Journal of Urban Economics 121 (2021) 103302

Contents lists available at ScienceDirect

Journal of Urban Economics

journal homepage: www.elsevier.com/locate/jue

The Cost of Traffic: Evidence from the London Congestion Charge☆

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A B S T R A C T

This paper exploits the implementation of the London Congestion Charge (LCC) to provide credible estimates on the willingness to pay to avoid traffic using the housing market. This policy curtails road traffic by imposing a fee on anyone driving into the charge zone. My results show that the LCC is associated with significant improvement in traffic conditions and housing values. Instrumenting local traffic conditions with the enforcement of the LCC, and limiting the analysis to properties proximate to the charge boundary, I find that the elasticity of housing values with respect to traffic is -0.30. These findings suggest that the consequential improvement in traffic conditions due to the LCC has generated substantial windfall of more than £3.8 billion for homeowners in the zone.

1. Introduction

Traffic congestion is an urban disamenity generated from the agglomeration of economic activities. Attracted by productivity gains and amenities in cities, firms and individuals congregate in urban areas and compete for space, attributing to outward expansion of cities. With the proliferation of automobiles, the surge in traffic on roads inevitably leads to congestion, an ubiquitous problem many cities around the world faces. These traffic delays affect London as well. Average on-road commuting speed in the 1990s was slower than that at the beginning of twentieth century before car travel became prevalent (Newbery, 1990). By 2002, travel speed for motor vehicles during morning peak hours fell by almost 30% compared to that in 1974, from 14.2 to 10.0 miles per hour, and drivers spent, on average, 27.6% of their on-road time stationary (Department of Environment and the Regions, 1998).

Traffic is also a major source of air pollution. According to figures from Environmental Protection Agency, automobiles contribute to more than 50% of the nitrogen oxide, 30% of the volatile organic compounds and 20% of the PM10 in US.[1] These emissions have detrimental effects on health outcomes, increasing infant mortality, reducing birth weight and inducing premature births (Currie and Walker, 2011; Knittel et al., 2016). Heavier traffic can also increase the risk of traffic accidents and fatalities (Li et al., 2012; Green et al., 2016). It is evident that traffic externalities are undesirable and can affect the attractiveness of neighbourhoods, influencing household location decisions.

This paper measures the average marginal willingness to pay (WTP) to avoid negative traffic externalities (e.g noise pollution, traffic exhaust, elevated traffic accident risk and congestion delays) using the housing market. Because an explicit market for traffic does not exist, the hedonic approach is broadly adopted in the literature to value this non-market amenity.[2] The idea is that traffic varies across space and, holding all other factors constant, differences in home values should reflect the willingness to pay (WTP) to avoid traffic. While the concept is simple, attempts to estimate the casual effect of traffic on home prices are fraught with difficulties. First, traffic is not randomly distributed across space and the heaviest traffic is usually around the city center where economic activities are congregated. Unobserved neighbourhood differences between properties across space are likely to confound the estimates. Second, more affluent households who incur costlier time delays could sort themselves from congested neighbourhoods to reduce commuting time. The concern is whether the WTP to avoid traffic could be confounded with the WTP for better neighbourhoods.

Bearing these challenges in mind, this paper exploits the substantial but localised changes in traffic conditions induced by the London Congestion Charge (LCC) to recover the cost of traffic. The charge boundary is drawn around the city centre to alleviate congestion from the most

☆ I would like to thank the editor and the two anonymous referees for the useful comments and suggestions. I would also like to thank Antonio Bento, Chris Cunningham, Christian Hilber, Diego Puga, Daniel Sturm, Gilles Duranton, Jos Van Ommeren, Killian Heilmann, Matthew Turner, Henry Overman, Hans Koster, Steve Gibbons, Stefano Carattini, Nic Sanders, Olmo Silva, Felipe Carozzi, Sefi Roth, Vernon Henderson and the other participants from the UEA Summer School in Barcelona, London School of Economics Work-In-Progress seminar, University of Southern California, Eureka Seminar in VU Amsterdam, National University of Singapore Brown Bag Seminar, UEA European Conference in Copenhagen, AEA-ASSA conference in Philadelphia for their comments. This paper is part of my PhD thesis in the London School of Economics. The earlier version of this paper is titled "Traffic Externalities and Housing Prices: Evidence from the London Congestion Charge".

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[1] For more information, refer to https://www.epa.gov/air-pollution-transportation/smog-soot-and-local-air-pollution.

[2] The hedonic approach has been used extensively in the literature to value other non-market amenities since it is formalized by Rosen (1974). Some examples include school quality (Black, 1999; Bayer et al., 2007; Gibbons et al., 2013), air quality (Chay et al., 2005), health hazards (Gayer et al., 2000; Davis, 2004; Currie et al., 2015), crime (Thaler, 1978; Gibbons, 2004; Tang and Le, 2019) and transportation accessibility (Gibbons and Machin, 2005).

https://doi.org/10.1016/j.jue.2020.103302
Received 9 July 2019; Received in revised form 3 May 2020
Available online 26 November 2020

gridlocked roads in London. A flat fee of £5 is imposed for driving into the charge zone during weekdays from 7:00am to 6:30pm. This Pigouvian tax forces drivers to internalize the congestion externalities they impose on others. Closing the gap between the marginal private cost and the marginal social cost of driving, the LCC reduces equilibrium traffic volume and pushes it closer to socially optimum level (Pigou, 1924; Vickrey, 1963). The effects were immediate. Six months into implementation, the volume of cars into Central London fell by 27% and average travel speed was 20% higher than before (TfL, 2003a).

Estimation is based on a difference-in-difference instrumental variable (IV) approach for sales around the charge boundary. I rely on the implementation of the LCC as an IV for changes in local traffic conditions and examine its effect on house prices. Put differently, I am exploiting the sharp variation in traffic conditions in and around the zone induced by the charge. I then compare the changes in traffic flow with the changes in house prices before and after the LCC is implemented to recover WTP estimates to avoid traffic. To obtain consistent estimates for these parameters, the charge must not only significantly affect traffic flow, but it must also influence house prices only via changes in traffic conditions (also known as exclusion restriction).

I identify several possibilities that this assumption could be violated and adopt different strategies to mitigate them. First, unobserved shocks to neighbourhoods could be correlated with the enforcement of the LCC. Hence, I restrict the analysis to sales close to the charge boundary (up to 500 m) such that I am comparing properties in similar neighbourhoods but at different sides of the charge boundary. Second, home purchasers could pay more to relocate into the charge zone because residents living inside enjoy a 90% waiver to the charge. Exploiting sales that are entitled to the discount but are outside the charge zone, I demonstrate that these subsidies have a negligible effect on home prices. Furthermore, affluent households, who incur higher cost for being caught in the traffic, could sort themselves into the charge zone. These households could purchase better quality units, affecting the composition of houses sold after the charge is enforced. Conducting a battery of balancing tests on a rich set of housing and neighbourhood characteristics, I do not find households sorting across the boundary, and any changes in the composition of houses sold after the charge is enforced.

The headline finding is that homeowners moving into the charge zone pay more to enjoy better traffic conditions. After the LCC is implemented, traffic volume is 8.77% lower (1562 fewer vehicles every day) relative to neighbourhoods outside the charge zone, illustrating the efficacy of the charge in reducing traffic. Corresponding to this improvement in traffic conditions, home prices are approximately 2.84% (£18,555) higher in the zone. Putting these results together, the instrumental variable (IV) estimates suggest that the elasticity of housing values with respect to traffic volume is around −0.30. These estimates remain stable and significant across a battery of robustness tests. Multiplying these capitalization gains with the number of dwellings in the charge zone, I document that the LCC has generated substantial windfall of more than £3.8 billion for homeowners in the zone. This gain measures the present value of the local benefits associated with the LCC. Further analyses reveal that these house price gains could stem from safer roads and better air quality after the charge is enforced.

The remainder of this paper is structured as follows. Section 2 provides an overview on the Congestion Charge in London. Section 3 describes the existing literature on this subject. Section 4 outlines the data and Section 5 illustrates the identification strategy. Findings are then discussed in Sections 6 and 7 concludes.

2. Road pricing in London

The initial Congestion Charge Zone (CCZ) covered a total of 21 square kilometres (slightly more than 1% of the Greater London Area) and encompassed the financial centre (Bank), parliament and government offices (Palace of Westminster), major shopping belts (Oxford Circus) and tourist attractions (Trafalgar Square, Westminster Abbey, Big Ben, St Paul Cathedral etc).[3] Fig. 1 shows the CCZ. The boundary was drawn to isolate the most congested areas in Central London. It was bordered by major inner ring roads such as Edgeware, Vauxhall Bridge, Pentonville, Park Lane, Marylebone, Tower Bridge and Victoria to divert traffic displaced by the charge. Drivers travelling on these roads are not required to pay unless they turn into the zone.

To protect residents and businesses outside the zone, off-street parking enforcement was improved to deter anyone from avoiding the charge by parking their vehicle outside and walking into the charge zone. The CCZ crosses the River Thames to the South and covers parts of the Lambeth and Southwark boroughs. Although this is an area not typically considered as Central London, it was incorporated for the ease of implementation and operation (Richards, 2006).

On the 17th of February 2003, a flat fee of £5.00 was levied on commuters driving into the zone between 7:00am and 6:30pm from Monday to Friday excluding public holidays.[4] Residents living in the zone and those living outside in the discount zones are entitled to a 90% waiver to the LCC for their first registered vehicle.[5,6] These discount zones for the CCZ and the WEZ are shaded in stripes as shown in Fig. 1. Residents living in these areas are entitled to the discount due to parking and severance issues. This policy was an outcome of extensive consultations with various stakeholders. Other than to reduce congestion, the LCC was implemented to generate revenues to enhance the public transit by increasing frequency and routes of buses and tube. Reduced travel time and enhanced reliability could encourage commuters to switch from private to public transport when commuting into the zone.

The tax levied increased to £8.00 on the 4th July 2005 to further reduce traffic and raise revenues. On the 19th of February 2007, charging was extended to Central West London (known as the Western Extension Zone - WEZ) because of congestion in that area. Operating hours of the LCC were reduced by half an hour from 7:00am to 6:00pm. The westward extension is circumvented by Harrow Road, Scrubs Lane, West Cross Route, the Earls Court One-Way system, Chelsea Embankment and the River Thames to the South.[7] This area is labelled WEZ in Fig. 1. However, under tremendous pressure from residents and businesses in West London, on the 24th of December 2010, the WEZ was scrapped. Between 2011 to 2015, the charge in the original CCZ underwent another two hikes. The charge was raised from £8 to £10 on the 4th January 2011 and from £10 to £11.50 on 16th June 2014.

Initial impact assessment by Transport for London (TfL) showed significant improvement in traffic conditions after the charge was enforced in 2003. These results are very consistent to those reported in this study. All day travel speeds were almost 20% higher (from 14.3km to 16.7km per hour) and minutes of delay fell by 30% (TfL, 2003a). This was largely due to a 27% overall drop in the number of private automobiles in Central London. A change in composition of inbound traffic into the zone was observed: the volume of bicycles, buses and taxis went up by 28%,

[3] To reduce confusion and for convenience, the initial Congestion Charge Zone will be abbreviated as the CCZ, the Western Extension Zone will be abbreviated as WEZ, and LCC represents both the CCZ and WEZ from this point onwards.

[4] The rationale for levying a flat fee, other than the difficulty in imposing time varying fees to reduce congestion during peak hours, is that vehicular volume on roads seems fairly uniform across the day.

[5] Other groups excluded from the charge include public transport(taxis and buses), motorcycles, bicycles, environmentally friendly vehicles (battery powered or hybrid cars), vehicles driven by disabled individuals (blue badge holders), vehicles with 9 seaters or more and emergency service vehicles.

[6] This 90% discount could violate exclusion restriction as home buyers moving into the CCZ or WEZ could be paying more for homes for LCC discounts. Details will be provided in subsequent sections on how I address this concern.

[7] Unlike the Original CCZ, the WEZ is bounded by physical features. There is a concern whether the neighbourhoods South of River Thames are different from those in the North such that it might not be a suitable control group. Hence, I exclude transactions south of River Thames in my robustness test (refer to column 5 of Table 3). Results remain robust in these regressions.

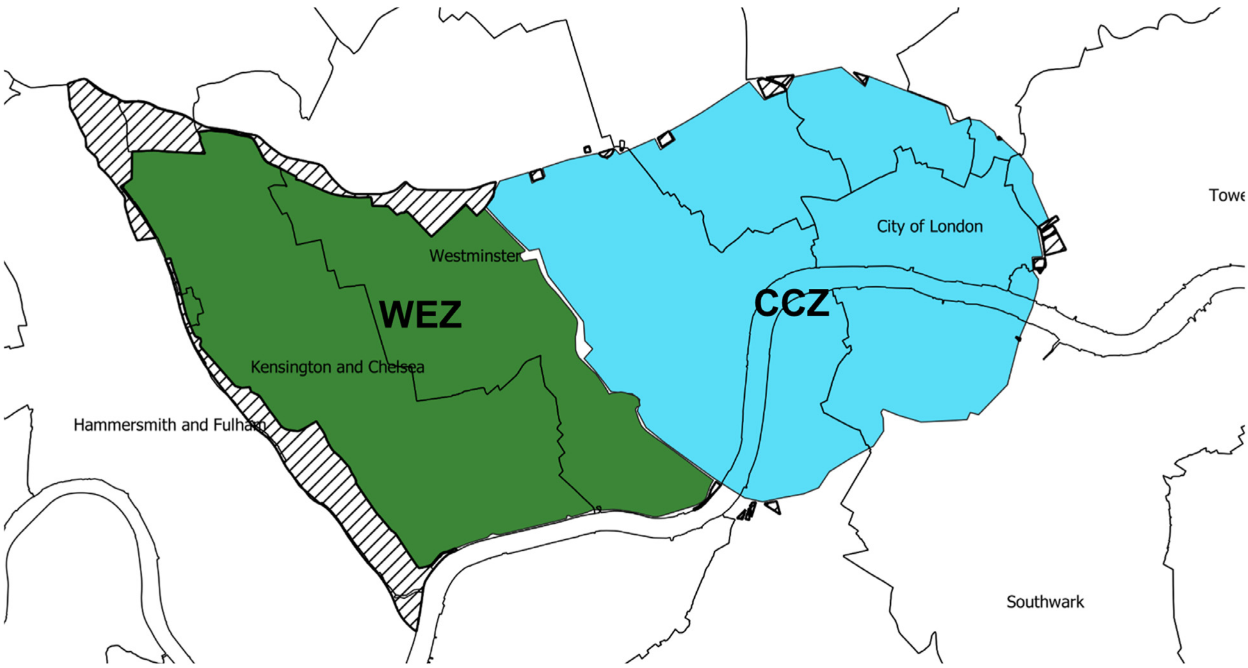

Fig. 1. Map of the Original Congestion Charge Zone (CCZ) & Western Extension Zone (WEZ) Source: Transport for London (TfL).

