How does economic activity adapt to pollution pricing?

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Abstract

Policymakers around the world are exploring ways to tackle greenhouse gas emissions, but when evaluation focuses on narrow margins, policies can have unintended consequences. We exploit the phased introduction of London's Ultra-Low Emission Zone (ULEZ), a tax on highly-polluting vehicles, which has heterogeneous spatial impacts. This is due to the arbitrary boundaries and variation in the extent to which households are impacted based on pre-existing economic choices. We use a shift-share event study and regression discontinuity methods to study how the ULEZ affects economic activity across four important margins: vehicle investment, switching commuting method, firm relocation and house prices. We show the initial announcement of the ULEZ had large, significant positive effects on adoption of ultra-low emission vehicles. There is some evidence that firms relocate outside the zone after the policy is announced. The introduction of the policy had a positive impact on house prices within the zone. Individuals more-exposed to the zone use public transport more after the policy is introduced.

JEL: H23; R40; R48; Q58

Keywords: low emission zones; pollution pricing; spatial economics

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1 Introduction

There are high social costs to air pollution.[1] Due to both the intensity of pollution exposure and the number of people exposed, these costs are greatest in urban areas. Governments have implemented a variety of policy responses in the transportation sector, a key source of urban air pollution. In Europe, "low emissions zones" now prohibit or heavily tax the use of highly-polluting vehicles in many city centers. There are several ways households and firms may adapt to such corrective taxes: driving less, switching to other transit modes, changing their home/work location, investing in less-polluting vehicles or by keeping behaviour constant and paying the pollution price. In this project, we estimate economic responses to the introduction and subsequent expansions of London's Ultra Low Emission Zone (ULEZ).

We exploit the phased introduction of London's ULEZ and a shift-share event-study design (Borusyak, Hull, and Jaravel 2022) to study the adaptation of economic activity along all major margins and provide a framework for monitoring the effectiveness of this policy throughout future phases in near-real time. The phased introduction of the ULEZ changes which vehicles can drive into particular areas of London without paying a fee, affecting commuter-belt postcodes heterogeneously based on their location and pre-existing economic choices. Affected individuals can react by purchasing ULEZ-compliant vehicles, switching to public transport, working from home more, by changing the location of their home or employer, or pay the charge to drive into the Zone.

The ULEZ, described by the BBC as "the most radical plan you've never heard of," was introduced on 8th April 2019 as a £12.50 fee to drive a highly-polluting vehicle into central London.[2] However, the ULEZ exempts residents from taxation and thus applies only to commuters. In 2021, the ULEZ expanded in size by about tenfold and is no longer exempt to residents. It expanded further on 29th August 2023 to cover all

[1] Chay and Greenstone 2005; Currie and Neidell 2005; Currie and Walker 2011; Deschenes, Greenstone, and Shapiro 2017; Alexander and Schwandt 2019; Deryugina, Heutel, Miller, Molitor, and Reif 2019.

[2] https://www.bbc.com/news/uk-england-london-47638862.

London boroughs, and most of Greater London.

There is distinctive geographic variation in the pattern of the ULEZ "treatment," as those commuting into the ULEZ face the strongest incentives to substitute towards less-polluting vehicles, public transport, or towards working patterns that require less physical presence in Central London. We propose to use this policy variation to analyse how individuals adjust their economic activity in response to the policy.

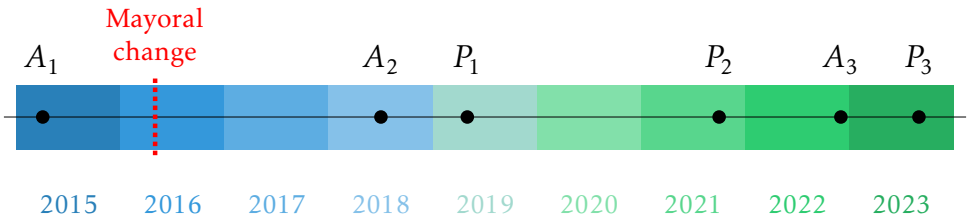


Figure 1: Timeline of ULEZ announcements and implementation. A = announcement, P = policy introduction. Subscripts indicate the first, second and third expansions of the policy.

The ULEZ was first confirmed in March 2015, and the initial zone in Central London officially came into force in April 2019. The ULEZ expansion to cover a wider area of London was confirmed in June 2018, and this expansion began in September 2021. The final expansion to include Greater London was announced in November 2022, and this began in August 2023. Figure 1 plots the timeline and Figure 4 shows the spatial expansion of the policy.

Large investment responses to the ULEZ are immediately visible in public-use tabulations of Driver and Vehicle Licensing Authority (DVLA) data by postcode district on vehicle registrations. These data are counts of the number of all registered vehicles and all tax-exempt vehicles (ULEVs) by postcode and quarter; it is illegal to drive an unregistered vehicle. To identify treated postcodes, we use data from the 2011 UK Census on commuting flows by origin and destination and calculate the share of commuters in each postcode who commute by car to destinations in the ULEZ. Figure 2 is suggestive of a sharper rise in ULEVs in regions where individuals are more exposed to the ULEZ due to their commuting behaviour.

We repeat this exercise for the ULEZ exposure for the expansion of the zone which was announced in May 2016. This expanded zone went up to the North and South

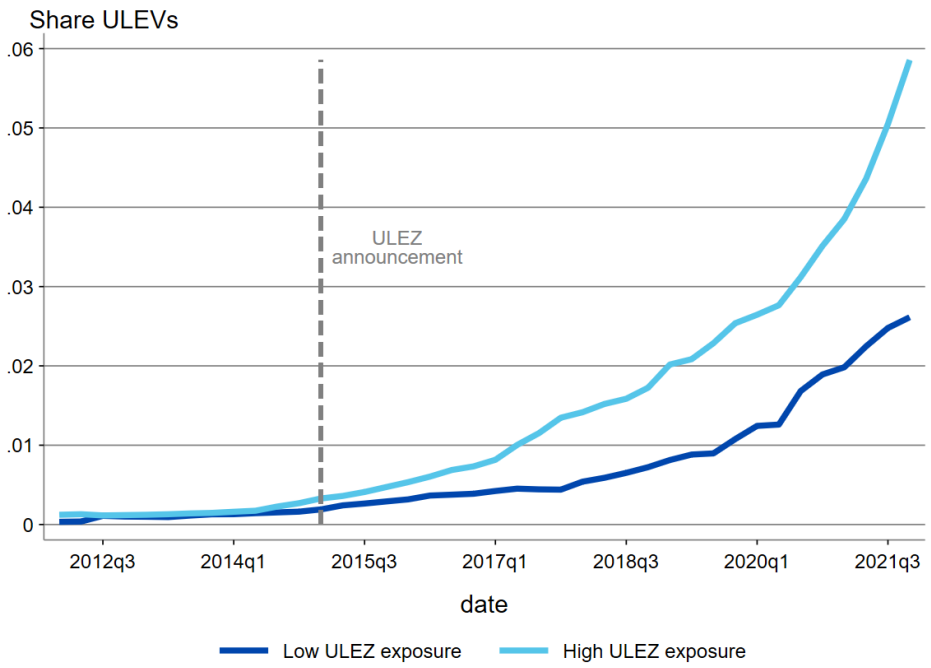


Figure 2: Adoption of ultra-low emissions vehicles in high and low ULEZ exposure postcode districts

Circular roads, and was implemented in September 2021. This increased the share of commuters driving into the ULEZ across many postcodes. Once again, Figure D1 in the appendix highlights a sharp rise in adoption of ULEVs for those more affected by the expansion, at the time the expansion was announced.

We use two empirical research designs to estimate the causal impact pollution pricing has on economic activity. For outcomes related to commuting behaviour (such as ULEV registration, public transport use and homeworking), we employ a shift-share differences-in-differences (DiD) design (Bartik 1991; Borusyak, Hull, and Jaravel 2022; De Chaisemartin and d'Haultfoeuille 2022; Roth, Pedro HC Sant'Anna, Bilinski, and Poe 2023). We interact pre-existing commuter patterns at the postcode district level with time-varying coverage of the ULEZ. For outcomes related to location choice (firm creation and house transactions and prices), we instead employ a regression discontinuity design (Frölich and Huber 2019; Cattaneo and Titiunik 2022) and compare variables just inside and outside the ULEZ as the boundaries change.

In preliminary results, we show that there is a large, positive and significant effect of ULEZ exposure on ULEV adoption. Initial results suggest an average 1.3% rise in

the share of electric vehicles by the end of 2019, for each 1% increase in the share of affected commuters in a postcode district. The median postcode district has 1% of commuters affected by the ULEZ, and 0.3% of vehicles are ULEVs. Thus the impact is also significant in economic terms. We also find evidence that the introduction of the ULEZ has differentially affected the value of sold residential properties, with a boost for house prices within the zone. Initial results on public transport substitution behaviour suggest little aggregate effect, but differential impacts on those inside/outside the ULEZ. The rest of the empirical analysis is still work in progress.

There is much existing research on policies aimed at changing driving behaviour, especially taxing certain vehicles or taxing driving in specific zones. The closest research to ours are Barahona, Gallego, and Montero (2020) and Herzog (2023). The former paper investigates the effect of a policy introduced in 1992 in Santiago, Chile. This policy restricted the use of certain vintages of vehicles which were deemed more-polluting. They find the policy was effective at encouraging switching towards cleaner vehicles, and that this was welfare-improving. Likewise, the ULEZ places limits on older vintages of vehicles. Herzog (2023) focuses on the same geographic setting as we do, by investigating the introduction of the earlier Congestion Charge (CC) in London in 2003. They find evidence the policy reallocated commuters between driving and public transport, with differential impacts across skill groups, leading the benefits to accrue progressively. Road traffic was reduced by approximately 1%, taking into account endogenous sorting and substitution towards un-taxed driving routes. For more information on the background and impact of London's CC, we refer the interested reader to Leape (2006).

The impact of such policies on housing has also been investigated (Tang 2021; Gruhl, Volhausen, Pestel, and Moore 2022; Aydin and Kurschner Rauck 2023), with evidence that house prices respond positively. Driving taxes and low-emission zones are often motivated by aiming to reduce air pollution, and the evidence suggests mixed results on this front (Simeonova, Currie, Nilsson, and Walker 2019; Wolff and Zhai 2021; Gu, Deffner, Kuchenhoff, Pickford, Breitner, Schneider, Kowalski, Peters,

Lutz, Kerschbaumer, Slama, Morelli, Wichmann, and Cyrys 2022; Bernardo, Fageda, and Flores-Fillol 2021).

This paper makes three contributions. First it provides causal evidence of how the economic geography of work changes in one of the world's largest cities in response to pollution pricing. It thus fills a gap in the emerging literature on the spatial impacts of climate change (Castro-Vincenzi 2022; Desmet and Rossi-Hansberg 2023; Ponticelli, Xu, and Zeume 2023) and climate mitigation policies (Arkolakis and Walsh 2023; Colas and Saulnier 2023; Gilbert, Gagarin, and Hoen 2023). Second, it provides a rich set of policy-relevant elasticities that can inform the large literature on the optimal design of pollution pricing (Peltzman and Tideman 1972; Van Der Ploeg and Withagen 2014; Clausing and Wolfram 2023). Third, alongside a few likeminded papers (Clemens and Lewis 2022; Fetzer, Gazze, and Bishop 2023; Fetzer 2023; Fetzer, Palmou, and Schneebacher 2023) this paper provides a framework for how to analyse policy responses in near-real time using a combination of real-time, granular data sources and transparent, pre-registered research design.

The rest of this paper is organised as follows. Section 2 provides an overview of the ULEZ and its introduction. Section 3 presents our framework. Section 4 describes the data we use. Section 5 discusses our empirical approach. Section 6 presents our empirical results. A final Section 7 concludes and outlines next steps.

2 An introduction to the ULEZ

The Ultra Low Emission Zone (ULEZ) is an area of London for which an emission-standard based daily levy of £12.50 applies to non-compliant vehicles. The zone operates 24 hours a day, 7 days a week. The daily charge currently applies to residents of the ULEZ as well as commuters, however this was not always the case. The criteria for charging the levy is based on European emission standards. A penalty charge of £180 is applied for non-compliance. This charge is in addition to the Congestion Charge (CC) and applies to cars, motorcycles, vans, specialist vehicles (up to and including 3.5 tonnes) and minibuses. Vans and minibuses are also be subject to Low Emission Zone (LEZ) charges. Boris Johnson, then Mayor of London, announced the zone (covering the same central area as the Congestion Zone in 2015) would come into effect in September 2020. Sadiq Khan, Johnson's successor, introduced the Toxicity charge or 'T-charge', a £10 emissions surcharge for older, more polluting vehicles in October 2017, which covered the same area as the Congestion Zone. The T-charge was replaced by the ULEZ when it came into effect in April 2019, ahead of schedule. The ULEZ was expanded out to the North and South Circular roads in 2021. In November 2022, Sadiq Khan announced the expansion of the zone to cover all 32 London boroughs from August 2023. This matches the existing Low Emissions Zone (LEZ) boundary.

The expanded ULEZ is part of the effort to help improve air quality in and around London and reduce the impact on the health of residents and visitors to the city. The ULEZ is principally aimed at reducing levels of two key air pollutants from vehicle exhausts: nitrogen dioxide (NOx) and fine particle matter (PM). These pollutants have been linked to premature deaths and stunted growth of children lungs.

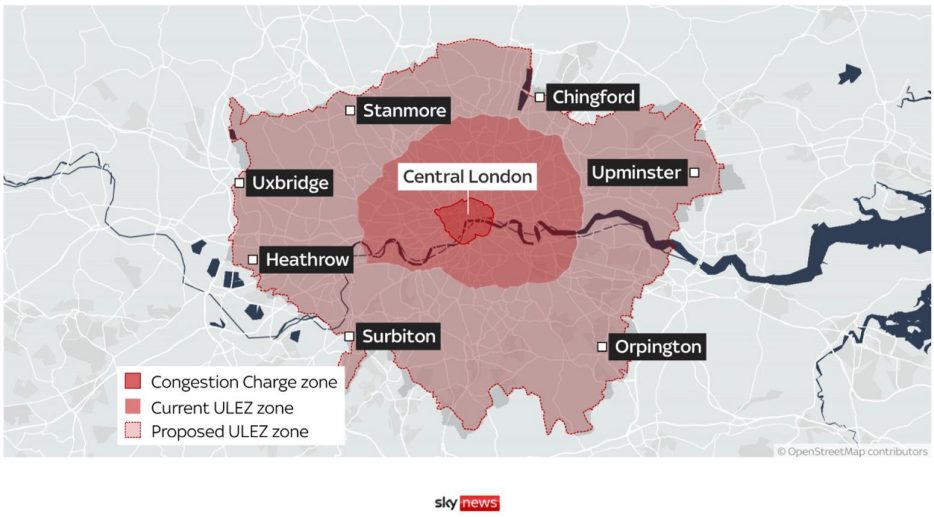


Figure 3: The geographic footprint of the ULEZ over time (source: Sky News)

3 Conceptual framework

Given widespread beliefs in the public debate that the primary impact of the ULEZ is on commuting behaviour,[3] we focus our analysis on the economic geography of work across Greater London. Individuals currently driving into London for work in non-ULEZ compliant vehicles have the following options when the policy applies to them:

1. Commuting **mode** margin:
   (a) Purchase an ULEZ-compliant vehicle.
   (b) Switch to public transport.
   (c) Work from home more often.
2. Commuting **distance** margin:
   (a) Change employer location (for instance, by switching jobs).
   (b) Move home.
3. **Do nothing** and pay the ULEZ charge.

Our main null hypotheses state that the introduction of the ULEZ does not affect economic activity on any of the three commuting **mode** margins and any of the two

[3] https://www.theguardian.com/environment/2023/aug/29/it-has-come-in-too-quickly-sense-of-injusti

commuting **distance** margins. Our set of secondary null hypothesis is that economic activity does not react to announcements (**strong version**) or reacts equally across all margins (**weak version**). Our final set of secondary hypotheses states that post-codes do not react differentially to policy announcements based on policy-relevant characteristics (e.g., the share of existing vehicle types eligible for different scrappage payment schemes).

1. $H_{0,1}$: There is no differential change in economic behaviour (in terms of purchasing electric vehicles, using public transport, working from home, work location or home location) for those that are 'treated' by the introduction of the ULEZ compared to those that are not.

2. $H_{0,2}$: Outcome variables of interest do not react (or do not react differentially) to news announcements about upcoming policy changes.

