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THE IMPACT OF LOW EMISSION ZONES ON VEHICLES FLEET: Evidence from France*

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L’impact des zones à faibles émissions sur le parc automobile en France

Cet article examine les effets des zones à faibles émissions (ZFE) sur la composition du parc automobile et le marché automobile en France. Nous montrons que les ZFE favorisent le remplacement anticipé des véhicules anciens et plus polluants par des alternatives moins polluantes. Cet effet reste toutefois limité par rapport au renouvellement tendanciel du parc, lié au remplacement progressif des véhicules anciens devenus obsolètes par des véhicules plus récents. Les ajustements se produisent principalement au moment de l’achat, plutôt que par une augmentation des mises au rebut ou un remplacement plus précoce des véhicules. Les réactions d’anticipation sont marquées et les ménages adaptent leurs comportements d’achat dès l’annonce, souvent plusieurs années à l’avance, de la mise en place des ZFE, malgré des sanctions limitées.

Mots-clés : Zones à faibles émissions, pollution locale, restrictions de circulation

Codes JEL : I18, Q52, Q53

The Impact of Low Emission Zones on Vehicles Fleet: Evidence from France

This paper examines the effects of Low-Emission Zones (LEZs) on vehicle fleet composition and car market dynamics in France. We find that LEZs encourage the early replacement of older and more polluting vehicles with cleaner alternatives. This effect, however, remains small relative to the natural renewal of the fleet, as older vehicles gradually become obsolete and are replaced by newer ones. Adjustments occur primarily at the point of purchase, rather than through accelerated scrappage or earlier vehicle replacement. Anticipatory responses are pronounced, reflecting forward-looking behavior in a context of early policy announcements, despite limited enforcement.

Keywords: Low emission zones, local pollution, driving restrictions

JEL Code : I18, Q52, Q53

1 Introduction

Traffic is an important factor driving persistent air pollution in urban areas (Heydari et al., 2020). Emissions from road vehicles contribute substantially to respiratory health problems (Godzinski and Suarez Castillo, 2024), prompting city authorities worldwide to enforce car usage restrictions. A first wave of driving restrictions uniformly applied to all vehicles regardless of their emission levels. A second wave of policies have implemented vintage-specific driving restrictions, motivated by the fact that newer vehicles tend to emit less local air pollutants (Chen and Borken-Kleefeld, 2016; Jacobsen et al., 2023). These policies sharply restrict the access of older, more polluting vehicles to urban areas while imposing lighter or no restrictions on newer, cleaner ones (Barahona et al., 2020). Low Emission Zones (LEZs henceforth) are a particularly stringent instance of this second set of policies whereby some vehicles become fully ineligible to drive in the restricted areas.

This study aims to evaluate the impact of Low Emission Zones (*Zones à faibles émissions*, ZFE) in France on the vehicle fleet in circulation within the cities affected by these traffic restrictions. It focuses on the 10 LEZs gradually introduced between 2017 and 2023 in Paris and several large regional metropolitan areas to reduce air pollution, which exceeded European legal standards in these cities. As in other countries that adopted similar policies earlier, each LEZ defines a perimeter covering all or part of the urban core and restricts access, during all or part of the week, for the most polluting vehicles, including passenger cars, light commercial vehicles or heavy-duty vehicles.

There are two main motivations for studying the change in the fleet in response to LEZs. First, this type of measure is typically costly for impacted drivers, but the magnitude of the welfare loss depends very much on their ability to substitute toward non forbidden ways of getting to the zoned areas. This can occur mainly through using public transportation or purchasing eligible vehicles. Given the low degree of substitutability between personal vehicles and public transportation (Hensher, 1998; Pastori et al., 2018; Urbanek, 2021), changes of vehicles are likely to be a primary margin of adjustment to LEZs. Second, in France, as in other contexts, the implementation of LEZs has been gradual, in part in order to let households adjust progressively to the new legislation. Given that cars are a durable good, their purchase are a forward-looking decision. Accordingly, even if a LEZ is announced and not strictly implemented yet, households might still integrate future effective restrictions in their choice. Therefore, change in fleet composition are a leading indicator of changes in air quality in impacted areas.

This paper relies on the Statistical Register of Road Vehicles, constructed by linking technical inspection records with vehicle registration certificate data. This source allows us to measure, at the city level, the annual stock of vehicles in circulation since 2011, disaggregated by vehicle type, vintage, fuel type, GHG emission, and Crit'Air sticker. We complement these data with parameters on NOx and PM2.5 emissions by vehicle characteristics, which allows us to estimate local pollutant emissions from cars. The Crit'Air system is the classification used to determine whether a vehicle is allowed to circulate within a LEZ. It ranks passenger cars on a scale from 1 to 5 based on fuel type and year of first registration, with higher values corresponding to more polluting vehicles. The classification favors gasoline-powered vehicles over diesel-powered vehicles, which emit higher levels of local pollutants for comparable characteristics, and newer vehicles over older ones.

The identification of the LEZ effect relies on a difference-in-differences strategy that exploits the staggered implementation of the policy across cities. Treated units are cities whose local authorities, namely intermunicipal communities (ICs, in French *Établissements publics de coopération intercommunale* or EPCIs) implemented a LEZ. The control group is constructed from non-treated IC with similar characteristics.

We find that, following LEZ implementation, the stock of older and more polluting passenger cars declines relative to comparable cities without LEZs, while the share of cleaner vehicles increases gradually.

To interpret the magnitude of the effects, we compare the estimated impact of LEZs with the mechanical renewal of the car fleet that would have occurred in their absence. This comparison shows that LEZs do accelerate the transition toward cleaner vehicles, but that their effect remains modest relative to the natural replacement of older cars by newer ones. Over a five-year window, the stock of cleaner cars (Crit'Air 1 and electric), increases by 88.4% in cities introducing an LEZ, but only 5.8 percentage points of this increase are attributable to the policy itself. For more polluting vehicles (Crit'Air 3 and 4), LEZs reinforce an already ongoing decline: they account for around 4.5 to 5.5 percentage points of total observed declines of 34.5% and 53.6%, respectively. This corresponds to roughly one tenth of the total decline for Crit'Air 3 vehicles and one sixth for Crit'Air 4 vehicles. Finally, the stock of very polluting vehicles (Crit'Air 5 and unclassified), drops by 64.1% over the period, but the additional effect attributable to LEZs is not statistically significant.

This translates into a 7% decline in NO_x emissions from resident passenger cars two years after implementation, as well as a 2% reduction in $PM_{2.5}$ and GHG emissions, attributable to the ZFE policy. These estimates are not based on theoretical emission factors, which are known to underestimate actual emissions (Reynaert, 2021), but on real-world emissions measures that are consistent with aggregate emissions.

The main adjustment occurs at the point of purchase. Scrappage and resale responses remain limited, indicating that LEZs do not primarily induce households to replace vehicles earlier than planned. Instead, when households eventually change vehicles, they shift demand toward cleaner alternatives. Both new and second-hand purchases strongly respond to LEZ adoption, although the estimates for new vehicles are more fragile, notably because of pre-existing differences between treated and control areas. Using a gravity model of second-hand car flows, we show that this reallocation of demand contributes to a spatial displacement of more polluting vehicles toward less regulated areas.

We also document pronounced anticipation effects. Adjustments in purchase behavior begin before formal implementation, reflecting the institutional context in which LEZs were mandated nationally in 2019 and announced several years in advance at the local level. Anticipation is strongest on purchases, consistent with the durable nature of vehicles and forward-looking household behavior, as buyers internalize expected future access restrictions at the time of acquisition.

Beyond average effects, we find substantial spatial heterogeneity and spillovers. Responses vary markedly across cities, consistent with differences in LEZ design, including perimeter size and the set of restricted vehicles. Within treated cities, effects are stronger in central municipalities than in suburban ones. In addition, we find clear spillovers to neighboring ICs, suggesting that exposure to LEZ restrictions extends beyond the strict policy perimeter, plausibly through commuting and other mobility flows. Effects are also stronger in middle- and low-income municipalities, where the initial fleet is more polluting, and weaker in high-income municipalities.

Related literature. Our paper relates to a growing literature on the environmental and economic effects of urban driving restrictions. Earlier policies which implemented solely temporal restrictions (what time of the day or day of week) with no conditions on the type of cars being used have a mixed record. In particular, in the case of the *Hoy No Circula* (HCN) in its instance implemented in Mexico City, several studies (see e.g. Eskeland and Feyzioglu, 1997; Davis, 2008; Gallego et al., 2013) point to increase in fleet size and a shift toward dirtier vehicles. LEZs, by setting trageted restrictions on polluting cars, are likely to avoid these pitfalls (Barahona et al., 2020). Galdon-Sanchez et al. (2023) find that Madrid LEZ has reduced congestion (consistent with Tassinari, 2024) and pollution. They further document a decline in spending on local businesses in the restricted areas, which consumers compensate by an increase in online shopping. Wolff (2014) estimates the effect of LEZs in Germany on air pollution and the shift toward greener vehicles among residents. He compares LEZs to areas without LEZs before and after the implementation of LEZs. He finds a decrease urban air pollution by approximately nine percent without increasing pollution in non-traffic areas, explained in part by the fact that residents near LEZs tend to switch to cleaner vehicles. The health benefits are significant, estimated at around two billion dollars, compared to a one billion dollar cost for upgrading vehicles. Consistent with Wolff (2014) we find that the fleet shifts toward less polluting cars.

More closely related to our paper, Fardella et al. (2023) examines the impact of vintage-specific driving restrictions on air pollution and vehicle usage in Santiago, Chile. Using discontinuity in terms of vintage, before and after the reform, they find a shift toward cleaner vehicles in targeted areas. However, their empirical estimates combined with a model of the second market, suggest that, as restricted cars become cheaper, they are exported in nearby areas which offsets part of the gains in terms of air quality within the targeted area.[1] Looking at Madrid, Balaguer et al. (2023) find that scrapping increase within the LEZ and conclude that thanks to this scrapping effect "the social gains from LEZs are not limited to improving the air quality inside it" as cleaner vehicles also drive in areas nearby the LEZ.

Plan of the paper. Our paper is structured as follows. Section 2 examines the institutional context of the low-emission zone policy, tracing its progressive implementation and detailling the restrictions imposed on car owners. Then, in section 3, we introduce our administrative data sources. In section 4 we develop our empirical approach, we adopt a stacked-event difference-in-difference strategy to leverage the staggered implementation of the policy. Building on our data, in section 5 we provide a descriptive analysis on the features of the car fleet between 2011 and 2025. Finally, section 6, presents our findings on the policy's impact on fleet evolution at the city level.

2 The low-emission zone policy in France

The low-emission zone (LEZ) policy (*zones à faibles émissions*, ZFE) designates specific areas within cities where only low-emission vehicles are allowed. By restricting access to certain areas for the most polluting vehicles, this policy aims to reduce the concentration of harmful pollutants such as nitrogen dioxide (NO_2) and fine particles (PM_{10} and $PM_{2.5}$). According to the Ministry of Ecological Transition, every year in France, more than 40,000 premature deaths are due to fine particles, and 7,000 to nitrogen oxides.[2]

Vehicle classification. In France, low-emission zones restrict access to vehicles based on their Crit'Air sticker and vehicle category. Vehicle owners are required to obtain a Crit'Air sticker, at a cost of a few euros, and display it on their windshield. The Crit'Air classification is determined by the vehicle type (cars, light commercial vehicles, heavy goods vehicles, etc.), its Euro emission standard (closely related to the vehicle's original registration), and the type of fuel/energy it uses (electric, petrol, diesel), which when combined approximate the vehicle's emission level. Vehicles are classified from Crit'Air E (electric and hydrogen vehicles) to Crit'Air 5 (older diesel vehicles). Cars registered before 1997, deemed excessively polluting, are not classified. Appendix Figure 8 provides detailed classification rules for cars and light commercial vehicles.

[1] Relatedly, Börjesson et al. (2021) develop a simple model to show how LEZ welfare cost to drivers can be derived from changes in the prices of restricted vehicles on the second hand market. Applying the model to an hypothetical LEZ for light vehicles in Stockholm, prohibiting diesel cars of Euro 5 (or lower) and gasoline cars of Euro 4 (or lower) to enter the city center, they find that cost outweight the benefit by a large margin.

[2] In the European Union, Watkiss et al. (2005) report that PM_{10} alone is estimated to cause 348,000 premature deaths annually.

LEZ policies are designed to toughen over time: access restrictions typically begin with non-classified vehicles, followed by successive bans on Crit'Air 5, 4, and lower-rated vehicles. The most stringent LEZs ultimately plan to allow only Crit'Air E and Crit'Air 1 vehicles.

General policy framework. In France, low-emission zones result from a gradual policy process. They have replaced the earlier *zones à circulation restreinte* (ZCR), an experimental framework introduced in 2015 that allowed local authorities to restrict traffic on air-quality grounds. Only a few pioneering urban areas, notably Paris, Grenoble and Strasbourg, implemented a ZCR during this initial phase.

The 2019 Mobility Orientation Law (*Loi d'orientation des mobilités*) made the establishment of LEZs mandatory in cities regularly exceeding European thresholds for pollutants such as nitrogen dioxide or particulate matter. At the time of the law's adoption, eleven cities[3] were identified as falling under this category and were required to implement a LEZ within the next two years. The scope of the policy was subsequently broadened by the 2021 Climate and Resilience Law (*Loi Climat et résilience*), which made LEZ mandatory for all cities with more than 150,000 inhabitants, regardless of air quality.

The LEZ policy has sparked considerable public debate. Critics have emphasized its potential economic impact on low-income households and small businesses, which may struggle to afford newer, cleaner vehicles. From 2023 onwards, implementation consequently became more flexible than initially planned. Only cities that still exceed air-pollution legal thresholds on a regular basis are required to ban specific vehicle categories (Crit'Air 4 vehicles in 2024 and Crit'Air 3 vehicles in 2025). Compared with the eleven cities identified in 2019, only Paris and Lyon still fell into this category in 2023. The remaining cities among the 43 cities with more than 150,000 inhabitants are required to establish a LEZ but are not subject to binding targets regarding vehicle bans. This gradual relaxing culminated in 2025 with a vote in the National Assembly making LEZs optional. However, the legislative process is still ongoing, and this repeal has not been enforced yet.

Local implementation. In France, low-emission zones are implemented by intermunicipal communities (*établissements publics de coopération intercommunale*, EPCIs). An IC is a French local authority that groups several municipalities in order to jointly manage economic development, spatial planning, transport, waste and raise local taxes. Within the national legal framework described above, ICs determine the geographic perimeter of the LEZ (for instance a central area or a wider perimeter, with possible exemptions for major roads), the time periods during which restrictions apply and the categories of vehicles covered (cars, light commercial vehicles, two-wheelers, heavy goods vehicles). They also define the schedule according to which access conditions based on Crit'Air categories are introduced or tightened. Finally, both at the national and local levels, LEZ rules have been made more flexible. For example, the ban on Crit'Air 2 vehicles in the Greater Paris (*Métropole du Grand Paris*, MGP), initially planned for 2024, is now scheduled for 2030.

As of 2023, there were 12 LEZs in mainland France (Paris, Lyon, Aix–Marseille, Toulouse, Nice, Montpellier, Strasbourg, Grenoble, Rouen, Reims, Clermont-Ferrand and Saint-Étienne).[4] Fourteen LEZs were added in 2025, but they are generally less ambitious. In most cases, only a small share of the vehicle fleet, consisting of the oldest and most polluting vehicles, is effectively banned from traffic.

Sanctions. In LEZs, driving a non-authorised vehicle is subject to a fixed fine of €68 for light vehicles and €135 for heavy goods vehicles. In practice, however, sanctions related to LEZs have so far been very limited. As shown in Table 2, the number of LEZ fines remains extremely small compared with

[3] Reims, Grenoble, Lyon, Marseille, Montpellier, Nice, Paris, Rouen, Strasbourg, Toulon and Toulouse.

[4] The last two LEZs do not target passenger cars and are included only in the results for light commercial vehicles.

Table 1: Population share of the city covered by the LEZ perimeter

City	Share	City	Share	City	Share
Angers	0.388	Le Havre	0.641	Pau	0.633
Annecy	0.536	Lille	1.000	Reims	0.086
Annemasse	0.810	Lyon	0.490	Rennes	0.443
Bordeaux	0.670	Marseille	0.150	Rouen	0.509
Caen	0.445	Montpellier	0.806	St.-Étienne (2023)	0.344
Clermont-F. (2024)	0.239	Nancy	1.000	St.-Étienne (2025)	0.853
Clermont-F. (2025)	1.000	Nantes	0.624	Strasbourg (2019)	0.016
Dijon	0.599	Nice	0.080	Strasbourg (2022)	1.000
Grenoble (2017)	0.131	Nîmes	0.558	Toulouse	0.520
Grenoble (2020)	0.618	Paris (2017)	0.304		
Grenoble (2021)	0.885	Paris (2019)	0.729		

Reading note: In Angers, 38.8 % of the population lives within the LEZ perimeter.
Coverage: Cities that had implemented a LEZ by 2025. When the perimeter changed over time, each version is reported separately. Total population is measured at the level of the intermunicipal community.
Data source: INSEE, Fideli, transport.data.gouv.fr, authors' calculations.

Table 2: Recorded traffic fines by type, 2017–2024 (in thousands)

	2017	2018	2019	2020	2021	2022	2023	2024
LEZ fines	0.3	6.5	12.6	5.6	5.2	4.8	2.7	2.3
Administrative traffic fines	1,851.6	1,642.7	1,645.8	1,478.5	1,617.2	1,673.8	1,533.8	1,033.1
of which: insurance	748.8	765.0	824.9	715.3	827.8	847.9	754.9	287.9
of which: technical inspection	470.5	283.1	255.7	210.7	193.2	192.2	155.8	147.7
Total traffic fines	29,068.7	25,844.2	24,742.8	23,240.6	26,744.0	29,193.9	29,190.5	26,512.2

Reading note: In 2019, 10,900 LEZ related fines were recorded.
Coverage: LEZ-related fines cover the operation of a motor vehicle, a public passenger transport vehicle, or a goods vehicle weighing over 3.5 tonnes within a restricted traffic zone without the required air quality certificate or with a non-compliant certificate (offence codes 31897, 31898, 31899, 32385, 32386, and 32387)..
Source: ONISR, *Bilan des infractions au code de la route en France*, 2023 and 2024.

other categories of traffic fines. Even at their peak in 2019, LEZ-related fines amounted to fewer than 12,600 cases nationwide, representing less than 0.05 % of total traffic fines recorded that year. Moreover, between 2019 and 2024, the number of LEZ fines fell by about 80 %, while those related to administrative traffic rules remained at much higher and relatively stable levels. By contrast, insurance and vehicle inspection-related fines, which are the two main administrative traffic violations to which LEZ sanctions belong, consistently account for several hundred thousand fines each year.

Most of the time, local authorities decide to only partially apply LEZ sanctions. In many areas, during an initial "educational phase", drivers are checked and informed but not fined. Although automated enforcement using license plate recognition has been planned for the longer term, it has so far remained manual.

Financial incentives. Two national policies, not connect to LEZs, aim to encourage vehicle replacement, particularly for low-income households. In 2024, the ecological bonus (*bonus écologique*) was a state subsidy for the purchase or lease of a new vehicle and could reach up to 7,000 euros. The conversion bonus (*prime à la conversion*), which can be combined with the ecological bonus, aims to support households who purchase or lease a cleaner vehicle in exchange for scrapping an old one. In 2024, the bonus could reach up to 5,000 euros for an electric car, depending on the household income level.

An additional subsidy of 1,000 euros was granted if the driver lives or works in a LEZ. Local authorities could also offer additional support for cleaner vehicle purchases, up to 6,000 euros in Paris and 3,000 euros in Lyon. These local subsidies can be combined with national policies.

3 Data

Road vehicle register. Data on the number of vehicles in circulation, the annual traveled distance, as well as on new and used vehicle purchases and, more generally, all measures of the vehicle stock, are drawn from the Road Vehicle Statistical Register (*Répertoire statistique des véhicules routiers*, RSVERO). The annual RSVERO files are produced by the statistical department of the French Ministry of Ecological Transition (*Service des données et études statistiques*, Sdes).

RSVERO results from the merger of two primary administrative sources:

- The Vehicle Registration System (*Système d'immatriculation des véhicules*, SIV), managed by the National Agency for Secure Titles (*Agence nationale des titres sécurisés*, ANTS) provides detailed technical characteristics of vehicles (cars, light commercial vehicles, heavy goods vehicles, etc.), information on the vehicle user (owner or long-term renter), and records administrative events throughout the vehicle's life cycle (initial registration, change of ownership, address changes, destruction, etc.).

- Vehicle technical inspection records, collected by the Technical Union of the Automobile, Motorcycle, and Cycle (*Union technique de l'automobile, du motocycle et du cycle*, Utac), include odometer readings recorded at each inspection. Comparing successive readings makes it possible to measure travelled distance between two inspections. In addition, regular inspections serve as a "sign of life," ensuring that vehicles recorded in the register are effectively in circulation.

The annual RSVERO files used in this study cover vehicles subject to mandatory periodic technical inspections. This scope includes the vast majority of road vehicles, with notable exceptions such as two-wheelers, which are therefore excluded from our analysis, even though they are affected by LEZ policies. For each vehicle, the annual files provide detailed information on vehicle characteristics, presence in the fleet in a given year, annual characteristics of the user, and annual distance travelled. Each vehicle is geographically located at the place of residence of its user, as recorded on the registration certificate.

In this study, we focus on vehicles in circulation on January 1st of each year from 2011 to 2025, at the municipal level. We restrict the analysis to cars and light commercial vehicles. Coaches and buses represent a negligible share of the fleet, while trucks are likely to be used far from their place of registration for most of the time. By contrast, locating cars and light commercial vehicles at the municipality of residence provides a more reasonable approximation of their place of use. LEZ exposure is therefore defined on the basis of the driver's residential address as recorded on the vehicle registration certificate.[5]

The data allow us to track the evolution of vehicle fleets by vehicle type (car or light commercial vehicle), Crit'Air sticker category, type of owner (private or professional), and year of first registration and Euro emission standards. In addition, RSVERO makes it possible to identify vehicles that change owners or municipalities within a given year. As a result, we can compute, for each municipality and each year, the number of vehicles purchased (new or used), sold, or scrapped. For transactions involving a change in geographic location, origin and destination municipalities can also be identified.

