Air Pollution, Road Transport, and Spatial Spillovers: Evidence from the Low Emission Zone in London

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Abstract:
Low emission zones (LEZs) have been implemented widely in Europe to tackle air pollution sourced from vehicular emissions. We quantify the effectiveness of the world's largest LEZ - London's LEZ - in reducing its target pollutant, PM10. Using a difference-in-difference (DID) framework, we find that the least stringent phase I of London's LEZ first worked against the desired direction and increased the roadside PM10 level by about 8 percent, whereas phase II significantly drove down the roadside PM10 in London by 7 percent. Phase II also reduced the PM10 in proximate areas by 5 percent, leading to positive spatial spillovers. We explore the underlying behavioral reasons contributing to the divergent policy effect across stages. We show that the traffic volume of the targeted heavy goods vehicles (HGVs) continued to grow upon the implementation of phase I. In contrast, light goods vehicles (LGVs) regulated by phase II of the LEZ showed a declining traffic flow. We explain this phenomenon using sunk cost fallacy. Monetary outlay associated with the LEZ policy induced drivers to overconsume the road usage to get their money's worth. This tendency is short-lived and would decay over time. Evidence from the energy consumption sector supports our arguments.

Key Words: Low Emission Zone, Particulate Matter, Difference-in-Difference

JEL Codes: H23, Q51, Q53, Q58, R41

I. Introduction

Road transport and the resulting vehicular emission have become one of the leading challenges facing European nations. Recent reports by the European Environmental Agency (EEA) point out that the transportation sector accounts for the emissions of about 47% nitrogen oxides and 13% particulate matter across 33 EEA countries (EEA 2015, 2016). Besides, road transport constitutes over 20% of the carbon dioxides emissions in Europe and is the only source of greenhouse gas (GHG) emission that steadily trended up since 1990 (EEA 2016). High levels of air pollution have been documented to impose significant social costs, causing increased school absence rates (Currie et al. (2009); Chen et al. (2018)) and lower academic performance (Ebenstein et al. (2016)), reduced labor productivity (Zivin Graff and Neidell (2012); Hanna and Oliva (2015); Chang et al. (2016); Archsmith et al. (2018); He et al. (2019); Chang et al. (2019)), raised infant mortality rates (Chay and Greenstone (2003); Cesur et al. (2017)), and shortened life expectancy (Chen et al. (2013); Heutel and Ruhm (2016)).

The issue of transport-related pollution emissions is more notable in urban areas. In Europe, about one-fifth to one-third of the urban population were exposed to PM10 concentrations above the EU and WHO reference levels (EEA 2013) by the year of 2011. Outdoor exposures to air pollution cause nearly 600,000 premature deaths in EU nations annually (WHO (2015)). The reduction in life expectancy and human capital resulting from air pollution can be associated with 1.575 trillion pounds annual loss (equivalent to 137 trillion US dollars).

Over recent decades, policymakers in European countries have increased the scale of actions to attenuate air pollution coming from road transportation.[1] The Low Emission Zone (LEZ) is one of the most widely adopted traffic policies in urban areas in Europe. It is an incentive-based regulation targeted at reducing emissions from specific categories of diesel-engine vehicles. The first generation of LEZs was launched in Stockholm, Göteborg, and Malmo in Sweden under the name of environmental zones (*Miljözon*) in the late 1990s (Holman et al. (2015)). Heavy goods vehicles (HGVs) are required to equip with certified emission control devices or a replaced engine

[1] For instance, congestion charge schemes were introduced in major cities like Stockholm and London, aiming at shifting the peak-hour demand for roads. In the United Kingdom, legislation tightening the standards of diesel and petrol fuels used for road transport was updated frequently, while the consumption of green vehicles was among the most heavily subsidized areas. In the year 2018, the low-emission vehicles grant in the UK provides discounted prices to consumers purchasing eligible vehicles through subsidizing dealership by £1,500 to £8,000 based on vehicle type.

before entering a LEZ-city. Following the earliest practice, Germany, France, and Italy also established LEZs to regulate entrance from heavily polluting vehicles into specified areas (see Wolff and Perry (2010) for a review). Despite the widespread adoption of LEZs, only a handful of research has examined the effectiveness of this policy on shifting the traffic patterns and improving the air quality in the designated areas. Besides, very few research has explored the underlying mechanism that motivates a transition in traffic flow and the possible avoidance behaviors triggered by LEZ policy.

This paper provides empirical evidence on the environmental and behavioral effects of the largest LEZ in the world – the LEZ implemented in the Greater London area (hereafter "London" for simplicity). Launched on Feb 4, 2008, London's LEZ leveraged on a strictly enforced pricing scheme to discourage the emissions of PM10 from heavily polluting vehicles within the zone 24 hours a day, 365 days a year, including national and public holidays. The policy incorporated multiple phases, with each phase being a more advanced stage with a broader scope of vehicles under regulation or more restrictive emission standards for the already included vehicles. Upon establishment, the LEZ came with rigorous enforcement techniques with the installment of over 300 cameras on major and minor roads accompanied by an automatic plate recognition system that monitored compliance behaviors inside London.

London's LEZ covers an area of about 1,600 square kilometers, where over 8 million population resides. Nevertheless, existing empirical analysis on the environmental impact of London's LEZ primarily relies on limited-scale air quality data. Ellison et al. (2013) compare the changes of particulate matter (PM10) and nitrogen oxides (NOx) measured by three stations inside London and one station outside London after the LEZ implementation. Results show that the LEZ brought minimal impact on the PM10 emissions. Jones et al. (2012) analyze air quality changes in late 2007, during which the LEZ policy was publicly announced but not yet implemented. The authors collect hourly data from three monitoring stations and uncover a significant improvement in air quality inside the zone. However, most of the environmental benefits are found to be attributed to the nation's gradual replacement of ultra-low sulfur fuels to "sulfur-free" fuels, instead of the pre-compliance adjustments to London's LEZ.[2]

[2] Ultra-low sulfur diesel (with a maximum of 15 ppm of sulfur) was introduced in the UK since 1999. The sulfur-free requirement further pushes down the standard to 10 ppm.

Researchers have mixed findings for the effect of LEZs operated in other European cities. Boogaard et al. (2012) analyze the changes of traffic-related air pollutants in urban roadside areas versus suburban locations in five Dutch cities following the introduction of LEZs. The study finds no effect of the LEZ policy on street-level air quality and no significant decline in traffic intensity at all but one urban location. Wolff and Perry (2010) and Wolff (2013) examine multiple different sized LEZs in Germany. They show that, on average, the LEZs have reduced the PM10 by 9 percent, but larger ones are estimated to generate more pronounced effects than smaller ones.

In this paper, we make four contributions to the existing literature. First, we combine the most comprehensive data from a network of air monitoring systems spanning from London to Oxford, Cambridge, and other major cities in England. The spatially distributed sample consisting of 65 stations allows us to create a rich panel of air quality observations. Second, besides the policy's treatment effect inside London, we also identify its spillover effect using stations located adjacent to the LEZ border. Meanwhile, we uncover substantial geographical heterogeneity of the environmental impact across roadside, urban background, and industrial areas. Third, we use traffic flow data combined with fuel consumption of a variety of vehicles to show the behavioral impact of London's LEZ policy. We find evidence of both desired and undesired behavioral adjustments, which led to distinctive policy effects across phases. Lastly, we provide psychological explanations to the observed outcome and discuss policy implications.

In the primary regression, we apply a difference-in-difference (DID) method on 36 monitoring stations located along major representative roads within and far (i.e., at least 25 miles away) from the LEZ. We use station-specific fixed effects to account for heterogenous baseline levels of air quality and a group of time fixed effects to control for both long-run trends and seasonal variations of pollution that happen nationwide. Our estimates of interest identify the roadside air quality changes occurring in each phase of London's LEZ compared to that in distant locations with similar environmental characteristics and weather conditions.

In our preferred model with the richest set of control variables, we find that the phase I of London's LEZ - the least stringent phase - did not effectively reduce PM10 inside London. Instead, it worked against the desired direction and triggered an 8 percent increase in PM10 during its operating period. In contrast, the second phase with a broader scope of subject vehicles and tighter emission standards generated a 7 percent reduction of PM10 inside London. These impacts were salient only along major roads where vehicular emissions constitute the most significant source of air pollution. No comparable effect was found in the urban background (e.g., residential) and industrial areas. Besides, there was no evident improvement of air quality in London during the nine-month announcement period of the LEZ.

Using stations located sufficiently close to (i.e., within 10 miles) the LEZ border, we also estimate that phase II has effectively reduced the roadside PM10 nearby London by about 5%, generating a positive spillover that was 2% less than the primary treatment effect during the same period. This indicates a spatially decaying influence of the LEZ outside of the target areas. We did not find a significant spillover effect in any other period, which could be either due to a lack of intensive policy treatment or because of opposing trends of externality that offset each other.

We explore the reasons underlying the divergent treatment effects in the first two phases of London's LEZ. Combining data on fuel consumption and traffic flow, we show that the distinctive policy effects can largely be explained by dramatically different traffic patterns following the implementations of phase I and II. Specifically, phase I has motivated an increasing volume of not only subject heavy goods vehicles (HGVs) by 10.7%, but also non-subject light goods vehicles (LGVs) by 9.7%. Although these vehicles are composed of a greater proportion of cleaner ones, their uphill absolute number created a dominant and adverse environmental effect on the concentrations of PM10 in phase I. As the policy proceeded to phase II, however, the number of both HGVs and LGVs traveling in London gradually declined by 5.5% and 7.4%, respectively. The reduced traffic flow thus worked with rising compliance rates to improve the air quality in London.

We use the concept of sunk cost fallacy (Arkes and Blumer (1985); Thaler (1980)) to explain the psychological motivation of the observed behavioral patterns. We propose that road consumers with a substantial monetary outlay associated with the emission criteria of the LEZ would tend to overconsume their road usage to get their money's worth. For example, individuals who upgraded their vehicles' filtering system, converted to gas, or reorganized the fleet to comply with the LEZ policy may increase their travel frequency to enjoy a higher perceived value of each trip. Likewise, drivers who paid a daily entrance fee for the privilege of using the roads inside the zone may be triggered to travel a longer distance within a day to avoid multiple entrances on different dates. We show that these behavioral motives created a net impact of a larger traffic volume shortly after the launch of the LEZ, although any incurred costs should be considered as irrelevant in a rational decision-making process. We extrapolate the sunk cost fallacy to be manifest with more sizable monetary outlays, in which frequent usage would reduce the feeling of "loss" from past transactions. Similarly, vehicles that temporarily enjoyed the exemption of emission requirements in the early stage of the LEZ may be motivated to exhaust their consumption. Sheltered by the public provision of roads, these drivers could also overconsume their road usage to obtain a higher perceived value of the free trip. Consequently, we observe an upward trending traffic volume of all types of vehicles in phase I. As the policy proceeded, however, a broader scope of vehicles was brought under regulation, shifting the reference point and activating a hedonic adaptation procedure. As drivers gradually adjusted to the new rules and policies, the effect of sunk cost slowly decayed.

Th present paper sits within the exploration of behavioral adjustments following incentive-based traffic regulations. Davis (2008) analyzes the environmental effect of a license plate program Hoy No Circula (HNC) launched in Mexico City in 1989. The HNC policy banned a specific group of drivers from driving on roads each day of the week based on the last digit of the license plate number. The author finds ineffectiveness of the HNC on reducing major air pollutants during its operation and an adverse effect of the policy on air quality during non-operating hours. Undesired behavioral adjustments in the form of acquiring a second, heavily polluting vehicle and substituting toward highly emitting taxis are shown to have contributed to the adverse effect of the HNC. Chen et al. (2013) examine a slightly revised license plate program in Beijing during the 2008 Olympic Games. Compared with non-Olympic cities, Beijing experienced a 25 percent reduction of air pollution index (API) when the license place program was in operation. The magnitude of the air quality improvements, however, faded away shortly after the closing of the Olympic Games and the end of the policy, reflecting a strong behavioral tendency towards the status quo. Similarly, Viard and Fu (2015) find that Beijing's driving restriction was effective in reducing air pollution concentrations but has also led to a reduction in labor supply by 9 to 17 percent during its operation period.