3. $H_{0,3}$: Outcome variables of interest do not react differentially based on policy-relevant characteristics of the postcode.

3.1 Model

We sketch a simple model of commuting, following some of the ideas in Ommeren and Dargay (2004) and Monte, Redding, and Rossi-Hansberg (2018).

3.1.1 Environment

Utility:

$$U_{ij\omega} = \frac{b_{ij\omega}}{\kappa_{ij}} \left(\frac{C_{i\omega}}{\alpha} \right)^{\alpha} \left(\frac{H_{i\omega}}{1-\alpha} \right)^{1-\alpha}$$

for individual ω commuting from location i to location j. They receive idiosyncratic amenity b, pay commuting cost κ, purchase C consumption and H housing services. The budget constraint satisfies $C_{i\omega} + Q_i H_{i\omega} = w_j - \kappa_{ij}$, where Q_i is the housing price.

Solving the utility maximisation problem yields the indirect utility function:

$$V_{ij\omega} = \frac{b_{ij\omega}}{\kappa_{ij}}(w_j - \kappa_{ij})Q_i^{\alpha-1}$$

Firm: firms produce output with a labour input and constant returns to scale $Y_j = Z_j L_j$. They choose input L_j to maximise profits. The wage is the outcome of Nash bargaining $\max_{w_j}(w_j - \kappa_{ij})^{\beta}(Z_j - w_j)^{1-\beta}$ which yields a wage which is the weighted average of commuting costs and local productivity $w_j = \beta\kappa_{ij} + (1-\beta)Z_j$.

Add in firm location choice (prior to making input and output choices).

Housing market: the demand for housing services is determined from utility maximisation.

$$H_{i\omega}^d = (1-\alpha)\frac{w_j - \kappa_{ij}}{Q_i}$$

Aggregating over all individuals living in i:

$$H_i^d = \sum_j \sum_{\omega \in (i,j)} (1-\alpha)\frac{w_j - \kappa_{ij}}{Q_i} = \frac{1-\alpha}{Q_i}\sum_j N_{ij}(w_j - \kappa_{ij})$$

where N_{ij} are the number of people living in i and working in j. The supply side is simply $H_i^s = A_i Q_i^{\epsilon}$. Therefore the equilibrium housing price is:

$$Q_i = \left[\frac{1-\alpha}{A_i}\sum_j N_{ij}(w_j - \kappa_{ij})\right]^{\frac{1}{1+\epsilon}}$$

Commuting: individuals have three commuting options with different costs:

1. Pay tax and drive old car: $\kappa_1 = \frac{\gamma\bar{k}}{s(N_d)^{\eta}}$
2. Invest in new car and drive (pay no tax): $\kappa_2 = \frac{\bar{k}}{s(N_d)^{\eta}} + \phi$
3. Take public transport: $\kappa_3 = \bar{k}\bar{s}$

where $\bar{k}$ is a fixed commuting cost, s represents speed of commuting which is a function of congestion N_d with speed elasticity of cost $\eta > 0$. For drivers who pay the tax $\gamma > 1$ we scale up costs, whereas those who invest in a new non-taxable vehicle pay

a separable cost $\phi > 0$. The probabilities of taking each mode of transport follow a multinomial logit: $P_j = \frac{\exp(W_j)}{\sum_i \exp(W_i)}$, where $W_j = -\kappa_j$ is the indirect commuting utility of choosing option j.

Congestion: we specify a congestion function such that the speed of commuting depends negatively on the number of drivers N_d:

$$s(N_d) = \bar{s} \exp(-\delta N_d)$$

Market clearing: the number of drivers N_d must be consistent with the probabilities and total number of individuals N:

$$N_d = N \times (P_1 + P_2)$$

In addition, the total labour employed in region j will be equal to the sum of all the commuters from other regions i to j: $L_j = \sum_i N_{ij}$.

3.1.2 Comparative statics

Effect of tax on commuting costs: the tax on old vehicles γ affects commuting costs of driving directly and indirectly via congestion.

$$\frac{d\kappa_1}{d\gamma}\frac{\gamma}{\kappa_1} = 1 + \eta\delta N_d \epsilon_{N_d,\gamma}$$

$$\frac{d\kappa_2}{d\gamma}\frac{\gamma}{\kappa_2} = \frac{\kappa_2 - \phi}{\kappa_2}\eta\delta N_d \epsilon_{N_d,\gamma}$$

where $\epsilon_{N_d,\gamma}$ is the elasticity of congestion to the tax, which we show below will be negative and small. Thus the tax makes commuting by car *more* costly in old vehicles and *less* costly in new vehicles (by reducing congestion).

Commuting costs from i to j will be weighted by the probabilities that individuals choose each method, so $\kappa_{ij} = P_1\kappa_1 + P_2\kappa_2 + P_3\kappa_3$. And this responds to the tax:

$$\frac{d\kappa_{ij}}{d\gamma}\frac{\gamma}{\kappa_{ij}} = \left(\eta\delta N_d \epsilon_{N_d,\gamma}\right)\left(\frac{P_1\kappa_1 + P_2(\kappa_2 - \phi)}{\sum_\ell P_\ell \kappa_\ell}\right) + \gamma\frac{P_1\kappa_1}{\sum_\ell P_\ell\kappa_\ell}$$

which highlights that the response of commuting costs to the driving tax depends positively on the share of taxable vehicles being used for commuting in each region $\frac{P_1\kappa_1}{\sum_\ell P_\ell\kappa_\ell}$.

Effect of tax on investment in new vehicles: the relative probability of using an old versus a new vehicle:

$$\frac{P_1}{P_2} = \exp\left(\phi - (\gamma - 1)\frac{\bar{k}}{s(N_d)^\eta}\right)$$

The elasticity with respect to the driving tax γ yields:

$$\frac{dP_1/P_2}{d\gamma}\frac{\gamma}{P_1/P_2} = -\left[\frac{\gamma\bar{k}}{\bar{s}^\eta} + (\gamma - 1)\kappa_1\delta\eta\frac{dN_d}{d\gamma}\right]$$

The elasticity of P_1/P_2 could be positive or negative, given $\frac{dN_d}{d\gamma}$ is negative. In other words, the relative probability of paying the driving tax rather than buying a new car can *rise*, which at first glance seems unintuitive. This result is due to the tax reducing congestion, which encourages driving (in old and new cars) at the margin. The net effect is the relative benefit of buying a new car decreases, even though the absolute number of those investing in a new vehicle rises.

Effect of tax on congestion: we can differentiate the equilibrium condition:

$$\frac{\partial N_d}{\partial\gamma} = N \times \left(\frac{\partial P_1}{\partial\gamma} + \frac{\partial P_2}{\partial\gamma}\right)$$

where $\frac{\partial P_i}{\partial\gamma} = -P_j\frac{d\kappa_j}{d\gamma}$. Combining with the response of commuting costs to the tax, we obtain:

$$\frac{dN_d}{d\gamma} = \frac{P_1\kappa_1}{\frac{1}{N} - \eta\delta(P_1\kappa_1 + P_2(\kappa_2 - \phi))}$$

For large N, the number of commuters in the economy, this derivative is negative.

Hence the elasticity of congestion N_d with respect to the driving tax on old vehicles γ is negative.

Effect on house prices: there are three channels we highlight for the effect of the driving tax γ on house prices: (1) wages, (2) commuting costs, (3) number of commuters.

$$\begin{aligned}\frac{dQ_i}{d\gamma} &= \frac{1-\alpha}{1+\epsilon}\frac{1}{A_i Q_i^{\epsilon}}\sum_j\left(\frac{dN_{ij}}{d\gamma}(w_j-\kappa_{ij})+N_{ij}\left(\frac{dw_j}{d\gamma}-\frac{d\kappa_{ij}}{d\gamma}\right)\right)\\ &= \frac{1-\alpha}{1+\epsilon}\frac{L_i}{A_i Q_i^{\epsilon}}\sum_j\left(\frac{d\kappa_{ij}}{d\gamma}\left(\epsilon_{N_{ij},\kappa_{ij}}\frac{w_j-\kappa_{ij}}{\kappa_{ij}}-(1-\beta)\right)\right)\end{aligned}$$

We will assume that higher commuting costs from i to j reduce the number of commuters on that route, so $\epsilon_{N_{ij},\kappa_{ij}} < 0$. Thus the sign of $\frac{d\kappa_{ij}}{d\gamma}$ determines the response of house prices to the driving tax, and our previous analysis showed it is positive. This leads house prices to respond negatively to the driving tax, where the driving tax is present.[4]

Effect on firm creation: A simple approach is to see how consumption responds to the tax, and proxy firm creation with local demand for consumption?

[4]To link this to our context, it is resident locations where the tax is levied, not workplace locations. Individuals within the Ultra Low Emission Zone are exempt from paying the tax, so we treat regions outside the zone as those subject to the tax.

4 Data

This section describes available data sources for all relevant margins. Not all data sources are at present publicly accessible. Where data access presents an insurmountable hurdle, the final paper will note this discrepancy from the pre-registered analysis plan and unobservable margins will be carefully modelled as part of the residual.

The list of postcodes in each expansion of the ULEZ is released via freedom of information requests and we manually check for consistency with other sources. The rapid widening of the ULEZ is plotted in Figure 4, with the white boundaries highlighting the number of postcodes within each area.

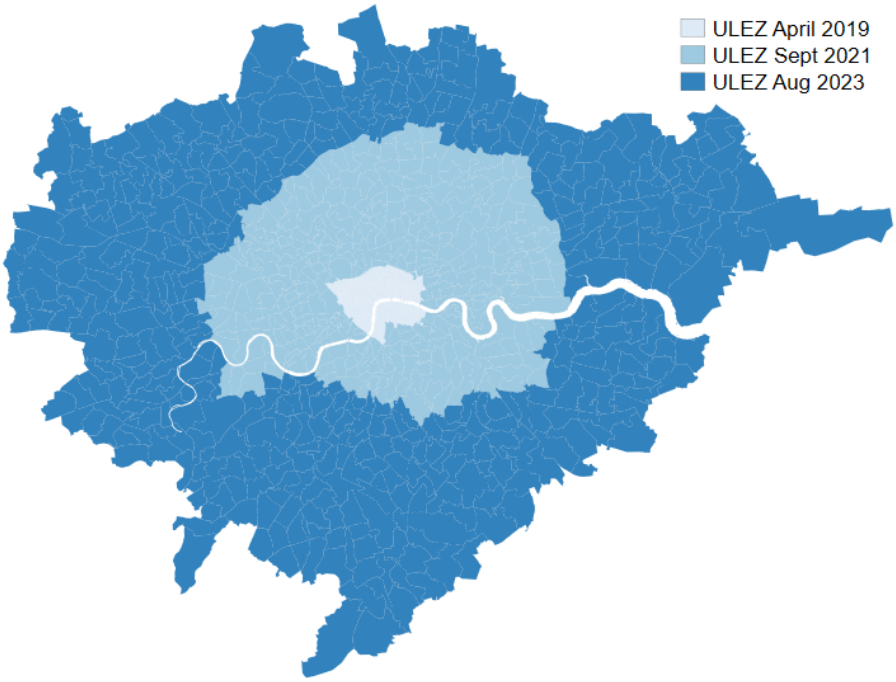


Figure 4: The evolution of London's ULEZ expansion

Table 1 captures an overview of our data and approaches for four margins of economic adjustment to the policy. We document the level of geographic and time aggregation, the resulting number of observations and our identification approach.

Across all specifications, we also use data from:

1. Postcode district crosswalks to output areas (OAs), lower- (LSOAs) and middle-super layers (MSOAs). These areas have 310, 1,500, 7,500 average residents,

Table 1: Cleaned data summary

Margin	Geography	Time period	# obs.	Identification
Electric vehicles	Postcode district	2012 - 2021, quarterly	12,858	Event study DiD
House prices	Postcode	2012 - 2022, quarterly	474,246	RDD
Public transport	Postcode	2019, daily	145,872	DiD
Firm creation	Postcode district	2012 - 2018, quarterly	8,098	RDD

respectively.

2. Population at OA level, to construct ULEZ exposure and weights.

3. 2011 Census commuting behaviour to compute commuting shares.

4.1 Electric vehicle adoption

We use data from the UK Driver and Vehicle Licensing Agency (DVLA) to estimate the substitution towards electric vehicles in response to the ULEZ. Large investment responses to the ULEZ are immediately visible in public-use tabulations of DVLA data by postcode district on vehicle registrations. These data are counts of the number of all registered vehicles and all tax-exempt vehicles (ULEVs) by postcode and quarter. It is illegal in the UK to drive an unregistered vehicle. To identify treated postcodes, we use data from the 2011 UK Census on commuting flows by origin and destination and calculate the share of commuters in each postcode who commute by car to destinations in the ULEZ.

Figure 5 shows the sharp increase in registered ultra-low emission vehicles (ULEVs) in the late 2010s in London. This is not simply a function of more vehicles registered in the capital; ULEVs are taking up a greater share of all new registrations, rising to over 1% in 2019 and over 2% in 2021, as seen in Figure 6. The geographic distribution of ULEV adoption in Greater London is contained in the appendix.

4.1.1 Vehicle data sources

1. **Vehicle registrations** by postcode district and quarter, 2012 - 2022 (VEH0122).

2. **Ultra-low emission vehicle registrations** by postcode district and quarter, 2012 - 2022 (VEH0134).

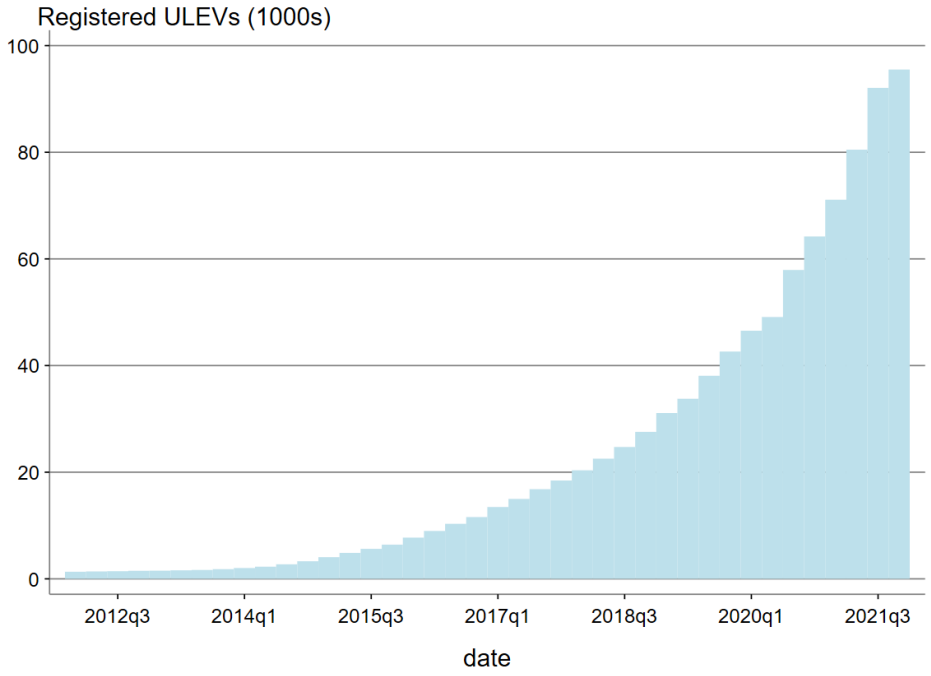


Figure 5: Adoption of ultra-low emissions vehicles in London

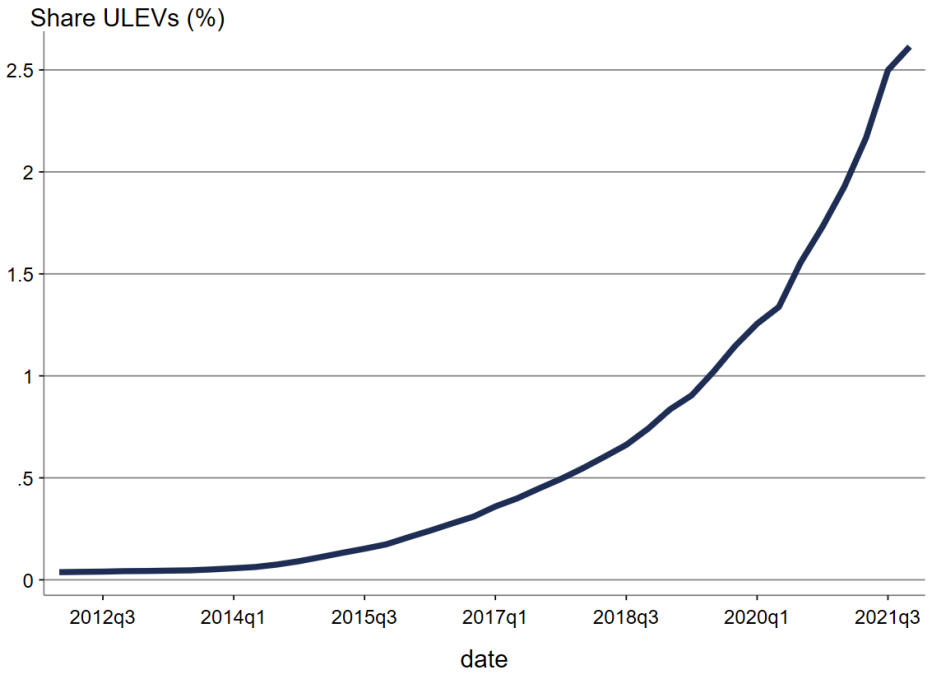


Figure 6: Adoption of ultra-low emissions vehicles in London

4.2 House prices

To establish if affected individuals move residence in order to avoid paying the tax, we use the Price Paid Data (PPD) from HM Land Registry. The PPD includes information on property sales in England and Wales submitted to HM Land Registry for registration and excludes all commercial transactions and not for value sales. We use the 'standard' price paid entries from 2012 to 2022 to compute quarterly postcode district-level average price paid and counts of sales. We then regress prices on property characteristics (e.g., dwelling type, tenure type) before averaging in order to mitigate composition effects.

