CEPREMAP
CENTRE POUR LA RECHERCHE ECONOMIQUE ET SES APPLICATIONS

Document de travail (Docweb) n°2601

London Clearing: Ultra Low Emission Zones Calling for Well-Being

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May 2026

Assainir l'air donc améliorer le bien-être ? Les effets de l'Ultra Zone à Faibles Émissions de Londres[1]

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Résumé : En réponse à la hausse de la pollution de l'air dans les zones urbaines, de nombreuses villes européennes ont adopté des zones à faibles émissions (LEZ), qui restreignent l'accès aux véhicules les plus polluants. Bien qu'efficaces pour améliorer la qualité de l'air, ces politiques restent controversées en raison des préoccupations liées à leur équité et à leur acceptabilité sociale. Cet article examine l'impact des extensions de l'Ultra Low Emission Zone (ULEZ) de Londres en 2021 et 2023 sur le bien-être subjectif (SWB). En utilisant les données de panel de la UK Household Longitudinal Study et une stratégie d'identification en différences-en-différences avec traitement échelonné, incluant des effets fixes individuels et annuels, nous comparons l'évolution de la satisfaction de vie des résidents vivant à l'intérieur et à l'extérieur des zones concernées. Nous constatons que l'extension de 2021 a entraîné une baisse de la satisfaction de vie d'environ 0,4 point — un effet qui est doublé pour les ménages à faible revenu — sans évidence de tendances différentielles préexistantes. Nous ne détectons pas d'effets statistiquement significatifs pour les Londoniens vivant dans la zone étendue en 2023 sur la fenêtre post-traitement actuellement disponible. Nous explorons les mécanismes susceptibles d'expliquer cette baisse et montrons que la perte de bien-être est principalement médiée par la dépendance à la voiture et la disponibilité des modes de transport. Bien que la politique ait accru le recours aux transports publics, nous montrons qu'une meilleure accessibilité aux transports publics atténue la baisse de bien-être des Londoniens. Ces résultats suggèrent que les LEZ peuvent engendrer des coûts de bien-être à court terme malgré les changements de comportement qu'elles induisent, soulignant la nécessité de mesures complémentaires pour renforcer leur acceptabilité sociale.

Mots-clés : Bien-être subjectif, Pollution de l'air, Zones à faibles émissions, Différence-en-différences

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Abstract: In response to rising urban air pollution, European cities have adopted Low Emission Zones (LEZs), restricting the most polluting vehicles. While effective in improving air quality, these policies remain controversial due to concerns

[1]I would like to thanks participants and discussants from the Parisian PhD Seminar on Economics and Environment (04/2025), EconomiX-CNRS PhD Workshop (10/2025), BeWell workshop (02/2026), Doctorissimes Paris 1 (04/2026). I would also like to thanks Dominique Meurs, Yann Algan, Elisabeth Tovar, Cornelia Mohren, Philipp Bothe, Lucas Perez and Thomas Jacquet for their valuable comments and insightful discussions.

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over fairness and acceptability. This paper examines the impact of London's 2021 and 2023 Ultra Low Emission Zone (ULEZ) expansions on subjective well-being (SWB). Using panel data from the UK Household Longitudinal Study and a staggered difference-in-differences design with individual and year fixed effects, we compare changes in life satisfaction among residents inside and outside the affected areas. We find that the 2021 expansion led to a decline in life satisfaction by approximately 0.4 points – which doubles for low-income households – with no evidence of pre-existing differential trends. We do not detect statistically significant effects within the available post-treatment window on Londoners living in the expanded zone in 2023. We explore the mechanisms driving this decline and find that the well-being loss is fundamentally mediated by car dependency and transport mode availability. While the policy increased reliance on public transport, we show that a higher accessibility to public transport reduces the well-being decline of Londoners. These findings suggest that LEZs can generate short-term welfare costs despite achieving behavioural change, highlighting the need for complementary measures to enhance social acceptability.

Keywords : Subjective well-being, Air pollution, Low-emission zones, Difference-in-differences

JEL Codes: I31, Q53, H23, R48

1 Introduction

Climate change and global warming are among the most pressing global challenges of our time, largely driven by the increase in greenhouse gas emissions resulting from modern lifestyles (Calvin et al. 2023). In Europe, one of the most significant sources of these emissions is the transport sector which accounts for a quarter of the EU's CO2 emissions in 2019 — private car use is responsible for 60.6% of these transport emissions — due to the high number of individuals relying on it for daily commuting and the frequency of car journeys (European Environment Agency. 2022). Even more alarmingly, domestic transport is the only sector where emissions kept increasing by 33.5% in the past three decades, even though the EU aims to achieve a 90% reduction in greenhouse gas emissions from transport by 2050 compared to 1990 levels (European Climate Law, 2021).

In addition to their contribution to long-term climate disruption, motorized vehicles are a major source of local air pollution, emitting large quantities of harmful pollutants such as particulate matter (PM_{10}, $PM_{2.5}$), nitrogen dioxide (NO_2), and other nitrogen and sulfur oxides (NO_X, SO_X). A growing body of epidemiological and clinical research has established that these pollutants have severe and wide-ranging effects on physical health (Godzinski and Suarez Castillo 2021), contributing to both acute and chronic conditions which can even lead to death. In 2015, ambient $PM_{2,5}$ was the fifth-ranking mortality risk factor in the world, with 4.2 million deaths caused due to long exposure and 103.1 million disability-adjusted life-years (Cohen et al. 2017). According to the European Environment Agency (EEA 2024), exposure to $PM_{2,5}$ alone accounts for over 239,000 premature deaths annually in Europe, with additional mortality linked to ozone (O_3, 70,000 deaths) and nitrogen dioxide (NO_2, 48,000 deaths).

Beyond mortality and morbidity, a growing literature documents the adverse effects of air pollution on mental health, including higher incidence of depression, anxiety, and psychological distress (Roberts et al. 2019, Zundel et al. 2022). These effects operate through multiple channels such as biological inflammation or oxidative stress (Arias-Pérez et al. 2020, Lodovici and Bigagli 2011) affecting both the short-term emotional state and long-term psychological well-being of exposed populations.

Beyond its well-documented effects on physical and objective mental health, air pollution also affects individuals' subjective experience of their quality of life. In recent years, a growing body of research—emerging from the field of Happiness Economics—has used Subjective Well-Being (SWB) measures to better capture how individuals perceive and evaluate their lives under varying environmental conditions (Clark, Flèche, et al. 2018). SWB metrics, and in particular life satisfaction, are increasingly recognized as meaningful indicators of overall well-being and are now routinely included in large-scale household surveys following systematic rules allowing geographic and timely comparison (OECD 2013). They provide a complementary perspective to traditional economic indicators, allowing researchers to assess the experiential and psychological effects of environmental quality (Krekel and MacKerron 2020) by capturing both the direct and indirect effects of externalities (Frey, Luechinger, and Stutzer 2010).

A substantial literature has shown that air pollution has consistently negative effects on SWB, across multiple pollutants and geographical scales. In a systematic review of 15 empirical studies, Li et al. (2018) find that increased concentrations of NO_2, SO_2, and PM_{10} are significantly associated with lower levels of life satisfaction and happiness, whether measured at the national (eg. Luechinger 2010), regional (eg. Ferreira et al. 2013), or individual level (MacKerron and Mourato 2009, Xin Zhang, Xiaobo Zhang, and Chen 2017). More recent work by Maarraoui et al. (2023) expands this analysis to include $PM_{2,5}$, and confirms these detrimental effects in the context of the United Kingdom: a 1% increase in ambient concentrations of NO_2, PM_{10}, and $PM_{2,5}$ reduces the odds of reporting higher levels of happiness by 9%, 9.5%, and 10.7%, respectively, even after controlling for a broad set of socio-demographic characteristics. Also studying the United Kingdom context, Abed Al Ahad (2024) finds similar negative results, highlighting the direct and indirect relationship between air pollution and SWB with health playing a major mediating role.

The health and well-being impacts of air pollution are particularly pronounced in urban areas, where both population density and the intensity of economic activities contribute to elevated pollution levels and a greater exposure of individuals to harmful pollutants. This urban concentration magnifies the scale of externalities generated by traffic-related emissions, not only for residents but also for the large number of commuters travelling in and out of cities on a daily basis (Borck and Schrauth 2024) even though intensive public transport, high densification of activities and functional diversity of jobs decreases the average carbon 'carprint' of households (Blaudin de Thé, Carantino, and Lafourcade 2021). In fact, the daily flows of commuters, especially in metropolitan regions, significantly contribute to local pollution (Leroutier and Quirion 2022). These patterns create a disconnect between where emissions are produced and where they are experienced, leading to spatial inequalities in exposure (Samoli et al. 2019), as well as perceived unfairness in who bears the burden of pollution (Banzhaf, Ma, and Timmins 2019).

In response to the health and environmental costs of urban air pollution, many European cities have adopted Low Emission Zones (LEZs)—designated areas where access is restricted to vehicles that do not meet specific emission standards. These policies aim to reduce exposure to harmful pollutants by phasing out the most polluting vehicles, especially in densely populated urban centers. While LEZs differ in design, enforcement, and scope across countries, they are increasingly viewed as cost-effective tools for improving air quality (ADEME 2023). Several studies have documented their effectiveness in reducing concentrations of NO_2, $PM_{2.5}$, and PM_{10} in targeted zones (Beshir and Fichera 2022, Sarmiento, Wägner, and Zaklan 2023, Zhai and Wolff 2021). By improving air quality, these interventions can yield direct public health benefits, such as reduced incidence of respiratory diseases, cardiovascular conditions, and mental health symptoms (Brehm et al. 2024, Moreno et al. 2022).

The effectiveness of LEZs goes beyond the direct improvement in air quality. These zones also trigger behavioral adaptations that can alter transport patterns and individual routines. By making car use more costly or restricted, LEZs can incentivize a shift towards public transportation, cycling, walking, or even remote work. For instance, the expansion of London's ULEZ has led to a modal shift among school children from passive to active transportation modes, such as walking and cycling (Xiao et al. 2024). Among working-age adults, similar trends have been observed, with increased use of public transport and active commuting (Tarriño-Ortiz et al. 2022, Mueller et al. 2025). However, such adaptations are not uniform across the population: socio-demographic factors, baseline travel habits, and perceptions of LEZ fairness shape individuals' responses to the policy (Tarriño-Ortiz et al. 2022).

However, despite their environmental and health benefits, LEZs often face public resistance. In several countries—including France where they might be dismantled—large-scale projects have been delayed or scaled back due to widespread opposition. The most common criticism is that such policies are socially regressive: lower-income households are more likely to own older, more polluting vehicles and are less able to afford compliant alternatives. This exclusion risk is particularly acute in areas with poor public transport infrastructure. For instance, Liotta (2025) shows that 6 out of 8 French LEZs disproportionately restrict access to jobs for low-income workers compared to wealthier individuals, due in part to limited public transit in suburban zones. More broadly, research shows that environmental policies perceived as unfair or costly tend to face lower public support—even when proven effective (Dechezleprêtre et al. 2022). The visibility of financial burdens (fines, vehicle replacement) contrasts sharply with the delayed and diffuse nature of environmental benefits, further reducing acceptability (Drews and Van Den Bergh 2016) that might even translate into political backlash (Colantone et al. 2024).

Ultimately, LEZs may influence how individuals evaluate their quality of life. While environmental improvements can increase SWB, the behavioral constraints imposed by the policy may offset or even reverse these gains. For example, Beshir and Fichera (2022) find that residents of inner London reported higher happiness and life satisfaction after the introduction of the ULEZ. However, their analysis is based on repeated cross-sectional data, which cannot account for individual fixed effects over time. Moreover, by focusing only on Central London working individuals, the analysis may be capturing effects specific to a highly urbanised, well-connected, and relatively affluent population, with particular transport characteristics and employment structures that do not generalise to the broader UK context. In contrast, Sarmiento, Wägner, and Zaklan (2023) use panel data to study LEZs in Germany and find a short-term drop in well-being following implementation—despite documented improvements in air quality. Their results suggest that negative effects are concentrated in the first five years and tend to fade over time, pointing to a possible adaptation dynamic.

In this context, there is a growing need to continue to evaluate not only the environmental effectiveness of LEZs, but also their broader direct and indirect impact on individuals' subjective well-being. While air quality improvements are often well documented, less is still known about how these benefits — along with the behavioural constraints they impose — translate into people's lived experience and life satisfaction. This perspective is key to assessing the social sustainability and long-term acceptability of environmental regulations.

This paper contributes to this emerging field by being the first analysis evaluating the 2021 and 2023 expansions of London's Ultra Low Emission Zone (ULEZ) through the lens of SWB. Using rich panel data from the UK Household Longitudinal Study (UKHLS) and recent difference-in-differences estimators adapted to staggered treatment timing, we estimate the effect of the policy on life satisfaction for individuals living inside the newly regulated area. Our empirical strategy allows us to control for the potential positive environmental benefits (via improved air quality) and negative social costs (via mobility restrictions) to take into account further unobservable effects on individuals' life satisfaction. We further explore the dynamics of these effects over time and across subgroups. To our knowledge, it is the first longitudinal study observing the effect of LEZ policies on commuting transport modes of workers.

In doing so, this paper contributes to three strands of literature: the economics of happiness applied to environmental policy evaluation, the causal identification of policy impacts using panel data, and the political economy of climate policy acceptability.

The remainder of this paper is organized as follows. Section 2 presents the institutional framework governing the LEZ and ULEZ policies. Section 3 describes the data used in the analysis and provides descriptive statistics for the constructed sample. Section 4 outlines the empirical strategy. Section 5 reports the main results from the difference-in-differences analysis, while Section 6 explores potential underlying mechanisms. Finally, Sections 7 and 8 discuss the findings, conclude and outline avenues for future research.

2 Institutional Settings

The development and implementation of LEZs across Europe is embedded in a broader regulatory framework aimed at improving ambient air quality. Since Directive 1999/30/EC, the European Union has progressively introduced binding pollutant concentration limits, further reinforced by

Directive 2008/50/EC, which notably established threshold values for fine particulate matter. In 2024, the EU adopted Directive 2024/2881, significantly tightening these standards in line with updated recommendations from the World Health Organization. The new targets—10 $\mu g/m^3$ for $PM_{2.5}$, 20 $\mu g/m^3$ for PM_{10}, and 40 $\mu g/m^3$ for NO_2—represent a doubling of ambition compared to previous limits for particulate matter. These legislative developments are directly linked to the achievement of several Sustainable Development Goals (SDGs), including SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), SDG 10 (Reduced Inequalities), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) (European Commission, 2024).