21% and 22% respectively. Surveys conducted echoed similar findings with the majority of the drivers switching to public transport and others travelling during off-charging hours (TfL, 2005). Though the number of commuters using rail did not increase, the number of bus passengers during morning peak periods were 38% higher(TfL, 2004). No evident displacement of traffic into neighbouring uncharged roads and weekends were recorded as traffic conditions were fairly similar compared to those during pre-charged periods. The LCC also improved air quality and led to a 12% reduction in both NO and PM_{10} in the charge zone (TfL, 2004). Overall, evidences suggest that residents living in the charged zone are benefiting from the charge.

3. Literature review

To estimate the marginal willingness to pay (WTP) to avoid traffic, the hedonic property value approach is widely adopted in the existing literature. An association between traffic externalities, measured by traffic volume (Hughes and Sirmans, 1992) or noise (Palmquist, 1992; Andersson et al., 2010), and housing prices are established using regression adjusted for differences in observable housing and neighbourhood characteristics. A review of the previous literature indicates that the doubling road traffic volume could reduce home values by 0.5–3.0%, while every decibel increase in traffic noise corresponds to a 0.3%-0.6% reduction in transacted home prices. Estimates, however, appear to vary across studies that adopt different specifications and perverse relationships are sometimes reported. These results suggest that cross-sectional estimates could be biased as there are unobserved differences in neighbourhood and housing characteristics between sales that are correlated with traffic conditions.

Several studies address the issue of omitted confounders by focusing on ”natural experiments” that produces an exogeneous shock to the amenity of interest to estimate WTP parameters.[8] Chay et al. (2005) rely on the implementation of the Clean Air Act in the 1970s to identify exogenous variation in air quality and examine its impact on housing prices. Gibbons and Machin (2005) measure the price for better public transport accessibility by examining the impact of a new metro line on the housing market. Black (1999) and Gibbons et al. (2013) quantify the value of good schools by comparing sale prices of homes proximate to one another but on different school districts. In similar fashion, this study relies on the implementation of the LCC that induces sharp variation in traffic conditions across the charge boundary to recover the WTP to pay to avoid traffic.

Previous literature shows that the Congestion Charge reduced traffic jams and improved air quality. Beevers and Carslaw (2005) show that air quality inside the charge zone improved after the LCC is implemented. The levels of CO_2, NO and $PM10$ fell by 19.5%, 12% and 11.9% respectively. Similar results are echoed by Green et al. (2018) although they show that the concentration of NO_2 has increased after the LCC is enforced. They propose that this could stem from the substitution of diesel-based vehicles, such as buses and taxis, in the zone as they are waived from the charge. This combustion of diesel contributes to more nitrogen oxides than the combustion of petrol.

Roads in the zone are reportedly much safer after the LCC is implemented. Li et al. (2012) reveal that car casualties fell by 5.2% although there are more fatalities associated with motorcycles (1.8%) and bicycles (13.5%). This could be driven by the switch to two wheelers that are not subjected to the charge. Larger effects are observed by Green et al. (2016). The LCC coincides with a 32%-36% fall in accidents and 25%-35% decline in serious injuries and fatalities. No displacement of collisions to neighbouring areas outside the charge zone are documented.

There are several previous attempts to quantify the benefits associated with the charge using the housing market. Most of these studies have surprisingly documented insignificant or negative effects. The closest to this study is unpublished research conducted by Zhang and Shing (2006). They examine the effect of the CCZ in 2003 on a sample of residential sales in London from 2000 Q1 to 2006 Q1 and show that home prices are 8.5% lower in the zone after the charge is implemented. Percoco (2014) investigate the effect of the Milan EcoPass on housing prices. Examining average property values across 192 Micro-zones between 2006 and 2009, he reports that prices are 1.2% to 1.8% lower after the tax is introduced. Given that the LCC improves local traffic conditions, it is surprising to observe that the charge reducing house prices in the charge zone. The contradictory relationship documented in these studies could stem from omitted confounders due to the lack of

[8] For the advantages associated with quasi-experimental approaches of hedonic methods for environmental valuation refer to Kuminoff et al. (2010).

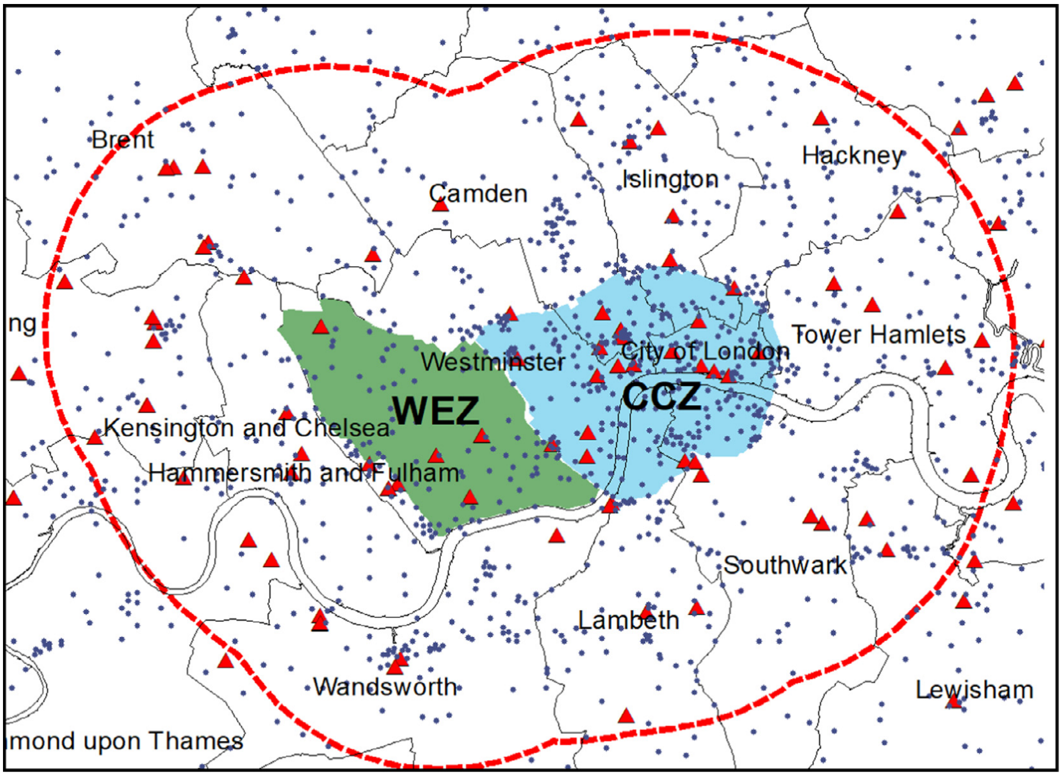

Fig. 2. Location of traffic count points (in dots) and London Air Quality Network (LAQN) Air Quality Monitors (in triangles) within 5 km from the LCC Boundary (in dash line).

controls, incorporating of transactions fairly far from the charge boundary and adoption of coarse spatial fixed effects.[9] Agarwal et al. (2015) improve the estimation by removing time-invariant neighbourhood unobservables with postcode fixed effects. They examine the effects of an increase in the Singapore Electronic Road Pricing (approximately £0.50) on retail, office and residential prices. While retail property values are adversely impacted by the hike, residential property values are unaffected. This is reasonable considering that an immaterial hike in the charge is unlikely to significantly improve traffic conditions to influence housing values.[10]

In contrast, this research improves on the existing literature on several fronts. This is the first paper that links the effects of the LCC on house prices via traffic conditions using an instrumental variable framework. This allow us to directly estimate the elasticity of house prices with respect to traffic volume to measure the WTP to avoid negative traffic externalities. Second, by relying on the LCC as a natural experiment to tackle the issue of omitted con-founders and sorting, this research is a significant improvement to the existing literature that rely on largely cross-sectional hedonic regressions.

4. Data

Average annual daily traffic flow (AADF) collected at each count point (CP) from 2000 to 2010 is retrieved from the Department of Transport (DfT).[11] These count points are located along roads and traffic is manually counted at these locations to provide junction-to-junction traffic flow. There are a total of 2523 CPs in London and most of them clustered around Central London as shown in Fig. 2. To accurately measure the local traffic conditions for each transacted property, I first match the count points to roads based on location and road names. Subsequently, I draw 100 m buffers from these matched-roads.[12] The traffic conditions for each property will be determined by the traffic flow from the nearest road. Properties outside this 100 m buffer are omitted from the analysis as I cannot reliably measure traffic conditions. For an illustration, refer to Fig. 3.

Housing transactions from 1st January 2000 to 24th December 2010 are collected from Land Registry database.[13] Property characteristics include sale price, property type (detached, semi-detached, terraced, flat or maisonette), tenure (leasehold or freehold) and whether the property is new or second-hand. The Land Registry covers all the transactions made in United Kingdom. Given that terrace and flat housing constitute bulk of the transactions in Central London (close to 95%), other property types, such as detached and semi-detached housing, are removed from the analysis to reduce sample heterogeneity.[14] All the transactions are geo-coded using the address postcode. For a subset of transactions,

[9] In unreported parsimonious specifications without granular geographical fixed effects, I observe results that are similar to these studies. Results are available upon request.

[10] This point is reinforced by my results in Table A.7 summarized in Data Appendix. Most of the CC increments do not have perceptible impacts on traffic and housing values.

[11] Each site is counted by a trained enumerator on a *neutral day* in that year for a twelve hour period. A *neutral day* is a weekday between March and October, excluding all public holidays and school holidays. The idea is that traffic on these days are reflective of an "average" day across the year. There are more than 10,000 manual count points across UK.

[12] Concerned that 100 m buffer might be too big to accurately measure local traffic conditions, I reduce this buffer to 50 meters. I further re-weight my estimates, giving heavier weights to transactions that are closer to the roads with traffic data. None of these specifications appear to materially influence the results and are summarized in column 8 and 9 of Table 3.

[13] The cut off date coincides with the removal of the WEZ to avoid capturing any effects from this event. Additional results on the removal of the WEZ can be found in Table A.7. In short, the removal of the charge did not attribute to a significant rebound in traffic flow although house prices could have increased. The absence of any deterioration in traffic conditions and the removal of the need to pay the congestion charge could explain why home prices escalated after the WEZ is removed.

[14] As explained in latter sections, I am exploiting the variation in house prices and traffic conditions within a postcode (or building). Hence, it is improbable to have repeated sales of these single-family properties and they are likely to drop out of estimation. I further supplement results for the full sample of sales, including detached and semi-detached

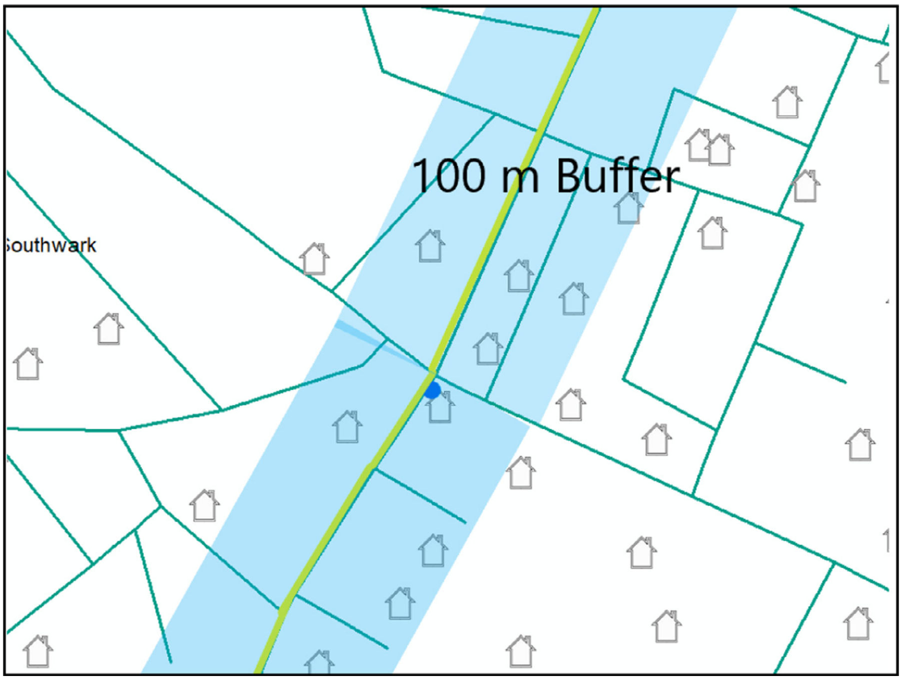

Fig. 3. An illustration on how local traffic conditions for each property are measured.

additional property characteristics, such as floor area, number of bathrooms and bedrooms and age, are merged from Nationwide Transaction database for balancing tests.

Information on the boundaries of the CCZ and WEZ and the areas entitled to 90% resident discount are from the shapefiles provided by Transport of London (TfL). Using Geographic Information Systems (GIS) mapping, together with the official dates of implementation/announcement of the LCC from TfL, I determine whether or not postcodes are in the charge zone and compute Euclidean distances from the charge boundary. Further information on the locations of tube stations and bus stops are retrieved from TfL Open data source. I measure public transport accessibility based on the distance of each postcode from the nearest public transport node using GIS.

Census Data at Output Area (OA) level are collected from two waves, in 2001 and 2011, to measure the quality of neighbourhoods.[15] This include the percentage of (1) minority residents and (2) uneducated residents, (3) unemployment rate and the percentage of (4) lone parent households. I merge data from Census 2001 for any transactions before 2006 and data from Census 2011 for transactions made after 2006.

Shapefiles detailing the location of heritage buildings and parks are provided by MAGIC.[16] Using GIS, I measure the distance of each postcode from the nearest Grade 1 park. Grade 1 parks are parks with international and historical significance. I further draw a 200 m buffer around each postcode and compute the number of Grade 1 heritage buildings within each buffer. Designation is done by Historic England and is determined by the age, historical and architecture significance of the building. Only the top 2.5% of the buildings are classified as Grade 1. Shapefile for River Thames is provided by Digimap. A buffer of 200 m is drawn from River Thames and postcodes inside this area are assumed to have a river view.

