# How does economic activity adapt to pollution pricing? Evidence from London's ULEZ

Jakob Schneebacher<sup>1,2</sup>, (r) Fizza Jabbar<sup>1</sup>, and (r) Joel Kariel<sup>1</sup>

<sup>1</sup>Competition and Markets Authority (CMA)

<sup>2</sup>King's College London (KCL)

February 15, 2024

#### 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 Emissions Zone (ULEZ) and a shift-share event study design to study how the ULEZ changes economic activity along all major margins and provide a framework for evaluating the policy through future phases in near-real time. The phased introduction of the ULEZ affects who can drive into particular areas of London without paying a fee, affecting commuter-belt postcodes heterogeneously based on pre-existing economic choices. Affected individuals can react by purchasing ULEZ-compliant vehicles, switching to public transport, working from home or changing the location of their home or employer. We estimate elasticities on all these margins. In preliminary work, we show that the initial introduction of the ULEZ had large, significant positive effects on the adoption of ultra-low emissions vehicles. However, there is no evidence of an effect on house prices. A public, preregistered analysis plan allows us to evaluate the effect of ongoing policy changes in near-real time.

**JEL**: H23; R40; R48; Q58

Keywords: low emission zones; pollution pricing; spatial economics

**Acknowledgements:** Many thanks to Evan Soltas who initiated this project with one of the authors. We appreciate his careful thoughts about identification and thank him for sharing his code. Any views expressed are solely those of the authors and cannot be taken to represent those of the Competition and Markets Authority.

### 1 Introduction

There are high social costs to air pollution.<sup>1</sup> 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 Emissions Zone (ULEZ).

We exploit the phased introduction of London's ULEZ and a shift-share eventstudy 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 in October 2017 as a £10 fee to drive a highly-polluting vehicle into central London during peak congestion hours.<sup>2</sup> In April 2019, the fee rose to £12.50 and expanded to all hours. However, the ULEZ exempts residents from taxation and thus applies only to commuters. In 2021, the ULEZ expanded in size by about tenfold

<sup>&</sup>lt;sup>1</sup>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.

<sup>&</sup>lt;sup>2</sup>https://www.bbc.com/news/uk-england-london-47638862.

and is no longer exempt to residents. It expanded further on 29 August 2023 to cover all 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.

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 1 is suggestive of a sharper rise in ULEVs in regions where individuals are more exposed to the ULEZ due to their commuting behaviour.



Figure 1: Adoption of ultra-low emissions vehicles in high and low ULEZ exposure postcode districts

However, there is little evidence of significant divergence in the trends of sold house prices using Price Paid Data (PPD) from HM Land Registry. These data include all non-commercial property sales by postcode district. Figure 2 plots the average house sale price for postcode districts with high or low exposure to the ULEZ based on 2011 commuting data.



Figure 2: Average log sold house price in high and low ULEZ exposure postcode districts in London

We use two empirical research designs to estimate the causal impact pollution pricing has on economic activity. For outcomes measured at the commuter home postcode district (such as ULEV registration, public transport use, house transactions and prices 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 measured at the employer postcode, we instead employ a regression discontinuity design (Frölich and Huber 2019; Cattaneo and Titiunik 2022) and compare establishment counts 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. On the other hand, we find no evidence that the introduction of the ULEZ has differentially affected the value of sold residential properties. 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; Co-las 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 outlines out main hypotheses. Section 7 presents our empirical results. A final Section 8 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 emissionstandard 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. 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 the 29 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,<sup>3</sup> 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.

The following sections outline 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.

### 4 Data

The following data sources will be used across all specifications:

1. Postcodes subject to ULEZ (initially, and then two expansions).

<sup>&</sup>lt;sup>3</sup>https://www.theguardian.com/environment/2023/aug/29/it-has-come-in-too-quickly-sense-of-injusti

- 2. Postcode district **crosswalks** to output areas (OAs), lower- (LSOAs) and middlesuper layers (MSOAs). These areas have 310, 1,500, 7,500 average residents, respectively.
- 3. Population at OA level, to construct ULEZ exposure and weights.
- 4. 2011 Census commuting behaviour to compute commuting shares.

#### 4.1 Electric vehicle adoption

We propose to use administrative 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 publicuse 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 4 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 5. 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 4: Adoption of ultra-low emissions vehicles in London



Growth in electric vehicle registration share in London, 2012 - 2021

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

### 4.2 Home location

To establish if affected individuals move residence in order to escape the ULEZ, 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 6: Price of sold houses and number of transactions in London

#### 4.3 Substitution towards public transport

Commuters may also substitute towards public transport in response to the tax on highly-polluting vehicles. We propose to use Transport for London (TfL) underground station-level average entry data to track the response of commuters who face the strongest incentives to substitute. A freedom of information (FOI) request has been submitted for this data. We will then compute centroid postcode distance to underground stations in order to assign each postcode to its nearest station.

