Environmental Effects of the London Congestion Charge: a Regression Discontinuity Approach

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Abstract

This paper aims to evaluate the causal effect of the London Congestion Charge on the level of pollution. To this end, we have assembled a unique dataset. This consists of daily observations, concentrating on eight pollutants: CO, NO, NO2, NOX, O3, PM2.5, PM10, SO2. By using a regression discontinuity design in time series; with thresholds centered on the dates of the introduction of the charge and of the beginning and end of Western Expansion, a negligible and adverse impact of the charge is documented. When a spatially disaggregated model is estimated, it emerges that the road pricing scheme has induced a decrease in the concentration of NO, NO2 and NOX in the charged area and an increase in surrounding areas. A general deterioration of pollution concentration is found in the case of O3, PM2.5, PM10. These results are consistent with an overall increase in traveled kilometers, due to traffic diversion from the charged to the uncharged area. Furthermore, there is an unclear, possibly adverse, impact of increased speed on pollution.

Keywords: London Congestion Charge, Pollution, Regression Discontinuity Design.

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1 Introduction

In 2013, congestion cost \$8.5 billion and 82 hours per driver in London. These figures are expected to rise by 63% in 2030 (Gordon and Pickard, 2014). Similar costs are faced by most of the world cities. Furthermore, there is a large consensus and empirical study on the negative effects of exposure to high levels of pollution on human health. According to Cohen et al. (2004), urban pollution causes up to 6.4 million premature deaths every year. Given this empirical evidence, policy makers are implementing measures at local level to decrease the concentration of some pollutants; in particular, through transport policy actions (OECD, 2010; Greater London Authority, 2006).

To cope with the external costs of transport, several cities have introduced - or are considering to introduce - road pricing schemes, as in the case of: London (Banister, 2003), Milan (Rotaris et al., 2010), Hong Kong (Ison and Rye, 2005), Singapore (Santos, 2005), Stockholm (Eliasson et al., 2009) and several Norwegian cities (Leromonachou et al., 2006).

In the case of London, along with pollution, congestion was considered to be one of the reasons that led to the then Mayor of London, Ken Livingstone, overseeing the implementation of the London Congestion Charge (henceforth denoted as LCC). In fact, London road users spend over ten billion minutes in traffic queues on major roads every year (Transport for London, 2009). The LCC, introduced in 2003 and then modified to extend the treated area, is probably the most known and studied example (Banister, 2003; Givoni, 2012; Ison and Rye, 2005; Prud'homme and Bocarejo, 2005; Quddus et al., 2007; Santos and Bhakar, 2006; Santos and Fraser, 2004; Santos and Shaffer, 2004). However, literature has not reached a consensus on the socio-economic convenience of such measures, since infrastructure and administrative costs seem to exceed the benefits in terms of a reduction in external costs (Mackie, 2005; Prud'homme and Bocarejo, 2005; Raux, 2005).

The aim of this paper is to estimate the causal effect of the LCC on environmental quality in London. In the first year of its operation, the charge reduced road congestion in the affected areas by 18%. Additionally, it lowered the volume of traffic and road congestion by 30% in the affected areas (Kelly et al., 2011). The environmental implications of the scheme are not clear a priori since, in theory, it aims to reduce traffic and should generate a decrease in pollution. However, it additionally aims to increase speed, with an increase in fuel consumption and then, in pollution. The behavior of drivers modifying their routes to avoid the charged area is a further issue. Therefore, the environmental consequences of the LCC cannot be unequivocally determined a priori and need to be empirically estimated.

In early works, Atkinson et al. (2009) found limited evidence to demonstrate the impact of the LCC on air pollution. As the authors clearly state, their approach is based on descriptive statistics, making it difficult to consider their estimates of the charge's causal effect. In fact, Givoni (2012) has argued in favor of a more robust statistical analysis of the effects of road pricing experiences. This is because figures used in ex post evaluations are, in general, unreliable and biased by other phenomena (confounding factors) not considered in the analysis. To deal with this identification issue, we adopt an econometric framework consisting of the estimation of a parameter measuring a break in the trend of time series of concentration of pollutants. In particular, following Percoco's early work (2013; 2014a) on the case of Milan, we adopt a Regression Discontinuity Design (RDD) to estimate a local average treatment effect of the introduction of the congestion charge. This approach allows for a counterfactual identification of the effect of the policy. As a result, it provides reliable estimates of the impact of the LCC in a short timeframe around the date of the scheme's introduction.

To estimate the effect of road pricing, we make use of some policy actions. These are: the introduction of the LCC, and the start and end of the Western expansion of the charged area. With these interventions, we study the variation in the concentration of pollution by using a unique dataset of daily concentrations of: CO, NO, NO2, NOX, O3, PM2.5, PM10, SO2 over the years 2000-2013, for 132 monitoring stations in London. We use both a London-wide average of pollution concentration and a RDD model with spatial heterogeneity. Results indicate a negligible or adverse impact of road pricing, most likely because of spatial displacement of traffic from the charged area to neighboring areas, possibly with an increase in traveled kilometers.

2 The London Congestion Charge

London's fight against pollution has its origins in the second half of the XIX century; although it was only after the Great Smog of 1952 that the first policies were introduced, aiming to improve air quality. This event was disastrous for Londoners: a huge blanket of smog covered the entire city for four days and, by some estimates, caused the deaths of 4,000 people (Mayor of London, 2002). Since then, air quality has much improved; although it remains one of the European cities with the highest levels of pollution. Road transport is a major cause of the high concentration of pollutants, accounting for about 40% of emissions of nitrogen oxides and more than 60% of particulates (Greater London Authority, 2006; Kelly et al., 2011).

In an attempt to reduce traffic flow, the LCC was introduced on February 17th, 2003. The objective was to reduce congestion in the central area of London, covering an area of 22 sq. km, or 1.4% of the territory of Greater London. LCC consists of a daily payment to obtain permission to move freely in the area. The policy's enforcement is achieved through the use of cameras and the automatic recognition of cars' license plates. The charge is in operation from Monday to Friday, from 7:00 AM to 6:00 PM. Initially, the scheme provided for a daily fee of £5. Subsequently, this increased to the current rate of £10. Exemptions are provided for the means of public utility, such as: buses, vehicles of law enforcement and for all vehicles powered by alternative sources of fuel. Finally, for the vehicles of the residents in the area, the price is discounted by 90%.

The original area covered was largely contained by the Inner London Ring Road. Hence major areas, such as; the West End, the City of London and the financial district, fell under this new policy. A later extension (the so-called Western Expansion), beginning on February 2007 and ending on December 2010, increased the size of the area covered to parts of West London. Additionally, it shortened the charging hours by 30 minutes to 6:00 PM. This extension nearly doubled the area covered by the LCC. This is because it included the areas of Kensington and Chelsea, covering approximately 41.5 sq. km. or 2.6% of the metropolitan area of London. Figure 1 shows the area of the LCC and of the Western Expansion. Over time, pricing of the charge has also increased. The original £5 charge was increased in July 2005 to £8 per day and, since January 4th, 2011, it has had a base daily rate of £10.

