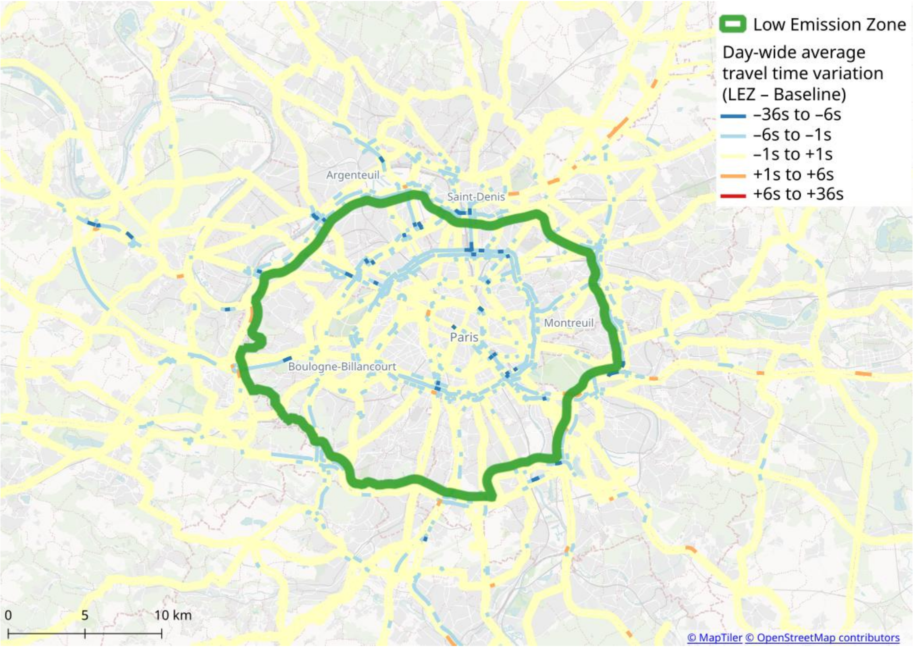

Figure 6: Variation in daily average travel times at the road-segment level
Note. Only major roads are represented.
Reading example: A value of -5 s indicates that the average travel time over the day on the road segment is decreased by 5 seconds in the LEZ scenario compared to the baseline scenario.

On the *Boulevard Périphérique*, a heavily congested ring road surrounding Paris, the travel time at 8 a.m. decreases from 59 min to 55 min for a full loop in the clockwise direction, and from 62 min to 56 min in the counter-clockwise direction.

In terms of public transit, Figure 7 shows how the daily flow of passengers varies across public transit segments when the LEZ is implemented. A public-transit segment is defined as a pair of stops directly connected by some public-transit line. Passenger flow increases on almost all segments, especially in the segments within the LEZ, where passenger flows were initially the largest. This is consistent with the predicted increase in public transit mode share (from 18.4 % to 19.7 % in the LEZ scenario).

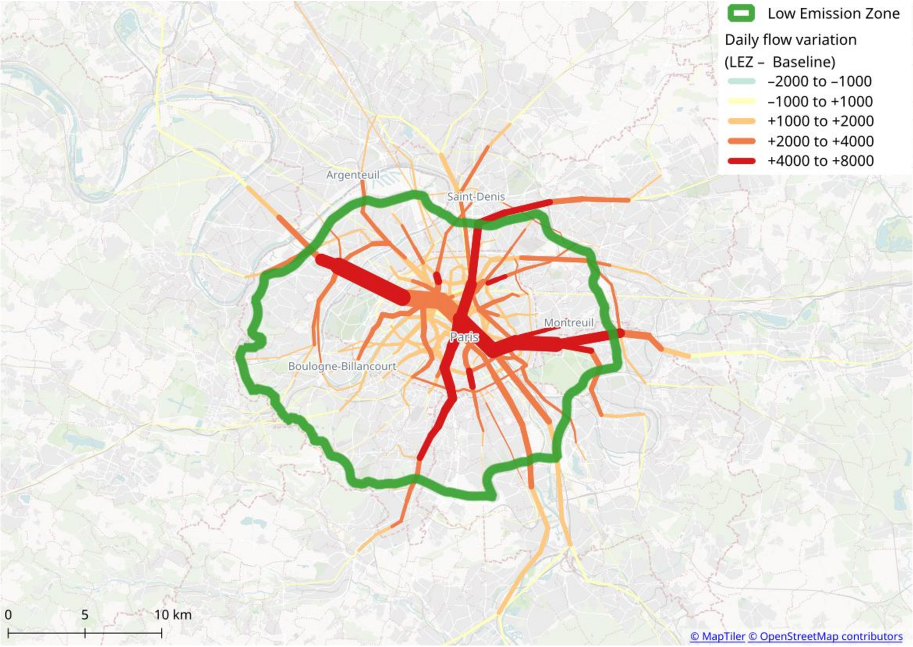

Figure 7: Variation of daily flows on public-transit segments
Note. The segment width is proportional to the baseline flow. Bus segments are excluded.
Reading example: A value of +2000 indicates that there are 2000 more daily passengers on that segment in the LEZ scenario compared to the baseline.

The two primary mass-rapid transit lines in Île-de-France, RER A and RER B, show noticeable changes in passenger flows. RER A, which runs along the west-east axis across Paris, sees a 3.2 % increase in total daily passenger-kilometers, equivalent to an additional 372 thousand passenger-kilometers. RER B, operating along the north-south axis, records an ever larger relative increase of 5.4 %, or 311 thousand additional passenger-kilometers.

The two public-transit lines with the largest relative increases in passenger-kilometers are tramways T7 and T10. Tramway T7 experiences a 28.2 % increase, adding 14 thousand passenger-kilometers. Similarly, tramway T10 see a 21.8 % rise, equivalent to an additional 13 thousand passenger-kilometers. Both lines run along the southern edge of the LEZ.

6.2 Pollution Results

Table 5 summarizes the results on pollutant emissions and their impact on health. The health surplus is computed following the methodology of the European Environment Agency.[10] Following Le Frioux et al. (2024), the years of potential life lost due to premature death is set to 10.4 years and the price of a year of life lost is set to 106 985 €. While vehicle-kilometers decrease by 3.9 % in the LEZ scenario, pollutant emissions show larger reductions: −4.5 % for CO_2, −9.2 % for NO_x, −7.6 % for $PM_{2.5}$. This is primarily because the reduction in vehicle-kilometers is driven by the most polluting vehicles (see below).