Our research explores the phenomena of sunk cost fallacy in the context of environmental regulation. When the cost of a transaction exceeds the benefit, individuals will tend to overweigh the sunk cost and systematically bias their choices according to the monetary outlay. Experimental evidence suggests that consumers are likely to attend more events if the price of a season ticket to the events is higher (Arkes and Blumer (1985)). Similarly, individuals would have a stronger incentive to go to a basketball game on a blizzard day if they (or their friends) have paid a higher price for it (Thaler (1980); Olivola (2018)). While experimental research in marketing and psychology has supported sunk cost fallacy, to our best knowledge, the present work provides the first piece of evidence on this behavioral pattern empirically in a large-scale, real-world setting. Although other driving forces are also possible, sunk cost fallacy provides the most plausible explanation to the observed phenomenon. Our study sheds light on the close linkage between effective behavioral modifications and the desired environmental outcome.

Previous research suggests that sunk cost fallacy is a short-run bias that will decay over time. In Arkes and Blumer's (1985) work, there was no systematic difference in the frequency of attending events across price groups after the first semester that the season ticket was purchased. Gourville and Soman (1998) show that the spike of going to a fitness club comes after the arrival of the semi-annual pre-payment bill and diminishes as time passes by. Our findings provide consistent evidence of the adaptation theory of human behaviors. In particular, as drivers adjusted to the LEZ emission regulations several months after the policy launch date, the traffic volume in London gradually declined in the subsequent phases.

The paper proceeds as follows. Section II provides background information on London's LEZ, including an outline of subject vehicles and the charging schemes. Section III summarizes the air quality and weather data in our sample. Section IV specifies the econometric model and discusses the identification strategies in the estimation of the treatment and spillover effects of the LEZ. Section V provides estimation results and performs various robustness checks for the model. Section VI further combines data in traffic flow and fuel consumption to show the underlying mechanisms of our results and discusses possible behavioral and psychological motivations. Section VII concludes with a few limitations of the current research and some possible extensions.

II. Policy background

Road transport contributes dominantly to the particulate matter concentrations in London. According to Transport for London (2011), vehicular emissions form a total of 60% PM10 in London and almost 80% PM10 in Central London, threatening to undermine human health, reduce labor supply, and slow down social and economic development. London's LEZ is one of a series of intensive controls in response to the overwhelming concerns regarding urban air pollution. The policy was publicly announced in May 2007 and went into effect in February 2008. The zone covers almost the entire region of Greater London with a total area of over 1,600 square kilometers (see Figure 1). The policy leverages on a pricing scheme that disincentivizes the usage of heavily emitting motor vehicles inside London. The first phase of the LEZ targeted at heavy goods vehicles (HGVs) and trucks that violated the EU III emission standards on PM10 (see Table 1 for EU emission criteria). The second and third phases, launched July 2008 and Oct 2010, respectively, progressed to include light goods vehicles (LGVs), larger vans, and minibuses under the EU III regulation. Starting from phase IV in Jan 2012, the minimum emission requirements was tightened to EU IV to further facilitate pollution control. Table 2a and 2b outlines the implementation date, subject vehicles, emission standards, charges and penalty fees in each phase of the LEZ.

London's LEZ is one of the most stringent traffic regulations in history. It operates on a 24-hour schedule all year round, including national and public holidays. The policy comes with rigorous enforcement strategies with the installment of over 300 cameras on major highways and truck roads. The network of cameras automatically reads and recognizes vehicle plates and transmit the data to the TfL system to check compliance. Drivers of incompliant vehicles who plan a trip to London may choose to retrofit, reorganize the fleet, or convert to gas to meet the emission standards. Unplanned drivers are notified by advance warning signs approaching the LEZ area, allowing them to detour to avoid entering the zone (see Figure 2). It is important to note that the LEZ charging scheme applies to daily road usage with no restriction on the total miles traveled. Driving within the zone across midnight will result in double charges, while parking inside London will be exempt from the policy.

The LEZ policy is among a series of intensive traffic regulations established in the Greater London area in response to the increasing concerns regarding urban road usage. On Feb 17, 2003, a congestion charge scheme (CCS) was launched in Central London to alleviate traffic jams during peak hours. The CCS imposed a daily fee of £5.00 (increased to £8.00 in July 2005, £10.00 in January 2011, and £11.50 in June 2014) for parking and driving within the zone between 7 am and 6 pm on weekdays, excluding public holidays. Research shows that the CCS policy has reduced the average time of traveling inside Central London by about 30% (Leape (2006)) and the occurrence of traffic accidents by over 40% (Green et al. (2016)). Furthermore, Green et al. (2016) find that the CCS creates a positive spillover effect, reducing fatal accidents happening in adjacent areas and neighboring periods. Nevertheless, model-based estimations on the environmental impact of CCS indicate minimal policy benefits. As Tonne et al. (2008) show, the introduction of CCS reduced concentrations of NO2 and PM10 in Central London by only 1.3% and 0.8%.[3]

Compared with the CCS, the LEZ features not only a broader region and a 24/7 operation schedule but also a distinctive pricing scheme with much higher daily charges and strong penalties. We expect this pricing scheme to motivate short-term sorting of road consumers based on their elasticities of demand, marginal willingness to pay, and travel frequencies. Frequent travelers with inelastic demand and higher willingness to pay are more likely to comply with the emission standards. Drivers who make occasional trips to London may choose to make a one-time payment for entrance. Other travelers are likely to detour and avoid entering the zone. Data on vehicle composition indicate that the first group of drivers constitutes the majority of the target population. According to TfL (2010), the LEZ has achieved a compliance rate of 98% (phase I) and 96% (phase II), respectively, within months after its implementation.

Besides driving restrictions, the United Kingdom government also imposed legislation on the quality of fuels to abate traffic-related air pollution. From June 2007, diesel and petrol used for road transport started to transition towards cleaner, “sulfur-free” fuels (i.e., with less than 10 ppm sulfur). The transition was completed in 2009, partially overlapping with the operation of the LEZ. While the sulfur-free policy has been documented to reduce the SO2 emission effectively, previous literature (e.g., Jones et al. (2012)) finds a minimal marginal impact of it on the PM10 concentrations in London. This is probably because roadside PM10 is primarily sourced from non-exhaust emissions such as brake and tire wear while reducing the sulfur component of fuel does not have a direct relationship with particle combustion. Since the sulfur-free upgrade on fuel composition is a nationwide trend, we expect it to generate no cross-sectional difference in the effect inside London versus that in other areas. Thus, the treatment effect of the LEZ can be identified by netting out the common trends occurring in all regions from the air quality improvements experienced by London in each policy period. Our model incorporates additional time fixed effects to account for both long-run and short-term air quality trends across the nation.

Pre-policy assessments on the potential environmental and health effects of London’s LEZ have mixed results. Carslaw and Beevers (2002) predict that among the various proposed versions

[3] Authors’ calculation based on the estimation results provided by the paper.

of the LEZ, even the most ambitious one would be undifferentiable with a scenario where a "do nothing" were in place within five years. Kelly et al. (2011) extrapolate that the LEZ would reduce the PM10 emissions by 2.6% in 2008 and 6.6% by 2012 with the impact being most salient along roadways. In a feasibility study, Watkiss (2003) estimate the reduced PM10 in London attributed to the LEZ policy to reach up to 23% by 2010.

III. Data

This paper assesses the environmental effect of London's LEZ by focusing on the PM10 concentrations before and after the implementation of each phase. PM10, or particulate matter with less than 10 micrometers in diameter, is the target air pollutant under all LEZ emission criteria. We obtain PM10 data from 65 air quality stations monitored by two networks: London Air Quality Network (LAQN) and Air Quality England (AQE). The LAQN spans over the entire region of Greater London, providing data on daily PM10 levels in almost all boroughs. The AQE covers areas outside of London, including the East of England, North West, South East, West Midland, and Yorkshire and the Humber. Our primary estimation sample contains thirty-six stations located along roadside or curbside, where the transport sector forms the most significant source of PM10. A typical roadside station resides within 1 meter from a representative highway or truck road and monitors air quality 2-3 meters from the ground. Besides the primary sample, our data contain twenty-one stations located in urban background (e.g., residential) areas away from major sources of pollution, and eight stations near industrial sites. Regardless of geographical features, we classify station groups based on the relative distance from each station to the LEZ border. In the primary sample, 23 (64%) roadside stations inside London are directly affected by the LEZ policy. Five (13.9%) roadside stations within 10 miles outside the LEZ border can be potentially affected by the policy spillover effects. On the one hand, drivers retrofit or reorganize the fleet to comply with the LEZ emission requirements carry positive spillover to the surrounding areas. On the other hand, detouring vehicles that strategically avoid entering the zone may generate negative externality and deteriorate the air quality near London. The stations sufficiently close to the LEZ border thus experience the net impact of these oppositely directional forces. Additionally, our sample contains eight (22.2%) roadside stations in major cities and districts non-adjacent to the LEZ border and at least 25 miles away from London. This group of stations is presumably not influenced by the LEZ because of its isolation to the zone and therefore provides baseline air quality trends in the United Kingdom. We provide evidence of this argument in Section V. Figure 3 plots the location of all air quality stations in our sample.

We estimate the impact of London's LEZ over six years from 2005 to 2010. This time window starts roughly 2.5 years before the LEZ announcement and covers the full length of both phases I and II. Due to maintenance issues and funding shortages, the LAQN began to experience a massive closure shortly before the end of 2010, threatening to reduce our sample size by almost a half if subsequent years were included. Because of this limitation, we focus primarily on the first two phases of the LEZ and make no conclusive inference on the following periods.

We plot the density distribution of logarithm daily average roadside PM10 within, nearby (< 10 miles), and far from (> 25 miles) London in Figure 4. In general, stations sitting very close to the outer border of the LEZ are the least polluted, followed by those in major cities far from the LEZ. London has the highest PM10 level on average, which largely comes from a heavy right tail of the density distribution. Table 3 summarizes the basic statistics of roadside PM10 within and outside of London. In our primary sample, 6.7% observations in London exceeded the EU 24-hour PM10 limit of 50 ug/m3. Nearby and farther observations exceeded the same limit by 2.9% and 3.5%, respectively.

Airborne particles can be attracted and absorbed by raindrops and thus are highly sensitive to precipitation and other meteorological parameters. To control for these potential confounders, we collect data on a rich set of weather variables from five stations under the network of Weather Underground and Weather Spark. These variables include daily average relative humidity, temperature, hours of precipitation, air pressure, and average and maximum wind speeds. We spatially map each air quality station with the closest weather station to build up a comprehensive panel. Table 3 provides descriptive summary statistics of the included weather conditions from 2005 to 2010. Compared to other regions, London is slightly warmer ($t = -10.58$, p-value = 0.000) and less humid ($t = 20.79$, p-value = 0.000) with about three hours of rain per day. London also has a marginally lower daily average wind speed ($t = 3.68$, p-value = 0.000) and a higher daily maximum wind speed ($t = -6.93$, p-value = 0.000) than other regions. These climate factors may lead to a higher level of PM10 within London during our sample period.

IV. Model

We use a difference-in-difference (DID) model to assess the LEZ treatment effect on the target area. Let i denote air quality station and t denote date. We structure the logarithm of daily average PM10 as a function of LEZ policy dummies, policy phase and treatment group dummies, station fixed effects (FE), time trends FE, weather and other control variables. The model takes the following form:

$$\log(PM10_{it}) = \sum_{\tau=0}^{\tau=3} \beta_\tau \cdot P\tau_t + \sum_{\tau=0}^{\tau=3} \gamma_\tau \cdot P\tau_t \cdot In_i + Yr_t + Q_t + \alpha_i + \boldsymbol{\Theta X_{it}} + W_t + H_t + \varepsilon_{it} \quad (1)$$

. $P\tau_t$ equals 1 if t is on or after the implementation date of phase τ ($\tau = 0, 1, 2, 3$ with $\tau = 0$ being the policy announcement period) and 0 otherwise. In_i is an indicator variable that equals 1 if station i is located inside the LEZ border and 0 otherwise. Yr_t and Q_t are year and quarter fixed effects capturing both long-run and seasonal waves of air quality, respectively. These trends exist because of a gradual replacement of heavily polluting vehicles by cleaner ones and an upgrade of fuel composition due to technological advancement or legislation enforcement throughout the nation. α_i is a vector of station level fixed effects capturing time-invariant factors such as road types that contribute to air quality differences across stations. $\boldsymbol{X_{it}}$ is a vector of weather variables, including relative humidity, hours of rain, temperature, air pressure, and average and maximum wind speeds. W_t and H_t measure the impact of weekends and holidays, respectively, on the level of PM10 through shifting human-centered activities. ε_{it} is the error term absorbing the effect of any random shock on PM10 concentrations. In equation (1), the coefficient of interest is γ_τ that measures the impact of phase τ on the air quality inside London. It assesses the change of PM10 experienced exclusively by within-LEZ stations, controlling for the prevailing trends captured by β_τ at all stations in phase τ and other covariates.