In practical terms, member states and cities exceeding these thresholds—or assessed as unlikely to comply—are required to develop concrete measures to reduce pollution and ensure compliance. LEZs have become central to such plans, particularly in densely populated urban environments where road traffic remains a major source of local emissions.

Prior to 2008, London consistently ranked among the most polluted cities in Europe, with road transport accounting for over two-thirds of local emissions (Transport for London, 2008[1]). In response, and under the coordination of the Greater London Authority (GLA), the Department for Environment, Food and Rural Affairs (DEFRA), and the Department for Transport (DfT), a LEZ was introduced as the most promising tool to accelerate air quality improvements. Announced in May 2007 by the Mayor of London and implemented in early 2008, the LEZ initially targeted only heavy-duty vehicles—such as lorries, coaches, and large vans—and covered almost the entire Greater London area. Operating continuously throughout the year, the zone aimed to phase out the most polluting vehicles by incentivizing fleet renewal. Although early air quality improvements were moderate, empirical analyses suggest a significant effect on the composition of the heavy vehicle fleet, with an increase in compliance through technological upgrading (Ellison, Greaves, and Hensher 2013).

Building on this experience, the city adopted a more ambitious strategy in 2019 by launching the Ultra Low Emission Zone (ULEZ), focused for the first time on private vehicles. Replacing the earlier T-Charge (2017), the ULEZ came into effect in April 2019 in Central London, overlapping with the existing Congestion Charge Zone. It required all vehicles entering the area—regardless of ownership type—to comply with strict Euro emission standards: Euro 4 for petrol vehicles and Euro 6 for diesel. Non-compliant vehicles were subject to a £12.50 daily charge, applicable 24/7. The zone initially covered $21km^2$ but was designed for future expansions. To facilitate compliance and raise awareness, the city deployed automated number plate recognition cameras, dedicated signage, and a targeted public information campaign. A £61 million scrappage scheme was also introduced to support low-income households, disabled residents, and small businesses in replac-

[1] https://tfl.gov.uk/info-for/media/press-releases/2008/february/londons-poor-air-quality-tackled-with-launch-of-low-emission-zone

ing non-compliant vehicles (Transport for London, 2022[2]). The scrappage scheme was expanded several times, ultimately reaching a total budget of £210 million. Under the scheme, owners of non-compliant cars received a £2,000 grant upon scrapping their vehicle, with higher compensation available for vans and certain specialised vehicles. In September 2024, the programme was closed to new applicants due to budgetary constraints. By that time, £186 million had already been distributed to approximately 53,000 households.

In response to persistent air quality challenges and broader environmental ambitions, the ULEZ was significantly expanded in October 2021 to include the area within the North and South Circular Roads—thereby covering a much larger portion of Greater London and affecting approximately 3.8 million residents. While the same standards and charges applied, the population impacted by this second phase was socioeconomically more diverse and predominantly residential. A third and final expansion occurred on August 29, 2023, extending the ULEZ to all 33 London boroughs, effectively aligning it with the original 2009 LEZ boundary and bringing approximately 9 million residents under its scope (Figure 1).

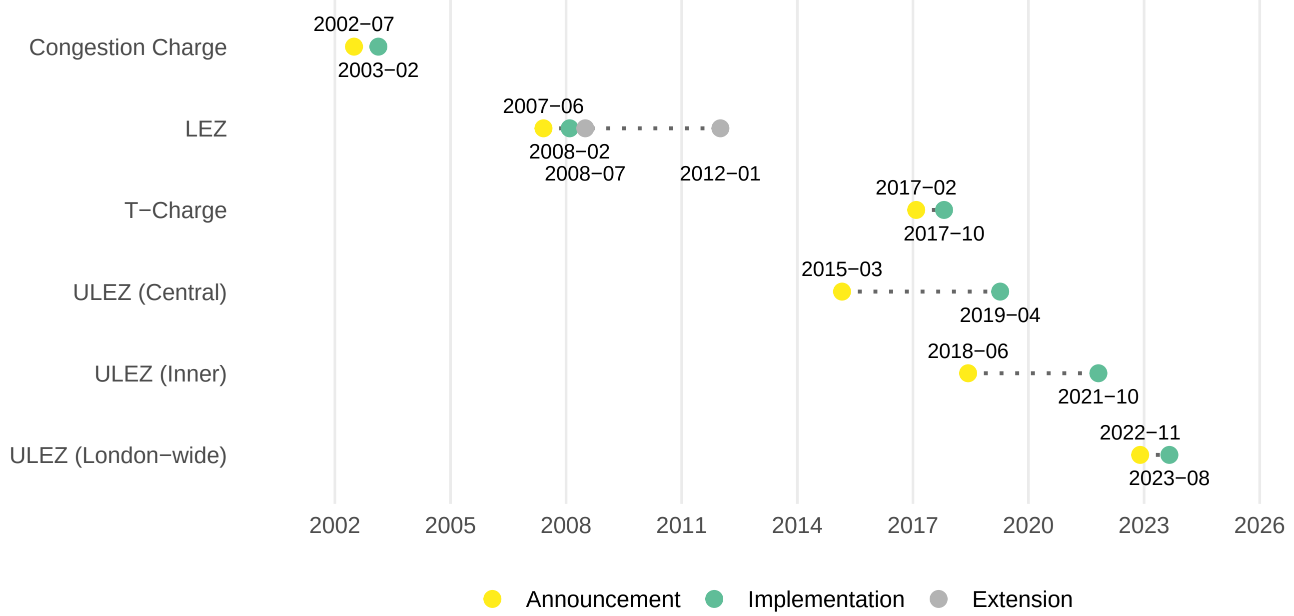

Figure 1: Vehicle Restrictions Policies in London

This staged implementation—spanning multiple years and geographic areas—provides a unique setting for evaluating the effects of the policy using panel data methods. In particular, the combination of staggered treatment timing and spatial variation is well suited for modern difference-in-differences designs with multiple time periods and treatment cohorts (Callaway and Sant'Anna

[2]https://tfl.gov.uk/cdn/static/cms/documents/london-wide-ulez-scrappage-scheme-evaluation-report.pdf

2021).

3 Data

3.1 Individual-Level Data

This paper relies on data from Understanding Society: the UK Household Longitudinal Study (UKHLS)[3], a nationally representative panel survey tracking many lives aspects of individuals and households across the United Kingdom. Since its launch in 2009, UKHLS has followed over 100,000 individuals from approximately 40,000 households, collecting annual information on a wide range of topics including demographics, education, employment, income, health, subjective well-being, and transport behaviour. Respondents aged 16 and over complete an individual adult questionnaire either through face-to-face interviews, online self-completion or by telephone.

For this study, we focus on waves 7 to 15 of the UKHLS, covering the years 2017 to 2024. Observations from 2025 are excluded, as Wave 15 ends in May 2025, resulting in too few cases to provide a reliable analysis. We restrict the sample to individuals residing in: Greater London, the main treatment area impacted by the 2021 and 2023 expansions of the ULEZ, and a set of the largest cities in England used as the control group, including Birmingham, Manchester, Liverpool, Leeds, Sheffield, and Bristol—all major urban areas not affected by the ULEZ during the study period[4]. We chose these cities specifically because of the public transport available in each (tramway, buses, train stations), although the London Underground remains an exception. The panel structure of the dataset enables us to observe the same individuals before and after the introduction of the ULEZ, a key requirement for identifying its causal effects through longitudinal estimation strategies.

Table 1 provides summary statistics for individuals living in Greater London versus those residing in the control regions. Overall, the two populations appear broadly comparable in terms of age, gender, employment status, and education level. The average age is slightly lower in London (47 vs. 46.9), and the employment rate is similar (61%). Educational attainment shows some variation, with a higher proportion of London respondents holding a university degree, but the distribution across other qualification categories remains close. Household characteristics such as the average number of cars and children are also relatively similar, though car ownership is

[3]University of Essex, Institute for Social and Economic Research (ISER). (2024). Understanding Society: Waves 1-14, 2009-2023 and Harmonised BHPS: Waves 1-18, 1991-2009. [data collection]. 19th Edition. UK Data Service. SN: 6614, http://doi.org/10.5255/UKDA-SN-6614-20.

[4]Birmingham and Bristol implemented "Clean Air Zones" policies, respectively in June 2021 and in November 2022. Like LEZs, they aim at banning polluting cars from specific urban areas. Individuals that might be affected by the policy are excluded from controls. Very few observations are lost because the policy impacts small urban territories.

slightly lower in London (1.3 vs. 1.03), consistent with megalopolis living conditions. We observe significant differences in household monthly net income[5], consistent with the higher standards of living specific to the London region. We account for this variation by applying a logarithm function on this variable in our model. These descriptive patterns suggest that the treated and control samples are comparable, supporting the validity of the identification strategy based on differences in treatment timing and location.

	Outside London				London			
Variable	mean	sd	min	max	mean	sd	min	max
Demographics								
Age	46.98	18.89	16	95.0	46.90	17.98	16	100
Employment: Employed	0.61	0.49	0	1.0	0.61	0.49	0	1
Employment: Not employed	0.39	0.49	0	1.0	0.39	0.49	0	1
Marital: Partner	0.42	0.49	0	1.0	0.42	0.49	0	1
Marital: Single	0.58	0.49	0	1.0	0.58	0.49	0	1
Qualification: A-Level	0.19	0.40	0	1.0	0.17	0.37	0	1
Qualification: Degree	0.32	0.47	0	1.0	0.40	0.49	0	1
Qualification: GCSE	0.18	0.39	0	1.0	0.18	0.39	0	1
Qualification: None	0.13	0.33	0	1.0	0.07	0.25	0	1
Qualification: Other	0.08	0.26	0	1.0	0.08	0.27	0	1
Qualification: Postgrad	0.10	0.30	0	1.0	0.10	0.30	0	1
Sex: Female	0.53	0.50	0	1.0	0.51	0.50	0	1
Sex: Male	0.47	0.50	0	1.0	0.49	0.50	0	1
Household Characteristics								
Household monthly net income	3469.92	2254.44	0	61447.7	4260.84	3230.97	0	80190
Number of cars	1.30	0.97	0	7.0	1.03	0.97	0	12
Number of children	0.42	0.85	0	6.0	0.39	0.83	0	6
ULEZ Exposure								
Lives in 2019 ULEZ	0.00	0.00	0	0.0	0.02	0.12	0	1
Lives in 2021 ULEZ	0.00	0.00	0	0.0	0.37	0.48	0	1
Lives in 2023 ULEZ	0.00	0.00	0	0.0	0.60	0.49	0	1
Observations	4521.00				8551.00			
Weighted N (sum of weights)	3985.31				9345.72			

Table 1: Descriptive statistics (London vs Controls)

A distinctive feature of the UKHLS is the availability of precise geographical identifiers, including the Lower Layer Super Output Area (LSOA) of residence. LSOAs are small census units typically covering 1,000 to 3,000 residents and 400 to 1,200 households, which makes them well suited for spatially linking individuals to area-level environmental policies. By combining each respondent's LSOA with their exact interview date, we are able to determine whether they were living in a treated area—defined by the ULEZ 2021 or 2023 boundary extensions—at the time of the survey (Figure 2). Due to very limited observations in the original ULEZ 2019 area (Central London), we exclude individuals residing in that zone from the main analysis[6]. However, we retain the possibility of studying spatial spillover or gradient effects among individuals living nearby in extended robustness checks. We also exclude individuals moving from one zone to another after being treated and some individuals might be interviewed the same year due to the complex struc-

[5] sum of monthly total net personal income - no deductions received by all household members

[6] LSOA maps of control cities can be found in the Appendix Figure 18

ture of the survey so we only retain the first interview results when it occurs.

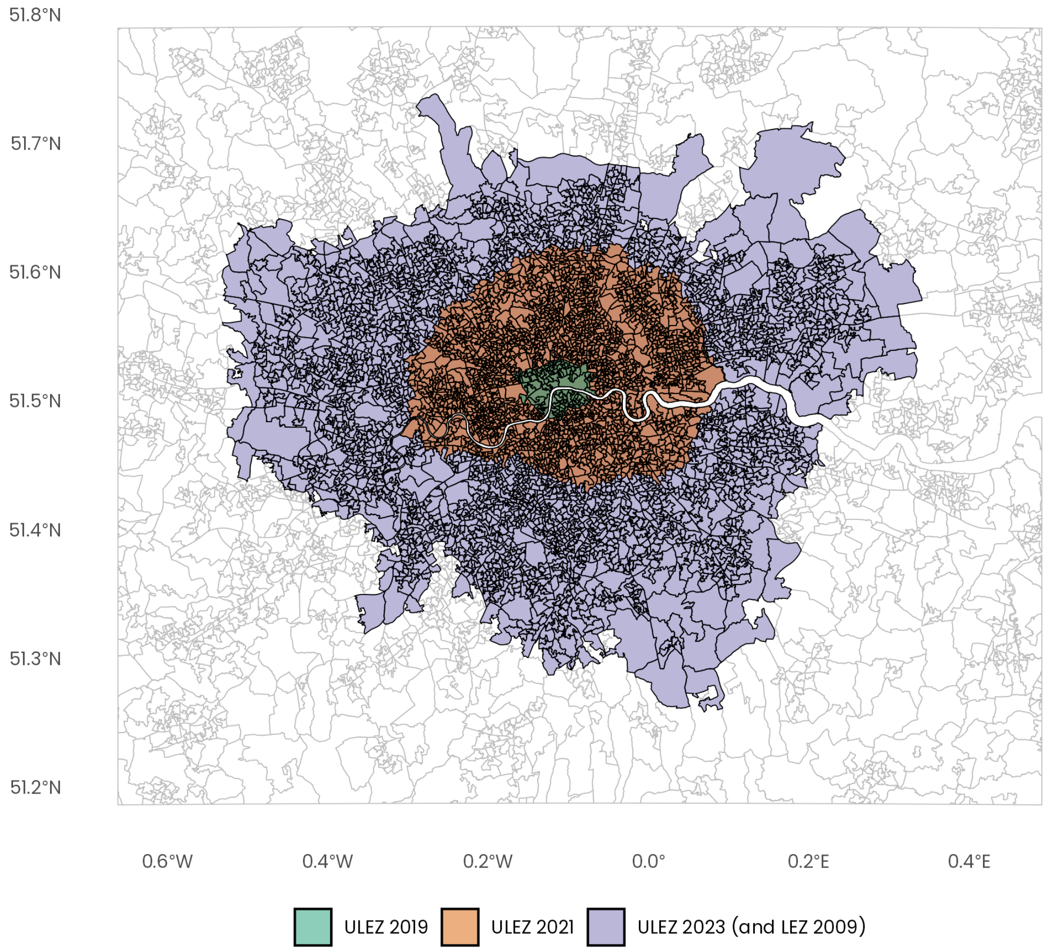

Figure 2: LSOA partition of Greater London, by ULEZ extensions

Importantly, UKHLS provides rich subjective well-being data, including: overall life satisfaction (measured on a 1 Completely Dissatisfied – 7 Completely Satisfied scale), domain-specific satisfaction such as health and emotional variables such as the feeling of being downhearted and depressed (Table 2). These subjective outcomes allow us to examine not only the objective effects of the policy (e.g., on exposure to air pollution or travel behaviour), but also how individuals perceive and internalize changes in their environment. Following previous studies such as Maarraoui et al. 2023 and Sarmiento, Wägner, and Zaklan 2023, we use life satisfaction as our main outcome, while also leveraging the panel structure to control for time-invariant individual characteristics.