[5] Although drivers are legally required to update this address after moving, some may fail to do so, or may do so only with a delay, which introduces some uncertainty into the measurement of the vehicle fleet located within LEZs.

Car pollution. Our pollution estimates are not based on theoretical emission factors, which are known to underestimate actual emissions (Reynaert, 2021), but on real-world emission measures that are consistent with aggregate emissions.

For greenhouse gas emissions, we rely on unitary tank-to-wheel GHG emissions already available in the RSVERO dataset for each car. As explained in (Trevien et al., 2024), Sdes adjusts homologated values for real-world driving conditions using observed fuel-consumption data.[6]

RSVERO does not provide information on local air pollutants. Following the approach proposed by Leroutier and Quirion (2022), we construct emission factors for NOx and PM2.5 using OMINEA, the French national inventory system for air pollutant and greenhouse gas emissions compiled by Citepa.[7] These factors correspond to average real-world emissions per kilometer by year, Euro standard, and fuel type. After merging with RSVERO, we combine them with annual vehicle mileage, inferred from technical inspection records, to approximate annual emissions from passenger cars registered in each city. Appendix 8.2 describes in detail how these factors are constructed. A degree of approximation remains, since for a given year we assign the same emission factor to all vehicles with the same Euro standard and fuel type. These estimates, however, should not be interpreted as direct measures of local ambient pollution: vehicles registered in a given city may drive elsewhere, vehicles registered outside the city and other types of vehicles may circulate within it, and pollutant concentrations also depend on meteorological conditions.

Census. This paper also uses the Annual Census Survey collected by INSEE (*Institut national de la statistique et des études économiques*, the French statistical office) from 2011 to 2024. We use information on automobile ownership, defined as the number of cars used by each household, and compute its distribution at city level. The Census also provides information on commuting modes and on the workplace for employed individuals. However, these data cannot be matched to RSVERO records, which prevents us from identifying the Crit'Air classification of vehicles owned by households or used for commuting. We can nonetheless estimate changes in car possession and car modal share following LEZ implementation.

It is important to note that Census data collection in France is spread over five years. For municipalities with fewer than 10,000 inhabitants, the Census is exhaustive and conducted once every five years: municipalities are divided into five groups, with one group surveyed each year. For municipalities with 10,000 inhabitants or more, data collection takes place every year on a rotating sample of dwellings, covering approximately 8% of dwellings annually. As a result, Census figures reported for a given reference year (e.g., 2018) aggregate information collected over five years (e.g., between 2016 and 2020). Indicators from a full Census wave are therefore smoothed across years and may combine pre- and post-treatment observations, which is not appropriate for LEZ evaluation.

We therefore use each Annual Census Survey separately. This is not an issue for large municipalities, where the annual sample size is sufficient to track year-to-year changes in car ownership and commuting modal shares before and after LEZ implementation. It is more problematic for small municipalities, as the five rotation groups were not designed to ensure representativeness at the city level. Consequently, city-level outcomes may be noisy due to small-municipality sampling, which may inflate the standard errors of treatment effect estimates.

[6] These data come from spritmonitor.de, a collaborative platform covering more than 700,000 drivers across Europe. RSVERO vehicles are matched to their closest counterparts in spritmonitor.de using technical characteristics such as brand, model, year, power, and fuel type. The resulting estimates are then made consistent with official Secten-Citepa inventories, which are based on national fuel deliveries, by applying upward correction factors of around 4 percent for both diesel and petrol vehicles.

[7] Citepa (*Centre Interprofessionnel Technique d'Études de la Pollution Atmosphérique*) is the institute mandated by the French government to compile these inventories in accordance with international conventions.

Complementary source. Several complementary data sources are used in this study. We rely on the FIDELI dataset (*Fichier démographique sur les logements et les individus*), compiled annually by INSEE, to measure the average standard of living at the municipal level, defined as disposable income per consumption unit. FIDELI is also used to compute the share of residents of each city living within the LEZ perimeter. This is achieved by combining geocoded individual place-of-residence information with the geographic boundaries of LEZs, which are provided as cartographic files on the `data.transport.gouv.fr` platform.

We also use the functional urban area zoning (*aires d'attraction des villes*, AAV), to determine the total population of the urban area where each LEZ is located.

Finally, we use the Admin Express database provided by the French National Geographic Institute (IGN). This dataset contains, in particular, the geographic boundaries of municipalities and ICs, as well as the location of their administrative centers. These data allow us to compute distances between municipalities and ICs used in the empirical analysis.

4 Empirical Strategy and Identification

4.1 Definition of treatment and control groups

Our baseline unit of analysis is the IC (intercommunal community,*Établissement public de coopération intercommunale*). As stated above, ICs are responsible for the design and implementation of LEZs, making them a natural unit of analysis for this policy. For the sake of simplicity, we will refer to ICs as "cities" in the remainder of this paper. Defining treatment at the IC level also allows us to capture spillovers within it. Because vehicle registration is determined by the municipality of residence of the owner, restricting treatment to the formal LEZ perimeter would neglect exposure for residents of neighboring municipalities who routinely travel into the restricted area.

An EPCI is considered treated from the first year in which passenger-car LEZ restrictions become effective (restrictions for light commercial vehicles may apply earlier; see Table 17). The treatment group consists of EPCIs that implemented such restrictions by 2024. The control group includes EPCIs corresponding to the central municipality of functional urban areas with more than 300,000 inhabitants, the lower population threshold for LEZs introduced until 2023.[8] Table 3 reports the composition of the treatment and control groups by functional urban area size. Note that some EPCIs in the control group implement a LEZ in 2025. We retain them in the control group and present robustness checks in the results section (see subsection 6.2), showing this choice has little influence on the estimated LEZ impacts and improves comparability between treated and control units.

A final clarification concerns Paris, which is excluded from the baseline specifications. First, Paris is substantially larger than the other cities in the sample, making it difficult to construct a credible control group. A robustness check reported in the results section confirms this difficulty, as the common-trends assumption is no longer satisfied when Paris is included in the treated group (see subsection 6.2). Second, the Paris LEZ was introduced much earlier than in other cities, in 2017, at a time when the share of highly polluting vehicles (Crit'Air 4, Crit'Air 5, and non-classified vehicles) was considerably higher (see Section 5). As a result, the effects may differ substantially from those observed in other LEZs. Third, the 2017 LEZ was introduced only at the scale of the city of Paris, with an extension to the IC level (*Métropole du Grand Paris*) in 2019, complicating the evaluation due to changes in the policy perimeter,

[8]We rely on the population of the functional urban area rather than that of the IC itself, as this statistical zoning provides a more consistent basis for comparing city size, whereas IC boundaries may reflect local policy considerations.

Table 3: Composition of the treatment and control groups by functional urban area size

Functional urban area size	Control group	Treatment group
200,000–<300,000 inhabitants	14	0
300,000–<400,000 inhabitants	11	1
400,000–<500,000 inhabitants	8	0
500,000–<700,000 inhabitants	3	2
700,000–<1,000,000 inhabitants	2	3
≥1,000,000 inhabitants (excluding Paris)	2	3
Paris functional urban area	0	1

Reading note: Among central ICs of functional urban areas with between 300,000 and less than 400,000 inhabitants, 11 belong to the control group and 1 implemented a LEZ before 2024. The two LEZs that do not apply to cars (Saint-Etienne and Clermont-Ferrand), but only to light commercial vehicles, are not counted as treated and are included in the control group.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants.
Source: INSEE, Census, 2022.

all the more so in the presence of anticipatory effects, as is the case with this policy.[9] That said, the synthetic analysis method, whose results are presented in subsection 6.3, allows us to estimate the impact of this specific LEZ on the vehicle fleet and the car market.

4.2 Baseline identification: stacked difference-in-differences

Setup and notation. We identify the effect of LEZ implementation on fleet composition using a difference-in-differences framework at the city level. The treatment consists in the introduction of passenger-car LEZ restrictions. Let C_i denote the year in which such restrictions become effective in city i. For cities that never implement a LEZ during the period of analysis, we set $C_i = \infty$, following standard event-study notation. Formally,

$$C_i = \infty \iff \text{LEZ}_i = 0$$

where LEZ_i is an indicator equal to one for cities that eventually implement a LEZ.

Let $Y_{it}(c)$ denote the potential outcome (car fleet by Crit'Air sticker, car sales and purchases, and NO_x, $\text{PM}_{2.5}$, and GHG emissions, etc.) for city i in year t if LEZ restrictions are first implemented in year c. Here, c is a potential treatment timing—a fixed value indexing the counterfactual—while C_i is the random variable representing the actual (observed) treatment timing for unit i. The observed outcome is $Y_{it} = Y_{it}(C_i)$.

A standard linear event-study formulation of potential outcomes is:

$$Y_{it}(c) = \alpha_i + \lambda_t + \sum_{\tau \neq K} \delta_\tau \, \mathbb{1}(t - c = \tau) + \varepsilon_{it},$$

where α_i are IC fixed effects, λ_t are year fixed effects, and the coefficients δ_τ capture dynamic treatment effects, relative to the omitted reference period K.

Identification. Identification relies on a parallel trends assumption in potential outcomes. In the absence of treatment, outcomes in ICs that eventually implement a LEZ would have followed the same

[9] The LEZ perimeters in Strasbourg and Grenoble were also gradually extended, but only during the period preceding the introduction of passenger-car traffic restrictions; these extensions applied exclusively to light commercial vehicles.

evolution as outcomes in ICs that never implement a LEZ:

$$\mathbb{E}[Y_{it}(\infty) - Y_{i,t-1}(\infty) \mid \text{LEZ}_i = 1] = \mathbb{E}[Y_{it}(\infty) - Y_{i,t-1}(\infty) \mid \text{LEZ}_i = 0].$$

This assumption is plausible given our restriction of the control group to central ICs of functional urban areas with more than 300,000 inhabitants, which ensures institutional and demographic comparability between treated and control units.

Stacked difference-in-differences design. LEZ adoption is staggered over time, between 2021 and 2023. In the presence of staggered treatment timing, estimating dynamic treatment effects using standard two-way fixed effects event-study specifications may yield biased estimates, as emphasized by recent contributions (De Chaisemartin and d'Haultfoeuille, 2022; Sun and Abraham, 2021; Borusyak et al., 2024). To address these concerns, we rely on a stacked difference-in-differences design close to Cengiz et al. (2019) and Dube et al. (2023).

For each cohort of treated cities, we construct a cohort-specific dataset that combines treated units with a control group that is never exposed to LEZ restrictions over the analysis period. Control cities are therefore duplicated across stacks, as in standard stacked DiD implementations. cities are grouped into cohorts defined by the year of first implementation C_i.

Estimation. We estimate event-study specifications over a window around treatment, constructing lead and lag indicators $\mathbb{1}(\tau = k)$ for $k \in [-5, 2]$. We omit $\tau = -3$ as the reference period. This choice is motivated by the potential presence of anticipation effects, as LEZ policies are announced several years before their effective implementation. Periods immediately preceding treatment may therefore already reflect behavioral adjustments in response to forthcoming restrictions.

The baseline specification is estimated using Poisson pseudo–maximum likelihood (PPML). This approach accommodates zero-valued outcomes and allows treatment effects to be interpreted in multiplicative terms. Treatment effects are identified by interacting event-time indicators with an indicator for cities belonging to the treated cohort:

$$\mathbb{E}[Y_{its} \mid \cdot] = \exp\left(\sum_{\tau \neq -3} \beta_\tau \, \mathbb{1}(C_i - t = \tau) \times \mathbb{1}(\text{LEZ}_i = 1) + \alpha_{is} + \delta_{ts}\right)$$

where s indexes the stack in the stacked dataset and Y_{its} denotes outcomes such as fleet size, scrappage, and second-hand inflows and outflows, measured at the IC–year level and, in some specifications, by Crit'Air category. The fixed effects α_{is} absorb time-invariant heterogeneity at the IC-by-stack level, while δ_{ts} capture stack-specific year shocks. The coefficients β_τ therefore capture dynamic treatment effects on the treated. Standard errors are clustered at the IC-by-cohort level.

5 Descriptive statistics

Before turning to the econometric analysis, we present descriptive statistics on the evolution of the passenger car fleet in large urban areas over the past decade, distinguishing between the treatment and control groups. These stylized facts provide preliminary evidence on how vehicle stocks and flows evolved in cities exposed to LEZ policies relative to comparable urban areas. In line with the baseline econometric specifications, the treatment group comprises the nine LEZ (excluding Paris) that introduced passenger-car restrictions by 2024: Reims (in 2021), Rouen, Lyon, Marseille, Montpellier, Strasbourg (in

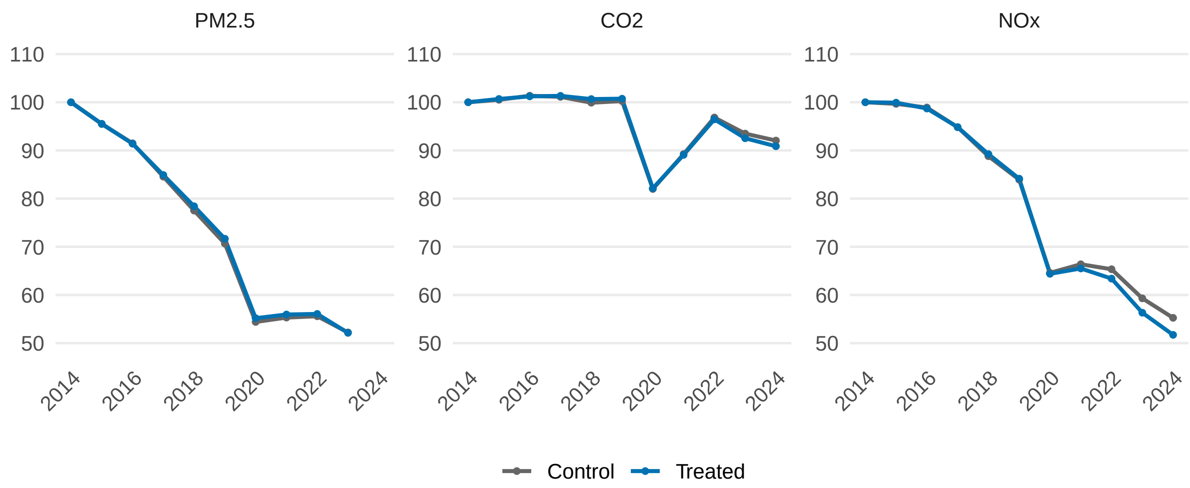


Figure 1: Pollution from passenger cars (2014 indexed to 100)

Reading note: In 2022, the total amount of PM2.5 emitted by passenger cars registered in the treated group was 56% of its 2014 level.
Data sources: SDES, RSVERO, OMINEA, Citepa, 2014–2024.
Coverage: Central ICs of functional areas with more than 300,000 inhabitants, excluding Paris.

2022), Nice, Grenoble and Toulouse (in 2023). The control group consists of 26 central ICs of functional urban areas with more than 300,000 inhabitants that had not implemented a LEZ by 2024.

These descriptive figures are not intended to provide a graphical representation of the identification strategy itself, since the latter is defined relative to each city's year of implementation and treatment is staggered across cities. Instead, they document the aggregate evolution of outcomes over time and provide a useful benchmark for comparing treated and control cities up to 2020, when none of the LEZs in our treatment group had yet been implemented, and from 2023 onward, once all of them were in place.

Car pollution. Figure 1 reports the evolution of emissions from passenger cars for three pollutants, $PM_{2.5}$, NO_x, and CO2, indexed to 100 in 2014. These estimates do not measure ambient pollution, but annual emissions from passenger cars registered in each group (see Section 3). Local air pollutants decline markedly over the period in both the treatment and control groups. By 2024, PM2.5 and NO_x emissions are roughly half of their 2014 level. These downward trends largely reflect the gradual renewal of the vehicle fleet and the tightening of emission standards over time, which have substantially reduced local pollutant emissions from newer vehicles (Jacobsen et al., 2023). The decline in NOx is somewhat stronger in the treated group after 2022, which roughly corresponds to the start of LEZ implementation, but most of the observed decline is common to LEZ and non-LEZ cities. By contrast, trends are very similar in both groups for PM2.5 and CO_2. They remain close to their 2014 level until 2019, before dropping sharply in 2020, reflecting the reduction in distances traveled during the Covid-19 pandemic.

All in all, the evolution of local pollutant emissions is very similar in treated and control cities. This partly reflects the way NOx and PM2.5 emissions are constructed: emission factors vary by year, Euro standard, and fuel type, and are then combined with annual vehicle mileage. Because these categories remain relatively broad, this approach likely smooths out part of the heterogeneity in vehicle emissions and may partly explain the close trends observed in the two groups.

Car fleet. Figure 2 shows that the share of passenger cars equipped with a Crit'Air sticker is substantially higher in LEZ cities than in the control group as early as 2017. One explanation is that

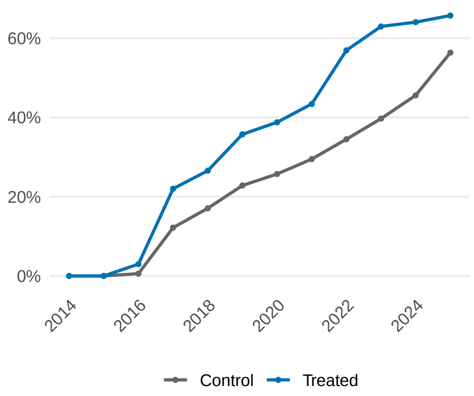


Figure 2: Share of passenger cars with a Crit'Air sticker
Reading note: Note: in 2016, the share of passenger cars equipped with a Crit'Air sticker reaches 0.9% in the control group and 4.4% in the treated group.
Data source: Sdes, RSVERO, 2014-2025.
Coverage: Central ICs of functional areas with more than 300,000 inhabitants, without Paris.

the Crit'Air sticker is not used exclusively for LEZ access restrictions, but also for differentiated traffic schemes during pollution peaks (*circulation différenciée*). However, this mechanism is activated only rarely and remains of secondary importance relative to LEZs. This early adoption in the control group is therefore more likely to reflect temporary or occasional use of drivers visiting another city where a LEZ is in force. The gap between the two groups widens markedly in 2022, when most cities in the treatment group effectively implemented passenger-car LEZ restrictions. Some convergence is observed from 2024 onwards, which may be related to the fact that some control cities implemented a LEZ in 2025.

We next examine the composition of the passenger car fleet by Crit'Air category. Throughout the paper, we group Crit'Air E and Crit'Air 1 vehicles, which correspond to the cleanest segment of the fleet, as Crit'Air E (electric vehicles) vehicles remain rare over the period. Symmetrically, we group Crit'Air 5 and non-classified vehicles, since the latter category, which includes all cars first registered before 1997, is also small, especially toward the end of the period. Figure 3 highlights pronounced changes in fleet composition over time in both the treatment and control groups between 2014 and 2025. These dynamics are largely driven by a mechanical renewal process: older vehicles progressively exit the fleet as they become obsolete and are replaced by more recent ones. Because Crit'Air classification is directly determined by the year of first registration, this renewal process mechanically generates substantial shifts in fleet composition over time. Some differences emerge by the end of the period between treatment and control groups. The share of Crit'Air E and Crit'Air 1 cars is around seven percentage points higher in LEZ in 2025, whereas it was very similar in both groups at the beginning of the period. Conversely, the shares of Crit'Air 2, 3, and 4 cars are lower in LEZ cities. Crit'Air 5 and non-classified cars are initially more prevalent in the control group, but the gap gradually narrows over time and eventually converges to a similar low plateau in both groups. The remaining vehicles in these categories may be less responsive to LEZ restrictions, since they may include collector cars, exempt from LEZ rules, cars owned by households living outside the LEZ perimeter and rarely circulating within it, or cars that are used only infrequently.

Car purchases and sales. Car purchases and sales are more likely to respond quickly and sharply to traffic restrictions. A distinction is made between new and second-hand vehicles, since new car purchases only involve Crit'Air E, 1 and 2 vehicles (by definition, no vehicle registered after 2011 is classified under Crit'Air 2). Figure 4 shows that purchases of Crit'Air 2 vehicles, which correspond

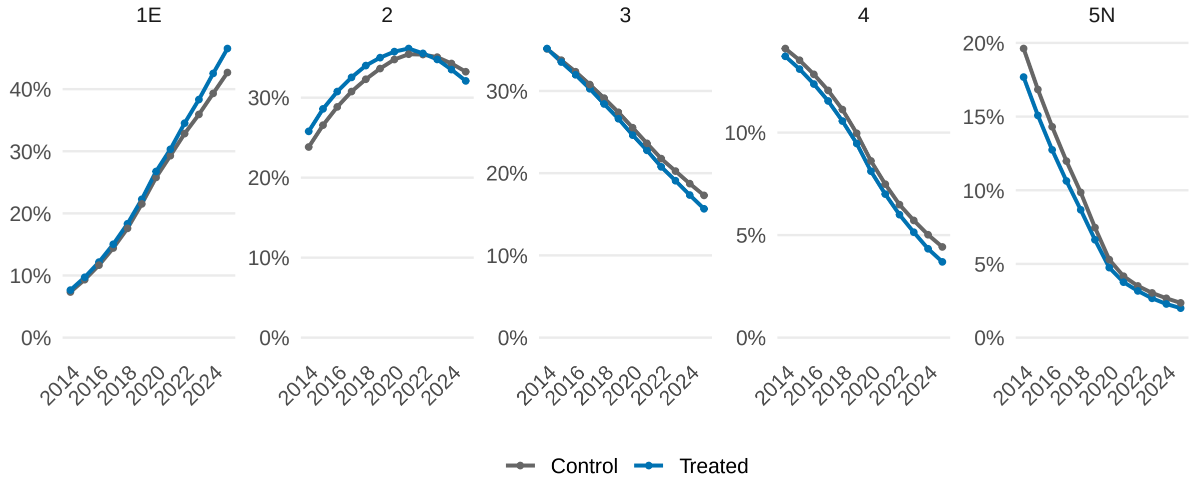


Figure 3: Composition of the passenger car fleet by Crit'Air category

Reading note: in 2016, Crit'Air 1 vehicles represent 11.7% of the passenger car fleet in the control group and 12.2% in the treated group.
Data source: Sdes, RSVERO, 2014-2025.
Coverage: Central ICs of functional areas with more than 300,000 inhabitants, without Paris.