Since each station monitors air quality at a continuous scale, ε_{it} could be correlated across time for the same station i. Several reasons may lead to various degrees of this correlation. For instance, measurement errors of air quality due to instrument imprecision and maintenance issues can consistently affect the PM10 variability at a given station. Extreme weather conditions may also generate persistent random shocks of air quality over a short period. To account for these possibilities, we use clustered standard errors ε_{it} at the station level in the main specification. Alternative error structures are tested and discussed in the robustness checks.

Besides the policy treatment effect, we also estimate the potential spillover effect of the LEZ along major roadways sufficiently close to the border of the zone. The externality arises from two opposing behavioral adjustments. First, road consumers with an elastic demand for roads and a lower willingness to pay can choose to detour to avoid entering the zone. The detouring traffic, mainly consisting of non-compliant vehicles, could drive up the roadside particulate level nearby London. At the same time, when drivers comply with a tighter emission criterion, regions surrounding the zone would benefit. The net impact thus depends on the intensity of these behavioral adjustments, changes in vehicle composition, and the volume of traffic entering and exiting London. Under a similar difference-in-different framework, we estimate the net spillover effect using stations located within 10 miles outside the zone.

$$\log(PM10_{it}) = \sum_{\tau=0}^{\tau=3} \delta_\tau \cdot P\tau_t + \sum_{\tau=0}^{\tau=3} \varphi_\tau \cdot P\tau_t \cdot Nearby_i + Yr_t + Q_t + \alpha_i + \Theta X_{it} + W_t + H_t + v_{it} \quad (2)$$

In equation (2), we use $Nearby_i$ to indicate that a station i is located within 10 miles of the LEZ border. The coefficient φ_τ captures the impact of phase τ on roadside PM10 surrounding London. We estimate equation (2) using the same group of control stations as in equation (1) – those located in cities and districts non-adjacent to and 25 miles away from London. The meanings of the other covariates remain the same as in equation (1), and v_{it} is clustered at the station level.

Because of the non-stationarity property of air pollutants, one may concern that the spillover generated by detouring vehicles would spread across the LEZ border and bias the treatment effect of the policy. This may happen if a sufficiently large number of stations in equation (1) are located along the LEZ border. In our sample, however, a majority of stations are concentrated around the center of Greater London. Only 7 out of 23 treated stations in London reside in boroughs immediately adjacent to the border of the zone. As Figure 3 Panel B shows, these 7 stations generally are positioned towards the inner region of the corresponding borough. Therefore, we expect minimal contamination from outside vehicles. Yet since traffic flow and compliance behaviors are monitored only inside London, we are unable to observe the vehicle composition near the zone or quantify the impact of detouring vehicles. In cases where these spillovers do feedback to the target zone, the estimated policy effect in London will be driven towards zero. To summarize, the difference-in-difference frameworks outlined by equations (1) and (2) provide conservative, lower-bound estimates on the effect of the LEZ on the treated and nearby areas, respectively.

Before performing empirical analysis, one concern may be that the pre-treatment air quality trends across treated and control groups are parallel. If this assumption is violated, the air quality differential captured by the treatment coefficient on the treated should instead be attributed to external factors resulting in the non-parallel trend absent of the policy. We test the parallel trend assumption using the following equation:

$$PM10_{it} = \phi_0 + \phi_1 Tr_i + \phi_2 Yr_t + \phi_3 \cdot Tr_i \cdot Yr_t + \Theta X_{it} + W_t + H_t + \omega_{it} \quad (3)$$

Tr_i is an indicator that equals 1 if station i is treated (i.e., station i is in the treatment group in equation (1) or in the nearby group in equation (2)) and 0 otherwise. Yr_t is a continuous measure of year capturing the long-run trend of air quality. Other control variables are inherited from equations (1) and (2). Equation (3) is a nested model comprising two sub-equations:

$$\begin{cases} PM10_{it} = \phi_0 + \phi_2 Yr_t + \Theta X_{it} + W_t + H_t + \omega_{it} \; when \; Tr_i = 1 \;\; (3a) \\ PM10_{it} = \phi_0 + \phi_2 Yr_t + \Theta X_{it} + W_t + H_t + \omega_{it} \; when \; Tr_i = 0 \;\; (3b) \end{cases}$$

If pre-treatment trends are parallel across groups, there should be no statistical difference in the coefficient ϕ_2 obtained from equations (3a) and (3b). This would result in an insignificant ϕ_3 in the nested equation (3). We test this hypothesis using observations before the LEZ announcement across the treated versus control and nearby versus control groups, respectively.

V. Estimation Results

We first plot the raw levels of PM10 across 36 roadside stations inside, nearby, and far from the LEZ between 2005 and 2010. Figure 5a depicts the locally weighted smooth curves (LOWESS) by station groups. The LOWESS curves reserve both long-run trends and short-term waves and are robust to extreme outliers (Cleveland 1979). Figure 5a reveals an overall improvement of air quality in all areas of the United Kingdom. It also shows strong and consistent seasonal variations of PM10 within each year of the observation window. In general, winter months experienced higher levels of PM10 than summer months.

Figure 5b plots the deseasonalized PM10 across the sample stations. We obtain the deseasonalized PM10 by subtracting the coefficient of the quarter indicator λ_q $(q = 1,2,3)$ from the observed values of PM10.

$$PM10_{it} = \lambda_0 + \lambda_1 Q1_t + \lambda_2 Q2_t + \lambda_3 Q3_t + \mu_{it}$$

As Figure 5b illustrates, the deseasonalization process partially smooths out seasonal variations of PM10. However, there was still an apparent spike of PM10 around the introduction date of LEZ phase I for inside and nearby stations. Besides, a positive gap between the PM10 in London and that in the control areas started to emerge from the LEZ announcement, during which period the control areas experienced a rather stable level of air quality. This important evidence suggests that, even though pre-compliance behaviors took place throughout the policy announcement period, our control stations far from London are not affected by the LEZ-induced vehicle upgrades. Thus, the DID framework is valid in capturing the policy treatment effect. From the middle of phase II, PM10 inside London began to decline dramatically, closing the gap between the treated and the control areas. During the six-year period, the air quality in and surrounding London reveals very consistent and parallel trends, with the former being about 4 ug/m3 higher than the latter.

The hypothesis that pre-treatment trends are parallel across treatment groups is supported by the statistical test specified by equation (3). As Table 4 shows, the interaction between the indicator for inside (or nearby) group and the year trend is insignificant, suggesting no systematic difference in the air quality patterns across station groups before the announcement of the LEZ.

Table 5 displays our estimation results for equation (1) using (from left to right) the least to the richest sets of control variables. Column (1) represents a baseline DID model with a single treatment dummy, phase dummies, and their interactions, excluding long-run trends, weather covariates, and other controls. We find strong and disparate impacts of the LEZ on London's air quality during the first two phases. Some of this disparity may be attributed to differences in time-varying variables such as weather conditions and seasonal patterns across stations. Without controlling for these factors, the model carries relatively low explanatory power, and the estimated coefficients could be biased. Column (2) replaces the treatment dummy by a vector of station fixed effects that account for heterogeneous PM10 levels when the policy was not in place. Meanwhile, column (2) incorporates year and quarter fixed effects to control for long-run time trends and seasonal fluctuations of air quality. The model provides similar results as column (1) with marginally improved explanatory power. Column (3) additionally includes weather covariates as well as indicators for weekends and holidays. The rich set of control variables substantially drive up the explained variation of PM10 and reduce the upward biased estimates on the policy treatment effect.

Controlling for all other factors, we estimate that phase I of London's LEZ with the least stringent emission criteria on HGVs and trucks yielded an 8.4% *increase* of PM10 inside London. When the policy progressed to phase II with the same emission requirements applying to LGVs as well, we observe a significant *reduction* of London's PM10 by 7.2%. The counterintuitive treatment effect in phase I is unlikely a result of drivers mistakenly traversing the target zone and detouring to exit since LEZ was publicly announced eight months before launch. Meanwhile, the TfL placed advance warning signs to notify drivers when they approach the zone. We also find the phenomena to be hardly explained by control stations being subject to other environmental regulations that help to decrease roadside pollution by a higher degree than the LEZ. As Figure 5b shows, the PM10 level at control stations remained flat during the LEZ announcement period before declining with all other stations in phase I. Both graphical and statistical evidence suggests that the local spike of PM10 around the introduction date of phase I was experienced almost exclusively by stations inside and near London and thus should be attributed to factors pertaining to London. We speculate the contrasting policy effects in the first two phases to be a consequence of drivers' behavioral adjustments through thoughtful mental processes.

The weather variables in the richest model all have expected signs of coefficients. We find that an additional hour of precipitation would reduce PM10 by about 2 percent, and every 1 percent increase in humidity would raise the PM10 level by 0.5 percent. Interestingly, our results also show that moderate wind helps reduce the PM10 level, while heavy wind could drive up the PM10 concentration. This result is consistent with previous literature (e.g., Harrison et al. (2001); Qian et al. (2016)) that suggests a U-shaped relationship between the concentration of large particles and wind speed. When other meteorological conditions are held constant, raising the average wind speed helps the dilution process of coarse particles. However, a high level of maximum wind speed can blow the suspended particles into the air. We find roadside PM10 is 12.1% and 7.6% less during weekends and holidays, respectively.

Tables 6 and 7 perform robustness checks for the results in Table 5 column (3). We first consider a more stringent correlation assumption on ε_{it}. Specifically, we consider the errors to be independent across both stations and years, which is plausible since road construction, changes in traffic patterns, and maintenance work on monitoring stations would cause any time-level correlation of random shocks to decay over time. As Table 6 column (1) shows, clustering standard errors at the station-year level slightly raises the significance of the treatment effect in phase I while leaving that for phase II unchanged. Table 6 column (2) makes a stronger serial correlation assumption on ε_{it} by using Newey-West standard errors with a maximum lag of 7 days. We find minimal adjustments to the magnitude of standard errors, and our results in both phase I and II remain robust.

Next, we relax the assumption that random errors distribute independently across stations and consider possible cross-sectional correlations of errors across roadside areas. The mapping between weather and air quality stations could be one of the leading factors contributing to this error correlation. In Table 6 columns (3) and (4), we cluster standard errors by UK regions and region-years, respectively.[4] Estimations based on these specifications produce consistent results with those in the main regression. We also consider the possibility of a strong cross-sectional correlation and limited time-series correlation of errors. This applies to scenarios where traffic patterns on different roads are much similar for each day, but that on various dates can be largely different because of the daily charging scheme of the LEZ. Using clustered standard errors by day, we show in Table 6 column (5) that the key regressors in the model remain statistically significant. Lastly, because the LEZ was operated inside London, we cluster standard errors by the treated and control areas. This generates only two clusters, and correspondingly the significance level of the treatment effect in phase I slightly declines to the 10% level, white that in phase II remains at the 5% level. To summarize, our model produces results that are robust across various error structures.

We next consider the impacts of extreme outliers in driving our results. In Table 7 column (1), we exclude observations on New Year's Eve and New Year's Day since a substantial proportion of particulate matter on these dates would be attributed to fireworks. We keep the holiday dummy in our sample and cluster standard errors by stations. Estimation results show that

[4] We consider a relatively broad definition of England regions and have six regions in our sample: London, East of England, North West, South East, West Midland, Yorkshire & the Humber.

excluding observations on the fireworks' days brings minimal changes to the coefficients of interest. Besides outliers on specific dates, we also consider possible misreports on PM10 due to machine malfunctioning or extreme weather that the data ratification process fails to account for. Based on the distribution of PM10 for all roadside stations, we exclude observations that fall within the top 5 percentile (about 50.8 ug/m3) from the regression. Table 7 column (2) shows the estimation results using the refined dataset. We find no evidence that our results are driven by extremely high PM10 observations in the sample.