Finally, the UKHLS includes detailed information on transport behaviour of working individuals, such as the usual mode of commuting[7], time and distance to work, and whether respondents

[7]We combine variables in broader transport mode groups: Driving (Car, Moto, Taxi), Public Transport (Subway,

work from home. These variables allow us to explore behavioural adjustments in response to the ULEZ, as well as to test for potential mechanisms linking the policy to subjective well-being. To our knowledge, this is the first study to combine such detailed individual-level well-being and transport data with a spatially explicit policy evaluation of the ULEZ.

	Outside London				London			
Variable	mean	sd	min	max	mean	sd	min	max
Subjective well-being								
Life Satisfaction	5.11	1.39	1	7	4.99	1.46	1	7
Health Satisfaction	4.76	1.57	1	7	4.83	1.58	1	7
Feeling depressed	2.19	1.04	1	5	2.13	1.04	1	5
Feeling happy	2.88	0.59	1	4	2.89	0.60	1	4
Observations (raw N)	4635.00				8553.00			
Observations (weighted N, sum of weights)	4107.47				9557.94			
Commuting behaviours (employed only)								
Time commuting	25.83	21.55	0	420	33.72	24.82	0	180
Motorized vehicle to work	0.49	0.50	0	1	0.21	0.41	0	1
Takes public transport to work	0.11	0.32	0	1	0.32	0.46	0	1
Cycles to work	0.02	0.16	0	1	0.05	0.22	0	1
Walks to work	0.13	0.33	0	1	0.16	0.36	0	1
Observations (raw N)	1937.00				3602.00			
Observations (weighted N, sum of weights)	1967.42				4470.67			

Table 2: Outcomes descriptive statistics (London vs Outside)

3.2 Air Pollution Trends

To assess environmental exposure to air pollution, we combine the UKHLS survey data with high-resolution modeled pollution estimates from the UK Department for Environment, Food and Rural Affairs (DEFRA). In particular, we use data from the Pollution Climate Mapping (PCM) model, a nationally validated source that provides annual concentrations of major air pollutants across the UK, including NO_2, PM_{10} and $PM_{2.5}$ (DEFRA, 2024[8]). The PCM data are produced using a combination of ambient air quality monitoring station readings, emissions inventories, and atmospheric dispersion modeling, and are used by the UK government to evaluate compliance with national and EU regulatory standards. The estimates are provided at a 1×1 km grid resolution, offering sufficient granularity to capture meaningful variation in pollution levels at the local scale, including within urban areas such as Greater London.

To link these environmental data to individuals in our sample, we match each respondent's LSOA of residence to the corresponding pollution grid cell. When an LSOA intersects multiple grid cells, we compute the spatial average of pollution estimates weighted by area. This approach ensures consistency with the geographic precision of the UKHLS while preserving variation in pollution exposure across space and time. This linkage allows us to construct individual-level annual exposure profiles to NO_2, PM_{10} and $PM_{2.5}$ throughout the 2017–2024 period (Figure 3). We then use these pollution variables as control variables in several models to isolate the effect

Bus, Train) and Active Mobility (Walking, Cycling).

[8]https://uk-air.defra.gov.uk/research/air-quality-modelling?view=modelling

of the ULEZ on life satisfaction from broader trends in air quality. However since air quality improvement is a direct result of the implementation of the policy, we must take into account a possible endogeneity when adding these controls.

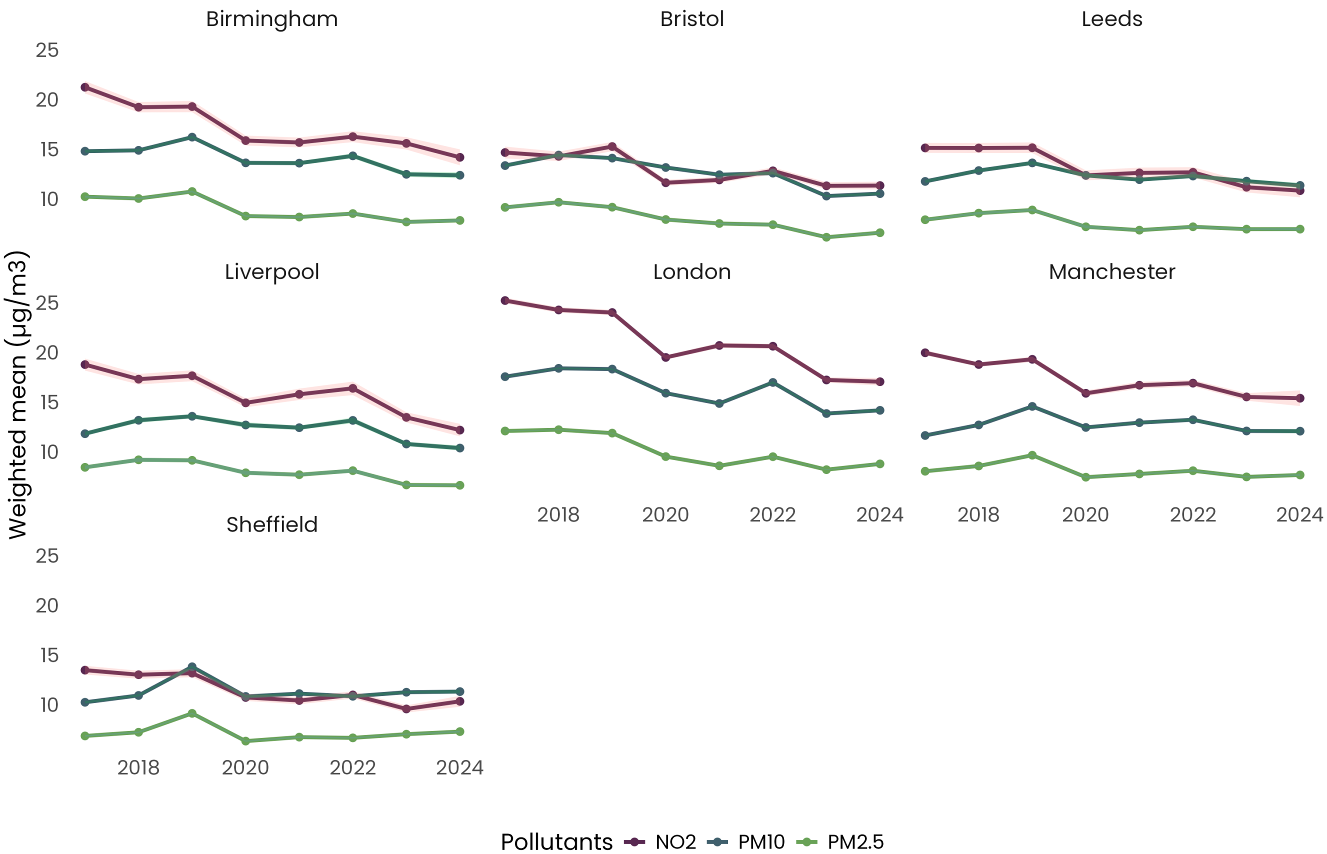

Figure 3: Individual-level pollutants mean time series 2017 - 2024

4 Empirical Strategy

The causal effect of the ULEZ policy is identified by exploiting its staggered geographic expansion over time. While the ULEZ was first introduced in Central London in April 2019, this initial area was limited and heavily business-focused. The first major expansion occurred in October 2021, extending the zone to the area bounded by the North and South Circular Roads, significantly increasing the number and diversity of affected residents. A second expansion, covering all Greater London boroughs, was implemented in August 2023.

We construct treatment indicators using precise geographic information available in the UKHLS, linking each respondent's LSOA to the corresponding policy coverage at the time of interview. An individual is considered "treated" from the year they first reside within the expanded ULEZ area. This definition allows us to exploit both temporal and spatial variation in policy exposure.

4.1 Baseline Model: Two-Way Fixed Effects

As a baseline study, we focus exclusively on the October 2021 expansion of London's ULEZ. While a further expansion of the ULEZ took place in August 2023, this latest policy phase is only included afterwards in the empirical analysis, as the latest available wave of UKHLS data (Wave 15) only covers observations up to May 2025, allowing us to study a single full year of treatment for these treated residents. Given this limited post-treatment window and the small number of surveyed individuals affected by the 2023 expansion, this group is excluded to preserve identification quality and statistical power in this TWFE specification. Accordingly, we restrict the treated sample to individuals living within Greater London but outside the original 2019 ULEZ, and inside the 2021 ULEZ boundary, as identified using precise LSOA-level geolocation and the date of the interview. All London residents not treated in 2021 are excluded from the analysis, in order to avoid contaminating the control group with units potentially exposed to earlier or later ULEZ phases. To summarize, treated individuals live in the area affected by the ULEZ 2021 expansion while individuals that make up the control group live outside the region of London, in the six largest cities in England after the capital.

We begin with a standard Difference-in-Differences (DiD) specification with individual and year fixed effects, estimated on longitudinal data from the UKHLS:

$$Y_{it} = \beta \times D_{it} + \alpha_i + \lambda_t + X_{it}^{'}\gamma + \epsilon_{it} \tag{1}$$

where Y_{it} denotes self-reported life satisfaction (or other outcome of interest) of individual i at time t in our main specification. The variable D_{it} is an indicator equal to one if individual i resides within the area affected by the 2021 ULEZ extension after the policy implementation, and zero otherwise. α_i and λ_t are individual and year fixed effects, respectively. The vector X_{it} includes a set of time-varying controls usually used in the literature (Beshir and Fichera 2022, Brehm et al. 2024, Maarraoui et al. 2023) that may influence subjective well-being, such as household income, employment, marital status, number of children. We add the number of cars owned by the household in several specifications to isolate the residual well-being impact of the policy beyond observable adjustments in car ownership. In addition, we control for local air pollution exposure ($PM_{2.5}$, PM_{10}, and NO_2), measured at the LSOA level and matched to individuals based on their location. While air quality improvement is one of the primary objectives of the ULEZ and therefore constitutes a key channel through which the policy may affect subjective well-being, controlling for pollution allows us to isolate the non-environmental components of the policy's impact. Specifically, this specification identifies the well-being effect of residing in the regulated area conditional on local air quality, thereby capturing adjustment costs, mobility constraints, and financial burdens independently of environmental benefits.

We acknowledge that pollution is itself an outcome of the policy and therefore a post-treatment variable. Consequently, these estimates should not be interpreted as total causal effects, but rather as conditional effects that neutralize the environmental channel. This approach provides a lower-bound estimate of the short-run welfare costs associated with regulatory constraints.

Individual fixed effects absorb all time-invariant unobserved heterogeneity, such as personality traits or stable socio-demographic characteristics, while year fixed effects capture national shocks common to all individuals (e.g., the COVID-19 pandemic). All models are estimated with longitudinal survey weights provided by the UKHLS to ensure representativeness. Following the survey documentation, standard errors are clustered at the Primary Sampling Unit (PSU) level and stratification is accounted for in order to reflect the complex survey design. We also report robustness checks with alternative clustering levels (e.g., LSOA or city level). Identification of causal effects relies on the parallel trends assumption: in the absence of treatment, life satisfaction trajectories of individuals living inside and outside the ULEZ area would have evolved similarly. We assess this assumption both graphically (Figure 4) and through pre-treatment placebo tests.