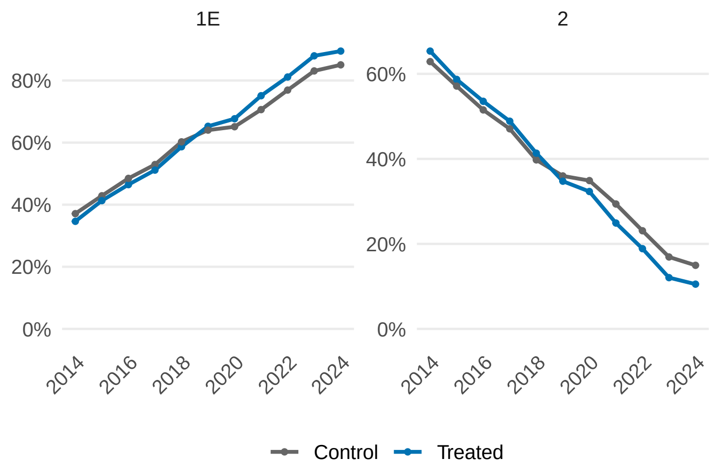
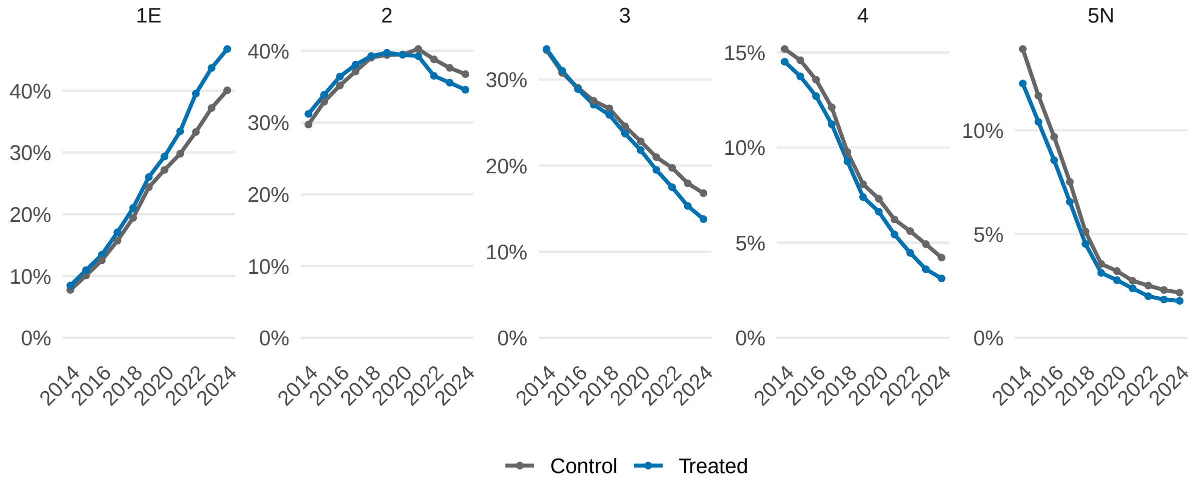
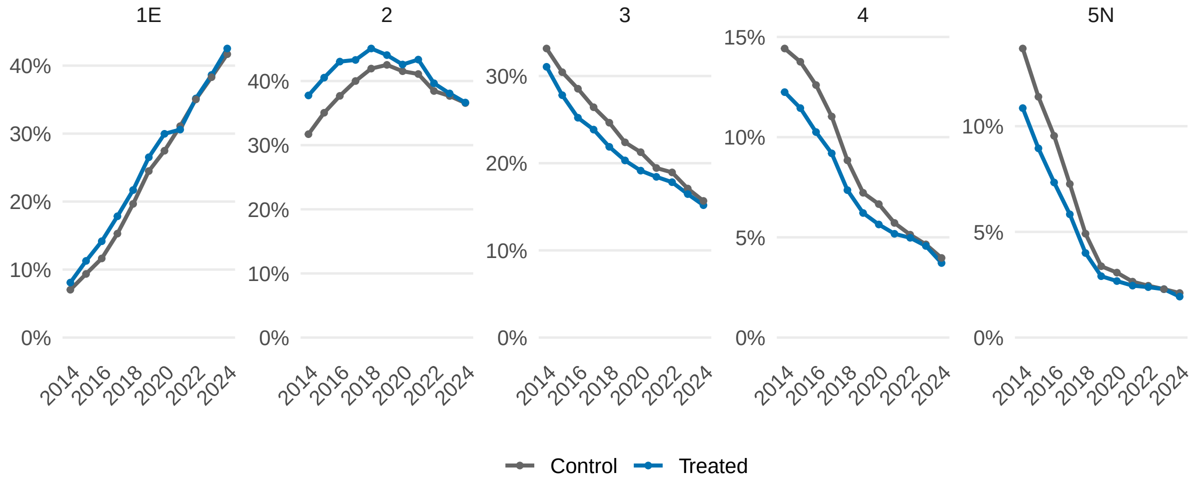


Figure 4: Composition of new passenger car purchases

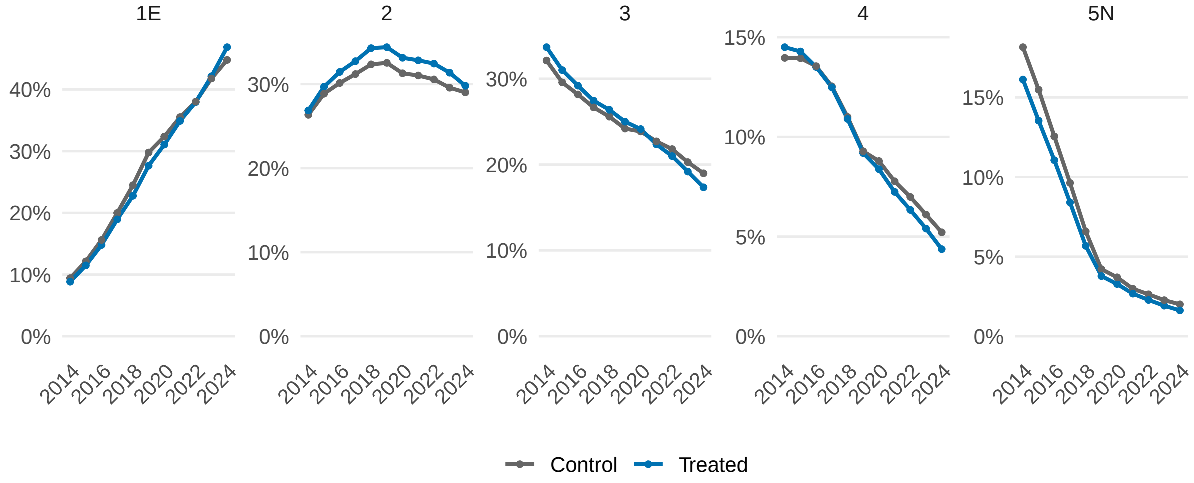
Reading note: in 2016, Crit'Air 1 vehicles account for 48.5% of new passenger car purchases in the control group and 46.5% in the treated group.
Data source: Sdes, RSVERO, 2014-2025.
Coverage: Central ICs of functional areas with more than 300,000 inhabitants, without Paris.



(a) External second-hand passenger car purchases



(b) External second-hand passenger car sales



(c) Internal second-hand passenger car transactions

Figure 5: Passenger car second-hand transactions by Crit'Air category

Reading note: In 2016, Crit'Air 1 vehicles account for 12.5% of external second-hand passenger car purchases in the control group, compared with 13.4% in the treated group.

Data source: Sdes, RSVERO, 2014-2025.

Coverage: Central ICs of functional areas with more than 300,000 inhabitants, without Paris.

to diesel cars, decline sharply in both the treatment and control groups. From 2018 onwards, however, the decline is somewhat steeper in LEZ cities, while trends are largely parallel prior to that date. The gap observed here between treatment and control cities may appear surprising, as Crit'Air 2 vehicles are scheduled to be banned only in the longer run and not in all LEZs. Nevertheless, vehicle purchases typically reflect long-term decisions, and households may anticipate future restrictions. Moreover, ban schedules were announced well in advance, even if subsequently postponed in many cities. For example, the ban on Crit'Air 2 vehicles in the Paris LEZ was announced in 2019 for implementation in 2024 and has since been postponed to 2030.

For the second-hand market, we distinguish transactions according to whether the counterpart is located within the same city or outside the city. This distinction matters because the expected effect of LEZs on within-city transactions is, at first sight, ambiguous, as buyers' and sellers' incentives point in opposite directions. Figure 5 shows that the composition of incoming second-hand passenger car flows from outside the city (panel *External second-hand passenger car purchases*) was very similar in the treatment and control groups in 2014, but gradually shifted toward cleaner vehicles in LEZ cities over the period. For outgoing flows (panel *External second-hand passenger car sales*), sales of higher-emission vehicles (Crit'Air 3 to 5) were less frequent in LEZ cities in 2014, and gradually converged toward the levels observed in the control group by 2024. By contrast, for intra-city second-hand transactions (panel *Internal second-hand passenger car transactions*) display less clear patterns, as expected, since they mainly capture reallocations within the local market.

6 Results

6.1 Baseline effects at the city level

Estimates of the impact of LEZ on the passenger car fleet are based on an event-study design, following the stacked difference-in-differences methodology described in Subsection 4.2. The analysis is conducted over an event-time window spanning five years before to two years after implementation ($\tau \in [-5, 2]$), with coefficients interpreted as semi-elasticities relative to the reference period $\tau = -3$. We examine several dimensions of the passenger car fleet introduced in the descriptive statistics, including air pollution, car use and ownership, new car purchases, and second-hand market transactions.

Before assessing the impact of LEZs on the main outcomes of the policy, air pollution and the car fleet, we first examine whether LEZ implementation affects propensity to order a Crit'Air sticker. Compliance depends not only on a vehicle's eligibility for a given Crit'Air category, but also on the owner actually ordering the sticker and displaying it on the windshield. In our data, we only observe whether a sticker was ordered, not whether it was ultimately displayed on the vehicle, but we view sticker orders as a meaningful proxy for compliance. Figure 6 summarizes the estimated effects of LEZ implementation on the number of cars without a sticker.[10]

First, pre-treatment coefficients are statistically insignificant, providing support for the parallel-trends assumption. Second, LEZ implementation induces an immediate and sizeable adjustment in the segment of vehicles without a Crit'Air sticker. The stock of non-sticker vehicles declines sharply at the time of implementation, by about 26 percent in the implementation year and by more than 30 percent one year later, before becoming statistically indistinguishable from zero by event time $\tau = 2$. This pattern is consistent with a rapid response by vehicle owners, who complete the administrative steps required to

[10]This outcome is preferable for our estimation strategy because the large mass of zeros for cars with stickers before the introduction of the Crit'Air system may create problems for the estimation of some fixed effects.

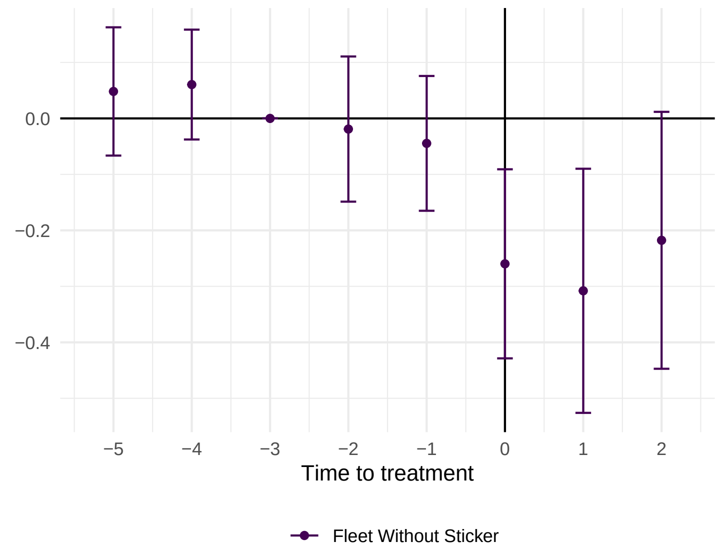


Figure 6: Effect of LEZ on Crit'Air sticker orders
Reading note: One year after implementation, the total number of passenger cars without Crit'Air sticker is about 31 % lower in LEZ ICs than in the control group.
Method: Event-study estimates from stacked difference-in-differences using PPML, relative to the cohort-specific reference year ($\tau = -3$). Fixed effects include IC × cohort and year × cohort, with no additional control variables. Standard errors are clustered at the IC × year level.
Data source: Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

obtain a Crit'Air sticker in order to comply with the new regulatory constraints. There is no evidence of anticipation effects for this outcome, as there is no clear incentive to affix a Crit'Air sticker prior to the entry into force of LEZ restrictions. Overall, this pattern points to high policy salience: drivers appear aware of the new rules and adjust as soon as enforcement becomes binding.

Air pollution. We then assess the impact of LEZs on car-related pollutant emissions. As stated before, we measure only the emissions generated by the circulation of passenger cars owned or rented by residents of a given city, not directly the local air. Focusing on the two most locally harmful pollutants, the estimated impact is larger for NOx: emissions attributable to resident cars fall by about 7 % two years after LEZ implementation (Figure 7).

The reduction in PM2.5 and CO_2 emissions is smaller, around 2 % for different reasons. For PM2.5, the tightening of Euro standards, sharply reduced NOx emissions across gasoline, LNG, LPG, and diesel vehicles, whereas declines in PM2.5 are concentrated among diesel vehicles. Particulate emissions were already low for other internal-combustion vehicles, as illustrated by the 2019 parameters reported in Table 9 in the Appendix. This implies that the decline in particulate emissions can only come from a limited share of the vehicle fleet.

For CO_2 emission, this result is more surprising since Crit'Air certificate is primarily designed to rank vehicles according to local air pollutants and not CO_2. In particular, the classification penalizes diesel vehicles, which are high emitters of local pollutants (Table 9 in the Appendix) but are slightly better in terms of GHG emissions: for vehicles of the same weight, power, and age, gasoline cars emit on average about 25% more GHGs than diesel cars (Babet and Trevien, 2023). At the same time, vehicle CO_2 emissions tend to decline gradually over time: on average, a car emits 1.2% less CO_2 than a car with the same weight, fuel type, and power that was registered one year earlier, reflecting technological

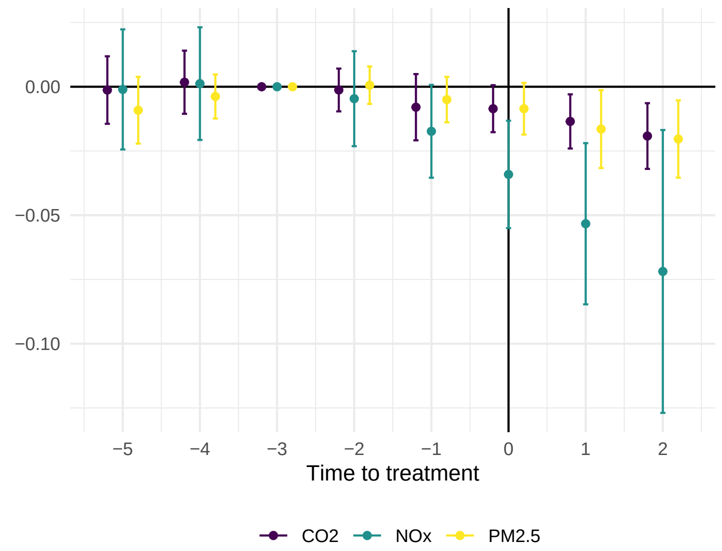


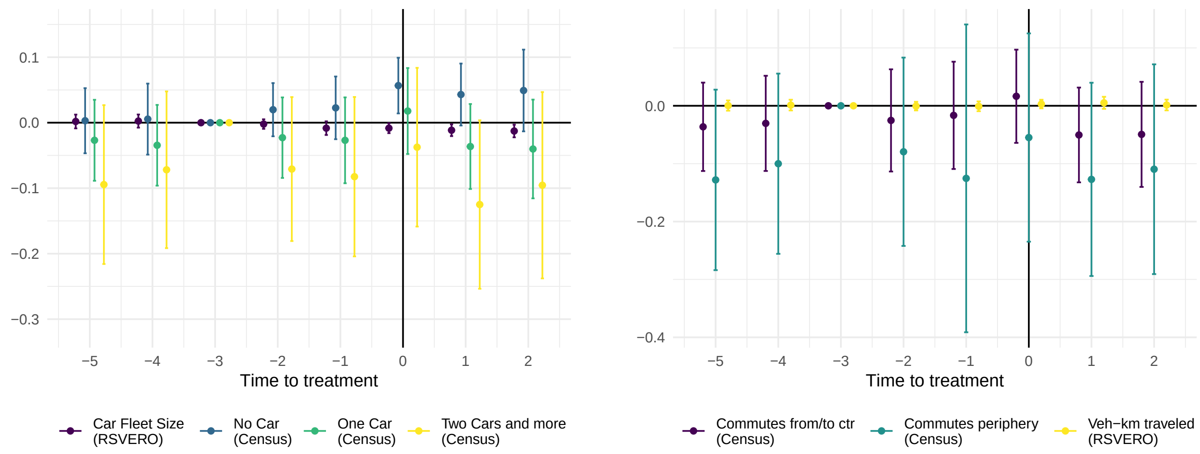
Figure 7: Effect of LEZ on Pollution due to Cars

Reading note: One year after implementation, total NOx emissions from passenger cars are about 5% lower in LEZ ICs than in the control group.
Method: Event-study estimates from stacked difference-in-differences using PPML, relative to the cohort-specific reference year ($\tau = -3$). Fixed effects include IC $\times$ cohort and year $\times$ cohort, with no additional control variables. Standard errors are clustered at the IC $\times$ year level.
Data source: Citepa, Ominea, Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

improvements in engines. The fact that GHG emissions nevertheless fall in LEZs suggests that the potentially adverse effect of phasing out diesel vehicles is more than offset by fleet renewal, possibly combined with changes in vehicle characteristics, such as a shift toward smaller cars, which we do not observe here.

Car use. The impact of LEZs on car use appears limited (Figure 8). On the intensive margin, we find no evidence of a significant effect on vehicle-kilometres travelled (e.g. the aggregate annual distance driven by passenger cars) . Using Census data, we also find no detectable change in car commuting patterns: the number of commuters traveling by car remains stable, both for trips between peripheral municipalities and for trips to or from the city's central municipality. Overall, these results indicate that drivers do not reduce their car use following the implementation of LEZs. We find no evidence of a decline in car trips or of substitution toward alternative modes of transport, despite the restrictions targeting the most polluting vehicles.

On the extensive margin, the total passenger car fleet exhibits only modest changes following LEZ implementation. Point estimates indicate a small but statistically significant decline of about 1 percent by the second post-treatment year. Consistent with this, Census indicates a mild adjustment in car ownership: the share of households reporting no car increases by 6% in LEZs. Large effects are not expected for a policy that is not explicitly designed to curb vehicle ownership and may also reflect the influence of other contemporaneous public policies aimed at reducing car use. In particular, local authorities that choose to implement LEZs may also be more likely to adopt complementary measures affecting car ownership or usage, such as urban highway closures (Bou Sleiman, 2023), expansion of cycling infrastructure (Daniele et al., 2022), removal of on-street parking spaces, or investments in public transport, including tramway systems.



Extensive margin Intensive margin

Figure 8: Effect of LEZ on Car Use

Reading note: One year after implementation, the total number of passenger cars in the fleet is about 1 % lower in LEZ ICs than in the control group.
Method: Event-study estimates from stacked difference-in-differences using PPML, relative to the cohort-specific reference year ($\tau = -3$). Fixed effects include IC $\times$ cohort and year $\times$ cohort, with no additional control variables. Standard errors are clustered at the IC $\times$ year level.
Data source: Insee, Annual Census Surveys, Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

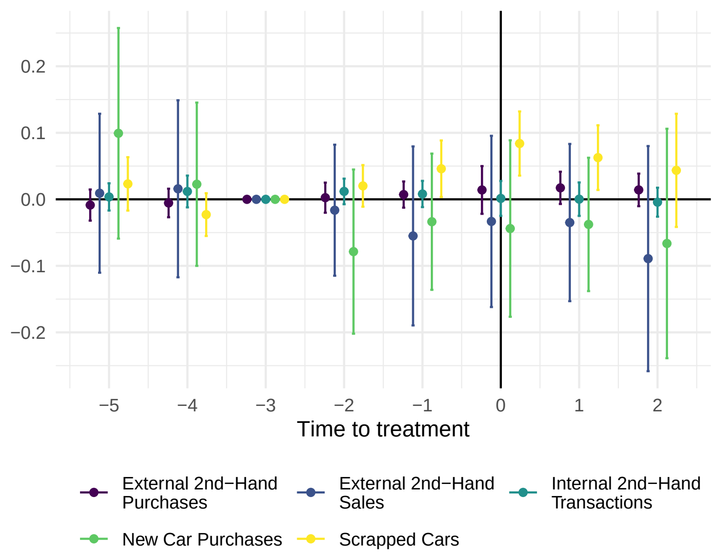


Figure 9: Effect of LEZ on Aggregated Passenger Car Market

Reading note: One year after implementation, there is no statistically significant difference in the total number of new car purchases between LEZ ICs and the control group.
Method: Event-study estimates from stacked difference-in-differences using PPML, relative to the cohort-specific reference year ($\tau = -3$). Fixed effects include IC $\times$ cohort and year $\times$ cohort, with no additional control variables. Standard errors are clustered at the IC $\times$ year level.
Data source: Insee, Annual Census Surveys, Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

Aggregated Car market. LEZ implementation may also affect aggregate vehicle flows into and out of a given city. Vehicle scrappage increases significantly at the time of LEZ implementation, with estimated effects of about 6 to 8 percent in the first two post-treatment years, before becoming statistically insignificant thereafter (Figure 9). By contrast, aggregate outcomes on the new and second-hand markets do not exhibit statistically significant responses. We now turn to the composition of transactions, which is more likely than the agregated vehicle flows to respond to LEZ implementation.

Crit'Air sticker. Disaggregating LEZ effects by Crit'Air category provides additional insight into the adjustment mechanisms induced by the policy (Figure 10). The most pronounced and systematic effects concern external second-hand purchases, that is, second-hand purchases from sellers located outside the city. As discussed above, we distinguish second-hand transactions depending on whether the counterpart is located within the same city, since LEZs simultaneously affect local demand and supply, making internal transactions more difficult to interpret.