According to the pre-policy assessment (Kelly et al., 2011), roadside areas may experience the most pronounced policy effect due to a substantial portion of PM10 contributed by road traffic. We test the existence of geographical heterogeneity in the policy effect using the difference-in-difference model on (i) urban background stations located in residential neighborhoods and (ii) industrial stations near factories and industrial plants, respectively. Table 8 reports our estimation results. Consistent with Kelly et al. (2011), neither of these stations produce significant estimates on the effect of the LEZ in any phase. The spatially decaying policy impact implies that the social benefit or cost of London's LEZ would be borne almost exclusively by individuals living close to roadways and those who spend a substantial amount of time in traffic every day.

Driving regulations like the LEZ may modify individual behaviors in both desired and undesired directions. On the one hand, vehicles making efforts to comply with the required EU emission standards would bring in long-run environmental benefits throughout the nation. On the other hand, drivers notified by advance signs may strategically detour to avoid any charge, causing longer miles traveled and higher emissions surrounding the restricted area. The net spillover effect thus depends on the relative magnitude of these opposing impacts. Table 9 displays the estimation results for the spillover effect using specification (2) with five roadside stations located within 10 miles of the LEZ border. As in the main regression, we leverage on the same group of control stations located at least 25 miles away from the LEZ border to provide background trends. We find that phase II of the LEZ has generated a 5 percent lower PM10 nearby London. This suggests a dominant impact of greener vehicles that travel across the LEZ border. The spillover effect is 2.2 percentage points (about 30%) less than the treatment effect of the LEZ within London, indicating the policy effect would spatially decay when moving farther from the zone. In all other phases, we find no measurable spillover along major roadways near London.

VI. Discussion

The LEZ aims at improving air quality in London by incentivizing road consumers to retrofit, convert to gas, or reorganizing the fleet of their heavily polluting vehicles. When such behavioral modifications are successful, we should observe an evident decline of PM10 proportionate to the concentration of PM10 contributed by the targeted vehicles. According to TfL (2011), the LEZ achieved a 98% compliance rate for HGVs and a 96% compliance rate for LGVs several months after its implementation. The contrasting policy effect in the first two phases thus cannot be explained by differences in the compliance behaviors of drivers.

Statistics show that within the Central London area, nearly 50% PM10 by road transport cannot be treated using emission requirements (TfL (2011)). These particulates are sourced from tire and brakes instead of vehicle exhausts. Out of the remaining 50% PM10, only 5.5% can be attributed to HGVs, while 13% comes from LGVs. Prior to the implementation of the LEZ, roughly 85% of HGVs driving in London already meet the EU III emission standards, leaving small room for marginal improvements. By the launch date of phase II, about 80% LGVs meet the EU III standards, making it more likely to bring in measurable benefits.

Next, we analyze the changes of traffic patterns for the subject vehicles from 2005 to 2010. We start by constructing a multiplicative model on the PM10 emissions attributed to the number of compliant versus non-compliant vehicles.

$$PM10_t = (w_1 NCV_t + w_2 CV_t) \times OtherFactors_t \tag{4}$$

In equation (4), NCV_t is the volume of non-compliant vehicles at time t and CV_t is the number of compliant vehicles. w_1 and w_2 capture the partial impact of dirty and clean vehicles on air pollution, respectively, and we expect $w_1 > w_2$. Intuitively, equation (4) proposes that other factors in the atmosphere can magnify the impact of traffic exhausts and lead to accumulation of PM10. With the compliance rate defined as $r_t = \frac{CV_t}{NCV_t + CV_t} \times 100\%$, equation (4) can be transformed into

$$\log PM10_t = \log SV_t + \log[(w_1 - w_2)(1 - r_t) + w_2] + \log(OtherFactors_t) \tag{5}$$

where $SV_t = NCV_t + CV_t$ is the number of total subject vehicles. Equation (5) serves as the starting point of our following analysis. It unpacks two channels for a rising PM10: by increasing the number of subject vehicles SV_t traveling inside the zone or by decreasing the compliance rate r_t. The net change of roadside air quality thus depends on the size of these two effects.

To investigate changes in the traffic pattern, we first collect from the UK Department of Transportation annual average daily traffic flow (AADF) of HGVs and LGVs on major roads in five UK regions where at least one sample station resides. For each region, we use the AADF in 2008 (i.e., the year in which both phases I and II started to operate) as the reference and calculate the relative traffic flow as an index in other years. As Figures 6a and 6b show, heavy and light goods vehicles in London delineated distinctive traffic patterns during the policy implementation year. Despite an overall declining trend of HGVs in other regions from 2007 to 2009, London instead experienced a spike of HGVs in 2008, leading to a smaller long-run reduction of PM10 over the years.[5] This contrasts with a steeper decline of LGVs in London compared to other regions in the year 2008. The disparity indicates that the increased volume of HGVs in the first phase may have contributed to an adverse policy effect.

We further collect data on the annual fuel usage in London from the UK Department of Energy and Climate Change. In Figure 7a, we plot the aggregated consumption of diesel versus petrol by year from 2005 to 2010. Consistent with the traffic patterns, demand for diesel in London reached a local spike of almost 1250 thousand tons in 2008. Conversely, petrol fuel usage has been declining steadily over time, falling from over 1300 thousand tons in 2005 to roughly 1000 thousand tons in 2010.

In Figure 7b, we decompose the annual diesel consumption by type of vehicles. Diesel cars are the biggest consumer of diesel fuel and have a continuously growing share of demand. This is consistent with TfL's 2011 report. Especially in Central London, taxis and cars jointly contribute more than half of all vehicle exhausts, which can be treated by emission control requirements. HGVs and diesel-engine LGVs each consume roughly a quarter of diesel fuels, followed by buses. In 2008, HGVs surpassed LGVs and became the second-largest consumer of diesel. This result goes in line with the traffic trends shown in Figures 6a and 6b, reflecting a slight shift in consumer preference towards using heavier vehicles upon the introduction of the LEZ.

[5] In the DID regression, we did not stress on the year 2010 in which phase III started to operate. But we do note that 2010 shows very similar traffic patterns for both HGVs and LGVs as 2008. Specifically, London experienced a heavier spike of HGVs and a sharper decline of LGVs than any other region in the UK in 2010.

To further investigate how the demand for road affects London's air quality, we obtain from the TfL the number of subject vehicles and the compliance rate from mid-2007 to the end of 2009. The data are recorded every Sunday with a starting point shortly after the announcement of the LEZ policy. Although the data cover only about three-quarters of phase II, the compliance rate of both HGVs and LGVs reached over 95% by the end of the observation period (see Figure 8). Accompanying with a rising compliance rate, however, the number of both HGVs and LGVs during phase I was slightly higher than that in the neighboring periods. As Figure 9 shows, the launch of phase I features a discontinuity of the traffic volume of all types of vehicles. Admittedly, this discontinuity is largely driven by the substantial reduction of traffic low during the holiday season from late Dec 2007 to the start of Jan 2008. Nevertheless, the LOWESS curves still reveal the long-term patterns of traffic volume in a meaningful way because of the model weighting parameters that shield the local waves against extreme outliers (Cleveland 1979).

We construct the following two-stage-least-squares (2SLS) model to assess the impact of the LEZ on the number of subject vehicles and the vehicle composition – the two contributing channels towards changes in air quality in London.

Stage 1:

$$f(SV_{it}) = \sum_{\tau=1}^{\tau=2} \rho_\tau \cdot P\tau_t + Yr_t + Q_t + \vartheta_i + \boldsymbol{\Theta X_{it}} + W_t + H_t + \epsilon_{it} \tag{6a}$$

$$f(r_{it}) = \sum_{\tau=1}^{\tau=2} \pi_\tau \cdot P\tau_t + Yr_t + Q_t + \vartheta_i + \boldsymbol{\Theta X_{it}} + W_t + H_t + \epsilon_{it} \tag{6b}$$

Stage 2:

$$\log(PM10_{it}) = \eta_1 f\left(\widehat{SV_{it}}\right) + \eta_2 f(\widehat{r_{it}}) + Yr_t + Q_t + \vartheta_i + \boldsymbol{\Theta X_{it}} + W_t + H_t + \epsilon_{it} \tag{6c}$$

Consistent with the notations in equation (5), we use SV_{it} and r_{it} to denote the total number of subject vehicles (either HGVs or LGVs) and the corresponding compliance rate at a within-LEZ station i at time t, respectively. We consider two alternative forms of $f(\cdot)$ – the untransformed level $f(x) = x$ and its logarithmic form $f(x) = \log x$. Other covariates (i.e., $P\tau_t$, α_i, X_{it}, W_t, H_t) have the same meaning as those in equation (1), and we cluster ϵ_{it} at the station level.

This two-stage model works to provide insight into the channels through which the policy affects the environment inside the zone. When the implementation of phase τ has successfully incentivized drivers to lower vehicular emissions, we would expect to obtain a positive π_τ in equation (6b). Absent of an increased traffic volume, the coefficient ρ_τ in equation (6a) should be insignificant. The phase dummies $P\tau_t$ in the two equations in the first stage serve as instrumental variables (IVs) that affect the PM10 only through altering the targeted vehicles' traffic flow and changing the proportion of compliant vehicles out of all subject ones.

In estimating equations (6a) to (6c), we use linearly interpolated values of SV_{it} and r_{it} to accommodate the daily level observations on air quality.[6] Like the main regression, we focus on roadside stations only as they are subject to the most pronounced effect from changes in traffic patterns. Table 10 presents the empirical results of the 2SLS model with untransformed vehicle flow and compliance rate (i.e., $f(x) = x$). We find that the implementation of phase I has successfully improved the compliance rate of HGVs by 8.4 percentage points. However, it also motivated an increased number of HGVs by about 4 thousand per day. According to the second stage estimates, every thousand HGVs in phase I is expected to drive up PM10 by 4.6%. Thus, the impact of traffic volume would play a dominant role in the change of air quality in London in phase I (3.96×0.046>0.084×0.916).

In a similar model structure, Table 11 shows how the LEZ affects air quality through altering the traffic patterns of LGVs in London. Consistent with previous literature (for example, see Ferm and Sjöberg (2015)), we find LGVs play a much weaker role than HGVs in shifting the roadside particulates. In contrast with phase I, the operation of phase II has significantly disincentivized about two thousand LGVs to enter the zone per day. This works in conjunction with 12.7 percentage points higher compliance rate of LGVs and a continuously growing compliance rate of HGVs to reduce the PM10 concentrations in London. The downward trend of the traffic flow of both HGVs and LGVs in phase II largely attenuated the environmental pressure on roadways and has benefited areas both within and outside the zone.

Tables 12a and 12b provide robustness checks for the 2SLS estimation results displayed by Table 10 and 11, respectively. We first consider excluding the holiday period from Dec 24, 2007, to Jan 3, 2008, since data in this period may be the main force driving the discontinuous

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[6] We use linearly interpolated data for two reasons. First, we have a limited number of observations in the early announcement period of the LEZ. However, the earliest stage is expected to carry the most dramatic change in the compliance rate. From Figure 8, we also see that approaching the end of the observation window, the compliance rates in both phases grow very slowly. The marginal change over time is minimal since the compliance rate is capped at 100%. Therefore, we use the interpolated data to extract more variation from the traffic sector to explain the air quality fluctuations at the day level.

traffic flow around the implementation date of phase I in Figure 9.[7] As Table 12a columns (1) and (2) show, removing this period from our sample leads to a slightly lower impact of phase I on the number of HGVs ($\rho_1 = 2.9$ thousand compared to 4 thousand in stage I displayed by panel A). Nevertheless, the results still suggest a dominant effect of traffic flow on the air quality in London ($\lambda = 0.04$ is significant in stage II in Table 12a).

Table 12b columns (1) and (2) perform the same robustness checks on the traffic patterns of LGVs. Despite small adjustments to the estimated effect of the LEZ phases I and II on the traffic volume ($\rho_1 = 2.5$ compared to 3.1, $\rho_2 = -2.4$ compared to -2.1 in Table 11), all estimates remain statistically significant. In the second stage, excluding the holiday period causes an unmeasurable change to the effect of subject vehicles on the roadside PM10 in London ($\eta_1 = 0.04$), whereas the vehicle composition plays an insignificant role in explaining the fluctuations of PM10 ($\eta_2 = -0.17$ is insignificant compared to -0.27 in Table 11). In short, our results show that the traffic volume is likely a key contributing factor to London's air quality.