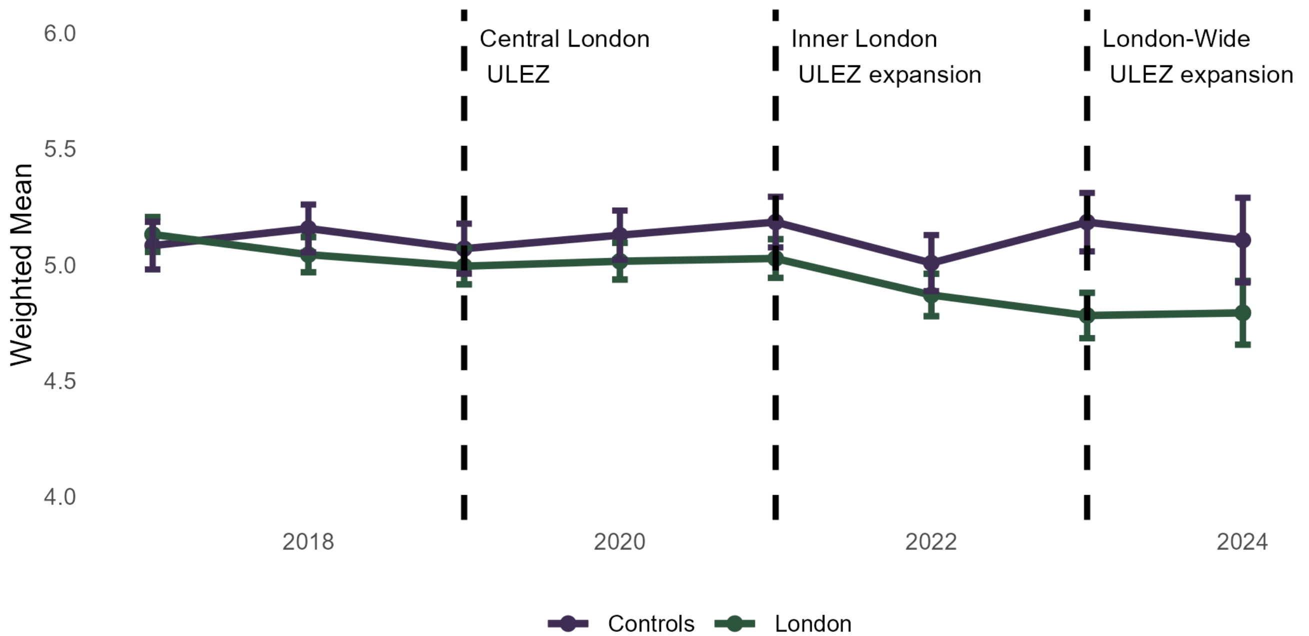

Figure 4: Individual-level life satisfaction mean trend 2017 - 2024

We further estimate an event-study difference-in-differences specification to examine the dynamic effects of the 2021 ULEZ extension on life satisfaction. Specifically, we regress the outcome on a set of leads and lags of the treatment indicator relative to the year of implementation, while controlling for individual and year fixed effects as well as time-varying covariates:

$$Y_{it} = \alpha_i + \lambda_t + \sum_{k \neq 0} \beta_k \cdot \mathbf{1}[t - T_i = k] \times D_i + X'_{it}\gamma + \varepsilon_{it}, \quad (2)$$

where Y_{it} is life satisfaction for individual i at time t (or other outcome of interest), D_i indicates whether the individual resides within the ULEZ 2021 area, and T_i denotes the year of treatment. The coefficients β_k capture the effect k years before ($k < 0$) or after ($k > 0$) the policy implementation, relative to the year immediately preceding treatment ($k = 0$). Standard errors are also clustered at the PSU level and account for the survey stratification.

4.2 Staggered Difference-in-Differences

The expansion of London's Ultra Low Emission Zone provides a natural staggered treatment design, as different groups of individuals are exposed to the policy at different points in time. While the baseline analysis focuses on the October 2021 expansion, the second extension of the ULEZ to all Greater London boroughs introduce heterogeneity in treatment timing that raises important identification issues for conventional TWFE estimators.

It is now well established that, in settings with staggered adoption and heterogeneous treatment effects, TWFE estimators may produce biased estimates due to the implicit use of already-treated units as controls and the presence of negative weighting across group-time comparisons (Goodman-Bacon 2021, Chaisemartin and D'Haultfœuille 2020)[9]. To address these concerns, we complement the baseline TWFE analysis with estimators that are explicitly designed for staggered treatment adoption.

4.2.1 Sun and Abraham (2021): Main Staggered DiD Specification

Our main staggered difference-in-differences analysis relies on the interaction-weighted event-study estimator proposed by Sun and Abraham (2021). This approach provides a regression-based solution to the biases arising in TWFE models under staggered adoption by fully interacting cohort indicators with relative event-time dummies. By construction, this estimator avoids the negative weighting problem inherent to standard TWFE estimators by ensuring that cohort-specific effects are identified using comparisons with never-treated or not-yet-treated units.

Formally, we estimate the following interaction-weighted event-study specification:

$$Y_{it} = \alpha_i + \lambda_t + \sum_{g} \sum_{k \neq -1} \beta_{g,k}, \mathbf{1}[G_i = g] \cdot \mathbf{1}[t - g = k] + X_{it}'\gamma + \varepsilon_{it}, \tag{3}$$

where Y_{it} denotes the life satisfaction of individual i (or other outcome of interest) at time t, α_i and λ_t are individual and year fixed effects, and $G_i = g$ identifies the cohort of individuals first exposed to the ULEZ policy in year g. The indicator $\mathbf{1}[t - g = k]$ captures the number of periods relative to the treatment year, with the period immediately preceding treatment ($k = -1$) serving as the reference category. The coefficients $\beta_{g,k}$ therefore measure cohort-specific dynamic

[9] As a reminder, to address these concerns in the TWFE specification we exclude individuals living in the ULEZ 2023 area from our controls.

treatment effects at different horizons before and after the policy implementation, relative to the pre-treatment baseline.

In our context, identification relies on comparisons between treated individuals and appropriate control units, namely individuals living outside London who are never exposed to the ULEZ policy but who still have an urban lifestyle comparable with Londoners, as well as individuals residing in areas affected by later policy expansions who are not yet treated at the time of comparison. This structure allows us to exploit both the temporal and spatial variation generated by the staggered expansion of the ULEZ. We further assess the sensitivity of our results to alternative control groups and to specifications allowing for differential responses to common shocks.

This interaction-weighted event-study framework offers several advantages in our context. First, it naturally accommodates individual and time fixed effects, survey weights, and a rich set of time-varying covariates. Second, it allows us to explicitly trace the dynamic effects of the policy and to assess the presence of differential pre-treatment trends. Finally, in a setting with a relatively short post-treatment window—as is the case for the ULEZ expansions observed in the UKHLS—the Sun and Abraham estimator provides greater precision in finite samples than fully nonparametric alternatives such as Callaway and Sant'Anna estimator while remaining robust to treatment effect heterogeneity. For these reasons, we rely on this estimator as our primary specification for dynamic treatment effects.

5 Results

We proceed in four steps. First, we document the average effect of the 2021 ULEZ extension on subjective well-being using a TWFE estimation. Second, we examine the dynamic and cohort-specific effects using a staggered DiD framework. Third, we study behavioural adjustments in commuting patterns and test for anticipatory responses. Finally, we assess whether these behavioural changes account for the observed welfare effects.

5.1 TWFE Framework: 2021 ULEZ Inner London Extension

Table 3 reports the estimated effects of the 2021 extension of the ULEZ on self-reported life satisfaction using a TWFE framework. Across the three specifications, the interaction term between residence in the affected area and the post-2021 period is consistently negative and statistically significant at the 1% level. The magnitude of the ATE coefficient is equal to 0,26 points on the life satisfaction scale, suggesting that individuals living within the newly regulated zone experienced a reduction in well-being relative to comparable individuals outside the zone after the policy change. When controlling for air quality improvement, we estimate a life satisfaction decline close to 0.3

points. Since air pollution is a post-treatment variable, including it as a control may mechanically block part of the policy's causal pathway. We therefore do not interpret these coefficients as average treatment effects, but rather as conditional effects that isolate non-environmental channels. The baseline specification without pollution controls remains our preferred estimate of the total net impact.

The main effect of the post-2021 indicator is positive, indicating that average life satisfaction of the sample increased from its baseline level. The main effect of residence in the ULEZ 2021 area is negative but not statistically significant, which confirms that the estimated impact stems from the policy implementation rather than from pre-existing differences across locations. Overall, the results point to a modest but robust decline in life satisfaction among residents of the extended ULEZ-inner London area. This suggests that the short-term impact of the policy was perceived negatively by affected individuals, potentially due to mobility constraints, adjustment costs, or opposition to the measure, rather than through improvements in local air quality, which are not detectable in this specification.

Dependent Variable:	Life Satisfaction		
Model:	(1)	(2)	(3)
Variables			
In ULEZ 2021 × Post 2021	-0.2555***	-0.2571***	-0.3037***
	(0.0831)	(0.0832)	(0.0993)
In ULEZ 2021	-0.3047	-0.3858	-0.7595
	(0.4295)	(0.4661)	(0.5409)
Post 2021	0.3368*	0.3380*	0.3562**
	(0.1773)	(0.1765)	(0.1749)
Car Owner		-0.1818	-0.1910
		(0.1484)	(0.1466)
log(PM10)			1.608
			(1.198)
log(PM2.5)			-1.298
			(1.054)
log(NO2)			0.3210
			(0.5365)
Fixed-effects			
Individual	Yes	Yes	Yes
Year	Yes	Yes	Yes
Socio-demographic Controls			
	Yes	Yes	Yes
Fit statistics			
Observations	7,224	7,224	7,224
R^2	0.59029	0.59076	0.59121
Within R^2	0.00704	0.00818	0.00925

Clustered (psu & strata) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*
Controls: Log(household net income), marital status, number of children, employment status

Table 3: Difference-in-Differences TWFE ULEZ 2021

We also estimate the same TWFE specification on other measures of subjective well-being, including self-rated health, feelings of depression, and hedonic happiness. The results, reported in the Appendix Table 5, show that the ULEZ extension does not significantly affect subjective health. However, we find a negative impact on hedonic happiness, which is strongly correlated with life satisfaction, and a positive effect on depressed feeling. This pattern suggests that the decline in life satisfaction following the policy is mirrored by short-run changes in individuals' experienced happiness and mental health.

5.2 Staggered Difference-in-Differences Framework

Figure 5 presents the cohort-specific dynamic effects of the ULEZ expansions on life satisfaction[10], estimated using the interaction-weighted event-study estimator proposed by Sun and Abraham (2021). In this specification, the control group is composed of individuals who are not yet exposed to the ULEZ at a given point in time. This includes both residents of large English cities outside London—who are never treated in our sample—and individuals belonging to cohorts that are treated at a later date[11].

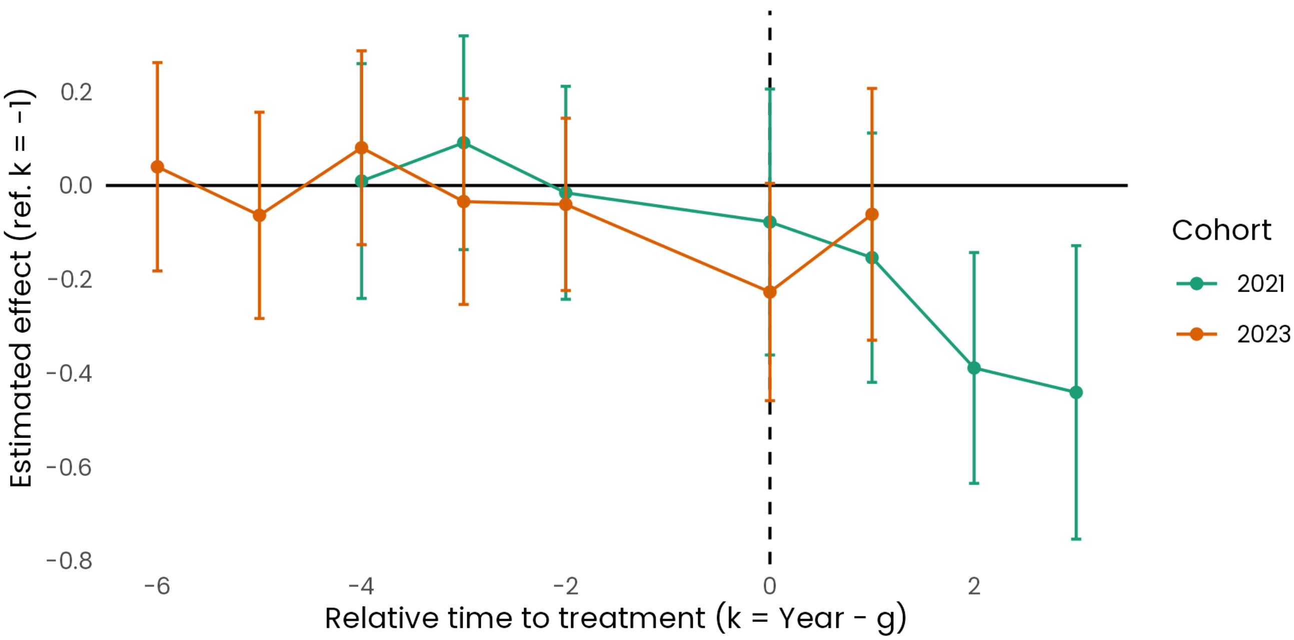

Figure 5: Staggered Difference-in-Differences framework

For both cohorts, estimates show no evidence of differential pre-treatment trends: coefficients in the years preceding the policy are small and statistically indistinguishable from zero, supporting the identifying assumption of parallel trends. In the year of implementation, the estimated effect is close to zero, indicating no immediate impact on life satisfaction.

By contrast, a clear and persistent decline in life satisfaction emerges in the post-treatment period for individuals exposed to the ULEZ inner London expansion in 2021. One year after exposure, life satisfaction decreases by approximately 0.4 points relative to the pre-treatment baseline. This negative effect keeps a similar magnitude in the second year after exposure. The gradual nature of the response suggests that the well-being effects of the policy materialize with delay. The

[10]Control variables: log(household net income), marital status, number of children, employment status

[11]For example, when estimating the effect for the 2021 cohort, treated individuals are compared to residents of other large cities as well as to individuals in the 2023 cohort prior to their exposure. After 2023, only residents of untreated cities remain in the control group.

magnitude of these results is similar from our findings when applying the TWFE specification. We also note that the decline in life satisfaction for this population becomes statistically significant exactly when the 2023 expansion is implemented. We cannot disentangle both effects at this point of the analysis.

In contrast to the 2021 cohort, the estimates for the individuals exposed to the 2023 ULEZ extension do not display a post-treatment decline in life satisfaction one year after the implementation. Surprisingly, we can observe a decrease in life satisfaction during the year of implementation.

Pre-treatment coefficients are also small and stable, providing no indication of anticipatory effects prior to the policy implementation. Furthermore, the staggered DiD estimates confirm that the negative effect identified in the TWFE framework is not an artifact of inappropriate control groups, but reflects genuine cohort-specific treatment effects. It is important to note that our empirical strategy identifies short-run treatment effects of the ULEZ extension on subjective well-being. Given the limited post-treatment window available in the UKHLS, particularly for the 2023 expansion, our estimates capture transitional responses rather than long-term welfare effects.

