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"And Breathe Normally": The Low Emission Zone impacts on health and well-being in England.

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“And Breathe Normally”: The Low Emission Zone impacts on health and well-being in England.

Habtamu Ali Beshir* Eleonora Fichera†

Abstract

Air pollution is a global concern for its negative externalities on the climate, but also on the healthcare sector and human capital accumulation. Yet, there is scant evidence on the effectiveness of clean air transport policies. In this study we investigate the effects of London's Low Emission Zone (LEZ) and Ultra-Low Emission Zone (ULEZ) on health and well-being. We exploit the temporal and spatial variation of these policies, implemented in Greater London (LEZ) and Central London (ULEZ) in 2008 and 2019, respectively. Using a difference-in-differences approach and linked survey and administrative data, we find LEZ has significantly reduced PM_{10} by 12% of the baseline mean and ULEZ has reduced both NO_2 by 12.4% and PM_{10} by 27%. We also show improvements in health with LEZ reducing limiting health problems by 7%, COPD by 14.5% and sick leave by 17%; and ULEZ reducing number of health conditions by 22.5%, anxiety by 6.5%, and sick leave by 18%. A back of the envelope cost-benefit analysis indicates savings for £963.7M for the overall population.

Keywords: Air Pollution; Well-being, Low Emission Zones.

JEL Classification: I25; J1; O12

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1 Introduction

Air pollution is a key contributor to climate change, the most urgent global concern (UNEP, 2019). The Inter-governmental Panel on Climate Change (IPCC) 2018 report (Inter-governmental Panel on Climate Change, 2018) and the 2021 COP26 both highlight the importance of maintaining global temperature rises within 1.5C, with a number of actions including reduction of pollutants. In addition to its impact on climate change, air pollution imposes other negative externalities: i) on the healthcare sector contributing to cardiovascular diseases, lung cancer and respiratory diseases, affecting hospital admissions and mortality; and ii) on the wider economy by reducing job productivity and hindering human capital accumulation. In December 2020, Southwark Coroner's Court found that air pollution "made a material contribution" to the death of Ella Kissi-Debrah, a black girl from South London. Although this is the first time that air pollution has been included in the death certificate, evidence on its causal impact on health is still mounting.

This paper investigates the health and well-being effects of one of the largest traffic pollution policies in Europe, the Greater London's Low Emission Zone (LEZ) and the toughest one in the world, the Ultra Low Emission Zone (ULEZ in Central London). Our identification strategy exploits a quasi-experiment. We use the fact that LEZ and ULEZ were not introduced in all English cities at once. There is temporal and spatial variation as LEZ was introduced on the 4^{th} of February 2008 in Greater London and ULEZ was introduced on 8^{th} of April 2019 in Central London. Exploiting the temporal and spatial variation in the introduction of LEZ and ULEZ, we use a difference-in-differences methodology where we compare exposed areas in Greater London and Central London to comparable unexposed areas in England before and after the introduction of the policies.

We make three main contributions to the literature. Firstly, our study is the first to evaluate the effectiveness of both LEZ and ULEZ on air pollution and health. Previous studies have investigated the impacts of London's LEZ on air pollution and vehicle fleet composition (Ellison et al., 2013) and air quality and children's health (Mudway et al., 2019). However, both studies have used a before and after comparison, limiting causal inference. Our difference-in-differences methodology compares exposed areas in Greater and Central London to other unexposed cities in England before and after the introduction of LEZ and ULEZ. As an initial step, we evaluate the effectiveness of Greater London's LEZ and Central London's ULEZ and find significant reductions in particulate matter (PM_{10}) and nitrogen dioxide (NO_2). Then, we assess the effects of these policies on health and well-being and find decreases in long-term health conditions, heart related diseases, and chronic obstructive pulmonary disease (COPD) and improvements in well-being.

Secondly, using rich survey and linked administrative data, we are able to control for a number of individual and area-level characteristics that can impact both air pollution and health. Most studies examining the relationship between air pollution and health have used large administrative, often hospital data (Janke, 2014; Neidell, 2009; Moretti and Neidell, 2011; Schlenker and Walker, 2016; Holub et al., 2020; Coneus and Spiess, 2012; Beatty and Shimshack, 2014). Whilst there are clear advantages in these data in terms of its frequency and sample size, they do not contain rich information on the socioeconomic characteristics of individuals. This is one of the key elements in the question of causality as exposure to pollution is endogenously determined by individual choices, often correlated with their socioeconomic background. A study by Coneus and Spiess (2012) has used the German Socio-Economic Panel (GSOEP) survey, a longitudinal dataset containing rich information on employment, income as well as health, but it has only focused on the child health effects of air pollution.

Finally, we investigate the effect of ULEZ on well-being. There is not much evidence on the impact of air pollution on less tangible health outcomes (Zhang et al., 2017; Li et al., 2021). For instance, Zhang et al. (2017) have explored the impact of air pollution on three measures of mental health and subjective well-being: life satisfaction, the Center for Epidemiologic Studies Depression scale (CES-D) and a self-reported measure of happiness. Li et al. (2021) have investigated non-cognitive effects of air pollution using a longitudinal survey in China. They have used psychological distress, self-satisfaction, self-esteem, happiness and confidence in the future as noncognitive trait measures. However, the identification strategy of both studies only relies on the assumption that all potential omitted confounders are time-invariant.

Air pollution is at the forefront of policy debates in the European Union (EU) and the United Kingdom (UK). With its Eighth Environment Action Programme for the period 2021-2030, the EU aims to reduce exposure to air pollution by reducing emissions and by setting target values for air quality. The U.K. 2019 Clean Air Strategy (Department for Environment Food and Rural Affairs, 2019) outlines the legally-binding targets to reduce air pollutants by 2020 and 2030 and strategies to achieve these targets in a number of sectors, including transport. One of the motivations for this interest is that air quality is the largest environmental health risk in the U.K.

Car exhaust is a major source of ambient air pollution in urban areas (Schwandt and Alexander, 2019; Currie and Walker, 2011). This is evident from variation in air pollution when traffic is disrupted in cities (Bauernschuster et al., 2017; He et al., 2019). Different policies have been adopted in many cities (countries) to curb air pollution in their jurisdiction. Examples include: congestion pricing in Stockholm and London (Simeonova et al., 2019; Green et al., 2020), and license plate based restrictions in Mexico City and Beijing (Davis, 2008; Viard and Fu, 2015). The most popular policy, especially in Europe, is the Low Emission Zone scheme (Wolff and Perry, 2010; Wolff, 2014).

Many epidemiological studies relate particulate air pollution to respiratory and cardiovascular symptoms, hospitalizations, and mortality (Pope III, 2000; Pope III and Dockery, 2006). However, as these studies do not account for selection into pollution and avoidance behaviour, it is hard to draw any causal inference (Graff Zivin and Neidell, 2013; Janke, 2014; Neidell, 2009).

Using quasi-experimental methods and accounting for avoidance behaviour, economists have contributed to the literature by estimating the causal effect of air pollution on health and mortality (Janke, 2014; Neidell, 2009; Moretti and Neidell, 2011; Schlenker and Walker, 2016; Holub et al., 2020; Coneus and Spiess, 2012; Beatty and Shimshack, 2014). For instance, Deryugina et al. (2019) have provided causal evidence that air pollution, acute fine particulate matter in particular, increases mortality rate of elderly people in USA and Currie and Neidell (2005) have found that a reduction in carbon monoxide in 1990s saved many infant lives in California. Some of these studies have also explored the effect of air pollution on human capital and cognition, labour productivity and mental health/well-being outcomes (Zhang et al., 2017; Li et al., 2021; Graff Zivin and Neidell, 2012). For instance, Graff Zivin and Neidell (2012) and Chang et al. (2016) have documented the link between air pollution and workers productivity.

The remainder of the paper is organized as follows. The next section summarises the existing literature. Section 3 describes the policies evaluated in this paper. Section 4 is about our data. Section 5 explains our empirical strategies and in Section 6 we provide our results. Section 7 is for discussing our cost benefit analysis. Finally, we conclude in Section 8.

2 Existing literature

Our study relates to three strands of the literature. Firstly, there are studies examining the impact of air pollution on physical and mental health. Epidemiological studies on this question tend to focus only on modelling trends and seasonal cycles. These studies have found associations between air pollution and a number of health outcomes such as exacerbation and onset of diabetes (Anderson et al., 2012; Brook, 2008; Eze, 2014; Chen, 2013), 30 day mortality by cardio-respiratory problems (Pope and Ezzati, 2009), cancer (Turner, 2020; Cohen, 2000) and stroke (Shah, 2015; Lee, 2018) , respiratory diseases (Liu, 2013; de Leon, 1996), central nervous system (CNS) (Badadjouni, 2017), Quality Adjusted Life Years (QALYs) and Disability Adjusted Life Years (DALYs) (Coyle, 2011; Adamkiewicz, 2014), cardiovascular diseases (CVDs) (Franklin et al., 2015), mental health and subjective wellbeing (SWB) (Zhang et al., 2017), neonatal health outcomes and allergies (Lacasana M., 2005; Nordling, 2008). All in all, these studies have found deterioration of health outcomes: exposure to an increase of $10\mu g/m^3$ for a 2-day averaged $PM_{2.5}$ is associated with a 1.76% increase in stroke incidence as well as a 1.18% increase in all cause mortality. An increase of $2.97\mu g/m^3$ in NO_2 is associated with a 9% increase in the onset of Parkinson's Disease. A meta analysis of studies in North America and Europe has found an increase of 8% in the risk for lung cancer incidence or mortality per $10\mu g/m^3$, with more mixed results for other types of cancers (Turner, 2020). There is a 41% increase in acute asthma exacerbations per $10\mu g/m^3$ increases in PM_{10} (Anderson et al., 2012).

These studies however do not account for behavioural responses, where selection into pollution generates endogeneity in the relationship between pollution exposure and health. Economists have tried to address it in a number of ways, either by means of rich individual and area level characteristics, by using natural experiments or instrumental variables, or by exploiting within-area changes in air pollution with fixed-effects approaches (Janke, 2014; Neidell, 2009; Moretti and Neidell, 2011; Schlenker and Walker, 2016; Holub et al., 2020; Coneus and Spiess, 2012; Beatty and Shimshack, 2014). For instance, Janke (2014) has used hospital and air pollution data in England to explore the impact of pollutants on admissions, by controlling for air pollution warnings. She has found an 8% reduction in admissions that is not affected by the exclusion of pollution warnings. In contrast, Neidell (2009) has found that ignoring smog alerts at the Los Angeles zoo underestimates the O_3 impact on admissions by more than 60%. Moretti and Neidell (2011) have used the California Hospital Discharge Data and an instrumental variable approach where exposure to ozone is determined by boat traffic in the port, to examine the short-term impact of pollution on respiratory emergency admissions. After controlling for a number of weather factors, they have found that a five-day increase of 0.01 parts per million (ppm) in ozone leads to a 4.7 percent increase in hospitalisations. Using Hospital Episodes Statistics (HES) and pollution and weather data, Beatty and Shimshack (2014) have explored the impact of pollutants on children respiratory treatments with a Middle Layer Super Output Area (MSOA) fixed effect approach. They have found that a 10 percent increase in a month's CO pollution increases the probability of respiratory treatment for a child by 2.1-2.2 percent. Whilst O_3 impacts are of similar magnitude, PM_{10} effects are not statistically significant.

Medical and epidemiological research have highlighted the biological pathways linking health to pollution: air pollution and specifically PM exposure (often considered the most lethal pollutant, Wolff (2014)) is related to markers of systemic inflammation such as cytokines IL-6, TNF-$\acute{\alpha}$, and C-reactive protein (CRP) which in turn have been associated with the onset of acute myocardial infarction (Anderson et al., 2012). Exposure to PM triggers changes in coagulation and platelet activation, constituting risk factors for cardiovascular diseases. PM also leads to pulmonary oxidative stress and inflammation and generates reactive oxygen species (ROS) that can cause pulmonary damage even in the short run. NO_2 results in nose and throat irritation, and increases sensitivity to respiratory infections (Pestel and Wozny, 2021).

There is surprisingly little evidence on the effect of air pollution on less tangible health outcomes such as mental health, well-being and non-cognitive skills (Zhang et al., 2017; Li et al., 2021). Yet, medical research has shown that air pollution and PM are sources of neuroinflammation (Calderon-Garciduenas, 2011) which, together with ROS, is related to the onset of CNS diseases, enhancing the progression of neurodegenerative disorders such as Alzheimer's and Parkinson's diseases, and also atherosclerosis (Badadjouni, 2017). As there is evidence of white matter injury, air pollution can also induce structural brain effects (Badadjouni, 2017). These biological mechanisms can impact the prefrontal cortex, which delivers executive functions such as personality and emotion (Buoli, 2018; Borghans et al., 2008). A recent study by Zhang et al. (2017) has used three measures of mental health and subjective well-being: life satisfaction, the Center for Epidemiologic Studies Depression scale (CES-D) and a self-reported measure of happiness. Using matched longitudinal survey, air quality and weather data, the authors have found that hazardous air pollution[1] is associated with a 0.323 points increase in hedonic unhappiness (equivalent to 12.92% of the sample mean), 1.378 in mental well-being (i.e. CES-D from 0-24), equivalent to 48.5% of the sample mean, and 0.199 in depressive symptoms (i.e. CES-D score greater than four), equivalent to 63.7% of the sample mean. Air pollution has also been found to be associated with gloominess and irritation with mild headaches (Chang and Gross, 2014; Chang et al., 2016), psychiatric distress (Rotton and Frey, 1984), depressive symptoms (Szyszkowicz, 2007), and eye irritations (Nattero and Enrico, 1996). Li et al. (2021) have investigated non-cognitive effects of air pollution using a sample of adolescents in the China Family Panel Studies (2012-2014). They have found that an increase in mean API of 15 points would increase psychological distress by 0.15 points (equivalent to 5.5% of the sample mean), and decrease self-esteem by 0.20 points (equivalent to 0.9% of the sample mean). However, the identification strategy of these studies only relies on the assumption that all potential omitted confounders are time-invariant.