Following the assumptions under equations (4) and (5), we may test the robustness of the 2SLS model by replacing the linear traffic volume and vehicle composition by their logarithmic values ($f(x) = \log x$). Columns (3) and (4) of Table 12a and 12b display the estimation results using the logarithm functional forms. We find very consistent results with those displayed in Tables 10 and 11. Specifically, the operation of phase I pulled up the traffic flow of HGVs by 11% and that of LGVs by 9.7%. At the same time, the impact of a 1% increase in traffic volume of both HGVs and LGVs outweighs the environmental benefit of a 1% change in their compliance rates (|1.97|>|-1.12| and |1.13|>|-0.19|). Combining our results from Table 10 to Table 12b, we conclude that an increasing demand for road in phase I of the LEZ largely explain the adverse effect of the policy in this period.

We explore the psychological motivations behind the increased usage of road during phase I. We propose that drivers who either pay to enter the zone or spend money on vehicle upgrade would tend to overconsume the road usage to get their money's worth. This behavioral phenomenon challenges one of the classical economics assumptions that states past monetary

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[7] The original 2SLS model includes both holiday and weekend dummies in every stage of the equations. In the regression without the holiday period, we still keep all these dummy variables to account for the impact of non-work days on traffic patterns and reduce the effect of linear interpolation on the estimation results.

outlay (i.e., sunk costs) should be regarded as irrelevant in a decision-making process. This notion of sunk cost fallacy, rooted in the prospect theory by Kahneman and Tverskey (1979) and developed by Thaler (1983), represents an important behavioral bias resulting from loss aversion. It has been demonstrated by a series of marketing and psychological experiments. For instance, a person is more likely to attend more events if the price of the season ticket to the events is higher (Arkes and Blumer (1985)). Likewise, individuals have a stronger incentive to go to a basketball game on a blizzard day if they (or their friends) have paid a higher price for it (Thaler (1980); Olivola (2018)). In short, taking previous monetary outlay into the current decision-making process would result in individuals engaging in more consumption activities to maximize the quality of the deal or the perceived utility from the transaction.

With sunk cost fallacy in effect, we predict that drivers would likely increase their road usage when a substantial expenditure has occurred following the introduction of the LEZ. The higher level of consumption can take the form of either an increased frequency of trips to London or longer total miles traveled within each trip. The former would drive up the number of subject vehicles observed on the road, while the latter would result in rising fuel consumption with a constant vehicle volume. We show from Tables 10 to 12b that HGVs subject to the emission requirements in phase I do seem to respond by increasing the number of trips within the zone. Our fuel consumption data in Figures 7a and 7b, even though highly aggregated, support this argument. The sunk cost fallacy is expected to influence consumer behaviors more if the demand is inelastic and strategic avoidance of the zone was not an option. At the same time, drivers temporarily exempt from the regulation may exhaust their consumption because of the privilege of being able to consume the road free of charge. These behavioral biases collectively pushed up the traffic volume of vehicles in the earliest phase of the LEZ.

Psychological theory suggests that human happiness would remain at a relatively stable level (a "hedonic set-point") regardless of short-term fluctuations due to life events (Brickman and Campbell (1971)). With the LEZ gradually progressing, the impact of sunk cost fallacy faded away and road consumers return to their status quo travel patterns. As a result, the fraction of cleaner vehicles grew without attracting an intensive traffic flow in the second phase of London's LEZ. The net environmental effect became dominated by a higher compliance rate, giving rise to a downward trend of PM10 in London in the subsequent stages of the policy.

VIII. Conclusion

In this paper, we estimate the impact of London's LEZ on roadside PM10. Using a difference-in-difference model, we show that the first phase of the LEZ worked against the desired direction and led to 8 percent increased concentrations of PM10 along major roadways in London. The second phase, on the other hand, effectively reduced the roadside PM10 in London by about 7 percent. Evidence from traffic and energy sectors suggests that both heavy and light goods vehicles experienced a slightly escalated traffic flow in phase I. In contrast, their traffic volumes in phase II significantly declined. This disparity explains the opposite policy effects in the first two phases despite a continuously climbing compliance rate for both types of subject vehicles.

We use sunk cost fallacy and hedonic adaptation to explain the phenomena we find. We propose that the increased traffic flow in phase I can be caused by the drivers' tendency to maximize the perceived quality of deal. When a substantial amount of expenditure associated with the LEZ emission criteria has occurred, drivers would be induced to engage in more consumption of road to get their money's worth. This behavioral bias is short-lived as drivers slowly adjust to a new reference point. Consequently, the environmental benefit brought by vehicles complying to the emission standards started to dominate the effect, producing a reduced level of PM10 inside London.

Our analysis has a few limitations. First, we did not extend our estimation to subsequent phases beyond 2010 due to data limitation. Second, our traffic data do not contain geographical information that allows us to build the link between borough-level treatment effect and traffic volume. Potential extensions of the same line of research include assessing the health effect of London's LEZ using the number of hospital visits for respiratory symptoms, asthma, or chronic diseases. Additionally, previous research shows individual happiness can be strongly affected by air quality. We invite future researchers to investigate the impact of the LEZ on the perceived life satisfaction for London residents.

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Tables and Figures

Table 1: EU Emission Standards for PM

Standards	Date	PM (g/kWh)
EU I	1992 (≤ 85 kW)	0.612
	1992 (> 85 kW)	0.36
EU II	Oct 1996	0.25
	Oct 1998	0.15
EU III	Oct 1999 (EEV only)	0.02
	Oct 2000	0.10 (exceptions applied)
EU IV	Oct 2005	0.02
EU V	Oct 2008	0.02
EU VI	Jan 2013	0.01

Note: (1) EEV refers to enhanced environmentally friendly vehicles. (2) The EU III (Oct 2000) standards is 0.13 for engines of less than 0.75 dm^3 *swept volume per cylinder and a rated power speed of more than 3000* min^{-1}.

Table 2a: London's Low Emission Zone (LEZ) schemes (within our sample period)

	Starting date	Subject vehicles	Emission standards	Standard Charge for Entrance	Penalty Charge of Illegal Entrance
Policy announcement	May 3, 2007	/	/	/	/
Phase I	Feb 4, 2008	Heavy goods vehicles, trucks	Euro III	£200	£500 if paid within 14 days, £1000 o.w.
Phase II	Jul 7, 2008	Light goods vehicles	Euro III	£100	£250 if paid within 14 days, £500 o.w.
Phase III	Oct 4, 2010	Larger vans, minibus	Euro III	£100	£250 if paid within 14 days, £500 o.w.

Notes: (1) Each phase is more stringent regulation scheme with a broader scope of vehicles and/or tighter emission requirements to the already included vehicles. (2) Heavy goods vehicles (HGVs) are goods vehicles that are greater than 12 tonnes gross vehicle weight (GVW). Affected trucks are diesel engine vehicles over 3.5 tonnes GVW. Light good vehicles, or LGVs, are good vehicles between 3.5 and 12 tonnes GVW. Affected larger vans are diesel engine vehicles between 1.205 and 3.5 tonnes GVW or motor caravans between 2.5 and 3.5 tonnes GVW. Affected minibuses are diesel passenger vehicles with more than 8 seats (including driver's seat) and less than 5 tonnes GVW. Affected busses and coaches are diesel passenger vehicles with more than 8 seats (including driver's seat) and more than 5 tonnes GVW.

Table 2b: London's Low Emission Zone (LEZ) schemes (Beyond our sample period)

	Starting date	Subject vehicles	Emission standards	Standard Charge for Entrance	Penalty Charge of Illegal Entrance
Phase IV	Jan 3, 2012	Buses, coaches, heavy goods vehicles	Euro IV	£200	£500 if paid within 14 days, £1000 otherwise
Ultra LEZ	Apr 8, 2019	Cars, vans, motorcycles,	Euro IV for petrol; Euro VI for diesel	£12.5	£65 if paid within 14 days, £130 otherwise
		lorries, buses, coaches	Euro IV for petrol; Euro VI for diesel	£100	£500 if paid within 14 days, £1000 otherwise

Note: Unlike the LEZ which covers the entire Greater London, the ultra LEZ is only implemented in the central London area. It complements the existing congestion charge and is operating on the same schedule with the LEZ (24 hours a day, 7 days a week, including weekends and holidays).

Table 3: Summary statistics, roadside stations only

	unit	Inside London (within LEZ)		Outside London (nearby + far from the LEZ)	
		Mean	Std. Dev.	Mean	Std. Dev.
PM10	ug/m3	27.29	13.30	25.03	11.08
Log PM10	/	3.21	0.44	3.13	0.41
Humidity	%	72.65	11.40	74.46	12.36
Hours of rain	hour	3.07	4.29	3.07	4.28
Temperature	°F	53.14	10.40	52.32	10.61
Air pressure	mBar	29.97	0.31	29.97	0.32
Avg. wind speed	mph	8.48	3.96	8.59	4.29
Max. wind speed	mph	14.36	4.93	14.09	5.39
# of stations	/	23		13	
# of obs.	/	46,126		26,921	

Notes: Summary statistics are provided based on the sample period from Jan 1, 2005 to Dec 31, 2010. Weather data are spatially mapped with air quality data based on the relative distance between a weather station and an air quality station.

Table 4: Results on the Parallel Trends Before the LEZ Policy

	(1) Roadside station located inside vs far away from London	(2) Roadside station located nearby vs far away from London
Group indicator Tr (1=yes, see notes)	600.762	-350.223
	(520.286)	(630.995)
Year	1.447***	1.479***
	(0.225)	(0.195)
Tr × Year	-0.299	0.173
	(0.259)	(0.315)
Weather, weekend, and holiday controls	Yes	Yes
# of observations	24,592	10,019
R2	0.2011	0.2094

Notes: In column (1), the group indicator Tr equals 1 if a station is located inside London and 0 if a station is far from London (i.e., control group). In column (2), the group indicator Tr equals 1 if a station is located nearby London and 0 if a station is far from London (i.e., control group).
** $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

Table 5: Estimation Results for the Effect of London's LEZ on Roadside PM10

	(1)	(2)	(3)
	Baseline diff-in-diff model	Diff-in-diff w/ heterogeneous station FE	w/ heterogeneous station FE & all other controls
Policy effect			
Announcement × treated	-0.008	-0.010	-0.017
	(0.022))	(0.021)	(0.021)
Phase I × treated	0.122***	0.122***	0.084**
	(0.038)	(0.038)	(0.037)
Phase II × treated	-0.088***	-0.083***	-0.072***
	(0.022)	(0.020)	(0.019)
Phase III × treated	0.056	0.062	0.082*
	(0.043)	(0.043)	(0.041)
Weather conditions			
Humidity	/	/	0.005***
			(0.001)
Temperature	/	/	0.006***
			(0.001)
Hours of rain	/	/	-0.020***
			(0.001)
Wind speed (avg)	/	/	-0.044***
			(0.002)
Wind speed (max)	/	/	0.008***
			(0.001)
Air pressure	/	/	0.170***
			(0.017)
Other controls			
Weekends	/	/	-0.121***
			(0.010)
Holidays	/	/	-0.076***
			(0.005)
Phase FE	Yes	Yes	Yes
Year FE	No	Yes	Yes
Quarter FE	No	Yes	Yes
Station FE	No	Yes	Yes
# of stations	31	31	31
# of observations	62,888	62,888	62,671
R2	0.0240	0.0620	0.3008

*Note: (1) This table shows the estimation results based on equation (1) using roadside stations located inside as the treatment group and those at least 25 miles away and in district not bordering London as the control group. Clustered standard errors by station in parentheses. (2) * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