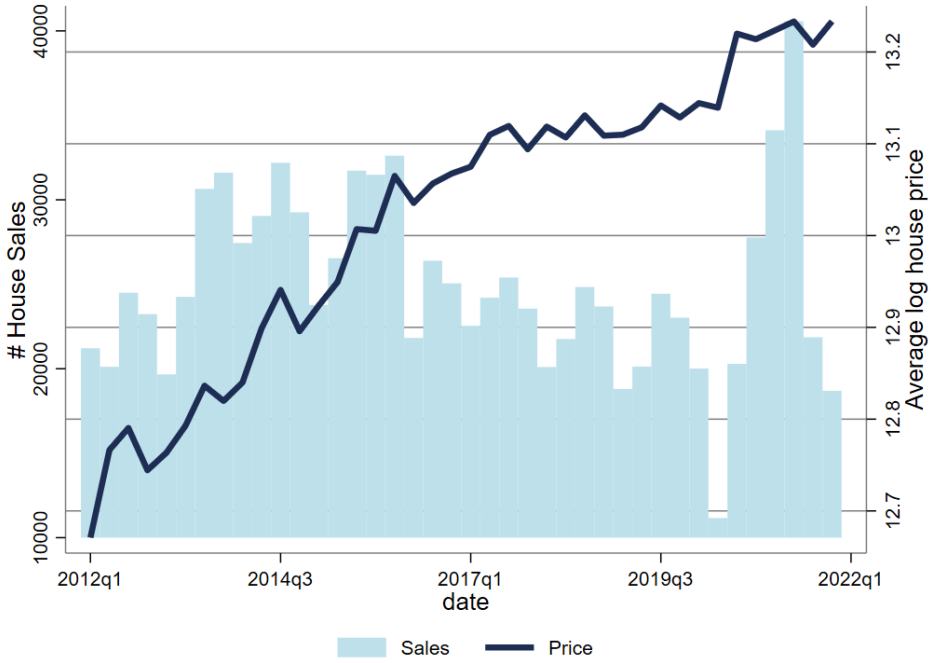


Figure 7: Price of sold houses and number of transactions in London

4.3 Public transport substitution

Commuters may also substitute towards public transport in response to the tax on highly-polluting vehicles. We use Transport for London (TfL) underground station-level average entry data to track the response of commuters who face the strongest incentives to substitute. The data includes station-level daily entry and exit counts for

2019, the year in which the ULEZ was first introduced.[5] We map London stations to postcodes and aggregate up to the postcode level.

4.4 Working from home

Individual-level homeworking rates for the UK are collected at a monthly basis by the UK Survey on Working Arrangements and Attitudes (UK SWAA), collected by a team of academic researchers at https://www.wfhresearch.com. We have approached the researchers for data at small geographic aggregations. Failing that, the UK Labour Force Survey (LFS) provides annual homeworking rates at the individual level with geographic identifiers.

4.5 Establishment location

The Longitudinal Business Database (LBD) is a new, quarterly firm-level set of data spines by the UK Office for National Statistics (ONS) based on the UK's business register, the Inter-Departmental Business Register (IDBR). [6] It inherits firm and establishment postcodes from the IDBR and will be accessible through the ONS Secure Research Service (SRS). Recent analysis by the ONS uses establishment postcodes to identify labour reallocation dynamics (https://escoe-website.s3.amazonaws.com/wp-content/uploads/2023/05/23161728/Jones-Site-Level-Business-Dynamism.pdf).

We obtain postcode sector firm entry rates by quarter. For disclosure we remove any postcode sector × quarter where fewer than 10 firms are born. Figure D6 plots the distribution of detrended[7] firm entry rates over time in London. Although firm entry has stayed steady on average, there is evidence of a rise in spatial variation.

[5] http://crowding.data.tfl.gov.uk/

[6] For more information about the LBD, see Lemma, Lui, Romaniuk, Schneebacher, and Wolf 2023.

[7] We regress the firm entry rate (new firms divided by all firms) at the postcode sector × quarter level on year and quarter fixed effects. The resulting residuals are used.

4.6 Computing ULEZ exposure

There is geographic variation in how 'exposed' different areas are to 'shock' of the ULEZ, based on commuting behaviour into the ULEZ. Commuters and individuals living just outside the ULEZ face the greatest incentive to substitute towards less polluting vehicles or public transport. There are two sources of randomness with regards to the policy announcement: (1) randomness of the ULEZ boundary, (2) randomness of the share of people who drive into the ULEZ.

In order to compute the ULEZ exposure variable, we follow two steps:

1. **Allocate ULEZ by postcode district** - we have ULEZ assignment at the postcode level, but vehicle registrations are at the postcode district level which is more aggregated. We compute a population-based allocation at the postcode district level, which represents the share of residents who live within the ULEZ. For example, W1 4GE is in the ULEZ with 1,000 people, but W1 7PU with 500 people is not. Therefore W1 has a population-adjusted ULEZ score of 0.66.

2. **Compute ULEZ exposure by postcode district** - we calculate the vehicle-weighted shares of (ULEZ-taxable) commuting multiplied by the ULEZ score. For example, we compute the share of commuting that involves driving into the ULEZ from 2011 Census data.

Figure 8 maps the ULEZ exposure by postcode district for London in the second quarter of 2019.

The widening of the ULEZ leads to (weakly) increasing exposure to the ULEZ for a given postcode district, and more postcode districts becoming exposed to the ULEZ via commuting behaviour. Figure 9 highlights the impact on both the intensive and extensive margin across postcode districts in London.

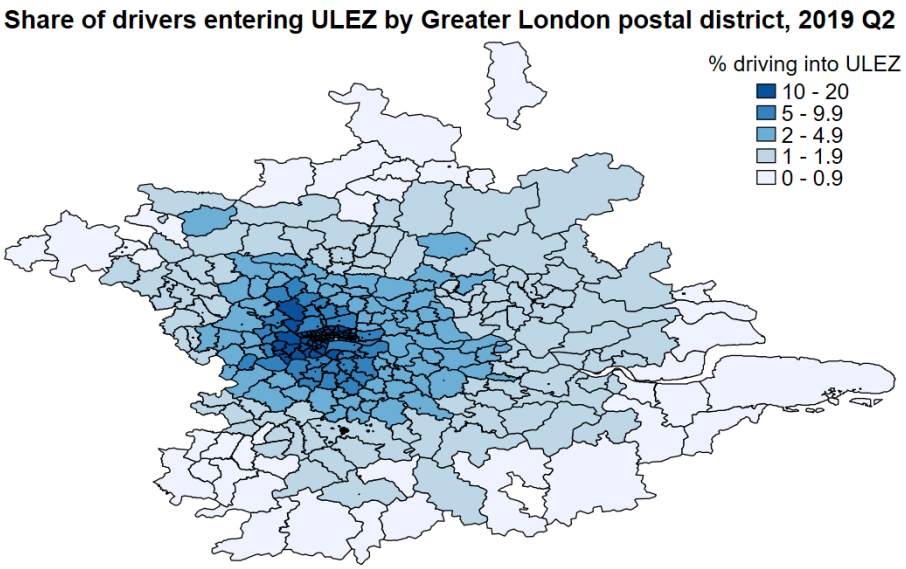


Figure 8: ULEZ exposure by postcode district

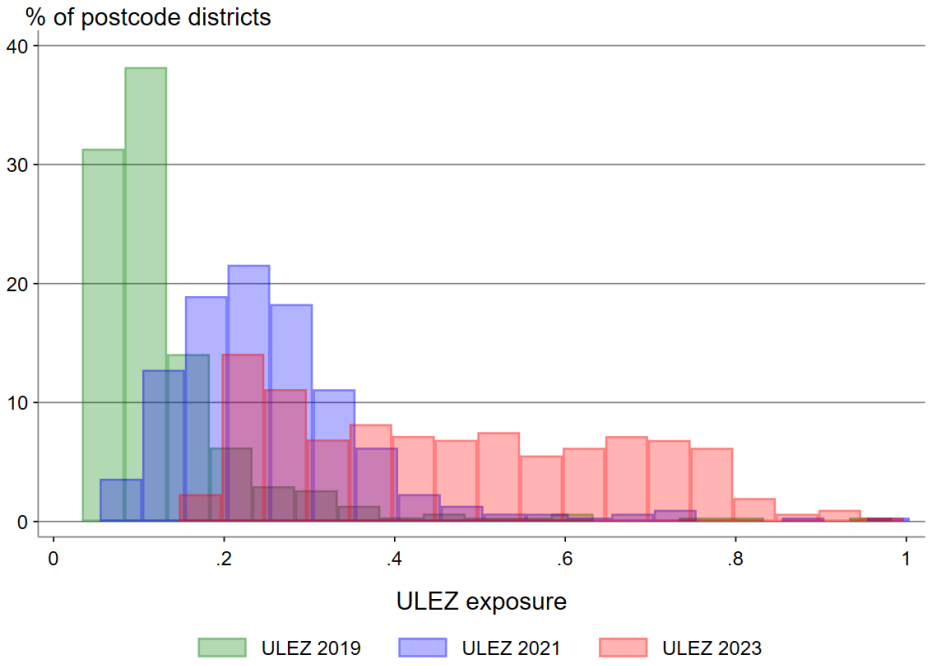


Figure 9: Histogram of computed ULEZ exposures for London's postcode districts

5 Empirical Approach

Our primary empirical approach is a shift-share event-study design of the following form:

$$\text{Outcome}_{it} = \alpha_i + \alpha_t + \beta \text{ULEZ}_i + \gamma_t \text{ShareDriveULEZ}_i + \varepsilon_{it} \quad (1)$$

where Outcome_{it} is one of the outcomes of interest in postcode district i, ULEZ_i is an indicator that i is in the 2019/2021/2023 ULEZ, and ShareDriveULEZ_i is the share of commuters in i who drive into the 2019/2021/2023 ULEZ. γ_t is the coefficient of interest. This event-study design works for the following outcomes: adoption of ULEVs, commuter numbers (with postcode districts assigned to nearest underground stations) and working-from-home rates.

For house prices and establishment locations we will use a regression discontinuity design (RDD) at the postcode level around the boundary of the ULEZ.

$$\begin{aligned}\text{Outcome}_{it} = \alpha_i + \alpha_t + \beta\text{ULEZ}_i + \delta\text{DistanceToULEZ}_i \\ + \eta\text{ULEZintroduced}_t + \theta\text{ULEZ}_i \times \text{ULEZintroduced}_t + \varepsilon_{it}\end{aligned} \tag{2}$$

where ULEZintroduced_t is a binary indicator for dates before/after the introduction of the ULEZ, and DistanceToULEZ_i is the number of miles from a postcode to the ULEZ boundary.

5.1 Differences-in-differences: estimation details

At its core, the DiD approach concerns identifying the causal impact of some (potentially non-random) treatment across units, over time. The key identifying assumption is that the relevant outcome of treated and non-treated units would have evolved *in parallel* in the absence of the treatment. It must also be that there is no causal effect of the treatment *prior* to its implementation. The 'parallel trends' assumption alongside the 'no anticipation' assumption permit identification of the average treatment effect on the treated (ATT).

Typically this would be estimated with a two-way fixed effects (TWFE) estimator. Equation (1) presents a time-varying TWFE estimator. However there are potential threats to identification: staggered rollout of treatment; heterogeneous treatment effects; non-parallel trends; multiple treatments; continuous treatment. The DiD liter-

ature has exploded in recent years (Callaway, Goodman-Bacon, and Sant'Anna 2024; Borusyak, Jaravel, and Spiess 2024; Chaisemartin and D'Haultfoeuille 2020; Sun and Abraham 2021; Callaway and Pedro H.C. Sant'Anna 2021; Goodman-Bacon 2021), with the aim of highlighting these issues and carefully describing the relevant assumptions in different contexts. Two key issues with a simple TWFE estimator is that researchers may be using 'bad controls' or averaging treatment effects with negative weights.

Our context features a continuous treatment which describes the exposure of postcode districts to ULEZ via the quasi-fixed pre-committed economic decisions of residents - their home and work locations, and commuting choice. The treatment has 'no anticipation' because prior to the initial announcement date in the first quarter of 2015, there had only been a consultation on the ULEZ (just one quarter prior). The policy had no public presence prior to this. We provide plots of Google Trends Web Search results for 'Ultra Low Emission Zone London' and 'ULEZ London' as supporting evidence.

We do not have staggered rollout, as all units are treated at the time of the policy announcement. However we do have multiple treatments, due to the ULEZ expansions which lead postcode districts to become more heavily treated over time. Put differently, the share of commuters who are affected by the ULEZ changes as the taxable area expands.

Our baseline event study plots γ_t from the time-varying TWFE in equation (1). We also compute the average TWFE coefficient, where γ doesn't vary over time. Given the focus of the recent literature on binary treatments, we also consider splitting ULEZ exposure at the median to convert treatment to binary. This allows us to follow the methodologies of Chaisemartin and D'Haultfoeuille 2020, Gardner 2022, and Clarke, Pailanir, Athey, and Imbens 2023.

It is important to check the validity of parallel trends. The standard approach is to compare the outcomes of treated and untreated groups prior to the treatment date. Placebo tests are another approach, where researchers run DiD on synthetic or fake

treatment units. A placebo test can be run with treatment units that are not actually treated, or with an outcome variable that the researcher thinks should be unaffected by the treatment.

6 Results

This section presents the first set of our results. Thus far we have detailed results on ultra-low vehicle adoption adoption, and preliminary results on house prices, public transport use and business creation. We are in the process of obtaining data on working from home.

6.1 ULEV adoption results

To get a sense of the correlations in the data, Figure 10 presents a scatter of the share of ULEVs in a postcode district and the exposure to the initial ULEZ expansion. The relationship is positive and statistically significant.

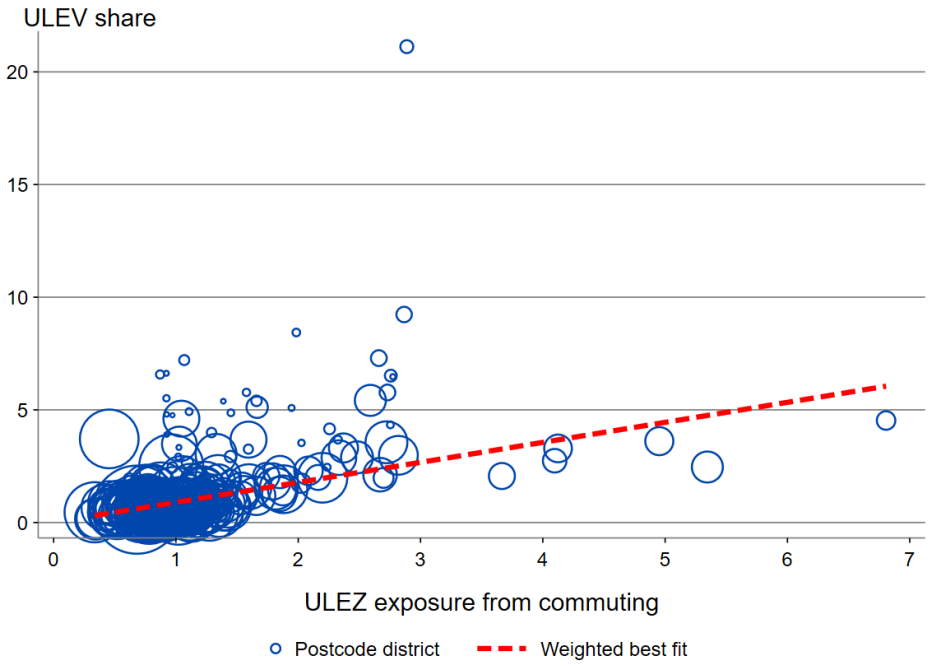


Figure 10: Relationship between ULEV adoption and ULEZ exposure.