Taken together, these results reveal substantial heterogeneity in the effects of the ULEZ across policy phases. The adverse impact on SWB is concentrated among individuals affected by the 2021 expansion, while no comparable effect is detected for the 2023 extension. Several factors may account for this difference. First, the 2021 expansion affected a denser and more residentially diverse population, for whom compliance costs—such as vehicle replacement or increased commuting constraints—may have been more salient. Second, the 2023 expansion may have been partially anticipated following the earlier reform, allowing households to adjust in advance and mitigating its impact on well-being. The negative effect on well-being for the 2023 cohort during the year of implementation, despite similar regulatory constraints, strongly suggests that anticipation and prior adaptation play a central role in shaping the welfare consequences of low-emission zones. Finally, differences in local transport alternatives or enforcement intensity across areas may also contribute to the observed heterogeneity.

These results are consistent with Sarmiento, Wägner, and Zaklan (2022) who also find a decrease in life satisfaction during the five first years of exposure before reverting to insignificance. Overall, the cohort-specific analysis highlights the importance of accounting for staggered treatment adoption and treatment effect heterogeneity when evaluating large-scale urban environmental policies. By isolating the dynamic effects for each expansion phase, the Sun and Abraham estimator reveals that the negative well-being effects of the ULEZ are not uniform over time, but instead depend critically on the timing and context of policy implementation.

5.3 Cohort-Specific Effects Among Workers

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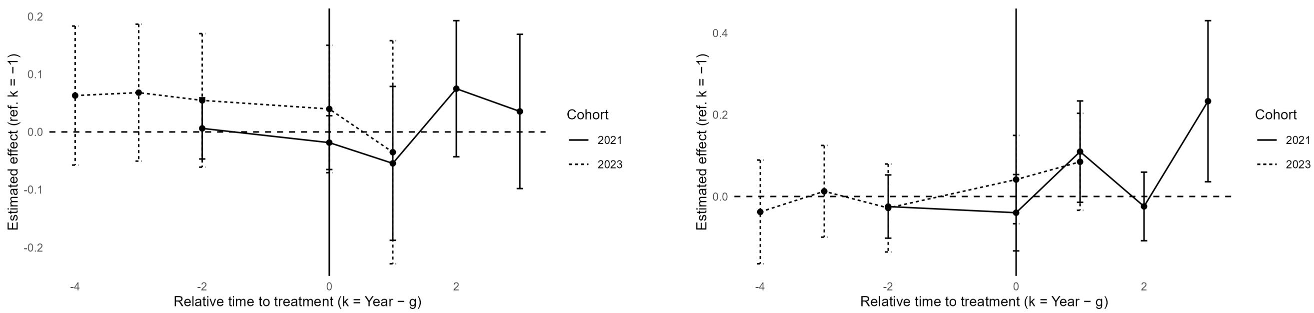
5.3.1 Transport Adjustments And Anticipation Mechanisms

We next examine commuting behaviour not as an outcome of interest per se, but as a potential mechanism and a way to assess anticipation and adjustment dynamics prior to the policy becoming binding. Figure 6 reports cohort-specific event-study estimates of the impact of the ULEZ on commuting behaviour among workers[12]. We examine four dimensions of transport behaviour to commute to work: individual vehicle use, public transport use, active mobility (walking or cycling) and time spent commuting.



(a) Using car, moto or taxi to commute

(b) Using public transports (Bus, Underground or Train) to commute

Figure 6: Cohort-specific dynamic effects of the ULEZ on transports mode used to commute

We first observe a significant increase in public transport use among individuals exposed to the 2021 ULEZ expansion, especially after the 2023 ULEZ implementation. This result is consistent with official reports indicating an increase in the proportion of rail trips taken by Londoners between 2023 and 2025[13]. In contrast, the use of individual vehicles do not significantly vary at the extensive margin among treated workers and changes in active mobility are limited and imprecisely estimated (Appendix Figure 16).

Consistent with these patterns, we also find no evidence of changes in commuting time around the policy implementation, although estimates are imprecise and heterogeneous across cohorts (Figure 7).

[12] Questions about the main mode of travel to work were first asked in Wave 10 of the UKHLS. Due to the structure of the survey, and to ensure there were enough respondents for a single year, we start the analysis in 2019.

[13] https://content.tfl.gov.uk/travel-in-london-2025-the-travel-behaviour-of-london-residents-based-on-the-ltds-acc.pdf

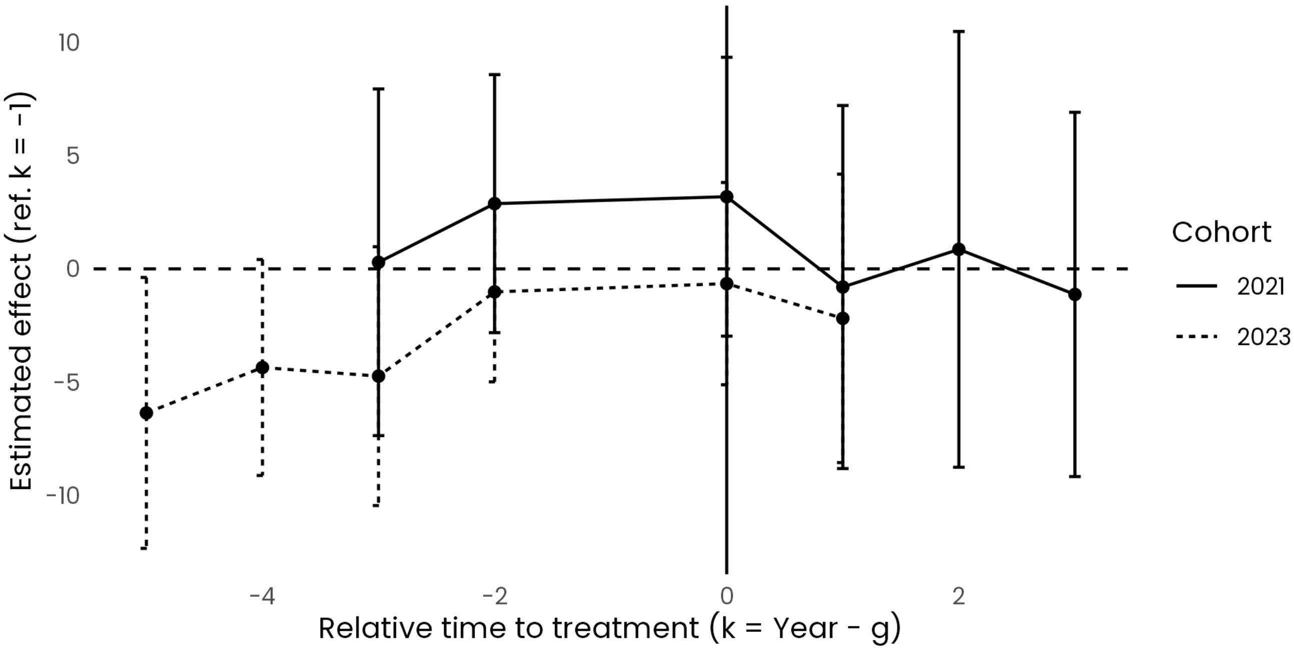


Figure 7: Cohort-specific dynamic effects of the ULEZ on time commuting

Taken together, these results indicate that individuals adjust their commuting behaviour in response of the policy, particularly by increasing reliance on public transport. This result is consistent with Tarriño-Ortiz et al. 2022 which also documents an increase in public transport use after the Madrid's LEZ implementation. Given these substantial adjustments in commuting behaviour, we next examine whether the estimated effects persist when conditioning on transport mode and commuting time among workers.

5.3.2 Life Satisfaction Effect On Workers

To further refine the analysis, we investigate the impact of the ULEZ expansions specifically on the sub-sample of employed individuals. Workers often face rigid commuting schedules and fixed workplace locations, making them potentially more sensitive to changes in transportation costs and mobility constraints. Figure 8 reports cohort-specific event-study estimates for this group[14].

The baseline estimates for workers reveal a gradual decline in life satisfaction for the 2021 cohort. While pre-treatment coefficients are statistically indistinguishable from zero—validating the parallel trends assumption—life satisfaction decreases progressively following exposure. Although the point estimates remain statistically insignificant in the immediate aftermath ($k = 1, 2, 3$), the downward trend suggests a cumulative well-being erosion. In contrast, no significant effects are detected for the 2023 cohort, which may reflect a shorter observation window or preemptive behavioral adaptation following the earlier policy phases in Central London.

[14]Control variables: log(household net income), marital status, number of children, employment status

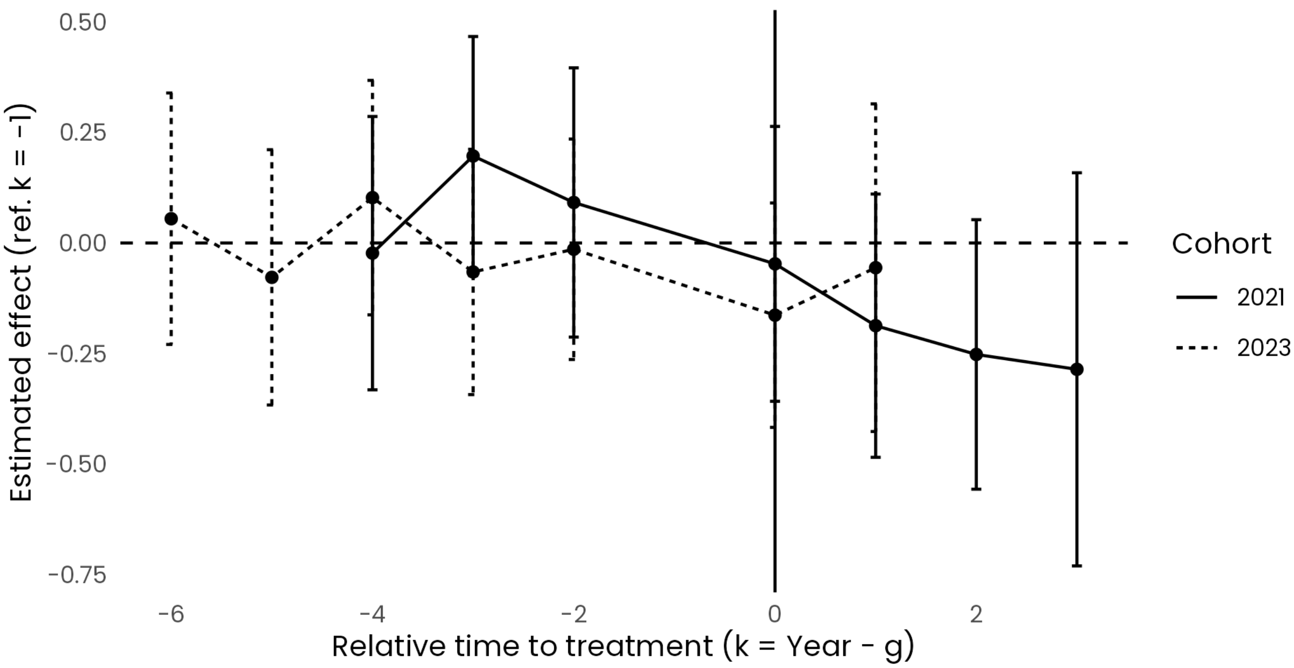
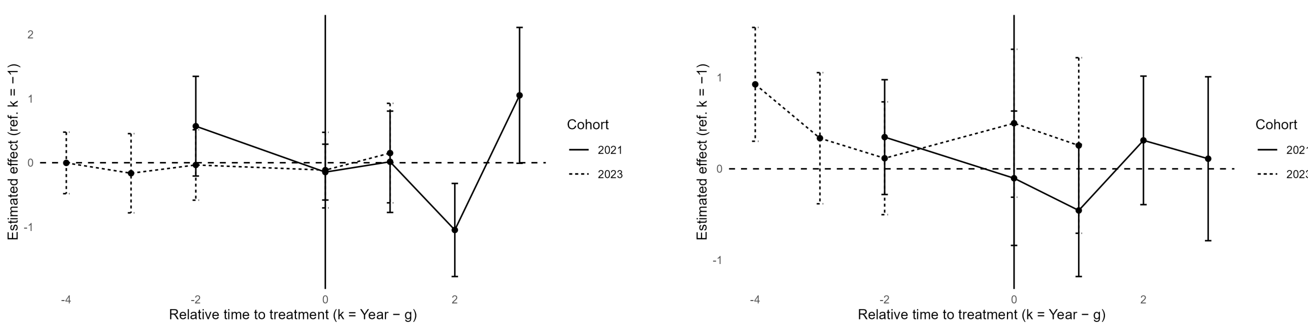


Figure 8: Cohort-specific dynamic effects of the ULEZ on life satisfaction among workers (Sun and Abraham, 2021)

However, the aggregate response of workers masks significant heterogeneity driven by commuting preferences. To isolate the primary channel of this well-being shock, we decompose the sample according to the primary mode of transport used for commuting. Figure 9 presents the results for car users and public transport users.



(a) Car users

(b) Public transports users

Figure 9: Cohort-specific dynamic effects of the ULEZ on life satisfaction among workers (Sun and Abraham, 2021)

The divergence between the two groups is striking. Among car-dependent workers, the implementation of the ULEZ is associated with a discernible reduction in life satisfaction. For the 2021 cohort, the negative impact becomes particularly salient two years after the treatment when the ULEZ 2023 is implemented, suggesting that the financial burden of the daily charge or the logistical challenges of replacing a non-compliant vehicle directly translate into lower subjective well-being. Conversely, workers who rely on public transport exhibit no significant variation in life satisfaction across any of the treatment periods.

These results provide robust evidence that the ULEZ expansion acts as a specific shock to car-based mobility. For public transport users, the policy appears wellbeing-neutral in the short run, as it neither significantly worsened their daily commuting experience nor imposes new financial constraints. For motorists, however, the policy introduces a structural increase in the cost of commuting if the vehicle is not compliant, particularly for those whose workplace is located within the expanded zone. This confirms that the aggregate decline in well-being observed in the previous sections is fundamentally mediated by transport mode dependency.