Table 5: Pollution-related results

	Baseline	LEZ	Variation	Observed value
CO_2 emissions (tonnes)	21 925	20 947	−4.5 %	21 079 (2021)[a,b]
NO_x emissions (tonnes)	33.70	30.61	−9.2 %	46.84 (2021)[a,c]
$PM_{2.5}$ emissions (tonnes)	2.91	2.69	−7.6 %	2.96 (2021)[a,d]
Premature deaths from NO_2	5.46	4.92	−9.9 %	7.83 (2019)[e]
Premature deaths from $PM_{2.5}$	6.22	5.41	−13.0 %	20.73 (2019)[e]
Total health surplus (10^6 €)	−12.993	−11.484	−11.6 %	

Note. All results are for an average working day. The simulated region encompasses 12.3 millions individuals.

[a] Source: `https://data-airparif-asso.opendata.arcgis.com/datasets/73bba8b50bae442697e89b89a70191b7_0/explore` and `https://www.citepa.org/fr/secten/`.

[b] In 2021, 11 500 kt of CO_2 where emitted by road transport in Île-de-France (Air'Parif), with private vehicles contributing 55 % (Citepa, national level). The yearly value is divided by 300 to approximate daily emissions.

[c] In 2021, 27 130 t of NO_x where emitted by road transport in Île-de-France (Air'Parif) with private vehicles contributing 52 % (Citepa, national level). The yearly value is divided by 300 to approximate daily emissions.

[d] In 2021, 1400 t of $PM_{2.5}$ where emitted by road transport in Île-de-France (Air'Parif) with private vehicles contributing 63 % (Citepa, national level). The yearly value is divided by 300 to approximate daily emissions.

[e] Source: `https://www.airparif.fr/sites/default/files/document_publication/Rapport-Enquete-Mortalite.pdf`. These figures include all pollution sources, not just road transport.

The health costs associated with pollution from NO_2 and $PM_{2.5}$ show even greater reductions, decreasing by 11.6 % from 12.993 million euros to 11.484 million euros per day. The fact that the health costs reduction exceed the drop in emissions can be explained by air quality improving most in densely populated areas, a finding confirmed by the maps presented below. These results highlight the importance of using a detailed pollution model, like METRO-TRACE, which accounts for fleet composition, pollutant dispersion, and population exposure.

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[10] Source: `https://www.eea.europa.eu/en/analysis/publications/assessing-the-risks-to-health/` [accessed 2026/01/06]

Figure 8 confirms that the reduction in vehicle-kilometers is driven by the most polluting vehicles (Crit'Air 3 or worse), which see a decrease of around 6.24×10^6 km (−22.5 %). In contrast, vehicle-kilometers for cleaner Crit'Air E, 1 and 2 vehicles increase by around 1.36×10^6 km (1.4 %). This can explain why emissions drop more sharply than total vehicle-kilometers.

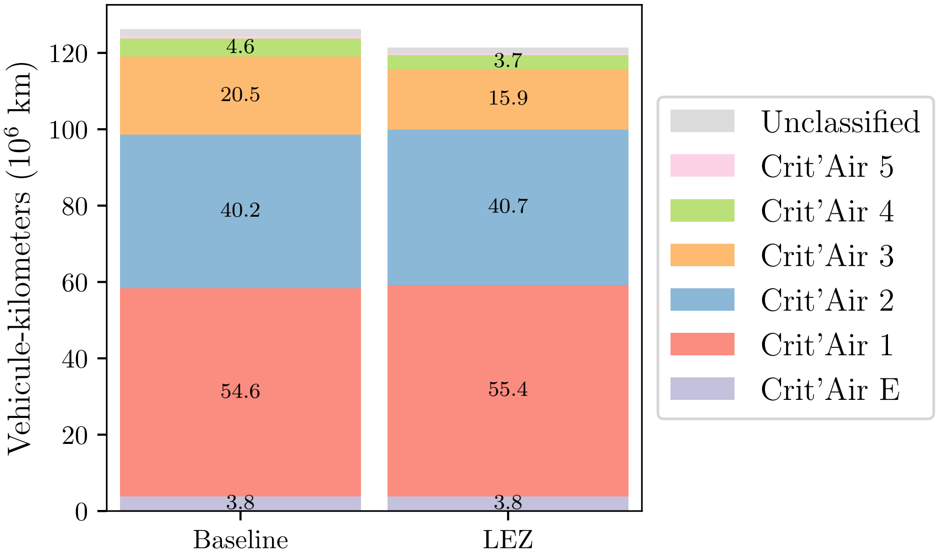
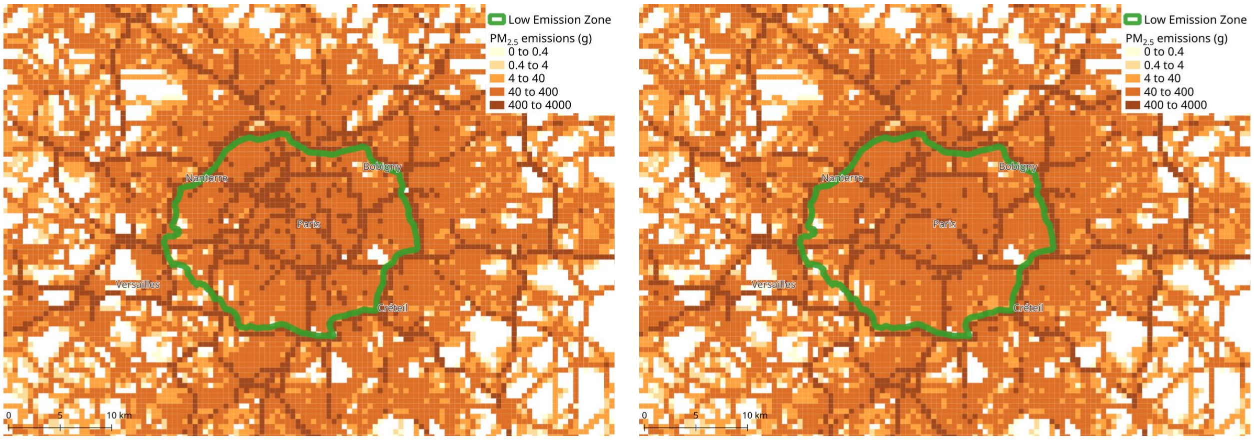