Secondly, there are studies examining the impact of transport policies on air quality and health. As car exhaust has been identified as the major source of urban air pollution (Schwandt and Alexander, 2019; Currie and Walker, 2011), different policies have been adopted to tackle this problem such as congestion pricing in Stockholm and London (Simeonova et al., 2019; Green et al., 2020), license plate based restrictions in Mexico City and Beijing (Davis, 2008; Viard and Fu, 2015), and Low Emission Zone (LEZ) schemes, popular in Europe (Pestel and Wozny, 2021; Wolff and Perry, 2010; Ellison et al., 2013; Wolff, 2014; Margaryan, 2021).

Congestion Pricing Zones (CPZ) have been effective at reducing air pollution and improving health. Using geo-referenced inpatient and outpatient hospital data, Simeonova et al. (2019) have found that CPZ in Stockholm had reduced NO_2 and PM_{10} levels by 15-20 and 10-15 percent, respectively. They have also found reductions in hospital visits for acute asthma attacks among children aged 0-5. Green et al. (2020) have investigated the impact of the London Congestion Charge (CCZ) using different administrative datasets such as traffic, weather and pollution data at the Local Authority level. They have found that CCZ have led to reductions in CO and PM_{10} by about 20% of the sample mean. However, NO_2 increased because it is

[1] The authors have defined an Air Pollution Index (API), with API$>$ 301 indicating "hazardous" air quality according to the U.S. Environmental Protection Agency (EPA).

linked to diesel powered vehicles that were exempt from CCZ such as buses and taxis.

Studies looking at the effectiveness of license plate restriction policies in Mexico City and Beijing (Davis, 2008; Viard and Fu, 2015) have not found evidence of air quality improvements. Instead, evidence from vehicle registrations and automobile sales indicates that the programs have led to an increase in the total number of vehicles in circulation as well as a change in the composition of vehicles toward taxis and used, and thus higher-emitting, vehicles.

LEZ policies have been introduced in many cities in Europe (Pestel and Wozny, 2021; Wolff and Perry, 2010; Ellison et al., 2013; Wolff, 2014; Margaryan, 2021; Gehrsitz, 2017). For instance, several German cities have adopted LEZ since 2007. Pestel and Wozny (2021) have investigated the health effects of the German LEZ focusing on PM_{10} and NO_2, the two main pollutants generated by traffic. Using air monitoring measurements and the universe of German hospital quality reports, they have found that LEZ has decreased the total annual number of days with PM_{10} levels above the regulatory threshold of $50\mu g/m^3$ by 7.7 days, equivalent to 50% of the sample mean. They have also found a decrease of about 25 percent of the sample mean of yearly mean NO_2 levels above $40\mu g/m^3$. In terms of health effects, they have found that LEZ reduces the total number of diagnosed diseases by about 1.4 percent, and diseases of the circulatory system by 2.9 percent. Unlike the previous study, Margaryan (2021) have been able to identify the patient location using individual-level hospital admission data giving more precise estimates of the treatment effects. They have found a reduction of 7-13 percent of cerebrovascular diseases for the overall population and in the over 65s. However, they have not found statistically significant impacts on other health outcomes such as diabetes and other chronic respiratory illnesses potentially because Germany has implemented disease management programmes for these outcomes. Ellison et al. (2013) is one of the two studies examining Greater London's LEZ, but it has only used a before and after analysis finding modest reductions in PM_{10}. Using registered vehicles data from the Driver and Vehicle Licensing Agency (DVLA) in the UK and the Transport for London's data on penalty charge notices, together with pollution data readings at Greater London's monitoring stations from 2001 to 2011, they have found the mean concentrations of PM_{10} to have reduced by 13% and NO_x by 0.5-1.5%.

Most of these studies have used quasi-experimental methods such as difference-in-differences, and have estimated the impact of policies first on pollution and then on health outcomes. Some of them have examined the mechanisms underlying the effectiveness of these policies, including changes in the number and composition of the car fleet Margaryan (2021); Green et al. (2020); Ellison et al. (2013). Margaryan (2021) have found that the share of Euro 1 cars has dropped from 20% in 2007 to 2% in 2017, with an increase in the share of Euro 4 cars from 40% to 80%. Ellison et al. (2013) have also found a change in the fleet composition with a decline of Pre-Euro III vehicles from 51.4% in 2006 to 46.2% at the end of 2007. In London there has been an increase in the replacement rate of Large Commercial Vehicles (LCVs) in anticipation of the changes at the end of 2011. Mudway et al. (2019) have also examined LEZ in London by focusing on its children health impacts. Using a cross-sectional survey of over 2,000 children, they have found a reduction in the number of children living where NO_2 limit values were greater than the EU annual limit of $40\mu g/m^3$.

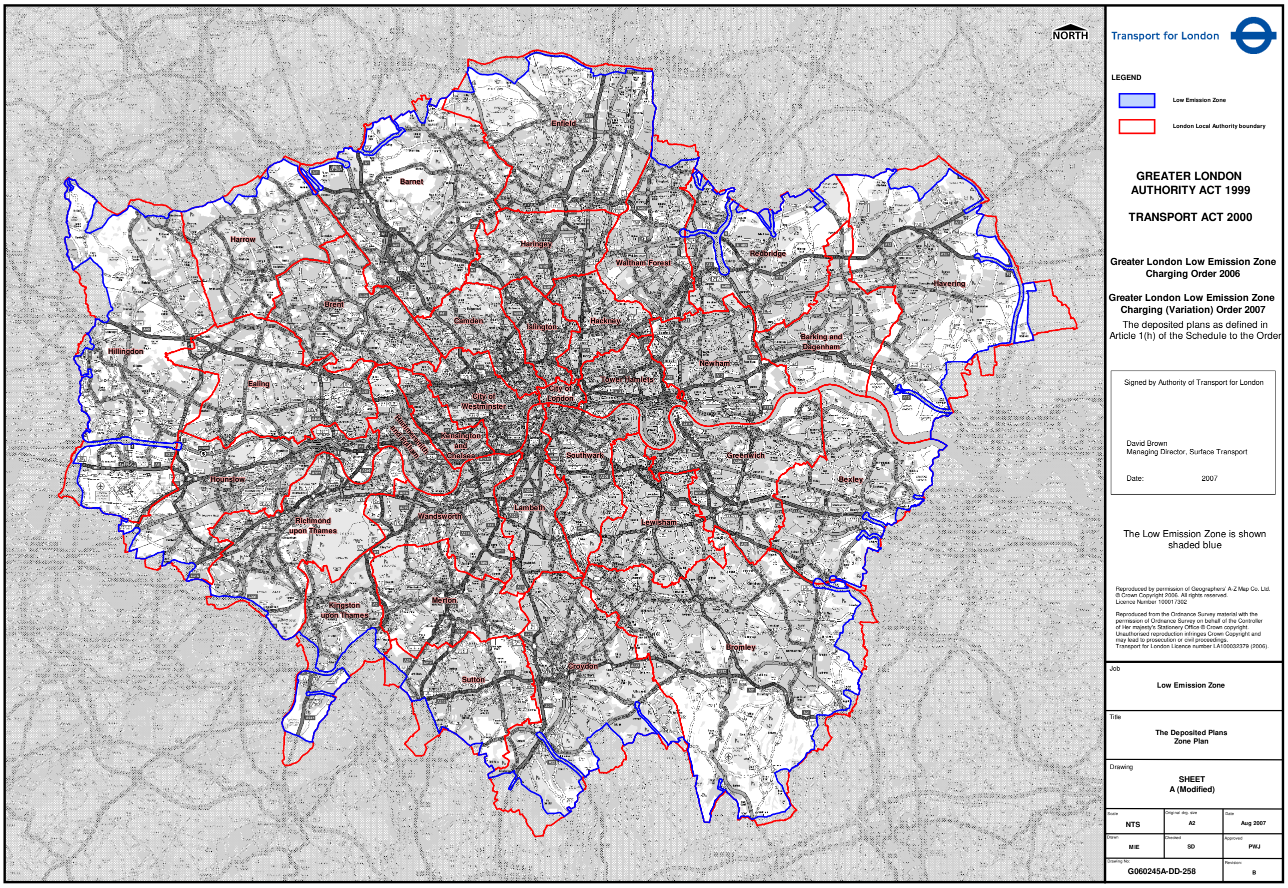
Finally, there is increasing evidence on non-health impacts of air pollution. Some studies have evaluated the pharmaceutical expenditure effects of air quality (Rohlf et al., 2020; Klauber et al., 2021; Deschenes et al., 2017; Williams and Phaneuf, 2019). For instance, Rohlf et al. (2020) have shown that LEZ lowers pharmaceutical expenditures for heart and respiratory diseases by €15.8M per year in the German treated cities. Other studies have explored the labour market and education impacts of air pollution. Specifically, Graff Zivin and Neidell (2013) have found that a 10 parts per billion (ppb) increase in ozone reduces farm worker productivity by 5.5% (or 700M a year). Chang et al. (2016) have shown that a $10\mu g/m^3$ rise in $PM_{2.5}$ inhibits manufacturing worker productivity by 6% (or 18bn a year). A 10-unit spike in API reduces office worker productivity by 0.35% (or 2.2bn a year) (Chang et al., 2019). Ebenstein et al. (2016) have investigated the impact of transitory $PM_{2.5}$ exposure on student matriculation exams between 2000 and 2002 in Israel. Exploiting the differential timing of exposure to pollution due to the scheduling of exams, they have found that exposure to an additional 10 units of $PM_{2.5}$ leads to a 1.64 unit decline in student exam score, a 0.15 decline in years of college education, and a 30 decline in monthly salary. Using an instrumental variable approach exploiting dust from the Sahara desert on the Iberian peninsula, Holub et al. (2020) have found that a $10\mu g/m^3$ reduction in average PM_{10} reduces work absence rate by 0.03 percentage points (equivalent to 1.1% of the sample mean).

3 Background

Between 2003 and 2019, the period we consider, there have been two major transport policies affecting London's air quality, namely, the Low Emission Zone (LEZ) and the Ultra Low Emission Zone (ULEZ). We now describe each one in turn.

Low Emission Zone (LEZ). In the years before the implementation of LEZ, London's outdoor air pollution was the worst of any city in the UK and among the worst in Europe. In particular, key pollutants, particulate matter (PM_{10}) and nitrogen dioxide (NO_2), levels failed to meet national and European air quality targets (Transport for London, 2008). As a result, the London Low Emission Zone (LEZ) was adopted on the 4^{th} February 2008 to target road traffic pollution. As shown by the blue boundaries in Figure 1, LEZ

Figure 1. Low Emission Zone in Greater London



covers almost all of Greater London[2]. This policy sets minimum emissions standards on vehicles and targets specifically the most polluting ones such as older, heavier diesel-fuelled vehicles. LEZ was implemented in four stages. Phase 1, introduced in February 2008, applied to diesel-powered heavy goods vehicles (HGVs) weighing greater than 12 tonnes with a minimum standard of Euro III for particulate matter (PM). Phase 2 followed in July 2008 applying to all lorries over 3.5 tonnes, as well as to buses and coaches with a minimum standard of Euro III for PM. Initially, phase 3 was supposed to start from October 2010 including larger vans and minibuses with a minimum standard of Euro III for PM; and from January 2012, phase 4 was supposed to start with a minimum standard tightened to Euro IV for PM for HGVs over 3.5 tonnes, buses and coaches (Transport for London, 2008). However, phase 3 was delayed and later phase 3 and 4 were introduced simultaneously in January 2012[3].

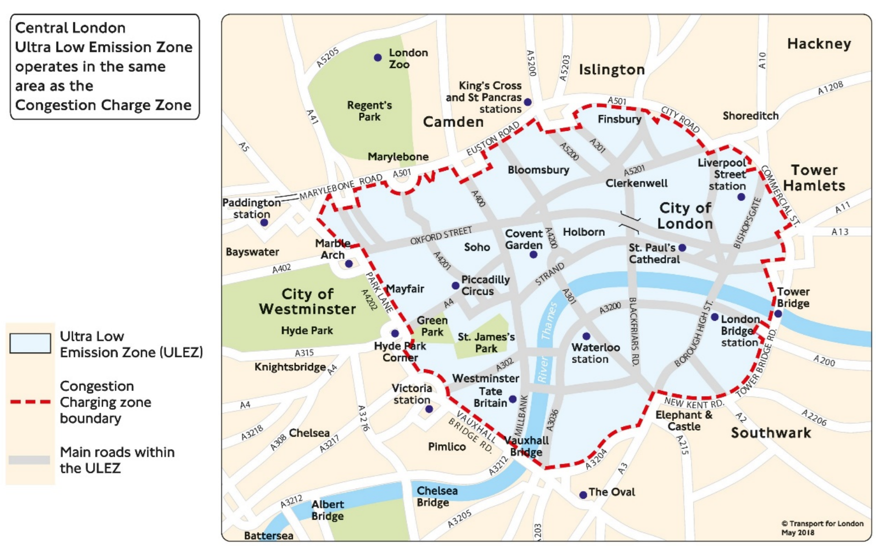
[2] The red boundaries indicate each of the 32 Local Authorities in Greater London including Central London.