5. Identification strategy

Traditionally, hedonic regressions estimating the effects of traffic on house prices adopt the following specification:

$$Y_{ijt} = \boldsymbol{\beta}^{\mathbf{OLS}}\mathbf{T_{ijt}} + X_i'\phi + V_{jt}'\omega + \tau_t + \varepsilon_{ijt}, \qquad \varepsilon_{ijt} = \alpha_i + \theta_{ijt} \tag{1}$$

where Y_{ijt} is the logarithm of price for property i in neighbourhood j sold at time t. $\mathbf{T_{it}}$ is the logarithm of local traffic conditions measured by local traffic volume near property i at time t. The key variable of interest, $\boldsymbol{\beta}^{\mathbf{OLS}}$, measures the percentage change in home prices from a 1% change in local traffic flow. This exercise exploits the variation of traffic conditions and home prices across space and over time. To minimise salient differences between housing transactions, researchers usually control for time-invariant property specific characteristics X_i' (e.g number of bedrooms, property size, garage) and time-variant neighbourhood characteristics V_{jt}' (e.g crime, unemployment rates). For consistent estimation, the least square estimator of $\boldsymbol{\beta}^{\mathbf{OLS}}$ requires $E[\varepsilon_{ijt}|T_{ijt}] = 0$.

In reality, this assumption is likely to be violated if there are omitted time invariant (α_i) or time-variant unobservable (θ_{ijt}) that could covary with traffic conditions and influence home prices. The heaviest traffic is usually found in neighbourhoods around the Central Business District (CBD). These neighbourhoods are quite different from areas further away from the city center. For instance, properties nearer to the CBD are usually better connected to transportation nodes and are closer to major shopping belts. If these differences are unaccounted for, they are likely to attribute to a downward bias to the WTP to avoid traffic. The straightforward solution widely used in the literature is to include property fixed effects (α_i) and compare changes in home prices with changes in traffic conditions over time.

There are still issues employing this strategy. First, it requires repeated transactions of the same property over time. This is unlikely given the illiquid nature of real estate due to high transaction costs. Second, it is improbable to observe much variation of traffic in a particular location over time unless these areas experience major developments that generate economic activities and attract more road traffic. These developments are likely to increase the attractiveness of neighbourhoods and influence local home prices. Hence, traffic conditions are likely to covary with unobserved time-variant shocks to house prices (θ_{ijt}) such that $E[\theta_{ijt}|T_{ijt}] \neq 0$.

housing, in Table A.4 in Data Appendix. In short, the estimated effects for the full sample are quite comparable to the baseline results in Table 2.

[15] Smallest geographical area in which Census data is collected. There are a total of 175,434 OAs across England and Wales (25,053 OAs in London) with around 110 to 140 households per OA.

[16] For more information, refer to http://magic.defra.gov.uk/

Hence, to overcome these challenges, I instrument local traffic conditions ($\mathbf{T_{it}}$) using the London Congestion Charge (LCC). In other words, I am now exploiting the sharp variation in traffic conditions induced by the LCC to measure the cost of traffic. The system of equations to be estimated includes:

$$T_{ijkt} = \lambda_k + \boldsymbol{\gamma}\mathbf{LCC_{it}} + X_i'\rho + V_{jt}'\kappa + \psi_t + \nu_{ijkt}, \tag{2}$$

$$Y_{ijkt} = \pi_k + \boldsymbol{\zeta}\mathbf{LCC_{it}} + X_i'\delta + V_{jt}'\eta + \upsilon_t + \epsilon_{ijkt}, \tag{3}$$

$$Y_{ijkt} = \alpha_k^{IV} + \boldsymbol{\beta}^{\mathbf{IV}}\widehat{\mathbf{T_{ijkt}}} + X_i'\phi^{IV} + V_{jt}'\omega^{IV} + \tau_t^{IV} + \varepsilon_{ijkt}, \tag{4}$$

where LCC_{it} is an indicator variable that **takes the value of 1 if property** i is located in the Congestion Charge Zone (CCZ) or the Western Extension Zone (WEZ) **and is sold after charge is implemented in 2003 and 2007 respectively.**[17] Given the lack of repeated sales of the same unit over the sample period, postcode fixed effects ($\alpha_k^{IV};\lambda_k;\pi_k$) are included instead.[18] There are, on average, 12 units sharing one postcode in London and they are usually properties in the same building/block.[19] τ_t^{IV}, υ_t and ψ_t represent year-quarter fixed effects that control for trends in house prices and traffic flow across areas over time. X_i' represents a vector of housing characteristics (housing tenure, new build, house type), while V_{jt}' represents a vector of neighbourhood-by-year (education qualifications, unemployment rate, racial composition and % of lone-parent households) or location-by-year (proximity to River Thames, heritage buildings, parks etc.) characteristics. I further control for distance from the LCC boundary-by-year fixed effects and its second polynomial to partial out trends in sale prices and traffic flow that could be correlated with distance from the charge boundary.

Eq. (2) is the *first stage* regression that estimates the effectiveness of the LCC in reducing local traffic flow surrounding each property. The dependent variable, T_{ijkt}, is the natural logarithm of the average daily road traffic flow from vehicles with four or more wheels. The efficacy of the charge is captured by γ that measures the percentage change in the traffic flow. Eq. (3) measures the impact of the LCC on home prices and ζ denotes the percentage change in house prices. If the implementation of the LCC reduces traffic flow within the charge zone, and home buyers moving into the zone value this improvement in traffic conditions, I expect γ to be <0 and ζ to be >0.

Eqs. (2) and (3) combine to form the *instrumental variable regression* in Eq. (4) that identifies the causal effect of traffic on home prices. The main results of this paper come from the estimation of β_{IV}, which measures the direct elasticity of traffic and house prices. $\widehat{T_{ijkt}}$ denotes the traffic conditions instrumented with LCC_{it}. Since β_{IV}, is exactly identified, it is simply the ratio of the two reduced form parameters ($\beta_{IV} = \frac{\zeta}{\gamma}$). For the instrumental variable estimator to provide a consistent estimator of the hedonic price schedule gradient, the conditions are:

- LCC_{it} affects local traffic conditions [$\boldsymbol{\gamma} \neq 0$] (**Relevance**)
- LCC_{it} is as good as randomly assigned. (**Independence**)
- LCC_{it} influences home prices only through changes in traffic conditions. (**Exclusion Restriction**)

While it is straightforward to show instrument relevance from first-stage F-statistics, it is challenging to ensure independence and exclusion restriction. To begin with, it is improbable that the charge zone is drawn exogenously as the policy is targeted towards curtailing traffic along the most congested roads in Central London. Therefore, I progressively restrict the analysis to properties close to the charge zone from 1000m to 500m from the charge boundary. To visualize, refer to Fig. 4. The assumption now is that the CCZ and WEZ are as good as randomly drawn between similar neighbourhoods around the charge boundary. This strategy is possible because the charge induces sharp discontinuous changes in traffic conditions around the boundary. This strategy also minimizes the risk of unobserved time-variant neighbourhood shocks from driving the estimates as these properties are in similar neighbourhoods. Moreover, the congestion charge is exogenous to shocks from local economic activities and developments that could directly affect house prices.

There are, however, still instances where the exclusion restriction could be violated. For instance, home owners living in the charge zone are entitled to a 90% waiver of the charge. The concern is whether house price effects are capturing the present value of these savings. Second, the risk of using postcode (α_k) rather than address fixed effects (α_i) is that WTP estimates could be driven by changes in the composition of housing sales within postcodes after the charge is implemented. For instance, if better quality houses are sold after the charge is enforced and these attributes are not reliably accounted for, WTP estimates could be overestimated. I conduct a battery of balancing tests on observable characteristics to allay these concerns. I also assess the sensitivity of the WTP estimates to local price trends, measurement errors and other correlated effects. They are described in detail in the robustness section.

6. Empirical results

In this section, I examine the effects of the London Congestion Charge on traffic and house prices. First, I describe the dataset with summary statistics. I then examine the impact of the LCC on both traffic and home prices before combining the estimates to recover the WTP to avoid traffic. Next, I assess the sensitivity of the estimates to a battery of robustness tests. I then examine the impact of the LCC on traffic safety and air quality to understand why homeowners are paying more to reside in the charge zone. Finally, I discuss the policy implications associated with my findings.

The main results from the analysis are as follows: First, the implementation of the LCC reduces traffic flow and increases home prices in the charge zone. Putting these estimates together using an instrumental variable (IV) approach, I document the elasticity of housing values with respect to traffic flow to be around 0.30. These IV estimates are much larger, more robust and stable compared to naive OLS estimates. Third, my findings also show that by reducing traffic flow, the LCC improves traffic safety and air quality in the charge zone.

6.1. Descriptive statistics

Table 1 reports summary statistics for all sales inside and outside of the charge zone (Panel A), and sales inside and outside but within 1000m from the charge boundary (Panel B). The rationale is to illustrate how constraining the analysis to properties near the LCC boundary can attenuate differences in housing, location and neighbourhood characteristics that could affect WTP estimates. In total, there are 79,984 sales from 7746 unique postcodes inside the charge zone and 341,099 sales from 96,941 postcodes outside. Even when I limit the analysis to properties within 1000 m from the LCC boundary, there are still 24,520 sales (from 2223 postcodes) outside and 28,970 sales (from 2854 postcodes) inside the zone. The sheer number of sales illustrates how densely built Central London is. Approximately 60% of these transactions within 1000 m from the LCC boundary took place after the charge is implemented.

Properties are more expensive inside in the charged zone but these price differences are smaller when I compare properties closer to the boundary. As shown in Panel B, properties in the LCC (£754,078) are,

[17] I also examine the effects of various charge increments in 2005, 2011 and 2014 on traffic and house prices. Due to space constraints, I relegate these findings to Table A.7 in Data Appendix. In short, these events do not have sizable effects on traffic conditions and home prices. A plausible explanation is that the increments of the charge are too small to significantly reduce traffic flow and affect house prices.

[18] Including address fixed effects is not feasible as it reduces the sample by more than 70% because there are limited repeated sales of the same property.

[19] Postcodes are fully nested in the London Congestion Charge Zone, meaning that there are no buildings that crosses the charge boundary. Hence, the empirical setup is different from a canonical difference-in-difference setup as the dummy variable denoting properties in the charge zone will be automatically dropped with the inclusion of postcode fixed effects.

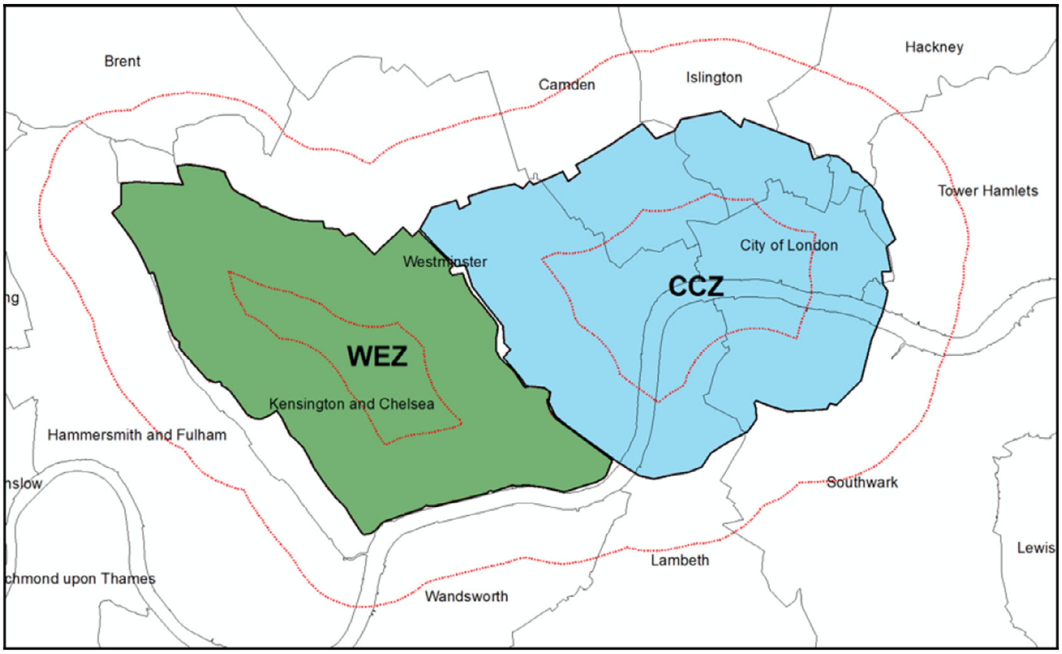

Fig. 4. The London Congestion Charge Zone (CCZ & WEZ) and 1 km buffers (in dash line) from the LCC boundary.

on average, transacted at prices much higher than properties outside the LCC (£565,403). This is expected as properties in the zone are better connected to transportation nodes, major shopping belts, central business districts, and tourist attractions. Even when I restrict the analysis to proximate neighbourhoods within 1 km from the LCC boundary, the disparity in traffic conditions persist. In particular, in Panel B, daily traffic volume is much higher outside the LCC (22,322) compared to traffic flow in the zone (20,018) and this could be due to the LCC. Surrounding housing characteristics, sales in the charge zone are more likely to be flats and leasehold properties, and less likely to be terrace and new builds. In terms of location, they are usually closer to parks and are more likely to be surrounded by buildings with heritage value. Residents living inside the charge zone are more likely to be educated, and less likely to be unemployed, to be of minority race, and to be single-parents. These differences in housing, location and neighbourhood characteristics across the LCC boundary are minimized once I limit the analysis to properties within 1 km in the LCC boundary in Panel B.

Panel C further reports unconditional differences of the natural logarithm of sale prices and daily traffic volume outside and inside the LCC before and after the enforcement of the charge. Similar to before, I limit the analysis to areas within 1000m from the charge boundary. Two main results emerge. First, while traffic conditions improve after the charge is implemented, these effects are stronger for areas inside the zone. In particular, traffic flow in the zone is 29% lower after charge is implemented. These effects are slightly larger than the 26% reduction recorded outside the zone, suggesting that the LCC induce a 3% reduction in traffic flow. This unconditional estimate is less than half of the 8.77% documented in the regression analysis (See Panel A Column 1 of Table 2).[20] Second, corresponding to the improvement in traffic conditions, house prices experience a 25% increment inside the charge zone. These effects are smaller at 19% for properties outside the zone, suggesting that the LCC attribute to a 6% increase in housing values. This effect is much larger than the 2.84% recorded in the regression analysis (See Panel B Column 1 of Table 2). Putting these estimates together, the estimated unconditional elasticity is around -2, which is considerably larger than the conditional elasticity of -0.30. The disparity in the WTP estimates could be accentuated by observed and unobserved differences that are minimized in the regression analysis reported in the next section.