Figure 8: Vehicle-kilometers by Crit'Air category

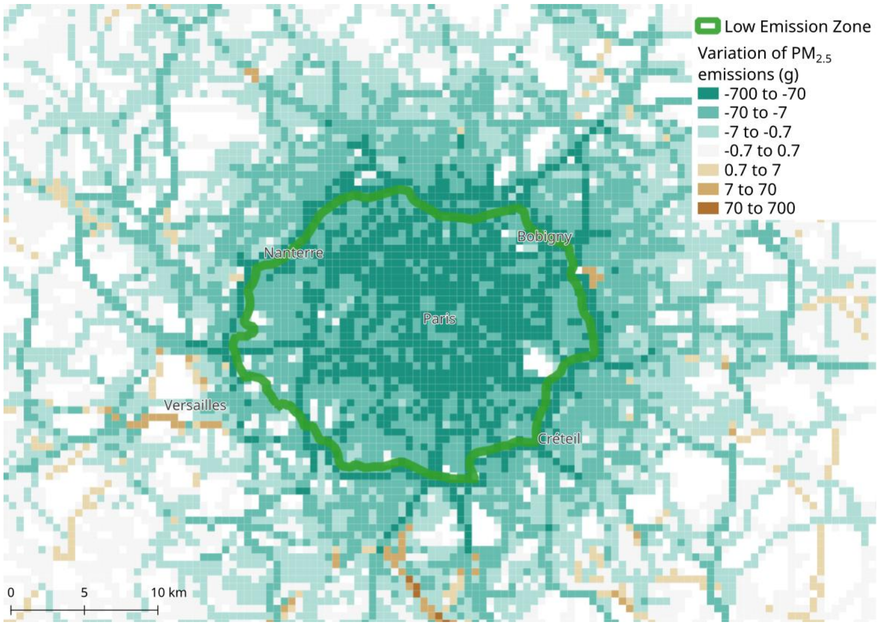
Next, we analyze the geographic distribution of pollution. Figure 9 shows $PM_{2.5}$ emissions for both scenarios, along with the difference between them. Emissions in both scenarios are concentrated on major highways and densely populated areas (Paris and surroundings). In the LEZ scenario, emissions decrease by 7.6 %, especially inside the LEZ and on certain highways outside it. However, some roads outside the LEZ see slightly larger emissions, likely due to rerouting from some vehicles. The maps of NO_x emissions, not shown here, present very similar patterns as $PM_{2.5}$ emissions.

Figure 10 illustrates $PM_{2.5}$ concentrations in the atmosphere, with the highest pollution levels observed in Paris and areas extending up to 30 km eastward. This pattern aligns with the assumption of an eastward wind, which is the dominant wind direction in the region.

In the LEZ scenario, air quality improves almost everywhere, especially in highly polluted areas inside and east of the LEZ. While a different wind direction would shift the areas benefiting most from improved air quality, it is unlikely to alter the relatively even distribution of health benefits across the population. Wind speed, however, could have a more significant impact, as it determines how long pollutants remain in the atmosphere. The assumption



(a) Baseline scenario (b) LEZ scenario

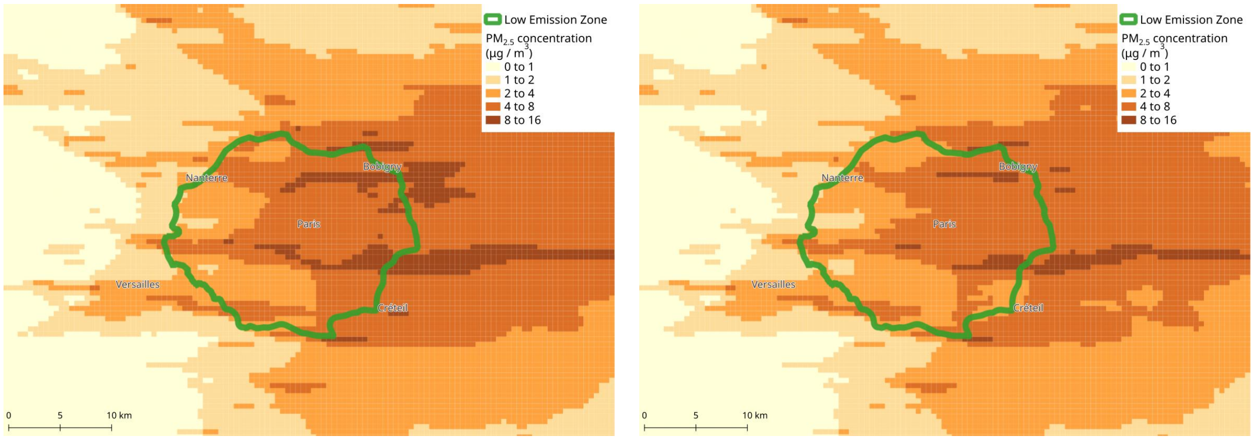


(c) Change in emissions (LEZ vs baseline)

Figure 9: Daily PM$_{2.5}$ emissions from car trips on a 500 m grid

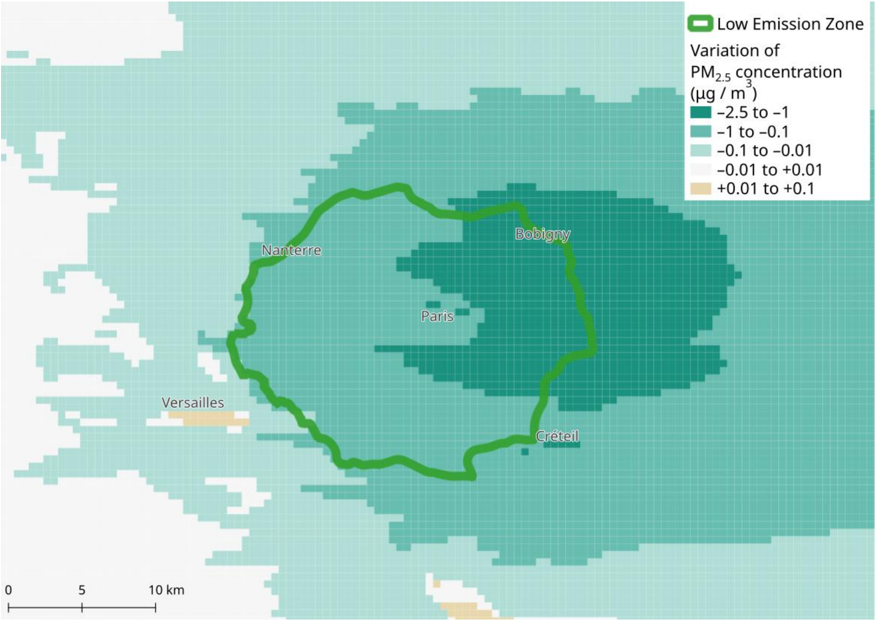
of a 10 km/h wind speed aligns well with observed data on premature deaths (see Table 5), justifying its use in this analysis.