[3] The delay in the introduction of LEZ phase 3 was criticised for putting poorer Londoners at risk. See, for example, https://www.standard.co.uk/news/uk/delay-extension-low-emission-zone-boris-johnson-inquest-ella-kissidebrah-b127781.html

LEZ operates 24 hours a day, every day of the year. Its targets are enforced using Automatic Number Plate Recognition (ANPR) cameras. Non-compliers pay a £100 charge for light goods vehicles and minibuses, or £200 for heavy goods vehicles, buses and coaches. Other cities such as Oxford in 2014, Brighton in 2015, and Norwich in 2008 also adopted LEZ-type clean air policies over a limited area in their jurisdiction.

Ultra Low Emission Zone (ULEZ). To further improve London's air quality, the Mayor introduced ULEZ in central London from the 8^{th} of April 2019. Figure 2 shows the area covered by ULEZ. This scheme is the toughest of any city in the world. It is intended to further improve London's air quality by requiring strict emission standards such as: Euro 4 for petrol cars and vans; Euro 6 for diesel cars; Euro 6 for diesel vans; Euro 6 for lorries, buses and coaches; and Euro 3 for motorcycles. ULEZ replaces the Toxicity-Charge (T-Charge), announced on the 17^{th} of February and come into force on the 23^{rd} October 2017, in Central London. T-Charge was considered as a stepping-stone for ULEZ and it was seen as the starting point for a change in the vehicle fleet in Central London (Greater London Authority, 2019). Also, since 2008, LEZ was operational in Central London, being part of Greater London. ULEZ operates 24 hours a day, every day of the year. Vehicles that do not meet these standards must pay: £12.50 per day for cars, motorcycles and vans or £100 per day for lorries, buses and coaches.

FIGURE 2. Ultra Low Emission Zone, Central London



4 Data

To investigate the impacts of these low emission policies, we match geographical data on policy exposure to station level pollution data and individual level survey data on health. We now explain each of these datasets in detail.

Geo-coordinates of exposed areas. We use postcode data from Transport for London (TfL) to identify areas covered by LEZ and ULEZ. We compare treated (Greater London for LEZ and Central London for ULEZ) cities with non treated cities in England. In most of our analysis, we restrict our data to major cities and towns in England. To analyse the impacts of Greater London's LEZ, we restrict our data from 2003 to 2015, while in the ULEZ analysis, we extend the data from 2003 to 2019 to encompass all the schemes in Central London (LEZ, TC, and ULEZ).

Air pollution and weather data. To analyse the air pollution effect of LEZ and ULEZ, we use daily average data on two main pollutants. We use daily average nitrogen dioxide (NO_2) and daily average particulate matter with an aerodynamic diameter of less than ten (PM_{10}) from the UK Air Quality Archive. We focus on these two pollutants for the following reasons. Firstly, LEZs work by limiting vehicles from entering the zones; and in cities vehicle exhaust is the dominant source of these pollutants. Secondly, the aim of the LEZs in London was to tackle the concentration of these pollutants (for instance Greater London's LEZ aims to tackle reduction of emissions of PM_{10}, while ULEZ aims to reduce harmful NO_2). Thirdly, as described in the literature, medical and epidemiological research have identified PM_{10} and NO_2 as triggers of systemic inflammation. Fourthly, other studies evaluating transport policies tackling air pollution have also focused on NO_2 and PM_{10}. Finally, these two pollutants are adequately recorded in monitoring stations located in both treated and control cities (unlike other pollutants such as $PM_{2.5}$).[4]

We also use data from the Met Office - MIDAS Land Surface Stations on daily average weather variables (rainfall, temperature and wind). Table 1 presents summary statistics of pollutants and weather variables.

For the LEZ sample, panel A of Table 1 shows the average NO_2 and PM_{10} levels for treated (London) and all other cities and towns in England with pollution data between 2003 and 2015. The average NO_2 and PM_{10} levels are 35 and 21.7 $\mu g/m^3$, respectively.

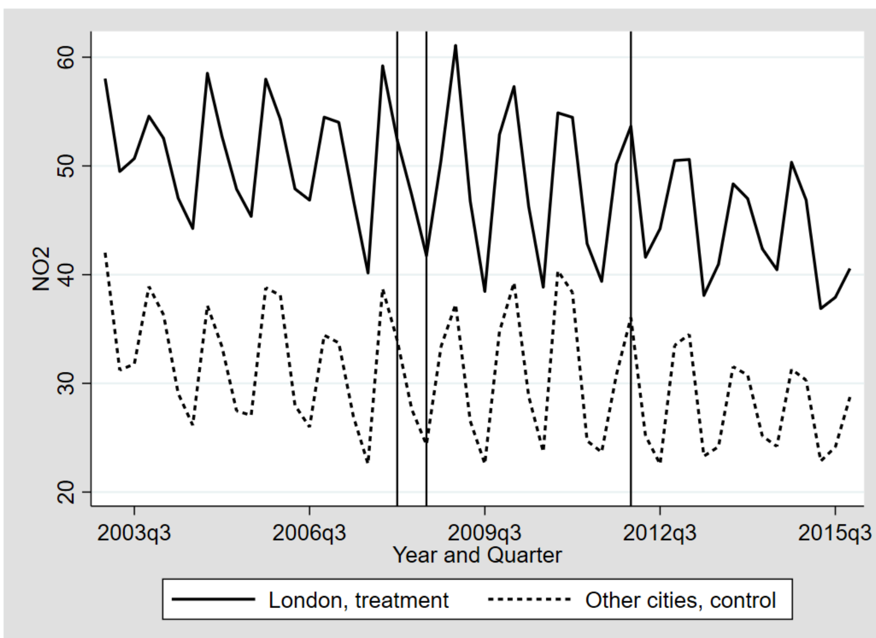
In the ULEZ analysis, we have Central London as treated group, where there are two background monitoring stations. For better comparison, we drop all kerbside and roadside monitoring stations from the control cities. Panel B of Table 1 provides the average NO_2 and PM_{10} levels along with summary statistics

[4] NO_2 is a primary precursor for $PM_{2.5}$ and the majority of NO_2 converts to particulate nitrate (a component of $PM_{2.5}$) within a few days (Lin and Cheng, 2007; Alexander and Schwandt, 2019).

Table 1: Descriptive statistics of main variables

	Mean	Standard Dev.	Min	Max	Observation
	Panel A: LEZ sample (2003-2015)				
NO_2	34.906	22.515	0.000	265.000	271479
PM_{10}	21.671	12.243	0.000	194.000	151519
Average Precipitation	2.008	4.244	0.000	88.200	271477
Average Temperature	11.415	5.697	-11.950	32.150	271479
Mean Wind Speed	8.511	4.656	0.000	50.750	271479
Mean Wind Direction	196.808	71.296	0.000	359.167	271479
	Panel B: ULEZ sample (2003 to 2019)				
NO_2	26.926	16.331	0.000	179.000	233080
PM_{10}	19.131	10.958	0.000	194.000	138305
Average Precipitation	2.111	4.412	0.000	192.000	233074
Average Temperature	11.236	5.636	-11.950	32.800	233080
Mean Wind Speed	8.752	4.813	0.000	45.833	233080
Mean Wind Direction	199.544	69.465	0.000	359.167	233080

FIGURE 3. NO_2 trend before and after LEZ

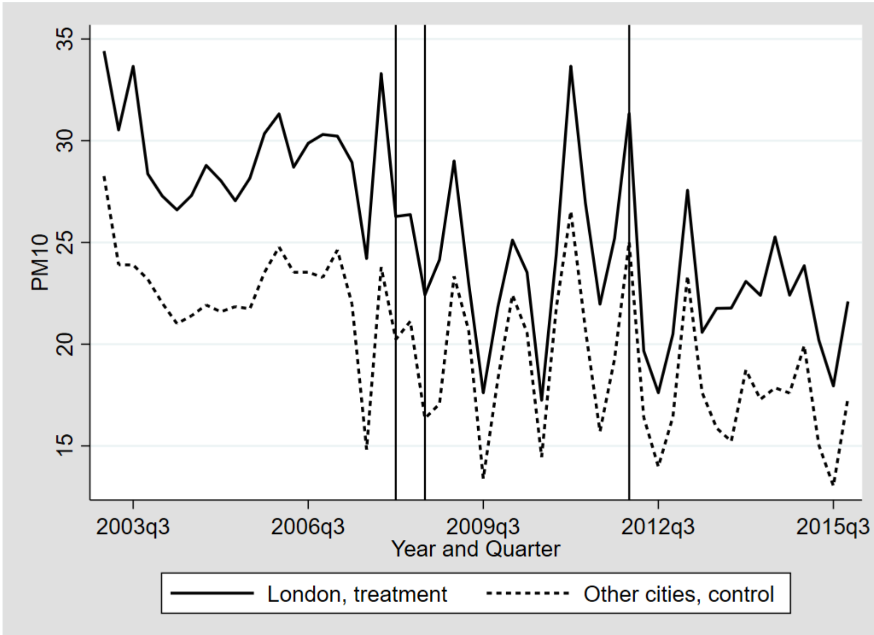


Trends of NO_2 before and after the implementation of the LEZ. The figure shows the differences in NO_2 between LEZ (London) and other control cities. The vertical lines indicate when each LEZ phase was implemented in London: phase 1 in February 2008, phase 2 in July 2008, and phase 3/4 in January 2012.

of the weather controls. Between 2003 and 2019, the average NO_2 and PM_{10} level are 27 and $19\mu g/m^3$, respectively.

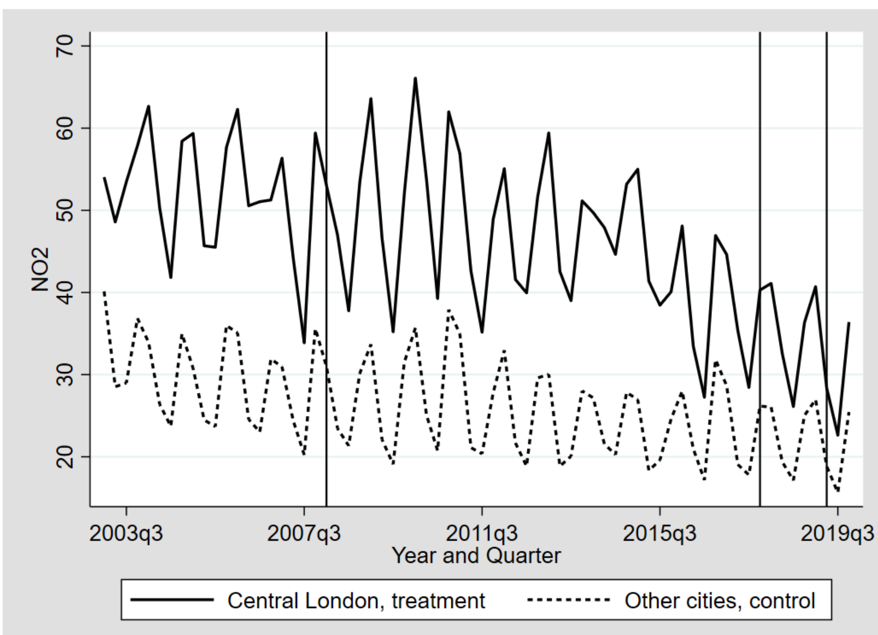
Figures 3, 4, 5, and 6 show the trends of NO_2 and PM_{10} before and after the implementation of the policies. Figures 3 and 4 show the differences in NO_2 and PM_{10} between LEZ (London) and other control cities. The vertical lines indicate when each LEZ phase was implemented in London: phase 1 in February 2008, phase 2 in July 2008, and phase 3/4 in January 2012. Figures 5 and 6 depict the differences in NO_2

FIGURE 4. PM_{10} trend before and after LEZ



Trends of PM_{10} before and after the implementation of the LEZ. The Figure shows the differences in PM_{10} between LEZ (London) and other control cities. The vertical lines indicate when each LEZ phase was implemented in London: phase 1 in February 2008, phase 2 in July 2008, and phase 3/4 in January 2012.

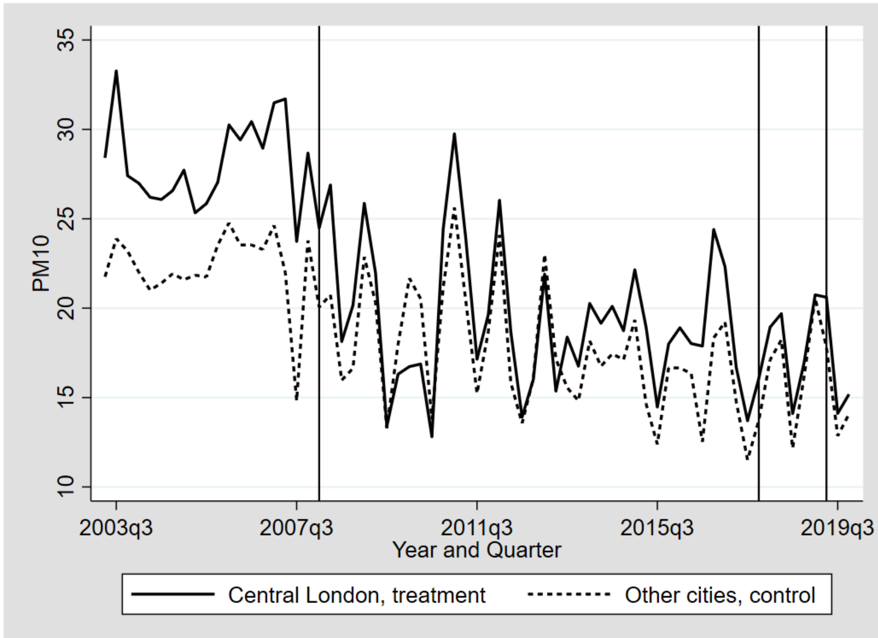
FIGURE 5. NO_2 trend before and after ULEZ



The figure shows the differences in NO_2 between ULEZ (Central London) and other control cities. The first vertical line corresponds to the time when LEZ was implemented in February 2008, the second line indicates the announcement of the T-charge in February 2017 and the third line indicates the implementation of ULEZ in April 2019.

and PM_{10} between ULEZ (Central London) and other control cities. The first vertical line corresponds to the time when LEZ was implemented in February 2008, the second line indicates the announcement of the

FIGURE 6. PM_{10} trend before and after ULEZ



The figure shows differences in PM_{10} between ULEZ (Central London) and other control cities. The first vertical line corresponds to the time when LEZ was implemented in February 2008, the second line indicates the announcement of the T-charge in February 2017 and the third line indicates the implementation of ULEZ in April 2019.