6.2. Baseline estimates

Table 2 present the baseline estimates of the LCC on traffic volume and house prices in the charge zone. I begin the analysis incorporating neighbourhoods up to 1000m from the LCC boundary in column (1), before progressively restricting the sample up to 500 m in column (5). Doing so reduces the sample by more than 40% from 53,490 to 31,689 transactions. This strategy abates the risk of unobserved neighbourhood differences between properties inside and outside the charge zone from biasing the estimates.

Panel A reports the impact of the LCC on local traffic flow in the zone. These estimates are important by themselves as they illustrate the strength of the LCC as an instrumental variable for traffic flow. After the introduction of the LCC, I observe that traffic flow in the zone is 8.77% lower when compared to neighbourhoods outside but within 1000m from the LCC boundary.[21] These effects remain fairly stable when I streamline the sample to comparable neighbourhoods around the LCC. Within 900m, the effect increases to 9.20% and within 800m, this effect is 9.38%. This effect further increases to 9.60% when I constrain the sample to areas within 700m from the charged boundary. Estimated effects remain stable at 9.40% and 9.35% when construed to areas within 600m and 500m from the LCC boundary respectively. In absolute terms, I am looking at between 1562 and 1700 less vehicles inside the zone everyday after the LCC is enforced.[22]

The estimates become larger when I limit the analysis to observations closer to the charge boundary, suggesting that traffic is displaced from inside to outside the charge zone. The charge could force drivers

[20] In the regression analysis, I further adopt a border discontinuity strategy that draws inferences from housing prices and traffic flow closer to the charge boundary to minimize unobserved neighbourhood differences. These areas are more susceptible to traffic displacement from the LCC, and could explain why estimates on traffic flow are much larger surrounding these models.

[21] As it is a log-linear model, capitalization effects are computed by taking the exponential of the point estimates before subtracting by one. For instance, $Exp(-0.0918) - 1 \approx 8.77\%$. The same conversion is applied for housing prices.

[22] This is obtained by multiplying the point estimates with the average pre-treatment traffic volume.

Table 1
Summary statistics for entire sample and sales within 1 km from the LCC boundary.

	(1) Panel A: All Sales	(2)	(3) Panel B: 1km	(4)
	Outside LCC	Inside LCC	Outside LCC	Inside LCC
Sale Price	469951.02	883611.45	565403.38	754077.92
	(588.24)	(3617.31)	(2939.96)	(4741.21)
Log Sale Price	12.90	13.37	13.06	13.26
	(0.00)	(0.00)	(0.00)	(0.00)
Traffic Volume	18698.97	19571.96	22322.80	20017.85
	(26.02)	(55.83)	(90.22)	(77.10)
CCZ/WEZ Treatment	0.00	0.46	0.00	0.60
	(0.00)	(0.00)	(0.00)	(0.00)
New build	0.11	0.10	0.20	0.16
	(0.00)	(0.00)	(0.00)	(0.00)
Flat/Mansionette	0.78	0.89	0.91	0.93
	(0.00)	(0.00)	(0.00)	(0.00)
Terraced house	0.22	0.11	0.09	0.07
	(0.00)	(0.00)	(0.00)	(0.00)
Leasehold	0.78	0.90	0.91	0.94
	(0.00)	(0.00)	(0.00)	(0.00)
Dist to Park	2417.84	874.22	1406.19	1044.20
	(2.22)	(2.14)	(5.74)	(4.47)
Heritage buildings (200m)	0.05	0.46	0.30	0.51
	(0.00)	(0.00)	(0.01)	(0.01)
Thames River View	0.09	0.06	0.11	0.05
	(0.00)	(0.00)	(0.00)	(0.00)
% with no education	15.02	10.18	14.37	11.23
	(0.02)	(0.03)	(0.07)	(0.05)
Unemployment Rate	4.73	3.90	4.95	3.97
	(0.00)	(0.01)	(0.02)	(0.01)
% of Lone Parent Households	6.14	3.47	5.59	3.97
	(0.01)	(0.01)	(0.03)	(0.02)
% of Minority Race	29.63	24.74	34.24	27.86
	(0.03)	(0.05)	(0.10)	(0.08)
No. of Sales	341099	79984	24520	28970
No. of Postcodes	96491	7746	2223	2854

Panel C: Unconditional Difference in means

		Before	After	Differences
Log Traffic Flow	Outside LCC	9.98	9.72	-0.26
		(0.01)	(0.01)	(0.01)
	Inside LCC	9.88	9.58	-0.29
		(0.01)	(0.01)	(0.01)
	Differences	-0.10	-0.14	-0.03
		(0.01)	(0.01)	(0.01)
Log Sale Prices	Outside LCC	12.93	13.11	0.19
		(0.01)	(0.00)	(0.01)
	Inside LCC	13.09	13.34	0.25
		(0.01)	(0.00)	(0.01)
	Differences	0.16	0.23	0.06
		(0.01)	(0.01)	(0.01)

Table 1 record the means and standard error of means (in parenthesis) of variables employed in this analysis. Panel A encompasses all sales outside (Outside LCC) and inside (Inside LCC) of the charge zone, while Panel B restricts the analysis to sales inside (Inside LCC) the charge zone and sales outside but within 1 km from the LCC boundary (Outside LCC). Panel C summarizes the unconditional difference in means for log sale prices and log traffic flow before and after the enforcement of the LCC inside and outside the charge zone.

to detour the charge zone using roads circumventing the LCC, inducing a surge in traffic in areas close to but outside the charge zone. This displacement of road traffic, although not an ideal outcome for the LCC, induces larger variation in traffic conditions between proximate neighbourhoods around the charge boundary. This makes the policy an ideal instrument for identifying the WTP to avoid traffic because it generates large variation in local traffic conditions even between properties in the same neighbourhood just inside and outside the charge zone.[23]

Panel B presents the impact of the LCC on property values in the charged zone. Overall, I document significant house price appreciation in the charge zone after the LCC is introduced across distance bandwidths. When compared to residential sales within 1000m from the boundary, house prices in the charge zone are 2.84% higher. These effects increase to 3.20% relative to houses within 900m and 3.82% within 800m. Further restricting the analysis to housing units just 700m and 600m, I observe price responses at around 3.63% and 3.44% respectively. Finally, looking at sales 500m from the LCC boundary,

[23] The presence of traffic displacement means estimates from Panel A of Table 2 could overstate the efficacy of the LCC in reducing traffic flow. Hence, in Table A.5 in Data Appendix, I exclude ring roads closest to the LCC boundary and include roads further away. The idea is that these ring-roads circumventing the LCC are carrying most of the displaced traffic. Two main results emerge: (1) removing these ring-roads reduces the effectiveness of the LCC, suggesting that traffic displacement could indeed inflate the effectiveness of the LCC; (2) incorporating roads further away from the charge zone could capture the relocation of economic activities from the CBD. For instance, the emergence of Canary Wharf could attract more traffic and this, like traffic displacement, can overstate the effectiveness of the LCC on reducing traffic.

Table 2
First Stage, Reduced form, IV and OLS estimates from sample 1000m to 500m from the LCC Boundary.

	(1) 1000m	(2) 900m	(3) 800m	(4) 700m	(5) 600m	(6) 500m
Panel A: First Stage (Log Traffic)						
LCC	-0.0918***	-0.0965***	-0.0985***	-0.1009***	-0.0987***	-0.0982***
	(0.0168)	(0.0175)	(0.0187)	(0.0200)	(0.0209)	(0.0220)
R2	0.98	0.98	0.98	0.98	0.98	0.98
Mean Traffic	17,797	17,769	17,761	17,717	17,716	17,650
Δ Traffic	-1562	-1635	-1667	-1700	-1665	-1651
Panel B: Reduced Form (Log House Price)						
LCC	0.0280***	0.0315***	0.0375***	0.0357***	0.0338***	0.0278**
	(0.0100)	(0.0105)	(0.0112)	(0.0118)	(0.0127)	(0.0133)
R2	0.76	0.75	0.75	0.75	0.75	0.75
Mean HP	653,898	653,376	652,714	651,308	650,083	648,806
Δ HP	18,555	20,931	24,958	23,655	22,381	18,320
Panel C: IV Regressions						
ln(Traffic)	-0.3047***	-0.3267***	-0.3808***	-0.3536***	-0.3430**	-0.2835*
	(0.1176)	(0.1188)	(0.1281)	(0.1307)	(0.1440)	(0.1474)
R2	0.08	0.07	0.07	0.06	0.07	0.07
No.of Postcodes	5077	4646	4253	3843	3432	2996
1st Stage F-Statistics	29.84	30.54	27.73	25.46	22.31	19.88
Panel D: Naive OLS Regressions						
ln(Traffic)	-0.0197	-0.0170	-0.0250	-0.0225	-0.0250	-0.0262
	(0.0216)	(0.0224)	(0.0236)	(0.0249)	(0.0278)	(0.0316)
Obs	53,490	49,654	45,168	40,789	35,770	31,689
R2	0.76	0.75	0.75	0.75	0.75	0.75

Dependent variable is the logarithm of annual average daily traffic volume for vehicles with 4 wheels or more for Panel A and the logarithm of transacted house prices for Panel B, C and D. Each coefficient is from a different regression. Sample is constrained to properties within 1000m (Column 1) to 500m (Column 6) from the LCC boundary. All regressions are estimated with postcode and year quarter fixed effects. Other control variables include housing characteristics (leasehold, newbuild and terrace dummies), neighbourhood characteristics by-year (% of residents with no education qualifications, % of residents with minority races, unemployment rate and % of lone parent households) and location characteristics by-year (River Thames view dummy, counts of heritage buildings within 200m, distance of the property from nearest park, and distance from the LCC boundary and its second polynomial). For more information on the variables, refer to Table A.1 in Data Appendix. Mean Traffic is the average daily traffic flow in the zone before the LCC is implemented. Mean HP is the average transacted prices (in 2015 £value) for properties in the zone before the LCC is implemented. Δ Traffic and Δ HP denote the absolute effects of the LCC on average daily traffic volume and house prices (in 2015 £value) respectively. 1st Stage F-stats reported is the Kleibergen-Paap rk Wald F statistic from first stage regressions. Robust standard errors (in parenthesis) are clustered at output area. * p<0.10, ** p<0.05, *** p<0.01.

I document that property values are around 2.82% higher than before. In absolute monetary terms, the LCC increases housing values in the charge zone by a magnitude of between £18,320 and £24,958 (2015 values).[24] All these estimates are significant at least at 5% level.

Collectively, these results indicate that the implementation of the LCC resulted in substantial improvement in traffic conditions and property values in the charge zone relative to areas outside. In Panel C, I present IV (instrumental variable) estimates (β_{IV}) of the WTP to avoid traffic from Equation 4. These estimates are simply the ratio of ζ and γ. Results reveal that a 1% increase in traffic volume corresponds 0.30% decrease in housing values for sales 1000m from the LCC boundary. This elasticity ranges from -0.33 to -0.38 when I restrict the analysis sales 800 to 900m from the LCC. Constraining the analysis to properties within 700m from the LCC boundary reduces the elasticity to around -0.35. Further limiting the analysis to sales 600m from the boundary reduces the elasticity to around -0.34. Finally, the elasticity of housing values with respect to traffic volume is around -0.28 for sales around 500m from the LCC boundary. Based on these estimates, homeowners are paying around £11.1 to £15.0 (2015 values) for 1 less vehicle in front of their residence in perpetuity given that real estate are long-lived assets. Strong first stage F-statistics (>10) further show the strength of the LCC as an instrumental variable for traffic flow even for areas bordering the charge zone.

Finally, in Panel D, I present naive Ordinary Least Square (OLS) estimates (β_{OLS}) from Eq. (1). These estimates are essential because they reveal how typical results reported in the literature contrast from IV estimates and illustrate how exploiting the exogenous variation in traffic conditions induced by the LCC could improve identification of the WTP to avoid traffic. These OLS estimates are very small and are not statistically distinguishable from zero at any conventional levels. 1% increase in traffic is associated to a 0.017% to 0.026% reduction in housing values. These results suggest that either home buyers do not care about negative traffic externalities or conventional OLS estimates are severely biased by omitted variables. In contrast, the IV estimates are around 20 times larger and are significant at conventional levels. These results are congruent with the findings reported by Chay et al. (2005) when measuring WTP for air quality using an IV strategy.

6.3. Robustness and Placebo tests

Tables 3 presents additional robustness tests to provide more assuring evidences. As observed earlier in Table 2, the WTP estimates for properties from 500 m to 900 m are fairly consistent to the estimates for properties within 1 km from the LCC boundary. Hence, I conduct the robustness test with sales within 1 km from the LCC boundary, unless otherwise stated, to balance between the external validity of the findings and the bias driven by unobserved neighbourhood differences across the boundary. Like before, I present estimates from first stage and reduced form regressions, before combining these estimations to produce IV estimates on the WTP to avoid traffic.

Announcement Effects: In Column (1), I replicate earlier results but with the announcement dates of the original CCZ.[25] This addresses the

[24] This is computed by multiplying the estimates on the pre-treatment average home prices adjusted to 2015 price levels in the charge area within the distance bandwidth from the LCC boundary.

[25] A similar analysis is conducted for the announcement dates of the WEZ. Again, I do not observe significant changes in house prices and traffic conditions after the WEZ is announced. Results are available upon request.

Table 3
Robustness Tests.