Table 6: Robustness Checks for the Effect of London's LEZ on Roadside PM10

	(1)	(2)	(3)	(4)	(5)	(6)
	Clustered SE by station-year	Newey-West SE	Clustered SE by region	Clustered SE by region-year	Clustered SE by day	Clustered SE by LEZ
Policy effect						
Announcement	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017
× treated	(0.024)	(0.016)	(0.015)	(0.021)	(0.018)	(0.016)
Phase I ×	0.084***	0.084***	0.084***	0.084***	0.084***	0.084*
treated	(0.028)	(0.026)	(0.023)	(0.016)	(0.024)	(0.007)
Phase II ×	-0.072***	-0.072***	-0.072***	-0.072***	-0.072***	-0.072**
treated	(0.022)	(0.024)	(0.009)	(0.010)	(0.020)	(0.002)
Phase III ×	0.082**	0.082***	0.082	0.082**	0.082***	0.082**
treated	(0.035)	(0.027)	(0.054)	(0.035)	(0.025)	(0.002)
Weather conditions						
Humidity	0.005***	0.005***	0.005*	0.005***	0.005***	0.005
	(0.000)	(0.000)	(0.002)	(0.001)	(0.001)	(0.003)
Temperature	0.006***	0.006***	0.006***	0.006***	0.006***	0.006*
	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)
Hours of rain	-0.020***	-0.020***	-0.020**	-0.020***	-0.020***	-0.020
	(0.001)	(0.000)	(0.004)	(0.002)	(0.002)	(0.005)
Wind speed	-0.044***	-0.044***	-0.044***	-0.044***	-0.044***	-0.044
(avg)	(0.001)	(0.001)	(0.005)	(0.004)	(0.003)	(0.008)
Wind speed	0.008***	0.008***	0.008*	0.008***	0.008***	0.008
(max)	(0.001)	(0.001)	(0.003)	(0.002)	(0.002)	(0.004)
Air pressure	0.170***	0.170***	0.170***	0.170***	0.170***	0.170
	(0.017)	(0.007)	(0.017)	(0.028)	(0.021)	(0.039)
Other controls						
Weekends	-0.121***	-0.121***	-0.121***	-0.121***	-0.121***	-0.121**
	(0.005)	(0.003)	(0.011)	(0.008)	(0.013)	(0.009)
Holidays	-0.076***	-0.076***	-0.076***	-0.076***	-0.076***	-0.076
	(0.006)	(0.008)	(0.011)	(0.024)	(0.028)	(0.015)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes
Phase FE	Yes	Yes	Yes	Yes	Yes	Yes
Station FE	Yes	Yes	Yes	Yes	Yes	Yes
# of stations	31	31	31	31	31	31
# of obs.	62,671	62,671	62,671	62,671	62,671	62,671
R2	0.3008	/	0.3008	0.3008	0.3008	0.3008

*Notes: This table presents results on the robustness checks for the error term in our main specification displayed by Table 5 column (3). Newey-West standard errors are estimated with a maximum lag of 7 days. Regions are defined as England regions including London, East of England, North West, South East, West Midland, and Yorkshire and the Humber. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

Table 7: Robustness Checks for the Effect of London's LEZ on Roadside PM10 (cont'd)

	(1)	(2)
	Excluding New Year's Eve and New Year's Day	Excluding PM10 in the top 5 percentile
Policy effect		
Announcement × treated	-0.020	-0.008
	(0.021)	(0.020)
Phase I × treated	0.084**	0.080**
	(0.037)	(0.038)
Phase II × treated	-0.072***	-0.068***
	(0.019)	(0.017)
Phase III × treated	0.081*	0.081*
	(0.041)	(0.041)
Weather conditions		
Humidity	0.005***	0.005***
	(0.001)	(0.001)
Temperature	0.007***	0.006***
	(0.001)	(0.001)
Hours of rain	-0.020***	-0.019***
	(0.001)	(0.001)
Wind speed (avg)	-0.044***	-0.043***
	(0.002)	(0.002)
Wind speed (max)	0.008***	0.007***
	(0.001)	(0.001)
Air pressure	0.167***	0.166***
	(0.017)	(0.017)
Other controls		
Weekends	-0.120***	-0.120***
	(0.010)	(0.009)
Holidays	-0.066***	-0.089***
	(0.005)	(0.009)
Year FE	Yes	Yes
Quarter FE	Yes	Yes
Phase FE	Yes	Yes
Station FE	Yes	Yes
# of stations	31	31
# of observations	62,384	62,043
R2	0.3006	0.2950

*Notes: This table provides results on the robustness checks for our main specification in Table 5 column (3). Column (1) excludes New Year's Day and Eve. Column (2) excludes roadside PM10 observations that fall within the top 5 percentile of the full-sample distribution of PM10. Both columns have standard errors clustered by station. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

Table 8: Geographical Heterogeneity of the Effect of LEZ

	(1) Urban background	(2) Industrial
Policy effect		
Announcement × treated	0.098	0.156
	(0.064)	(0.130)
Phase I × treated	-0.026	-0.073
	(0.063)	(0.080)
Phase II × treated	0.025	-0.072
	(0.053)	(0.059)
Phase III × treated	-0.006	-0.054
	(0.061)	(0.088)
Weather conditions		
Humidity	0.006***	0.000
	(0.001)	(0.001)
Temperature	0.007***	0.007**
	(0.001)	(0.003)
Hours of rain	-0.020***	-0.023***
	(0.002)	(0.005)
Wind speed (avg)	-0.050***	-0.036***
	(0.002)	(0.006)
Wind speed (max)	0.009	0.002
	(0.002)	(0.003)
Air pressure	0.217***	0.146*
	(0.016)	(0.064)
Other controls		
Weekends	-0.071***	-0.283***
	(0.008)	(0.065)
Holidays	-0.038***	-0.113**
	(0.007)	(0.037)
Phase FE	Yes	Yes
Year FE	Yes	Yes
Quarter FE	Yes	Yes
Station FE	Yes	Yes
# of stations	18	8
# of observations	35,785	15,626
R2	0.3333	0.2230

*Note: (1) Urban background stations are typically located in residential areas away from major sources of pollution. Industrial stations are located closed to industrial plants with a significant proportion of pollution coming from industrial emissions. Clustered standard errors by station in parentheses. (2) According to the monitoring system, each class of stations would broadly represent air quality levels in similar locations. (3) * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

Table 9: Estimation Results for the Spillover Effect of London's LEZ

	Coeff	SE
Policy effect		
Announcement × treated	0.014	(0.038)
Phase I × treated	0.057	(0.040)
Phase II × treated	-0.050**	(0.019)
Phase III × treated	0.094	(0.060)
Weather conditions		
Humidity	0.002*	(0.001)
Temperature	0.005***	(0.001)
Hours of rain	-0.015***	(0.002)
Wind speed (avg)	-0.034***	(0.003)
Wind speed (max)	0.002	(0.002)
Air pressure	0.149***	(0.028)
Other controls		
Weekends	-0.126***	(0.013)
Holidays	-0.055***	(0.008)
Phase FE	Yes	
Year FE	Yes	
Quarter FE	Yes	
Station FE	Yes	
# of stations	13	
# of observations	26,714	
R2	0.2566	

*Note: We estimate the spillover effect of London's LEZ using roadside stations located within 10 miles outside the LEZ boundary as the "nearby" group potentially affected by the policy and those located in regions non-adjacent to the LEZ boundary and at least 25 miles away as the control group. Clustered standard errors by station in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

Table 10: Results for the Two-Stage-Least-Squares Estimation on the Effect of London's LEZ on Air Quality Using Traffic Flow and Compliance Rate of the Subject Vehicles in Phase I as Instruments

	Coeff	SE
Stage II: DV = log(PM10)		
Fitted number of phase I subject vehicles	0.046***	(0.006)
Fitted compliance rate of phase I subject vehicles	-0.916***	(0.348)
Year FE	Yes	
Quarter FE	Yes	
Station FE	Yes	
Weather & Other controls	Yes	
# of stations	23	
# of observations	17,977	
R2	0.2855	
Stage I (panel A): DV = Number of phase I subject vehicles		
Phase I	3.960***	(0.107)
Phase II	-2.317***	(0.159)
Year FE	Yes	
Quarter FE	Yes	
Station FE	Yes	
Weather & Other controls	Yes	
# of stations	23	
# of observations	17,977	
R2 (adjusted)	0.2682	
Stage I (panel B): DV = Compliance rate of phase I subject vehicles		
Phase I	0.084***	(0.000)
Phase II	0.004***	(0.000)
Year FE	Yes	
Quarter FE	Yes	
Station FE	Yes	
Weather & Other controls	Yes	
# of stations	23	
# of observations	17,977	
R2 (adjusted)	0.9849	

*Note: This table shows the estimation results for the 2SLS model using roadside stations located inside London. Clustered standard errors by station in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

Table 11: Results for the Two-Stage-Least-Squares Estimation on the Effect of London's LEZ on Air Quality Using Traffic Flow and Compliance Rate of the Subject Vehicles in Phase II as Instruments

	Coeff	SE
Stage II: DV = log(PM10)		
Fitted number of phase II subject vehicles	0.036***	(0.004)
Fitted compliance rate of phase II subject vehicles	-0.272**	(0.129)
Year FE	Yes	
Quarter FE	Yes	
Station FE	Yes	
Weather & Other controls	Yes	
# of stations	23	
# of observations	17,977	
R2	0.3828	
Stage I (panel A): DV = Number of phase II subject vehicles		
Phase I	3.090***	(0.053)
Phase II	-2.129***	(0.135)
Year FE	Yes	
Quarter FE	Yes	
Station FE	Yes	
Weather & Other controls	Yes	
# of stations	23	
# of observations	17,977	
R2 (adjusted)	0.3402	
Stage I (panel B): DV = Compliance rate of phase II subject vehicles		
Phase I	0.018***	(0.000)
Phase II	0.127***	(0.001)
Year FE	Yes	
Quarter FE	Yes	
Station FE	Yes	
Weather & Other controls	Yes	
# of stations	23	
# of observations	17,977	
R2 (adjusted)	0.9799	

*Note: This table shows the estimation results for the 2SLS model using roadside stations located inside London. Clustered standard errors by station in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

Table 12a: Robustness Checks for the Two-Stage-Least-Squares Estimation on the Effect of London's LEZ on Air Quality Using Traffic Flow and Compliance Rate of the Subject Vehicles in Phase I as Instruments

	Excluding Dec 24, 2007-Jan 3, 2008		Using logarithmic traffic patterns	
	(1)	(2)	(3)	(4)
	Coeff	SE	Coeff	SE
Stage II: DV = log(PM10)				
Fitted number of phase I subject vehicles	0.041***	(0.005)	/	
Fitted compliance rate of phase I subject vehicles	-0.310	(0.249)	/	
log (Fitted number of phase I subject vehicles)	/		1.971***	(0.261)
log (Fitted compliance rate of phase I subject vehicles)	/		-1.118***	(0.357)
Year FE	Yes		Yes	
Quarter FE	Yes		Yes	
Station FE	Yes		Yes	
Weather & Other controls	Yes		Yes	
# of stations	23		23	
# of observations	17,758		17,977	
R2	0.3554		0.2625	
Stage I (panel A): DV = Number of phase I subject vehicles (columns 1&2) or log (Number of phase I subject vehicles) (columns 3&4)				
Phase I	2.934***	(0.091)	0.107***	(0.003)
Phase II	-2.783***	(0.151)	-0.055***	(0.004)
Year FE	Yes		Yes	
Quarter FE	Yes		Yes	
Station FE	Yes		Yes	
Weather & Other controls	Yes		Yes	
# of stations	23		23	
# of observations	17,977		17,977	
R2 (adjusted)	0.3497		0.2250	
Stage I (panel B): DV = Compliance rate of phase I subject vehicles (columns 1&2) or log (Compliance rate of phase I subject vehicles) (columns 3&4)				
Phase I	0.084***	(0.000)	0.094***	(0.000)
Phase II	0.005***	(0.000)	0.002***	(0.000)
Year FE	Yes		Yes	
Quarter FE	Yes		Yes	
Station FE	Yes		Yes	
Weather & Other controls	Yes		Yes	
# of stations	23		23	
# of observations	17,758		17,977	
R2 (adjusted)	0.9866		0.9829	