T-charge in February 2017 and the third line indicates the implementation of ULEZ in April 2019.

Health and other area-level data. For the health analysis, we use the Quarterly Labour Force Survey (QLFS) (Office for National Statistics, Social Survey Division, Northern Ireland Statistics and Research Agency, Central Survey Unit, 2021). The QLFS is a large survey that collects information from approximately 40,000 households and approximately 100,000 individuals every quarter since 1992. It collects a range of information on education, personal characteristics of individuals, employment, labour income, benefits and health of individuals. We use the secure access dataset containing Lower Layer Super Output Areas (LSOA)[5] available from 2005, which are used to assign exposure to the LEZs.

As measures of physical health we consider variables such as having health problems lasting 12 months or more; experiencing health problems that have limited/limit activity; suffering from chest/breathing problems, asthma, bronchitis; and having heart, blood pressure, blood circulation problems; number of health conditions the individual suffers from; and lastly whether individual asked sick leave recently. For these outcomes, we construct an indicator variable that equals one if the individual ever had health problems longer than 12 month and zero otherwise; an indicator variable that equals one if the individual is experiencing health problems limiting activity and zero otherwise; an indicator variable that equals one if the individual is

[5]There are 34,753 LSOAs in England. Each LSOA contains approximately 3,000 residents or 1,200 households.

suffering from chest/breathing problems, asthma, bronchitis and zero otherwise; an indicator variable that equals one if the individual is having heart, blood pressure, blood circulation problems and zero otherwise; and a dummy variable that is equal to one if the individual has asked sick leave recently and zero otherwise. We also construct the total number of health conditions out of the 17 potential problems listed in QLFS.[6]

We add to this data a few area-level characteristics such as the average house prices provided by the Office for National Statistics at the Middle Layer Super Output area (MSOA)[7] level and the Index of Multiple Deprivation (IMD) used to rank every LSOA in England according to their relative level of deprivation. IMD is a continuous measure of relative deprivation combining seven domains such as income, employment, health and disability, education skills and training, barriers to housing and other services, crime and living environment.

Table 2 presents the descriptive statistics of the variables used in the LEZ analysis. Panel A of Table 3 presents the descriptive statistics of these outcomes and also other controls that are used in the ULEZ analysis.

To show the effects of the schemes on measures of well-being, we use information from the Annual Population Survey (APS) (Office for National Statistics, Social Survey Division, 2021). The APS uses data from the QLFS from 2004 on and contains a sample of approximately 320,000 respondents. Since 2012, however, APS contains subjective well-being information of all individuals aged 16 and over.[8]

We consider measures of satisfaction, feelings of worthiness, happiness, and anxiety. Specifically, individuals were asked how satisfied they are with life nowadays (0=not at all, and 10=completely); to what extent do they feel that things they do in life are worthwhile (0=not at all, and 10=completely); how happy did they feel yesterday (0=not at all, and 10=completely); and how anxious did they feel yesterday (0=not at all, anxious and 10=completely anxious). We also consider information on general health. Individuals respond if their health in general is either Very Good, Good, Fair, Bad, or Very Bad. Using this information we also defined additional outcome (Good Health): a binary outcome that takes 1 if general health is very good or good; and 0 otherwise. Panel B of Table 3 presents the descriptive statistics of these variables and controls used in this analysis.

[6]These health questions are asked to all respondents of age 16 and older. However, for those above 75 years old, only those who are not ill or distressed and want (able) to continue the survey are interviewed about their health conditions. To avoid selection problem, our sample is restricted to people of age 16 to 74.

[7]There are 7,201 MSOAs in England. Each MSOA contains approximately 15,000 residents or 6,000 households.

[8]Similarly, our sample is restricted to people of age 16 to 74.

Table 2: Descriptive statistics of main variables in health effect of LEZ

	Mean	SD	Obs.
	LEZ Sample: QLFS January 2005 to December 2015		
Ever had health problem longer than 12 month (1=yes)	0.339	0.473	1250779
Chest/ breathing problems, asthma, bronchitis (1=yes)	0.075	0.264	1250779
Health problem limits activity (1=yes)	0.190	0.392	1250769
Heart, blood pressure, blood circulatory problems (1=yes)	0.113	0.317	1250779
No. of health conditions	0.758	1.464	1250779
Had any sick leave in the last week(1=yes)	0.024	0.152	784656
Gender	0.476	0.499	1256836
Age	42.739	15.938	1256836
Ethnicity:			
White	0.805	0.396	1255679
Asian	0.091	0.287	1255679
Other ethnic	0.104	0.305	1255679
Type of Housing:			
Owner	0.234	0.423	1256040
Mortgage	0.397	0.489	1256040
Renting	0.369	0.483	1256040
Economic activity status:			
In Employment	0.626	0.484	1256836
Area level controls:			
Rank of IMD score (1= least deprived)	0.5	0.289	32482
log House Price (real)	12.293	0.52	129489

Table 3: Descriptive statistics of main variables in health and wellbeing effects of ULEZ

	Mean	SD	Obs.
	ULEZ Sample: QLFS January 2005 to December 2019		
Ever had health problem longer than 12 month (1=yes)	0.261	0.439	2113166
Chest/ breathing problems, asthma, bronchitis (1=yes)	0.054	0.225	2113166
Heart, blood pressure, blood circulatory problems (1=yes)	0.066	0.249	2113166
No. of health conditions	0.445	0.965	2113166
Had any sick leave in the last week(1=yes)	0.022	0.145	2119110
Gender	0.515	0.500	2119228
Age	42.099	13.132	2119228
Ethnicity:			
White	0.920	0.272	2118370
Asian	0.037	0.188	2118370
Other ethnic	0.043	0.204	2118370
Type of Housing:			
Owner	0.212	0.409	2118404
Mortgage	0.542	0.498	2118404
Renting	0.246	0.431	2118404
Area level controls:			
Rank of IMD score (1= least deprived)	0.5	0.289	32482
log House Price (real)	12.293	0.52	129489
	ULEZ Sample: APS April 2012 to March 2020		
General Health	1.739	0.756	697513
Good Health	0.856	0.351	697513
Feeling Happy	7.491	1.992	447039
Feeling Worthiness	7.948	1.485	446321
Feeling Satisfied	7.708	1.563	447108
Feeling Anxious	2.871	2.753	446748
Gender	0.510	0.500	712579
Age	42.852	13.226	712579
Ethnicity:			
White	0.901	0.299	712242
Asian	0.046	0.209	712242
Other ethnic	0.054	0.225	712242
Type of Housing:			
Owner	0.223	0.416	712245
Mortgage	0.499	0.500	712245
Renting	0.278	0.448	712245
Area level controls:			
Rank of IMD score (1= least deprived)	0.5	0.289	32844
log House Price (real)	12.293	0.52	129615

5 Empirical Strategy

Like most of the studies evaluating the effects of clean air transport policies, we first investigate the impact of LEZ and ULEZ on air quality and then we examine their health and well-being effects.

Air Quality effects of LEZ and ULEZ. To investigate the air quality effects of LEZ in Greater London, we estimate the following model using OLS:

$$P_{ict} = \alpha_0 + \beta_0(\text{London}_c * \text{Post}_t) + \theta_0 \text{London}_c + \gamma_0 \text{Post}_t + \pi_0 W_{ict} + \zeta_0 \tau_t + S_i + \varepsilon_{ict} \tag{1}$$

where P_{ict} are the NO_2 or PM_{10} daily averages at the monitoring station i located in city c, measured at time/date t. London_c equals one if city c is a city where LEZ was implemented, zero otherwise (i.e. a dummy equal to 1 for Greater London, 0 for other cities). Post_t takes on value one for the period on or after the implementation of LEZ, and 0 otherwise. W_{ict} is a vector of weather controls (i.e. rain, temperature, wind). τ_t contains a set of time fixed effects and trends (month fixed effects, year fixed effects and treatment specific time trends). Furthermore, we also control for monitoring station fixed effects, S_i. We are interested in the difference-in-differences (DID) coefficient β_0, estimating the impact of LEZ on air quality.

To assess the air quality effects of ULEZ and the other policies that were in place in Central London (i.e. LEZ and TC), we estimate the following model using OLS:

$$\begin{aligned} P_{ict} = \alpha_1 + \beta_1(\text{CL}_c * \text{PostLEZ}_t) + \beta_2(\text{CL}_c * \text{PostTC}_t) + \beta_3(\text{CL}_c * \text{PostULEZ}_t) + \\ \theta_1 \text{CL}_c + \gamma_1 \text{Post}_t + \pi_1 W_{ict} + \zeta_1 \tau_t + S_i + \eta_{ict} \end{aligned} \tag{2}$$

where P_{ict} are the NO_2 or PM_{10} daily averages at the monitoring station i located in city c, measured at time/date t. CL_c equals one if city c is a city where ULEZ, TC, and LEZ were implemented, zero otherwise (i.e. a dummy equal to 1 for Central London, 0 for other cities). Post_t is a vector taking on value one for the period on or after the implementation of LEZ, TC and ULEZ, respectively; and 0 otherwise. W_{ict} is a vector of weather controls (i.e. rain, temperature, wind). Furthermore, we also control for month and year fixed effect as well as treatment specific time trends, τ_t, in addition to monitoring station fixed effects, S_i. β_1, β_2 , and β_3 are the DiD coefficients of the impact of LEZ, TC, ULEZ, respectively, on air quality.

Health effects of LEZ and ULEZ. To investigate the physical health effects of LEZ in Greater London, we estimate the following specification using linear probability model (LPM):

$$H_{imct} = \alpha_2 + \delta_0(\text{London}_c * \text{Post}_t) + \vartheta_0\text{London}_c + \chi_0\text{Post}_t + \lambda_0 X_{imct} + \xi_0\tau_t + D_m + \upsilon_{imct} \quad (3)$$

where equation (3) is similar to equation (1), except that H_{imct} indicates each physical health outcome experienced by individual i, from MSOA m, located in city c, observed at time t. X_{imct} contains pre-determined individual characteristics such as age, sex, ethnicities; as well as other controls such as type of home ownership, employment status, and area level controls (LSOA IMD rank and average MSOA house prices). Furthermore, we also control for month, year fixed effects and treatment specific trends, τ_t, as well as MSOA fixed effects, D_m. We are interested in δ_0, the DiD impact of LEZ on physical health.

To assess the physical and well-being effects of ULEZ and the other policies in Central London (i.e. LEZ and TC), we estimate the following model:

$$\begin{aligned} H_{imat} = \alpha_3 + \delta_1(\text{CL}_a * \text{PostLEZ}_t) + \delta_2(\text{CL}_a * \text{PostTC}_t) + \delta_3(\text{CL}_a * \text{PostULEZ}_t) + \\ \vartheta_1\text{CL}_a + \chi_1\text{Post}_t + \lambda_1 X_{imat} + \xi_1\tau_t + D_m + \nu_{imat} \end{aligned} \quad (4)$$

where equation (4) is similar to equation (2), except that H_{imat} indicates each physical health and well-being outcome experienced by individual i, living in MSOA m, working in area a, and observed at time t. Unlike in equation (3), in this analysis, we do not observe people living in Central London as it is a largely a working area. As a result, we are forced to compare people working in central London (exposed to the policies) to the individuals working in other parts of England. In the QLFS and the APS, there are 17 regions reported as areas where individuals go to work.[9]. X_{imat} contains pre-determined individual characteristics such as age, sex, ethnicities; and type of home ownership. Furthermore, we also control for month and year Fixed effects as well as treatment specific trends, τ_t, and MSOA fixed effects, D_m. We are interested in $\delta_1, \delta_2, \delta_3$, measuring the DiD impacts of LEZ, TC, and ULEZ on physical health and well-being, respectively.[10]

Inference. For inference, we report robust standard errors that are clustered at the city level to deal with correlation within cities. When the number of treated groups is very small, this inference method is unreliable.

[9] These are: Central London; Inner London; Outer London; Tyne & Wear; Rest of Northern Region; South Yorkshire; West Yorkshire; Rest of Yorks & Humberside; East Midlands; East Anglia; Rest of South East;, South West; West Midlands Metropolitan; Rest West Midlands; Greater Manchester; Merseyside; and Rest of North West. To be consistent with the previous air quality analysis, we exclude Inner and Outer London from the control group because LEZ was in place then.

[10] Well-being is measured in the APS only 2012 onwards. Thus, in equation 4, we can only estimate the well-being effects of ULEZ (and TC). It should also be noted that Central London is mainly a working location, so we only estimate the impact of these policies on working individuals.

In our case, we have a single treated group (Central London for ULEZ and Greater London for LEZ). In such a case, alternative inference methods are considered (Donald and Lang, 2007; Conley and Taber, 2011; Cameron et al., 2008). However, in cases where there is heteroskedasticity generated from variation in group sizes, these methods are not preferred as well. For instance, when the number of observations in the treated groups is small relative to the number of observations in the control groups, the methods lead to over-reject the null hypothesis (Ferman and Pinto, 2019). In our case, London is a single treated unit and it has a large number of observations compared to the other control cities. As a result, we also report p-values produced by the procedure proposed by Ferman and Pinto (2019) in our main results.