The maps of NO_x concentrations, not shown here, present very similar patterns as $PM_{2.5}$ concentrations.



(a) Baseline scenario

(b) LEZ scenario



(c) Change in concentration (LEZ vs baseline)

Figure 10: $PM_{2.5}$ concentrations on a 500 m grid

Figure 11 shows the day-average population density (measured in person-days). It accounts for the time spent at home, the time spent doing activities, and the time spent en-route (only for car trips).[11] As expected, population density is highest within the LEZ,

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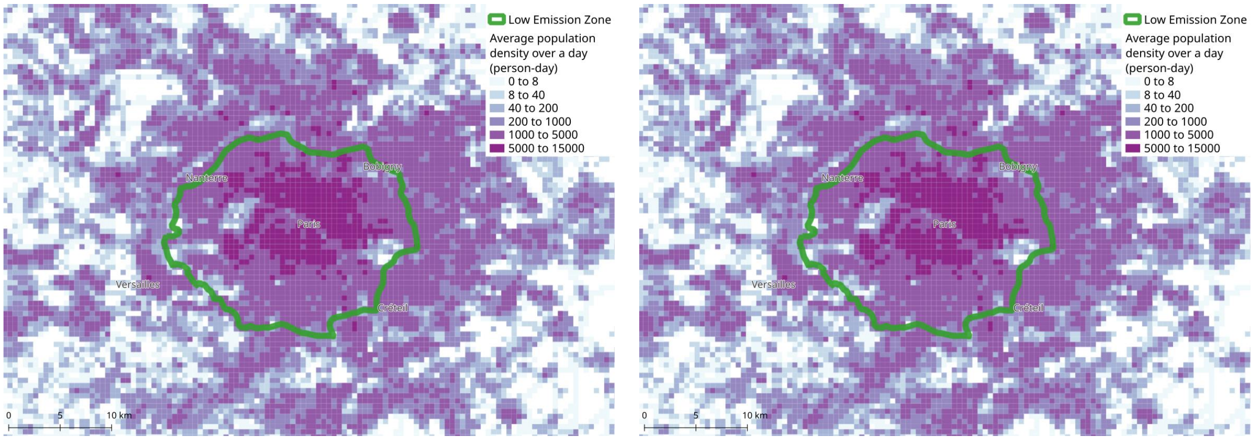
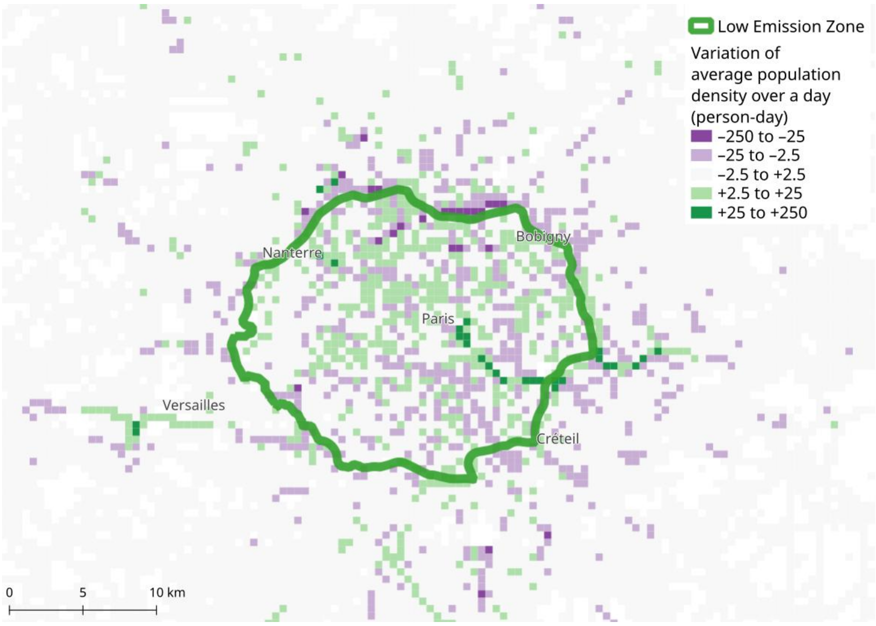
[11] Individuals who do not travel are assumed to spend the entire day at home. Those who travel by public transit, bicycle or walking are "teleported" from their origin location to their destination location in the middle of the trip. The same assumption is used in Poulhès and Proulhac (2021).

underscoring the importance of improving air quality in this area. The population density patterns remain almost identical between the scenarios, due to activity patterns being fixed.