	(1) Announce	(2) Shrank	(3) Expand	(4) Pcd>=5	(5) North	(6) Transport	(7) Rem Near	(8) 50m Houses	(9) IDW
Panel A: First Stage (Log Traffic)									
LCC	0.0095	-0.0266	0.0306	-0.0921***	-0.1165***	-0.0857***	-0.1032***	-0.1111***	-0.0835***
	(0.0069)	(0.0187)	(0.0260)	(0.0174)	(0.0185)	(0.0167)	(0.0199)	(0.0212)	(0.0168)
R2	0.99	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.98
Mean Traffic	17,784	18,859	17,515	17,776	17,771	17,797	17,697	17,684	17,797
Δ Traffic	170	-496	545	-1565	-1954	-1461	-1735	-1860	-1426
Panel B: Reduced Form (Log House Price)									
LCC	-0.0042	-0.0086	-0.0024	0.0262**	0.0280**	0.0319***	0.0363***	0.0305**	0.0267**
	(0.0178)	(0.0158)	(0.0143)	(0.0102)	(0.0110)	(0.0098)	(0.0118)	(0.0141)	(0.0106)
R2	0.73	0.73	0.78	0.73	0.75	0.76	0.75	0.74	0.77
Mean HP	653,231	675,357	405,187	652,432	653,854	653,898	655,288	649,900	653,898
Δ HP	-2767	-5783	-951	17,321	18,556	21,186	24,255	20,112	17,673
Panel C: IV Regressions									
ln(Traffic)	-0.4463	0.0536	-0.0531	-0.2844**	-0.2402**	-0.3723***	-0.3523***	-0.2742**	-0.3193**
	(1.9081)	(0.6192)	(0.4654)	(0.1187)	(0.0987)	(0.1298)	(0.1252)	(0.1299)	(0.1373)
Obs	14,283	47,351	47,451	47,760	48,730	53,490	43,118	28,903	53,490
R2	0.04	0.10	0.16	0.07	0.07	0.07	0.08	0.06	0.08
No.of Postcodes	1905	3836	4577	3016	4556	5077	4241	2749	5077
1st Stage F-Statistics	1.90	2.02	1.38	27.96	39.76	26.33	26.89	27.51	24.82

Dependent variable is the logarithm of annual average daily traffic volume for vehicles with 4 wheels or more for Panel A and the logarithm of transacted house prices for Panel B and C. Each coefficient is from a different regression. Sample is constrained to sales 1 km from the LCC boundary unless otherwise stated. All regressions are estimated with postcode and year quarter fixed effects. Other control variables include housing characteristics (leasehold, newbuild and terrace dummies), neighbourhood characteristics by-year (% of residents with no education qualifications, % of residents with minority races, unemployment rate and % of lone parent households) and location characteristics by-year (River Thames view dummy, counts of heritage buildings within 200m, distance of the property from nearest park, and distance from the LCC boundary and its second polynomial). For more information on the variables, refer to Table A.1 in Data Appendix. In (1), the treatment period (LCC_{it}) is defined by the announcement window and begins the day the CCZ is announced officially by the Transport for London (TfL) and ends the day before the CCZ is implemented. In (2) and (3), I create artificial treatment zones by expanding and shrinking the LCC by 1 kilometre. To visualize, refer to Fig. 5. In (4), I remove any sales in postcodes with less than 5 repeated transactions over sample period. In (5), I remove any sales south of the River Thames. In (6), I include distance to tube-by-year and number of buslines-by-year fixed effects. In (7), I exclude sales that are 100 meters or less from the charge boundary (both inside and outside the zone). In (8), I remove any transactions that are beyond 50 m from the nearest roads that I can reliably measure traffic flow. In (9), estimates are weighted inversely according the distance from transacted property from matched road. Mean Traffic is the average daily traffic flow in the zone before the LCC is implemented. Mean HP is the average transacted prices (in 2015 £value) for properties in the zone before the LCC is implemented. Δ Traffic and Δ HP denote the absolute effects of the LCC on average daily traffic volume and house prices (in 2015 £value) respectively. 1st Stage F-stats reported is the Kleibergen-Paap rk Wald F statistic from first stage regressions. Robust standard errors (in parenthesis) are clustered at output area. * p<0.10, ** p<0.05, *** p<0.01.

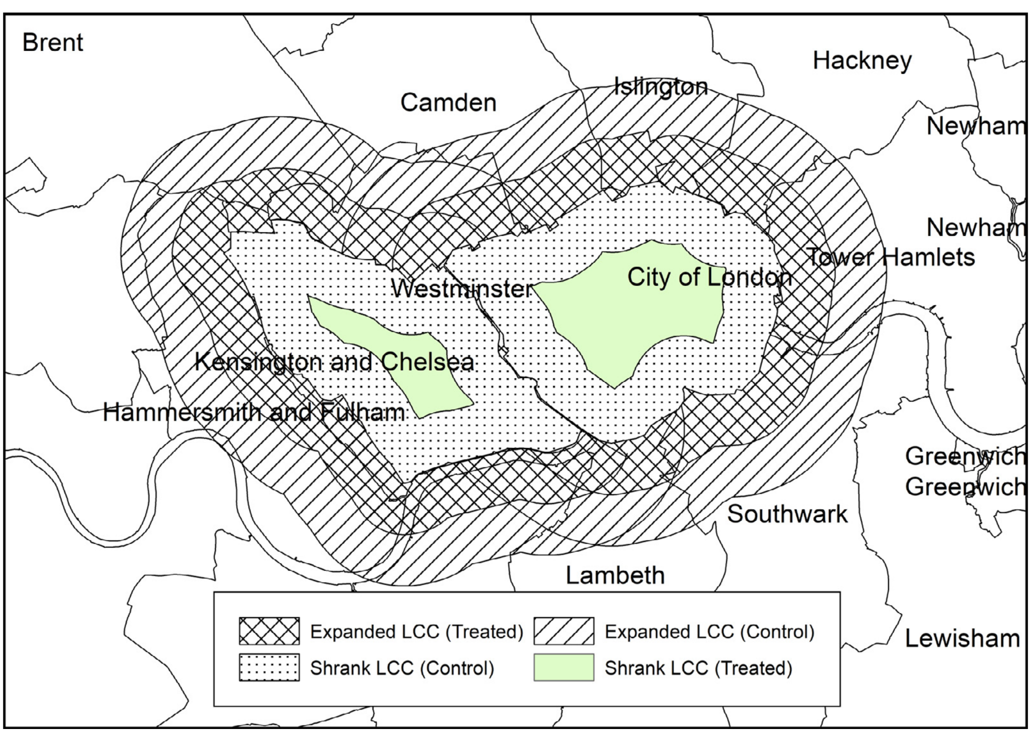

Fig. 5. Shrank and Expanded Placebo LCC.

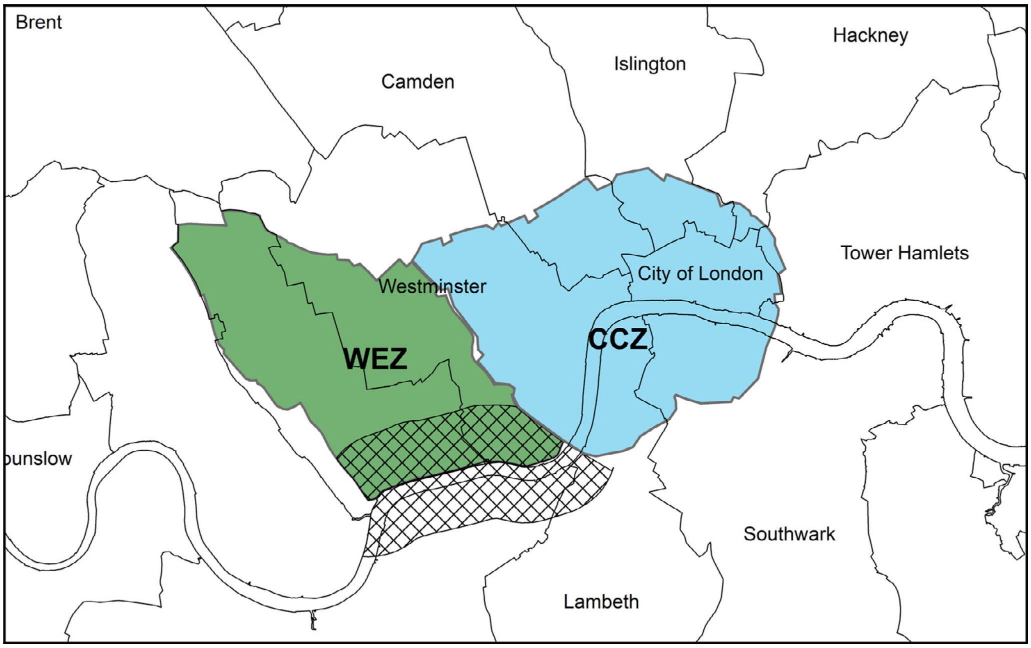

Fig. 6. The London Congestion Charge Zone (CCZ & WEZ) and the omitted areas (shaded in cross) north and south of River Thames around the WEZ.

concern whether there are any house prices and traffic response to the announcement of the charge before the implementation.[26] The treatment period is defined as the day the CCZ is officially announced by TfL (1st February 2002) and ends the day before the CCZ is implemented (16th February 2003).[27] I omit any sales after the enforcement of the charge to ensure that these estimates are not capturing any implementation effects. Although I observe traffic is marginally heavier after the CCZ is announced, homebuyers do not respond to the news. A possible explanation is that the residents were uncertain initially of the effectiveness of the novel policy to reduce traffic and improve accessibility, consistent with the findings from a survey conducted by TfL (TfL, 2003b).

CBD Effects: Another concern is whether the effects on traffic and house prices could be associated with changes to the Central Business District (CBD), violating the exclusion restriction. This could be an issue since the charge zone overlaps with the CBD. The emergence of Canary Wharf around the implementation of the LCC led to considerable decentralization of economic activities from the CBD. The relocation of economic activities could reduce the attractiveness of the CBD, leading to a fall in house prices and traffic flow in the zone unrelated to the charge, confounding the WTP estimates.[28]

Although limiting the analysis to sales bordering the LCC could mitigate this problem, to further allay this concern, I create artificial treatment areas by shrinking and expanding the LCC. For the shrank zones, neighbourhoods at 0–1 km from the boundary inside the LCC are denoted as control area (Shrank Control Area) and neighbourhoods beyond 1 km from the boundary in the charge zone are denoted as treated area (Shrank Treatment Area). Conversely, for expanded LCC, area between 0 and 1 km outside the actual CCZ are flagged as treated area (Expanded Treatment Area) while area between 1 and 2 km outside the actual LCC are denoted as control area (Expanded Control Area). For an illustration, refer to Fig. 5. Column (2) and (3) report estimates associated with these shrank and expanded placebo areas. As observed, I do not document any spurious effects on traffic flow and house prices in these artificially created charge zone. These results suggest that earlier findings are unlikely to be driven by the emergence Canary Wharf as an alternative business district.

Insufficient Transactions: Another issue is that there are inadequate repeated observations within some postcode such that outliers could be driving the estimates. Thus, I drop any postcodes with less than 5 repeated transactions over the sample period in Column (4). This reduces the number of observations marginally by about 14% but does not materially effect the estimates as they remain fairly similar to those reported earlier.

Physical Barriers: An additional concern is whether the LCC overlaps with physical constraints (hills, rivers, forest etc.) or major infrastructures (railways, flyovers etc.) such that even restricting the analysis to proximate areas on different sides of the boundary will not eliminate unobserved neighbourhood differences. While this is not a concern for the CCZ as the zone covers areas south of River Thames due to the ease of charge implementation, the south of the WEZ is bounded by River Thames. Hence, I exclude housing transactions 1km north and south of River Thames around the WEZ from the analysis. For an illustration of the areas excluded, refer to Fig. 6. Results are summarized in Column (5). Estimates are fairly comparable to earlier results but the WTP estimate is slightly smaller at 0.24. One plausible explanation is that I am now excluding higher income households living near River Thames in the WEZ who might have a higher WTP to avoid traffic externalities.

Public Transport Capitalization Effects: One of the correlated effects associated with the implementation of the LCC is the channelling of charge revenues on improving public transportation. This could increase the values for homes outside the zone that are better connected to public transportation nodes as driving into the zone becomes more expensive after the charge is enforced. To partial out these effects, I include (1) binary variable denoting whether postcode j is within 200m from the nearest tube station and control for (2) the total number of bus lines from bus stops within 200m of the postcode. Both are interacted with year dummies as they are time-invariant. As seen in Column (6),

[26] Another concern is whether there are negative house price effects that predate the implementation of the charge such that any effects documented earlier is merely capturing mean reversion of home prices. As observed, this is not a concern as home prices are unaffected by the announcement of the CCZ.

[27] As hikes are announced only a few months before being enforced, there are insufficient pre-treatment property transactions. Hence, announcement effects are computed only for the initial implementation of the CCZ and WEZ (refer to Fig. A.9 in Data Appendix)

[28] From 1999 to 2005, the employment force in Canary Wharf surged by more than 100% from 40,000 to 87,000. This could be attributed to the development and opening of at least 10 commercial developments, including 8 Canada Street, One Churchill Place etc. For more information, refer to https://www.london.gov.uk/sites/default/files/gla_migrate_files_destination/londons-cbd-jan08.pdf.

Table 4
Balancing Test for Housing & Neighbourhood Characteristics.

	(1) New Build	(2) Flat	(3) Leasehold	(4) % No Education	(5) % Minority Race	(6) % Lone Parents	(7) Unemployment Rate
LCC	0.0142	0.0010	-0.0014	1.3981***	0.6432	0.1368	0.1799
	(0.0308)	(0.0040)	(0.0038)	(0.4906)	(0.6052)	(0.2420)	(0.1399)
Obs	53,490	53,490	53,490	53,490	53,490	53,490	53,490
R2	0.58	0.66	0.67	0.90	0.93	0.87	0.83
	(8) Floor Area	(9) Bathrooms	(10) Bedrooms	(11) Central Heat	(12) Garage	(13) Age	
LCC	-8.1493	-0.0117	-0.1252	-0.1240	-0.1236	-4.5503	
	(5.9594)	(0.0945)	(0.1511)	(0.2802)	(0.1377)	(8.9128)	
Obs	826	826	826	826	826	826	
R2	0.73	0.63	0.68	0.57	0.67	0.86	

Dependent variable is the respective housing/neighbourhood characteristics labelled in the headers. Each coefficient is from a different regression. *LCC* is a binary variable equals to one for properties that are inside the CCZ or WEZ after the charge is implemented. All regressions include post code, year quarter fixed effects, distance from the LCC boundary and its second polynomial. Sample is restricted to properties within 1 km from the LCC boundary. Columns 1 to 7 comprise of transactions from Land Registry, while Columns 8 to 13 comprise of sales from Nationwide Database. New Build, Flat and Leasehold are binary variables indicating whether property sold is a new build, is a flat and is leasehold property respectively. % No Education represents the percentage of residents in the same Output Area (OA) with no education qualifications % Minority Race represents the percentage of residents of minority race living in the same OA. % Lone Parents measures the percentage of single-parent households in the same OA. Unemployment Rate is the percentage of residents living in the same OA who are unemployed. Floor area is the size of unit in square meters. Bathrooms and Bedrooms are the count of Baths and Bedrooms in the unit. Central heating and Garage is a binary variable that denotes if unit has such facilities. Age is the number of years since the unit is built when it is sold. Robust standard errors clustered at Output Area (OA) are reported in parenthesis. * p<0.10, ** p<0.05, *** p<0.01.

upon controlling for these covariates, the effects on housing prices are marginally larger than earlier results in Table 2. This is consistent with the idea that house prices outside the LCC but close to transportation nodes have appreciated more and controlling for these effects increases the WTP to avoid traffic.