6 Results

6.1 Impact on Air Quality

Effects on Air Quality. Table 4 reports the baseline DiD coefficient, β_0 in equation (1), of the air quality effects of LEZ on NO_2 and PM_{10}. The table shows that while LEZ did not have a significant effect on NO_2, it significantly reduced PM_{10}. Specifically, in Column (2), LEZ significantly reduced average daily PM_{10} by 3.5 $\mu g/m^3$. This is equivalent to 12% of the average pre-LEZ PM_{10} level in Greater London.

Table 4: Estimated effect of LEZ on NO_2 and PM_{10}

	(1) NO_2	(2) PM_{10}
London*Post	-0.368	-3.455***
	(0.835)	(0.490)
Ferman-Pinto p-values	[0.504]	[0.000]
Baseline mean	50.903	29.160
Observations	271,477	151,519
Adjusted R-squared	0.661	0.374
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
Treatment Specific Linear Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. Ferman-Pinto p-values in brackets. The asterisks next to the coefficients are for p-values associated with the main (non-Ferman-Pinto p-values) regressions. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction. Baseline mean refers to average concentrations of the respective pollutant at stations inside LEZ before the implementation of the zone in Greater London.

Table 5 reports results on the impact on NO_2 and PM_{10} by different phases of LEZ. We disaggregate the LEZ indicator as follows: phase 1 is between the 4^{th} February 2008 and 6^{th} of July 2008; phase 2 runs from 7^{th} July 2008 to 2^{nd} of January 2012; and phase 3 covers the period after the 3^{rd} of January 2012. The table shows that LEZ seems to increase NO_2, especially during the first few months of its implementation (Phase 1).[11] However, the policy has a consistent reduction effect on PM_{10}. LEZ resulted in larger decrease in PM_{10} after Phase 2 and Phase 3, after the policy was expanded to affect more vehicle types and tighter restrictions were put in place. During Phase 2 LEZ significantly reduced average daily PM_{10} by 4.19 $\mu g/m^3$, which is equivalent to 14.4% of the average pre LEZ PM_{10} level level in Greater London. In Phase 3, LEZ also significantly reduced average daily PM_{10} by 4.18 $\mu g/m^3$, which is equivalent to 14.3% of the average pre LEZ PM_{10} level in Greater London.

Table 5: Estimated effect of Different Phases of LEZ on NO_2 and PM_{10}

	(1) NO_2	(2) PM_{10}
London*Post Phase 1	3.123***	-1.721**
	(1.111)	(0.712)
Ferman-Pinto p-values	[0.029]	[0.095]
London*Post Phase 2	-0.537	-4.196***
	(0.941)	(0.610)
Ferman-Pinto p-values	[0.348]	[0.000]
London*Post Phase 3	1.229	-4.185***
	(1.435)	(1.065)
Ferman-Pinto p-values	[0.161]	[0.000]
Baseline mean	50.903	29.160
Observations	271,477	151,519
Adjusted R-squared	0.662	0.375
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
Treatment Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. Ferman-Pinto p-values in brackets. The asterisks next to the coefficients are for p-values associated with the main (non-Ferman-Pinto p-values) regressions. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction. Baseline mean refers to average concentrations of the respective pollutant at stations inside London before the implementation of the LEZ in Greater London.

ULEZ started in Central London on the 8^{th} of April 2019, replacing the T-Charge. The T-Charge was announced on the 17^{th} of February 2017. Moreover, as Central London is also part of Greater London, it was affected by LEZ since February 2008. As a result, in Table 6, we also include exposure to LEZ and TC.

[11] In this phase, only HGVs (N3) vehicles were required to comply to LEZ rules. Buses & Coaches as well as goods vehicles between 3.5 and 12 tonnes in weight (N2) were not required to comply to LEZ. LEZ may have caused substitution of use of transportation away from N3 vehicles to N2 vehicles in this period. If these diesel-based vehicles (for instance Buses and Coaches) travelled more in Greater London in this period, it is likely that could cause increase in NO_2. Unfortunately, due to lack of monthly data, we could not test this hypothesis.

In Table 6, in Column (1), LEZ and TC have no significant effects on NO_2, while ULEZ significantly reduced NO_2. ULEZ reduces NO_2 by $6.5\mu g/m^3$, which is a 12.4% reduction compared to the baseline mean. In contrast, in Column (2), all schemes (LEZ, TC and ULEZ) have significant effects on PM_{10}. LEZ decreases PM_{10} by 5 $\mu g/m^3$, a 18% reduction compared to the baseline mean. TC reduces PM_{10} by 7 $\mu g/m^3$, a 25% reduction compared to the baseline mean. ULEZ reduces PM_{10} by 7.5 $\mu g/m^3$, a 27% reduction compared to the baseline mean.

Table 6: Estimated effect of LEZ, TC and ULEZ on NO_2 and PM_{10}

	(1) NO_2	(2) PM_{10}
CL*Post LEZ	1.833**	-5.090***
	(0.733)	(0.472)
Ferman-Pinto p-values	[0.123]	[0.000]
CL*Post TC	-1.128	-7.032***
	(1.093)	(0.632)
Ferman-Pinto p-values	[0.365]	[0.000]
CL*Post ULEZ	-6.456***	-7.489***
	(1.396)	(0.926)
Ferman-Pinto p-values	[0.000]	[0.002]
Baseline mean	52.301	28.120
Observations	233,074	138,302
Adjusted R-squared	0.620	0.338
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
Treatment Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. Ferman-Pinto p-values in brackets. The asterisks next to the coefficients are for p-values associated with the main (non-Ferman-Pinto p-values) regressions. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction. Baseline mean refers to average concentrations of the respective pollutant at stations inside Central London before the implementation of first policy (LEZ).

Effects on Vehicle Fleet. The reduction in air pollution we document above might be due to a change in the vehicle fleet composition towards less polluting vehicles. We could show it by examining changes in the vehicle fleet composition by Euro emission standards before and after the implementation of LEZ. Unfortunately, this information is not available from the U.K. Driver and Vehicle Licensing Agency (DVLA).

However, since 2012, the DVLA started providing statistics on the number of Ultra-low emissions vehicles (ULEVs) for each quarter by Local Authority. Exploiting this information, we provide evidence on the impact of TC and ULEZ on the number of ULEVs in Central London compared to other local authorities in England.

Figure 7. Number of ULEVs trend before and after ULEZ and TC

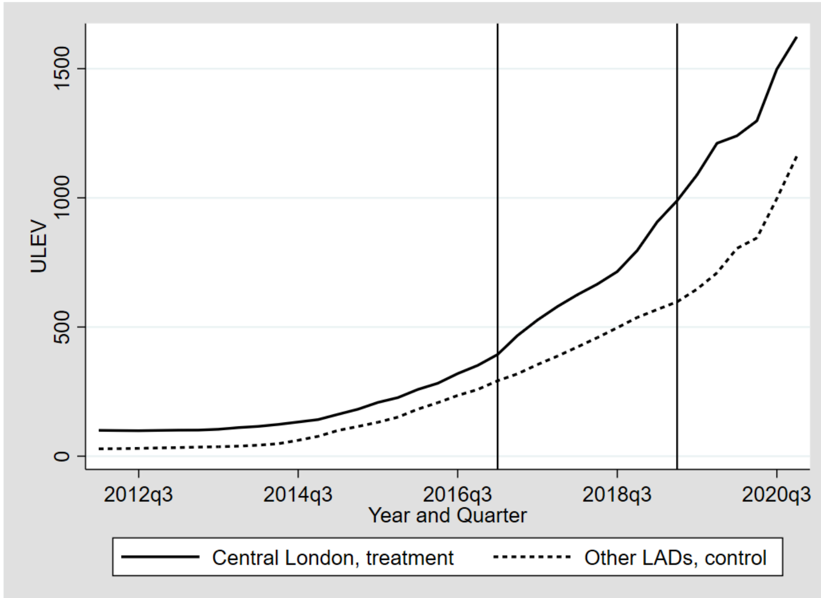


Figure 7 shows descriptively that the number of ULEVs has increased in England overall. However, since the introduction of the T-charge (the first vertical line depicted in Figure 7) the number of ULEVs has increased more in Central London than in other local authorities.

Table 7: Estimated effect of TC and ULEZ on Number of ULEVs licensed

	(1) Number of ULEVs
CL*Post TC	110.803
	(70.218)
CL*Post ULEZ	357.039**
	(140.798)
Observations	10,312
Adjusted R-squared	0.445
Local Authority District FE	Yes
Treatment Specific Trends	Yes

Robust standard errors (clustered at the LAD level) in parentheses.

This sharp rise becomes more pronounced after ULEZ came fully into force (the second vertical line depicted in Figure 7). To explore this more formally, we estimate the same DiD model as above with the number of ULEVs as dependent variable. Table 7 reports these results. We find that after the introduction of ULEZ about 357 new ULEVs were licensed in Central London compared to other local authorities.

6.2 Impacts on Health and Well-being

Table 8 presents results on the effect of LEZ on physical health outcomes. The table presents estimates on the probability of having health problem longer than 12 month (column (1)); experiencing chest/ breathing problems, asthma, bronchitis (column (2)); having health problem limits activity (column (3)), suffering from heart, blood pressure blood circulation problems (column (4)); number of health conditions (column (5)); and having had any sick leave in the last week (column (6)). LEZ had significant effects on all health outcomes except heart related problems and number of health conditions. However, using the Ferman-Pinto p-values, LEZ has a significant and negative effect only on the probability of having health problems limiting activity. In column (3), LEZ decreased the probability of having health problem that limits activity by 1.2 percentage points. Compared to the baseline mean, this corresponds to a 7% reduction in the health problems.

Table 8: Estimated Effect of LEZ on Health

	(1)	(2)	(3)	(4)	(5)	(6)
	Ever had health problems longer than 12 month	Chest/ breathing problems, asthma, bronchitis	Health problems limiting activity	Heart, blood pressure, circulatory problems	No. health conditions	Sick leave
London* Post LEZ	-0.012***	-0.006***	-0.012***	-0.000	-0.009	-0.004***
	(0.004)	(0.002)	(0.003)	(0.002)	(0.010)	(0.001)
Ferman-Pinto p-values	[0.219]	[0.137]	[0.001]	[0.932]	[0.683]	[0.148]
Baseline mean	0.283	0.0547	0.173	0.0908	0.565	0.0280
Observations	1,249,127	1,249,127	1,249,117	1,249,127	1,249,127	783,666
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. Ferman-Pinto p-values in brackets. The asterisks next to the coefficients are for p-values associated with the main (non-Ferman-Pinto p-values) regressions. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, employment status, LSOA level IMD rank, and MSOA level average house price as controls. Baseline mean refers to average value of the respective outcome for those in London before the implementation of LEZ. We apply weights provided by the survey.

Table 9 reports results from the effect of different phases of LEZ on physical health outcomes. Phases 2 and 3 are effective in reducing incidence of health problems such as heart, blood pressure and circulatory problems; health problems limiting activities; breathing problems (chronic obstructive pulmonary disease(COPD)); sick leave; as well as longer term health problems (using the Ferman-Pinto p-values). For instance, phase 2 of LEZ reduced the probability of having long-term health problems by 1.3 percentage points. Compared to the baseline mean, this translates into a 4.6% reduction in the incidence of long-term health problems. The LEZ reduced the probability of experiencing chest/breathing problems, asthma, bronchitis by 0.8 percentage points. This is equivalent to a 14.5% reduction in the incidence of chest/breathing problems, asthma, bronchitis in Greater London compared to the average pre-LEZ period. LEZ also decreased the probability of having health problems limiting activities by 1.2 percentage points. Comparing this estimate with the baseline mean, it translates into a 7% reduction in the health problems as a result of LEZ. LEZ reduced the probability of asking sick leave by 17% (or by 0.4 percentage points) in Greater London compared to the average pre-LEZ period. Moreover, phase 3 of LEZ results significant reduction on all outcomes (except sick leave) with stronger effects on heart related problems and number of health conditions.

Table 9: Estimated Effect of Different Phases of LEZ on Health

	(1)	(2)	(3)	(4)	(5)	(6)
	Ever had health problems longer than 12 month	Chest/ breathing problems, asthma, bronchitis	Health problems limiting activity	Heart, blood pressure, circulatory problems	No. health conditions	Sick leave
London*Post phase 1	-0.008**	-0.002	-0.002	-0.000	0.010	0.001
	(0.004)	(0.002)	(0.004)	(0.003)	(0.012)	(0.001)
Ferman-Pinto p-values	[0.498]	[0.619]	[0.891]	[0.951]	[0.759]	[0.904]
London*Post phase 2	-0.013***	-0.008***	-0.012***	-0.005*	-0.034***	-0.004***
	(0.004)	(0.002)	(0.003)	(0.003)	(0.011)	(0.001)
Ferman-Pinto p-values	[0.000]	[0.002]	[0.005]	[0.065]	[0.001]	[0.000]
London*Post phase 3	-0.012*	-0.009***	-0.007	-0.012***	-0.063***	-0.002
	(0.006)	(0.003)	(0.005)	(0.004)	(0.019)	(0.002)
Ferman-Pinto p-values	[0.000]	[0.003]	[0.027]	[0.000]	[0.000]	[0.317]
Baseline mean	0.283	0.0547	0.173	0.0908	0.609	0.0235
Observations	1,249,127	1,249,127	1,249,117	1,249,127	1,249,127	783,666
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. Ferman-Pinto p-values in brackets. The asterisks next to the coefficients are for p-values associated with the main (non-Ferman-Pinto p-values) regressions. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, employment status, LSOA level IMD rank, and MSOA level average house price as controls. Baseline mean refers to average value of the respective outcome for those in London before the implementation of LEZ. We apply weights provided by the survey.

Table 10 reports the impacts of different policies implemented in Central London on physical health outcomes for individuals working in Central London. LEZ and TC significantly reduced the incidence of all health problems. Similarly, ULEZ significantly reduced the incidence of all health problems, except heart and blood circulation problems and COPD.