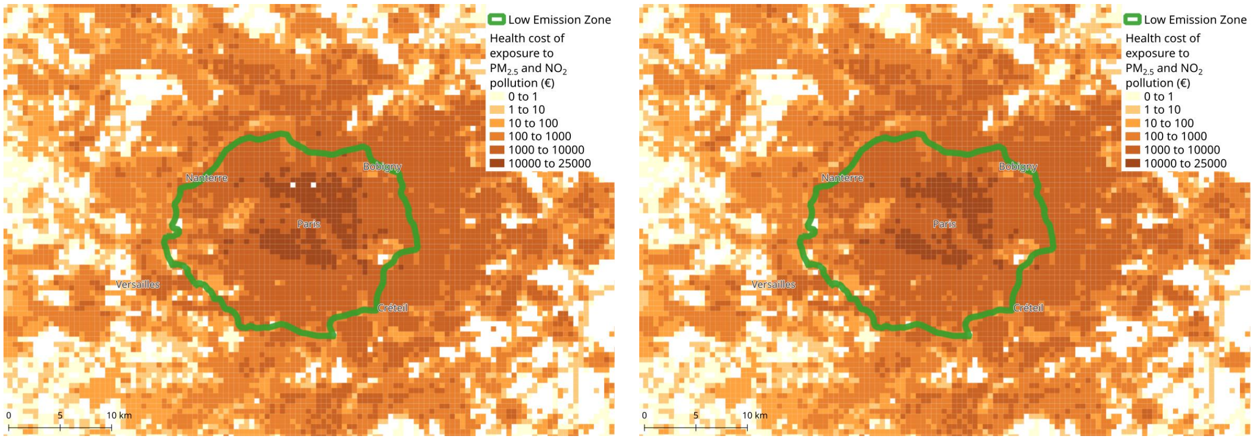
(a) Baseline scenario (b) LEZ scenario



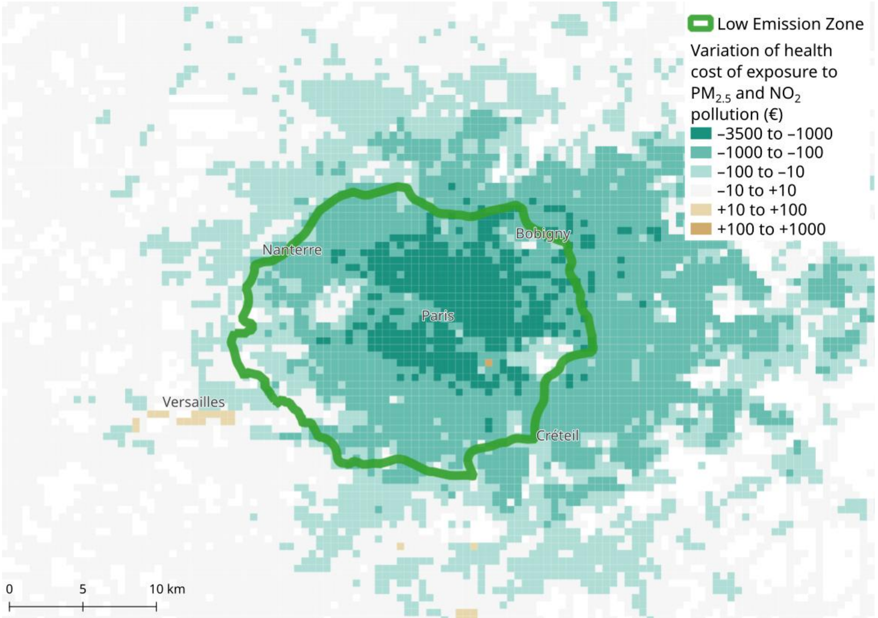
(c) Change in population density (LEZ vs baseline)

Figure 11: Day-average population density on a 500 m grid

Finally, Figure 12 maps the daily exposure cost to NO_2 and $PM_{2.5}$, computed by combining pollutant concentrations with population density. The highest exposure costs are observed in Paris and nearby areas, where both pollution and population density are high. Exposure costs are also large in the parts of the LEZ further away from Paris and in the east of the LEZ. The LEZ scenario shows a significant reduction in exposure costs in these areas.



(a) Baseline scenario (b) LEZ scenario



(c) Change in exposure cost (LEZ vs baseline)

Figure 12: Daily exposure cost to NO_2 and $PM_{2.5}$ pollutants on a 500 m grid

6.3 Spatial and Economic Inequalities

A basic benefit-cost analysis of the LEZ policy is provided in Table 6, indicating that the total daily individual and social benefits outweigh its total daily costs.

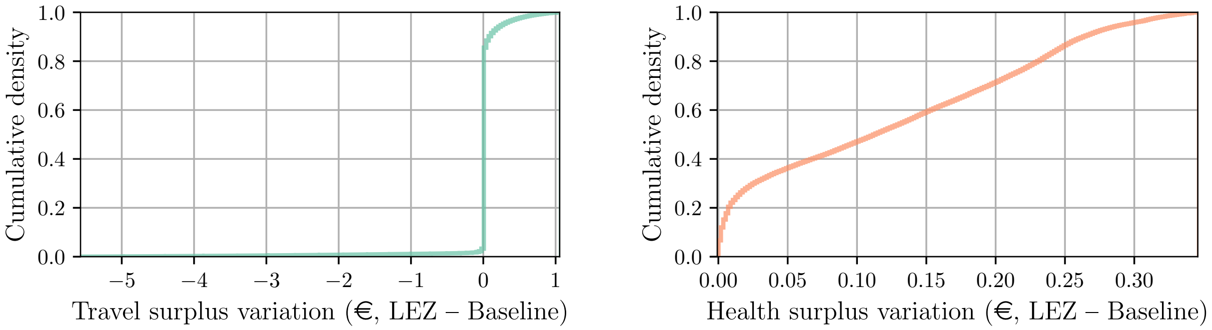
Table 6: Basic benefit-cost analysis of the LEZ policy

Decrease in travel surplus	−1 342 000 €
Reduction in health costs from pollution	1 509 000 €
Reduction of CO_2 emissions[a]	196 000 €
Total	363 000 €

Note. All values are for an average working day.

[a] Assuming a social cost of CO_2 of 200 €/t.

The social acceptability of the policy might however be undermined by two factors. First, while individuals directly feel the costs – primarily due to reduced freedom in their travel options – the benefits are less tangible. The improvements in air quality, for example, are not easily observable and may not be immediately linked to the policy. Second, there are great disparities in the change in individual travel surplus, as depicted in Figure 13a. The total travel surplus decreases by approximately 1.342 million euros, with around 2.11 % of individuals experiencing a reduction of more than 1 € in their travel surplus, accounting for a total loss of 1.972 million euros. This loss is partly offset by a surplus increase for approximately 17.69 % of the population. In contrast, changes in individual exposure to pollution are more evenly distributed, as shown in Figure 13b, with 98 % of the population experiencing a change in health exposure within the range of 0.00 € to +0.35 €.