A difference-in-differences regression of the ultra-low vehicle adoption share on the interaction of the 'treatment' (exposure to the ULEZ) and a post-policy indicator is the simplest way to see if the policy introduction differentially affected adoption of electric vehicles. Table 2 shows the results from this regression, with three different weighting specifications. In all regressions, we find a large and statistically significant relationship on the interaction term. This provides evidence that postcode districts

more exposed to the zone through driving commuting behaviour responded more to the policy introduction by adopting ULEVs at a higher rate.

Table 2: Difference-in-differences regression of ULEV share on ULEZ exposure interacted with a post-policy dummy

	(1)	(2)	(3)
	Dependent variable: ULEV share		
ULEZ exposure × Post-indicator	0.610***	0.406***	0.383***
	(0.137)	(0.056)	(0.049)
Weight	None	Vehicles	Population
N	9,325	9,325	9,325
R^2	0.649	0.704	0.744

Standard errors in parentheses, clustered at the postcode district level.
* $p < 0.1$, * $p < 0.05$, *** $p < 0.01$.
Fixed effects are postcode district, population-adjusted ULEZ measure and quarter-year.

Figure 11 shows time-varying coefficients from a differences-in-differences event study of ULEV adoption on ULEZ exposure, for the first ULEZ expansion announcement in Q1 2015. This specification controls for postcode district and quarter fixed effects, and whether or not an observation falls within the ULEZ itself. We cluster standard errors at the postcode district level.

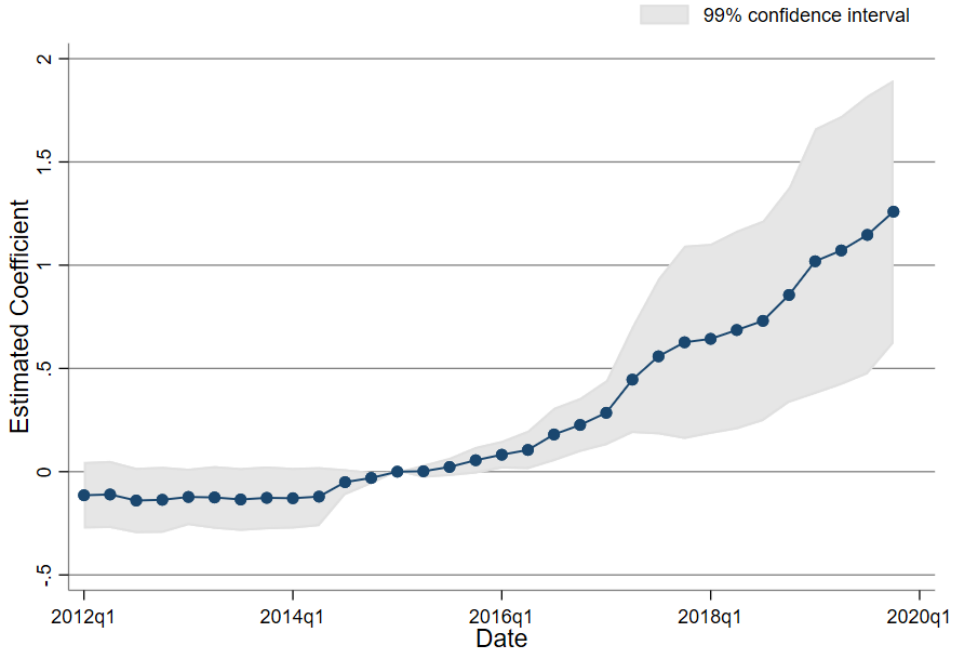


Figure 11: Baseline regression coefficients on ULEV adoption around first ULEZ announcement (Q1 2015)

These results suggest an average 1.3% rise in the share of electric vehicles by the end of 2019, for each 1% increase in the share of affected commuters in a postcode district. To put this into context, less than 2% of vehicle registrations in London at the end of 2019 were electric vehicles, and the average ULEZ exposure in London postcode districts is 1.2%.

The average treatment effect on the treated from a simple TWFE estimator with a time-invariant coefficient is 0.610, with a standard error of 0.137. This is a weighted average from the event study in Figure 11.

Chaisemartin and D'Haultfoeuille 2020 show that the TWFE estimator is a weighted sum of treatment effects, and the weights may be negative when heterogeneous treatment effects exist. We implement their robust estimator, and make ULEZ exposure binary with a cut-off at the median value. The results are shown in Figure 12. Given the binary treatment, the estimated coefficients are smaller in size, but the interpretation of the magnitude of the effects is very close.

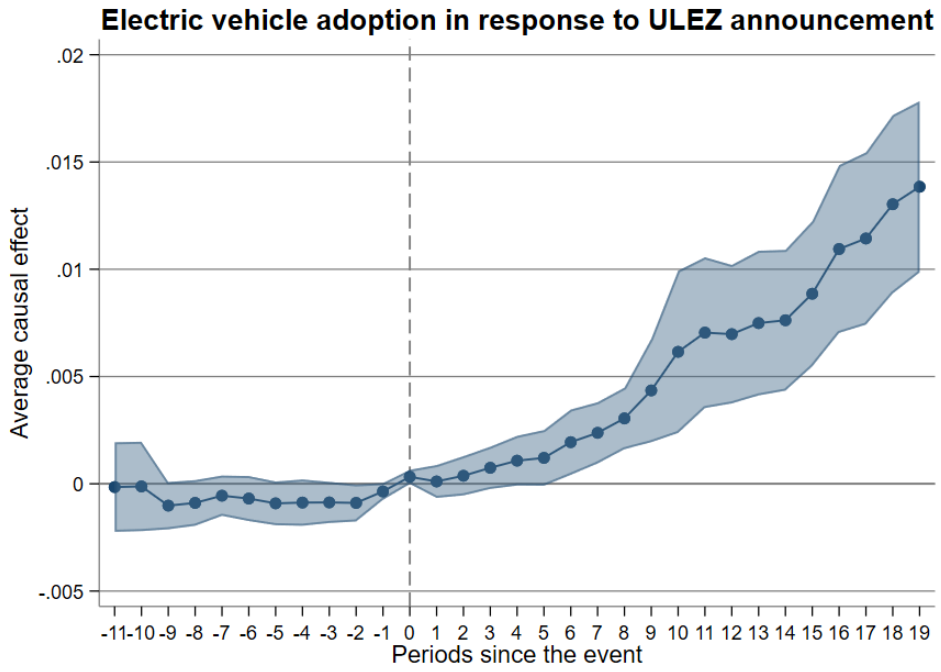


Figure 12: Chaisemartin and D'Haultfoeuille 2020 event study for ULEV adoption around first ULEZ announcement (Q1 2015)

We also implement the Clarke, Pailanir, Athey, and Imbens (2023) synthetic DiD estimator, which combines the synthetic control and DiD approaches. It leverages

the insights of synthetic control to ensure trends are parallel pre-treatment, by re-weighting control units accordingly. Once again we are restricted to binary treatment only, but the ATT is estimated at 0.005 with a standard error of 0.001 off 50 bootstrap replications. This is approximately in line with a weighted average that might be expected from Figure 12.

We implement the matrix completion approach of Athey, Bayati, Doudchenko, Imbens, and Khosravi (2021), which is a method to impute the missing counterfactuals due to treatment assignment. We implement this method with six 'placebo' pre-treatment periods in Figure 13. There's no evidence of pre-trends and the estimated time-varying ATTs are very much in line with our estimates from other methods.

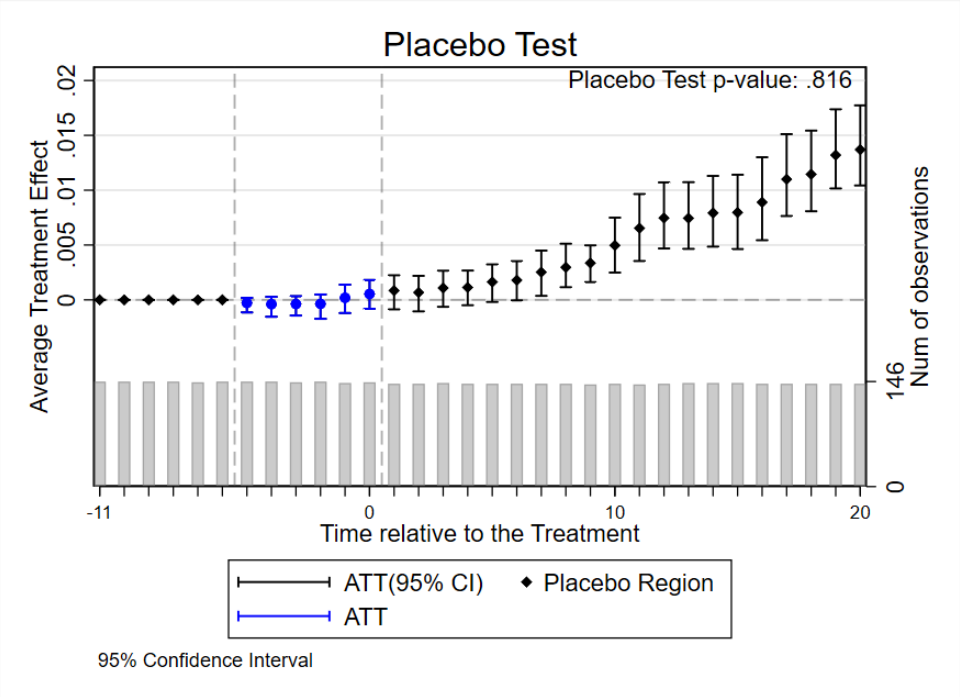


Figure 13: Athey, Bayati, Doudchenko, Imbens, and Khosravi 2021 matrix completion method to estimate event study for ULEV adoption around first ULEZ announcement (Q1 2015)

For robustness, we implement a bunch of parallel trend and placebo tests. The first runs the classic TWFE time-varying estimator on the pre-announcement data, with a fake treatment date in 2013 Q2. It shows no evidence of pre trends.

We implement two other placebo tests. The first randomly assigns treatment data over all units, and then re-runs the baseline event study. The second uses an outcome

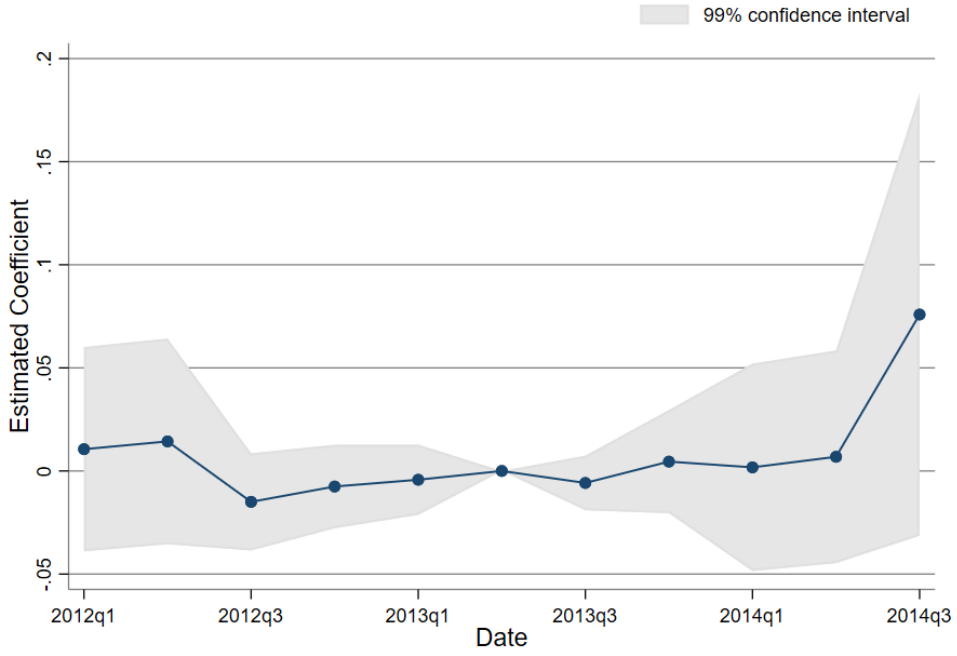
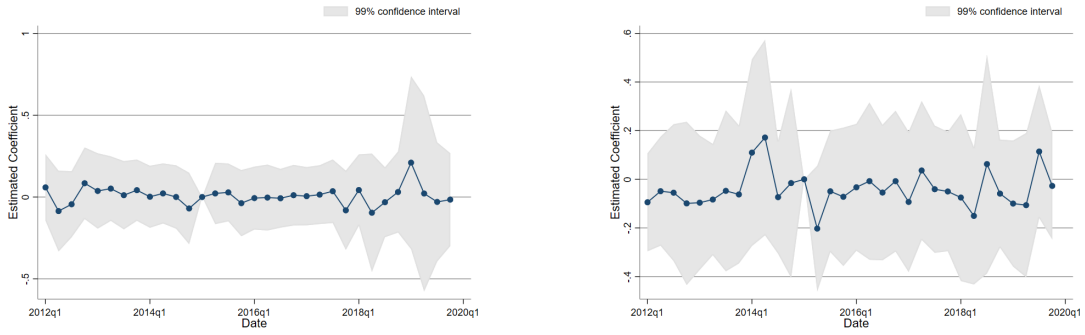


Figure 14: Placebo test on pre-announcement data with fake announcement date.

variable we suggest should be unrelated to the treatment; the number of total vehicles per capita. Both placebo tests show no effect, so they provide supportive evidence that there is a real effect of the ULEZ announcement on ULEV adoption.

We repeat this analysis for the ULEZ expansion announcement (Q2 2016) and find broadly similar results. Figure D8 in the appendix contains the baseline event study.



(a) Placebo test with randomly assigned treatment data.

(b) Placebo test with vehicles per capita as outcome variable.

Figure 15: Placebo tests

6.2 Public transport results

Figure 16 plots the change in average station entry after the initial ULEZ introduction in 2019 for postcodes with above and below median exposure to the ULEZ. On average, there is a small rise in the use of public transport after the policy is introduced, and this rise is greater in areas more exposed to the policy. However, the differences are not statistically significant.

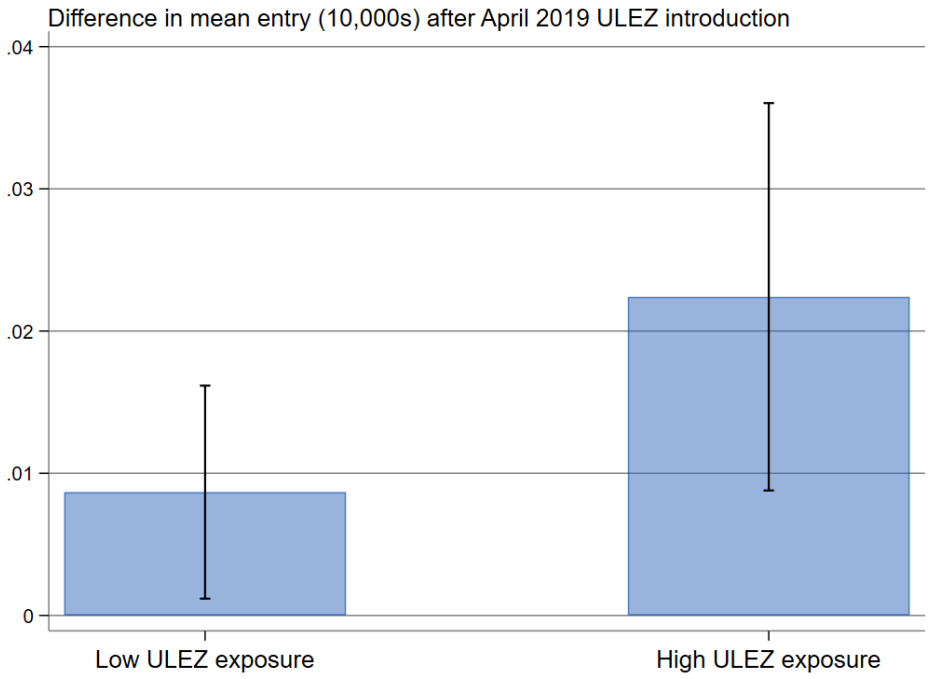


Figure 16: Average change in number of London underground entry after the April 2019 ULEZ introduction, split by postcodes with above and below median ULEZ exposure.