In column (2), exposure to LEZ for individuals working in central London reduced the probability of experiencing COPDs by 0.7 percentage points. This is equivalent to a 19% reduction. In column(4), exposure to LEZ reduced the probability of asking for sick leave by 0.5 percentage points. This translates into a 17.7% reduction compared to the baseline mean. The adoption of T-Charge decreased long-term health problems by

Table 10: Estimated Effect of LEZ, TC and ULEZ on Health

	(1)	(2)	(3)	(4)	(5)
	Ever had health problems longer than 12 month	Chest/ breathing problems, asthma, bronchitis	Heart, blood pressure, circulatory problems	No. health conditions	Sick leave
CL*Post LEZ	-0.012***	-0.007***	-0.007***	-0.038***	-0.005***
	(0.003)	(0.001)	(0.001)	(0.008)	(0.001)
Ferman-Pinto p-values	[0.058]	[0.027]	[0.056]	[0.001]	[0.000]
CL*Post TC	-0.031***	-0.008***	-0.012***	-0.063***	-0.004***
	(0.003)	(0.002)	(0.002)	(0.008)	(0.001)
Ferman-Pinto p-values	[0.000]	[0.040]	[0.002]	[0.000]	[0.026]
CL*Post ULEZ	-0.038***	-0.005	-0.008***	-0.075***	-0.005***
	(0.005)	(0.003)	(0.002)	(0.012)	(0.001)
Ferman-Pinto p-values	[0.000]	[0.449]	[0.226]	[0.010]	[0.004]
Baseline mean	0.169	0.0369	0.0419	0.251	0.0283
Observations	2,111,522	2,111,522	2,111,522	2,111,522	2,117,433
Month FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the region of work level) in parentheses. Ferman-Pinto p-values in brackets. The asterisks next to the coefficients are for p-values associated with the main (non-Ferman-Pinto p-values) regressions. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, LSOA level IMD rank, and MSOA level average house price as controls. Baseline mean refers to average value of the respective outcome for those in London before the implementation of LEZ. We apply weights provided by the survey.

18% , COPDs by 21.6% , heart diseases by 28.6%, and sick leave by 14%. And importantly, the introduction of ULEZ decreased long-term health problems by 22.5% , number of health conditions by 29.8% and sick leave by 17.7%.

Finally, Table 11 shows the impacts of TC and ULEZ on general health and well-being of individuals working in Central London. We find that ULEZ improved feelings of happiness, worthiness and satisfaction by 0.09, 0.1 and 0.095, points, respectively. These are equivalent to 1.3%, 1.3% and 1% of the baseline mean, respectively. The policy also reduces anxiety by 0.20 points, equivalent to 6.5% of the baseline mean.

6.3 Robustness Checks

Robustness on air quality effects of LEZ and ULEZ. Whilst we focused on the largest LEZ in Europe, the one in Greater London, there are other cities in England that have implemented LEZ-type policies such

Table 11: Estimated Effect of TC and ULEZ on General Health and Well-being

	(1) General health	(2) Good health	(3) Happy	(4) Worthwhile	(5) Satisfied	(6) Anxious
CL*Post TC	0.001	-0.004*	0.006	-0.008	-0.047***	0.023
	(0.007)	(0.002)	(0.014)	(0.012)	(0.011)	(0.024)
Ferman-Pinto p-values	[0.953]	[0.495]	[0.901]	[0.678]	[0.065]	[0.622]
CL*Post ULEZ	-0.048***	0.012***	0.094***	0.113***	0.095***	-0.200***
	(0.010)	(0.002)	(0.019)	(0.016)	(0.016)	(0.034)
Ferman-Pinto p-values	[0.050]	[0.102]	[0.076]	[0.000]	[0.028]	[0.056]
Baseline mean	1.621	0.907	7.422	7.720	7.622	3.082
Observations	696,877	696,877	446,614	445,899	446,685	446,326
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the region of work level) in parentheses. Ferman-Pinto p-values in brackets. The asterisks next to the coefficients are for p-values associated with the main (non-Ferman-Pinto p-values) regressions. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, LSOA level IMD rank, and MSOA level average house price as controls. Baseline mean refers to average value of the respective outcome for those in London before the implementation of TC. We apply weights provided by the survey.

as Oxford in 2014, Brighton in 2015, and Norwich in 2008. In Tables A.1, we check for the robustness of our results on air pollution to these additional areas in the following ways. Firstly, we exclude Oxford, Norwich and Brighton from the control cities. The results are presented in Panel A and B of the respective tables. Secondly, we include Oxford, Norwich and Brighton in the treatment group to capture the impacts of all LEZs in England (not just London). Our results are virtually similar to the baseline results.

We then check if our results are affected by the type of trends by using city specific treatment trends instead of treatment specific trends. Table A.2 (for LEZ) and Table A.7 (for ULEZ) report these results, where the effects are the same as the baseline results.

In Table A.3 and Table A.8, we report results from estimations that do not include weather controls. While all results are same with the baseline, we find a significant impact of LEZ on NO_2 reduction. Moreover, we no longer find a positive effect of phase 1 of LEZ on NO_2.

In order to have comparison cities that are more similar to Greater London, we restrict our sample to those with over 100,000 residents. Our results displayed in Table A.4 and Table A.9 are not altered.

To avoid outliers caused by the fireworks during New Years Eve and Day, in Table A.5 and Table A.10, we report results after excluding these two days from our sample. We find the same results as the baseline. Similarly, as large goods vehicles might not transport goods during weekends, we exclude weekends from our pollution data and estimate the effect of LEZ on on NO_2 and on PM_{10}. Table A.11 presents results that are similar to the baseline.

Phase 1 and 2 of LEZ were implemented only five months apart. As a robustness check, we show results where we combine these two phases (see Table A.6). We find that while there is no effect on NO_2, phase 1 & 2 and Phase 3 of LEZ significantly reduce PM_{10}.

Another concern is related to treatment timing with respect to LEZ. Following LEZ's announcement, drivers may retrofit or change their vehicles and as a result LEZ may have significant effects even before 2008. Specifically, air pollution in 2007 (1 year before our treatment period) may fall in comparison with earlier years. To test this, in Figure A.1 and Figure A.2, we plot the coefficients from an event study analysis (along with 95% confidence intervals) estimated from dynamic difference-in-differences models, where Equation (1) is modified such that treatment time is assigned for each year from 2003 to 2015. The reference period (omitted period) is 2003 (5 years prior from LEZ). The figures show that NO_2 and PM_{10} do not significantly change in the years just before the introduction of LEZ. While we find a significant drop in PM_{10} after 2008, Figure A.2 also shows a fall in 2005, confirming the need to use differential trends for exposed and unexposed cities (controlling for treatment specific or city specific trends) in our analyses.

Finally, we also show the sensitivity of our results by removing areas covered by Congestion Charging Zone (CCZ) and its western extension (WEZ) from the treatment zone in the models where we look at the impact of LEZ. Table A.12 reports our results remain unaffected.

Robustness on health and well-being effects of LEZ and ULEZ. In Table B.1, we check for robustness of our results with respect to other LEZ type policies in England. Similar to the air pollution analyses, first, we exclude Oxford, Norwich and Brighton from the unexposed cities. Second, we include Oxford, Norwich and Brighton in our exposed cities, in addition to London. All the results, presented in Panels A to C, are similar to the baseline ones.

Moreover, in Tables B.2, B.3 and B.4, we report results that allow for city and region of work specific trends instead of treatment specific trends. The results are the same as the baseline. In Table B.5 we report results from combining Phase 1 and 2 together in one treatment dummy. These results are similar to the baseline ones. Furthermore, Table B.6 presents results where we restrict the sample to cities more than 100,000 residents. We find that results are virtually similar to the baseline ones. We also report results estimated without controls (see Table B.7, Table B.8 , and Table B.9). Our baseline results are also not altered. For the physical health outcomes where there is enough variation at the LSOA level, we have also estimated models with LSOA fixed effects (where IMD is not included because it does not change over time) and our results are very similar (available from the authors on request).

In so far our results are based on applying survey weights. In Table B.10, Table B.11 and Table B.12, we present results estimated without survey weights which are virtually similar to our main ones. Finally, we report results obtained from restricting our sample to only employed people (see Table B.13) and removing the area covered by Central London's CCZ and its western extension (WEZ) from our treatment zone (see Table B.14). While for the former analysis our results are stronger, we find similar results to the baseline for the latter one.

7 Cost-Benefit Back of the Envelope Analysis

There is no official assessment of the costs and benefits of this policy. In this section we present a back-of-the-envelope cost-benefit analysis under a number of subjective assumptions. This is based on our in-sample estimates and is intended to provide a rough measure of LEZ/ULEZ's costs and benefits.

A feasibility report commissioned by the Greater London Authority (GLA) and Transport for London (TfL) amongst others, has estimated the start-up costs to be £36.5M, the operating costs to be £28.1M and the revenues £11.6M (Environment, 2003).

Based on our findings, there are 357 extra ULEVs, at an average cost of £27,747 (ONS, 2021), this equals to £9,905,679. It is important to highlight that there are other costs that are not accounted here such as running vehicles costs, and other behavioural factors such as switching to other means of transportations (e.g. public transport or car sharing).

Calculating the benefits of LEZ is even harder in the absence of official cost estimates. We attempt to take a wider perspective by considering not just the health benefits, but also the wider reported satisfaction by individuals and the impact on the labour market. We recognise we have not capture all relevant benefits, in terms of education, and reduction in drug expenditure for example. Using per capita cost of illness provided by Public Health England (2020) of £3,488 for COPD, and defining people with bronchitis as COPD patients who also have a limiting health condition for more than 12 months, 141400our estimates are a lower bound figure. Applying our findings to the population estimate of COPD people in London to be about 600,000 the London Assembly website, we have savings for just over £460,416M. Using the statutory sick pay (SSP) UK figure of £96.35 per week, for an estimated 141.4 million working days lost (ONS, 2018), and applying our estimates we have savings for over £15.5M. The calculation leads to £963,706,221 savings for the overall population, excluding the life satisfaction benefits.

8 Conclusions

Air pollution is at the forefront of policy debates in the European Union and the United Kingdom for its negative externalities not only on climate change, but also on job productivity, hindering human capital accumulation, and on the healthcare sector as it contributes to cardiovascular diseases (CVDs), lung cancer and respiratory diseases affecting hospital admissions and mortality. The death of Ella Kissi-Debrah, a black girl in South London, has marked the first time a Court stated air pollution was "a material contribution" to her death. However, evidence on the causal impact of the type of policies that can impact on air pollution and health is still mounting.

This paper has investigated the health and well-being effects of one of the largest clean air transport policies in Europe, the Greater London's Low Emission Zone (LEZ) and the toughest one in the world, the Ultra Low Emission Zone (ULEZ) in Central London. Exploiting the spatial and temporal variation of these policies, whereas LEZ was introduced on the 4^{th} of February 2008 in Greater London and ULEZ on the 8^{th} of April 2019 in Central London, we use a difference-in-differences approach to estimate the causal impact of these policies on health and well-being.

We have found that LEZ has significantly reduced PM_{10} by 12% of the baseline mean, with no significant impact on NO_2. However, ULEZ, the tougher policy, has reduced both NO_2 by 12.4% and PM_{10} by 27%. These reductions in pollutants have been brought about by changes in the vehicle fleet composition, where ULEZ has increased Ultra-Low Emission Vehicles (ULEVs) by about 357 units.

We have shown that LEZ leads to a 7% reduction in limiting health problems. This effect is stronger in the second phase of LEZ, where we have also observed a 4.6% reduction in the incidence of long-term health problems and an 17% reduction in the probability of asking sick leave. The impact of ULEZ on health is even more pronounced, as we have found a reduction in the probability of having long-term health problems by 22.5%, number of health conditions by 29.8% and sick leave by 17.7%. ULEZ has also improved feelings of happiness, worthiness and satisfaction by 1.3%, 1.3% and 1%, respectively. ULEZ also reduced anxiety by 6.5%.

How do these results compare to the literature? We compare our results to the studies focusing on clean air transport policies. Our results are within the range of findings on the effects of congestion charge policies with a PM_{10} reduction between 10-20 percent (Simeonova et al., 2019; Green et al., 2020), and of other European LEZ policies with a PM_{10} reduction between 13-50 percent (Ellison et al., 2013; Margaryan, 2021). Our weaker results on NO_2 are actually comparable to the literature as Ellison et al. (2013) have found only a modest reduction, and Green et al. (2020) have actually found an increase in NO_2 due to the type of vehicles. As expected, the toughest clean air policy in the world, ULEZ, has led to stronger reductions of both pollutants than found by previous studies for any of the other clean air transport policies.

It is harder to compare the health effects across studies because of the way they are differently measured. However, we find similar effects as others with a reduction in circulatory and cerebrovascular diseases between 2.9 and 13 percent (Pestel and Wozny, 2021; Margaryan, 2021). There are no studies examining the impact of clean air transport policies on well-being. However, our results compare favourably to the literature: Li et al. (2021) have examined the impact of air pollution on well-being and found hazardous air pollution decreases self-esteem by 0.9% (comparable to our worthiness result of 1.3%). Although they have not found any statistically significant impact on life satisfaction, it is hard to compare them because ULEZ is the toughest policy in the world and Li et al. (2021) have only examined the air pollution elasticity.

There are no studies examining the impact of clean air transport policies on job productivity. However, our results are higher than those found by Holub et al. (2020) where the Saharan desert dust is related to a reduction in weekly absence rate by 1.1% of the sample mean. This difference may be due to the stronger impact of LEZ and ULEZ on pollution than a temporary shock from the Saharan desert.