The stated objective of implementing the congestion charge was a 15% reduction in traffic in the central areas of London, with a simultaneous maintenance of traffic levels in the surrounding affected area. Transport for London (2006) reports that in the first years of the scheme's operation, the number of cars entering the central area of London significantly decreased by 21% - with respect to the pre-treatment period, although with no significant changes in travel time. However, when considering the effect of the policy at the level of congestion, the results are less positive. In regards to congestion considered as excess delay, above conditions not congestion; in the first years of the policy's operation, there was a substantial reduction in the level of congestion in the order of 30%. However, since 2006; despite the previously mentioned reduction in the number of vehicles, the congestion level has increased, compared to the levels prior to the policy. Overall, the LCC has had, at least in the early years of operation, the anticipated effect on the level of congestion and traffic in the affected area. It quite rapidly changed the habits and choices of the people concerned. Later, however, the effects of the policy have been mitigated. This can be justified by car users' adaptation of habits to the new policy; the interference of other schemes; or other exogenous factors. Figure 2 shows the timeline of the adoption of the LCC and variations in the setup.

The aim of the congestion charge was largely two-fold (TfL, 2004a).Firstly, to reduce congestion and secondly, to use the funds raised to improve transport infrastructure. In so far as private consumption of motor transport can be seen to impose negative externalities, e.g., increased congestion, noise, pollution etc., LCC can be thought of as a form of Pigouvian taxation. It can better equate the marginal private and social costs of transport; that is, to make individual agents incorporate external costs of their consumption into their private costs.

However, it should be noted that the marginal cost of congestion was not used as a basis for the charge. Instead, to find the optimal pricing scheme, simulations and models of household behavior were used to predict changes in traffic. Nonetheless, Santos and Shaffer (2004) state that the £5 per day charge is a reasonable approximation of the marginal congestion costs for an agent driving through the congestion charge zone.

The revenues raised are not insignificant. In 2009/10, the congestion charge revenue was £312.6 million, making up 8.7% of TfL group revenue. Since its establishment, the contribution to group revenue has remained relatively stable; in 2003/04 revenue was £186.7 million, making up 8% of group revenue. Due to direct and other expenditures, net income from congestion charging in 09/10 was £158.1 million. This is still a significant sum, considering that these funds are used to operate and improve TfL (TfL 2004a, 2010). A notable change came with the new Mayor of London; Boris Johnson. On November 27th, 2008, in keeping with his election manifesto, Johnson announced the planned abandoning of the Western Extension. Following subsequent consultation processes and legal reviews, this was later officially implemented. On January 4th, 2011, increased pricing for the remaining zone was applied; although the congestion charge was lifted from Christmas Eve 2010 to January 3rd, 2011 to coincide with the holiday period. The policy shift was met with both support and criticism. The TfL had stated that the LCC policy had had a “broadly neutral impact on the Central London economy”, with perceived benefits in the form of: improved public transport, better air quality, and fewer collisions and accidents (TfL, 2008). Furthermore, the

TfL's estimates suggested that this decision would lead to a £55-70 million loss of annual revenue, a large sum by any measure (TfL, 2008).

Although there is an abundance of analysis on the effect of the LCC on several aspects of the city, a causal analysis of its impact on environmental quality has not yet been conducted. The use of simple descriptive statistics may, in fact, pose severe bias in the evaluation of the policy, since it assigns to the LCC. Furthermore, the effect of other variables (confounding factors) can contribute to this.

3 Methodology and data

Our empirical approach is based on fairly recent literature using the Regression Discontinuity Design (henceforth denoted as RDD) to examine the impact of policies related to transport and air quality (Chen and Whalley, 2011; Davis, 2008; Percoco, 2013).

RDD is a non-experimental approach that uses ex post to evaluate a program's impact on a situation in which units are considered treated or not, according to a certain threshold in a reference variable (forcing variable). In our case, the date in which the LCC was implemented (or of the start and end of the Western Expansion) is used as a threshold that introduces an exogenous variation in the access of polluting vehicles in the city. Thus, the expected outcome is a reduction in the level of pollutants. It should be stated that RDD identifies the impact of LCC under mild assumptions; hence, it excludes the bias imposed by confounding factors.

In our analysis, we will make use of two basic models, relying on RDD. Firstly, we will estimate a spatially aggregated model, in which the outcome variable is the average concentration of a given pollutant, across all (or a sub sample of) monitoring stations. Secondly, we will account for the spatial heterogeneity of the policy's impact by using a panel model. Here, spatial variation comes from an interaction between the time of the LCC's introduction and the distance of the monitoring station from the boundary of the treated area.

As for the aggregated model, let y_0 and y_1 denote the counterfactual outcomes before and after the treatment T (the LCC or the Western Expansion), let x be the forcing variable (in our case, the time) and consider the following assumptions (Angrist and Pischke, 2009):

A1. E(y_g| T,x) = E(y_g| x), g=0,1

A2. E(y_g| x), g = 0,1 is continuous at $x = x_0$

A3. P(T=1|x)≡F(x) is discontinuous at $x = x_0$, i.e. the propensity score of the treatment has a discrete jump at $x = x_0$.

Following Imbens and Lemieux (2008) the goal is to estimate the parameter ρ on treatment of this form:

$$y_{t,T} = \theta + \rho LCC_t + f(\tilde{x}_{t,T}) + \eta_t \tag{1}$$

where $y_{t,T}$ in our case is the concentration of a given pollutant in day t whose treatment status is T (i.e. before or after the introduction of the LCC), θ is a constant, $\tilde{x}_{t,T}$ is the forcing variable properly normalized (a time trend centered at the date of the introduction of the LCC, i.e. 17 February 2003). Consequently,ρ expresses the impact of the treatment at $x_{t,T} = x_0$. The $f(\tilde{x}_{t,T})$ term is a p-th order parametric polynomial to account for non linearity of the relationship between the time trend and pollution and thus to control that the eventual break in $x_{i,T} = x_0$ is not due to unaccounted non-linearity. Lastly η_t is an error term. LCC is our treatment variable taking the value of 1 after the introduction of the congestion charge and zero before.

Seasonal and climatic factors are crucial in explaining the level of pollutants in the air. To deal with these problems in the reference model (1), seasonality is accounted for with day of the week, month and year dummies. Additionally, in most of the specifications, we control for weather conditions and standard errors were clustered by month.

Given the size of London and the problems of spatio-temporal aggregation, estimates of model (1) may be not fully reliable due to omitted heterogeneity of the effects. In particular, it is reasonable to assume that the distance from the treated area is the main determinant of the spatial diffusion of the impact of congestion charge on pollution. More formally, the heterogeneous local average treatment effect is defined as:

$$HLATE(x_t = x_0, d_i) = HLATE(x_0, d_i) = E[y_{i1}|x_0, d_i] - E[y_{i0}|x_0, d_i] \quad (2)$$

where d_i is the minimum Euclidean distance of monitoring station i from the boundary of the charged area, y_{i0}, y_{i1} are the concentration of a given pollutant as recorded at monitoring station i before and after the treatment. The identification of the HLATE in (2) needs two further assumptions (Percoco, 2014b):

A4. the interaction variable d_i must be continuous at x_0, the threshold;

A5. the interaction variable d_i must be uncorrelated with the error term in the outcome equation, conditional on x_i.

Assuming that the conditional expectation function E$[y_i|x_i, d_i]$ follows an additive process based on the columns of x_i and z_i then simple OLS can indeed estimate the parameters unbiasedly using the following specification:

$$y_{it} = \alpha_i + \rho LCC_t + \gamma LCC_t \cdot d_i + f(\tilde{x}_t) + \varepsilon_i \quad (3)$$

where α_i is a full set of station-specific fixed effects. In the case of equation (3), $HLATE = \rho + \gamma d_i$.