Removal of Sales closest to the LCC boundary: I further remove property sales than are within 100 m from the LCC boundary. The notion is that although restricting to properties close to the charge boundary can minimize unobserved neighbourhood differences, the spillover effects could be greater as well. For instance, pollutants from traffic emissions outside the zone could travel across the boundary into the zone. Moreover, properties very close to the charge boundary but inside the zone could be near to congested ring roads circumventing the zone to redirect traffic. Hence, homeowners living right next to the LCC boundary, despite being inside the zone, could be subjected to considerable negative traffic externalities from outside the zone, biasing WTP estimates. Results are summarized in Column (7). Removing these roads and property sales close to the charge boundary do not matter much. Although homeowners pay more for properties further inside the LCC that are less affected by the negative spillovers from outside the zone, the impact of the charge on traffic is larger as well, resulting in an elasticity that is within the range reported previously.

Measurement Error: Local traffic conditions could be inaccurately measured based on traffic flow up to 100m away from the property (See Figure 4). Although concerns of classical measurement error should be addressed by the IV strategy, I take two additional steps to reliably measure traffic conditions.[29] First, in Column (8), I restrict the analysis to properties within 50 m from roads. Here, I observe larger effects of the LCC on traffic flow. Putting them together, a 1% increase in traffic corresponds to a 0.27% fall in home prices. Second, in Column (9), I re-weight the estimates inversely based on the Euclidean distance of the property from the nearest road. Put differently, these estimates are placing more emphasis on sales that I can more precisely determine traffic conditions. Again, results are fairly consistent with a 1% increase in traffic flow corresponding to a 0.32% decrease in home prices.

Balancing Tests: Another concern is whether "better" households sort into the charge zone after the charge is implemented. Affluent homeowners, who incur higher congestion delays due to higher wages, could move into the zone after the LCC is introduced. The issue is whether the WTP to reside in the LCC could be confounded with the WTP to reside in better neighbourhoods. If these affluent households purchase better "quality" units (e.g penthouses) after the charge is enforced, sorting of households can affect the composition of houses sold in the charge zone, violating exclusion restriction.

To mitigate these concerns, I conduct a battery of balancing tests by estimating a specification similar to that in Eq. (3) but I replace house prices with various observable housing and neighbourhood characteristics. Results are summarized in Table 4. Columns 1–7 comprise of transactions from Land Registry database. The dependent variables for columns 1–3 are binary variables taking the value of one for properties that are new-build (New Build), flat (Flat) and leasehold (Leasehold). For columns 4–7, I examine different neighbourhood characteristics collected at Output Area that include percentage of residents with no education qualifications (% No Education), percentage of residents of minority race (% Minority Race), percentage of single-parent households (% Lone Parents) and percentage of residents who are unemployed (Unemployment Rate). Columns 8 to 13 comprise of sales from Nationwide database, a smaller subset of transactions with a richer set of housing characteristics.[30] These variables include floor area of unit in square meters (Floor Area), the count of baths (Bathrooms) and bedrooms (Bedrooms), whether the unit has central heating (Central Heat) and garage (Garage), and the age of the unit when it is sold (Age).

As observed, across the board, there are no significant changes in housing and neighbourhood characteristics for properties sold in the zone after the LCC is implemented. These results suggest that the WTP to reside in the LCC are unlikely to be driven by changes in the quality of housing or neighborhood characteristics. The only significant change is the increase in the proportion of uneducated residents living in the charged zone. In any case, this is unlikely going to bias the estimates as I control for this variable in my estimation.

[29] Measurement error could cause first stage estimates to be noisy but it is unlikely to induce attenuation bias in the second stage as it is improbable that the instrument is correlated with the measurement error in traffic flow. Hence, IV estimator remains consistent.

[30] I also estimated Eq. (3) with these hedonic characteristics as controls for the sample of transactions from Nationwide Database. The results are very similar to that reported in Table 2. However, due to the small sample size (less than 1,000 observations), I do not report the findings in this paper although it is available upon request.

Table 5
Reduced form estimates of the Congestion Charge Discount on House Prices.

	(1) 1000m	(2) 900m	(3) 800m	(4) 700m	(5) 600m	(6) 500m
LCC	0.0280***	0.0315***	0.0375***	0.0357***	0.0338**	0.0278**
	(0.0105)	(0.0110)	(0.0117)	(0.0124)	(0.0133)	(0.0140)
Discount	-0.0464	-0.0357	-0.0150	-0.0210	-0.0121	-0.0100
	(0.0352)	(0.0373)	(0.0391)	(0.0396)	(0.0436)	(0.0428)
Obs	53,490	49,654	45,168	40,789	35,770	31,689
R2	0.76	0.75	0.75	0.75	0.75	0.75
No.of Postcodes	5077	4646	4253	3843	3432	2996

Dependent variable is the natural logarithm of the transacted property prices. Each coefficient is from a different regression. Sample is constrained to sales within 1000m (Column 1) to 500 m (Column 6). *Discount* is a binary variable equals to one for properties that are inside the discount zone after the LCC is introduced. *LCC* is a binary variable equals to one for properties that are inside the CCZ or WEZ after the charge is implemented. All regressions are estimated with postcode and year quarter fixed effects. Other control variables include housing characteristics (leasehold, newbuild and terrace dummies), neighbourhood characteristics by-year (% of residents with no education qualifications, % of residents with minority races, unemployment rate and % of lone parent households) and location characteristics by-year (River Thames view dummy, counts of heritage buildings within 200m, distance of the property from nearest park, and distance from the LCC boundary and its second polynomial). For more information on the variables included, refer to Table A.1 in Data Appendix. Robust standard errors clustered at Output Area (OA) are reported in parenthesis.*p<0.10, ** p<0.05, *** p<0.01.

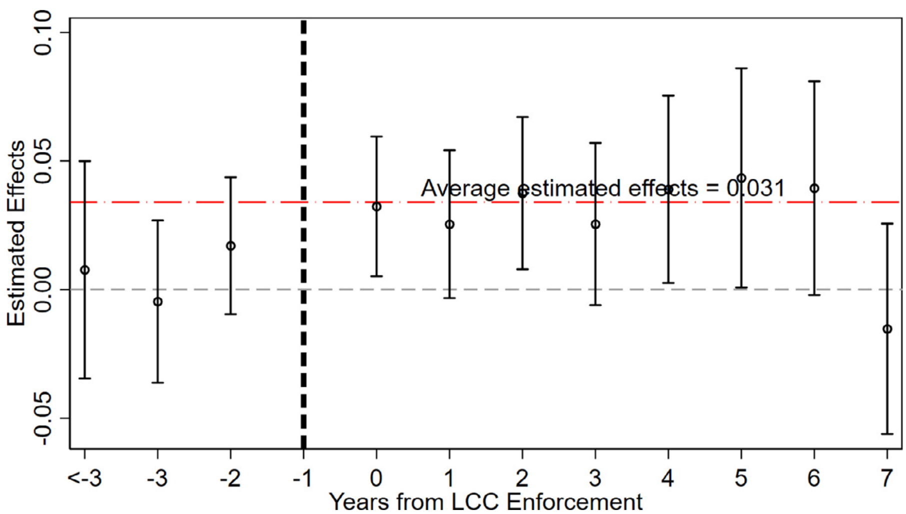

Fig. 7. Effects of the LCC on house prices before and after the enforcement of LCC. Each point denotes the estimated effects year before (leads) and after (lags) the implementation of the LCC. Reference group composes of transactions made a year before the LCC is implemented (denoted by the dash-line at year -1). Average estimated effect is the average effect across the years after the LCC is enforced relative to sales in LCC at year 1. Regression is estimated with postcode and year month fixed effects. Additional control variables include housing characteristics (leasehold, newbuild and terrace dummies), neighbourhood characteristics by-year (% of residents with no education qualifications, % of residents with minority races, unemployment rate and % of lone parent households) and location characteristics by-year (River Thames view dummy, counts of heritage buildings within 200m, distance of the property from nearest park, and distance from the LCC boundary and its second polynomial). For more information on the variables, refer to Table A.1 in Data Appendix. Sample of transactions (n=53,490) analyzed are within 1 km from the LCC boundary. The tails represent 95% confidence intervals constructed from robust standard errors clustered at Output Area (OA).

Discount Zone Effects: The exclusion restriction of the LCC holds only if the charge affects home prices through the improvement of traffic conditions. This, however, could be violated as residents living in the zone are entitled to a 90% waiver of the charge. Earlier estimates could be capturing the present value of these congestion charge savings. To address this concern, I exploit a feature of the LCC that allows some homeowners living close but outside the zone entitlement to 90% discount to charges due to parking and severance issues (TfL, 2009). For instance, residents living there might have designated parking lots inside the zone, or the nearest services and amenities (e.g hospitals, libraries etc) for these residents could be in the charged zone. These discount zones are shaded in stripes for the CCZ and the WEZ in Fig. 1.

I estimate a difference-in-difference regression analogous to Eq. (3) but I flag out housing transactions within these discount zones to examine whether home buyers pay for these subsidies. I expect house prices to appreciate in these areas after the charge is implemented if buyers are paying more to enjoy charge discounts. Like before, I present the results for sales 500–1000 m from the LCC boundary in Table 5. Although there are concerns that house prices in these discount zones could have reduced after the charge is implemented, these effects are too imprecise to be statistically significant any conventional levels.[31] Furthermore, these estimates become much smaller as soon as I constrain the analysis to sales closer to the charge boundary. Overall, these results suggest that earlier estimates are unlikely to be driven by homeowners paying more for the congestion charge discount.

Spurious time effects: Next, I examine whether there are any significant effects of the LCC on home prices before and after the LCC is implemented by employing the following **event study** regression:

$$Y_{ijkt} = \pi_k + \sum_{\mathbf{g}=<-3}^{7} \zeta^{\mathbf{g}} \mathbf{LCC}^{\mathbf{g}}_{\mathbf{it}} + X'_{jt}\delta + V'_{jt}\eta + \upsilon_t + \epsilon_{ijkt}, \tag{5}$$

where g represents the **number of years from the year the LCC is enforced** (e.g g = 0 represents the year the charge is enforced, g = -3 represents sales made 3 years before the charge is enforced). As before, LCC^{g}_{it} takes the value of 1 if property is within the LCC and is sold at g years from the year the LCC is enforced. Results are summarized in Fig. 7. Plotted estimates (ζ^{g}) are the effects on house prices across the different years relative to the properties in the charge zone sold

[31] Given that these properties in the discount zones are very close to the LCC boundary, traffic conditions could be adversely affected by the charge due to traffic displacement. If traffic conditions worsen in these areas, the downward pressure on housing values to due to traffic externalities could mask the WTP to pay for charge discounts. Hence, I conducted a similar analysis with traffic flow as the dependent variable to examine whether the charge affect traffic conditions in the discount zone. As observed in Table A.3, these estimates are too imprecise to provide conclusive evidences that the charge affected traffic conditions in the discount zone.

Table 6
Effect of the LCC on Traffic Accidents (Panel A) & Air Quality (Panel B).

	Panel A: Accidents				Panel B: Pollution		
	(1) Accidents	(2) Slight	(3) Serious	(4) Deaths	(5) NOX	(6) NO2	(7) PM10
LCC	-0.1018***	-0.1009***	-0.1373*	-0.3129	0.0684	-0.0630	-0.0751***
	(0.0323)	(0.0356)	(0.0714)	(0.3252)	(0.0495)	(0.1153)	(0.0076)
Obs	190,853	181,865	73,207	5372	976	965	916
Absolute Effects	-0.223	-0.225	-0.109	-0.094	7.763	-3.300	-2.242
% Δ	-9.679	-9.598	-12.831	-26.864	7.077	-6.105	-7.237
No.of Road/Station FEs	7013	6661	2565	187	15	15	17

Dependent variable is the counts of the total counts of (1) accidents, (2) slight injuries, (3) serious injuries and (4) deaths from accidents collected at road segment r at quarter t in Panel A and the natural log of average monthly concentrations of (5) NOX, (6) NO2 and (7) PM10 collected at monitoring station m in Panel B. Each coefficient is from a different regression. Panel A is estimated using Poisson regressions while Panel B is estimated using OLS. Each coefficient is from a different regression that denotes the effects of the LCC on collision outcomes in Panel A and air quality in Panel B. Sample is restricted to roads (Panel A) and monitoring stations (Panel B) within 1 km from the LCC boundary. In Panel A, all regressions include year-quarter and road fixed effects. In Panel B, all regressions include year-quarter and monitoring stations fixed effects, and controls from meteorological conditions that include wind speed, wind direction, temperature, relative humidity and barometric pressure. LCC is a binary variable that takes the value of 1 for roads (Panel A) or monitoring stations (Panel B) in the LCC after the charge is implemented. Robust standard errors, reported in the parenthesis, are clustered at road-level in Panel A and monitoring station in Panel B. * p<0.10, ** p<0.05, *** p<0.01.

one year before the LCC is enforced (denoted by dash line at year -1). As my analysis incorporates sales from 2000 to 2010, and I have two treatment areas (CCZ, which is implemented in 2003, and WEZ, which is implemented in 2007), the earliest sales can be made up to 7 years before the LCC enforcement. There are, however, very limited transactions from year -4 to -7 because they are made up by only sales in the WEZ.[32] Hence, to avoid imprecisely estimated coefficients from small sample sizes in these years, I classify transactions from 4 to 7 years under the category ”<-3” years. Tails denote the 95% confidence intervals. If there are no spurious house price effects before the charge is implemented, I expect ζ^g to be close to 0 when $g < 0$ (before the LCC is implemented).