5.4 Mechanisms

5.4.1 Access to Public Transport

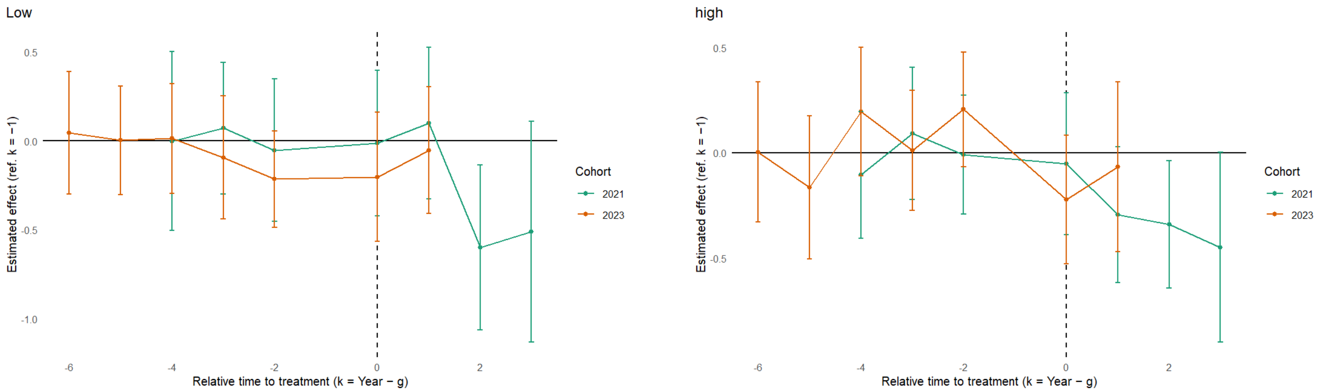
The decline in SWB following the ULEZ expansions suggests that the policy may have constrained individual mobility by increasing the cost of car-based travel. A primary candidate for the mitigation of this welfare loss is the availability of alternative transport modes. If the ULEZ acts as a tax on mobility, the welfare cost should be lower in areas where public transport provides a high-quality substitute for private vehicles.

To test this mechanism, we rely on a spatial analysis of the public transport network. Using OpenStreetMap (OSM) data[15], we construct a transport density score for each LSOA. This score is calculated by counting bus stops and rail stations within a 300-meter buffer[16] of the LSOA centroid, weighting rail stations more heavily (3 to 1 scale) to account for their greater capacity, speed and connection. we then partition the sample into two groups based on the median accessibility score: High Access and Low Access areas.

Figure 10 presents the event-study estimates for these two subsamples. In High Access areas, the impact of the ULEZ expansion on life satisfaction is relatively muted and statistically insignificant across most periods. Conversely, residents in Low Access areas experience a sharper decline in well-being following the 2021 expansion.

[15] we used the R package *osmdata* to gather all relevant data for this section.

[16] we adopt a conservative 300-meter buffer around LSOA centroids to define the immediate catchment area of public transport nodes. This threshold is motivated by the urban planning literature, which identifies 300 to 400 meters—approximately a five-minute walk—as the critical distance beyond which the elasticity of transit demand with respect to walking distance increases significantly (Daniels and Mulley 2013). By focusing on this narrow and conservative perimeter, we ensure that the High Access group reflects households for whom public transport represents a viable and low-cost alternative to private vehicle use, thereby minimizing measurement error from nominal accessibility that would not translate into actual modal shifts.



(a) Low Accessibility

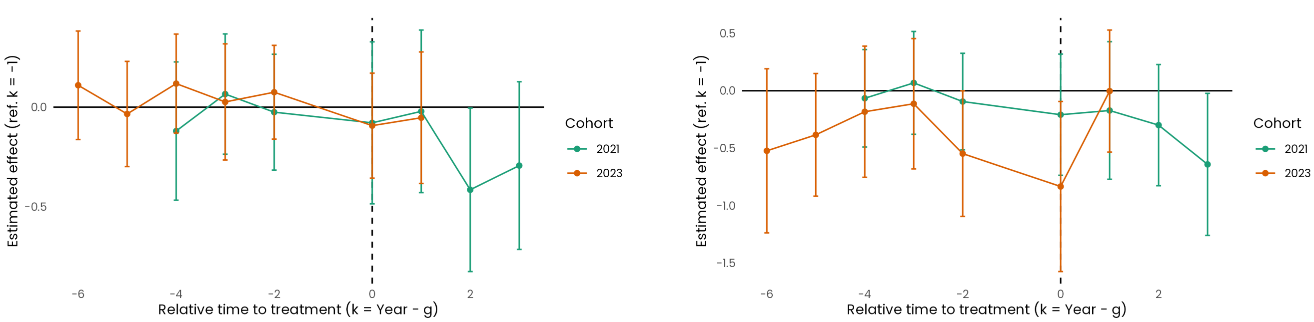
(b) High Accessibility

Figure 10: Heterogeneous effect of public transport accessibility on life satisfaction

These results provide empirical support for the ”captive user” hypothesis. In areas with poor transit alternatives, the ULEZ expansion likely represents a more rigid budget constraint, as households cannot easily switch modes to avoid the daily charge or the cost of vehicle replacement. This divergence suggests that the welfare costs of Low Emission Zones are not spatially uniform but are heavily contingent on the pre-existing density of the urban transport infrastructure. Consequently, the social acceptability of such environmental policies may depend as much on the quality of alternative public services as on the stringency of the environmental regulation itself.

5.4.2 Car Ownership

To complete the previous analysis, we compute our event-study while separating individuals owning a car or not. Figure 11 reports cohort-specific dynamic effects of the ULEZ on life satisfaction separately for car owners and non-car owners. Two distinct patterns emerge.



(a) Owns a car

(b) Does not own a car

Figure 11: Cohort-specific dynamic effects of the ULEZ on life satisfaction

Among individuals owning a car and living in the ULEZ 2021 area, negative effects on life satisfaction appear sharply around the 2023 expansion of the ULEZ. These effects are not preceded by significant pre-treatment trends. This pattern is consistent with the presence of direct and salient costs borne by car owners, such as monetary charges, vehicle replacement constraints, and increased regulatory pressure.

In contrast, among individuals without a car, no immediate decline in life satisfaction is observed in 2023 for individuals living in the 2021 ULEZ area. Instead, negative effects materialize in 2024. This delayed response suggests the presence of indirect or second-round effects affecting non-car owners, potentially through increased congestion in public transport, reduced commuting comfort, or broader changes in urban mobility conditions.

Interestingly, we observe a decline in life satisfaction in the year of the policy implementation among individuals without a car residing in the area affected by the 2023 ULEZ extension. One possible explanation is that these individuals rely more heavily on public transport and are therefore more exposed to congestion, crowding, or service disruptions following the policy. The expansion of the ULEZ may have increased demand for public transport in peripheral areas of Greater London, where access to transit services is generally weaker and less dense than in central zones (Nie et al. 2024).

Taken together, these results indicate that the well-being costs of the ULEZ are initially concentrated among individuals directly constrained by the policy, before diffusing more broadly to other population groups over time. While we do not formally identify the underlying mechanisms, this temporal shift highlights the importance of accounting for both direct and indirect well-being effects when evaluating urban environmental policies.

5.5 Income heterogeneity

A central concern in the debate over urban tolls and emission zones is their potential regressive impact. Since the ULEZ charge is a flat fee (£12.50 per day), it represents a larger share of the budget for low-income households. Furthermore, these households are statistically more likely to own older, non-compliant vehicles and have a lower marginal propensity to invest in newer, compliant alternatives[17]. To explore this distributive dimension, we examine whether the impact of the ULEZ expansions on life satisfaction varies across the household income distribution.

We partition the sample into three groups based on the net monthly household income reported in the UKHLS: Low, Medium, and High income. Figure 12 displays the event-study estimates for these three groups. The results reveal a marked gradient in the well-being response to the policy. While individuals in the Medium group show no statistically significant change in life satisfaction, residents in the Low income group experience a sharp and significant decline following the 2021 and 2023 expansion.

[17] As a reminder, the scrappage scheme helped 53,000 households between 2019 and 2024. Households could receive £2,000 for scrapping their old, polluting car.

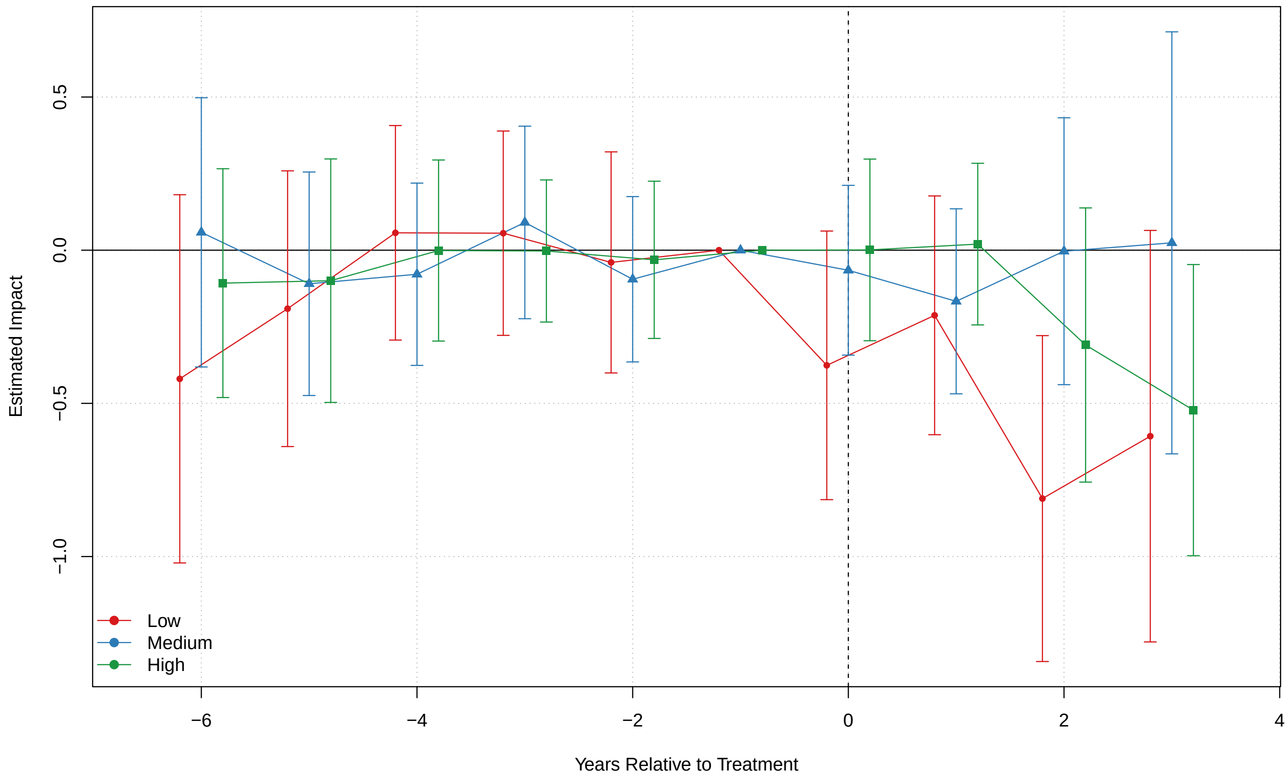


Figure 12: Life satisfaction event-study, by household income

The empirical results reveal a stark socio-economic gradient in the welfare response to the ULEZ expansions. Specifically, by 2023, the decline in life satisfaction for individuals in the lowest income tertile reaches a magnitude of approximately 0.8 points: the most substantial negative estimate identified in this study. This suggests that the policy's adverse effects are non-linearly distributed, with the most severe well-being losses concentrated among households with the tightest budget constraints.

Interestingly, this effect is predominantly observed among low-income residents within the 2021 expansion zone (Appendix 17). A plausible mechanism is that these individuals are more prominently working or traveling to the 2023 ULEZ area and were more severely impacted by indirect effects of the second expansion. This pattern underscores that the short run welfare costs of the ULEZ are disproportionately borne by the most economically vulnerable segments of the population.

Low-income households might face a "double burden": they must choose between the direct financial hardship of the daily fee and the utility loss associated with forced car-divestment. In many cases, the latter requires a transition to public transport modes that may offer lower levels of convenience or longer commuting times in peripheral areas. These findings are consistent with the literature on the regressive nature of flat-rate environmental taxes (Douenne and Fabre 2022) and suggest that the scrappage scheme was not able to totally offset this heteregeneous effect.

While the Mayor of London increased the scrappage scheme funding from £160 million in August 2023 to £210 million in February 2024 to mitigate the regressive nature of the policy (London-wide ULEZ Six Month Report), its effectiveness in preserving the welfare of the poorest households appears limited . The flat-rate grant of £2,000 may not have fully covered the replacement cost of a compliant vehicle in a period of high second-hand car inflation. Our findings of a persistent decline in life satisfaction among low-income individuals suggest that compensatory transfers, unless calibrated to the full replacement value or accompanied by more robust public transport subsidies, may be insufficient to offset the utility loss caused by the policy.

Surprisingly, we also find a negative and statistically significant effect on life satisfaction in the High income group for the last period of our analysis. This result suggests that even households with the financial capacity to comply with the regulation—either by paying the charge or upgrading their vehicles—are not immune to the broader systemic changes induced by the ULEZ expansion. One compelling explanation for this late-stage decline lies in the deterioration of substitute goods, specifically public transport quality. This finding coincides with a similar drop in well-being observed among individuals without cars (Figure 11), who potentially suffer from increased congestion within the transit network as former motorists shift their commuting modes. For high-income individuals, the welfare loss may therefore stem from a "second-order" effect: as the policy successfully pushes a massive volume of commuters toward the London Underground and bus networks, the resulting overcrowding and reduced service reliability may offset the benefits of living in a regulated zone.

6 Robustness Checks

6.1 Callaway and Sant'Anna Estimator

As a robustness check, we re-estimate the dynamic effects of the ULEZ using the group-time average treatment effects estimator proposed by Callaway and Sant'Anna 2021, which allows for heterogeneous treatment effects across cohorts and relies on explicit comparisons between treated and not-yet-treated units.

Figure 13 reports the cohort-specific dynamic effects for individuals first exposed to the policy in 2021 and 2023. For the 2021 cohort, the estimates show no evidence of differential pre-treatment trends, as all pre-policy coefficients are statistically indistinguishable from zero. Following the implementation of the ULEZ, we observe a gradual decline in life satisfaction, which becomes more pronounced in later post-treatment periods, particularly in 2023 and 2024. This dynamic pattern closely mirrors the results obtained using the Sun and Abraham estimator.