This finding is replicated in a more robust differences-in-differences regression in Table 3. We regress the number of station entries at each postcode × day on ULEZ exposure based on the share of commuters who drive into the ULEZ, a post-policy indicator and their interaction. The interaction is statistically significant even when we include a dummy for being inside the ULEZ and the distance to the ULEZ. This suggests that postcodes more exposed to the policy saw increased use of public transport after the policy was introduced.

Another way to see this result is to visualise the predicted interaction effects in Figure 17. This graph shows the predicted station entry from the model in column (1) of

Table 3: Difference-in-differences regression of station entry/exit on ULEZ exposure interacted with a post-policy dummy

	(1)	(2)	(3)	(4)
	Dependent variable: Station entry/exit (10,000s)			
ULEZ exposure × Post-indicator	2.242***	2.133*	2.195***	2.080***
	(0.687)	(0.688)	(0.776)	(0.779)
ULEZ exposure	38.346***	18.685*	39.819***	18.929
	(12.164)	(11.211)	(12.686)	(11.580)
Post-indicator	0.005	0.008	0.009	0.012
	(0.009)	(0.009)	(0.011)	(0.011)
ULEZ	2.045***	1.580***	2.075***	1.580***
	(0.558)	(0.563)	(0.549)	(0.558)
Distance to ULEZ		−0.117***		−0.124***
		(0.022)		(0.023)
Dependent var.	Entry	Entry	Exit	Exit
N	135,683	134,955	135,683	134,955
R^2	0.149	0.193	0.142	0.188

Standard errors in parentheses, clustered at the postcode level. * $p < 0.1$, * $p < 0.05$, *** $p < 0.01$.
Fixed effects are day, week, month, day of week, week of month.

Table 3. We can see the slightly higher impact of ULEZ exposure on station entry after the policy is introduced. The difference looks small, but for highly-exposed postcodes, this amounts to over 1,500 additional station entries per day, which is around a 0.05% rise in London underground use.

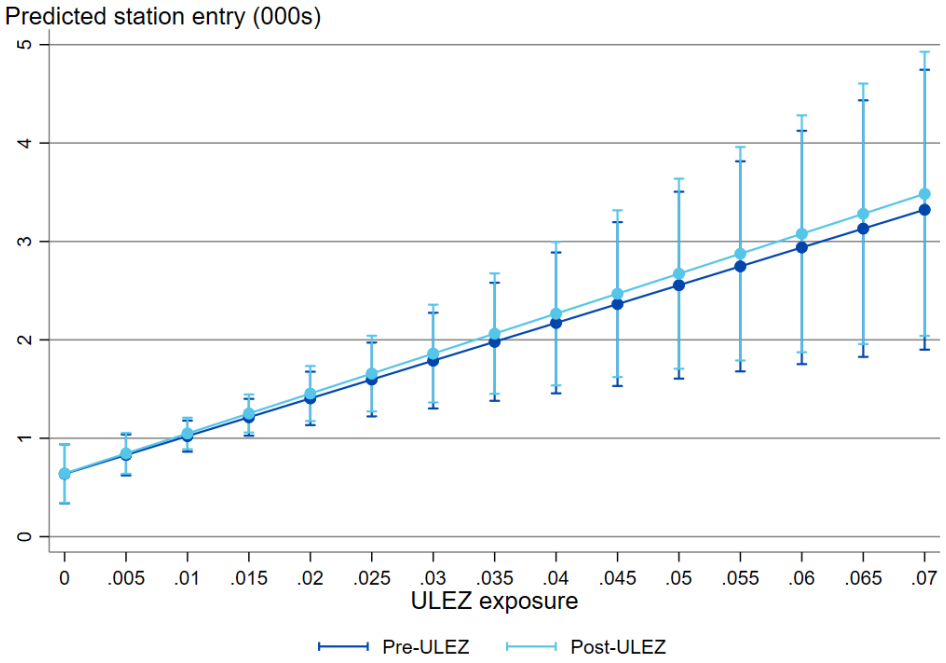


Figure 17: Marginal predicted effect of ULEZ exposure on station entry, pre- and post-policy introduction.

6.3 House price results

Figure 18 shows a positive relationship between the average house price and exposure to the ULEZ across postcode district in London. However, we hypothesise that any effect on house prices is best identified by comparing prices on either side of the zone boundary, before and after the policy is announced. House prices are a channel through which the effects of the tax may be soaked up; residents inside the zone benefit from (1) not having to pay the tax and (2) reduced congestion due to the tax.

A simple RDD plot indicates a discontinuity in house prices *only after the policy is announced*. Figure 19 plots the average log house price at 0.005 mile intervals within 1 mile of the ULEZ boundary, both before and after the ULEZ is announced. We fit

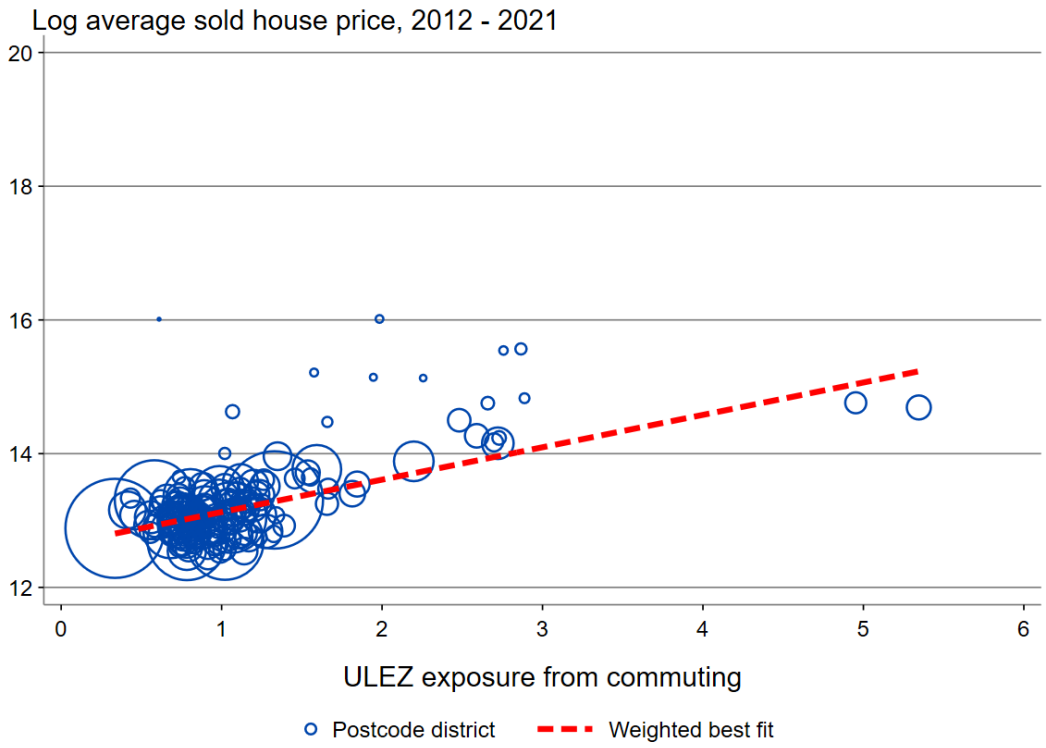


Figure 18: Positive relationship between log house price and ULEZ exposure by postcode districts in London

quadratic regression lines on either side of the boundary both before and after the policy announcement. While there is some evidence of a discontinuity in house prices around the border beforehand, there is a much larger gap in the regression lines either side of the boundary after the policy announcement.

To capture the effect of the introduction of the ULEZ on postcode-level house prices, we follow the RDD approach. We present three preliminary sets of results here. Firstly, we regress log house prices on the running variable – distance from the ULEZ boundary – alongside a binary ULEZ indicator, a binary post-policy indicator and their interaction, alongside year, quarter and 4-digit postcode fixed effects. Standard errors are clustered at the postcode level. We weight with a triangular kernel weight with a 2-mile bandwidth. We also consider focusing on just 1-mile from the boundary. The results are presented in Table 4.

Focusing on postcodes on either side of the 2019 ULEZ boundary (in columns (2) - (4)), house prices within the ULEZ are significantly lower on average, but around 13%

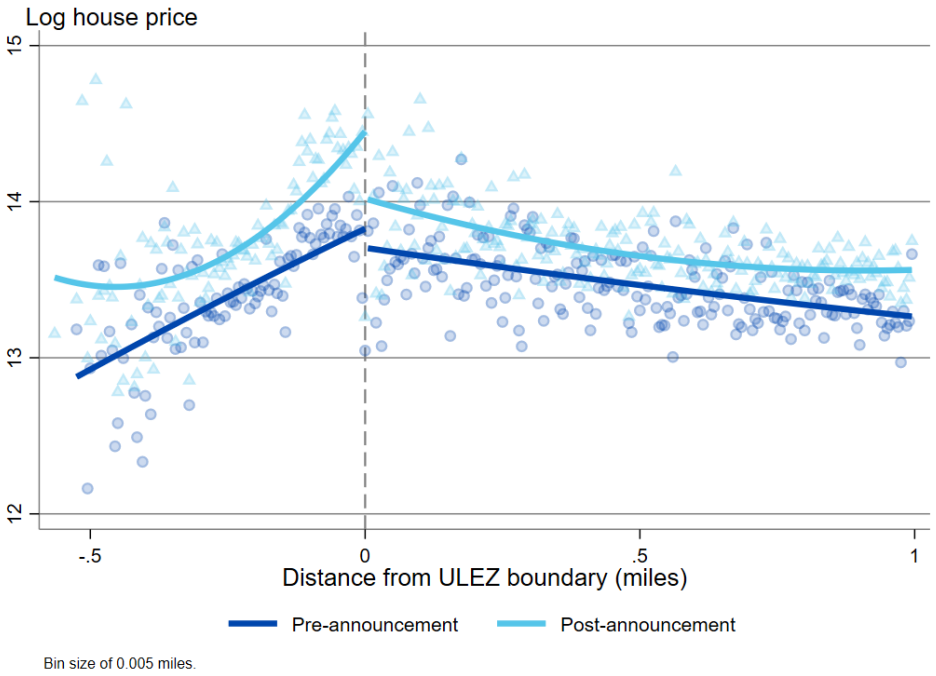


Figure 19: Binned average log house prices within 1 mile of the 2019 ULEZ boundary, before and after the policy announcement in March 2015.

higher after the policy was introduced.

Secondly, we run the baseline regression (log house price on distance from the boundary and an indicator for being inside the zone) in the pre- and post-announcement periods separately. This allows for more flexibility; for example, it allows the coefficient on 'distance' to vary over time. However, it makes statistical inference slightly more complicated, as we require bootstrapping to obtain standard errors. For comparison with Table 4, weighting is a triangular kernel weight and the fixed effects are the same (year, quarter, 4-digit postcode). The coefficient on the ULEZ indicator is negative in both periods, but it is 11.8% higher after the policy introduction. This result is consistent with our findings in Table 4. The distribution of 2,500 bootstrapped estimates is plotted in Figure D9 in the appendix, with a bootstrapped standard error of 0.046 implying a statistically significant positive effect of the policy announcement on house prices inside the zone.

Finally, we repeat our baseline RDD for a range of distances to the ULEZ boundary. Figure 20 plots the estimated coefficients and 95% confidence intervals as we widen the distance from the ULEZ boundary. The effect of the policy is approximately a 12%

Table 4: Baseline house price RDD for 2019 ULEZ boundary.

	(1)	(2)	(3)	(4)
	Dependent variable: Log house price			
ULEZ	0.019	-0.187***	-0.301***	-0.281***
	(0.025)	(0.035)	(0.043)	(0.043)
ULEZ x Post-indicator	0.056***	0.126***	0.131***	0.134***
	(0.014)	(0.015)	(0.015)	(0.016)
Distance	-0.075***	-0.214***	-0.423***	-0.394***
	(0.005)	(0.032)	(0.053)	(0.054)
Fixed Effects	Yes	Yes	Yes	Yes
Triangular kernel weight (2 mile)	No	Yes	No	Yes
Within 1 mile	No	No	Yes	Yes
N	458,150	111,757	54,322	54,322
R^2	0.375	0.366	0.358	0.345

Standard errors in parentheses, clustered at the postcode level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Fixed effects are year, quarter, 4-digit postcode.

higher house price for postcodes within the ULEZ, and this falls as we compare to house prices further from the boundary.

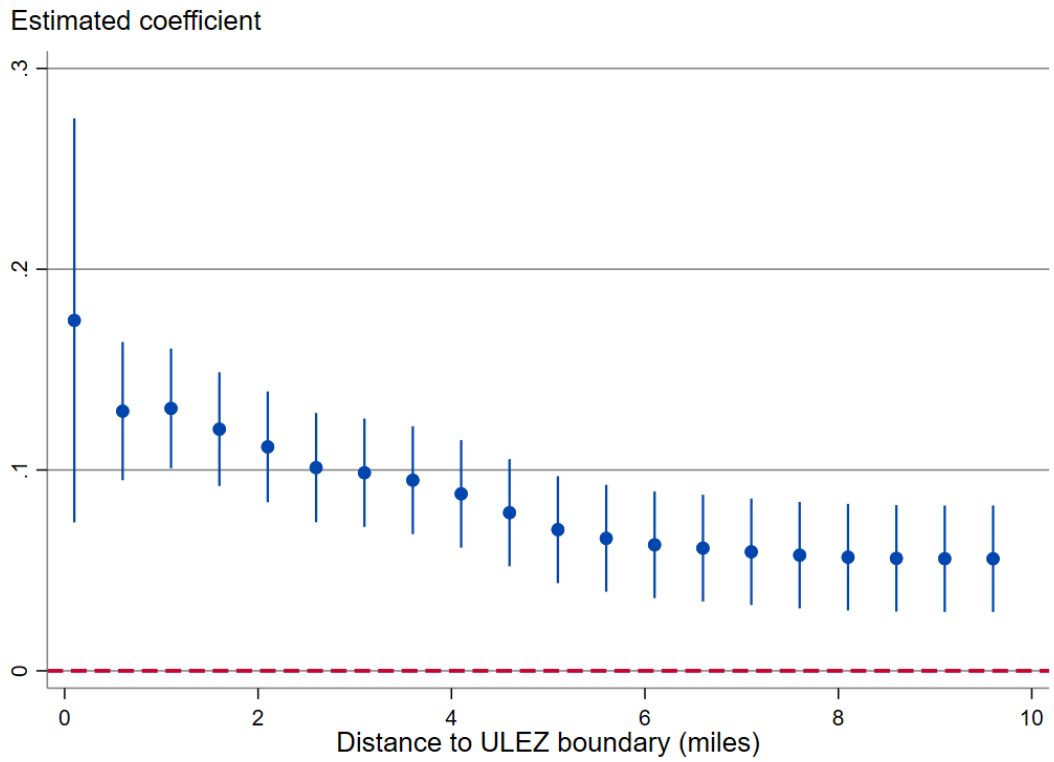


Figure 20: Baseline house price RDD for various distances from 2019 ULEZ boundary.

Further robustness checks are included in the appendix. Tables E1 to E5 adjust our

baseline RDD to allow for: asymmetry of distance inside vs outside the zone, different triangular weightings, allowing distance to interact with the post-announcement indicator, adjusting the functional form on distance, a 'donut' RDD (excluding the 0.05 miles on either side of the boundary). Each specification still returns a large positive and statistically significant estimate on the relationship between house prices and the interaction between being inside the zone after the policy announcement.

Overall, our results suggest that house prices within the ULEZ rose significantly in response to the policy introduction. Two possible explanations for this include the tax exemption for residents within the boundary and the expectation of reduced congestion/pollution due to the policy.

6.4 Firm creation results

Figure 21 plots detrended[8] firm entry rates averaged over postcode districts (weighted by number of firms), over time, for those within the ULEZ and those outside but within 2 miles. We normalise to the start of 2015 to measure deviations from the announcement date. This highlights different trends in firm entry inside and outside the ULEZ, with divergence beginning after the policy announcement, but accelerating a few years later.