#### 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). <sup>4</sup> 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 have requested access to this version of the LBD in the SRS. With it, we will be able to compute quarterly establishment counts by postcode and Standard Industrial Classification (SIC) section, unweighted and employment weighted.

### 5 Empirical Approach

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

$$Outcome_{it} = \alpha_i + \alpha_t + \beta ULEZ_i + \gamma_t ShareDriveULEZ_i + \varepsilon_{it}$$
(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<sub>i</sub> is the

<sup>&</sup>lt;sup>4</sup>For more information about the LBD, see Lemma, Lui, Romaniuk, Schneebacher, and Wolf 2023.

share of commuters in *i* who drive into the 2019/2021/2023 ULEZ.  $\gamma_t$  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), working-from-home rates and housing transaction prices.

Since we do not observe commuter inflows, for establishment locations a different empirical approach is needed. We will therefore use a regression discontinuity design (RDD) at the postcode level around the boundary of the ULEZ.

#### 5.1 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 7 maps the ULEZ exposure by postcode district for London in the second quarter of 2019.

% driving into ULEZ 10 - 20 5 - 9.9 2 - 4.9 1 - 1.9 0 - 0.9

Share of drivers entering ULEZ by Greater London postal district, 2019 Q2

Figure 7: ULEZ exposure by postcode district

#### 5.2 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 literature 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  $\gamma_t$  from the time-varying TWFE in equation (1). We also compute the average TWFE coefficient, where  $\gamma$  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 Main hypotheses

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 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 postcodes 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.

### 7 Preliminary 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 for house prices. We are in the process of obtaining data for public transport use, working from home, and business creation.

#### 7.1 ULEV adoption results

To get a sense of the correlations in the data, Figure 8 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 8: Relationship between ULEV adoption and ULEZ exposure.

Figure 9 shows time-varying coefficients from a differences-in-differences event study of ultra-low vehicle 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.

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 9.

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 treat-



Figure 9: Baseline regression coefficients on ULEV adoption around first ULEZ announcement (Q1 2015)

ment 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 10. Given the binary treatment, the estimated coefficients are smaller in size, but the interpretation of the magnitude of the effects is very close.

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 reweighting 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 10.

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' pretreatment periods in Figure 11. 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 10: Chaisemartin and D'Haultfoeuille 2020 event study for ULEV adoption around first ULEZ announcement (Q1 2015)



Figure 11: 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.



Figure 12: Placebo test on pre-announcement data with fake announcement date.

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 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.



(a) Placebo test with randomly assigned treat-(b) Placebo test with vehicles per capita as outment data. come variable.



#### 7.2 House price results

There is be a positive relationship between the average sale price of residential homes and ULEZ exposure across postcode districts in London, as in Figure 14.



Figure 14: Positive relationship between log house price and ULEZ exposure by postcode districts in London

However, Figure 15 presents the time-varying coefficients from the event study for the sale price of residential properties on ULEZ exposure. These initial results show no evidence that house prices have yet been causally impacted by the introduction of the zone.

Our results suggests that Londoners react to the initial introduction of the ULEZcompliant vehicles but do not relocate in such numbers that pricing effects can be detected. In ongoing work, we investigate the number of housing transaction (an indicator of sorting). We also test to what extent Londoners change their commuting behaviour (by switching to public transport or working from home more) or employers relocate to establishments outside the ULEZ.



Figure 15: Baseline regression coefficients on price of sold houses around first ULEZ announcement (Q1 2015)

### 8 Conclusion and next steps

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 aim to 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 ultralow emissions vehicle adoption, public transport use, homeworking patterns and the location of commuter homes and 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 commuting 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. However, we have not found evidence of an impact on the sale price of residential properties. In ongoing work we explore similar margins for public transport usage and establishment locations. For later expansions, we hope to add homeworking data as well. 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 commuters 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 shiftshare 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 (Feb. 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 (Sept. 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.
- 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 liter-ature". 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 introduction 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 Londonwide.
- 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 1: Summar	y Statistics	(London	postcode	districts	only)
-----------------	--------------	---------	----------	-----------	-------

	Mean	Ν	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

Note: 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 16: ULEV adoption by postcode district



Figure 17: Google Trends web search for ULEZ London



Figure 18: Distribution of true and simulated ULEZ exposure