Treated cities experience an immediate and persistent decline in purchases of older and less compliant vehicles, particularly Crit'Air 3 and Crit'Air 4. For these categories, coefficients become significantly negative already in the year preceding implementation, suggesting some degree of anticipation. They decrease further at $\tau = 0$, reaching magnitudes between 14 and 24 percent two years after treatment. Estimates for Crit'Air 5 and non-classified vehicles are substantially less precise, likely due to the small size of these categories in the fleet. By contrast, external purchases of cleaner vehicles (Crit'Air 1 and electric) increase sharply one year before implementation and remain significantly positive thereafter, with coefficients of around 11 to 12 percent in the post-treatment period. These opposite-signed effects across categories explain why aggregate external second-hand purchases remain close to zero: LEZs primarily reallocate demand across vehicle types rather than affecting the overall volume of second-hand inflows.

Purchases of Crit'Air 2 new vehicles decline sharply and persistently following LEZ implementation, with point estimates approaching 40 percent two years after treatment. These estimates are nevertheless imprecise and should be interpreted with caution, as the parallel-trends assumption is less reliable for this category: the coefficient five years before treatment is statistically significant at the 10 percent level. By contrast, estimates for new car purchases of Crit'Air 1 and electric vehicles remain small and statistically insignificant, and the corresponding pre-treatment coefficients support the common-trends assumption.

The impact on scrappage is concentrated among Crit'Air 5 and non-classified vehicles, the most polluting ones. These effects are temporary and no longer statistically significant after two years. The absence of significant scrappage effects for cleaner vehicles is consistent with their relatively young age and with the possibility of selling them outside LEZ areas. Indeed, we observe an increase in external sales of Crit'Air 4, 5, and non-classified vehicles, pointing to a spatial reallocation of more polluting cars toward untreated areas, which also contributes to improving fleet cleanliness within LEZ cities. Taken together, these results indicate that LEZs do not primarily lead households to bring forward the timing of vehicle replacement when their current car becomes non-compliant with LEZ regulations. While some scrappage and resale responses are observed, they remain limited in magnitude. Instead, the main adjustment occurs at the moment of replacement: when households eventually decide to change vehicles for reasons unrelated to the LEZ, they shift their demand toward cleaner alternatives. To better understand the implications of LEZs for areas not covered by such regulations, we use a gravity model of second-hand car flows (see subsection 6.6). The results indicate that LEZs generate spatial displacement of more polluting vehicles toward less regulated areas through used-car transactions. This displacement operates through one specific channel, second-hand markets, whereas effects on new-car purchases and scrappage reflect net changes in the overall fleet.

Finally, adjustments in fleet composition occur more gradually, as expected given slow vehicle turnover. The fleet-size panel shows modest but precisely estimated post-treatment declines for Crit'Air 2, 3, and 4

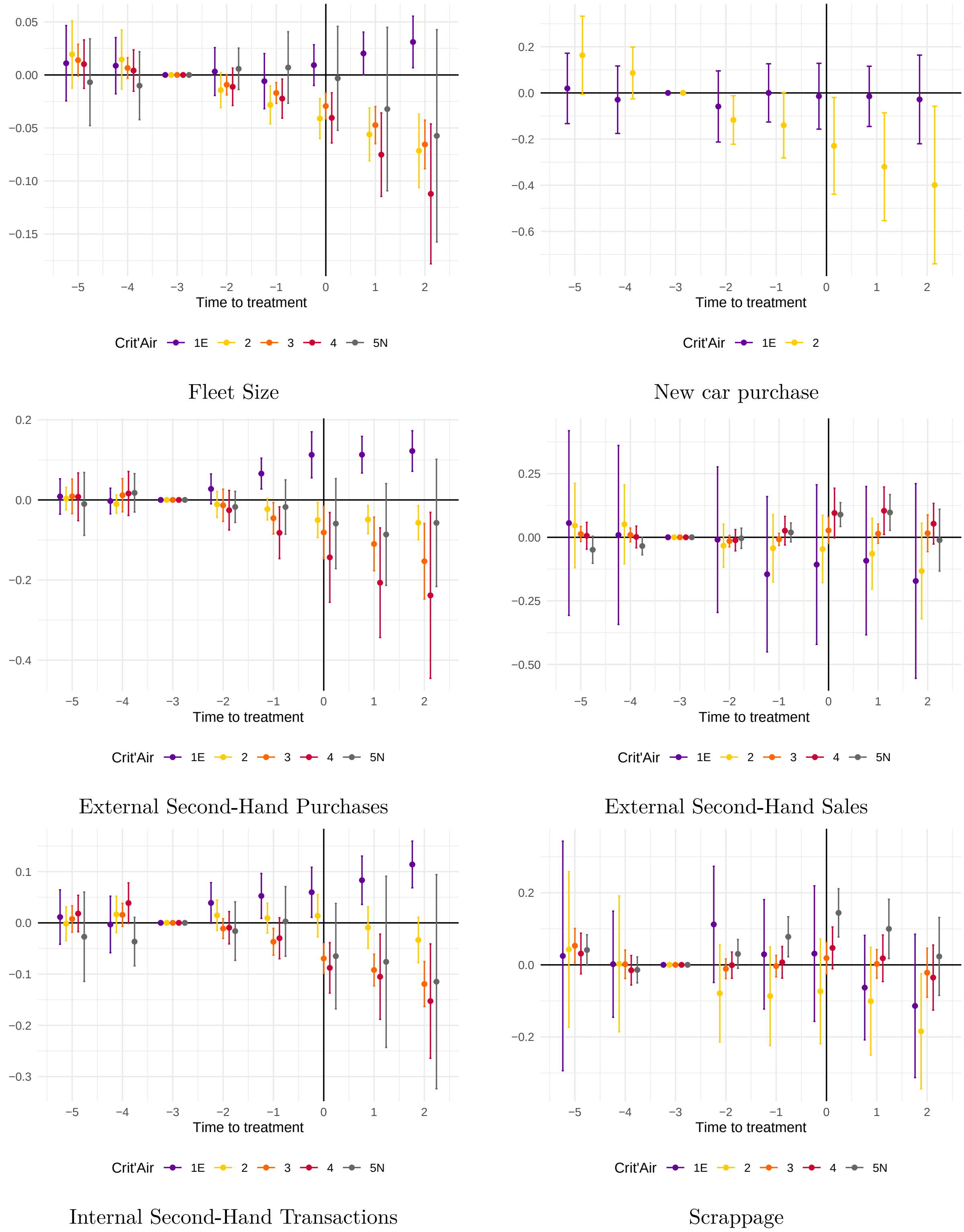


Figure 10: Effect of LEZ on passenger car fleet, by Crit'Air category

Reading note: One year after implementation, the number of Crit'Air 5 and non-classified scrapped cars is 10 % higher in LEZ ICs than in the control group.
Method: Event-study estimates from stacked difference-in-differences using PPML, relative to the cohort-specific reference year ($\tau = -3$). Fixed effects include IC $\times$ cohort and year $\times$ cohort, with no additional control variables. Standard errors are clustered at the IC $\times$ year level.
Data source: Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

Table 4: Quantification of LEZ effects on fleet size at $\tau = 2$

Crit'Air category	Fleet size at $\tau = -3$	Observed var. δ_2	Counterfactual var. δ_2^{CF}	LEZ effect $\delta_2 - \delta_2^{CF}$
1E	832,705	+88.4%	+82.6%	+5.8 pp
2	1,257,822	−4.3%	+2.8%	−7.1 pp
3	937,558	−34.5%	−30.0%	−4.5 pp
4	328,641	−53.6%	−48.1%	−5.5 pp
5N	223,426	−64.1%	*n.s.*	

Reading note: For Crit'Air 3 vehicles, the fleet in LEZ intercommunalities contracted by 34.5% between $\tau = -3$ and $\tau = 2$. In the absence of any LEZ, the counterfactual predicts a contraction of 30.0%, so that LEZs account for 4.5 percentage points of the observed decline.
Data source: Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

cars, with effects increasing over time, while the stock of Crit'Air 1 and E cars rises progressively.

We assess the magnitude of LEZ effects by comparing them with the baseline replacement dynamics of the vehicle fleet. These dynamics reflect the gradual obsolescence of older vehicles and their progressive replacement by newer, cleaner ones. Since French LEZs restrict access according to Crit'Air categories, which are closely linked to registration year, they can be viewed as accelerating this underlying renewal process. Specifically, at event time $\tau = 2$ (which corresponds to year 2023, 2024, or 2025 depending on the LEZ cohort), we compare the observed change in the fleet in treated intercommunalities relative to the cohort-specific reference year $\tau = -3$ (year 2018, 2019, or 2020 depending on the LEZ cohortZ) with the counterfactual change that would have occurred in the absence of the LEZ.[11]

Let Y_τ^T denote the aggregate observed fleet in LEZ at event time τ, and let $\hat{\beta}_\tau$ denote the PPML event-study coefficient at horizon τ. The PPML estimator $e^{\hat{\beta}_\tau}$ identifies the multiplicative treatment effect between $\tau = -3$ and τ. The counterfactual fleet level, i.e. what the fleet would have been absent any LEZ, is therefore recovered as

$$Y_\tau^{CF} = \frac{Y_\tau^T}{e^{\hat{\beta}_\tau}}. \tag{1}$$

Defining fleet variations relative to the reference year as $\delta_\tau = Y_\tau^T / Y_{-3}^T - 1$ and $\delta_\tau^{CF} = Y_\tau^{CF} / Y_{-3}^T - 1$, the LEZ effect in percentage points of the reference fleet is $\delta_\tau - \delta_\tau^{CF}$. Table 4 reports δ_2, δ_2^{CF}, and their difference for each Crit'Air category.

A first-order result emerges clearly from Table 4: LEZ effects are modest relative to the natural replacement dynamics of the fleet. Across all Crit'Air categories, the counterfactual variation δ_2^{CF} accounts for the bulk of the observed variation δ_2. The fleet is predominantly shaped by the ongoing obsolescence and renewal cycle, LEZs modulate this process at the margin. Within this overall pattern, both the direction and the relative magnitude of LEZ effects vary across Crit'Air categories. For Crit'Air 1 and electric cars, the observed fleet grew by +88.4% between $\tau = -3$ and $\tau = 2$, with LEZs contributing up to 5.8 percentage points to this growth. For Crit'Air 2 vehicles, the observed fleet declined by 4.3% over the same period, while the counterfactual suggests it would have grown by +2.8% absent the LEZ. For Crit'Air 3 and 4 vehicles, LEZs accelerated a contraction that was already under way. Estimated effects amount to −4.5 and −5.5 percentage points, respectively, compared with counterfactual declines of 30.0% and 48.1%. For Crit'Air 5 and non classified cars, the observed contraction over the period is large (−64.1%), consistent with the near-disappearance of this cohort from the fleet. The estimated LEZ

[11] We use $\tau = -3$ as the reference year because pre-trend coefficients are already statistically significant at $\tau = -2$ for several categories, so that $\tau = -3$ provides the cleanest pre-treatment baseline.

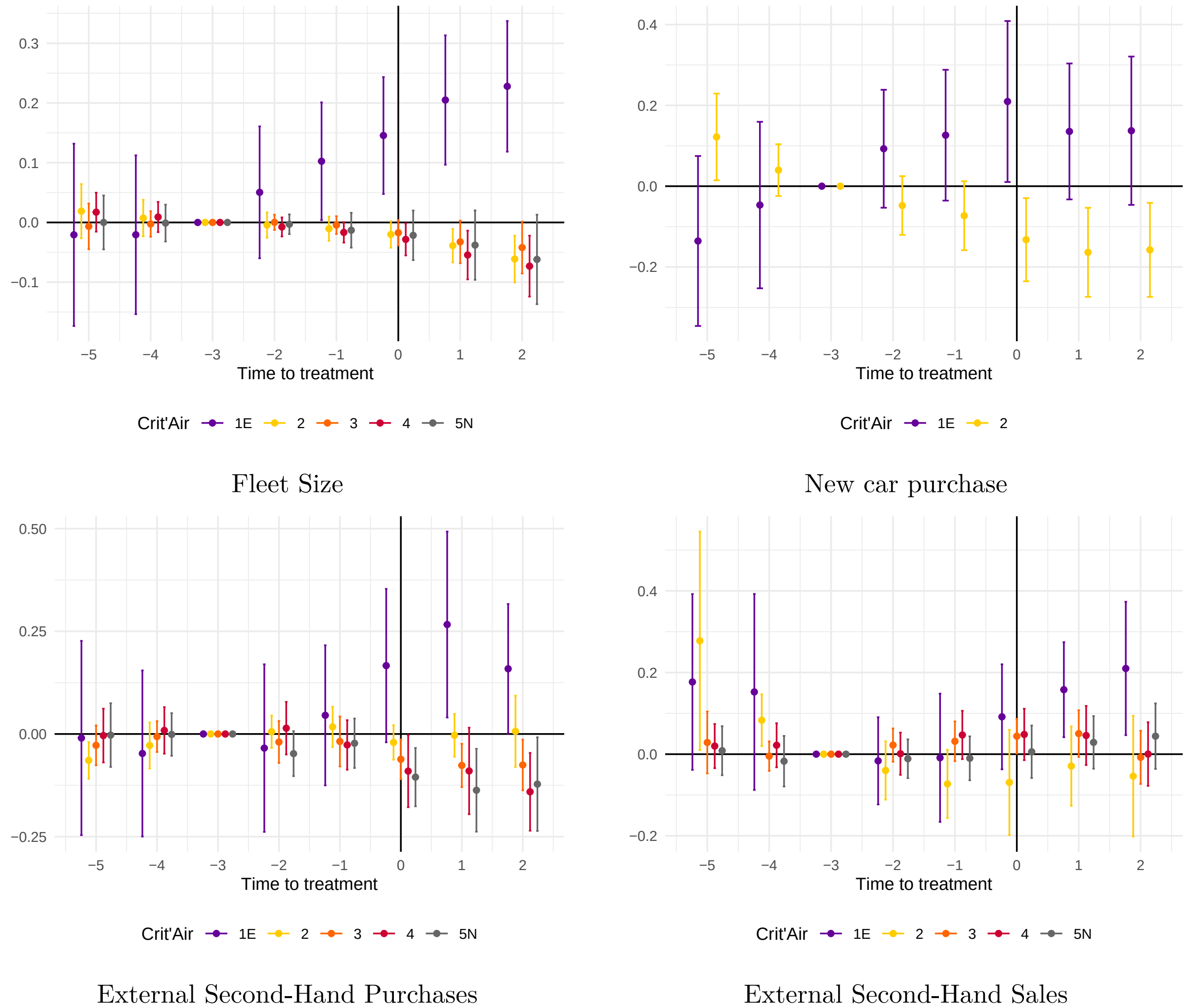


Figure 11: Effect of LEZ on the LCV fleet, by Crit'Air category

Reading note: One year after implementation, the fleet of Crit'Air 4 light commercial vehicles is about 5 % smaller in LEZ ICs than in the control group.
Method: Event-study estimates from stacked difference-in-differences using PPML, relative to the cohort-specific reference year ($\tau = -3$). Fixed effects include IC $\times$ cohort and year $\times$ cohort, with no additional control variables. Standard errors are clustered at the IC $\times$ year level.
Data source: Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

effect is not statistically significant.

Light commercial vehicles. We also document the impact of LEZ implementation on light commercial vehicle (LCV). LCVs represent a substantial share of the vehicle fleet and have been a specific target of LEZ policies, often facing earlier access restrictions than passenger cars. In some cases, LEZs apply exclusively to LCVs, notably in Clermont-Ferrand and Saint-Étienne (see Table 17). Accordingly, we adapt both the composition of the treatment group and treatment timing to reflect the specific year in which LCV restrictions became effective in each city.[12]

Figure 11 documents the impact of LEZ implementation on external second-hand light commercial vehicle (LCV) purchases by Crit'Air category. Overall, support for the common-trends assumption is

[12] The treatment years are defined as follows: Grenoble in 2017; Strasbourg in 2018; Rouen, Lyon, and Reims in 2021; Marseille, Toulouse, Montpellier, and Saint-Étienne in 2022; and Nice and Clermont-Ferrand in 2023.

weaker in this setting, particularly for new car purchases and external second-hand sales. This likely reflects the fact that our empirical design is less well suited to the evaluation of LCV-specific restrictions: treatment timing is more dispersed across cities, which may generate greater heterogeneity in treatment effect; second, during the treatment period, the LEZ perimeter expanded in several cities (see Figure 1), whereas our empirical approach is not designed to capture changes in treatment intensity. For these reasons, we restrict our interpretation to fleet size and external second-hand purchases, and we interpret the LCV results with caution overall.

We first note that estimated LEZ effects for Crit'Air 1 light commercial vehicles are consistently large but imprecisely estimated. This reflects the fact that petrol LCVs are relatively rare, accounting for about 7 % of the LCV fleet in 2024, compared with 44 % for passenger cars. As a result, the large estimated effect for Crit'Air 1 LCVs, around 29 % two years after implementation, should be interpreted in light of the small size of this segment of the fleet. As for passenger cars, external second-hand purchases of older and less compliant light commercial vehicles decline significantly following LEZ implementation, with particularly pronounced effects for Crit'Air 3, 4, 5 and non-classified vehicles. For these categories, coefficients become sharply negative at treatment and remain so in subsequent years, reaching magnitudes between 7 % and 16 % two years after implementation.

6.2 Robustness checks

Treatment Timing. The previous section shows that some fleet outcomes begin to change up to two years before the official implementation date, raising the concern that the baseline event-study estimates may partly capture contemporaneous policies or other shocks rather than the LEZ itself. The purpose of this subsection is to show that these early movements are consistent with anticipation effects related to forthcoming restrictions.

To this end, we consider an alternative treatment timing based on the 2019 Mobility Orientation Law (*Loi d'orientation des mobilités*, LOM), which made LEZ compulsory in 11 cities exceeding European air-quality standards (see Section 2): Reims, Grenoble, Lyon, Marseille, Montpellier, Nice, Paris, Rouen, Strasbourg, Toulon, and Toulouse. In this robustness test, we take 2019, the year of the law's adoption, as the treatment year and interpret it as the moment when the policy became credible enough to affect the behavior of car buyers and sellers through the prospect of future driving restrictions. At that time, only Paris had already implemented a passenger-car LEZ, while the remaining cities were expected to do so in subsequent years. As in the baseline specification, we exclude Paris from the sample and use cities not covered by the LOM obligation as the comparison group. Since large anticipation effects are less relevant when considering the adoption of the law itself, we use $\tau = -2$, corresponding to 2017, as the reference period in the event study. We do not use $\tau = -1$ because the law had already been introduced in Parliament by the government in 2018, and slight differences between LEZ and control cities are already visible that year, as discussed in the following paragraph.

Figure 12 reports differences in fleet composition as well as car market outcomes between cities targeted by the LOM obligation and other cities. Because treatment occurs earlier under this definition, the event-study window can be extended up to $\tau = 5$, corresponding to the year 2024. Parallel trends between LOM-designated cities and the control group are clearly satisfied up to 2018. Some limited statistically significant differences emerge in 2018 ($\tau = -1$) notably for Crit'Air 2 new car purchases (at the 10 percent significance level), as well as for Crit'Air 5 and non-classified external second-hand sales. In addition, differences in fleet composition become significant from 01/01/2019 onward, particularly for Crit'Air 2 and Crit'Air 3 vehicles. These limited early adjustments may reflect the fact that residents of targeted cities were already aware that air-pollution thresholds had been exceeded locally and that public

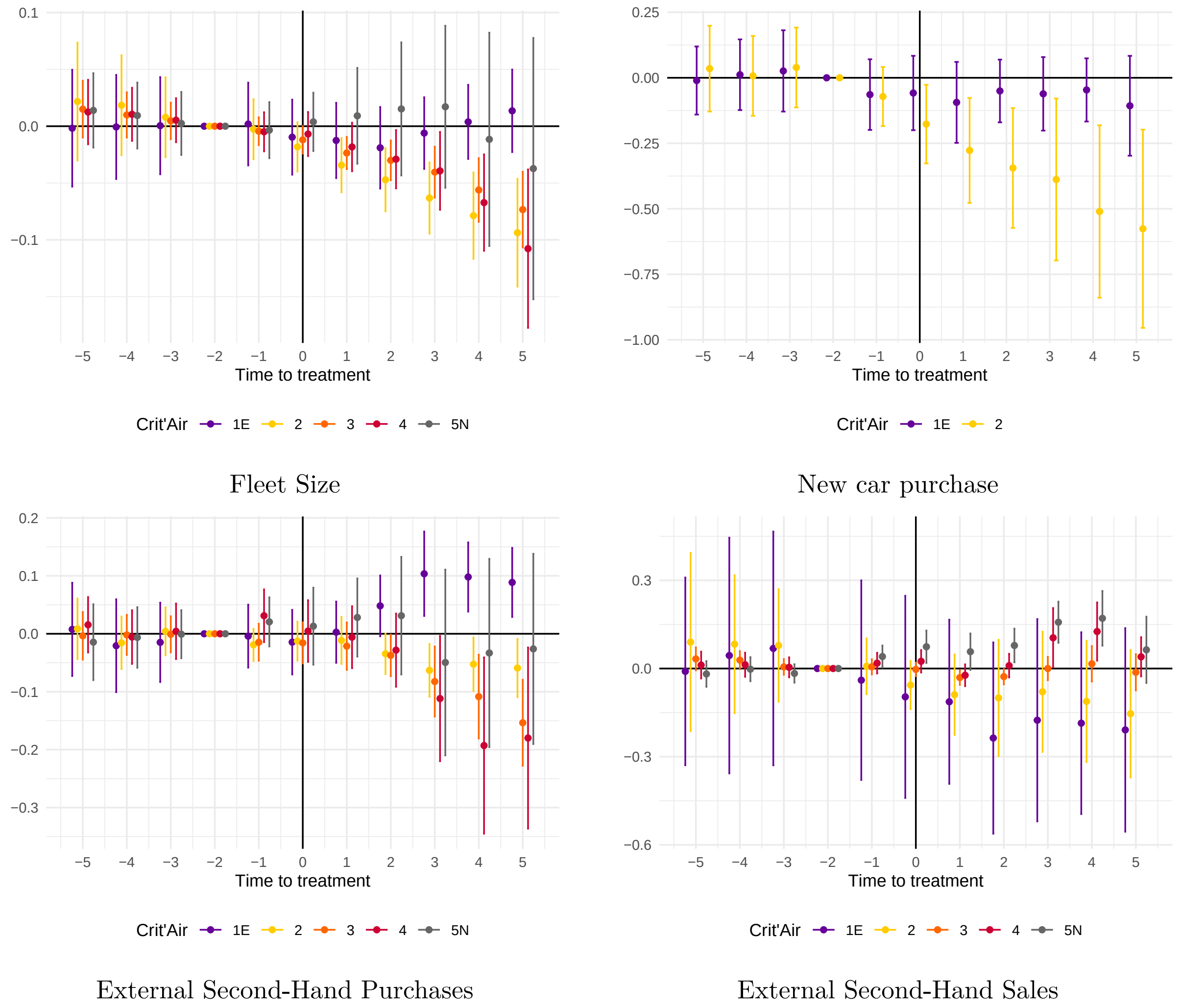


Figure 12: Effect of mandatory LEZ announcement on passenger car fleet, by Crit'Air category

Reading note: Four years after the 2019 LOM law was passed, the fleet of Crit'Air 4 passenger cars is about 7 % smaller in ICs subject to the obligation to implement a LEZ than in the control group.
Method: Event-study estimates from stacked difference-in-differences using PPML, relative to reference year ($\tau = -3$). Fixed effects include IC and year, with no additional control variables. Standard errors are clustered at the IC × year level.
Data source: Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

authorities were legally required to take action, following ongoing judicial procedures.[13] In addition, Strasbourg and Grenoble had already introduced LEZs for light commercial vehicles, which may have made future driving restrictions for passenger cars more credible. The anticipation effects identified in this robustness exercise are markedly more limited than those observed in the baseline specification, which uses the year of the first car ban as the policy starting point. Overall, these findings support the interpretation that anticipatory responses mainly arise once the obligation to implement a LEZ is publicly announced. We argue that this mechanism accounts for the anticipation effects observed in Figure 10 in years -1 and -2 prior to LEZ implementation, although the role of other factors or anticipation channels cannot be entirely excluded.