Focusing around the boundary, we conduct a simple RDD before and after the policy announcement. We see a drop in firm entry within the ULEZ (controlling for time, postcode district and number of firms as a proxy for economic activity) and a slight rise in firm entry outside the zone.

A more formal RDD treatment is presented in Table 5. We regress log firm entry on an indicator for the ULEZ, an indicator pre/post announcement and their interaction, along with the running variable which is the distance from the boundary. We include year, quarter and postcode letter[9] fixed effects. The six columns of Table 5 vary the specification in two ways: the weighting and the exclusion of certain regions. How-

[8] Postcode district firm entry rates are regressed on year and quarter fixed effects, and residuals are used for subsequent analysis.

[9] This is either 1 or 2 letters at the start of a full postcode.

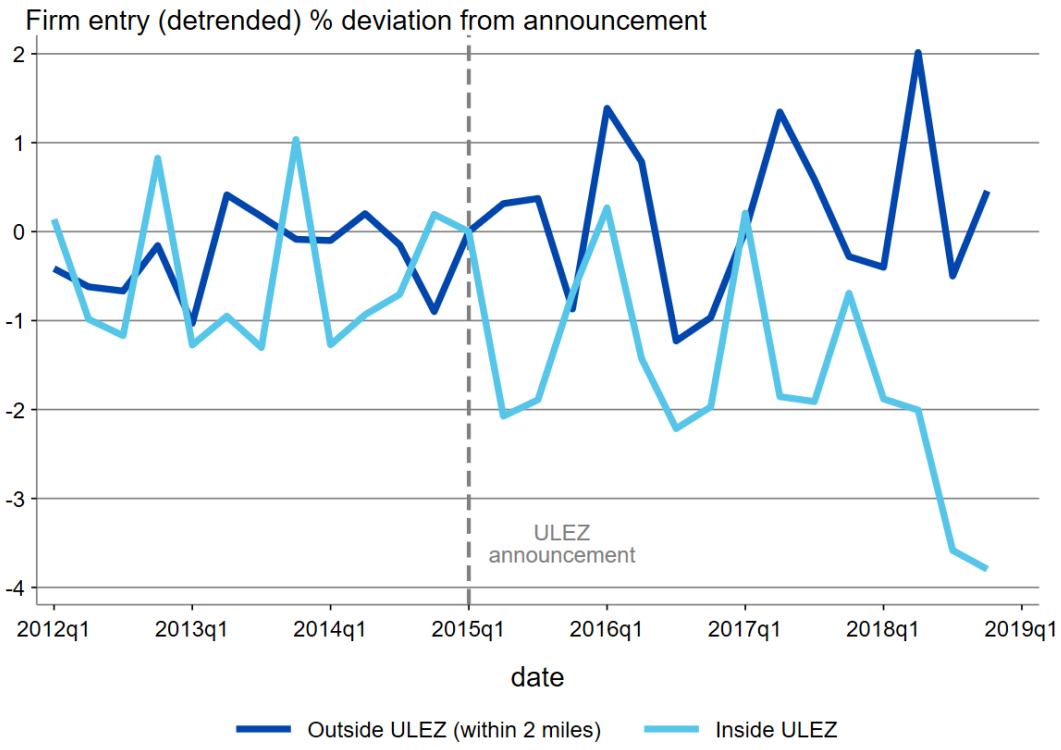


Figure 21: Diverging firm entry rates inside vs outside the ULEZ

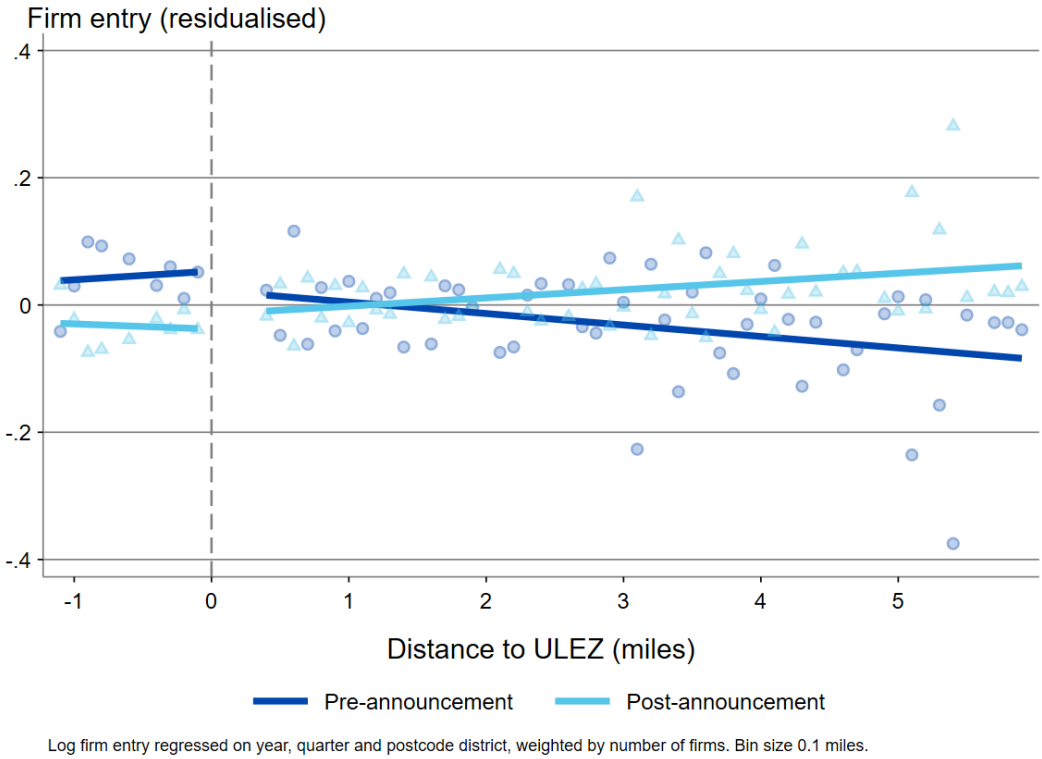


Figure 22: Regression discontinuity plot around ULEZ boundary, before and after policy announcement

ever, they consistently find that firm entry fell for postcode districts inside the zone *after* the policy was announced.

Table 5: Baseline firm entry RDD for 2019 ULEZ boundary.

	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent variable: Log firm entry					
ULEZ	0.390**	0.465**	0.209	0.280	0.166	0.239
	(0.195)	(0.195)	(0.173)	(0.180)	(0.187)	(0.197)
ULEZ x Post-indicator	-0.023	-0.056	-0.152***	-0.142***	-0.142**	-0.127*
	(0.053)	(0.054)	(0.048)	(0.050)	(0.066)	(0.071)
Weight	# firms	# firms	Triangular	Triangular	Combined	Combined
Distance to ULEZ	All London	<5 mi.	All London	<5 mi.	All London	<5 mi.
N	8,098	3,833	6,058	3,833	6,058	3,833
R^2	0.472	0.407	0.370	0.364	0.332	0.324

Standard errors in parentheses, clustered at the postcode district level.
* p<0.1, ** p<0.05, *** p<0.01. Fixed effects are year, quarter, postcode letter.

7 Conclusion

Air pollution carries high social costs, especially in urban areas. As a result, governments now increasingly experiment with policies that alter incentives to pollute. One high-profile example is London's Ultra Low Emissions Zone (ULEZ). Economists generally understand that people adapt their behaviour to incentives on many margins, often in unexpected ways (Dharmasena and Capps Jr 2012; Smith 2022; Malovaná, Bajzík, Ehrenbergerová, and Janku 2023).

In this paper, we evaluate how economic activity adapts as commuting incentives changes substantially, heterogeneously and dynamically for many Londoners. We bring together timely and granular data from many sources to estimate short and long-run elasticities for ultra-low emissions vehicle adoption, public transport use, house prices and the location of workplaces. To estimate the impact of the policy on behaviour, we use the time series of announcements and implementation dates alongside variation in the geographical reach of the ULEZ over time and pre-existing commmuting patterns.

In preliminary results we show that the announcement of the first ULEZ expansion in 2015 led to a large, positive and significant increase in the adoption of ultra-low emissions vehicles. The introduction of the ULEZ in 2019 led to an increase in public transport use, for areas which were more exposed to the tax. We also find a large positive increase on house prices within the ULEZ, compared to those on the other side of the boundary. Finally we show a fall in establishment creation inside the ULEZ and a rise outside the ULEZ in response to the policy announcement.

In ongoing work we explore the impact of further spatial expansions of the policy in greater detail. Beyond the backwards-looking estimation of these elasticities, the near-real time nature of most of our data sources allows us to evaluate future changes to London's ULEZ almost concurrently. In order to structure this analysis, we have publicly posted a pre-analysis plan (PAP).

The introduction of London's ULEZ features many interesting and time-varying design choices: in geographic coverage, in the treatment of residents versus com-

muters and in the incentives offered for the disposal of polluting vehicles. London's size and economic importance for the UK also make it a unique laboratory for pollution pricing. We hope that the estimates obtained in this project can inform better and more timely policy design choices, in the UK and abroad.

References

Alexander, Diane and Hannes Schwandt (2019). "The impact of car pollution on infant and child health: Evidence from emissions cheating". In.

Arkolakis, Costas and Conor Walsh (2023). *Clean Growth*. Tech. rep. National Bureau of Economic Research.

Athey, Susan, Mohsen Bayati, Nikolay Doudchenko, Guido Imbens, and Khashayar Khosravi (2021). "Matrix Completion Methods for Causal Panel Data Models". In: *Journal of the American Statistical Association* 116.536, pp. 1716–1730.

Aydin, E. and K. Kurschner Rauck (2023). "Low-emission zones, modes of transport and house prices: evidence from Berlin's commuter belt". In.

Barahona, Nano, Francisco Gallego, and Juan-Pablo Montero (2020). "Vintage-Specific Driving Restrictions". In.

Bartik, Timothy J (1991). "Who benefits from state and local economic development policies?" In.

Bernardo, Valeria, Xavier Fageda, and Ricardo Flores-Fillol (2021). "Pollution and congestion in urban areas: The effects of low emission zones". In.

Borusyak, Kirill, Peter Hull, and Xavier Jaravel (2022). "Quasi-experimental shift-share research designs". In: *The Review of Economic Studies* 89.1, pp. 181–213.

Borusyak, Kirill, Xavier Jaravel, and Jann Spiess (2024). *Revisiting Event Study Designs: Robust and Efficient Estimation*. Papers. arXiv.org.

Callaway, Brantly, Andrew Goodman-Bacon, and Pedro H. C Sant'Anna (2024). *Difference-in-differences with a Continuous Treatment*. Working Paper 32117. National Bureau of Economic Research.

Callaway, Brantly and Pedro H.C. Sant'Anna (2021). "Difference-in-Differences with multiple time periods". In: *Journal of Econometrics* 225.2. Themed Issue: Treatment Effect 1, pp. 200–230.

Castro-Vincenzi, Juan (2022). "Climate Hazards and Resilience in the Global Car Industry". In.

Cattaneo, Matias D and Rocio Titiunik (2022). "Regression discontinuity designs". In: *Annual Review of Economics* 14, pp. 821–851.

Chaisemartin, Clément de and Xavier D'Haultfoeuille (2020). "Two-Way Fixed Effects Estimators with Heterogeneous Treatment Effects". In: *American Economic Review* 110.9, pp. 2964–96.

Chay, Kenneth Y and Michael Greenstone (2005). "Does air quality matter? Evidence from the housing market". In: *Journal of political Economy* 113.2, pp. 376–424.

Clarke, Damian, Daniel Pailanir, Susan Athey, and Guido Imbens (2023). *Synthetic Difference In Differences Estimation*.

Clausing, Kimberly A and Catherine Wolfram (2023). *Carbon border adjustments, climate clubs, and subsidy races when climate policies vary*. Tech. rep. National Bureau of Economic Research.

Clemens, Michael A and Ethan G Lewis (2022). *The effect of low-skill immigration restrictions on US firms and workers: Evidence from a randomized lottery*. Tech. rep. National Bureau of Economic Research.

Colas, Mark and Emmett Saulnier (2023). "Optimal Solar Subsidies". In.

Currie, Janet and Matthew Neidell (2005). "Air pollution and infant health: what can we learn from California's recent experience?" In: *The Quarterly Journal of Economics* 120.3, pp. 1003–1030.

Currie, Janet and Reed Walker (2011). "Traffic congestion and infant health: Evidence from E-ZPass". In: *American Economic Journal: Applied Economics* 3.1, pp. 65–90.

De Chaisemartin, Clément and Xavier d'Haultfoeuille (2022). *Difference-in-differences estimators of intertemporal treatment effects*. Tech. rep. National Bureau of Economic Research.

Deryugina, Tatyana, Garth Heutel, Nolan H Miller, David Molitor, and Julian Reif (2019). "The mortality and medical costs of air pollution: Evidence from changes in wind direction". In: *American Economic Review* 109.12, pp. 4178–4219.

Deschenes, Olivier, Michael Greenstone, and Joseph S Shapiro (2017). "Defensive investments and the demand for air quality: Evidence from the NOx budget program". In: *American Economic Review* 107.10, pp. 2958–89.

Desmet, Klaus and Esteban Rossi-Hansberg (2023). "Climate Change Economics over Time and Space". In.

Dharmasena, Senarath and Oral Capps Jr (2012). "Intended and unintended consequences of a proposed national tax on sugar-sweetened beverages to combat the US obesity problem". In: *Health economics* 21.6, pp. 669–694.

Fetzer, Thiemo (2023). "Regulatory barriers to climate action: evidence from conservation areas in England". In.

Fetzer, Thiemo, Ludovica Gazze, and Menna Bishop (2023). "Distributional and climate implications of policy responses to energy price shocks". In.

Fetzer, Thiemo, Christina Palmou, and Jakob Schneebacher (2023). "How do firms cope with economic shocks in real time?" In.

Frölich, Markus and Martin Huber (2019). "Including covariates in the regression discontinuity design". In: *Journal of Business & Economic Statistics* 37.4, pp. 736–748.

Gardner, John (2022). *Two-stage differences in differences*.

Gilbert, Ben, Hannah Gagarin, and Ben Hoen (2023). *Distributional Equity in the Employment and Wage Impacts of Energy Transitions*. Tech. rep. National Bureau of Economic Research.

Goodman-Bacon, Andrew (2021). "Difference-in-differences with variation in treatment timing". In: *Journal of Econometrics* 225.2. Themed Issue: Treatment Effect 1, pp. 254–277.

Gruhl, Henri, Nicolas Volhausen, Nico Pestel, and Nils aus dem Moore (2022). *Air Pollution and the Housing Market: Evidence from Germany's Low Emission Zones*. Tech. rep. Ruhr Economic Papers.

Gu, Jianwei, Veronika Deffner, Helmut Kuchenhoff, Regina Pickford, Susanne Breitner, Alexandra Schneider, Michal Kowalski, Annette Peters, Martin Lutz, Andreas Kerschbaumer, Remy Slama, Xavier Morelli, Heinz-Erich Wichmann, and Josef

Cyrys (2022). "Low emission zones reduced PM10 but not NO2 concentrations in Berlin and Munich, Germany". In.

Herzog, Ian (2023). *The City-Wide Effects of Tolling Downtown Drivers: Evidence from London's Congestion Charge*. Tech. rep.

Leape, Jonathan (2006). "The London Congestion Charge". In.

Lemma, Yohannes, Silvia Lui, Louise Romaniuk, Jakob Schneebacher, and Nik Wolf (2023). *The UK Longitudinal Business Database*. Tech. rep. Working Paper.

Malovaná, Simona, Josef Bajzík, Dominika Ehrenbergerová, and Jan Janku (2023). "A prolonged period of low interest rates in Europe: Unintended consequences". In: *Journal of Economic Surveys* 37.2, pp. 526–572.

Monte, Ferdinando, Stephen J. Redding, and Esteban Rossi-Hansberg (2018). "Commuting, Migration, and Local Employment Elasticities". In: *American Economic Review* 108.12, pp. 3855–90.

Ommeren, Jos van and Joyce Dargay (2004). *The Optimal Choice of Commuting Speed: Consequences for Commuting Time, Distance and Costs*. Tinbergen Institute Discussion Papers 04-092/3. Tinbergen Institute.

Peltzman, Sam and T Nicolaus Tideman (1972). "Local versus national pollution control: Note". In: *The American Economic Review* 62.5, pp. 959–963.

Ponticelli, Jacopo, Qiping Xu, and Stefan Zeume (2023). *Temperature and Local Industry Concentration*. Tech. rep. National Bureau of Economic Research.