To make (3) operational for the analysis o the impact of the LCC, we need a further specification, that is we assume $d_i = 0$ for all monitoring stations located within the charged area because the interpretation of the distance from the boundary of the treated area, in this case would be unclear. To account for the heterogeneity of these stations with respect to the city-wide ATT, we have introduced a further variable, $CENTER$, that takes value 1 if the station is located in the treated area and zero otherwise. Therefore, the estimated equation is:

$$y_{it} = \alpha_i + \rho LCC_t + \gamma_1 LCC_t \cdot d_i + \gamma_2 LCC_t \cdot CENTER_i + f(\tilde{x}_t) + \varepsilon_i \tag{4}$$

It should be stated that station-specific fixed effects are of particular relevance in (4) to identify interactions as d_i and $CENTER_i$ are time-invariant. Finally, in all the specifications we make use of a 5th order trend polynomial.

The data used in the analysis were made available by the LAQN (London Air Quality Network). They comprise daily observations of pollution from several monitoring stations in London, over the years 2000-2013. These detectors are not homogeneous with regard to pollutants and weather conditions monitored, as well as for the location of the detector, with respect to the road surface. Not all variables are available for all stations. Of a total of 194, 136 monitoring stations were selected on the basis of availability of information for at least one of the variables of interest.

The dataset contains information on the concentration of eight pollutants: CO, NO, NO2, NOX, O3, PM2.5, PM10, SO2. Of those pollutants, only SO2 is less related to transportation. The concentrations of all the others are widely considered to be indicators of transport-related pollution (although not exclusively). Furthermore, information on: temperature, wind speed, rain and humidity is also available.

Table 1 shows a test for the difference of the average emission level, one year before and one year after the implementation of the LCC and Western Expansion. In this case, a negative value represents a decrease in the average level of emissions during the period after the implementation of the policy in question, and vice versa. The results show a significant decrease in the emission levels for almost all of the pollutants considered, with the exception of ozone in regards to the congestion charge. Instead, there were no statistically significant changes for fine particulate matter (PM2.5).

Before proceeding with the parametric analysis described in this section, figure 3 reports a graphical analysis, as in the spirit of Imbens and Lemieux (2008); and Lee and Lemieux

(2010). In particular, scatter plots report daily concentrations one year before and one year after the introduction of the LCC for the seven pollutants across the 136 monitoring stations of our sample. Local polynomial regressions are also added to highlight eventual breaks in correspondence of the introduction of the LCC. No significant drop in the concentration of pollution is detectable. In the following section, this result will be scrutinized in a more systematic way, through a parametric analysis.

4 Results

4.1 Spatially aggregated estimates

We start our analysis by estimating model (1) in time series, i.e., by using the London-wide average of pollution concentration as a dependent variable, with daily observations of pollution concentration. In table 2, results for the aggregated model are presented. In all specifications, we control for a polynomial trend of 5th order and for weather variables. In Panels A-D, the time frame is 2000-2005 and standard errors are clustered by month. Panel A reports baseline estimates with no significant effect of the LCC, with the sole exception of particulate matters, for which an increase by 12.46 $\mu g/m^3$ and 5.95 $\mu g/m^3$ for PM10 and PM2.5 respectively is found. Panel B and C report robustness checks by including three temporal lags of the dependent variable to account for possible temporal dependence in concentration. Here, all non-roadside stations are dropped to eliminate confusion in the production of pollution, induced by non-transport activities. Finally, in Panel D only roadside stations in the treated area are considered. Estimates across specifications are unstable in magnitude, although never significantly from a statistical point of view.

Panels E, F, G report the same models as in panels B, C, D but in a shorter time frame; that is, models have been estimated over the years 2002-2003 to increase precision in the identification of the policy's effect. Additionally, results in this case are qualitatively unchanged and show unsatisfactory results of the LCC, in terms of a reduction in the city's pollution.

In table 3, we study the effect of the Western Expansion, by considering the period 2006-2011, i.e., one year before and one year after the change of the LCC. In this case, the time trend is not normalized and the variable EXPANSION takes the value of 1 during the expansion and 0, otherwise. All specifications include a 5th order polynomial trend and weather variables. Panels A and B do not present significant results and only specifications in Panel C show some statistically significant estimates, with reductions in NO, NO2, NOX significant at 5% confidence level. However, it should be noted that the magnitude and the sign of the coefficients remain unstable across the Panels; and hence, these results cannot be considered as fully reliable.

In table 4, we consider both the LCC and the Western Expansion over the whole period 2000-2013, as well as another transport policy implemented in London in those years: the Low Emission Zone (henceforth denoted as LEZ). To achieve the second objective listed in Ken Livingstone's strategy; namely the reduction of working capital for each individual vehicle, the LEZ was introduced in February 2008 to an area that covers most of Greater London - 2,644 sq. km. The scheme imposes a restriction on the possibility of movement for the most pollutant vehicles. This is imposed 24 hours a day every day and enforcement is made by cameras. The scheme applies to trucks, buses and coaches, some types of van and minibuses. Over the years, the scheme has become increasingly stringent and new emissions requirements have been introduced. Vehicles that do not meet the LEZ requirements are forced to pay; £200 daily permits for trucks and buses and £100 for minivans and minibuses, with potential fines of £1,000 or £500 respectively. Onerous permits ensure full compliance with the scheme, even if, as pointed out by Kelly et al (2011), many of the vehicles potentially affected by the LEZ already meet the minimum criteria established by the policy. The policy, therefore, potentially only affects a small part of urban transport in London. According to descriptive statistics in Ellison et al. (2013), LEZ has decreased the concentration of PM10 by 2.46%-3.07%.

RDD identifies that the policy is only effective if no other policy is introduced. This implies that our model only identifies the impact of the LCC (or of the Western Expansion) if no policy affecting environmental quality is introduced in February, 2003 (or February, 2007). The introduction of the LEZ does not overlap with the introduction of the LCC. However, when considering a wider temporal window to estimate model (1), including a dummy variable equal to 1 after the introduction of the LEZ; and 0 before, might improve estimates of the impact of the Western Expansion, since there is some temporal overlap between the two policies. However, results in table 4 do not document any impact of the policies under scrutiny, with some exception showing an increase in O3 and PM10, although with low levels of statistical significance.

4.2 Spatial heterogeneity of policy impacts

In terms of statistical significance, the results of the aggregated model were unsatisfactory. This may be due to either; an absence of impact of road pricing on environmental quality, or to unaccounted spatial heterogeneity in pollution trends, as highlighted by Auffhammer et al. (2009; 2011). To deal with the latter, in this sub-section we present estimates of panel model (3).

In table 5, baseline models for the evaluation of the LCC are reported. They have all estimated over the years 2002-2003 with a 5th order polynomial trend; weather controls and three days of temporal lags of the dependent variable. In Panel A, an overall increase in the concentration of pollution in the whole city of London is detected, as all coefficients estimated for the treatment variable LCC are positive. Furthermore, with the sole exception of CO and

O3, they are statistically significant. Interestingly enough, if we consider the variables meant to capture heterogeneity, we find a displacement effect of pollution due to the introduction of the LCC. For O3 and SO2 in particular, the coefficient for $LCC_t \cdot d_i$ is positive and significant; whereas, the coefficient $LCC_t \cdot CENTER_i$ is negative and significant. This indicates that the introduction of the LCC has decreased the concentration of O3 and SO2 in the charged area and increased it in the surrounding areas, with a possible overall increase in the entire city's pollution. A similar pattern is detected for NO2 and PM10, although with lower levels of statistical significance. In Panel B, we restrict the area to monitoring stations within 15 kilometers from the treated area. In this case, results are qualitatively unchanged, although with lower levels of statistical significance (with the exception of PM10, for which there is an marginal increase in the level of significance).