[13] Conseil d'Etat decision of July 12, 2017

Control and treatment groups. Appendix Figure 18 shows that estimated responses of fleet composition and external second-hand purchases are sensitive to alternative definitions of the treated and comparison groups. We first examine the role played by the presence of 14 cities in the control group that are eventually treated in 2025. Given the anticipation effects documented above, including these cities in the control group may lead to an attenuation of the estimated treatment effect. To address this concern, Panel A excludes cities that are treated in 2025 from the control group. Point estimates are slightly larger under this restriction, although the differences are not statistically significant. However, the common-trends assumption appears less clearly satisfied in this specification. For this reason, we retain these later-treated cities in the control group in the baseline analysis. Panel B implements a more stringent test by restricting the treated group to cities implementing a LEZ in 2025 and using never-treated cities as the control group. The results indicate that the common-trends assumption is violated between these two populations. In particular, the fleet share of cleaner vehicles increases more rapidly in later-treated cities than in never-treated ones. Because parallel pre-trends are not satisfied, these differences cannot be interpreted as causal effects of LEZ implementation. However, they suggest that fleet composition in the 2025 LEZ cohort is shifting toward cleaner vehicles which is consistent with a potential, albeit limited, underestimation of the treatment effect.

A second robustness check concerns the exclusion of Paris in the baseline specification. In Panel C, Paris is added to the treated group. Under this specification, the common-trends assumption is no longer satisfied, as several pre-treatment coefficients exhibit systematic differences across groups. This sensitivity analysis supports our baseline design choices: Paris differs too markedly from other urban areas for a credible comparison group to be identified within this difference-in-differencies framework.

6.3 Between-city heterogeneity

Synthetic control method. We then turn to heterogeneity in the effect of LEZ implementation across treated cities. Rather than comparing each treated city to the simple average of untreated units, we construct for each treated IC a synthetic control (Abadie and Gardeazabal, 2003; Abadie et al., 2010). This approach provides each treated city with a counterfactual that more closely reproduces its pre-treatment dynamics, thereby reducing the risk of pre-existing discrepancies between treated and control cities.

Formally, for each treated city i, Crit'Air category k, and year t, the dynamic treatment effect Δ_{ikt} corresponds to:

$$\Delta_{ikt} = \Big[\log\big(Y_{ikt}\big) - \log\big(Y_{ik,C_i-3}\big)\Big] - \sum_{j\in\mathcal{G}} w_{ij}\Big[\log\big(Y_{jkt}\big) - \log\big(Y_{jk,C_i-3}\big)\Big] \tag{2}$$

where Y_{ikt} denotes car market outcome, $\mathcal{G}$ is the donor pool of untreated cities, and C_i the year of first LEZ implementation in city i. This framework adapts the PPML approach which is designed to estimate average treatment effects, into a log-difference specification better suited to assessing the response of individual cities. As in the baseline PPML specification, the outcomes are normalized to zero in the reference year $C_i - 3$. The weights w_{ij} measure the contribution of untreated city j to the synthetic control of treated city i and satisfy $w_{ij} \geq 0$ and $\sum_j w_{ij} = 1$.

The synthetic control is designed to match the pre-treatment evolution of the distribution of the outcome across Crit'Air categories over the years preceding the reference year $C_i - 3$. More precisely, for each treated IC i, the weights are obtained by solving:

$$\min_{w_{ij}} \sum_{t<C_i-3} \sum_{k} \left(\big[\log(Y_{ikt}) - \log(Y_{ik,C_i-3})\big] - \sum_{j\in\mathcal{G}} w_{ij}\big[\log(Y_{jkt}) - \log(Y_{jk,C_i-3})\big] \right)^2 \tag{3}$$

For a given treated city and outcome, a single vector of weights is used across all Crit'Air categories, ensuring that each treated city is compared to the same synthetic control. The canonical synthetic control method does not lend itself to the construction of confidence intervals: it relies on a single treated unit, yielding only one realization of the post-treatment outcome, and the number of control units receiving non-negligible weight is typically small, as illustrated by Abadie and Gardeazabal (2003), where only two donors carry substantial weight in the Basque Country application.

Results. Figure 13 presents the results of this synthetic control approach. In some cities, pre-treatment trends are not perfectly aligned between the treated city and its synthetic control for all Crit'Air categories, especially in Strasbourg and Saint-Etienne. This reflects the fact that the synthetic weights are not estimated separately for each Crit'Air category, but are instead constrained to be common across categories for a given treated city and outcome. The estimated treatment effects appear highly heterogeneous across cities. In most treated cities, including Paris, LEZ implementation is associated with a sharp and persistent decline in external purchases of older and more polluting vehicles, in particular Crit'Air 4, 5 and non-classified cars. These effects generally materialize within the two years prior LEZ implementation. They become stronger over time in Strasbourg, Paris, Grenoble, and Montpellier, while they tend to fade in Rouen, Reims, and Toulouse. The magnitude of the decline varies considerably across cities, ranging from moderate contractions to very pronounced drops exceeding 40–50 percent in some cases, such as Rouen or Strasbourg.

By contrast, Marseille and Nice do not exhibit a clear divergence from the control group. Both cities are characterized by relatively limited LEZ perimeters, covering only 15 percent and 8 percent of the population, respectively (see Table 1). In comparison, cities such as Montpellier, Rouen, and Strasbourg implement substantially larger LEZs, encompassing respectively 81, 51, and 100 percent of their populations. That said, the association between LEZ spatial coverage and second-hand purchase responses is not systematic. Reims, for example, displays pronounced shifts in the composition of external second-hand purchases despite a restricted LEZ perimeter, which covers only 9 percent of the population. Although we cannot test these mechanisms formally here, several factors may help explain this heterogeneity across cities, including the availability of alternatives to car use (e.g. public transport), the scale of local subsidies supporting the purchase of cleaner vehicles, and the structure of mobility flows, particularly the role of the LEZ-covered area in daily travel patterns.

In addition, we apply this approach to Clermont-Ferrand and Saint-Etienne, where the LEZ applies only to light commercial vehicles.[14] This exercise can be interpreted as a placebo test and is broadly supportive of the identification strategy. Changes in the composition of second-hand purchases are much smaller in these two cities than in cities where the LEZ applies to passenger cars.

The timing of responses also differs across cities. While some functional areas exhibit anticipatory dynamics, with adjustments beginning one to two years before formal implementation, others display abrupt breaks exactly at the cohort year. Notably, Lyon, Grenoble, and Strasbourg introduced LEZ restrictions for LCV years before restrictions applied to passenger cars (see Table 17).

Finally, Appendix Figures 19, 20, and 21 apply the same analytical framework to external second-hand sales, car fleet and new car purchases, respectively. They indicate that external second-hand sales respond sharply to LEZ implementation in Rouen, while effects remain limited in other cities. Marseille displays the opposite pattern: external second-hand sales of Crit'Air 1 vehicles increase modestly in the period immediately preceding LEZ implementation and persist in the subsequent years. Purchases of Crit'Air 2 new vehicles decline in Montpellier, Lyon, Paris, Strasbourg and Rouen following LEZ adoption, although, as in the baseline specification, the common trends assumption appears questionable for some cities.

[14] In each case, the treated city is excluded from the donor pool used to construct the synthetic control.

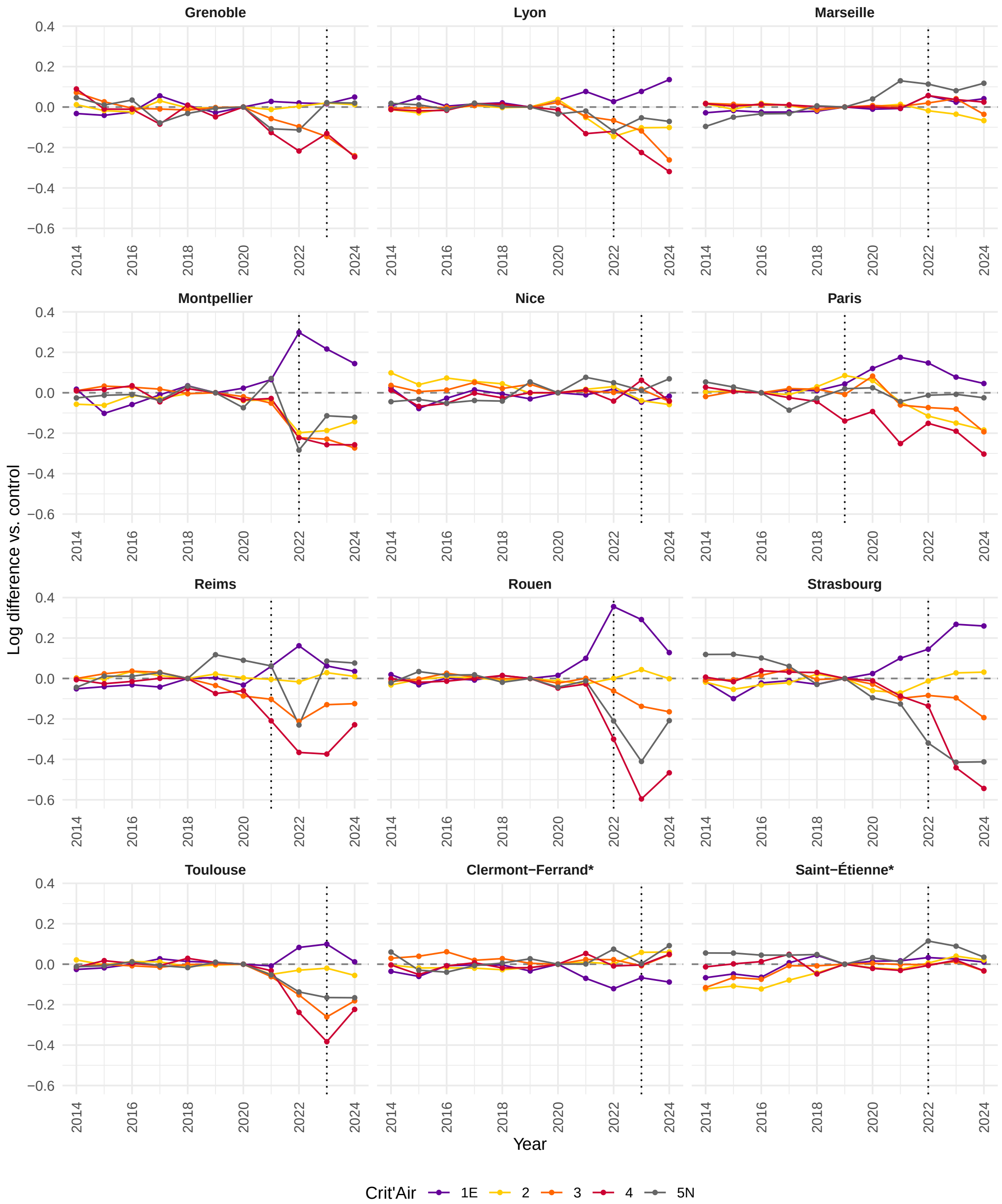


Figure 13: City-specific effects of LEZ on external second-hand car purchases by Crit'Air category

* Saint-Etienne and Clermont-Ferrand are not treated for passenger cars, as their LEZs apply only to light commercial vehicles; they therefore serve as placebo tests here.

Reading note: One year after LEZ implementation, the external second-hand car purchases of Crit'Air 4 passenger cars is about 60 % smaller in the Rouen IC than in the control group.

Method: For each treated functional area, difference in log external second-hand car purchases relative to its specific synthetic control, normalized to the cohort-specific reference year ($\tau = -3$). The vertical dotted line indicates the LEZ implementation year.

Data source: Sdes, RSVERO, 2011–2025.

Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

Finally, with the exception of Marseille, Grenoble and Nice, the composition of the aggregate car fleet shifts toward cleaner vehicles confirming a gradual adjustment of the vehicle stock in response to the policy.

6.4 Within-city heterogeneity: municipality-level effect

We now explore within-city heterogeneity by estimating our event-study specifications at a finer spatial scale. Instead of measuring the impact of LEZs at the level of the nine intercommunalities in the treated group, we estimate it at the level of the 588 municipalities that compose them. This allows us to document spatial heterogeneity in the effects of LEZs on local vehicle fleets. Specifically, we estimate a similar stacked PPML event-study design at the municipal level, weighting observations by municipal population to avoid giving disproportionate influence to small municipalities. In this setting, external second-hand purchases and sales refer to transactions in which the buyer or the seller is located outside the municipality (rather than outside the IC, as in the baseline analysis). To compare the magnitude of the effects between central municipalities and the suburban ring, and to examine heterogeneity across municipality income, we introduce interaction terms.

Table 5: Municipality Level Sample Description

	Count		Population (2021)	
	Control	Treated	Control	Treated
Panel A: City-Center Status				
Peripheral	733	526	3,965,156	3,130,448
Center	100	62	4,930,969	3,849,732
Panel B: Income Tercile				
Bottom third	99	47	2,887,494	1,979,951
Middle third	223	107	3,073,985	2,516,614
Top third	511	434	2,934,646	2,483,615
Total	833	588	8,896,125	6,980,180

Reading note: In the control group, 733 peripheral municipalities account for a population of 3,965,156 inhabitants in 2021.
Data source: Insee, Fideli, Census, IGN, Admin-Express.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

Central versus peripheral municipalities. To explore whether the impact of LEZs varies with a municipality's location within the city, we divide the municipalities into two groups of equal population. The first group consists of the municipalities closest to the city center, while the second includes peripheral municipalities (see table 5). We then interact the treatment variables with a dummy for belonging to the first group. The first set of estimates (Panel A in Figure 14), which does not include the interaction term, should therefore be interpreted as the treatment effect for peripheral municipalities. The second set of estimates, based on the interaction between treatment and the central-municipality dummy, captures the difference in treatment effects between central and peripheral municipalities. This specification makes it easier to assess whether the effects differ significantly within cities. The total treatment effect for central municipalities is thus given by the sum of the two coefficients in a given year. To account for trends that may differ between central and peripheral municipalities, but are common to both treated and control cities, we also include year $\times$ central-municipalities fixed effects.

Figure 14 shows that LEZ implementation has a significant impact even in peripheral municipalities (Panel A). External second-hand purchases increase for the cleanest category, Crit'Air 1 and E cars, starting one year before LEZ implementation. The fleet of Crit'Air 2 to 4 cars also declines, with estimated effects ranging from 7 to 8% two years after treatment. However, the impact of LEZs is stronger in central municipalities, as Panel B shows notable differences relative to peripheral municipalities for many outcomes. For external second-hand purchases, the decline in dirtier vehicles (Crit'Air 3 and more) is stronger, while the increase in cleaner vehicles (Crit'Air 1 and E) is also somewhat larger. Results for fleet composition and for external second-hand sales, reported in Appendix Figure 22, similarly indicate that LEZ impacts are larger in central municipalities. The only notable exception concerns new car purchases: the decline in Crit'Air 2 registrations seems stronger in suburban municipalities, but confidence intervals are wide and pre-trends are less convincing.

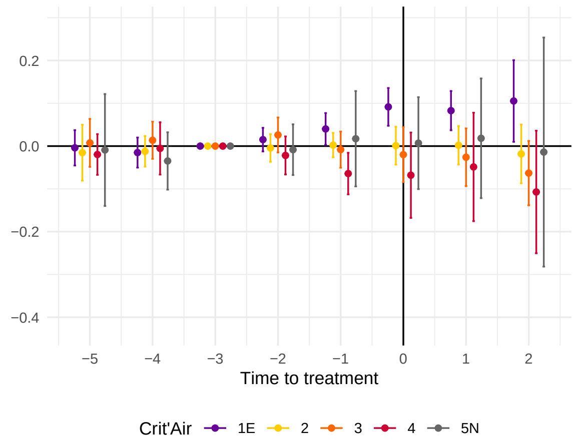
This pattern is mechanically consistent with the fact that central municipalities are typically included in the LEZ perimeter, whereas peripheral municipalities are only partially covered or not covered at all by the restrictions. As a result, drivers living in peripheral municipalities are affected by the policy only if they need to drive into the central part of the city, for instance for work or shopping.

Municipal income. Because individual-level income information for car users is not available, we assess distributional heterogeneity of LEZ effect using municipal income as a proxy. We divide municipalities into three groups of equal population based on the average standard of living of their residents. More precisely, municipalities in the treatment and control groups are jointly split into population-weighted terciles, using common thresholds for the whole sample (see table 5). As in the central-versus-periphery specification, we augment the treatment specification with interaction terms, using medium-income municipalities as the baseline group (Panel A in Figure 15). The coefficients for low- and high-income municipalities therefore capture differences in LEZ effects relative to medium-income municipalities. In this specification, we include additional fixed effects, namely interactions between year and central-, low-, and high-income municipality dummies, to account for trends that may differ across municipalities but are common to both treated and control cities.

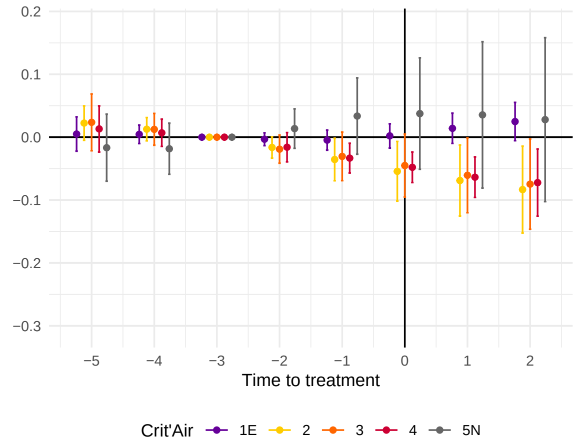
Figure 15 reports event-study estimates by municipal income for the passenger-car fleet and external second-hand purchases. Middle-income municipalities display similar effects to the aggregate ones estimated at the city level. Differences with low-income municipalities remain limited, although the decline in second-hand purchases of Crit'Air 2 and 3 vehicles appears somewhat stronger in low-income areas. Interestingly, Appendix Figure 23 points to a difference in the timing of the treatment effect on second-hand sales. While sales of older cars (Crit'Air 3 and more) increase from one year before treatment in medium-income municipalities, no anticipated effect is observed in low-income municipalities, where the estimated relative effect instead goes in the opposite direction in $\tau = -1$. This suggests that households in these municipalities cannot bring forward the sale of non-compliant vehicles, at least not before LEZ restrictions become binding, possibly because of tighter budget constraints.

In high-income municipalities, estimated effects are substantially smaller and often statistically insignificant, as reflected by relative effects of opposite sign. Comparable patterns are observed for external second-hand sales (see Appendix Figure 23). These heterogeneous responses are consistent with differences in initial fleet composition. In 2019, the last year without any LEZ implementation in our sample, Crit'Air 1 and electric vehicles account for about 24% of the fleet in high-income municipalities, compared with 22% in middle-income municipalities and only 19% in low-income municipalities. Conversely, the combined share of Crit'Air 4, 5 and non-classified vehicles reaches about 20% in low-income municipalities, against 17% in middle-income municipalities and around 14% in high-income municipalities. Low- and middle-income municipalities therefore start from a substantially more polluting baseline, mechanically allowing for larger adjustments following LEZ implementation. One notable exception concerns new

Panel A: Baseline (peripheral municipalities)

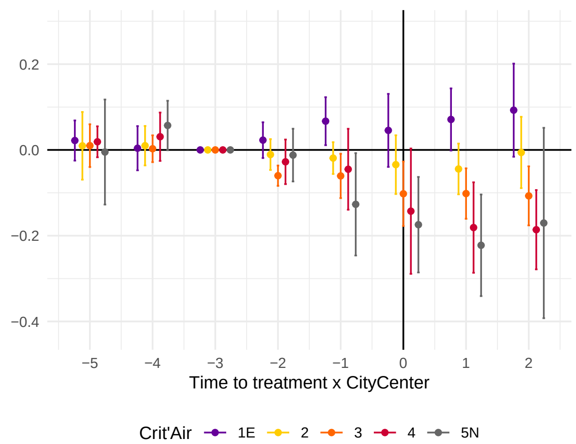


External Second-Hand Purchases

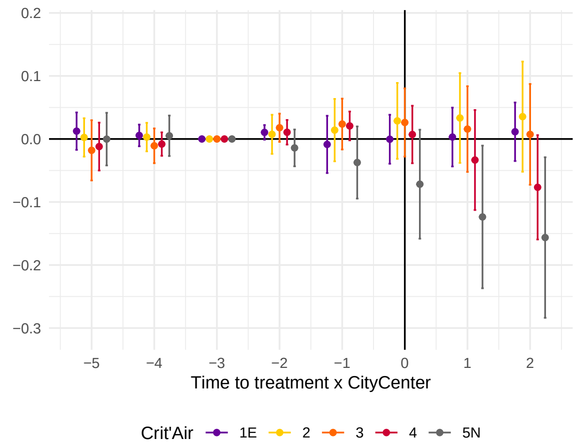


Fleet Size

Panel B: central vs peripheral municipalities



External Second-Hand Purchases



Fleet Size

Figure 14: Effect of LEZ on passenger car fleet, by Crit'Air category, in central and suburban municipalities

Reading note: One year after implementation, the fleet of Crit'Air 4 passenger cars is about 6% smaller in peripheral municipalities of LEZ ICs than in the control group.
Method: Event-study estimates from stacked difference-in-differences using PPML, relative to the cohort-specific reference year ($\tau = -3$). Fixed effects include municipality × cohort, year × cohort and year × cohort × central municipalities, with no additional control variables. Standard errors are clustered at the municipality × year level.
Data source: Sdes, RSVERO, 2011–2025, IGN, Admin-Express.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

car purchases. Crit'Air 1 new passenger car purchase increases following LEZ implementation only in high-income municipalities. Since, new car purchases are relatively rare among low- and medium-income households, changes in new vehicle demand primarily reflect the behavior of higher-income households, who are more concentrated in richer municipalities.