Roth, Jonathan, Pedro HC Sant'Anna, Alyssa Bilinski, and John Poe (2023). "What's trending in difference-in-differences? A synthesis of the recent econometrics literature". In: *Journal of Econometrics*.

Simeonova, Emilia, Janet Currie, Peter Nilsson, and Reed Walker (2019). *Congestion Pricing, Air Pollution and Children's Health*. Tech. rep. National Bureau of Economic Research.

Smith, Maxwell J (2022). "Evaluating potential unintended consequences of COVID-19 vaccine mandates and passports". In: *BMJ global health* 7.7, e009759.

Sun, Liyang and Sarah Abraham (2021). "Estimating dynamic treatment effects in event studies with heterogeneous treatment effects". In: *Journal of Econometrics* 225.2. Themed Issue: Treatment Effect 1, pp. 175–199.

Tang, Cheng Keat (2021). "The Cost of Traffic: Evidence from the London Congestion Charge". In.

Van Der Ploeg, Frederick and Cees Withagen (2014). "Growth, renewables, and the optimal carbon tax". In: *International Economic Review* 55.1, pp. 283–311.

Wolff, Hendrik and Muxin Zhai (2021). "Air pollution and urban road transport: evidence from the world's largest low-emission zone in London". In.

A Additional policy details

A.1 Scrappage and retrofit schemes

A scrappage scheme was introduced to help those on income support or disability benefit to comply with ULEZ standards. The original 2019 scheme offered up to £7,000 compensation for a car or van plus up to £2,500 if it was replaced by an electric vehicle. However, when ULEZ was expanded in 2021, the £61m scrappage scheme reduced the compensation to £2,000 for cars (and for a limited number of vans and £15,000 for heavy vehicles).

The ULEZ schemes also allows some vehicles to retrofit emissions reduction technology to meet Euro VI-equivalent levels of emissions. A vehicle with retrofitted emissions technology needs to be certified by the Government's Clean Vehicle Retrofit Accreditation Scheme (CVRAS). The CVRAS register contains approved and Clean Air Zones (CAZ) compliant companies and emission reduction systems, based on make, model and engine type. The CVRAS certifies emission technologies for black taxis, vans, minibuses, motorhomes, buses, coaches, HGVs and refuse vehicles.

Financial assistance to scrap or retrofit non-compliant vehicles in preparation for the latest expansion of the ULEZ (August 2023) was announced at the end of July 2023, and offers £2,000 for scrapping a car and £1,000 for motorcycles, and £5,000 for wheelchair accessible vehicles. Parts of the scrappage payment is converted to an annual bus and tram pass. Between £5,000 and £9,500 grant is available for scrappage or retrofit of vans and minibuses used by small businesses, sole traders, and charities. It was initially open to people on low incomes, disability benefits and child benefit as well as some businesses but was extended to all Londoners and small businesses on the 21 August 2023.

A.2 Policy details

The vehicle emissions standards are taken from the vehicle logbook data held by the Driver and Vehicle Licensing Agency (DVLA).

Cars. As petrol and diesel engines produce different types of emissions, they require different standards. The ULEZ requires cars to meet minimum 'Euro' emissions standards; the ULEZ standard for passenger cars is Euro 4 (NOx) for petrol cars and Euro 6 (NOx and PM) for diesel cars. Cars featuring older technology are less likely to meet the Euro 4 standards. Petrol cars that meet ULEZ standards are generally those that were first registered with the DVLA from January 2006 (although some cars registered as early as 2001 may also meet the standards). Diesel cars registered with he DVLA after September 2015 generally meet the ULEZ standards.

Large vans and minibuses. Euro 6 for diesel engines and Euro 4 for petrol engines. Non-compliant vehicles would be required to pay a daily charge of £12.50.

Motorcycles. Motorcycles, mopeds, motorised tricycles and quadricycles (L-category) need to meet minimum Euro 3 emissions standards for NOx. Euro 3 engines are those registered with the DVLA after July 2007.

Lorries, coaches and larger vehicles over 3.5 tonnes Gross Vehicle Weight (GVW). Heavy goods vehicles (HGVs), lorries, vans, motor caravans, motorised horseboxes, and other specialist vehicles below 3.5 tonnes.

A.3 Exemptions

- 'Historic vehicles' aged 40 years or older (if registered as historic vehicle tax class).
- Hybrid electric vehicles(HEVs), Plug-in hybrids electric vehicles (PHEVs) and fully battery-powered electric vehicles (EVs or BEVs).
- LPG (Liquefied Petroleum Gas) conversions, depending on the individual model and engine.
- London-licensed taxis.

- Specialist agricultural vehicles or other specialist vehicles (Motorised horseboxes, breakdown and recovery vehicles, snow ploughs, gritters, refuse collection vehicles, road sweepers, concrete mixers, fire engines, tippers, removal lorries, cranes).
- Military vehicles.
- Some showman's vehicles are eligible for 100% discount.
- Residents parked in the zone that do not drive.
- Buses, coaches and minibuses over 5 tonnes GVW.
- NHS patient that are clinically assessed as too ill to travel to an appointment on public transport are eligible to claim back any ULEZ charge.

ULEZ exemptions will be in place until 2025 for community transport vehicles and until 2027 for people receiving certain disability benefits and vehicles for people with disabilities.

A.4 Grace periods

Grace periods covering vehicles for disabled people are in place until 25 October 2027. Some businesses and charities also have a short grace period. Small business (50 employees), micro businesses (up to 10 employees), charities and sole traders with a registered address in London boroughs and city of London fall in this category if they ordered a new minibus or light van or retrofitted their light van or minibus and the delivery is due after 29 August 2023. There will be no exemption from the charges beyond 29 May 2024.

B ULEZ full timeline

- 27 October 2014: Mayor and TfL announce consultation on ULEZ.
- 30 December 2014: Reminder of ULEZ consultation ending soon.
- 26 March 2015: Mayor confirms ULEZ.
- 26 October 2015: Mayor and TfL finalise ULEZ requirements for taxi and minicabs.
- 17 February 2017: Mayor confirms £10 T-charge from October 23rd.
- 4 April 2017: Mayor launches consultation for replacing T-charge with ULEZ from 2019.
- 23 October 2017: T-Charge comes into effect.
- 3 November 2017: Mayor announces ULEZ will start in 2019.
- 30 November 2017: Mayor launches ULEZ expansion consultation.
- 8 June 2018: Mayor announces ULEZ to expand up to North and South Circular.
- 29 November 2018: First ULEZ signs go up in London.
- 8 March 2019: TfL reminds of ULEZ one-month countdown London ULEZ.
- 8 April 2019: ULEZ comes into force.
- 16 May 2019: TfL announces that 74 per cent of vehicles comply in first month.
- 15 May 2020: The Congestion Charge, Ultra Low Emission Zone and Low Emission Zone are reinstated.
- 6 August 2020: TfL announces installation of new infrastructure.
- 18 October 2021: TfL urges drivers to check their vehicle ahead of Ultra Low Emission Zone expansion on 25 October.

- 20 May 2022: TfL seeks views on expanding ULEZ.
- 25 November 2022: Mayor announces that ULEZ will be expanded London-wide.
- 30 January 2023: Mayor announces the scrappage scheme.
- 23 March 2023: Tfl data shows over 90% of cars driving in outer London already meet ULEZ standards.
- 21 April 2023: Tfl announces £18m allocated from scrappage scheme ahead of ULEZ expansion.
- 28 July 2023: High Court rules in favour of ULEZ expansion.
- 4 August 2023: Mayor announces expansion of scrappage scheme to all Londoners.
- 23 August 2023: Scrappage scheme becomes open to all Londoners.
- 29 August 2023: ULEZ expands London-wide.

C Data appendix

Table C1: Summary Statistics (London postcode districts only)

	Mean	N	StDev	Min	p(25)	p(50)	p(75)	Max
All Vehicles	12,587	11,645	8,259	49	7,325	12,007	17,648	66,267
ULE Vehicles	80.77	11,645	179.41	0	6	27	94	7531
Population	29,317	11,645	21,407	0.065	15,284	27,734	40,653	140,711
ULEZ	0.081	11,645	0.22	0	0	0	0	0.91
Taxable ULEZ Share	0.012	11,645	0.0075	0.0034	0.0078	0.0098	0.013	0.068
Share ULEVs	0.010	11,645	0.022	0	0.00056	0.0030	0.010	0.734
Vehicles per capita	48.25	11,645	731.53	0.039	0.34	0.50	0.68	13,649.70
ULEVs per capita	2.37	11,645	46.70	0	0.00023	0.0014	0.0052	2,013.64

Vehicle data from VEH0122 and VEH0134 from the DVLA. Commuting and population data from 2011 Census. Constructed variables computed by authors.

D Additional figures

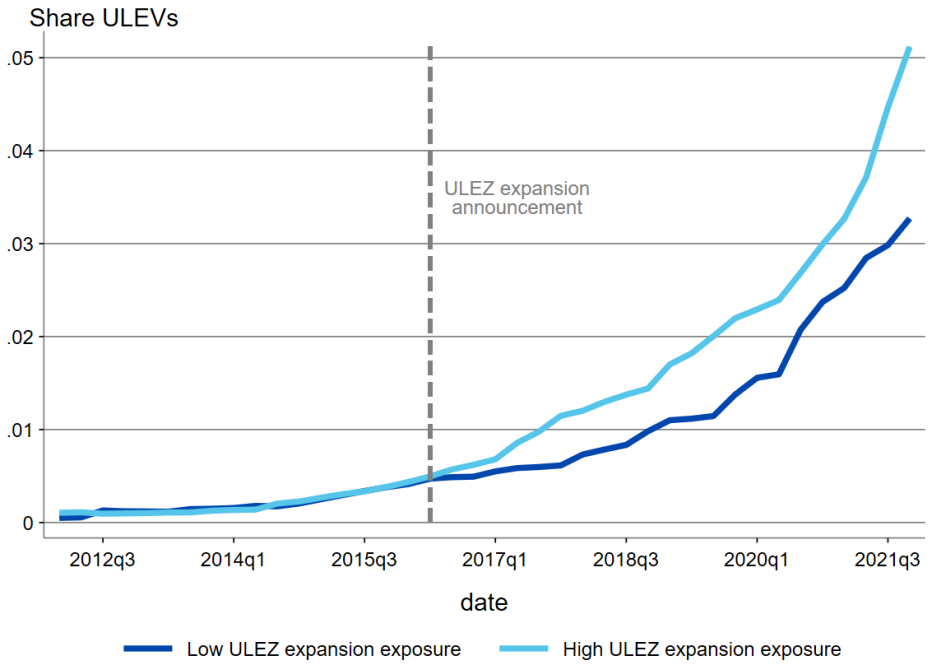


Figure D1: Adoption of ultra-low emissions vehicles in high and low ULEZ exposure postcode districts for the first expansion

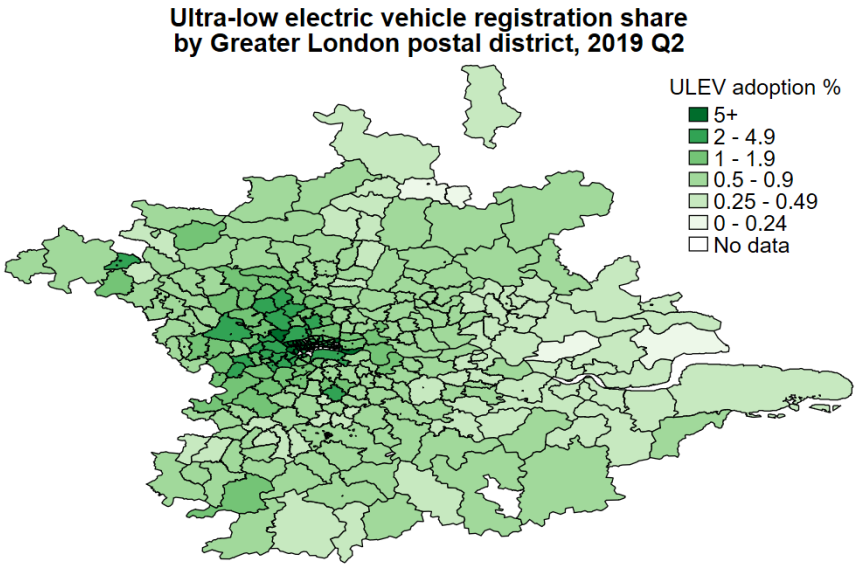


Figure D2: ULEV adoption by postcode district

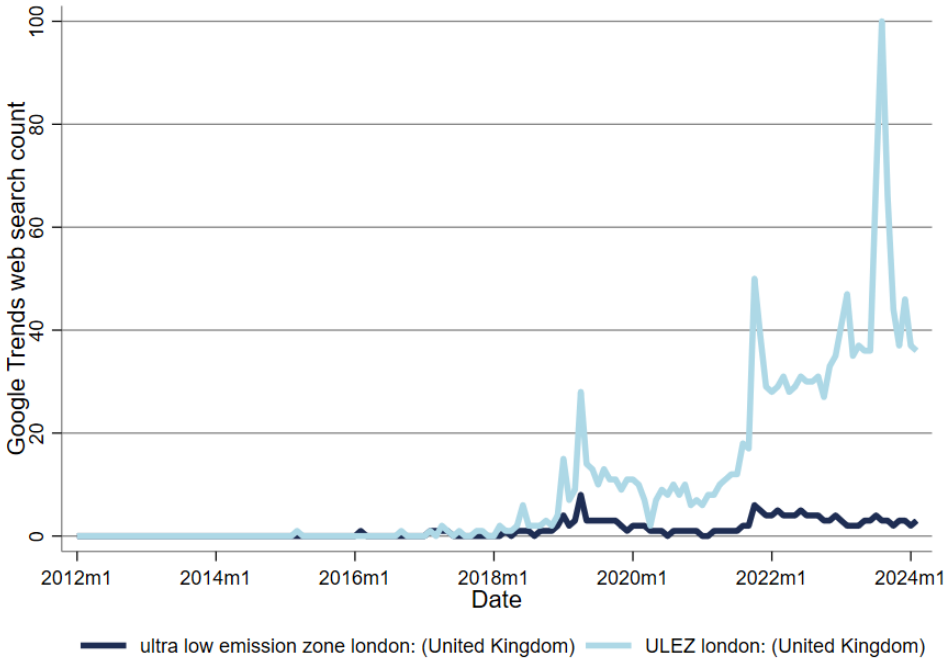


Figure D3: Google Trends web search for ULEZ London

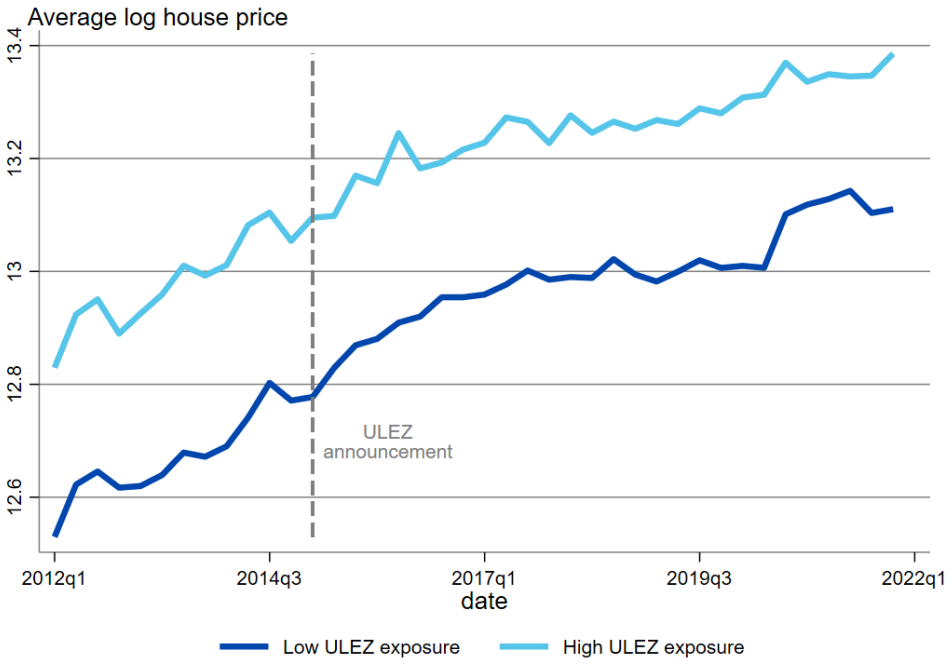


Figure D4: Average log sold house price in high and low ULEZ exposure postcode districts in London