In table 6, we explore the spatial heterogeneity in the effects of the Western Expansion. All specifications include a 5th order polynomial trend, weather controls and three days of temporal lags of the dependent variable. As in the previous sub-section, the time trend is not normalized and the variable EXPANSION takes the value of 1 during the expansion, and 0 otherwise. Variable Treat replaces variable CENTER and takes value of 1, if the monitoring station is located in the Western area of the charged zone and 0, otherwise (hence it also assumes value 0 in the area defined in 2003). Models reported in Panel A have been estimated over the years 2006-2011 and, in general, present unsatisfactory results; although a significant reduction in the concentration of NO, NO2, NOX, PM10, SO2 took place in the treated area (that is to say, the Western area). In panels B and C, the introduction of the Western Expansion and the end of the policy change are analyzed separately. The introduction of the policy has decreased the concentration of NO, NO2, NOX by 1.4-8.4 $\mu g/m^3$, depending on the matters. However, evidence of an increase in O3 by 4.33 $\mu g/m^3$, PM2.5 by 1.24 and PM10 by 3.23 is also provided. In the case of the end of expansion, a spatially heterogeneous picture emerges, as from estimates reported in Panel C; as a substantial increase in NO, NO2, NOX, O3 is detected, with sizable effect in the treated area of an order of magnitude of 0.99-4 $\mu g/m^3$. However, it must be stated that the end of the expansion has also decreased the concentration of O3, PM2.5 and PM10 by 3.7-4.1 $\mu g/m^3$.

4.3 Discussion

Overall, econometric results of both the aggregated and the spatial model show unclear effects of the congestion charge in London. For some pollutants, such as PM10 and SO2, an increase in the concentration was found. This can be due to the diversion of traffic from the city center to external areas, with a subsequent increase in the kilometers traveled and the potential of polluting emissions. This spatial pattern of traffic flow is consistent with the findings of ITO (2010), for which some areas of northern London witnessed an increase in traffic counts by more than 30% over the period 2001-2010.

This hypothesis can be further investigated by using data on traffic counts in the London area. In particular, the Department for Transport makes traffic counts for the period 2000-2013 available, with annual observations for 2,141 count points. Count points have been geolocalized and hence assigned to three groups: CENTER (if located in the congestion charge area), SURROUNDING (if located in a borough partially treated by the congestion charge or neighboring the charged area[1]), or in the control group. In column 1 in table 7, descriptive statistics of differences-in-mean is reported. In particular, statistics refer to the change in the mean of traffic counts before the treatment and after the introduction of the charge. It is noted that the pre-treatment mean is computed over the years 2000-2002, whilst the post-treatment mean is calculated over the years 2003-2005. Descriptive statistics show a decrease in the number of vehicles by 128,538 and 207,296 in the treated and controlled areas, although both estimates are not significantly different from zero. Interestingly, count points surrounding the treated area registered an average increase by 111,325 vehicles. This

[1]The following boroughs have been considered to be in the *SURROUNDING* group: Wandsworth, Lewisham, Greenwich, Newham, Waltham, Haringey, Barnet, Brent, Kensington, Hammersmith.

estimate is significant at a 99% statistical level. Together, these statistics imply a diversion of traffic from the treated to the surrounding area. However, a compelling parametric analysis is needed to account for unobserved heterogeneity and time trend. To this end, the following difference-in-difference model can be estimated over the years 2000-2005:

$$traffic_{it} = \alpha_i + \beta trend_t + \gamma post_t + \delta_1 CENTER_i \cdot post_t + \delta_2 SURROUNDING_i \cdot post_t + \varepsilon_{it} \tag{5}$$

where the dependent variable is the number of traffic count in year t at count point i, α_i are count point specific fixed effects, trend indicates a temporal trend, post is a dummy variable taking the value of one after 2002 and zero otherwise, CENTER and SURROUNDING are indicator variables for the treatment and surrounding group to which count point i belongs to. In model (2) in table 7 we consider $\delta_2 = 0$ and it emerges a decrease by 12,358 vehicles in the treated area with respect to the rest of the city, although this coefficient is not significant. In model (3) the full model is reported and it emerges that the introduction of the congestion charge has resulted in an increase in traffic counts by 279,596 vehicles. This figure is statistically significant, whereas no significant (at conventional level) change is found in the treated area.

Estimates in table 7 corroborate the hypothesis advanced in the previous section to justify the finding of a decrease in pollution concentration in the treated area and an increase outside of this area. However, results may still hide some heterogeneity in terms of traffic composition. In table 8, the sample is split into four categories (heavy goods vehicles, light goods vehicles, cars, motorbikes) and the number of bikes is added. Interestingly, the introduction of the LCC has decreased the number of heavy goods vehicles by 13,434 units in the treated area, although this estimate is only marginally significant. Additionally, no significant effect is found in the case of light goods vans; whilst, in model 3, a clear increase in the surrounding area by 242,411 cars is estimated. According to estimates in models 4 and 5, an increase by 34,664 and 30,335 occurred in the case of motorbikes and bikes. Hence, from an environmental perspective, a shift towards uncharged vehicles (and in this case, motorbikes) is not efficient. Another possible transmission channel might make a change in the kilometers traveled; drivers may be willing to avoid the charged area by traveling longer routes around the area. The UK Department of Transport provides statistics on kilometers × vehicles at the level of local authority. Estimates of the effect of the LCC in the treated and surrounding areas are not precise, since some local authorities are only partially treated. In this case, the assignment to the charged; surrounding or to the controlled area, is carried out on the basis of the share of surface treated. In particular, we consider the following local authorities as treated: City of London, Lambeth, Southwark, Tower Hamlets, Hackney, Islington, Camden, City of Westminster. Local authorities in the surrounding area are: Wandsworth, Lewisham, Greenwich, Newham, Waltham, Haringey, Barnet, Brent, Kensington, Hammersmith.

Table 9 reports estimates of the LCC on traveled kilometers by using a difference in means. As in the previous case, the pre-treatment mean is computed over the years 2000-2002, whilst the post-treatment mean is determined over the years 2003-2005. Interestingly, a decrease by 45,000 kilometers × vehicles was found in the treated area, whereas an increase by 39,000 kilometers × vehicles was found in the surrounding area. Therefore, also in this case, there is evidence of traffic diversion from the treated to the surrounding area which possibly explains the results in section 4.2.

Another important factor for the interpretation of the results presented in section 4.2 is the relationship between emissions of a given pollutant and average speed. In fact, the relationship between the production of nitrogen oxides and traveling speed is directly proportional to the vehicles with diesel engine (EEA, 2010). Thus, an increase of the vehicle's average speed is due to a greater production of nitrogen oxides. This might be relevant because of the reduction of congestion caused by the introduction of the charge, especially in the early years after the policy was introduced (Greater London Authority, 2006). However, the relationship between pollutants and average speed of vehicles is still not very clear, especially for ozone and particulates, and further studies are needed to shed light on this issue (EEA, 2010).

5 Conclusion

In this paper, the environmental effect of road pricing in London was studied with a RDD approach to estimate the causal impact of the LCC and of the Western Expansion. In particular, the exogenous variation in traffic flows after the introduction of the policies was used to estimate a variation into the concentration of: CO, NO, NO2, NOX, O3, PM2.5, PM10, SO2. Two classes of models have been estimated: one, in which the dependent variable is a city-wide average of pollution concentration; and two, a spatial panel model, in which impact heterogeneity has been assumed to depend on the distance from the treated area.

In the case of the aggregated model, a negligible effect of the policy was found. In the panel model, a spatial displacement effect was found, since a reduction in the concentration of several pollutant in the treated area and an increase in the surrounding areas was found.