As observed from Fig. 7, most of the pre-treatment estimates (g<0) are centered around zero, indicating that house prices in the charge zone did not experience significant changes before the enforcement of the LCC. Although these results suggest that houses could be sold at higher prices in year -2, this estimate (at 0.017) is not statistically significant at any conventional levels. The average estimated effect across post-treatment years relative to sales in year -1 is 0.031 (denoted by the horizontal dash line). House price effects in year +1, +3 and +7, however, are not precisely estimated to be statistically different from the baseline at a 10% level. This could be due to smaller sample sizes once I break down the effects into different years. However, the size of the effects in year +1 and +3 (0.025 for both years) are fairly comparable to the other post-treatment periods. Overall, although significant house price increments are not consistently documented across post treatment periods, these results suggest that earlier baseline estimates are unlikely to be driven by spurious trends prior to the enforcement of the LCC.

6.4. *Effects of the London Congestion Charge on traffic accidents & air quality*

In this section, I investigate why home buyers are willing to pay for better traffic conditions in the charge zone by examining the impact of the LCC on traffic collisions and air quality. To do so, I assemble data on (1) collision outcomes at road level from the STATS 19 Accident Database and (2) in-situ measurement of air quality from monitoring stations from the London Air Quality Network from 2000 to 2010. In short, I estimate difference-in-differences regressions analogous to Eq. (3) but I replace the dependent variable with collision outcomes and air quality.

Specifically, to measure the impact of the LCC on local traffic safety, I estimate the following regression :

$$A_{rt} = \alpha_r + \boldsymbol{\Psi}\mathbf{LCC_{rt}} + \omega_t + \varepsilon_{rt}, \tag{6}$$

where the dependent variable (A_{rt}) represents the year-quarterly count of accidents, slight injuries, serious injuries and deaths collected at road segment (r) for year-quarter (t).[33][34] Given that the dependent variables are discrete count outcomes, all regressions are estimated using Poisson Count models. α_r represents road-level fixed effects and ω_t denotes year-quarter fixed effects. The key variable of interest, LCC_{rt}, is an indicator variable that takes the value of 1 for roads inside the CCZ/WEZ after the charge is implemented. If the reduction in traffic due to the introduction of LCC makes roads safer, I expect Ψ to be < 0. Panel A of Table 6 reports the key estimate (Ψ). Consistent with the previous literature, I observe that the reduction in traffic flow due to the LCC improves traffic safety. Specifically, the counts of accidents, injuries and serious injuries are 9.67%, 9.60% and 12.83% lower after the LCC is implemented. Although the number of traffic fatalities are lower, the estimated effect is too imprecise to be statistically significant. In absolute terms, the number of accidents, slight injuries and serious injuries are 0.223, 0.225 and 0.109 lower per km.[35] These results are quite consistent when the specification is estimated for the full sample using OLS as shown in Table A.6 in Appendix.

To further measure the impact of the LCC on local air quality, I estimate the following regression :

$$P_{mt} = \alpha_m + \boldsymbol{\varphi}\mathbf{LCC_{mt}} + C'_{mt}\phi + \omega_t + \varepsilon_{mt}, \tag{7}$$

where P_{mt} is the natural logarithm of average monthly concentration of nitrogen oxide (NOX), nitrogen dioxide (NO2) and particulate matter 10 (PM10) collected at a monitoring station level (m).[36] Other than the inclusion of monitoring station (α_m) and year-quarter (ω_t) fixed effects, I further control for meteorological conditions (C'_{mt}) such as wind speed, wind direction, temperature, relative humidity and barometric

[32] For instance, the total number of sales made from year −4 to −7 in the WEZ is 2,724, which is less than the 2859 sales made in year −3.

[33] The reason why this is not conducted at a monthly level is because traffic accidents are fairly rare events and aggregation at a monthly level will lead to a disproportionate number of zeros in the dataset.

[34] The number of injuries, serious injuries and deaths are constructed by aggregating the number of individuals suffering from minor injuries, serious injuries and fatal injuries from the traffic accidents.

[35] These effects are computed by multiplying the effects with pre-treatment collision levels, before dividing this by the average road length in kilometers.

[36] There are other pollutants such as sulphur dioxide, PM2.5 and ozone. However, bulk of the observations around the sample period is missing for these outcomes.

pressure and their second polynomials. Panel B of Table 6 reports the key estimate (φ), which captures the percentage change in concentrations of various pollutants after the LCC is enforced. Across the different pollutants, I detect a significant 7.2% reduction in the concentration of PM10 in the charge zone after the LCC is implemented. Effects for NOX and NO2 are too imprecisely estimated to be significant at any conventional levels.[37] A plausible explanation is the displacement of road traffic across the boundary could worsen air quality outside. Air-borne pollutants could travel across the boundary, leading to a downward bias to the estimates. This is more likely in my context as I am comparing neighbourhoods right next to one another. Conversely, PM10 is heavier and is less likely to travel across the boundary.

Based on these estimates, I conduct a simple, but rather heroic, back-of-an-envelope exercise to understand whether the WTP estimates documented in this study are reasonable. The implementation of the LCC resulted in a 8.77% reduction in traffic flow (Column 1 Panel A of Table 2) that led to a 7.24% reduction in PM10 (Column 7 Table 6). These estimates suggest that a 1% increase in traffic corresponds to a 0.83% (7.24 ÷ 8.77) increase in PM10. Chay et al. (2005) report that the elasticity between house prices and particulate concentrations ranges from 0.20 to 0.35. Plugging in the lower bound of these estimates, the estimated impact of the increase in PM10 from traffic flow on housing values is around 0.166 (0.83% × 0.20). This is approximately 55% (0.166 ÷ 0.30) of the elasticity of house price with respect to traffic flow at 0.30 (Column 1 Panel C Table 2). The proportion goes to around 75% if I plug in the mid-range elasticity of 0.275. The rest of the 25–45% of the effects could stem from improved traffic safety, reduced noise pollution and travel time.[38] This exercise shows that the WTP estimates in this study are reasonable considering the effects of the LCC on PM10 and traffic accidents.

6.5. Discussion

In this section, I rely on earlier estimates to compute the localised economic benefits associated with the charge. The implementation of the charge, on average, increases home prices in the Congestion Charge Zone by £18,555.[39] Based on the Census estimates on the number of dwellings, there are a total of 205,383 houses in the CCZ and WEZ. This implies that the charge has generated an aggregate windfall of around £3.8 billion for homeowners in the zone relative to those outside the zone. This figure is meaningful as it presents monetary measure of the local benefits associated with the charge in perpetuity given the long-lived nature of real estate.

While a comprehensive cost benefit analysis of the LCC is out of the purview of this paper, it is still interesting to see how these local benefits measure up to the cost of implementing the charge. To compute the present value of the total cost to implement the LCC, I rely on estimates provided by Leape (2006). I assume the first year implementation cost to be around £163 million and the subsequent annual operating cost to be around £140 million (£23 million is the set up cost). Assuming that the inflation rate is 2.7% and discount rate is 3.0%, the present value net cost of implementing the charge for the next 30 years is approximately £4.15 billion (2015 values). Taking that the cost of implementing the Western Extension Zone (WEZ) to be the same as the CCZ, the total cost of enforcing the LCC is around £8.3 billion. Even without considering other benefits associated with the charge, such as reduction in travel time and improvement in air quality across London, the estimated windfall for homeowners in the zone is around 46% of the cost for implementing the charge.

There are policy implications associated with this study. This paper shows that households residing in the charge zone benefit from better traffic conditions that result in house price gains. This increase in value for houses inside the charge zone suggests the possibility for these ”winners” living inside the zone to compensate the ”losers” living outside. For instance, council taxes or property value taxes can be adjusted to capture these capitalization gains and they can be redistributed to ”losers” though public transport subsidies.[40] Furthermore, these WTP estimates to avoid negative traffic externalities can be useful in understanding the potential social cost or benefits associated with transportation infrastructures/policies such as roads, congestion charges and public transit that affect traffic flow around residential neighbourhoods.

7. Conclusion

This paper exploits the sharp but localised changes in traffic conditions induced by the London Congestion Charge (LCC) in the Congestion Charge Zone (CCZ) and the Western Extension Zone (WEZ) to estimate the marginal willingness to pay (WTP) to avoid traffic using the housing market. Using the LCC as an instrumental variable for traffic conditions, this study is an improvement from typical cross-sectional approaches that are blighted by omitted variable bias and sorting.

Results suggest that the LCC reduces traffic flow and increases house values in the charge zone. Comparing properties just inside and outside the charge boundary to reduce unobserved neighbourhood differences between properties, I observe that home buyers pay, on average, 2.84% (£18,555) more for their homes to enjoy 8.77% (1562 vehicles) reduction in traffic in the zone. Putting these results together, instrumental variable estimates indicate that the elasticity of housing values with respect to traffic flow is 0.30. These results are robust across a battery of robustness and placebo tests. Additional results suggest that home buyers could have paid more for better air quality and safer roads in the charge zone. My estimates suggest that the LCC generated substantial local wealth gains of around £3.8 billion for homeowners in the zone. This windfall measures the local benefits associated with the charge.

Given that congestion is fast becoming a salient issue for many cities around the world, this problem has drawn considerable interests from academics and policy makers. Yet, solutions such as constructing more roads (Duranton and Turner, 2011) and implementing fuel taxes (Anas and Lindsey, 2011) are notoriously ineffectual in reducing traffic jams. My findings suggest that congestion tolls improve traffic conditions in the charge zone, reducing congestion, pollution and accident externalities from driving. However, to ensure that the policy is effective in abating bottlenecks, there must be proper management of traffic around and beyond the charge zone to handle traffic displacement from drivers detouring the zone to avoid the charge. Also, it is imperative to provide a reliable and comprehensive public transport system to encourage commuters to switch from driving.

Appendix A. Data Appendix

I. Description of data

[37] The result for NOX merits more attention. Although imprecisely estimated, I observe a sizable increase in NOX concentration. This finding is consistent with that reported by Green et al. (2018). They explained that the implementation of the LCC could lead to the substitution of diesel-based vehicles, such as buses and taxis, in the charged zone as they are waived from paying the CC. The combustion of diesel produces more nitrogen oxides and this could explain the higher concentration of these pollutants in the zone.

[38] Unfortunately, I am not able to convert these estimates to housing values. First, I do not know the estimated reduction in noise pollution from the LCC as I do not have data on noise pollution. Second, I do not have WTP estimates associated with traffic safety and house prices.

[39] This is from the preferred specification of Column (1) in Table 2 where I restrict the analysis to properties no more than 1000m from the charge boundary.

[40] The policy for value extraction for funding public transport systems is not entirely new. Governor Andrew M. Cuomo in New York plans to designate transit improvement sub-districts and impose taxes to fund the subway system. For more information, refer to link.

Table A.1
Description of Variables used in the analysis.

Variable	Source	Description
Dependent Variable		
Housing Price (Y_{ijkt})	Land Registry	Natural logarithm of property price of transaction i at postcode k, neighbourhood j at quarter q of year t
Traffic Flow (T_{ijkt})	Department Of Transport	Natural logarithm of traffic flow from vehicles with 4 or more wheels for transaction i at postcode k at year t
Collision Outcomes (A_{rt})	STATS19	Counts of collisions outcome (Accidents, Slight injuries, Serious injuries and Deaths) at road section r at year-quarter t
Air Pollutant (P_{mt})	London Air Quality Network	Natural logarithm of air pollutant (NO_2, NOX & $PM10$) at monitoring station m at year-month t
Housing Characteristics (X'_{it})		
New Sales	Land Registry	Dummy denoting whether transaction i is new build
Terrace	Land Registry	Dummy denoting whether the property type for transaction i is terrace
Leasehold	Land Registry	Dummy denoting whether the tenure for transaction i is leasehold
Location/Neighbourhood Characteristics (V'_{jt})		
Distance to the CCZ/WEZ boundary	-	Elucidian distance of postcode j from the boundary of the CCZ/WEZ
Distance to nearest Grade 1 Park	Magic	Elucidian distance of nearest Grade 1 Park from postcode j in km
Counts of Heritage Buildings	Magic	Number of Heritage buildings within 200m from postcode j
River Thames View	Digimap	Binary variable = 1 if postcode j within 200m from River Thames, 0 otherwise
Minority race residents	Census 2001 & 2011	% of Asian/African/Middle Eastern and other minority race residents in OA
Unemployment rate	Census 2001 & 2011	% of unemployed working adults in OA
Uneducated residents	Census 2001 & 2011	% of residents in OA with no education qualifications
Lone parent households	Census 2001 & 2011	% of single-parent households in OA

II. Supplementary results further away from the LCC boundary (5km to 1km)

In this section, I increase the sample of transactions for analysis to up to 5 km from the LCC boundary. This allows us to understand how WTP estimates could vary for a larger sample of sales further away from the charge boundary. While these estimates may be more externally valid, they run a greater risk of being bias by unobserved neighbourhood shocks that could be correlated with the charge implementation. In these regressions, I truncate the top and bottom 0.5% of the transactions due to concerns that outliers could be driving the estimates. An inspection of the data reveals that sale prices at the top and bottom 0.5% could be as high as £41 million or as low as £90,000. Furthermore, these sales appear to be one off as repeated sales or other sales within the same postcode are recorded at much lower or higher prices, suggesting that these outlier prices are likely to be erroneously recorded.[41]

Panel A of Table A.2 reports the impact of the LCC on local traffic flow in the zone. These estimates are important by themselves as they illustrate the efficacy of the LCC in reducing traffic, and the strength of the LCC as an instrumental variable for traffic flow. After the introduction of the LCC, I observe that traffic flow in the zone is 5.61% lower when compared to neighbourhoods outside but within 5 km from the LCC boundary.[42] These effects remain fairly stable when I streamline the sample to more comparable neighbourhoods in proximity to the zone. Within 4 km, the effect increases to 5.82% and within 3 km, the effect is 6.15%. This effect further increases to 7.24% when I constrain the sample to areas within 2 km from the charged boundary and is even larger at 8.75% when construed to areas within 1 km from the LCC boundary. In absolute terms, I am looking at between 1056 and 1557 less vehicles inside the zone everyday compared to areas outside the charge zone.[43]

Panel B presents the impact of the LCC on property values in the charged zone. I observe significant house price appreciation in the charge zone after the LCC is introduced. When compared to residential sales within 5 km from the boundary, house prices in the charge zone are 2.89% higher. These effects drop to 2.66% relative to houses within 4 km and 2.47% within 3 kilometres. Restricting the analysis to housing units just 2 km in and out the LCC boundary, I observe stable price responses at around 1.98%. Finally, looking at sales 1 km or less from the LCC boundary, which reduces the sample by almost 80%, I document that property values are 2.39% higher than before. In absolute monetary terms, the LCC increases housing values in the charge zone by a magnitude of between £12,930 and £19,116.[44] All these estimates are significant at least at 5% level.