(a) Travel surplus

(b) Health surplus

Figure 13: Cumulative distribution function of the travel and health surplus (agent-level)

In this section, we analyze the spatial and socio-demographic characteristics of the winners and losers from the LEZ policy, focusing on the individual travel surplus, which shows the most significant inequalities and is directly perceived by the population. We define *LEZ winners* as individuals whose travel surplus increases by more than 1 € with the LEZ. They represent 1.2 % of the traveling population. Similarly, we define *LEZ losers* as individuals whose travel surplus decreases by more than 1 €. We also include in this group the 91 270 "trapped" agents assumed to travel with banned cars inside the LEZ because they have no feasible alternatives (see Section 5.2). These LEZ losers represent 3.3 % of the population. The remaining agents (95.5 % of the population) are classified as *LEZ neutrals*. They are not significantly affected by the policy.

Table 7 presents the total and mean travel and health surplus for the LEZ winners, losers, and neutrals. LEZ winners and losers receive comparable benefits from health improvements due to the policy (+0.13 € per LEZ winner, +0.15 € per LEZ loser). However, for the LEZ losers, this benefit is insignificant compared to the loss in travel surplus of 7.64 € on average.

Table 7: Travel and health surplus by population group

	LEZ Winner	LEZ Loser	LEZ Neutral
Count	122 170	344 800	9 908 530
Share of population traveling	1.2 %	3.3 %	95.5 %
Travel surplus variation (total, €)[a]	+202 000	−1 937 000	+376 000
Travel surplus variation (mean, €)[a]	+1.65	−7.64	+0.04
Health surplus variation (total, €)	+16 000	+53 000	+1 218 000
Health surplus variation (mean, €)	+0.13	+0.15	+0.12

[a] Excluding the "trapped" agents.

Table 8 compares the characteristics of agents and their trips across the three groups: winners, losers, and neutrals. LEZ winners are exclusively car owners, with a significant majority needing to travel inside the LEZ (91.7 %) and owning an authorized vehicle (98.6 %). Their trips are generally longer, averaging 55.1 km, and only a minority of them live inside the LEZ (27.0 %) or have access to public transit (42.5 %). This group is likely to benefit significantly from the reduced congestion produced by the LEZ. Additionally, some LEZ winners own banned cars but do not need to travel inside the LEZ, likely benefiting from reduce congestion outside the LEZ.

LEZ losers, in contrast, are almost exclusively composed of banned car owners (99.9 %) whose trips are within the LEZ (99.5 %).[12] Compared to LEZ winners, their trips tend to be shorter (30.8 km) and they have better access to public transit (65.9 %), but not as much as LEZ neutrals. Many in this group might experience a significant loss because they lose access to car-based modes and do not have suitable alternative.

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[12] The 0.01 % of LEZ losers owning authorized vehicles are agents negatively impacted by the adjustments in road congestion outside the LEZ.

Table 8: Characteristics of the agents and their trips by population group

	LEZ Winner	LEZ Loser	LEZ Neutral
Living in LEZ	27.0 %	53.3 %	40.4 %
At least one trip inside LEZ	91.7 %	99.5 %	61.2 %
Car owners	100.0 %	100.0 %	71.9 %
Banned car owners	1.4 %	99.9 %	18.0 %
Mean Euclidean distance for all trips	55.1 km	30.8 km	15.8 km
Access to public-transit for all trips[a]	42.5 %	65.9 %	84.3 %

[a] Share of agents for which all trips can be done by public transit (or short walking trips).

A common belief is that LEZs disproportionately harm individuals living far from city centers who lack access to public transit. However, Table 8 paints a different picture: LEZ losers are more concentrated inside the LEZ than outside, and they generally have better access to public transit than LEZ winners (though not as good as the LEZ neutrals).

Table 9 shows the mode shares for LEZ winners and losers in both the baseline and LEZ scenarios. LEZ winners are predominantly car drivers or passengers in both scenarios (83.5 % in the baseline, 85.5 % in the LEZ scenario). This group likely includes people who travel by car in the baseline scenario despite facing heavy congestion but benefit from reduced traffic with the LEZ. A notable proportion of LEZ winners are also pedestrians who might also benefit from the reduced road congestion for car alternatives (remember that the travel surplus does not only depend on the utility of the selected mode).

Table 9: Mode shares in the baseline and LEZ scenario for the LEZ winners and losers

	LEZ Winner Baseline	LEZ Winner LEZ	LEZ Loser Baseline	LEZ Loser LEZ
Car driver	72.4 %	74.1 %	72.1 %	21.5 %
Car passenger	11.1 %	11.4 %	6.6 %	3.0 %
Public transit	4.1 %	2.2 %	2.6 %	42.2 %
Bicycle	0.0 %	0.0 %	0.4 %	7.4 %
Walking	12.4 %	12.3 %	18.3 %	26.0 %

LEZ losers on the other hand, are also mostly car users in the baseline scenario (78.7 %), but many lose access to their preferred mode of transportation in the LEZ scenario. Only 24.5 % of LEZ losers continue traveling by car – mostly the "trapped" agents – with many switching to public transit (+39.6 p.p.), walking (+7.7 p.p.), or cycling (+7.0 p.p.).

Figures 14 and 15 illustrate the spatial distribution of LEZ winners and losers by municipality. LEZ losers are predominantly located within the LEZ, particularly around the zone's boundaries. In contrast, LEZ winners are more dispersed, in municipalities outside the LEZ. This suggests that the LEZ may favor individuals living outside the LEZ more than those within.