In particular, a significant decrease in the concentration of: NO, NO2, O3, PM10, SO2 was found in the treated area; and a contemporary increase in the concentration of: O3, PM2.5, PM10 was discovered out of the charged area. This pattern in the estimates is consistent with the hypothesis that the introduction of the congestion charge has diverted traffic in space and shifted drivers from charged to uncharged routes and, eventually, vehicles. Traffic data show that the number of circulating vehicles in the area surrounding the treated area by 279,596 vehicles; 242,441 of which were cars.

A substantial increase in the number of motorbikes and of bikes has also been detected in the city center. In terms of kilometers traveled, a decrease by 45,000 kilometers × vehicles was estimated in the treated area, along with an increase by 39,000 kilometers × vehicles in the surrounding area.

Overall, in terms of pollution concentration of the whole city, our results suggest that the congestion charge has a limited impact. This is possibly because of the spatial diversion of traffic. This result calls for careful consideration of the spatial extent and of the cross elasticity of traffic flows when implementing road pricing.

References

[1] Angrist, J. and J.S. Pischke (2009), Mostly Harmless Econometrics: An Empiricist's Companion, Princeton: Princeton University Press.

[2] Atkinson R.W., B. Barratt, B. Armstrong, H.R. Anderson, S.D. Beevers, I.S. Mudway, D. Green, R.G. Derwent, P. Wilkinson, C. Tonne, F.J. Kelly (2009), The impact of the congestion charging scheme on ambient air pollution concentrations in London, Atmospheric Environment, 43:5493–5500.

[3] Auffhammer, M., A.M. Bento, S.E. Lowe (2011), The city-level effects of the 1990 Clean Air Act amendments, Land Economics, 87(1):1-18.

[4] Auffhammer, M., A.M. Bento, S.E. Lowe (2009), Measuring the effects of the Clean Air Act amendments on ambient PM10 concentrations: the Critical importante of a spatially disaggregated analysis, Journal of Environmental Economics and Management, 58:15-26

[5] .Banister, D. (2003), Critical Pragmatism and Congestion Charging in London, International Social Science Journal, 176:248-264.

[6] Chen, Y. and W. Whalley (2012), Green Infrastrucutre: The Effects of Urban Rail Transit on Air Quality, American Economic Journal: Economic Policy, 4(1):58-97.

[7] Cohen A., Andersen R., Ostra B., Pandey K., Kryzanowsky M., Kunzli N., Gulschmidt K., Pope A., Romleu I., Samet J., Smith K., (2004) “The Global Burden of Disease due to Outdoor Air Pollution”, Journal of Toxicoloy and Environmental Health, Part A, 68: 1-7

[8] Davis, L.W. (2008), The Effect of Driving Restrictions on Air Quality in Mexico City, Journal of Political Economy, 116(1):38-81.

[9] EEA (2010) “Do lower speed limits on motorways reduce fuel consumption and pollutant emissions?”, Copenhagen: European Environment Agency.

[10] Eliasson, J., Hultkranz L., Nerhagen L., Smidlfet Rosqvist L. (2009), The Stockholm Congestion Charging Trial 2006: Overview of the Effects, Transportation Research Part A, 43(3):240-250.

[11] Givoni, M. (2012), Re-assessing the Results of the London Congestion Charging Scheme, Urban Studies, 49(5): 1089-1105.

[12] Gordon, S. and J. Pickard (2014), London’s $8.5bn traffic jam slows down growth, Financial Times, October 13, online edition.

[13] Greater London Authoruty, (2002) “50 years on: The struggle for air quality in London since the great smog of December 1952”, London: Greater London Authority.

[14] Ieromonachou, P., Potter, S. and Warren, J.P. (2006). Norway’s urban toll rings: evolving towards congestion charging, Transport Policy, 13(5), 29-40.

[15] Imbens, G. W., Lemieux, T. (2008), "Regression discontinuity designs: a guide to practice". Journal of Econometrics, 142 (2): 615-635.

[16] Ison S. and Rye T. (2005), Implementing Road User Charging: the Lessons Learnt from Hong Kong, Cambridge and Central London, Transport Reviews, 25(4):451-465.

[17] Kelly F, Anderson H.R., Armstrong B., Atkinson R., Barratt B., Beevers S., Derwent D., Green D., Mudway I. e Wilkinson P. (2011) “The Impact of Congestion Charging Scheme on Air Quality in London” – Health Effects Institute – Research Report n°155.

[18] Lee D., Lemieux T., (2008) “Regression Discontinuity Design in Economics”, Journal of Economic Literature 48 281-355.

[19] Lee,D.S.,Lemieux,T.(2010),"RegressionDiscontinuityDesignsinEconomics", Journal of Economic Literature, 48 (2): 281-355.

[20] Mackie, P. (2005), The London Congestion Charge: A Tentative Economic Appraisal – A Comment on the Paper by Prud’homme and Bocarejo, Transport Policy, 12(3):288-290.

[21] Mayor of London (2002), Statement by the Mayor concerning his decision to confirm the Central London Congestion Charging scheme order with modifications, London: Office of the Mayor of London.

[22] OECD (2010), “The transport system can contribute to better economic and environmental outcomes”, OECD Economic Survey: the Netherlands, Paris.

[23] Percoco, M. (2013), Is road pricing effective in abating pollution? Evidence from Milan, Transportation Research D, 25(December):112–118.

[24] Percoco, M. (2014a), The effect of road pricing on traffic composition: evidence from a natural experiment in Milan, Italy, Transport Policy, 31(January):55–60.

[25] Percoco, M. (2014b), Regional perspectives on policy evaluation, Heidelberg: Springer.

[26] Prud'homme R. and Bocarejo J.P. (2005), The London Congestion Charge: A Tentative Economic Appraisal, Transport Policy, 12(3):279-287.

[27] Quddus M.A., Carmel A. and Bell M.G.H. (2007), The Impact of Congestion Charge on Retail: The London Experience, Journal of Transport Economics and Policy, 41(1):113-133.

[28] Raux C. (2005), Comments on "The London Congestion Charge: A Tentative Economic Appraisal", Transport Policy, 12(4):368-371.

[29] Rotaris L., Danielis R., Marcucci E., Massiani J. (2010), The Urban Road Pricing Scheme to Curb Pollution in Milan, Italy: Description, Impacts and Preliminary Cost-Benefit Anal- ysis Assessment, Transportation Research A, 44:359-375.

[30] Santos, G. (2005), Urban Congestion Charging: A Comparison Between London and Singapore, Transport Reviews, 25(5):511-534.

[31] Santos G. and Bhakar J. (2006), The Impact of London Congestion Charging Scheme on the Generalised Cost of Car Commuters to the City of London from a Value of Travel Time Savings Perspecitve, Transport Policy, 13(1):22-33.

[32] Santos G. and Fraser G. (2006), Road Pricing: Lessons from London, Economic Policy, 21(46):263-310.

[33] Santos G. and Shaffer B. (2004), Preliminary Results of the London Congestion Charging Scheme, Public Works Management and Policy, 9:164-181.

[34] TfL (2004), Annual Report 2004, London: Transport for London.

[35] TfL (2006) "Central London Congestion Charging: Impacts monitoring. Fourth Annual Report", London: Transport for London.

[36] TfL (2008), “Impacts Monitoring – Sixth Annual Report”, London: Transport for London.

[37] TfL (2009), Travel in London Report number 1 (2009), London: Transport for London.

[38] TfL (2010), Annual Report 2010, London: Transport for London.