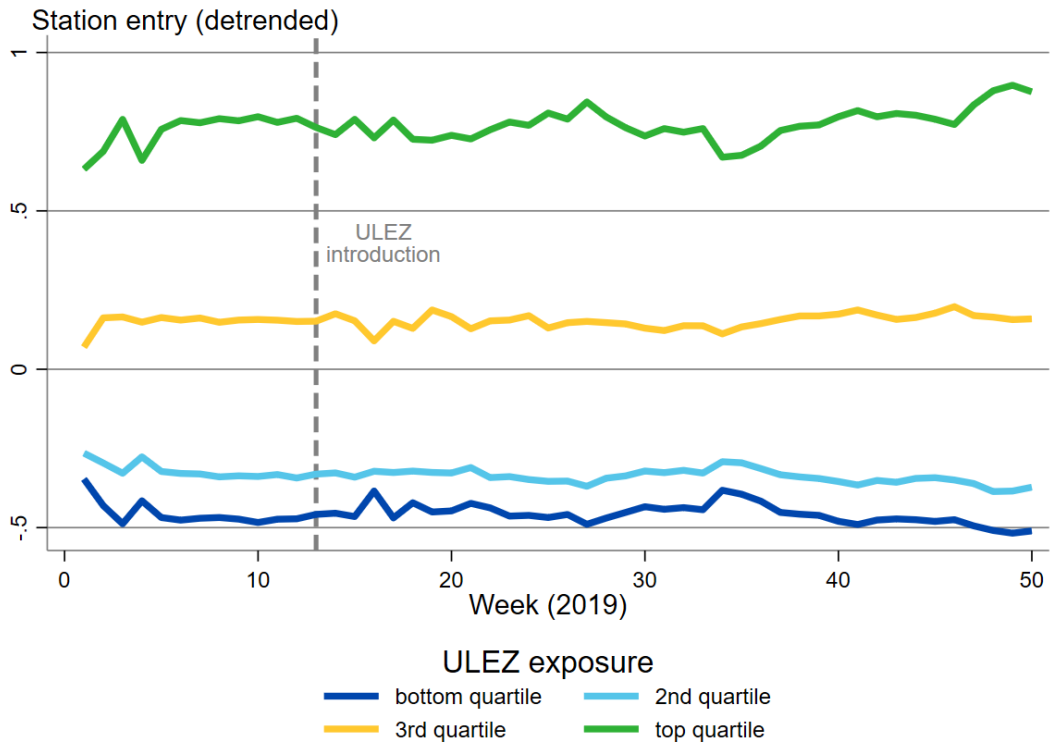


Figure D5: Weekly station entry (detrended) by quartiles of ULEZ exposure

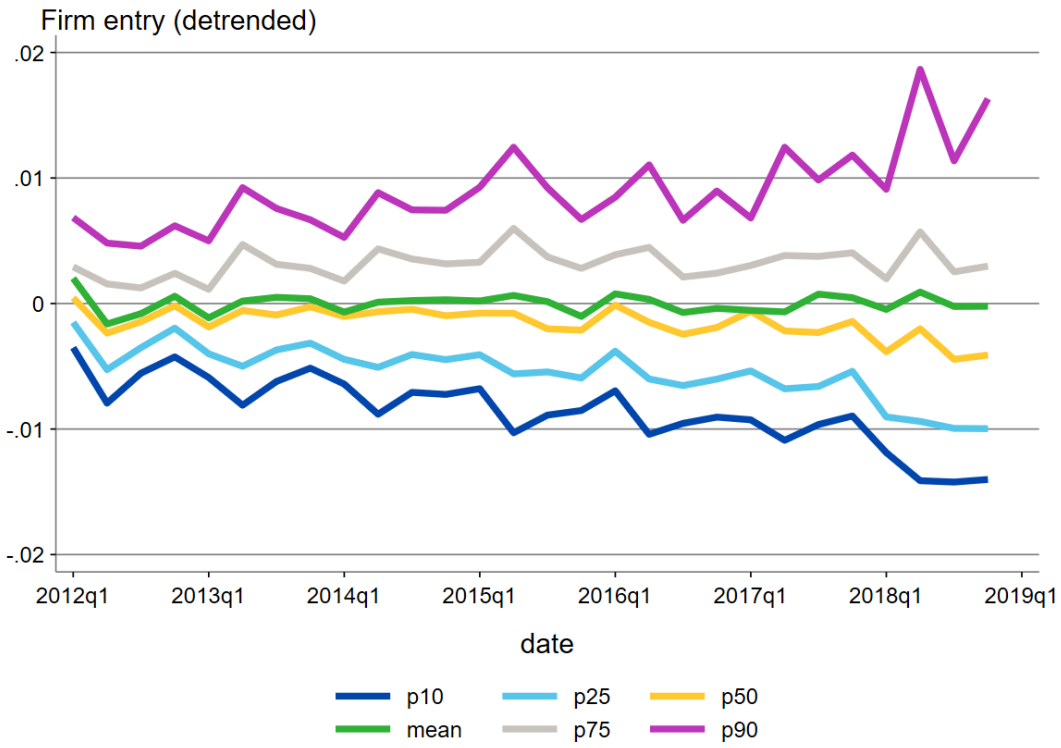


Figure D6: Evolution of distribution of seasonally adjusted firm entry rates by post-code sector

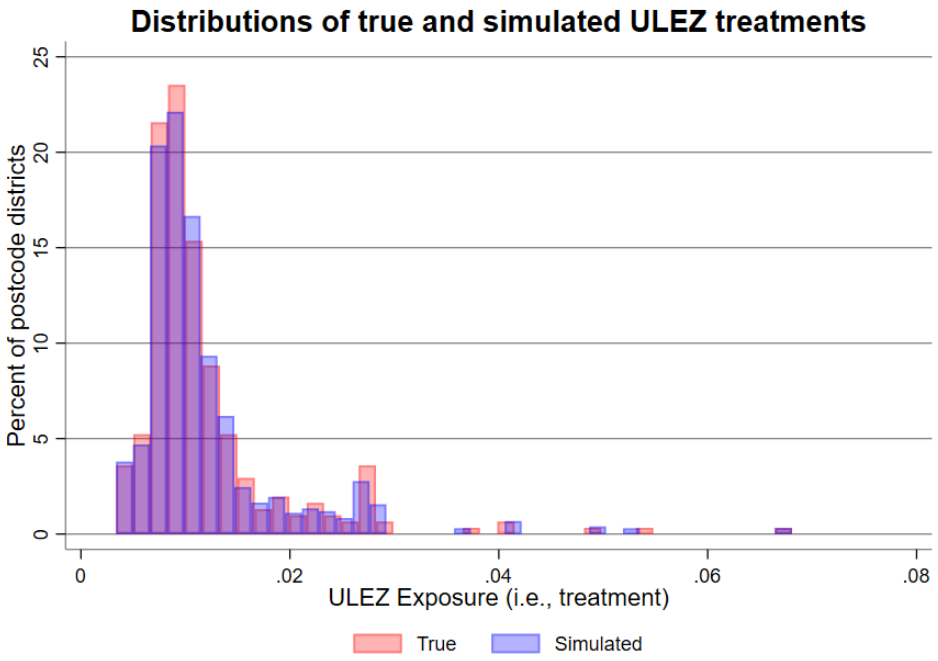


Figure D7: Distribution of true and simulated ULEZ exposure

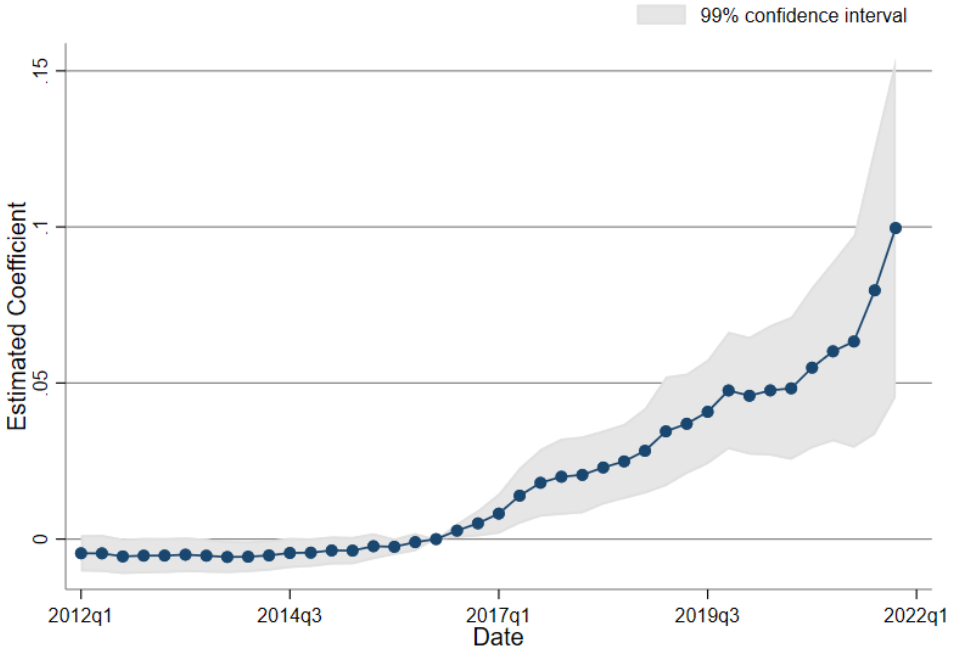


Figure D8: Baseline regression coefficients on ULEV adoption around ULEZ expansion announcement (Q2 2016)

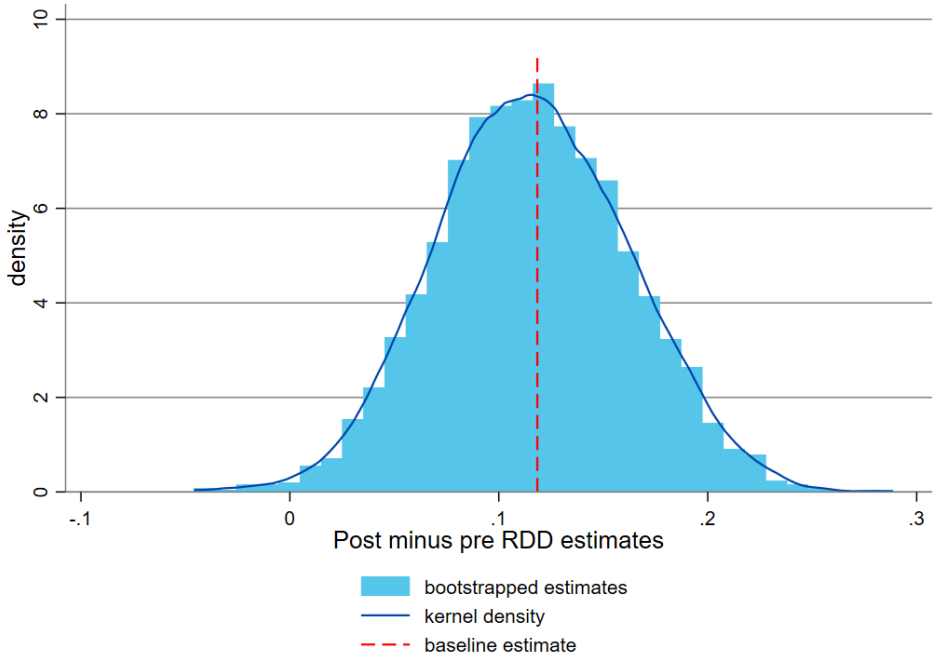


Figure D9: Bootstrapped estimates on the difference in the estimated coefficient on ULEZ indicator for house price RDD regression.

E Additional tables

Table E1: House price RDD for 2019 ULEZ boundary with distance heterogeneity

	(1)	(2)	(3)	(4)
	Dependent variable: Log house price			
Positive distance	-0.075***	-0.244***	-0.549***	-0.537***
	(0.005)	(0.032)	(0.058)	(0.059)
Negative distance	-0.012	-0.104	-0.194	-0.203
	(0.150)	(0.150)	(0.149)	(0.149)
ULEZ	0.035	-0.141***	-0.234***	-0.226***
	(0.037)	(0.041)	(0.045)	(0.046)
ULEZ × Post-indicator	0.056***	0.126***	0.131***	0.134***
	(0.014)	(0.015)	(0.015)	(0.016)
Fixed Effects	Yes	Yes	Yes	Yes
Triangular kernel weight (2 mile)	No	Yes	No	Yes
Within 1 mile	No	No	Yes	Yes
N	458,150	111,757	54,322	54,322
R^2	0.375	0.366	0.359	0.346

Standard errors in parentheses, clustered at the postcode level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
Fixed effects are year, quarter, 4-digit postcode.

Table E2: House price RDD for 2019 ULEZ boundary varying triangular bandwidths

	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent variable: Log house price					
ULEZ	-0.068	-0.237***	-0.245***	-0.187***	-0.146***	-0.099***
	(0.057)	(0.046)	(0.039)	(0.035)	(0.031)	(0.030)
ULEZ x Post-indicator	0.138***	0.139***	0.132***	0.126***	0.119***	0.112***
	(0.023)	(0.017)	(0.015)	(0.015)	(0.014)	(0.014)
Distance	0.209*	-0.315***	-0.319***	-0.214***	-0.163***	-0.104***
	(0.116)	(0.062)	(0.044)	(0.032)	(0.022)	(0.016)
Bandwidth (miles)	0.5	1	1.5	2	2.5	3
N	32,876	54,322	78,619	111,757	146,042	180,849
R^2	0.296	0.323	0.348	0.366	0.374	0.377

Standard errors in parentheses, clustered at the postcode level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
Fixed effects are year, quarter, 4-digit postcode.

Table E3: House price RDD for 2019 ULEZ boundary with distance interaction

	(1)	(2)	(3)	(4)
	Dependent variable: Log house price			
ULEZ	-0.036	-0.209***	-0.327***	-0.305***
	(0.025)	(0.036)	(0.045)	(0.045)
ULEZ x Post-indicator	0.133***	0.156***	0.168***	0.167***
	(0.014)	(0.021)	(0.029)	(0.030)
Distance	-0.089***	-0.236***	-0.458***	-0.427***
	(0.005)	(0.032)	(0.055)	(0.056)
Post-indicator x Distance	0.019***	0.031***	0.050*	0.048
	(0.001)	(0.012)	(0.030)	(0.032)
Fixed Effects	Yes	Yes	Yes	Yes
Triangular kernel weight (2 mile)	No	No	Yes	Yes
Within 1 mile	No	Yes	No	Yes
N	458,150	111,757	54,322	54,322
R^2	0.376	0.366	0.358	0.345

Standard errors in parentheses, clustered at the postcode level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
Fixed effects are year, quarter, 4-digit postcode.

Table E4: House price RDD for 2019 ULEZ boundary with polynomial distance

	(1)	(2)	(3)
	Dependent variable: Log house price		
ULEZ	-0.187***	-0.247***	-0.187***
	(0.035)	(0.048)	(0.049)
ULEZ x Post-indicator	0.126***	0.126***	0.127***
	(0.015)	(0.015)	(0.015)
Distance	-0.214***	-0.346***	-0.135
	(0.032)	(0.073)	(0.087)
$Distance^2$		0.085**	-0.502***
		(0.034)	(0.104)
$Distance^3$			0.273***
			(0.039)
Fixed Effects	Yes	Yes	Yes
Triangular kernel weight (2 mile)	Yes	Yes	Yes
N	111,757	111,757	111,757
R^2	0.366	0.366	0.367

Standard errors in parentheses, clustered at the postcode level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
Fixed effects are year, quarter, 4-digit postcode.

Table E5: House price 'donut' RDD for 2019 ULEZ boundary

	(1)	(2)	(3)	(4)
	Dependent variable: Log house price			
ULEZ	0.020	-0.201***	-0.334***	-0.318***
	(0.026)	(0.036)	(0.045)	(0.046)
ULEZ x Post-indicator	0.050***	0.121***	0.126***	0.130***
	(0.014)	(0.016)	(0.016)	(0.017)
Distance	-0.075***	-0.226***	-0.460***	-0.437***
	(0.005)	(0.032)	(0.055)	(0.056)
Fixed Effects	Yes	Yes	Yes	Yes
Triangular kernel weight (2 mile)	No	Yes	No	Yes
Within 1 mile	No	No	Yes	Yes
N	454,383	107,990	50,555	50,555
R^2	0.372	0.369	0.362	0.350

Standard errors in parentheses, clustered at the postcode level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Fixed effects are year, quarter, 4-digit postcode.