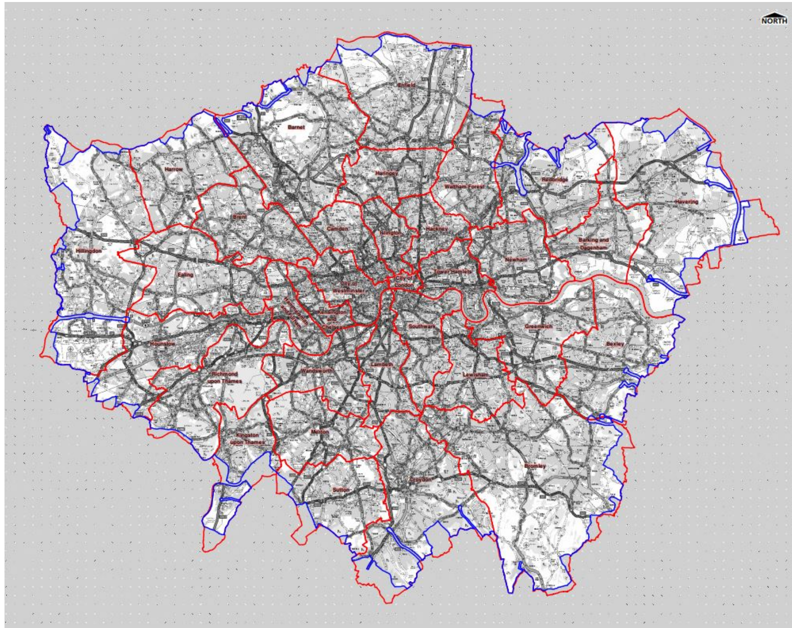
*Note: This table shows the robustness checks for the estimation of the 2SLS model in Table 8. Clustered standard errors by station in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

Table 12b: Robustness Checks for the Two-Stage-Least-Squares Estimation on the Effect of London's LEZ on Air Quality Using Traffic Flow and Compliance Rate of the Subject Vehicles in Phase II as Instruments

	Excluding Dec 24, 2007-Jan 3, 2008		Using logarithmic traffic patterns	
	(1)	(2)	(3)	(4)
	Coeff	SE	Coeff	SE
Stage II: DV = log(PM10)				
Fitted number of phase II subject vehicles	0.038***	(0.005)	/	
Fitted compliance rate of phase II subject vehicles	-0.174	(0.140)	/	
log (Fitted number of phase II subject vehicles)	/		1.132***	(0.134)
log (Fitted compliance rate of phase II subject vehicles)	/		-0.188*	(0.111)
Year FE	Yes		Yes	
Quarter FE	Yes		Yes	
Station FE	Yes		Yes	
Weather & Other controls	Yes		Yes	
# of stations	23		23	
# of observations	17,758		17,758	
R2	0.3760		0.4016	
Stage I (panel A): DV = Number of phase II subject vehicles (columns 1&2) or log (Number of phase II subject vehicles) (columns 3&4)				
Phase I	2.526***	(0.048)	0.097***	(0.002)
Phase II	-2.413***	(0.130)	-0.074***	(0.004)
Year FE	Yes		Yes	
Quarter FE	Yes		Yes	
Station FE	Yes		Yes	
Weather & Other controls	Yes		Yes	
# of stations	23		23	
# of observations	17,758		17,758	
R2 (adjusted)	0.3936		0.3042	
Stage I (panel B): DV = Compliance rate of phase II subject vehicles (columns 1&2) or log (Compliance rate of phase II subject vehicles) (columns 3&4)				
Phase I	0.019***	(0.000)	0.026***	(0.000)
Phase II	0.129***	(0.001)	0.145***	(0.001)
Year FE	Yes		Yes	
Quarter FE	Yes		Yes	
Station FE	Yes		Yes	
Weather & Other controls	Yes		Yes	
# of stations	23		23	
# of observations	17,758		17,758	
R2 (adjusted)	0.9824		0.9747	

*Note: This table shows the robustness checks for the estimation of the 2SLS model in Table 9. Clustered standard errors by station in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

Figure 1: London's LEZ boundary (source: Traffic for London)



Note: Blue boundary – LEZ; Red boundary: London local authority boundary

Figure 2a: Traffic signs within London's LEZ

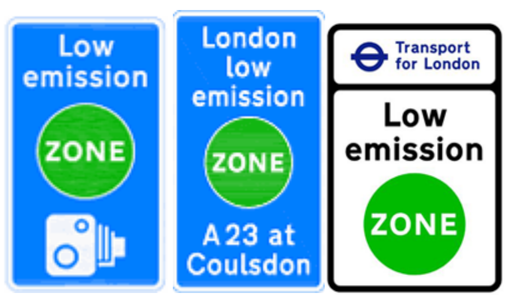


Figure 2b: Advance warning signs outside of London's LEZ

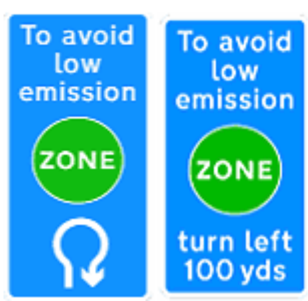
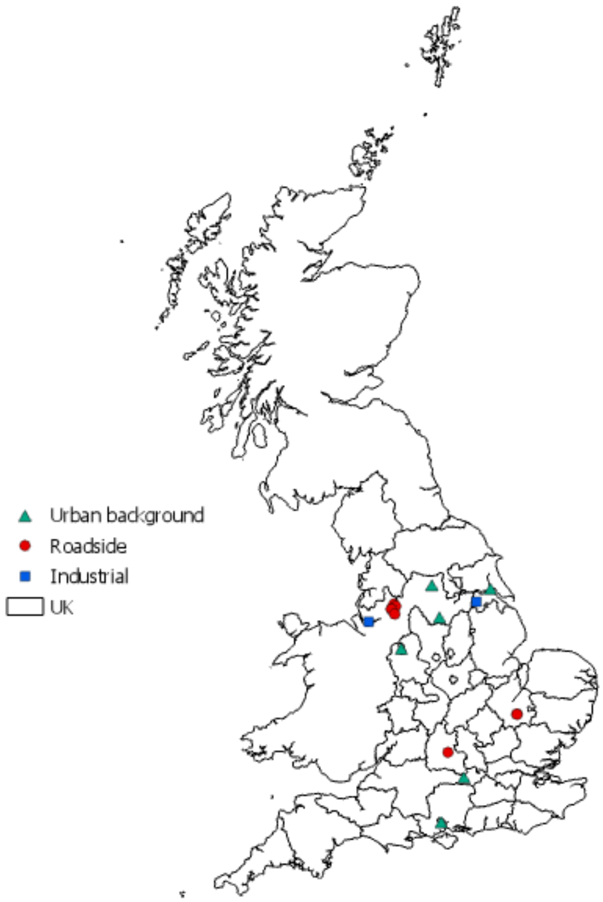


Figure 3: Station locations

Panel A: Control Stations (Located 25+ Miles from the LEZ Boundary)



Panel B: Treated (Within the LEZ) and Nearby Stations (< 10 Miles from the LEZ Boundary)

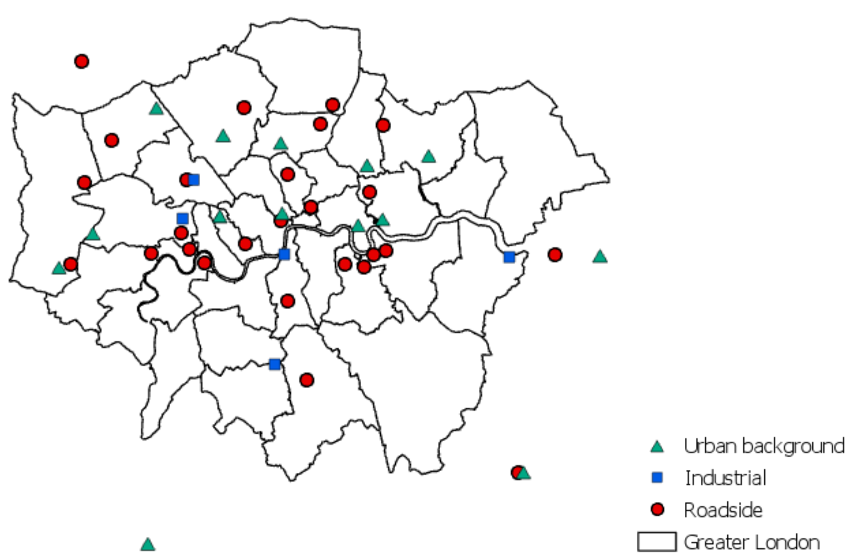


Figure 4: Kernal density distribution of log PM10, 2005-2010

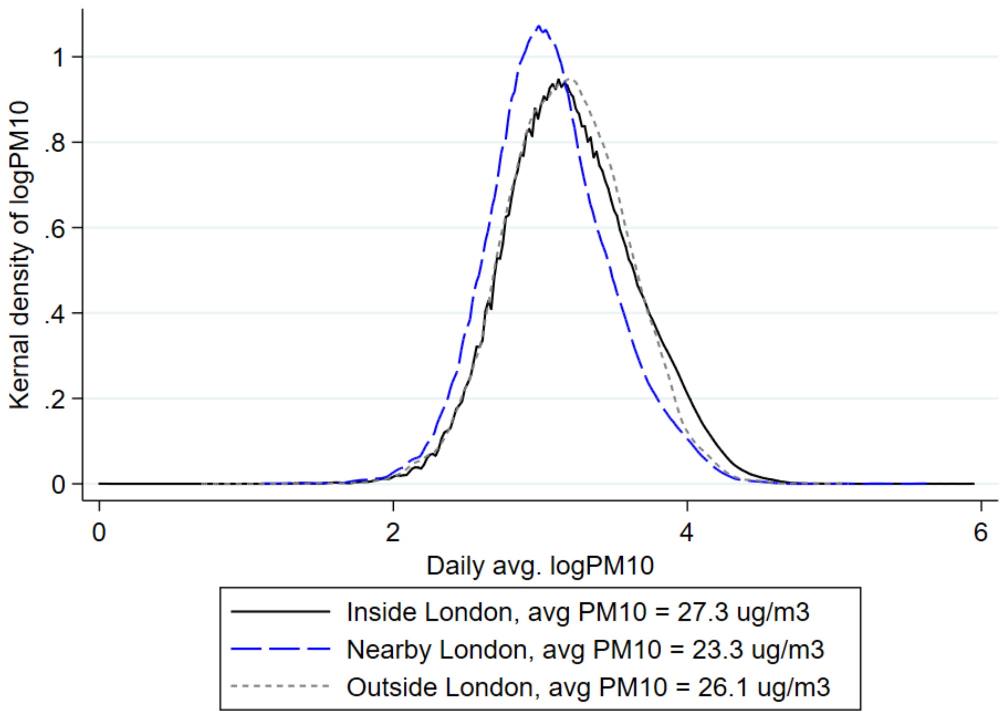


Figure 5a: Locally Weighted Smoothed Curve for Raw Concentrations of PM10, 2005-2010

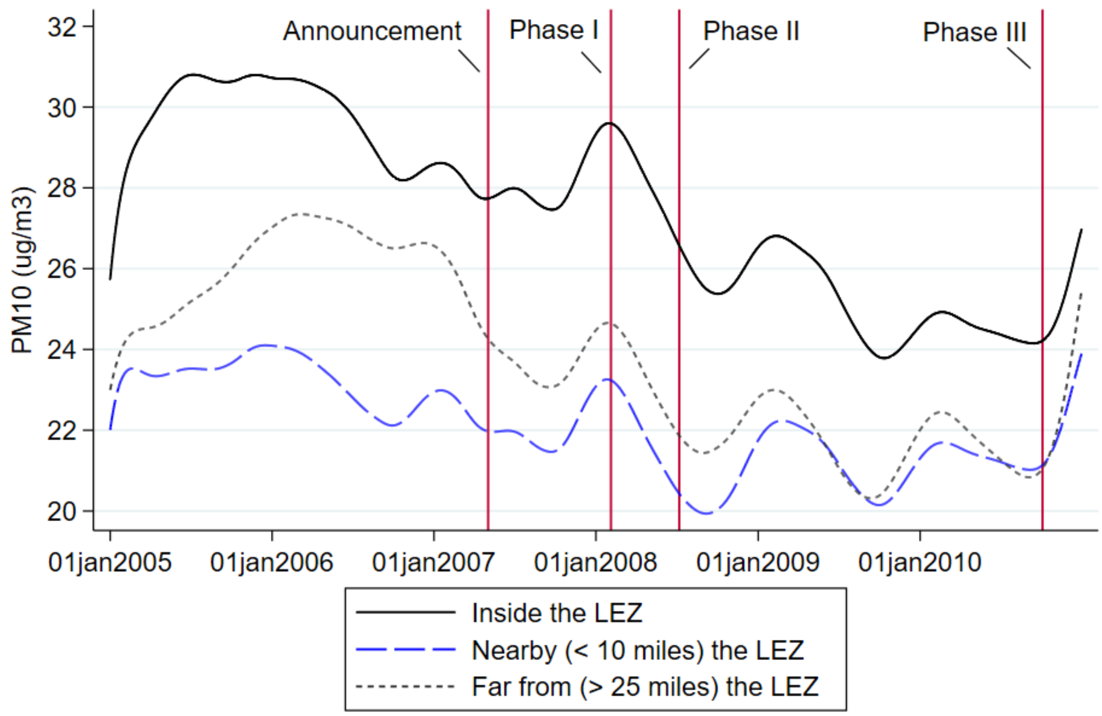


Figure 5b: Locally Weighted Smoothed Curve for De-Seasonalized Concentrations of PM10, 2005-2010