Table 1: Descriptive statistics

	CC			*Western Expansion*		
	Pre	Post	Difference	Pre	Post	Difference
CO	0.68	0.412	-0.268***	0.535	0.294	-0.241***
NO	43.408	33.352	-10.056***	39.794	35.751	-4.043***
NO2	47.195	46.68	-0.515***	48.336	47.676	-0.66***
NOX	113.65	97.897	-15.753***	109.325	102.828	-6.497***
O3	32.11	34.92	2.81***	34.344	33.538	-0.806***
PM2.5	14.12	14.106	-0.014	14.677	14.763	0.086
PM10	27.78	25.497	-2.285***	28.013	25.326	-2.687***
SO2	6.99	4.346	-2.642***	5.796	3.617	-2.179***

Table 2: The impact of the London Congestion Charge

	CO	NO	NO2	NOX	O3	PM10	PM2.5	SO2
				Panel A: Baseline models				
LCC	-0.072	0.666	7.068	8.418	7.501	12.461	5.949	1.682
	(0.63)	(0.08)	(2.74)*	(0.57)	(2.42)*	(3.84)**	(4.08)**	(1.28)
Obs.	2,190	2,190	2,190	2,190	2,190	2,190	2,190	2,190
R-squared	0.39	0.58	0.71	0.65	0.68	0.36	0.31	0.43
				Panel B: With temporal lags				
LCC	-0.061	-1.385	4.695	2.764	5.909	4.538	1.962	0.872
	(0.83)	(0.20)	(2.37)*	(0.22)	(2.60)*	(2.98)*	(3.25)**	(0.97)
Obs.	2,087	2,087	2,087	2,087	2,087	2,087	2,087	2,087
R-squared	0.59	0.66	0.76	0.70	0.75	0.60	0.57	0.56
				Panel C: Temporal lags, only roadside stations				
LCC	0.054	5.582	5.378	14.013	0.429	5.292	1.998	1.159
	(0.99)	(2.31)*	(3.64)**	(2.93)*	(0.18)	(3.44)**	(2.86)*	(1.85)
Obs.	2,087	2,087	2,087	2,087	2,087	2,087	2,087	2,087
R-squared	0.40	0.48	0.50	0.49	0.62	0.52	0.49	0.54
				Panel D: Temporal lags, only roadside stations in the treated area				
LCC	-0.111	0.287	9.268	10.266	-0.237	7.197	1.347	1.216
	(1.54)	(0.05)	(2.97)*	(1.10)	(0.11)	(2.81)*	(2.25)*	(1.32)
Obs.	2,087	2,087	2,087	2,087	2,087	2,087	2,087	2,087
R-squared	0.76	0.47	0.48	0.47	0.52	0.44	0.45	0.47
				Panel E: Temporal lags, only 2002-2003				
LCC	0.130	13.742	6.028	26.955	-0.576	5.156	2.240	2.985
	(2.53)*	(2.16)	(1.96)	(2.13)	(0.22)	(2.13)	(1.52)	(2.17)
Obs.	727	727	727	727	727	727	727	727
R-Squared	0.47	0.46	0.52	0.48	0.62	0.55	0.51	0.39
				Panel F: Temporal lags, only roadside stations in 2002-2003				
LCC	0.096	15.529	6.944	30.542	2.604	5.703	2.580	2.926
	(1.28)	(2.12)	(2.23)*	(2.14)	(1.17)	(2.33)*	(1.54)	(2.95)*
Obs.	727	727	727	727	727	727	727	727
R-squared	0.58	0.50	0.52	0.50	0.48	0.55	0.50	0.46
				Panel G: Temporal lags, only roadside stations in treated area in 2002-2003				
LCC	0.051	22.722	7.216	41.663	2.362	7.637	-0.864	4.371
	(0.67)	(2.26)*	(2.19)	(2.27)*	(1.13)	(3.13)**	(0.43)	(5.69)**
Obs.	727	727	727	727	727	727	727	727
R-squared	0.53	0.50	0.50	0.50	0.50	0.48	0.47	0.35

Notes: All specifications include a 5th order polynomial time trend, controls for wind speed, humidity, temperature, rainfalls and a series of dummies for day of the week, month and year. Models in Panels A-D have been estimated over the years 2000-2005. Standard errors are clustered by month. Significance levels: *** p<0.01, ** p<0.05, * p<0.1

Table 3: The impact of the Western expansion

	CO	NO	NO2	NOX	O3	PM10	PM2.5	SO2
	Panel A: Baseline with temporal lags							
EXPANSION	0.027	1.528	0.310	2.874	0.894	1.046	0.130	0.327
	(1.31)	(0.86)	(0.13)	(0.59)	(0.91)	(1.34)	(0.15)	(1.55)
Obs	2,552	2,552	2,552	2,552	2,552	2,552	2,552	2,552
R-squared	0.59	0.65	0.76	0.70	0.75	0.59	0.57	0.56
	Panel B: Temporal lags, only roadside stations							
EXPANSION	0.025	3.273	1.150	6.151	1.585	0.407	-0.091	0.746
	(0.64)	(0.52)	(0.62)	(0.53)	(0.76)	(0.25)	(0.07)	(2.26)*
Obs	2,552	2,552	2,552	2,552	2,552	2,552	2,552	2,552
R-squared	0.40	0.48	0.50	0.49	0.62	0.52	0.49	0.54
	Panel C: Temporal lags, only roadside and City stations							
EXPANSION	-0.035	-21.461	-6.369	-39.197	5.349	-1.773	-0.010	-0.606
	(2.32)*	(6.59)**	(3.94)**	(6.13)**	(5.53)**	(2.37)*	(0.02)	(2.23)*
Obs	2,552	2,552	2,552	2,552	2,552	2,552	2,552	2,552
R-squared	0.76	0.52	0.50	0.51	0.52	0.49	0.44	0.47

Notes: All specifications include a 5th order polynomial time trend, controls for wind speed, humidity, temperature, rainfalls and a series of dummies for day of the week, month and year. Models have been estimated over the years 2006-2011. Standard errors are clustered by month. Significance levels: *** p<0.01, ** p<0.05, * p<0.1

Table 4: Comparing policies

	CO	NO	NO2	NOX	O3	PM10	PM2.5	SO2
	Polynomial, weather variables and temporal lag							
CC	-0.053	-1.397	5.144	2.985	7.034	4.336	1.862	0.973
	(0.73)	(0.19)	(2.35)*	(0.23)	(2.51)*	(3.38)**	(2.87)*	(1.14)
EXPANSION	0.015	1.058	0.885	3.049	1.221	1.150	0.119	0.225
	(0.67)	(0.41)	(0.32)	(0.48)	(0.94)	(1.38)	(0.13)	(1.04)
LEZ	-0.017	-4.106	-1.534	-7.646	2.068	-1.703	-1.271	-0.343
	(1.17)	(1.03)	(1.14)	(1.01)	(1.75)	(1.97)	(2.29)*	(1.80)
Obs.	5,107	5,107	5,107	5,107	5,107	5,107	5,107	5,107
R-squared	0.41	0.42	0.33	0.32	0.44	0.39	0.41	0.36
	Polynomial, weather variables and temporal lag, only roadside stations							
CC	-0.013	-2.999	3.562	-1.043	4.820	3.222	1.524	0.452
	(0.20)	(0.37)	(1.37)	(0.07)	(3.17)**	(1.64)	(2.10)	(0.49)
EXPANSION	0.007	1.983	1.425	4.749	2.731	0.608	-0.348	0.702
	(0.12)	(0.65)	(0.43)	(0.62)	(1.88)	(0.62)	(0.28)	(2.99)*
LEZ	0.007	-5.931	-1.537	-10.408	2.107	-1.029	-1.604	-0.101
	(0.19)	(1.63)	(1.36)	(1.57)	(1.98)	(1.09)	(2.25)*	(0.43)
Obs.	5,107	5,107	5,107	5,107	5,107	5,107	5,107	5,107
R-squared	0.39	0.31	0.29	0.33	0.37	0.41	0.40	0.36