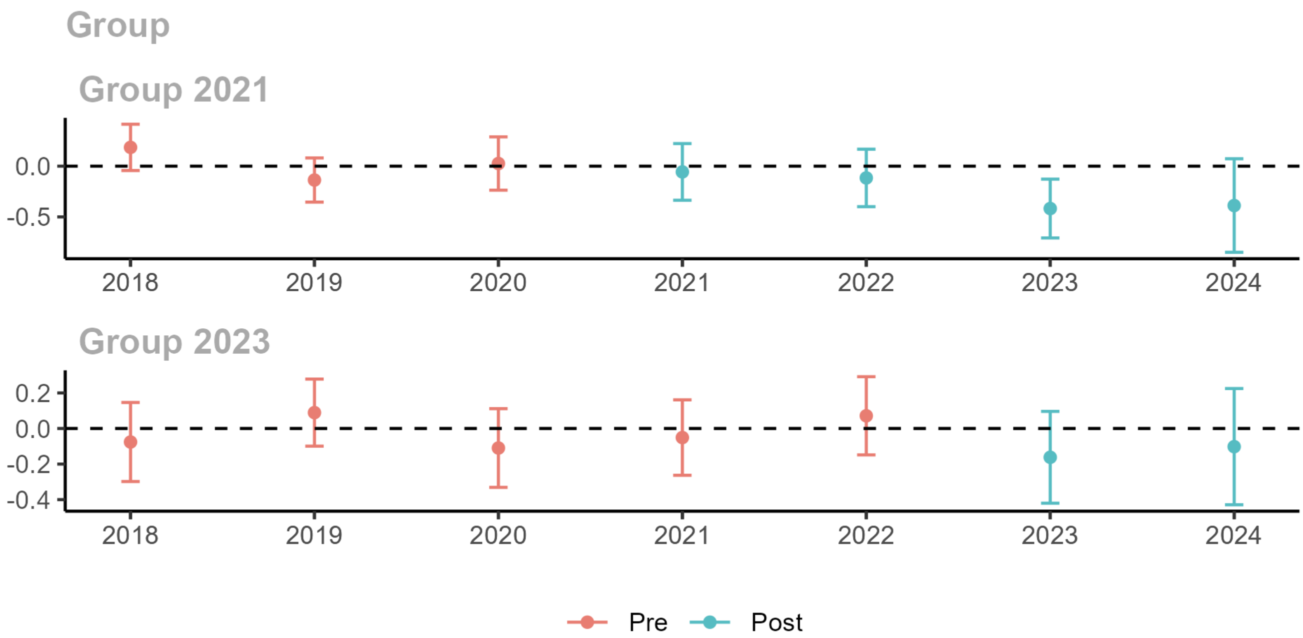


Figure 13: Staggered Difference-in-differences, Callaway and Sant'Anna estimator

For the 2023 cohort, the estimated effects remain imprecisely estimated and statistically insignificant throughout the post-treatment window. Given the very limited number of post-policy observations available for this group, this lack of precision is expected and should not be interpreted as evidence of the absence of an effect.

Overall, the Callaway and Sant'Anna estimates confirm the main findings of the paper: the negative impact of the ULEZ on life satisfaction is concentrated among individuals exposed to the 2021 expansion and emerges progressively after implementation, with no evidence of pre-treatment effects.

6.2 Anticipation and Placebo

To assess the validity of the parallel trends assumption and to rule out anticipation effects, we conduct Wald tests of the joint nullity of all pre-treatment coefficients in the Sun and Abraham event-study specification. Specifically, we test whether the coefficients associated with all leads of the treatment indicator (relative time $k \leq -2$) are jointly equal to zero for each treated cohort.

For the 2021 cohort, the null hypothesis of no pre-treatment effects cannot be rejected (Wald statistic = 0.74, p-value = 0.53), indicating the absence of differential pre-trends in life satisfaction prior to the policy implementation. For the 2023 cohort, the joint test also fails to reject the null at conventional significance levels (Wald statistic = 1.86, p-value = 0.097). Overall, these results provide no evidence of anticipatory effects on subjective well-being.

Importantly, this finding contrasts with the presence of anticipatory adjustments in commuting behaviour, suggesting that individuals may adjust observable behaviours in advance of the policy without experiencing a contemporaneous decline in life satisfaction. Together with the graphical evidence, these tests support the credibility of the identifying assumptions underlying our staggered difference-in-differences design.

We also conduct a placebo exercise in which the treatment date of the 2021 ULEZ expansion is artificially shifted one year earlier, to 2020. Individuals belonging to the 2023 cohort are recoded as never treated and therefore serve as additional controls. We then re-estimate the Sun and Abraham interaction-weighted event-study specification using this placebo treatment timing.

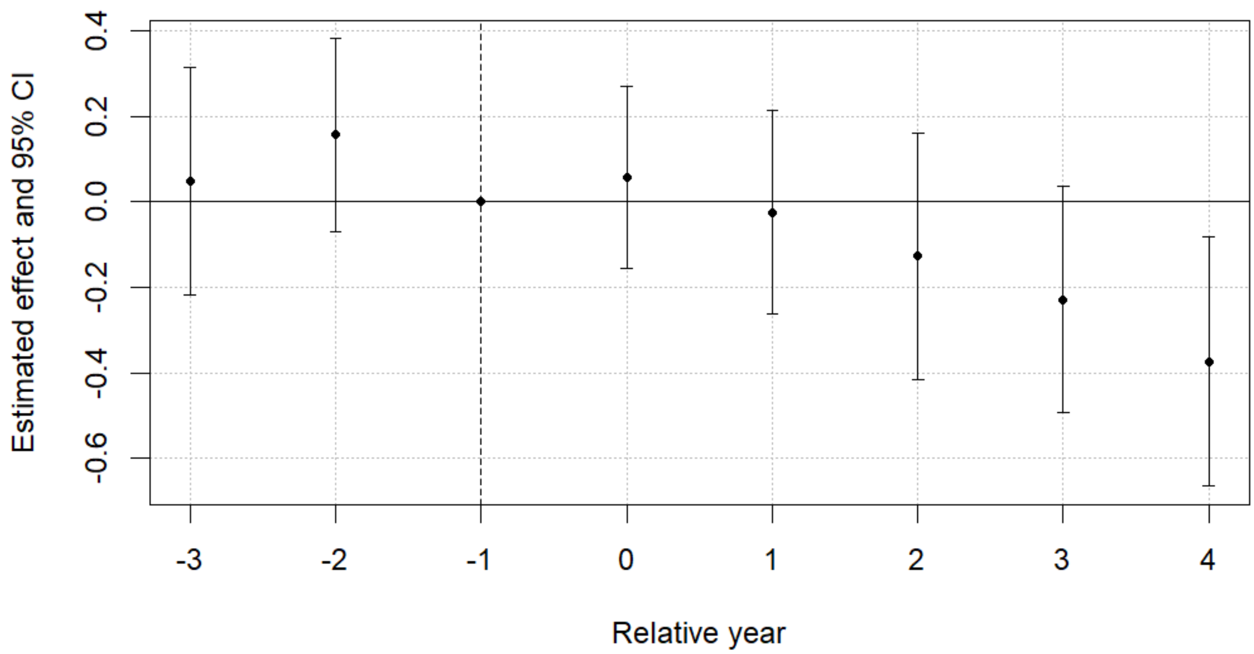


Figure 14: Placebo test: shifting 2021 cohort to 2020 and 2023 as never treated

Figure 14 shows no statistically significant effect around the placebo treatment date, and no systematic deviation from zero in the immediate post-treatment periods. This absence of a spurious treatment effect supports the validity of our identification strategy and suggests that the negative effects observed after the actual 2021 ULEZ implementation are not driven by pre-existing differential trends or model artefacts. While some imprecise estimates appear at longer horizons, these occur several years after the placebo intervention and are likely driven by noise or contamination from the true policy implementation. Overall, the placebo test strengthens confidence in the causal interpretation of our main results.

6.3 Alternative Control Group

As a final robustness check, we modify the composition of the control group by including all individuals living in urban areas outside the ULEZ, rather than restricting the comparison group to large English metropolitan areas as we previously did. This broader definition allows for greater heterogeneity in urban contexts and provides a stringent test of the sensitivity of our results to the choice of control group.

Figure 15 reports the corresponding event-study estimates using the Sun and Abraham estimator. Pre-treatment coefficients remain statistically indistinguishable from zero, indicating no evidence of differential pre-trends. Post-treatment effects display a small and gradual decline in life satisfaction following the 2021 ULEZ expansion, consistent with the baseline specification.

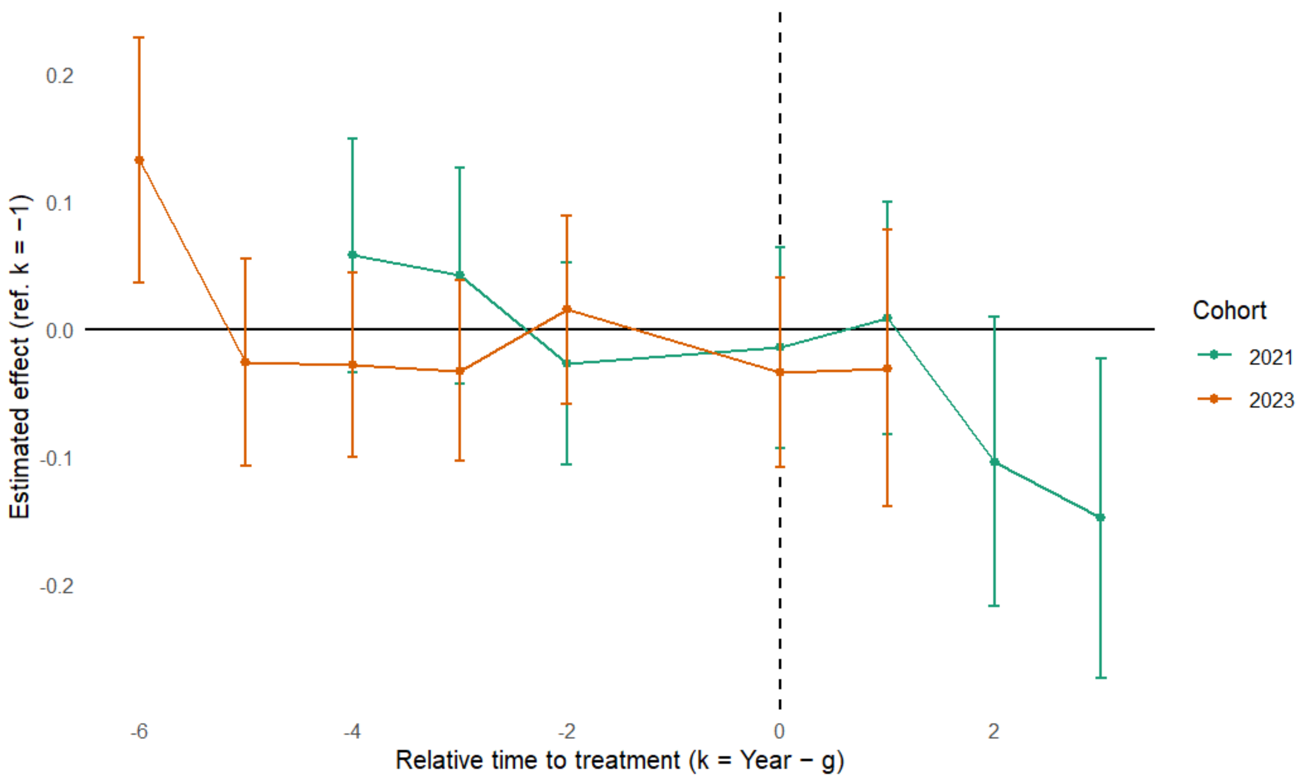


Figure 15: Staggered DiD - Extended Controls

Table 4 further reports results from the TWFE model estimated on the same sample (with individuals living in the 2019 and 2023 ULEZ area being excluded). The interaction term between ULEZ exposure and the post-2021 period remains negative and statistically significant, with a smaller magnitude to our main estimates. Taken together, these findings suggest that our results are not driven by the specific selection of comparison cities and remain robust when the control group is expanded to include a broader set of urban areas.

Dependent Variable:	Life Satisfaction
Model:	(1)
Variables	
In ULEZ 2021 × Post 2021	-0.0796**
	(0.0391)
In ULEZ 2021	-0.0512
	(0.0891)
Post 2021	0.0112
	(0.0244)
Car owner	0.0579**
	(0.0269)
Fixed-effects	
Individual	Yes
Year	Yes
Fit statistics	
Observations	138,182
R^2	0.59609
Within R^2	0.00058

Clustered (psu & strata) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 4: Difference-in-Differences TWFE ULEZ 2021, extended controls

7 Discussion

This paper provides new evidence on the short-run well-being effects of urban Low-Emission Zones by examining the 2021 and 2023 extensions of London's Ultra Low Emission Zone. Using longitudinal data and staggered difference-in-differences estimators that allow for heterogeneous treatment effects, we document a modest but robust decline in life satisfaction, between 0.2 to 0.4 points in a 1-7 scale, among residents directly exposed to the policy.

These effects should be interpreted as short-run, net impacts of the policy, conditional on contemporaneous changes in environmental conditions and individual characteristics. The absence of positive effects on subjective health does not imply that such benefits do not exist, but rather that they may materialize over longer horizons or remain imperfectly perceived in the short run. The estimates are in a similar range, even though they are slightly larger than the results in Sarmiento, Wägner, and Zaklan (2023) who find a general decline in life satisfaction between 0.13 and 0.2 points in a 1-10 scale[18]. This may be because we chose to construct a control group from

[18] As a comparison, in their seminal paper Clark and Oswald 1994 showed that the loss in well-being due to being unemployed was close to 0.8 points.

people living in large cities in England, whereas Sarmiento et al. restricted the control group to individuals living more than 25 km from LEZs. When we extend our control group to include all individuals living outside the London region, our estimates align more closely with those of Sarmiento et al.

A second key finding is that the negative effect of the ULEZ manifests primarily through life satisfaction and hedonic happiness, while no significant impact is detected on self-reported health. In addition, we show that the policy successfully altered commuting behaviour among workers, by increasing reliance on public transport.

Finally, cohort-specific and subgroup analyses reveal substantial heterogeneity in the timing and distribution of SWB impacts. The negative effects are concentrated among individuals first exposed in 2021 when the 2023 extension is implemented and differ across car ownership status commuting modes, income levels and public transport accessibility near households' home, pointing to unequal exposure to the short-run costs of the policy.