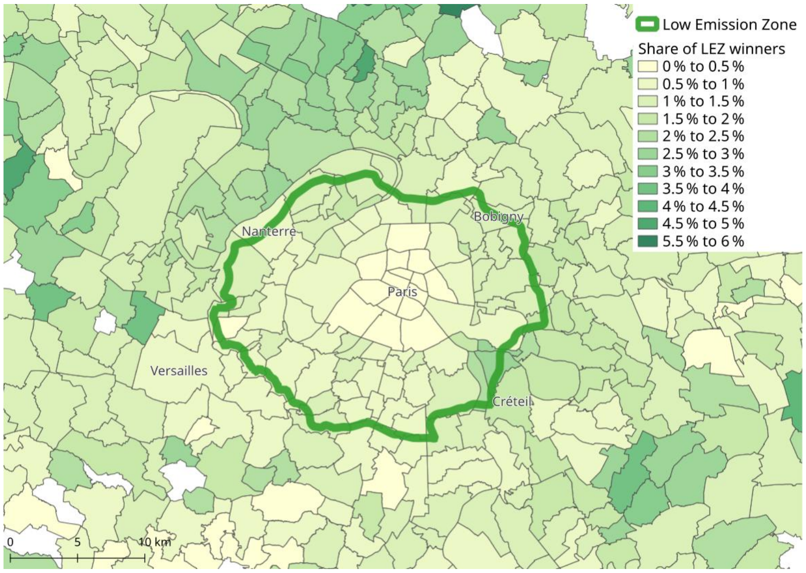


Figure 14: Share of LEZ winners by municipality

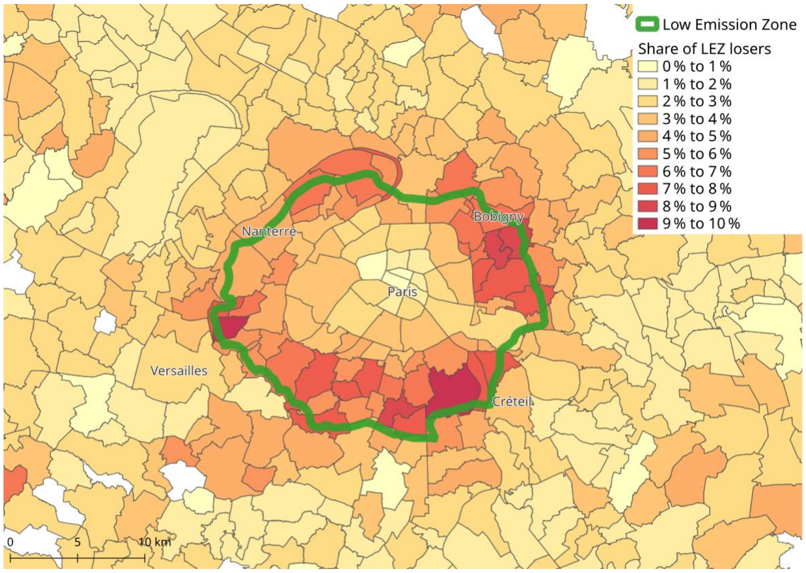
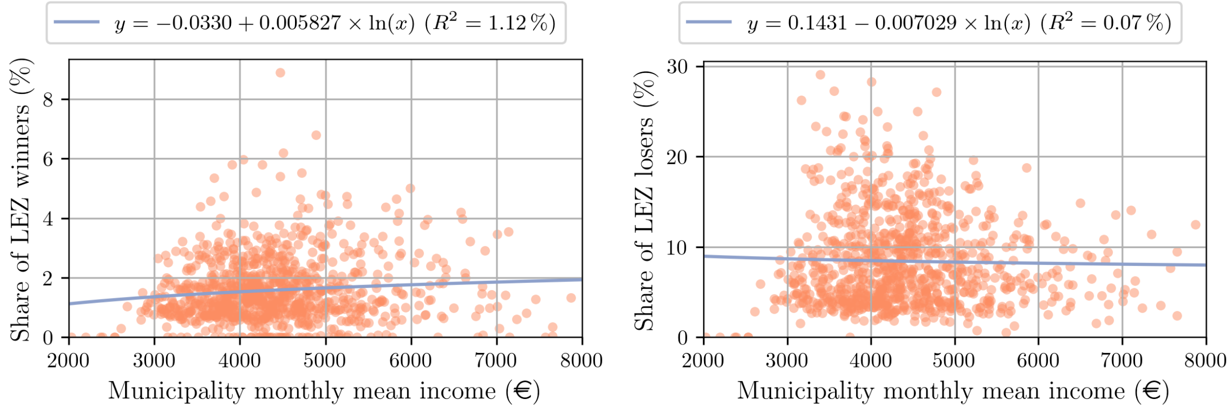


Figure 15: Share of LEZ losers by municipality

Analyzing the impact of the LEZ by socio-demographic characteristics, such as gender and socio-professional class, is unfortunately not feasible at the agent level because household vehicles were generated without considering correlations with these attributes (see Section 4.2). However, the vehicle fleets were generated based on the characteristics of municipalities, meaning that the shares of LEZ winners and losers computed at the municipality level are consistent. This allows us to analyze how these shares correlate with socio-demographic characteristics aggregated at the municipality level.

We focus on how the LEZ affects municipalities based on the average monthly disposable income over households. Figure 16 illustrates the share of LEZ winners and losers as a function of the mean income of the municipalities. Both figures also present the equation from an Ordinary Least Squares (OLS) regression of the share of LEZ winners or losers on a constant and the logarithm of the municipality's mean income.



(a) LEZ winners

(b) LEZ losers

Figure 16: Share of LEZ winners and LEZ losers as a function of the municipality mean income

Although the income coefficients have the expected sign (richer municipalities are expected to have a larger share of LEZ winners and a smaller share of LEZ losers), both OLS regressions show a low explanatory power, with poor R^2 values (1.12 % for the share of LEZ winners, and 0.07 % for the share of LEZ losers). These results suggest that LEZ winners and losers are distributed relatively evenly across low- and high-income municipalities, indicating that the LEZ does not significantly affect economic inequalities between municipalities.

6.4 Enabling Shifts in Car Ownership

The previous analysis assumes fixed car-ownership decisions. In practice, owners of banned vehicles may offset the constraints imposed by the LEZ by purchasing or renting newer vehicles. This section therefore explores a compensatory policy in which owners of banned cars are allowed to rent an electric vehicle (EV). The scenario is inspired by a French government initiative that enables low-income households to rent an EV for up to 200 € per month, subject to conditions such as residing at least 15 km from their workplace.

From a welfare perspective, the EV rental scheme can be interpreted as a targeted compensation mechanism that relaxes the binding mobility constraint faced by some agents under the LEZ. Rather than removing or weakening the environmental regulation, the policy expands the feasible choice set for affected individuals by restoring access to the car mode at a monetary cost. In a second-best setting, where vehicle ownership, residential location, and public-transport supply are fixed in the short run, such a mechanism can improve welfare by reducing large losses in travel surplus without undermining the environmental objective of the LEZ.

In the new simulation, the 1.615 million owners of banned vehicles are given the option to rent an EV at a daily cost of 10 €, corresponding to a monthly expenditure of 200 € assuming 20 days of use per month. This option is particularly valuable for individuals who need to travel within the LEZ and for whom public transit or active modes represent poor substitutes.