Notes: All specifications include a 5th order polynomial time trend, controls for wind speed, humidity, temperature, rainfalls and a series of dummies for day of the week, month and year. Models have been estimated over the years 2000-2013. Standard errors are clustered by month. Significance levels: *** p<0.01, ** p<0.05, * p<0.1

Table 5: Spatial heterogeneity of the impacts of the LCC

	(1) CO	(2) NO	(3) NO2	(4) NOX	(5) O3	(6) PM2.5	(7) PM10	(8) SO2
	Panel A: Only 2002-2003							
LCC	0.0417	10.68***	2.419**	22.15***	0.232	2.831**	5.038***	1.868***
	(0.0288)	(1.661)	(0.886)	(3.235)	(0.377)	(0.640)	(0.362)	(0.354)
LCC**d*	0.00136	0.0178	0.0420*	-0.0480	0.0491***	-0.0142	0.0135*	0.0216***
	(0.00189)	(0.0251)	(0.0207)	(0.0579)	(0.00970)	(0.0207)	(0.00610)	(0.00395)
LCC**CENTER*	0.0274	-1.870**	-1.440**	-0.592	-0.483***	-0.931*	-0.228***	-0.408**
	(0.0266)	(0.616)	(0.521)	(1.460)	(0.136)	(0.321)	(0.021)	(0.122)
Observations	13,861	44,537	44,650	44,794	15,135	3,877	34,351	19,664
R-squared	0.884	0.774	0.935	0.855	0.903	0.893	0.910	0.752
	Only 2002-2003 and Distance < 15 km							
LCC	0.0409	11.30***	2.404**	23.76***	0.196	3.300**	5.505***	2.019***
	(0.0387)	(1.407)	(0.959)	(2.624)	(0.499)	(0.680)	(0.324)	(0.324)
LCC**d*	0.00351	0.0589	0.0525	-0.0215	0.0812***	0.0595**	0.00953**	-0.0260
	(0.00376)	(0.0708)	(0.0434)	(0.146)	(0.0273)	(0.0114)	(0.0046)	(0.0224)
LCC**CENTER*	0.0394	-1.472*	-1.284**	-0.240	-0.727*	-1.344***	-0.213*	-0.439*
	(0.0325)	(0.782)	(0.512)	(1.891)	(0.334)	(0.145)	(0.0962)	(0.188)
Observations	9,424	33,082	33,271	33,385	11,689	3,201	25,711	15,041
R-squared	0.889	0.788	0.937	0.863	0.902	0.895	0.917	0.759

Notes: All specifications include a 5th order polynomial time trend, a three days temporal lag, controls for wind speed, humidity, temperature, rainfalls and a series of dummies for day of the week, month and year. Standard errors are clustered by month. Significance levels: *** p<0.01, ** p<0.05, * p<0.1

Table 6: Spatial heterogeneity of the impacts of the Western Expansion

	(1) CO	(2) NO	(3) NO2	(4) NOX	(5) O3	(6) PM25	(7) PM10	(8) SO2
				Panel A: Whole sample (2006-2011)				
EXPANSION	0.00133	0.479	0.641**	1.461	-0.786***	-0.217	0.969***	0.0455
	(0.00933)	(0.427)	(0.223)	(0.885)	(0.192)	(0.483)	(0.183)	(0.111)
EXPANSION**d*	0.000475	-0.0158	-0.0144**	-0.0402	0.0404	0.00733	0.00340	0.0150***
	(0.000578)	(0.0150)	(0.00510)	(0.0263)	(0.0230)	(0.0189)	(0.00472)	(0.00298)
EXPANSION**Treat*	0.000449	-1.343***	-0.949***	-3.161***	0.511	0.142	-0.273***	-0.204**
	(0.0103)	(0.355)	(0.111)	(0.583)	(0.346)	(0.390)	(0.0411)	(0.0615)
				Introduction of the Western Expansion (2006-2007)				
EXPANSION	-0.00508	-4.759***	-1.046***	-8.424***	4.327***	1.239**	3.231***	-0.121
	(0.00818)	(0.749)	(0.252)	(1.263)	(0.578)	(0.260)	(0.229)	(0.178)
EXPANSION**d*	-2.71e-05	-0.0252	-0.00372	-0.0418	0.0490	0.0307	0.0150	-0.00294
	(0.000436)	(0.0243)	(0.0148)	(0.0511)	(0.0384)	(0.0165)	(0.0118)	(0.00465)
EXPANSION**Treat*	-0.0267**	-0.00820	-1.025**	1.020	0.769	-1.000**	0.0359	0.0714
	(0.00940)	(0.526)	(0.363)	(1.190)	(0.486)	(0.311)	(0.0800)	(0.0648)
				End of the Western Expansion (2010-2011)				
EXPANSION	-0.0607***	12.20***	1.705*	19.70***	-3.681***	-3.827***	-4.129***	-0.367*
	(0.00706)	(1.969)	(0.771)	(3.670)	(0.610)	(0.525)	(0.285)	(0.151)
EXPANSION**d*	-0.000384	-0.0696**	-0.0267	-0.134**	0.0414*	-0.0209	0.00822	0.00897
	(0.000293)	(0.0268)	(0.0245)	(0.0561)	(0.0175)	(0.0221)	(0.00477)	(0.00512)
EXPANSION**Treat*	-0.00651	1.739***	1.022**	4.001***	0.983***	-0.888**	-0.894***	-0.701***
	(0.00963)	(0.450)	(0.348)	(0.747)	(0.210)	(0.264)	(0.0835)	(0.147)

Notes: All specifications include a 5^{th} order polynomial time trend, a three days temporal lag, controls for wind speed, humidity, temperature, rainfalls and a series of dummies for day of the week, month and year. Standard errors are clustered by month. Significance levels: *** p<0.01, ** p<0.05, * p<0.1

Table 7: Difference-in-differences in traffic within London (dependent variable is the number of vehicles; in thousands)

	(1) Descriptive statistics	(2) Least squares	(3) Least squares
CENTER	-128.538	-12.358	77.973
	(123.444)	(90.738)	(83.302)
SURROUNDING	111.325***		279.596***
	(23.332)		(89.434)
Control	-207.296		
	(231.211)		
Obs.		12,846	12,846
R. sq.		0.094	0.094

Notes: Column 1 reports descriptive statistics of changes in total vehicles between the pre-charge period (2000-2002) and the post-charge period (2003-2005). Models (2) and (3) are difference-in-differences models with count point fixed effect, a temporal trend and a *post* dummy taking the value of 1 after 2003 and 0 before. Models are estimated via least squares over the period 2000-2005. Dependent variable is the total number of vehicles. Standard errors in models 2 and 3 are clustered by local authority. Significance levels: *** p<0.01, ** p<0.05, * p<0.1.