The negative impact of the 2021 ULEZ extension on life satisfaction raises the question of the underlying mechanisms through which low-emission zones affect subjective well-being in the short run. While the primary objective of such policies is to improve environmental conditions and public health, their immediate effects may operate through a distinct set of channels that are more salient to individuals' daily lives.

First, the introduction of stricter vehicle regulations entails direct adjustment costs for residents living within the regulated area. These costs may include financial constraints related to vehicle compliance or replacement, reduced flexibility in mobility choices, and increased planning or uncertainty associated with daily travel. Such costs are likely to be particularly salient in the short run, before households have had sufficient time to fully adapt their behaviour or capital stock. We show that life satisfaction decline is larger among low income individuals than the others, thus supporting this hypothesis.

Second, the policy may generate indirect costs through changes in urban mobility patterns. Our results show a significant increase in public transport usage among workers. While consistent with the environmental objectives of the ULEZ, this modal shift may also lead to congestion, crowding, or longer travel times, especially in areas where public transport capacity is limited. Our analysis shows that individuals with lower access to public transport experience a greater life satisfaction decline. These indirect effects are not necessarily captured by observed commuting mode indicators alone, but may nevertheless affect SWB through increased stress or reduced perceived control over daily routines.

Third, the timing of costs and benefits is likely to be misaligned. Improvements in air quality and related health benefits may take time to materialize and to be perceived by individuals, whereas regulatory constraints and behavioural adjustments are immediate. In this context, short-run declines in life satisfaction may coexist with longer-run well-being gains that are not yet observable within the available time window. This temporal mismatch is a central challenge for the evaluation and social acceptance of environmental policies.

Finally, the heterogeneity in well-being responses across population subgroups suggests that these adjustment costs are unevenly distributed. In particular, the negative effects observed among individuals without access to private vehicles, with low income, and living in an area with low public transport density point to the importance of mobility constraints and spatial inequalities in shaping the perceived well-being consequences of the policy. Together, these mechanisms highlight that the short-run well-being costs of low-emission zones should not be interpreted as evidence against their long-term desirability, but rather as an indication of the transitional frictions associated with their implementation.

8 Conclusion

This paper provides new evidence on the short-run subjective well-being effects of urban low-emission zones, focusing on the 2021 and 2023 extensions of London's ULEZ. Using longitudinal data and recent staggered difference-in-differences estimators, we show that the policy led to a modest but robust decline in life satisfaction among affected residents, particularly among workers and specific subgroups facing mobility constraints. At the same time, we document substantial changes in commuting behaviour, with a shift away from private motorized transport toward public transport.

These findings highlight an important tension in the evaluation of environmental policies. While low-emission zones are effective at modifying behaviour and are likely to generate environmental and health benefits in the longer run, they may entail short-term welfare costs that are unevenly distributed across the population. Such costs are not necessarily captured by standard economic or environmental indicators, but are nevertheless relevant for policy acceptability and public support.

More broadly, our results underscore the importance of incorporating subjective well-being measures into the assessment of climate and environmental policies. Evaluations that focus exclusively on emissions or health outcomes may overlook transitional frictions and distributional effects that shape individuals' lived experiences. From a policy perspective, these findings suggest that accompanying measures—such as improvements in public transport capacity, targeted compensation, or gradual implementation—may play a crucial role in mitigating short-run well-being losses and enhancing the social sustainability of low-emission zones.

Future research should investigate the longer-term evolution of well-being effects as households adapt and environmental benefits become more salient, as well as the interaction between environmental regulation, mobility infrastructure, and social inequality in urban contexts.

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9 Appendix

9.1 Outcome variations

Dependent Variables:	General Happiness	Health Satisfaction	Feeling Depressed
Model:	(1)	(2)	(3)
Variables			
In ULEZ 2021 × Post 2021	-0.1240**	-0.1444	0.1770**
	(0.0527)	(0.1027)	(0.0834)
In ULEZ 2021	-0.1041	-0.4753	0.1501
	(0.2842)	(0.5786)	(0.3108)
Post 2021	0.1247**	0.3210**	-0.2274**
	(0.0612)	(0.1587)	(0.1147)
log(PM10)	0.3307	3.273**	-1.165
	(0.6109)	(1.358)	(1.091)
log(PM2.5)	-0.2196	-3.033**	0.9338
	(0.5350)	(1.209)	(0.9234)
log(NO2)	0.3446*	-0.3318	0.0597
	(0.1844)	(0.6047)	(0.3905)
Number of cars	-0.0195	0.0174	-0.0063
	(0.0343)	(0.0525)	(0.0396)
Fixed-effects			
pidp	Yes	Yes	Yes
Year	Yes	Yes	Yes
Fit statistics			
Observations	7,211	7,220	7,208
R^2	0.41534	0.56170	0.57178
Within R^2	0.00941	0.00533	0.00810

Clustered (psu & strata) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 5: Difference-in-Differences TWFE ULEZ 2021

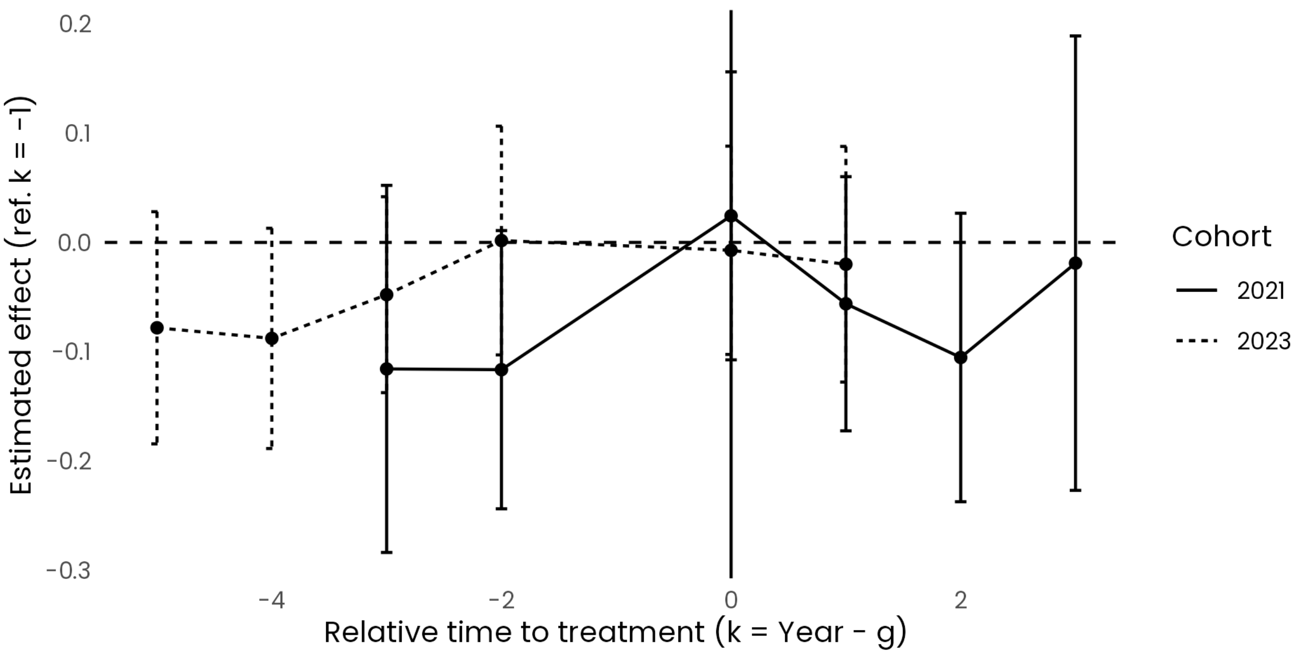

Figure 16: Staggered Difference-in-Differences: effect on Active Mobility

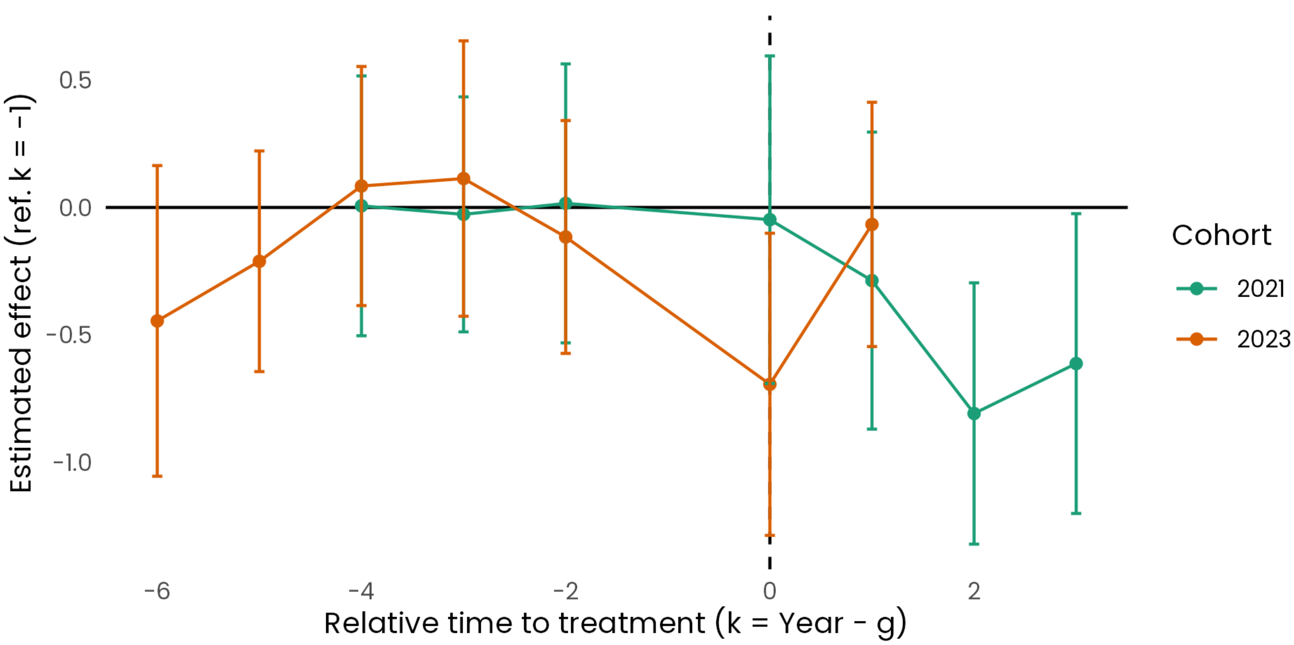

Figure 17: Income heterogeneity: Low income

9.2 Controls LSOA Map

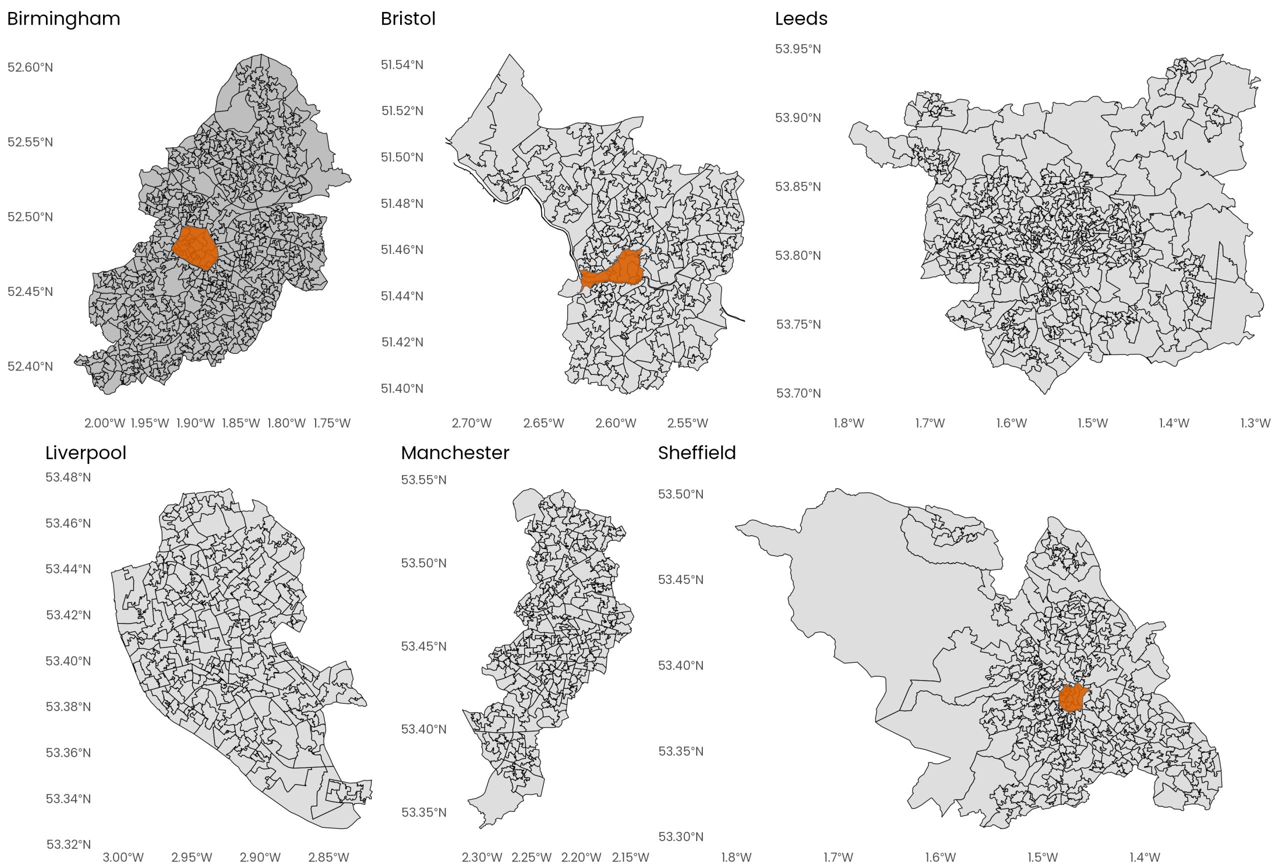

Figure 18: Control Cities by LSOA

Notes: Orange areas indicate CAZs located in control cities.