There is no official cost-benefit analysis of LEZ and in absence of it, it is hard to produce estimates accounting all relevant health and non-health costs. We use a back-of-the-envelope approach using our in-sample estimates of the health and non-health impacts and found that LEZ leads to just over £963.7M savings for the overall population, excluding its life satisfaction benefits.

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Appendix A Supplementary Tables

Table A.1: Robustness check excluding/including Oxford and Norwich, pollution

	(1) NO_2	(2) PM_{10}
	Panel A: Excluding Oxford, Brighton, and Norwich from control	
London*Post	-0.676	-3.502***
	(0.898)	(0.502)
Observations	250,517	145,452
	Panel B: Excluding Oxford, Brighton, and Norwich from control	
London*Post Phase 1	3.041**	-1.758**
	(1.223)	(0.745)
London*Post Phase 2 LEZ	-0.913	-4.261***
	(1.021)	(0.621)
London*Post Phase 3	0.861	-4.267***
	(1.558)	(1.078)
Observations	250,517	145,452
	Panel C: Including Oxford, Brighton, and Norwich in treatment	
In LEZ	0.574	-3.343***
	(0.852)	(0.522)
Observations	271,477	151,519
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
Treatment Specific Trends	Yes	Yes

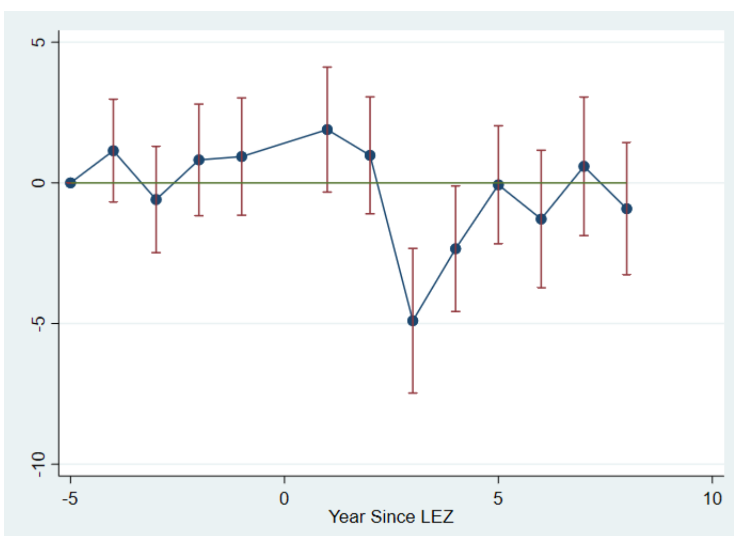
Robust standard errors (clustered at the city level) in parentheses. Ferman-Pinto p-values in brackets. The asterisks next to the coefficients are for p-values associated with the main (non-Ferman-Pinto p-values) regressions. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction.

Table A.2: LEZ on pollution: Controlling for city specific trend

	(1) NO_2	(2) PM_{10}
	Panel A: LEZ	
London*Post	-0.335	-3.638***
	(0.874)	(0.523)
Observations	271,477	151,519
	Panel B: LEZ Phases	
London*Post Phase 1	3.127***	-1.753***
	(1.046)	(0.629)
London*Post Phase 2	-0.433	-4.786***
	(1.011)	(0.657)
London*Post Phase 3	1.472	-5.524***
	(1.514)	(1.148)
Observations	271,477	151,519
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
City Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction.

FIGURE A.1. NO_2 Event Study Graph



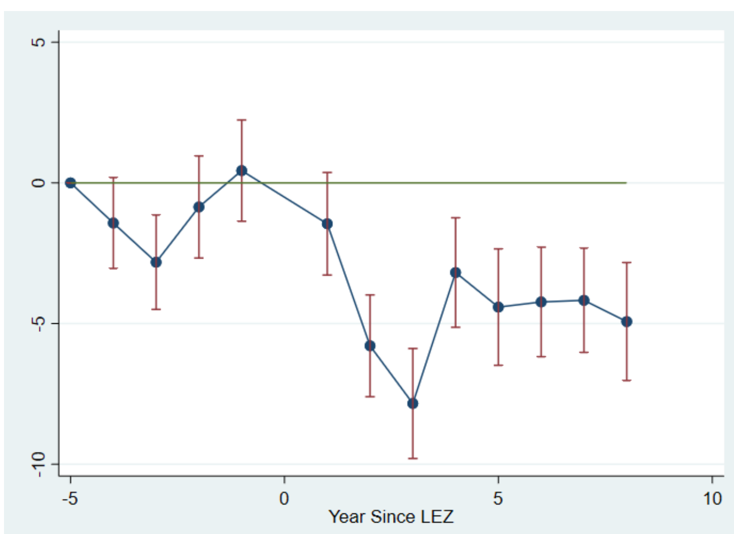
The figure depicts coefficients (along with 95% confidence intervals) estimated from dynamic difference-in-differences specification of Equation (1), where treatment time is assigned for each year from 2003 to 2015. The reference period (omitted period) is 2003 (5 years prior from LEZ).

Table A.3: LEZ effect on pollution: No Weather controls

	(1) NO_2	(2) PM_{10}
	Panel A: LEZ	
London*Post	-0.943**	-3.579***
	(0.422)	(0.392)
Observations	271,479	151,519
	Panel B: LEZ Phases	
London*Post Phase 1	0.435	-2.781***
	(0.379)	(0.512)
London*Post Phase 2	-1.239**	-4.163***
	(0.478)	(0.394)
London*Post Phase 3	-0.994	-4.570***
	(0.764)	(0.643)
Observations	271,479	151,519
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	No	No
Treatment Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction.

FIGURE A.2. PM_{10} Event Study Graph



The figure depicts coefficients (along with 95% confidence intervals) estimated from dynamic difference-in-differences specification of Equation (1), where treatment time is assigned for each year from 2003 to 2015. The reference period (omitted period) is 2003 (5 years prior from LEZ)

Table A.4: LEZ on Pollution: Restricting to cities over 100k population

	(1) NO_2	(2) PM_{10}
	Panel A: LEZ	
London*Post	-0.837	-3.482***
	(0.890)	(0.508)
Observations	238,283	135,855
	Panel B: LEZ Phases	
London*Post Phase 1	3.251***	-1.337**
	(0.940)	(0.589)
London*Post Phase 2	-1.063	-4.343***
	(1.005)	(0.653)
London*Post Phase 3	0.964	-4.242***
	(1.456)	(1.154)
Observations	238,283	135,855
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
Treatment Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction.

Table A.5: LEZ on pollution: Excluding New Years Eve and Day

	(1) NO_2	(2) PM_{10}
	Panel A: LEZ	
London*Post	-0.316	-3.417***
	(0.834)	(0.492)
Observations	269,992	150,646
	Panel B: LEZ Phases	
London*Post Phase 1	3.118***	-1.738**
	(1.112)	(0.711)
London*Post Phase 2	-0.477	-4.157***
	(0.940)	(0.613)
London*Post Phase 3	1.279	-4.167***
	(1.435)	(1.067)
Observations	269,992	150,646
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
Treatment Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction.

Table A.6: LEZ on pollution: Combining Phase 1 and 2

	(1) NO_2	(2) PM_{10}
London*Post Phase 1 & 2	0.345	-3.460***
	(0.928)	(0.568)
London*Post Phase 3	2.162	-3.474***
	(1.440)	(1.024)
Observations	271,477	151,519
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
Treatment Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction.

Table A.7: Effect of LEZ, TC and ULEZ using city specific trend, pollution

	(1) NO_2	(2) PM_{10}
CL*Post LEZ	1.537*	-5.632***
	(0.774)	(0.528)
CL*Post TC	-1.175	-7.405***
	(1.118)	(0.650)
CL*Post ULEZ	-6.686***	-8.244***
	(1.440)	(0.973)
Observations	233,074	138,302
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
City Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction.

Table A.8: Effect of LEZ, TC and ULEZ not including weather controls, pollution

	(1) NO_2	(2) PM_{10}
CL*Post LEZ	1.329***	-5.347***
	(0.476)	(0.421)
CL*Post TC	-2.060***	-6.477***
	(0.694)	(0.510)
CL*Post ULEZ	-6.103***	-6.749***
	(0.831)	(0.677)
Observations	233,080	138,305
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	No	No
Treatment Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction.

Table A.9: Effect of LEZ, TC and ULEZ restricting to cities with 100k population, pollution

	(1)	(2)
	NO_2	PM_{10}
CL*Post LEZ	1.264	-5.251***
	(0.802)	(0.498)
CL*Post TC	-2.080*	-7.229***
	(1.165)	(0.689)
CL*Post ULEZ	-7.776***	-7.875***
	(1.477)	(0.989)
Observations	203,211	126,265
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
Treatment Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction.

Table A.10: Effect of LEZ, TC and ULEZ excluding new years eve and day

	(1)	(2)
	NO_2	PM_{10}
CL*Post LEZ	1.831**	-5.103***
	(0.734)	(0.474)
CL*Post TC	-1.199	-7.062***
	(1.094)	(0.634)
CL*Post ULEZ	-6.538***	-7.554***
	(1.395)	(0.923)
Observations	231,802	137,516
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
Treatment Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction.

Table A.11: LEZ on pollution: Excluding weekends

	(1) NO_2	(2) PM_{10}
	Panel A: LEZ	
London* Post LEZ	-0.073	-3.453***
	(0.874)	(0.512)
Observations	192,965	107,519
	Panel B: LEZ Phases	
London* Post Phase 1	3.587***	-1.388*
	(1.144)	(0.758)
London* Post Phase 2	-0.218	-4.279***
	(0.974)	(0.633)
London* Post Phase 3	1.689	-4.181***
	(1.449)	(1.129)
Observations	192,965	107,519
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
Treatment Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction.

Table A.12: LEZ on pollution: Excluding CCZ and WEZ

	(1)	(2)
	NO_2	PM_{10}
	Panel A: LEZ	
London* Post LEZ	0.694	-3.536***
	(0.818)	(0.503)
Observations	253,261	143,118
	Panel A: LEZ Phases	
London* Post Phase 1	4.355***	-2.269***
	(1.060)	(0.703)
London* Post Phase 2	0.102	-4.331***
	(0.918)	(0.632)
London* Post Phase 3	1.166	-4.821***
	(1.386)	(1.098)
Observations	253,261	143,118
Monitoring Station FE	Yes	Yes
Month FE	Yes	Yes
Year FE	Yes	Yes
Weather Controls	Yes	Yes
Treatment Specific Trends	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Weather controls include: Average precipitation, average temperature, mean wind speed, and mean wind direction.

Table B.1: Estimated Effect of LEZ on Health, Excluding/Including Oxford and Norwich

	(1)	(2)	(3)	(4)	(5)	(6)
	Ever had health problems longer than 12 month	Chest/ breathing problems asthma, bronchitis	Health problems limiting activity	Heart, blood pressure, blood circulatory problems	No. health conditions	Sick leave
	Panel A: Excluding Oxford, Norwich and Brighton from the control, baseline					
London* Post LEZ	-0.013***	-0.007***	-0.012***	-0.001	-0.013	-0.004***
	(0.004)	(0.002)	(0.003)	(0.002)	(0.009)	(0.001)
Observations	1,219,562	1,219,562	1,219,552	1,219,562	1,219,562	764,071
	Panel B: Excluding Oxford, Norwich and Brighton from the contro, by Phase					
London*Post phase 1	-0.008**	-0.002	-0.003	-0.001	0.007	0.000
	(0.004)	(0.003)	(0.004)	(0.003)	(0.012)	(0.002)
London*Post phase 2	-0.013***	-0.009***	-0.011***	-0.005**	-0.036***	-0.004***
	(0.004)	(0.002)	(0.003)	(0.003)	(0.011)	(0.001)
London*Post phase 3	-0.011*	-0.010***	-0.006	-0.013***	-0.062***	-0.002
	(0.006)	(0.003)	(0.005)	(0.004)	(0.019)	(0.002)
Observations	1,219,562	1,219,562	1,219,552	1,219,562	1,219,562	764,071
	Panel C: Including Oxford, Norwich and Brighton in to the treatment					
In LEZ	-0.008**	-0.004*	-0.006*	0.001	0.002	-0.004***
	(0.004)	(0.002)	(0.004)	(0.002)	(0.017)	(0.001)
Observations	1,249,127	1,249,127	1,249,117	1,249,127	1,249,127	783,666
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, employment status, LSOA level IMD rank, and MSOA level average house price as controls. We apply weights provided by the survey.

Table B.2: Estimated Effect of LEZ on Health, city trend

	(1)	(2)	(3)	(4)	(5)	(6)
	Ever had health problem longer than 12 month	Chest/ breathing problems, asthma, bronchitis	Health problems limiting activity	Heart, blood pressure, blood circulatory problems	No. health conditions	Sick leave
	Panel A: LEZ					
London* Post LEZ	-0.012***	-0.006***	-0.012***	-0.000	-0.010	-0.004***
	(0.004)	(0.002)	(0.003)	(0.002)	(0.010)	(0.001)
Observations	1,249,127	1,249,127	1,249,117	1,249,127	1,249,127	783,666
	Panel B: By Phase					
London*Post phase 1	-0.008**	-0.002	-0.002	-0.000	0.010	0.001
	(0.004)	(0.002)	(0.004)	(0.003)	(0.012)	(0.001)
London*Post phase 2	-0.013***	-0.008***	-0.012***	-0.005*	-0.034***	-0.004***
	(0.004)	(0.002)	(0.003)	(0.003)	(0.011)	(0.001)
London*Post phase 3	-0.012*	-0.009***	-0.007	-0.012***	-0.063***	-0.002
	(0.006)	(0.003)	(0.005)	(0.004)	(0.019)	(0.002)
Observations	1,249,127	1,249,127	1,249,117	1,249,127	1,249,127	783,666
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, employment status, LSOA level IMD rank, and MSOA level average house price as controls. We apply weights provided by the survey.