6.5 Crit'Air cutoff validation: triple differences across vintages

To strengthen identification, we implement a triple-difference design that exploits the mechanical discontinuities in Crit'Air classification across adjacent vehicle vintages. This approach follows the logic of Barahona et al. (2020), who exploit regulatory thresholds in vehicle emissions standards. Importantly, this specification is not intended as an alternative estimate of the treatment effect but rather serves as a validation exercise. Because LEZs rely directly on Crit'Air stickers, changes in fleet composition and purchases should occur around the boundaries separating adjacent Crit'Air categories. By focusing on these discontinuities, the triple-difference approch helps ensure that the estimated effects are indeed driven by the Crit'Air classification itself rather than by gradual shifts in the composition of the vehicle fleet related to vehicle vintage.

From the baseline DiD to a triple-difference. We index observations by IC i, year t, cutoff k, and vintage v (year of first registration). In the French system, Crit'Air stickers are mechanically assigned based on fuel type and vintage (see Section 2 and Table 8). Each cutoff k is associated with a threshold vintage V_k: vehicles with $v \geq V_k$ receive the cleaner classification, while those with $v < V_k$ receive the more polluting one. Table 6 lists the cutoffs. For each cutoff, we restrict attention to vintages within a ± 3 year window around v_k.

Table 6: Crit'Air classification cutoffs by fuel type

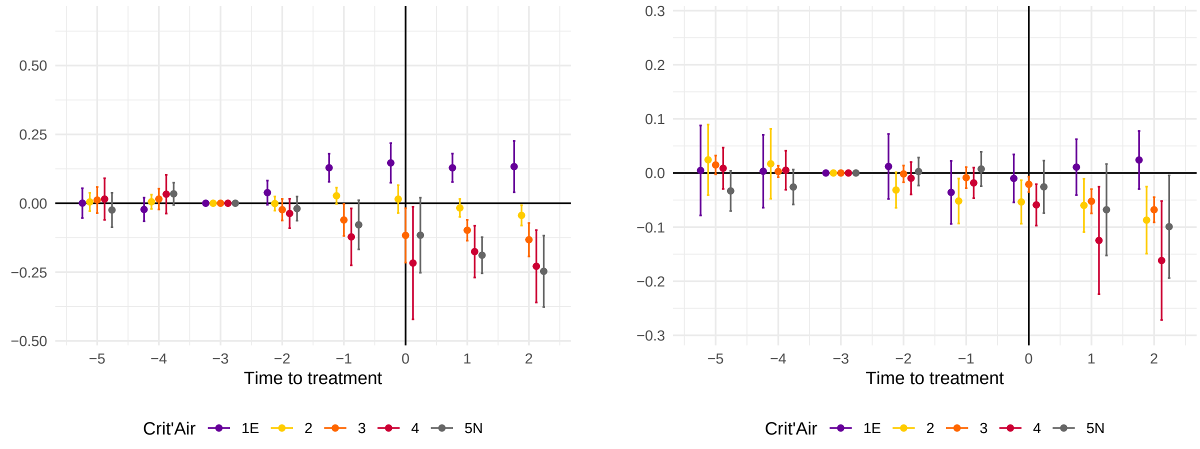
Cutoff k	Fuel	Categories	Cutoff vintage V_k
1	Petrol	Crit'Air 1 / Crit'Air 2	2011
2	Petrol	Crit'Air 2 / Crit'Air 3	2006
3	Diesel	Crit'Air 2 / Crit'Air 3	2011
4	Diesel	Crit'Air 3 / Crit'Air 4	2006
5	Diesel	Crit'Air 4 / Crit'Air 5	2001
6	Petrol	Crit'Air 3 / Non-classified	1997
7	Diesel	Crit'Air 5 / Non-classified	1997

Reading note: A diesel car first registered in January 2011 or later is classified as Crit'Air 2; if first registered earlier, it is classified as Crit'Air 3.
Source: Decree (Arrêté) of 21 June 2016 on air quality certificates (as amended), Annex I. Available at: https://www.legifrance.gouv.fr/loda/id/JORFTEXT000032749723.

The baseline specification in Section 4.2 compares LEZ ICs to non-LEZ cities, before and after implementation. We refine this comparison by introducing a third dimension of variation based on vehicle vintage. Consider a single cutoff k with threshold vintage V_k. Vehicles with $v < V_k$ receive the more polluting Crit'Air classification and are therefore restricted earlier, whereas vehicles with $v \geq V_k$ receive the cleaner classification and remain authorized for longer. This additional discontinuity allows us to distinguish vintages that are differentially exposed to the regulation depending on which side of the cutoff they lie.

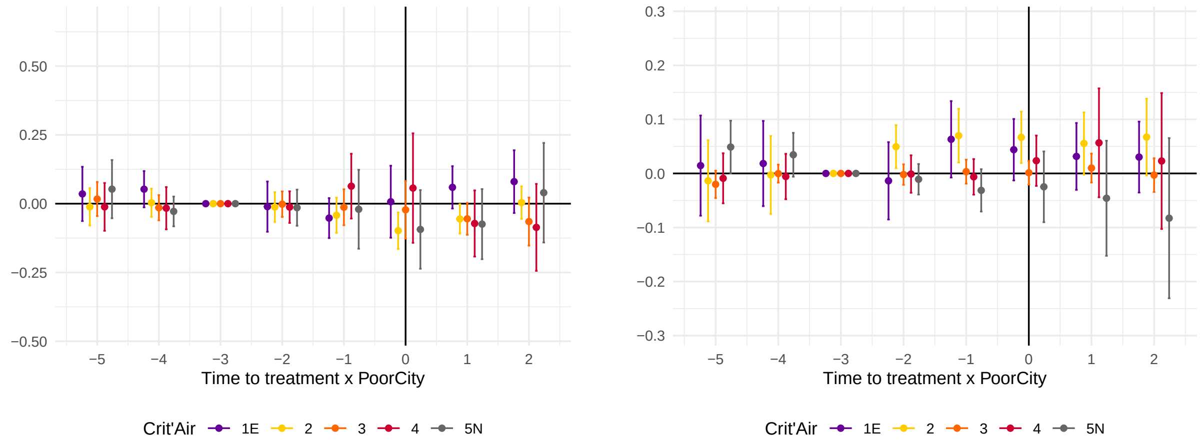
This generates a triple-difference structure: before versus after LEZ implementation $\times$ LEZversus non-LEZ IC $\times$ and sooner-affected versus later-affected vintages (below/above cutoff V_k). The identifying

Panel A: Baseline (medium-income municipalities)



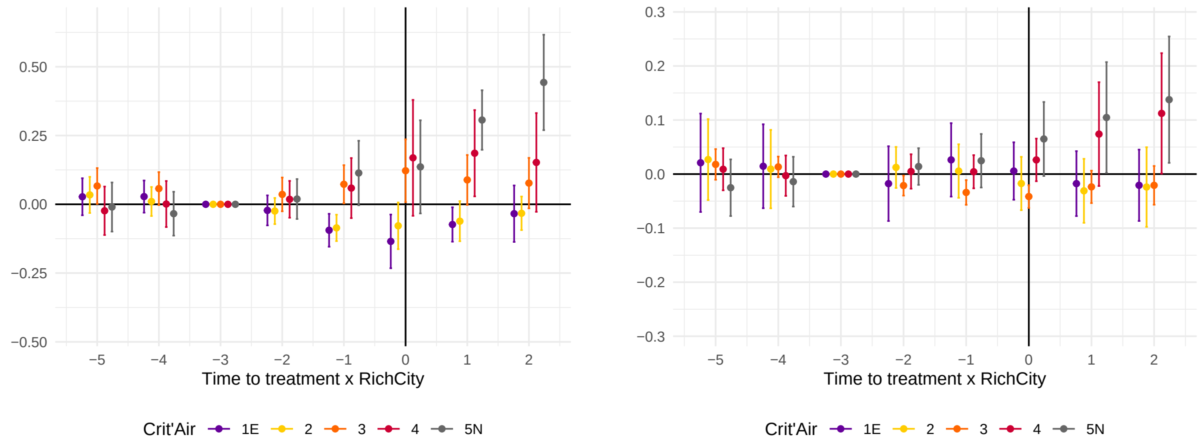
External Second-Hand Purchases — Fleet Size

Panel B: Low- vs medium-income municipalities



External Second-Hand Purchases — Fleet Size

Panel C: High- vs medium-income municipalities



External Second-Hand Purchases — Fleet Size

Figure 15: Effect of LEZ on passenger car fleet, by Crit'Air category and municipal income

Reading note: One year after implementation, the fleet of Crit'Air 4 passenger cars is about 18% smaller in medium-income municipalities within LEZ ICs than in the control group.
Method: Event-study estimates from stacked difference-in-differences using PPML, relative to the cohort-specific reference year ($\tau = -3$). Fixed effects include municipality $\times$ cohort year $\times$ cohort and year $\times$ central-, low- and high-income municipality dummies with no additional control variables. Standard errors are clustered at the municipality $\times$ year level.
Data source: Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

variation comes from comparing vintage trends in LEZ versus non-LEZ ICs, differentially for vintages on either side of the regulatory threshold.

Pooled specification. Our specification also pools data across several cutoffs in order to obtain a more compact and readable summary of the effects. The unit of observation is a city i × year t × cohort s × cutoff k × vintage v cell:

$$\mathbb{E}[Y_{itskv} \mid \cdot] = \exp\left(\sum_{\substack{\tau \neq -3 \\ \kappa \neq -1}} \beta_{\tau\kappa} \ \mathbb{1}(t - C_i = \tau) \times \mathbb{1}(v - V_k = \kappa) \times \mathbb{1}(\text{LEZ}_i = 1) + \gamma_{itks} + \theta_{vtks} + \mu_{iskv} \right)$$

By stacking all cutoff-specific datasets, we pool the identifying variation generated by each regulatory threshold. The fixed effects are cutoff-specific: γ_{itks} (IC × year × cutoff), θ_{vtks} (vintage × year × cutoff), and μ_{ivks} (IC × vintage × cutoff). The sample is restricted to a three-year window around each cutoff, with $\kappa \in [-3, 2]$ where $\kappa = v - V_k$, and $\kappa = -1$ is used as the reference category. Standard errors are clustered at the IC × cutoff × year level.

The pooled coefficient $\beta_{\tau\kappa}$ captures the average differential change in transactions LEZs at event time τ, for vintages at distance κ from cutoff. A positive $\beta_{\tau\kappa}$ for $\tau \geq 0$ and $\kappa \geq 0$ indicates that second-hand purchases shift toward cleaner vintages following LEZ implementation.

Results. Figure 16 present triple-difference event-study estimates for external second-hand purchases and sales, respectively. We pool cutoffs into two groups, as the estimated effects appear to differ across them. The two left panels report results for older cars (cutoffs 4 to 7, Crit'Air 3 and more), which are directly targeted by circulation bans in LEZs, while the two right panels report results for more recent cars (cutoffs 1 to 3, Crit'Air 1 to 3), which may become subject to such restrictions in the future.

Across specifications, we find no evidence of systematic differential pre-trends between adjacent vintages. Coefficients are generally small and statistically insignificant in the pre-treatment period, which suggests that vintages within the same window follow parallel trends prior to implementation. By contrast, treatment impacts become visible at or shortly after implementation, with significant changes in purchases or sales for vintages that are relatively better classified (shown in blue) compared with the vintage immediately below the Crit'Air cutoff (in red). Importantly, adjacent vintages that belong to the same Crit'Air category display no consistent divergence.

A distinction emerges between purchases and sales. For external second-hand purchases, LEZ effects are stronger and more persistent for relatively recent cars (Crit'Air 1 to 3) than for older ones (Crit'Air 3 and more). These patterns suggest forward-looking behavior at the time of vehicle acquisition: households appear to anticipate future tightening of access rules and adjust their purchases accordingly, even for vehicle categories that are not immediately restricted. In other words, purchase decisions seem to internalize the expected long-term usability of the vehicle. The smaller effects for older passenger cars may reflect the fact that traffic restrictions for these categories are implemented in close succession, limiting the relative advantage of adjacent vintages. For example, there is little advantage in purchasing a Crit'Air 4 vehicle rather than a Crit'Air 5 vehicle, since restrictions for these categories are often introduced within a short time interval, and sometimes simultaneously (see Table 17). By contrast, responses on the sales margin are concentrated around cutoffs involving more polluting vehicles (Crit'Air 3 and above). This pattern is consistent with limited anticipation on the sales margin: households tend to sell their vehicles when restrictions become binding. Conversely, there is little reason to sell a vehicle that is not yet targeted by restrictions, since owners can still postpone the transaction.

Taken together, these findings support the interpretation that the compositional changes in the car fleet documented in the baseline analysis are driven by the Crit'Air-based access rules rather than by confounding vintage trends.

6.6 Spatial reallocation: a gravity-based extension

Previous results showed that LEZ implementation shifts second-hand transactions toward cleaner cars. This pattern suggests a spatial reallocation across local markets, with more polluting vehicles being redirected away from LEZ areas and cleaner vehicles being relatively more likely to flow into them. To investigate these mechanisms, we next examine the spatial allocation of second-hand passenger-car transactions using a gravity-type model of bilateral flows between intercommunal communities. This framework allows us to identify separately the effects of LEZ adoption at the origin and at the destination.

This approach also addresses a key concern for the interpretation of our baseline estimates: a possible violation of the Stable Unit Treatment Value Assumption (SUTVA). In the second-hand market, LEZ restrictions potentially changed the composition of second-hand transactions and the passenger-car fleet outside treated cities, including in ICs used as controls. Using bilateral flows, we can compare transactions involving both treated and control ICs and trace how these flows are reallocated across local markets. The framework also allows us to assess spillover effects on ICs neighboring LEZs.

Gravity model. In this gravity model, the unit of observation is an origin IC $\times$ destination IC $\times$ year cell. In this setting, our stacked framework can no longer be applied, since control units are interconnected through bilateral flows and cannot be replicated separately for each cohort. Let F_{ijt} denote the number of second-hand transactions from origin IC i to destination IC j in year t. LEZ exposure is defined separately at the origin and destination. For control ICs, which are note treated, we assign a placebo treatment year equal to 2022, the median implementation year across the treated cohorts. These variables are equal to zero until 2021 and to one from 2022 onward. They should therefore be interpreted as controls for changes in second-hand market flows originating from or directed to control ICs during the main period of LEZ implementation. We estimate Poisson pseudo-maximum likelihood (PPML) gravity models:

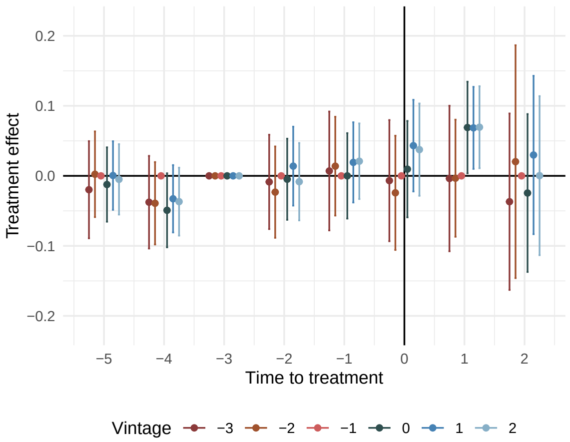
$$\begin{aligned}\mathbb{E}[F_{ijt} \mid \cdot] = \exp\Big(&\beta_1 \text{LEZOrigin}_{it} + \beta_2 \text{LEZDest}_{jt} + \beta_3 \text{LEZNeighOrigin}_{it} + \beta_4 \text{LEZNeighDest}_{jt} \\ &+ \beta_5 \text{CtrlOrigin}_{it} + \beta_6 \text{CtrlDest}_{jt} + \theta X_{ijt} + \alpha_{ij} + \delta_t\Big)\end{aligned}$$

where X_{ijt} includes time-varying controls, namely the logarithm of the vehicle fleet size at the origin and destination. The origin–destination fixed effects α_{ij} absorb all time-invariant bilateral determinants of flows, while δ_t captures common year shocks.[15]

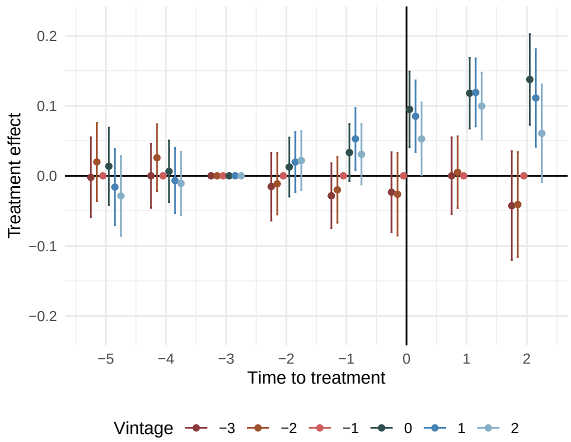
Results. Table 7 reports the results by Crit'Air category. As expected, LEZ implementation at destination significantly reduces inflows of the most polluting vehicles, particularly Crit'Air 4 and more, while inflows of the cleanest vehicles increase. Symmetrically, LEZ adoption at origin increases outgoing flows of polluting vehicles and reduces those of the cleanest ones.

Importantly, we find no evidence that these vehicles are systematically displaced toward the control group. The coefficients associated with control ICs generally have the same sign as those for treated areas, but smaller magnitudes. If polluting vehicles sold by LEZ residents were being reallocated toward control

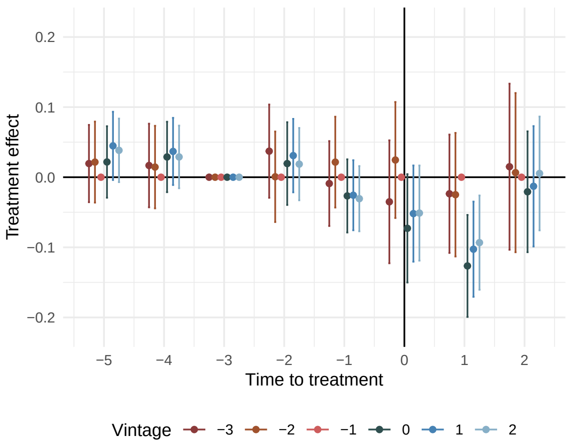
[15] Note that we do not include origin-year and destination-year fixed effects, as is standard in structural gravity (Head and Mayer, 2014): because LEZ adoption is an origin- or destination-side shock, such fixed effects would absorb LEZOriginit and LEZDestjt. The placebo-treated control IC dummies are meant to detect end-of-period common shocks across control ICs.



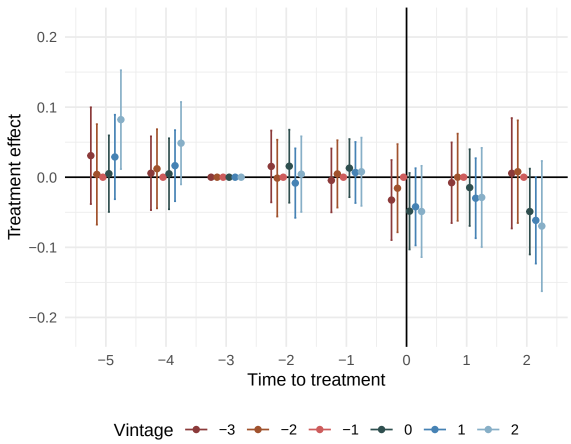
Second-Hand Car Purchases
Crit'Air 3, 4, 5 and Non-classified



Second-Hand Car Purchases
Crit'Air 1, 2 and 3



Second-Hand Car Sales
Crit'Air 3, 4, 5 and Non-classified



Second-Hand Car Sales
Crit'Air 1, 2 and 3

Figure 16: Triple-Difference estimates of LEZ effects on external second-hand car purchases
Reading note: One year after implementation, second-hand purchases of recent cars (Crit'Air 1 to 3) are 10 to 12% higher in LEZ ICs than in the control group when the vehicle has a Crit'Air sticker one grade cleaner.
Method: Event-study estimates from stacked triple-difference using PPML, relative to the cohort-specific reference year ($\tau = -3$). Fixed effects include IC × year × cohort, IC × vintage × cohort and year × vintage × cohort, with no additional control variables. Standard errors are clustered at the IC × vintage × year level.
Data source: Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

cities, one would instead expect coefficients of opposite sign. One possible explanation is that some control ICs implement LEZs in 2025: these attenuated effects may therefore reflect anticipatory responses prior to formal implementation, consistent with the patterns already visible in Figure 18. As already stated, this would imply that our baseline estimates understate the effect of LEZs, since the difference between treated and control areas would otherwise be larger. A second, non-exclusive, explanation is the presence of broader shocks affecting vehicle markets across large cities, such as a common shift in preferences toward cleaner cars. In that case, the estimated LEZ effect would be correctly estimated, and the results would mainly underscore the importance of choosing a control group comparable to treated cities.