Simulation results (Table 10) show that introducing the EV rental option increases average travel surplus relative to the LEZ scenario without compensation. While total vehicle-kilometers traveled rise slightly, local air pollution and associated health damages decline further due to the replacement of internal combustion vehicles by zero-emission EVs. The policy therefore improves welfare along two dimensions: it mitigates large individual utility losses while reinforcing the environmental effectiveness of the LEZ.

Among the 1.615 millions owners of banned cars, approximately 139 000 individuals (8.6 %) choose to rent an EV. Nearly all adopters rely on car use in the baseline scenario without LEZ. In the uncompensated LEZ scenario, only 42 % of them continue to use a car, with the remainder switching to public transit (45 %), cycling (11 %), or walking (1 %). The rental option thus acts as a partial compensating variation, allowing these agents to recover a substantial share of their lost travel surplus.

The EV rental policy effectively mitigates the adverse effects of the LEZ on vulnerable individuals. Among EV adopters, 94 % are classified as LEZ losers prior to the introduction of the rental option. Overall, the policy reduces the number of LEZ losers by 17 %. This result illustrates how second-best compensatory instruments can enhance the public acceptability of stringent environmental regulations by redistributing costs away from the most constrained individuals, without weakening the regulation itself.

Table 10: Measures of effectiveness for the simulated average day

	Baseline	LEZ	LEZ with EV rental
Global output (agent level)			
Average travel surplus	−28.81 €	−28.94 €	−28.68 €
Average daily travel time	01:09:14	01:11:09	01:08:48
Mode shares (tour-level)			
Car driver share	31.1 %	29.3 %	30.1 %
Car passenger share	5.5 %	5.4 %	5.5 %
Public transit share	18.4 %	19.7 %	19.0 %
Bicycle share	1.1 %	1.4 %	1.2 %
Walking share	43.9 %	44.2 %	44.2 %
Mode shares (weighted by Euclidean distance)			
Car driver share	53.3 %	51.2 %	52.9 %
Car passenger share	7.8 %	7.7 %	7.8 %
Public transit share	33.1 %	34.9 %	33.3 %
Bicycle share	1.0 %	1.2 %	1.0 %
Walking share	4.8 %	4.9 %	4.9 %
Road-traffic output (excluding truck trips)			
Travel time (10^3 hours)	3502	3307	3252
Time lost to congestion (10^3 hours)	379	348	315
Vehicle-kilometers (10^6 km)	126.28	121.40	124.60
Passenger-kilometers (10^6 km)	144.59	139.49	142.92
Pollution-related output			
CO_2 emissions (tonnes)	21 925	20 947	19 919
NO_x emissions (tonnes)	33.70	30.61	27.42
$PM_{2.5}$ emissions (tonnes)	2.91	2.69	2.41
Premature deaths from NO_2	5.46	4.92	4.56
Premature deaths from $PM_{2.5}$	6.22	5.41	4.77
Total health surplus (10^6 €)	−12.993	−11.484	−10.377

Note. All results are for an average working day.

7 Conclusion

This paper presents a comprehensive evaluation of the Low Emission Zone (LEZ) policy being implemented in the Greater Paris area, using a dynamic agent-based transport simulator (METROPOLIS2) to assess its short-term impacts on travel behavior, road congestion, and pollution emissions.

The aggregate results show that the benefits of the LEZ policy (improved air quality, reduced CO_2 emissions) outweigh its costs (decrease of travel surplus). Pollution reduction is permitted by the decrease of car trips, with the mode share of car trips decreasing by 1.9 p.p., leading to a 3.9 % decrease in total vehicle-kilometers traveled. The emission reductions far exceed the decrease in car trips, with CO_2 emissions falling by 4.5 %, nitrogen oxides (NO_x) by 9.2 %, and particulate matter ($PM_{2.5}$) by 7.6 %. These reductions highlight the LEZ's ability to target the most polluting vehicles effectively, supporting its primary goal of improving air quality.

Importantly, the analysis of premature deaths due to pollution exposure demonstrates the significant public health benefits of the LEZ. The number of premature deaths from exposure to NO_2 and $PM_{2.5}$ is expected to decline by 9.9 % and 13.0 %, respectively, with the greatest air quality improvements occurring within the LEZ, where population density is highest.

However, the distributional analysis reveals mixed results in terms of equity. While the health benefits of reduced pollution are distributed relatively evenly across the population, the impact on travel surplus shows greater disparities. A small set of residents — banned-vehicle owners living in the LEZ — face large reductions in travel surplus. For many, public transit is theoretically available but not a realistic substitute for specific trip chains, short but car-dependent activities, or atypical schedules. These findings nuance the common claim that LEZs primarily hurt suburban households with poor transit access (see e.g., Wang and Zhong 2025). Instead, the most affected are often urban residents with constrained mobility patterns.

This suggests that political resistance to LEZs may arise not from broad economic inequality but from localized clusters of high-intensity losses, which are more salient than diffuse health gains. Designing compensatory measures targeted at these groups may therefore be more effective than broad, undifferentiated subsidies.

Several limitations of this analysis should be noted. First, while we exploit data on the vehicle fleet at the municipality-level, we did not consider the correlation between vehicle ownership and the socio-demographic characteristics of households within municipalities. This omission could influence the distributional impacts of the LEZ since, within a municipality, lower-income households are more likely to own older, banned vehicles. Incorporating this correlation into the simulation model would offer a more precise understanding of how the LEZ affects different segments of the population.

Moreover, the focus on short-term impacts means that variables such as car ownership, destination choice, and residential location remain fixed. In reality, individuals may adapt to the LEZ over time by purchasing authorized vehicles, relocating closer to public transport, or altering their activity patterns.

To begin addressing these limitations, we extend the model to include an option for owners of banned cars to rent electric vehicles at a modest cost. The simulation results from this extension demonstrate the benefits of allowing such adaptation: average travel surplus increases, air pollution levels decline, and the number of individuals most negatively affected by the LEZ decreases. This adaptation not only enhances the policy's effectiveness but also underscores the importance of flexible solutions in mitigating its social and environmental impacts.

To conclude, our findings provide valuable insights into the potential effectiveness of the LEZ in reducing emissions and improving air quality in urban areas. By leveraging a detailed transport simulation, this study highlights the complex interactions between individual travel decisions and transportation policies, offering a robust framework for evaluating similar policies. Future research should investigate the long-term impacts of the LEZ, as well as the role of complementary policies, such as public transport improvements or changes in speed limits, in mitigating the social inequalities observed in this study.

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