Table 8: The effect of the London Congestion Charge on traffic composition (dependent variable is the number of vehicles by type; in thousands)

	(1) Heavy Goods Vehicles	(2) Light Goods vans	(3) Cars	(4) Motorbikes	(5) Bikes
CENTER	-13.434*	7.002	41.967	34.664***	30.335***
	(7.121)	(15.401)	(77.960)	(11.123)	(8.338)
SURROUNDING	-3.952	31.497	242.441**	3.592	-3.479
	(9.541)	(20.818)	(101.360)	(8.988)	(12.804)
Obs.	12,846	12,846	12,846	12,846	12,846
R. sq.	0.012	0.012	0.013	0.016	0.014

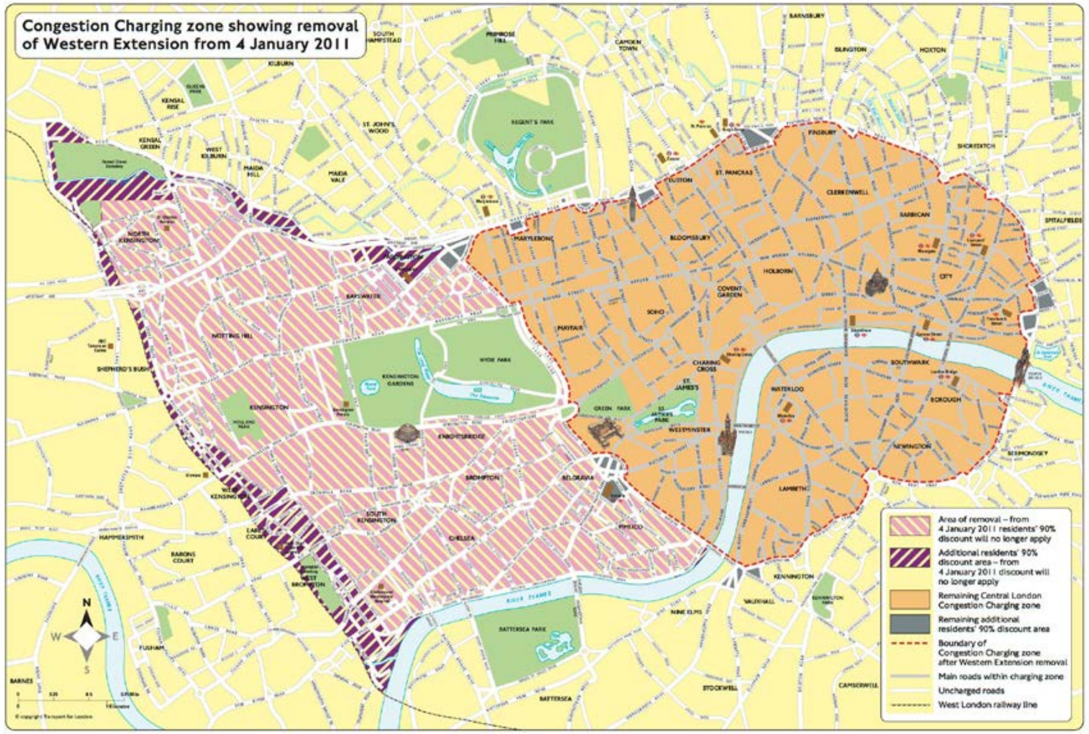
Notes: All models are difference-in-differences models with count point fixed effect, a temporal trend and a *post* dummy taking the value of 1 after 2003 and 0 before. Models are estimated via least squares over the period 2000-2005. Dependent variable is the total number of vehicles by type as reported in column headings. Standard errors are clustered by local authority. Significance levels: *** p<0.01, ** p<0.05, * p<0.1.

Table 9: The effect of the London Congestion Charge on kilometres travelled (Million of km*vehicles)

	Before	After	Implied DID
CENTER	3494.333	3353.000	-45,000**
SURROUNDING	5645.667	5588.667	39,333**
Control	10914.33	10818.000	

Notes: Data at local authority level. Treated local authorities are: City of London, Lambeth, Southwark, Tower Hamlets, Hackney, Islington, Camden, City of Westminster. Local authorities in the surrounding area are: Wandsworth, Lewisham, Greenwich, Newham, Waltham, Haringey, Barnet, Brent, Kensington, Hammersmith. Years before the London Congestion Charge are 2000-2002; years after the policy are 2003-2005. Significance levels: *** p<0.01, ** p<0.05, * p<0.1.

Figure 1: The LCC and the Western Expansion



Congestion Charging zone showing removal of Western Extension from 4 January 2011
Area of removal – from 4 January 2011 residents' 90% discount will no longer apply
Additional residents' 90% discount area – from 4 January 2011 discount will no longer apply
Remaining Central London Congestion Charging zone
Remaining additional residents' 90% discount area
Boundary of Congestion Charging zone after Western Extension removal
Main roads within charging zone
Uncharged roads
West London railway line
N
S
E
W
KILBURN
SOUTH HAMPSTEAD
PRIMROSE HILL
CAMDEN TOWN
BARNSBURY
ISLINGTON
HOXTON
KENSAL RISE
KENSAL GREEN
WEST KILBURN
MAIDA HILL
MAIDA VALE
ST. JOHN'S WOOD
REGENT'S PARK
EUSTON
ST. PANCRAS
FINSBURY
CLERKENWELL
SHOREDITCH
BARBICAN
SPITALFIELDS
NORTH KENSINGTON
MARYLEBONE
BLOOMSBURY
HOLBORN
CITY
BAYSWATER
COVENT GARDEN
SOHO
MAYFAIR
NOTTING HILL
HYDE PARK
KENSINGTON GARDENS
SHEPHERD'S BUSH
CHARING CROSS
ST. JAMES'S
SOUTHWARK
WATERLOO
BOROUGH
KENSINGTON
HOLLAND PARK
KNIGHTSBRIDGE
GREEN PARK
WESTMINSTER
NEWINGTON
BERMONDSEY
BROMPTON
BELGRAVIA
LAMBETH
WEST KENSINGTON
SOUTH KENSINGTON
PIMLICO
HAMMERSMITH
BARONS COURT
CHELSEA
WEST BROMPTON
KENNINGTON
RIVER THAMES
NINE ELMS
VAUXHALL
BATTERSEA PARK
FULHAM
STOCKWELL
CAMBERWELL
BARNES
BATTERSEA

Figure 2: Timeline of the setup and variations of the London Congestion Charge

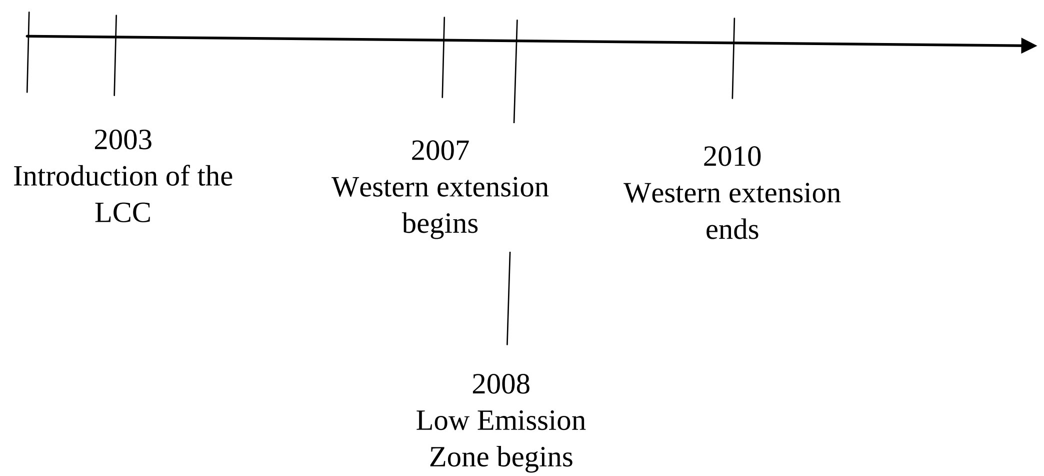


Figure 3: The effect of the introduction of the London Congestion Charge on pollution concentration