In addition, the results reveal spillovers to neighboring ICs. LEZ adoption in nearby areas affects bilateral flows in the same direction as direct treatment, although with smaller magnitudes. This indicates that adjustments in the second-hand market extend beyond the strict LEZ perimeter, likely because drivers residing near LEZ areas are frequently exposed to the restrictions through commuting and other recurrent travel.

Unlike changes in the vehicle fleet driven by new car purchases or scrappage, this spatial reallocation of vehicles still in circulation through the second-hand market does not, in itself, alter the aggregate environmental characteristics of the fleet at the country level. Instead, it primarily shifts more polluting vehicles away from LEZs and from the cities in the control group, which are the country's largest urban areas, and therefore likely toward less densely populated places. For greenhouse gas emissions, whose effects are global, this spatial reallocation is essentially without consequence. The implications are less straightforward for local air pollutants, whose concentrations depend on where emissions occur and are therefore partly linked to the driver's place of residence, as measured in our data. This does not imply, however, that the reallocation is a zero-sum game from a public health perspective, involving only a redistribution of exposure across populations. It may still generate public health gains, since for a given quantity of pollutants emitted, the number of people exposed is likely to be lower in less densely populated areas than in denser ones, such as LEZs and the cities in the control group.

Table 7: Gravity model on second-hand car flows by Crit'Air category with LEZ and neighboring IC effects

	1E (1)	2 (2)	3 (3)	4 (4)	5N (5)
LEZOrigin	-0.116***	0.165***	0.034	0.139***	0.149***
	(0.023)	(0.038)	(0.044)	(0.031)	(0.033)
LEZDest	0.046***	-0.011	-0.013	-0.188***	-0.226***
	(0.017)	(0.025)	(0.036)	(0.031)	(0.039)
CtrlOrigin	-0.011	0.049**	0.064***	0.029**	0.005
	(0.021)	(0.020)	(0.020)	(0.012)	(0.012)
CtrlDest	-0.071***	-0.007	-0.028*	-0.052***	-0.094***
	(0.015)	(0.013)	(0.015)	(0.016)	(0.017)
LEZNeighOrigin	-0.052**	0.076***	0.017	0.071***	0.078***
	(0.024)	(0.018)	(0.019)	(0.017)	(0.012)
LEZNeighDest	0.050***	-0.004	0.035	-0.052***	-0.069***
	(0.013)	(0.012)	(0.022)	(0.016)	(0.010)
log(FleetOrigin)	0.546**	0.468**	0.638***	0.068	0.014
	(0.266)	(0.237)	(0.122)	(0.052)	(0.046)
log(FleetDest)	-0.079	-0.359***	-0.493***	-0.195*	0.334***
	(0.176)	(0.119)	(0.081)	(0.107)	(0.064)
log(CritAirFleetOrigin)	1.14***	1.20***	1.06***	0.605***	0.667***
	(0.127)	(0.042)	(0.150)	(0.026)	(0.024)
log(CritAirFleetDest)	0.196*	0.213***	0.169	0.578***	0.631***
	(0.101)	(0.053)	(0.133)	(0.043)	(0.028)
Origin x Dest	✓	✓	✓	✓	✓
Year	✓	✓	✓	✓	✓
Observations	8,054,410	11,740,666	10,418,254	6,974,030	6,818,882
Pseudo R^2	0.901	0.888	0.894	0.846	0.868
Within Pseudo R^2	0.018	0.032	0.009	0.004	0.008

Reading note: Following LEZ implementation, the number of second-hand Crit'Air 4 vehicles leaving treated intermunicipalities through the second-hand market increases by 14%, while the number entering these areas declines by 19%.
Method: Gravity model of passenger-car second-hand flows estimated using PPML. Standard errors are clustered at origin $\times$ destination and year level.
Data source: Sdes, RSVERO, 2011–2025.
Coverage: Mainland France.

7 Conclusion

This paper shows that LEZ adoption accelerates the ongoing replacement of older and more polluting vehicles with cleaner alternatives as defined by the Crit'Air classification. The number of more polluting cars (Crit'Air 2 to 4) declines progressively after implementation, while the stock of cleaner cars (Crit'Air 1 and E) vehicles rises gradually. We find that LEZs encourage the early replacement of older and more polluting vehicles with cleaner alternatives. This effect, however, remains small relative to the natural renewal of the fleet, as older vehicles gradually become obsolete and are replaced by newer ones. This translates into a 7% decline in NO_x emissions from resident passenger cars two years after implementation, as well as a 2% reduction in $PM_{2.5}$ and GHG emissions. We also find effects for light commercial vehicles, which are often subject to LEZ restrictions earlier than passenger cars. However, because the empirical approach is less well adapted to this segment of the fleet, these results should be interpreted with caution.

The observed effects are primarily driven by a shift in used-car purchases toward less polluting vehicles. Significant effects are also estimated for new-car purchases, notably through a decline in diesel vehicles classified as Crit'Air 2. These results are less robust, however, particularly because of pre-existing differences between treated and control areas. Scrappage and resale responses are more limited, suggesting that LEZs do not primarily lead households to bring forward the timing of vehicle replacement when their current car becomes non-compliant with access restrictions. Overall, the evidence suggests that LEZs mainly affect the type of vehicle households choose when they eventually replace their car, rather than the timing of replacement itself. This compositional shift contributes to a spatial displacement of more polluting vehicles toward less regulated areas through second-hand transactions. The triple-difference validation further shows that adjustments align with Crit'Air cutoffs across adjacent vintages within fuel type, supporting the interpretation that it is the Crit'Air-based regulatory rule itself that drives these compositional changes. The results also highlight the importance of expectations and policy credibility. We document anticipatory responses that are closely linked to the institutional context in which LEZs were made compulsory by the 2019 *Loi d'orientation des mobilités* and frequently announced several years ahead of implementation. Anticipation effects are most pronounced on purchase margins, which is consistent with the durable nature of vehicles: households internalize the expected future usability of a car at the time of acquisition.

This mechanism operates in a context where enforcement has so far relied only marginally on sanctions. Despite the existence of formal monetary penalties for non-compliance, LEZ-related fines represent a negligible share of total traffic sanctions, peaking at fewer than 11,000 cases nationwide in 2019. In addition, in many cities, local authorities have chosen to delay the application of sanctions. During an initial "educational phase," drivers may be checked and informed about the rules, but are not fined. In addition to traffic restrictions, which constitute the core mechanism of LEZs, some local authorities have also introduced subsidies for the purchase of cleaner vehicles, on top of national support schemes. The effects estimated in this paper should therefore be interpreted as the combined impact of LEZ traffic restrictions and associated local subsidies. Our method does not allow us to disentangle the relative contribution of these different channels.

Beyond average effects, we document substantial heterogeneity and spatial spillovers. Effects vary markedly across cities, which is consistent with large differences in LEZ parameters such as perimeter size, restricted Crit'Air categories, and the scope of vehicles affected. Some cities experience sharp shifts away from polluting vehicles, while others, such as Marseille or Nice, show no effect. Within treated cities, effects are stronger in middle- and low-income municipalities, where the initial fleet is more polluting, and weaker in high-income municipalities, where vehicle fleets are already closer to LEZ requirements.

Within LEZ cities, effects are also more pronounced in central municipalities than in suburbs, reflecting the partial coverage of LEZ perimeters. The gravity analysis further highlights spillover effects on neighbouring areas, confirming that LEZ exposure extends beyond administrative boundaries, likely through commuting and other regular trips to regulated zones. Unlike changes driven by new-car purchases or vehicle scrappage, the spatial reallocation of vehicles through the second-hand market does not, by itself, improve the aggregate environmental characteristics of the vehicle fleet. Its main effect is to move the most polluting vehicles away from LEZs, likely toward less densely populated areas. This has little consequence for greenhouse gas emissions, whose effects are global. For local pollutants, however, welfare implications are less clear-cut: relocation changes where emissions occur, but may still reduce population exposure if a given amount of pollution is emitted in less densely populated areas.

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8 Appendix

8.1 LEZ policy

Table 8: Crit'Air classification rules for cars (M1) and light trucks (LCVs, N1)

Crit'Air label	Fuel	Euro standard	First registration
E	Electric, hydrogen	–	All years
1	Gas (LPG, CNG), plug-in hybrid	–	All years
1	Petrol	Euro 5 and 6	From 01/2011
2	Diesel	Euro 5 and 6	From 01/2011
2	Petrol	Euro 4	01/2006 – 12/2010
3	Diesel	Euro 4	01/2006 – 12/2010
3	Petrol	Euro 2 and 3	01/1997* – 12/2005
4	Diesel	Euro 3	01/2001 – 12/2005
5	Diesel	Euro 2	01/1997* – 12/2000
Non-classified	Petrol or diesel	Euro 1 or earlier	Up to 12/1996*

Reading note: a diesel vehicle (car M1 or LCV N1) complying with Euro 5 or Euro 6 and first registered from January 2011 onwards is assigned Crit'Air 2.
Source: Decree (Arrêté) of 21 June 2016 on air quality certificates (as amended), Annex I. Available at: https://www.legifrance.gouv.fr/loda/id/JORFTEXT000032749723.
* For LCVs (N1), the lower bound is 10/1997 instead of 01/1997 (and the non-classified cut-off is up to 09/1997 instead of up to 12/1996).

ZFE	Veh.	NC	5	4	3	2
Angers	All	01/25 (12m pilote)				
Annecy	All	01/25	01/28	01/29	01/30	
Annemasse	All	01/25	01/28	01/29	01/30	
Bordeaux	All	01/25				
Caen	Car	01/25				
Clermont-F. (mun.)	LT	07/23				
Clermont-F. (IC)	LT	03/25				
Dijon	LT	01/25 (suspended)				
Grenoble (mun.)	LT	01/17	01/17			
Grenoble (IC)	Car LT	07/23 05/19	07/23 05/19	01/24 07/20	01/25 (18m pilote) 07/22	 07/28
Le Havre	All	01/25				
Lille	All	01/25				
Lyon	Car LT	09/22 (4m pilote) 01/21	09/22 (4m pilote) 01/21	01/24 01/21	01/25 01/22	01/28 01/28
Marseille	All	09/22 (1m pilote)	09/22 (1m pilote)	09/23	Abandoned	
Montpellier	All	07/22	07/22	01/24	01/25 (pilote)	
Nancy	Car LT	01/28 01/25	01/28 01/25			
Nantes	All	01/25				
Nice	All	01/23–04/25	01/23–04/25	Abandoned		
Nîmes	All	01/25				
Paris (mun.)	All	01/17	01/17	07/19		
Paris (IC)	All	07/19	07/19	06/21	01/25 (24m pilote)	
Pau	All	01/25				
Reims	All	09/21 (4m pilote)	09/21 (4m pilote)	01/23	01/29	
Rennes	All	01/25	01/27	01/29	01/30	
Rouen	Car LT	09/22 (6m pilote) 07/21	09/22 (6m pilote) 07/21	09/22 (6m pilote) 07/21	Abandoned Abandoned	
Saint-Étienne	LT	01/22	01/25	01/25	01/27	
Strasbourg (mun.)	LT	09/18	09/18	09/19		
Strasbourg (IC)	All	01/22 (12m pilote)	01/22 (12m pilote)	01/23 (12m pilote)	01/24 (36m pilote)	01/27
Toulouse	Car LT	01/23 03/22	01/23 03/22	01/23 01/23		

Reading notes: Columns NC, 5, 4, 3, 2 refer to Crit'Air stickers; entries report restriction start dates (mm/yy). An empty cell means that no restriction is scheduled for the corresponding sticker. Restrictions may begin with a pilot phase (*phase pédagogique*), during which no penalty is applied in case of non-compliance; when applicable, the pilot duration is reported in months. When no duration is reported, the end date of the pilot phase is not yet known. "Abandoned" indicates that the restriction for the corresponding sticker was cancelled before implementation. "LT" refers to light trucks. "All" refers to passenger cars and light trucks when the implementation calendar is identical for both vehicle types. When a city is associated with several ZFE perimeters and different restriction dates across perimeters, these are reported on separate lines (e.g., "Paris (mun.)" for the City of Paris ZFE or "Paris (IC)" for the Greater Paris ZFE). Specific cases: the Dijon ZFE is currently suspended; the Nice ZFE was withdrawn in 04/25.

Figure 17: ZFE implementation calendar by Crit'Air sticker and vehicle category

8.2 Constructing Emission Parameters from OMINEA

We construct annual conversion parameters that translate passenger-car vehicle-kilometers traveled into emissions of NOx and particulate matter (PM1.0, PM2.5, PM10), using emission factors from the OMINEA database produced by CITEPA within the French official emissions inventory system.[16] OMINEA distinguishes several pollution sources for passenger vehicles, which we aggregate in our analysis: (i) exhaust emissions from passenger cars by driving condition, (ii) fuel evaporation for passenger vehicles, and (iii) non-exhaust emissions from road, tire, and brake wear.

These aggregated emission factors are expressed in mg per vehicle-km, for each combination of fuel type (Diesel, Gasoline, LPG, LNG, Electricity), network type (motorway, road, urban), Euro standard (before Euro 1; Euro 1–Euro 6; Euro 6c; Euro 6d-TEMP; Euro 6d), pollutant (NOx, PM1.0, PM2.5, PM10), and year (1990–2023).

Unlike OMINEA, our empirical data do not report vehicle-kilometers traveled by network type (motorway, road, urban). To bridge this gap, we construct network-type weights from OMINEA's annual vehicle-kilometers traveled by network type, available for 2018–2022, separately for each vehicle category defined by fuel type and Euro standard. For each vehicle category, we compute the annual share of total vehicle-kilometers driven on each network. For years prior to 2018 and after 2022, weights are fixed at their 2018 and 2022 values, respectively. Finally, for each year we compute a weighted average of the corresponding emission factors across driving conditions. The output is a set of annual emission parameters (mg/vehicle-km) by fuel type, pollutant, and Euro standard, which can be applied directly to annual kilometers traveled in our RSVERO data.

[16] Citepa, 2025, *Rapport OMINEA – 22e édition*

Euro standard	Diesel	Electric	Gasoline	LNG	LPG
NOx (mg/km)					
Non-classified	563.61	0.00	2503.55	3945.48	2601.81
1	690.84	0.00	548.66	568.05	543.18
2	719.24	0.00	298.06	304.50	266.40
3	793.45	0.00	115.93	117.94	130.56
4	587.74	0.00	63.72	63.56	69.90
5	592.91	0.00	49.02	56.59	62.00
6	502.16	0.00	32.23	27.94	16.64
6c	501.24	0.00	31.84	27.82	16.62
6d-TEMP	95.95	0.00	31.79	6.04	16.62
6d	83.62	0.00	29.20	6.48	17.84
$PM_{2.5}$ (mg/km)					
Non-classified	230.71	12.66	14.80	15.43	12.21
1	104.45	12.66	14.87	15.43	12.21
2	68.31	12.66	14.87	15.43	12.21
3	55.63	12.66	13.13	13.67	12.21
4	48.91	12.66	12.93	13.67	12.21
5	12.10	12.66	11.84	13.49	12.21
6	12.29	12.66	11.58	13.49	12.21
6c	12.30	12.66	11.61	13.49	12.21
6d-TEMP	12.29	12.66	11.44	13.49	12.21
6d	12.81	12.99	12.04	14.08	12.80

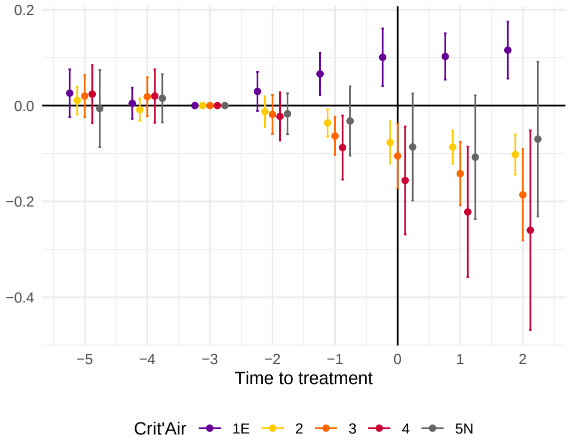
Table 9: Emission Factors by Euro Standard and Fuel Type for Cars in 2019

Reading note: In 2019, for Euro 6 diesel passenger cars, the NOx emission factor is 502.16 mg/km, while the $PM_{2.5}$ emission factor is 12.29 mg/km. "Non-classified" refers to pre-Euro vehicles (i.e., vehicles manufactured before the first Euro emission standard).
Data source: Citepa, Ominea emission inventory.
Coverage: Passenger cars, year 2019.

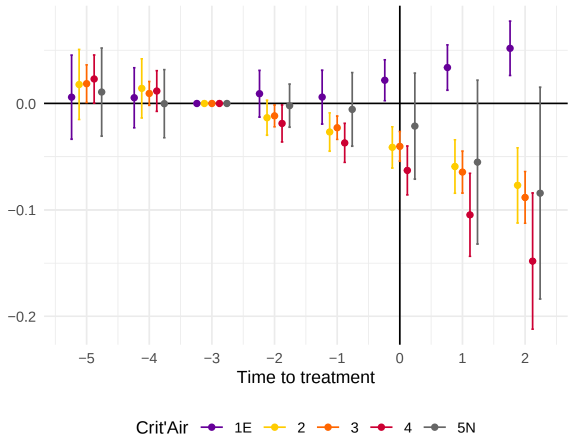
8.3 Supplementary results

8.3.1 Robustness checks

Panel A: Excluding LEZs implemented in 2025 from the control group

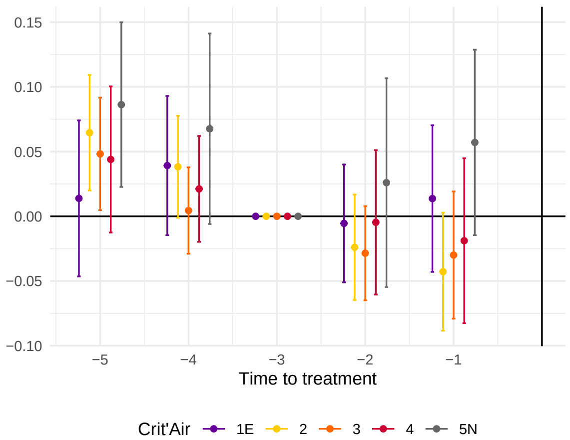


External Second-Hand Purchases

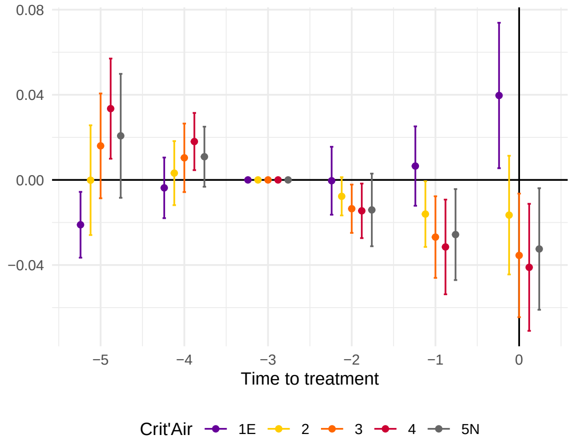


Fleet Size

Panel B: Restricting the treated group to LEZs implemented in 2025

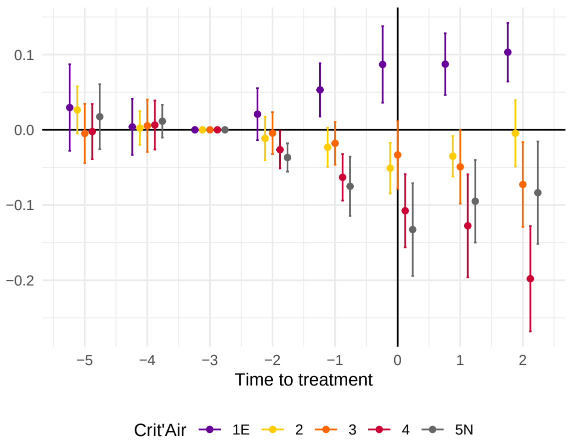


External Second-Hand Purchases

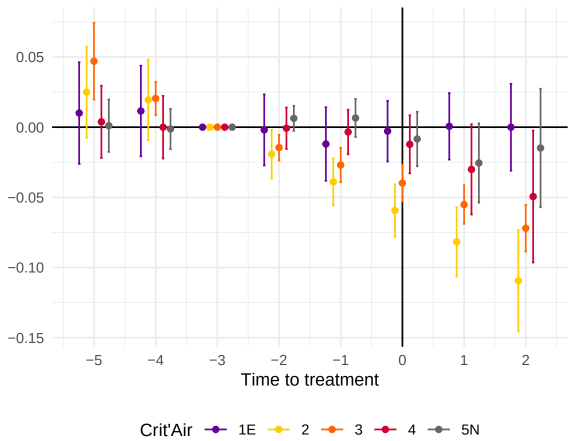


Fleet Size

Panel C: Including Paris in the treated group



External Second-Hand Purchases



Fleet Size

Figure 18: Effect of LEZ on passenger car fleet, by Crit'Air category with alternative control and treatment groups

Reading note: [to be completed].
Method: Event-study estimates from stacked difference-in-differences using PPML, relative to the cohort-specific reference year ($\tau = -3$). Fixed effects include IC $\times$ cohort and year $\times$ cohort, with no additional control variables. Standard errors are clustered at the IC $\times$ year level.
Data source: Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

8.3.2 Between-IC heterogeneity

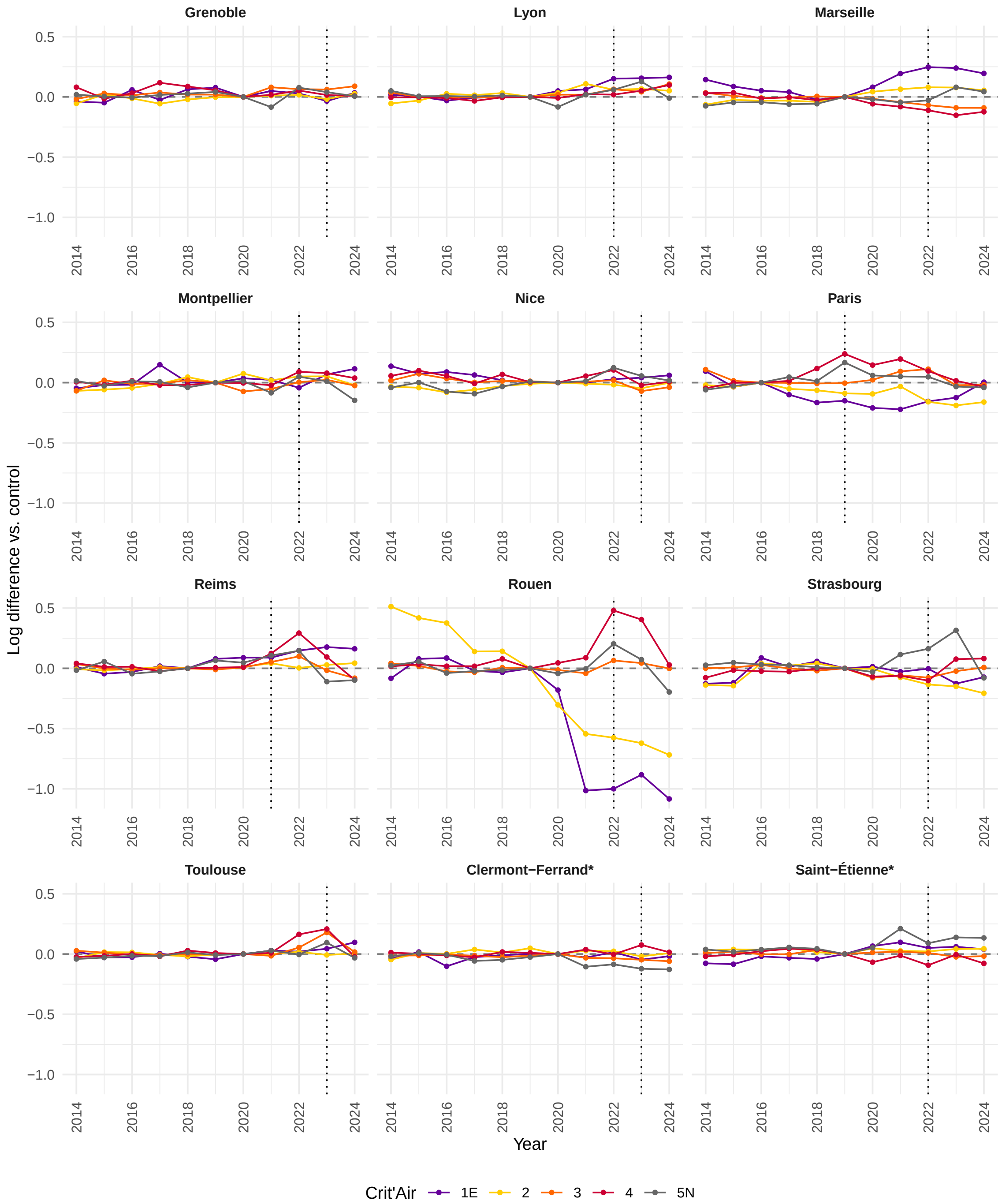


Figure 19: City-specific effects of LEZ on external second-hand car sales by Crit'Air category

* Saint-Etienne and Clermont-Ferrand are not treated for passenger cars, as their LEZs apply only to light commercial vehicles; they therefore serve as placebo tests here.