Table B.3: Estimated Effect of LEZ, TC and ULEZ on Health, region trend

	(1) Ever had health problems longer than 12 month	(2) Chest/ breathing problems, asthma, bronchitis	(3) Heart, blood pressure, blood circulatory problems	(4) No. health conditions	(5) Sick leave
CL*Post LEZ	-0.012***	-0.007***	-0.007***	-0.038***	-0.005***
	(0.003)	(0.001)	(0.001)	(0.008)	(0.001)
CL*Post TC	-0.031***	-0.008***	-0.011***	-0.064***	-0.004***
	(0.004)	(0.002)	(0.002)	(0.009)	(0.001)
CL*Post ULEZ	-0.039***	-0.005	-0.008***	-0.075***	-0.005***
	(0.005)	(0.003)	(0.002)	(0.014)	(0.002)
Observations	2,111,522	2,111,522	2,111,522	2,111,522	2,117,433
Month FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes
Region Specific Trends	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, LSOA level IMD rank, and MSOA level average house price as controls. We apply weights provided by the survey.

Table B.4: Estimated Effect of TC and ULEZ on General Health and Well-being, region trend

	(1) General health	(2) Good health	(3) Happy	(4) Worthwhile	(5) Satisfied	(6) Anxious
CL*Post TC	0.001	-0.004*	0.008	-0.007	-0.046***	0.019
	(0.007)	(0.002)	(0.015)	(0.012)	(0.011)	(0.024)
CL*Post ULEZ	-0.048***	0.013***	0.098***	0.115***	0.097***	-0.206***
	(0.010)	(0.002)	(0.018)	(0.016)	(0.017)	(0.035)
Observations	696,877	696,877	446,614	445,899	446,685	446,326
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Region Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, LSOA level IMD rank, and MSOA level average house price as controls. We apply weights provided by the survey.

Table B.5: Estimated Effect of LEZ on Health, phase 1 and 2 combined

	(1)	(2)	(3)	(4)	(5)	(6)
	Ever had health problems longer than 12 month	Chest/ breathing problems, asthma, bronchitis	Health problems limiting activity	Heart, blood pressure, blood circulatory problems	No. health conditions	Sick leave
London*Post phase 1 & 2	-0.011***	-0.006***	-0.009***	-0.003	-0.020**	-0.003**
	(0.004)	(0.002)	(0.003)	(0.002)	(0.010)	(0.001)
London*Post phase 3	-0.010*	-0.006**	-0.003	-0.010***	-0.044**	0.000
	(0.006)	(0.003)	(0.005)	(0.004)	(0.017)	(0.002)
Observations	1,249,127	1,249,127	1,249,117	1,249,127	1,249,127	783,666
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, employment status, LSOA level IMD rank, and MSOA level average house price as controls. We apply weights provided by the survey.

Table B.6: Estimated Effect of LEZ on Health, major cities

	(1)	(2)	(3)	(4)	(5)	(6)
	Ever had health problems longer than 12 month	Chest/ breathing problems, asthma, bronchitis	Health problems limiting activity	Heart, blood pressure, blood circulatory problems	No. health conditions	Sick leave
	Panel A: LEZ					
London* Post LEZ	-0.012***	-0.005**	-0.011***	0.000	-0.007	-0.004***
	(0.004)	(0.002)	(0.003)	(0.002)	(0.011)	(0.001)
Observations	1,086,572	1,086,572	1,086,562	1,086,572	1,086,572	680,728
	Panel B: by Phasel					
London*Post phase 1	-0.006	-0.001	-0.000	-0.000	0.012	-0.000
	(0.005)	(0.003)	(0.004)	(0.003)	(0.014)	(0.002)
London*Post phase 2	-0.013**	-0.008***	-0.012***	-0.005*	-0.040***	-0.004***
	(0.005)	(0.002)	(0.003)	(0.003)	(0.013)	(0.001)
London*Post phase 3	-0.012*	-0.010***	-0.008	-0.013***	-0.082***	-0.002
	(0.007)	(0.004)	(0.006)	(0.004)	(0.021)	(0.002)
Observations	1,086,572	1,086,572	1,086,562	1,086,572	1,086,572	680,728
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, employment status, LSOA level IMD rank, and MSOA level average house price as controls. We apply weights provided by the survey.

Table B.7: Estimated Effect of LEZ on Health, no controls

	(1)	(2)	(3)	(4)	(5)	(6)
	Ever had health problems longer than 12 month	Chest/ breathing problems, asthma, bronchitis	Health problems limiting activity	Heart, blood pressure, blood circulatory problems	No. health conditions	Sick leave
				Panel A: LEZ		
London* Post LEZ	-0.015***	-0.007***	-0.014***	-0.001	-0.015	-0.004***
	(0.004)	(0.002)	(0.003)	(0.002)	(0.011)	(0.001)
Observations	1,250,779	1,250,779	1,250,769	1,250,779	1,250,779	784,656
				Panel B: by Phase		
London*Post phase 1	-0.012***	-0.003	-0.006	-0.001	-0.004	0.000
	(0.004)	(0.002)	(0.004)	(0.003)	(0.013)	(0.001)
London*Post phase 2	-0.016***	-0.009***	-0.014***	-0.006**	-0.042***	-0.004***
	(0.005)	(0.002)	(0.003)	(0.003)	(0.013)	(0.001)
London*Post phase 3	-0.017**	-0.011***	-0.012**	-0.014***	-0.081***	-0.002
	(0.007)	(0.003)	(0.005)	(0.004)	(0.021)	(0.002)
Observations	1,250,779	1,250,779	1,250,769	1,250,779	1,250,779	784,656
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	No	No	No	No	No	No
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We apply weights provided by the survey.

Table B.8: Estimated Effect of LEZ, TC and ULEZ on Health, no controls

	(1)	(2)	(3)	(4)	(5)
	Ever had health problems longer than 12 month	Chest/ breathing problems, asthma, bronchitis	Heart, blood pressure, blood circulatory problems	No. health conditions	Sick leave
CL*Post LEZ	-0.014***	-0.007***	-0.009***	-0.042***	-0.005***
	(0.003)	(0.001)	(0.001)	(0.009)	(0.001)
CL*Post TC	-0.034***	-0.008***	-0.013***	-0.069***	-0.003***
	(0.004)	(0.002)	(0.002)	(0.010)	(0.001)
CL*Post ULEZ	-0.040***	-0.004	-0.010***	-0.075***	-0.004**
	(0.006)	(0.003)	(0.003)	(0.015)	(0.002)
Observations	2,113,166	2,113,166	2,113,166	2,113,166	2,119,110
Month FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes
Controls	No	No	No	No	No
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We apply weights provided by the survey.

Table B.9: Estimated Effect of TC and ULEZ on General Health and Well-being, no controls

	(1) General health	(2) Good health	(3) Happy	(4) Worthwhile	(5) Satisfied	(6) Anxious
CL*Post TC	0.006	-0.006**	0.001	-0.013	-0.064***	0.030
	(0.007)	(0.002)	(0.017)	(0.012)	(0.011)	(0.021)
CL*Post ULEZ	-0.045***	0.012***	0.089***	0.110***	0.083***	-0.190***
	(0.009)	(0.002)	(0.020)	(0.016)	(0.015)	(0.031)
Observations	697,513	697,513	447,037	446,319	447,106	446,746
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	No	No	No	No	No	No
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We apply weights provided by the survey.

Table B.10: Estimated Effect of LEZ on Health, no weight

	(1) Ever had health problem longer than 12 month	(2) Chest/ breathing problems, asthma, bronchitis	(3) Health problem limits activity	(4) Heart, blood pressure, blood circulatory problems	(5) No. health conditions	(6) Sick leave
	Panel A: LEZ					
London* Post LEZ	-0.011***	-0.005***	-0.011***	0.000	-0.004	-0.003***
	(0.003)	(0.002)	(0.003)	(0.002)	(0.010)	(0.001)
Observations	1,249,127	1,249,127	1,249,117	1,249,127	1,249,127	783,666
	Panel B: by PhaseI					
London*Post phase 1	-0.009**	-0.001	-0.002	-0.000	0.012	0.001
	(0.004)	(0.002)	(0.003)	(0.003)	(0.012)	(0.001)
London*Post phase 2	-0.011***	-0.008***	-0.012***	-0.004	-0.030**	-0.003***
	(0.004)	(0.002)	(0.003)	(0.003)	(0.012)	(0.001)
London*Post phase 3	-0.009	-0.009**	-0.007	-0.012***	-0.061***	-0.001
	(0.006)	(0.004)	(0.005)	(0.004)	(0.020)	(0.002)
Observations	1,249,127	1,249,127	1,249,117	1,249,127	1,249,127	783,666
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls FE	No	No	No	No	No	No
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, employment status, LSOA level IMD rank, and MSOA level average house price as controls.

Table B.11: Estimated Effect of LEZ, TC and ULEZ on Health, no weight

	(1)	(2)	(3)	(4)	(5)
	Ever had health problem longer than 12 month	Chest/ breathing problems, asthma, bronchitis	Heart, blood pressure, blood circulatory problems	No. health conditions	Sick leave
CL*Post LEZ	-0.012***	-0.007***	-0.006***	-0.037***	-0.005***
	(0.003)	(0.001)	(0.001)	(0.008)	(0.001)
CL*Post TC	-0.029***	-0.008***	-0.008***	-0.058***	-0.005***
	(0.003)	(0.002)	(0.001)	(0.008)	(0.001)
CL*Post ULEZ	-0.032***	-0.006*	-0.007***	-0.063***	-0.006***
	(0.005)	(0.003)	(0.002)	(0.012)	(0.002)
Observations	2,111,522	2,111,522	2,111,522	2,111,522	2,117,433
Month FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes
Controls FE	No	No	No	No	No
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, LSOA level IMD rank, and MSOA level average house price as controls.

Table B.12: Estimated Effect of TC and ULEZ on General Health and Well-being, no weight

	(1)	(2)	(3)	(4)	(5)	(6)
	General health	Good health	Happy	Worthwhile	Satisfied	Anxious
CL*Post TC	-0.001	-0.002	0.005	0.016	-0.033***	-0.008
	(0.005)	(0.002)	(0.012)	(0.010)	(0.010)	(0.022)
CL*Post ULEZ	-0.033***	0.008***	0.031	0.106***	0.078***	-0.172***
	(0.008)	(0.002)	(0.018)	(0.017)	(0.017)	(0.031)
Observations	696,877	696,877	446,614	445,899	446,685	446,326
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	No	No	No	No	No	No
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, LSOA level IMD rank, and MSOA level average house price as controls.

Table B.13: Estimated Effect of LEZ on Health, restricting for those in employment

	(1)	(2)	(3)	(4)	(5)	(6)
	Ever had health problem longer than 12 month	Chest/ breathing problems, asthma, bronchitis	Health problem limits activity	Heart, blood pressure, blood circulatory problems	No. health conditions	Sick leave
	Panel A: LEZ					
London*Post LEZ	-0.019***	-0.007***	-0.013***	-0.005**	-0.030***	-0.004***
	(0.004)	(0.002)	(0.003)	(0.002)	(0.009)	(0.001)
Observations	784,059	784,059	784,053	784,059	784,059	783,665
	Panel B: LEZ by phase					
London*Post phase 1	-0.011**	-0.002	-0.004	-0.003	-0.027***	0.001
	(0.005)	(0.002)	(0.004)	(0.002)	(0.010)	(0.001)
London*Post phase 2	-0.021***	-0.010***	-0.016***	-0.007**	-0.039***	-0.004***
	(0.005)	(0.002)	(0.003)	(0.003)	(0.010)	(0.001)
London*Post phase 3	-0.020***	-0.011***	-0.016***	-0.008*	-0.052***	-0.002
	(0.007)	(0.003)	(0.005)	(0.005)	(0.016)	(0.002)
Observations	784,059	784,059	784,053	784,059	784,059	783,665
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls FE	No	No	No	No	No	No
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, employment status, LSOA level IMD rank, and MSOA level average house price as controls. We apply weights provided by the survey.

Table B.14: Estimated Effect of LEZ on Health, removing CCZ area from treatment zone

	(1)	(2)	(3)	(4)	(5)	(6)
	Ever had health problem longer than 12 month	Chest/ breathing problems, asthma, bronchitis	Health problem limits activity	Heart, blood pressure, blood circulatory problems	No. health conditions	Sick leave
	Panel A: LEZ					
London*Post LEZ	-0.012***	-0.007***	-0.011***	0.000	-0.009	-0.005***
	(0.004)	(0.002)	(0.003)	(0.002)	(0.010)	(0.001)
Observations	1,230,595	1,230,595	1,230,585	1,230,595	1,230,595	772,441
	Panel B: LEZ by phase					
London*Post phase 1	-0.009**	-0.002	-0.002	-0.000	0.009	0.001
	(0.004)	(0.002)	(0.004)	(0.003)	(0.012)	(0.001)
London*Post phase 2	-0.011**	-0.009***	-0.012***	-0.004*	-0.033***	-0.004***
	(0.004)	(0.002)	(0.003)	(0.003)	(0.011)	(0.001)
London*Post phase 3	-0.009	-0.010***	-0.008	-0.012***	-0.062***	-0.001
	(0.006)	(0.003)	(0.005)	(0.004)	(0.019)	(0.002)
Observations	1,230,595	1,230,595	1,230,585	1,230,595	1,230,595	772,441
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
MSOA FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls FE	No	No	No	No	No	No
Treatment Specific Trends	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors (clustered at the city level) in parentheses. *** p<0.01, ** p<0.05, * p<0.1. We include age, gender, ethnicities, type of housing, employment status, LSOA level IMD rank, and MSOA level average house price as controls. We apply weights provided by the survey.