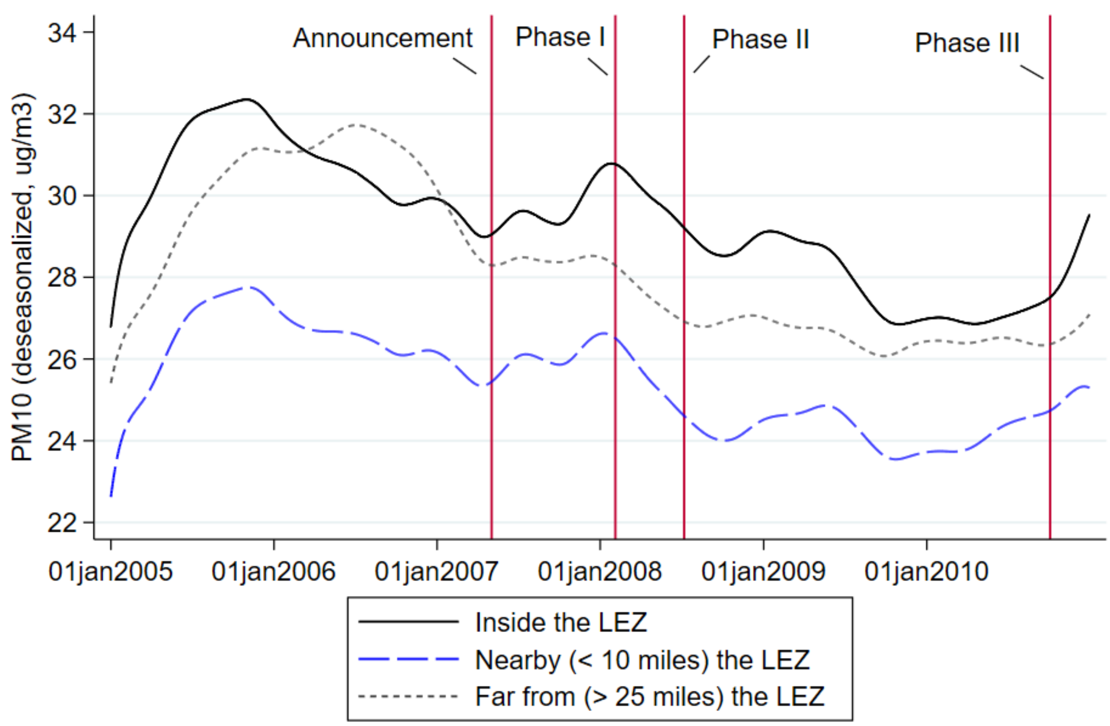


Figure 6a: Annual average daily traffic flow for HGVs, by UK regions, 2005-2010

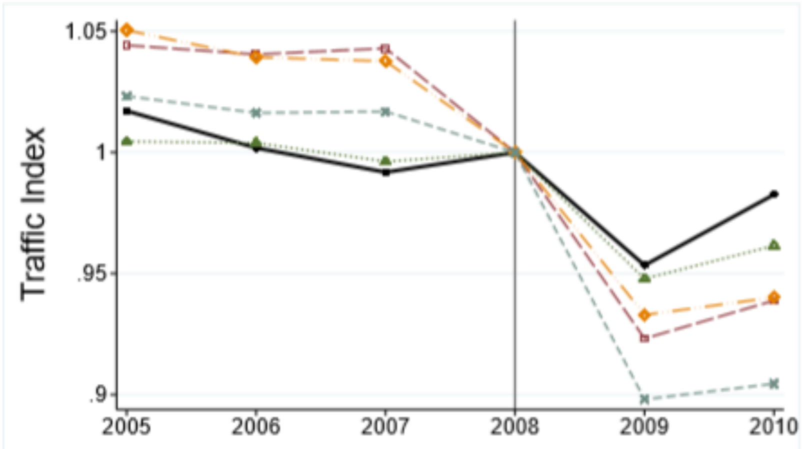


Figure 6b: Annual average daily traffic flow for LGVs, by UK regions, 2005-2010

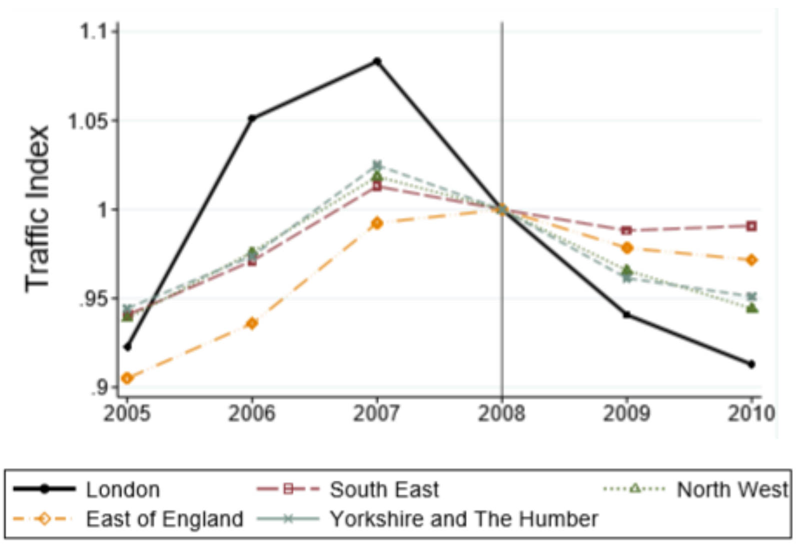


Figure 7a: Annual fuel consumption in London, by fuel types, 2005-2010

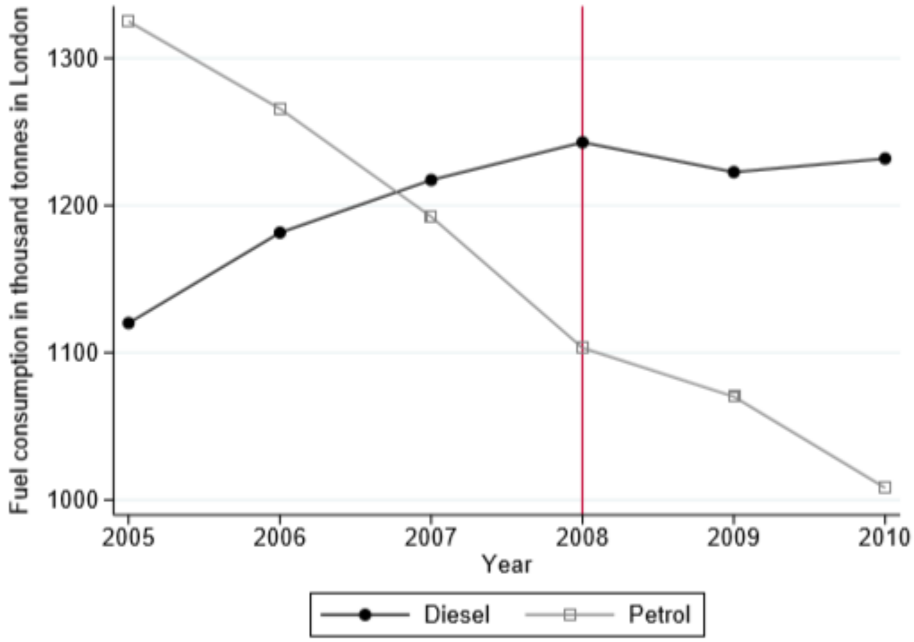


Figure 7b: Annual diesel fuel consumption in London, by type of vehicles, 2005-2010

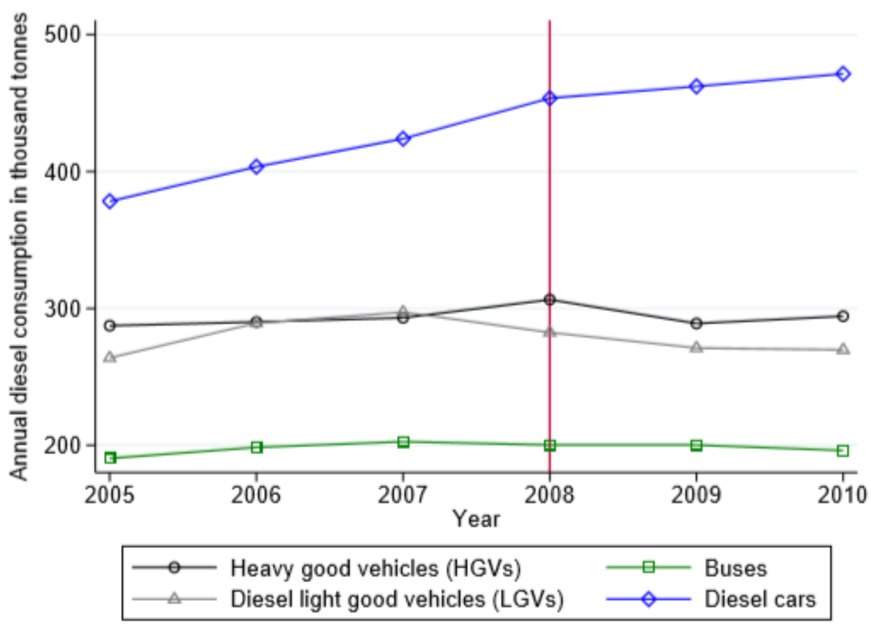


Figure 8: Compliance Rate of London's LEZ Phase I and Phase II

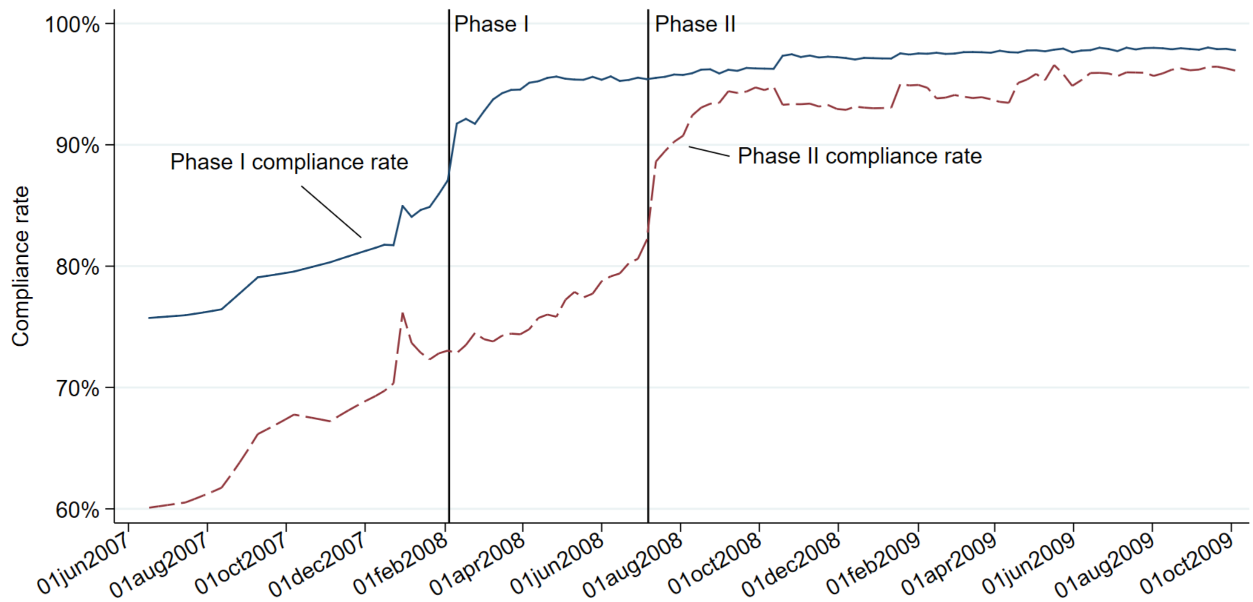


Figure 9: Number of Phase I and Phase II Subject Vehicles in London