Reading note: One year after LEZ implementation, the external second-hand car sales of Crit'Air 4 passenger cars is about 40 % higher in the Rouen IC than in the control group.

Method: For each treated functional area, difference in log for external second-hand car sales, relative to its specific synthetic control, normalized to the cohort-specific reference year ($\tau = -3$). The vertical dotted line indicates the LEZ implementation.

Data source: Sdes, RSVERO, 2011–2025.

Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

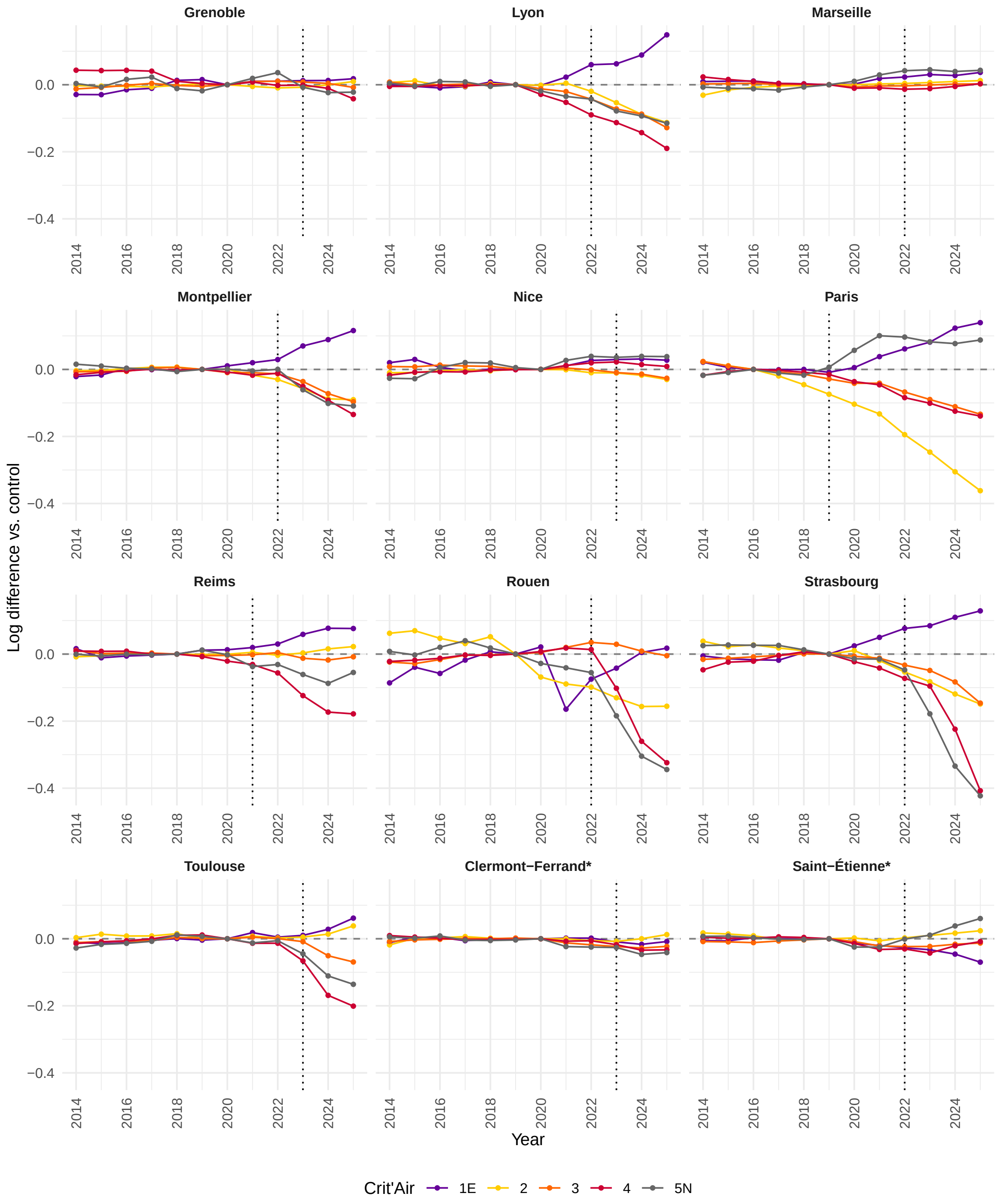


Figure 20: City-specific effects of LEZ on car fleet by Crit'Air category

* Saint-Etienne and Clermont-Ferrand are not treated for passenger cars, as their LEZs apply only to light commercial vehicles; they therefore serve as placebo tests here.
Reading note: One year after LEZ implementation, the fleet of Crit'Air 4 passenger cars is about 10 % lower in the Rouen IC than in the control group.
Method: For each treated functional area, difference in log for car fleet, relative to its specific synthetic control, normalized to the cohort-specific reference year ($\tau = -3$). The vertical dotted line indicates the LEZ implementation.
Data source: Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

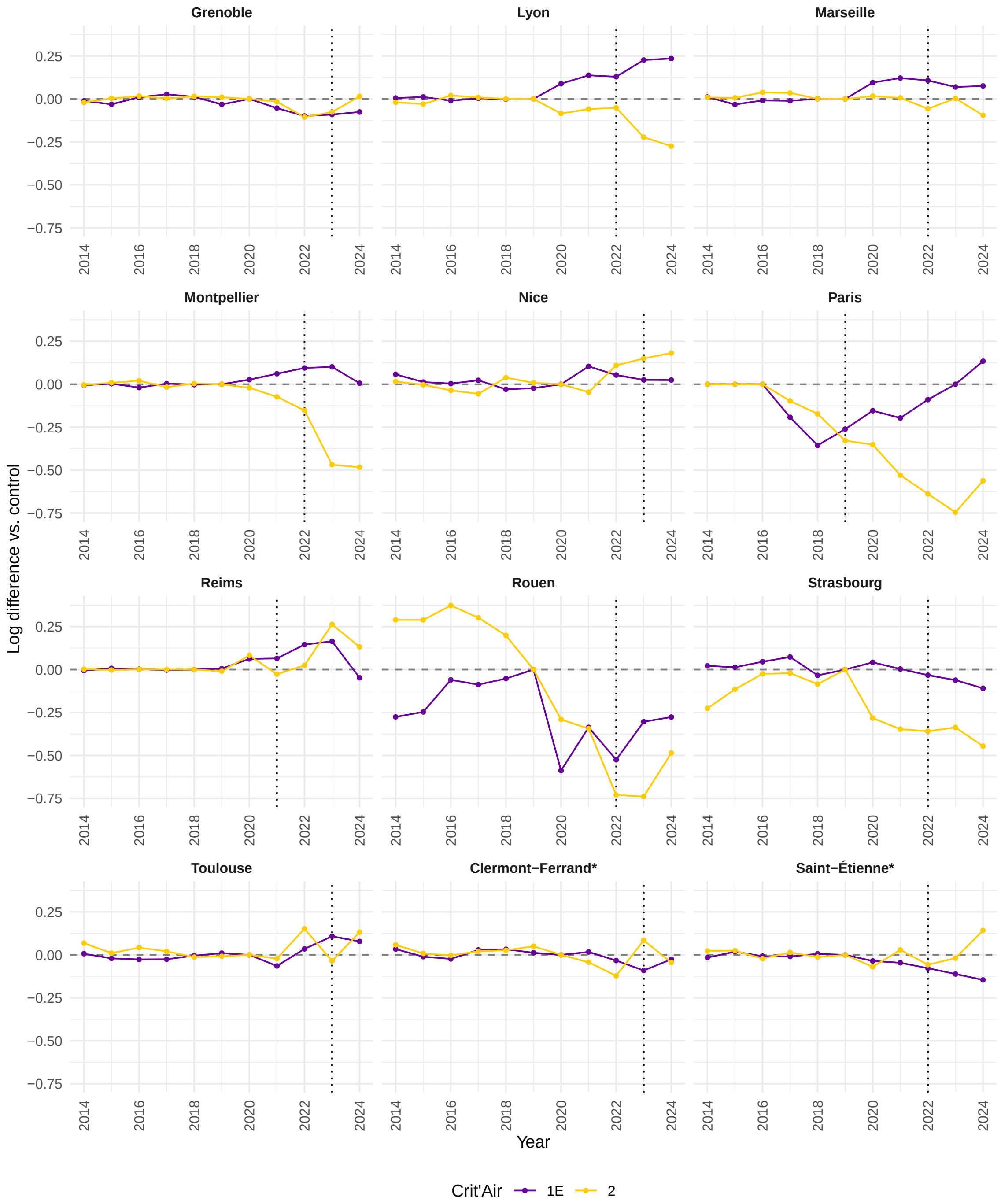


Figure 21: City-specific effects of LEZ on new car purchases by Crit'Air category

* Saint-Etienne and Clermont-Ferrand are not treated for passenger cars, as their LEZs apply only to light commercial vehicles; they therefore serve as placebo tests here.

Reading note: One year after LEZ implementation, the purchases of Crit'Air 2 new passenger cars is about 22 % lower in the Lyon IC than in the control group.

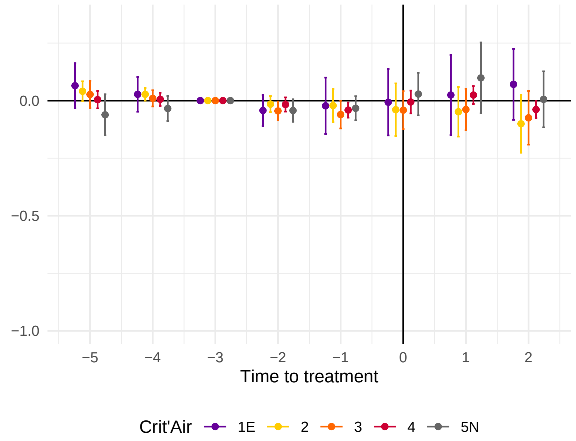
Method: For each treated functional area, difference in log for new car purchases, relative to its specific synthetic control, normalized to the cohort-specific reference year ($\tau = -3$). The vertical dotted line indicates the LEZ implementation.

Data source: Sdes, RSVERO, 2011–2025.

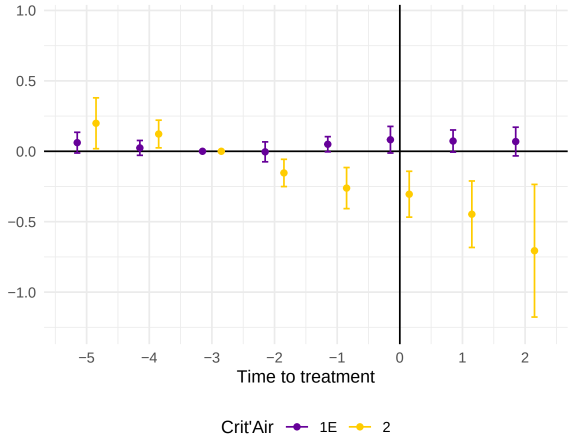
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

8.3.3 Within-IC heterogeneity

Panel A: Baseline (peripheral municipalities)

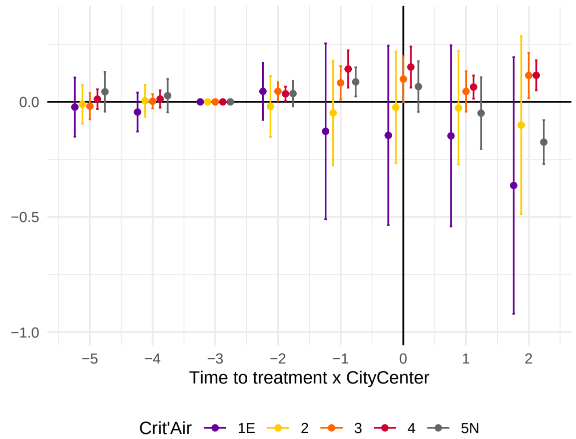


External Second-Hand Sales

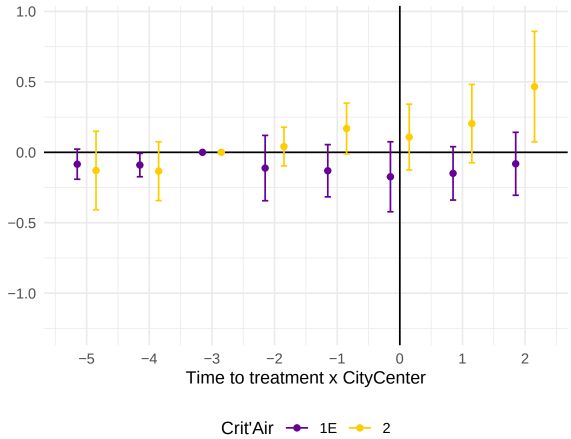


New car purchase

Panel B: Central vs peripheral municipalities



External Second-Hand Sales

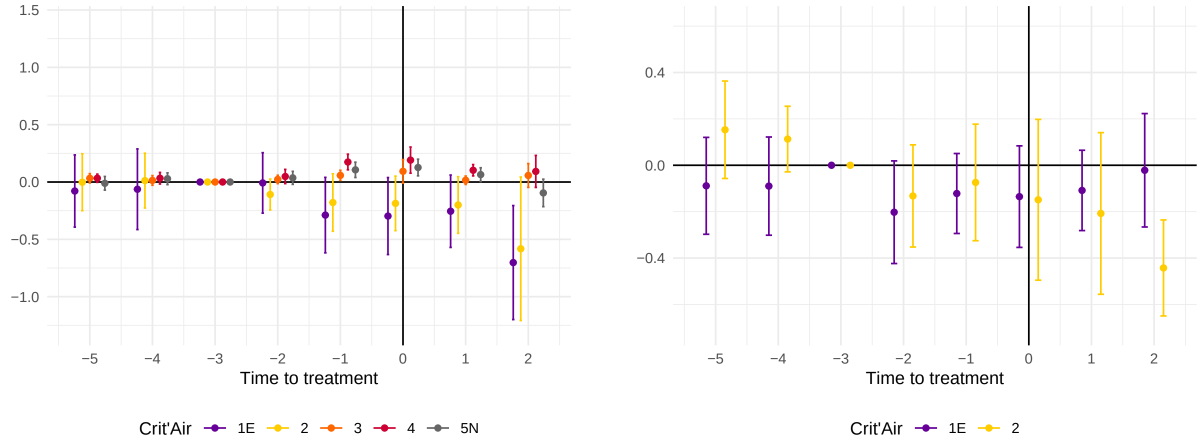


New car purchase

Figure 22: Effect of LEZ on passenger car fleet, by Crit'Air category, in central and suburban municipalities

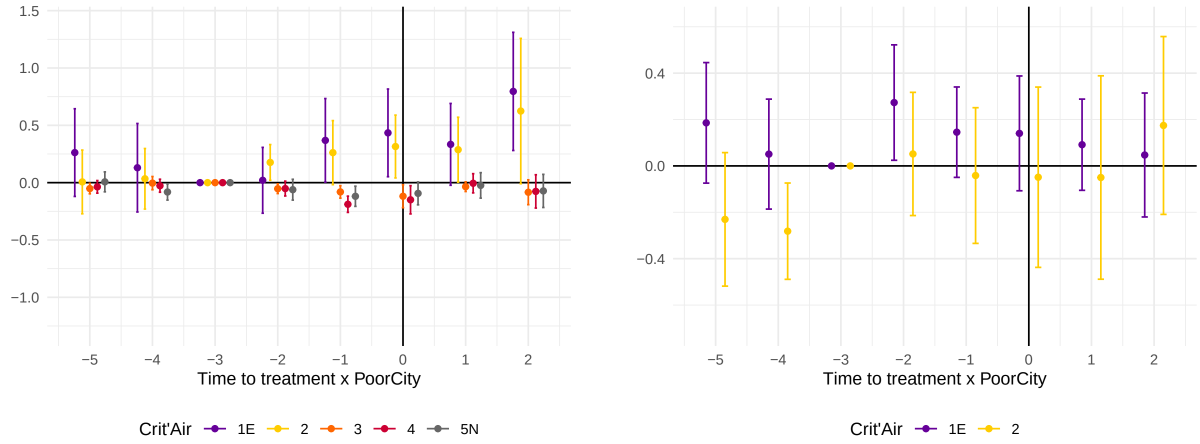
Reading note: One year before implementation, the number of external second-hand sales of Crit'Air 4 passenger cars is about 6% lower in peripheral municipalities within LEZ ICs than in the control group.
Method: Event-study estimates from stacked difference-in-differences using PPML, relative to the cohort-specific reference year ($\tau = -3$). Fixed effects include municipality × cohort, year × cohort and year × cohort × central-municipalities, with no additional control variables. Standard errors are clustered at the municipality × year level.
Data source: Sdes, RSVERO, 2011–2025.
Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

Panel A: Baseline (medium-income municipalities)



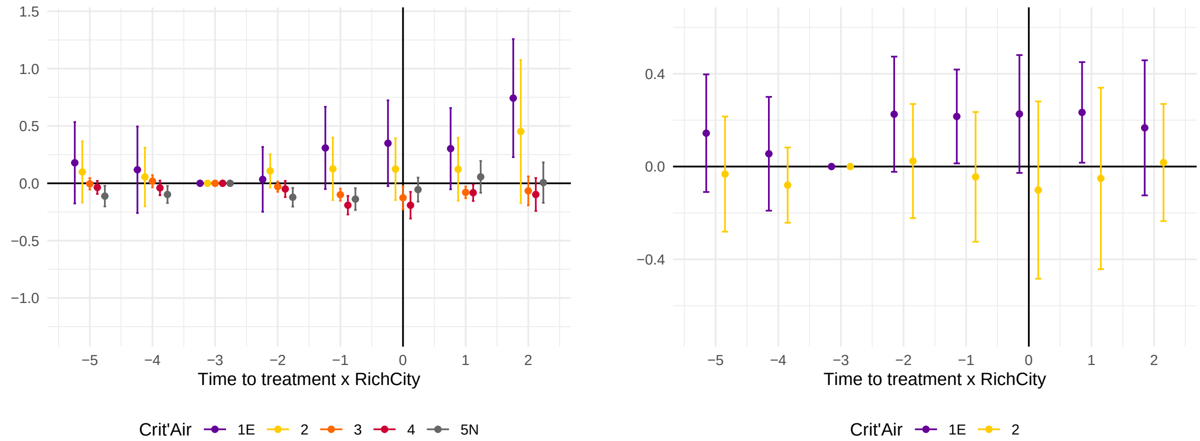
External Second-Hand Sales New Car Purchases

Panel B: Low vs- medium-income municipalities



External Second-Hand Sales New Car Purchases

Panel C: High- vs medium-income municipalities



External Second-Hand Sales New Car Purchases

Figure 23: Effect of LEZ on passenger car fleet, by Crit'Air category and municipal income

Reading note: One year before implementation, the number of external second-hand sales of Crit'Air 4 passenger cars is about 17% lower in medium-income municipalities within LEZ ICs than in the control group.]

Method: Event-study estimates from stacked difference-in-differences using PPML, relative to the cohort-specific reference year ($\tau = -3$). Fixed effects include municipality $\times$ cohort, year $\times$ cohort and year $\times$ central-municipalities, low-income municipalities and high-income municipalities dummies, with no additional control variables. Standard errors are clustered at the municipality $\times$ year level.

Data source: Sdes, RSVERO, 2011–2025.

Coverage: Central ICs of functional urban areas with more than 300,000 inhabitants, excluding Paris.

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