Putting these two estimates together in Panel C, I document that the direct elasticity between traffic volume and housing values ranges between 0.26 to 0.49. Although these IV elasticity estimates appear quite consistent with earlier results in Table 2, they are less stable across distance bandwidths. This is largely driven by the changes in estimated effects of the LCC on traffic conditions at different distances from the boundary, and could be driven by unobserved differences between properties inside and outside the charge zone further from the charge boundary.

[41] When I include these outlier sales in the analysis, I document a much larger elasticity range of 0.30 to 0.96. This disparity in WTP estimates is small (less than 0.01) when I limit the analysis to sales 1km from the charge boundary, suggesting that concerns of outliers driving the estimates is not a major concern in the baseline regression estimates.

[42] As it is a log-linear model, capitalization effects are computed by taking the exponential of the point estimates before subtracting by one. For instance, $Exp(-0.0577) - 1 \approx 5.61\%$. The same conversion is applied for housing prices.

[43] This is obtained by multiplying the point estimates with the average pre-treatment traffic volume.

[44] This is computed by multiplying the estimates on the pre-treatment average home prices adjusted to 2015 price levels in the charge area within the distance bandwidth from the LCC boundary.

Table A.2
First Stage, Reduced form, IV and OLS estimates from sales 5000m to 1000m from the LCC Boundary.

	(1) 5km	(2) 4km	(3) 3km	(4) 2km	(5) 1km
Panel A - First Stage (Log Traffic)					
LCC	-0.0577***	-0.0600***	-0.0635***	-0.0752***	-0.0916***
	(0.0119)	(0.0123)	(0.0129)	(0.0145)	(0.0168)
R2	0.98	0.97	0.97	0.97	0.98
Mean Traffic	18,829	18,828	18,570	18,106	17,792
Δ Traffic	-1056	-1096	-1142	-1312	-1557
Panel B - Reduced Form (Log House Price)					
LCC	0.0285***	0.0263***	0.0244***	0.0196**	0.0236**
	(0.0077)	(0.0078)	(0.0080)	(0.0086)	(0.0098)
R2	0.77	0.76	0.76	0.76	0.74
Mean HP	660,243	660,263	659,564	651,952	649,412
Δ HP	19,116	17,618	16,316	12,930	15,540
Panel C - IV Regressions					
ln(Traffic)	-0.4944***	-0.4389***	-0.3848***	-0.2611**	-0.2582**
	(0.1679)	(0.1574)	(0.1476)	(0.1238)	(0.1136)
R2	0.13	0.12	0.10	0.08	0.07
No.of Postcodes	15,010	13,098	10,731	7900	4948
1st Stage F-Statistics	23.51	23.85	24.09	26.86	29.56
Panel D - Naive OLS					
ln(Traffic)	0.0006	-0.0002	-0.0015	-0.0018	-0.0147
	(0.0088)	(0.0097)	(0.0105)	(0.0129)	(0.0214)
Obs	177,771	151,997	118,411	84,276	52,634
R2	0.77	0.76	0.76	0.76	0.74

Dependent variable is the logarithm of annual average daily traffic volume for vehicles with 4 wheels or more for Panel A and the logarithm of transacted house prices for Panel B. Each coefficient is from a different regression. LCC is a binary variable equals to one for properties that are inside the CCZ or WEZ after the charge is implemented. Sample is constrained to properties within 5 kilometres (Column 1) to 1 km (Column 5) from the LCC boundary. Panel A reports first regression estimates (γ) from Eq. (2) that measures the effect of the LCC on traffic flow in the charge zone. Panel B reports reduced form estimates (ζ) from Eq. (3) that measures the effect of the LCC on house prices in the charge zone. All regressions are estimated with postcode and year quarter fixed effects. Other control variables include housing characteristics (leasehold, newbuild and terrace dummies), neighbourhood characteristics by-year (% of residents with no education qualifications, % of residents with minority races, unemployment rate and % of lone parent households) and location characteristics by-year (River Thames view dummy, counts of heritage buildings within 200m, distance of the property from nearest park, and distance from the LCC boundary and its second polynomial). For more information on the variables, refer to Table A.1 in Data Appendix. Mean Traffic is the average daily traffic flow in the zone before the LCC is implemented. Mean HP is the average transacted prices (in 2015 £value) for properties in the zone before the LCC is implemented. Δ Traffic and Δ HP denote the absolute effects of the LCC on average daily traffic volume and house prices (in 2015 £value) respectively. 1st Stage F-stats reported is the Kleibergen-Paap rk Wald F statistic from first stage regressions. Robust standard errors clustered at Output Area (OA) are reported in parenthesis. * p<0.10, ** p<0.05, *** p<0.01.

Table A.3
Effect of the LCC on traffic flow in the Congestion Charge Discount Zone.

	(1) 1000m	(2) 900m	(3) 800m	(4) 700m	(5) 600m	(6) 500m
LCC	-0.0918***	-0.0965***	-0.0985***	-0.1009***	-0.0987***	-0.0982***
	(0.0177)	(0.0183)	(0.0197)	(0.0210)	(0.0220)	(0.0232)
Discount	-0.0757	-0.0820	0.0065	0.0063	0.0235	0.0198
	(0.0739)	(0.0840)	(0.0275)	(0.0287)	(0.0238)	(0.0247)
Obs	53,490	49,654	45,168	40,789	35,770	31,689
R2	0.98	0.98	0.98	0.98	0.98	0.98
No.of Postcodes	5077	4646	4253	3843	3432	2996

Dependent variable is the natural logarithm of traffic flow. Each coefficient is from a different regression. Sample is constrained to sales within 1km (Column 1) to 500 m (Column 6). $Discount$ is a binary variable equals to one for properties that are inside the discount zone after the LCC is introduced. LCC is a binary variable equals to one for properties that are inside the CCZ or WEZ after the charge is implemented. Dependent variable is the natural logarithm of the transacted property prices. All regressions are estimated with postcode and year-quarter fixed effects. Other control variables include housing characteristics (leasehold, newbuild and terrace dummies), neighbourhood characteristics by-year (% of residents with no education qualifications, % of residents with minority races, unemployment rate and % of lone parent households) and location characteristics by-year (River Thames view dummy, counts of heritage buildings within 200m, distance of the property from nearest park, and distance from the LCC boundary and its second polynomial). Robust standard errors clustered at Output Area (OA) are reported in parenthesis.*p<0.10, ** p<0.05, *** p<0.01.

III. Effects of the LCC on traffic flow in Discount Zone

Table A.4
First Stage, Reduced form & IV estimates from all sales 1000m to 500m from the LCC Boundary.

	(1) 1000m	(2) 900m	(3) 800m	(4) 700m	(5) 600m	(6) 500m
Panel A: First Stage (Log Traffic)						
LCC	-0.0922***	-0.0970***	-0.0992***	-0.1016***	-0.0995***	-0.0988***
	(0.0167)	(0.0174)	(0.0186)	(0.0199)	(0.0208)	(0.0219)
R2	0.98	0.98	0.98	0.98	0.98	0.98
Mean Traffic	17,798	17,769	17,760	17,717	17,716	17,650
Δ Traffic	-1567	-1643	-1677	-1712	-1678	-1661
Panel B: Reduced Form (Log House Price)						
LCC	0.0287***	0.0317***	0.0371***	0.0352***	0.0326**	0.0271**
	(0.0099)	(0.0104)	(0.0111)	(0.0118)	(0.0127)	(0.0133)
R2	0.76	0.75	0.75	0.75	0.75	0.75
Mean HP	654,362	653,841	652,936	651,441	650,224	648,940
Δ HP	19,043	21,034	24,659	23,346	21,519	17,827
Panel C: IV Regressions						
ln(Traffic)	-0.3112***	-0.3264***	-0.3737***	-0.3465***	-0.3272**	-0.2742*
	(0.1170)	(0.1173)	(0.1259)	(0.1284)	(0.1412)	(0.1458)
R2	0.08	0.08	0.07	0.07	0.07	0.08
No.of Postcodes	5126	4691	4292	3880	3467	3026
1st Stage F-Statistics	30.42	31.24	28.44	26.13	22.99	20.32
Panel D: Naive OLS Regressions						
ln(Traffic)	-0.0171	-0.0155	-0.0232	-0.0209	-0.0229	-0.0230
	(0.0216)	(0.0224)	(0.0236)	(0.0250)	(0.0279)	(0.0317)
Obs	53,982	50,102	45,552	41,126	36,074	31,939
R2	0.76	0.75	0.75	0.75	0.75	0.75

Dependent variable is the logarithm of annual average daily traffic volume for vehicles with 4 wheels or more for Panel A and the logarithm of transacted house prices for Panel B, C and D. Each coefficient is from a different regression. Sample is constrained to properties within 1000m (Column 1) to 500m (Column 6) from the LCC boundary. All regressions are estimated with postcode and year quarter fixed effects. Other control variables include housing characteristics (leasehold, newbuild and terrace dummies), neighbourhood characteristics by-year (% of residents with no education qualifications, % of residents with minority races, unemployment rate and % of lone parent households) and location characteristics by-year (River Thames view dummy, counts of heritage buildings within 200m, distance of the property from nearest park, and distance from the LCC boundary and its second polynomial). For more information on the variables, refer to Table A.1 in Data Appendix. Mean Traffic is the average daily traffic flow in the zone before the LCC is implemented. Mean HP is the average transacted prices (in 2015 £value) for properties in the zone before the LCC is implemented. Δ Traffic and Δ HP denote the absolute effects of the LCC on average daily traffic volume and house prices (in 2015 £value) respectively. 1st Stage F-stats reported is the Kleibergen-Paap rk Wald F statistic from first stage regressions. Robust standard errors (in parenthesis) are clustered at output area. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

IV. Supplementary results with full sample of sales including detached and semi-detached houses

Table A.5
Effects of the LCC on traffic flow for roads further away from the LCC boundary.

	(1) >=1km & <=5km	(2) >=2km & <=5km	(3) >=3km & <=10km	(4) >=5km & <=15km	(5) >=5km
LCC	-0.0832***	-0.0842***	-0.1085***	-0.1225***	-0.1276***
	(0.0185)	(0.0190)	(0.0182)	(0.0185)	(0.0185)
Obs	9675	8384	14,699	18,808	23,805
R2	0.98	0.97	0.98	0.98	0.98
No.of CP	848	746	1304	1665	1967
Δ Traffic	-1682	-1702	-2166	-2430	-2525

Dependent variable is the natural logarithm of annual traffic flow collected at a count point level. Each coefficient is from a different regression. *LCC* is a binary variable equals to one for roads that are inside the CCZ or WEZ after the charge is implemented. Column 1 constraints the analysis to roads within 5km from the LCC boundary but removes roads outside and within 1km from the LCC boundary. Column 2 constraints the analysis to roads within 5km from the LCC boundary but removes roads outside and within 2km from the LCC boundary. Column 3 constraints the analysis to roads within 10km from the LCC boundary but removes roads outside and within 3km from the LCC boundary. Column 4 constraints the analysis to roads within 15km from the LCC boundary but removes roads outside and within 5km from the LCC boundary. Column 5 incorporates all the roads removes the roads outside but removes roads outside and within 5km from the LCC boundary. All regressions are estimated with count point and year fixed effects. The mean daily traffic flow in the charge zone before the LCC is enforced is 21,075. Δ Traffic denotes the absolute effects of the LCC on average daily traffic volume. No. of Count Points report the total number of distinct count points in each regression. Robust standard errors clustered at ward level are reported in parenthesis.* $p<0.10$, ** $p<0.05$, *** $p<0.01$.

V. Effects of the LCC on traffic flow across London

Table A.5 presents the effects of the LCC on traffic flow. In these regressions, I exclude roads (or count points) closest but outside the LCC but incorporate roads further away. The idea is that these ring-roads circumventing the LCC are carrying most of the displaced traffic. Isolating these traffic displacement effects allow us to more accurately measure the impact of the LCC on traffic flow.

Table A.6
Effect of the LCC on Traffic Accidents estimated using OLS.

	(1) Accident	(2) Slight	(3) Serious	(4) Deaths
LCC	-0.0145***	-0.0135**	-0.0030*	-0.0001
	(0.0056)	(0.0060)	(0.0018)	(0.0003)
Obs	190,853	190,853	190,853	190,853
Absolute Effects	-0.19	-0.17	-0.04	-0.00
R2	0.24	0.20	0.08	0.04
No.of Road Segments	7013	7013	7013	7013

Dependent variable is the counts of the total counts of (1) accidents, (2) slight injuries, (3) serious injuries and (4) causalities from accidents collected at road segment r at quarter t within 1 km from the LCC boundary. All regressions include year-quarter and road fixed effects and are estimated using OLS. Robust standard errors, reported in the parenthesis, are clustered at road-level. * p<0.10, ** p<0.05, *** p<0.01.

In short, the effects of the LCC on traffic flow are smaller at 7.98% (column 1) and 8.07% (column 2) when I remove these ring roads within 1 to 2km and roads more than 5km from the charge boundary. These results show that traffic displacement along these ring roads could indeed inflate the efficacy of the LCC on reducing traffic. However, once I consider roads further from the LCC, I observe a rebound in the estimates. These effects become larger at 10.30% (column 3) when incorporate roads up to 10km but remove those within 3km from the LCC boundary. Effects are even stronger at 11.53% (column 4) when I consider roads up to 15km from the LCC and remove any roads less than 5km. Finally, incorporating all the roads across London, these effects considerably larger at 11.98% (column 5).

Why are these estimates larger when I incorporate roads further out? A plausible explanation is the relocation of economic activities in areas far from the LCC boundary that increases traffic flow, and hence the magnitude of the LCC effects. For instance, the emergence of Canary Wharf around the implementation of the LCC led to considerable decentralization of economic activities from the CBD. The straight-line distance between Canary Wharf and Trafalgar Square is around 8km. This means that estimates from column 4 and 5 could be capturing these decentralization effects. While the definitions of these distance cut-offs are arbitrary, this exercise shows the sensitivity of the estimates to traffic displacement.

VI. Effects of the LCC on accidents using OLS

VII. Effects of other congestion charge events on traffic & house prices

In this section, I report the effects of the other Congestion Charge events on traffic and housing values. These events include (1) the increase in the charge from £5 to £8 from the 4th of July 2005 ($CCZ2005$) and (2) from £8 to £10 from the 4th of January 2011 ($CCZ2011$), (3) the removal of the WEZ from the 24th December 2010 ($RemWEZ$) and (4) the increase in the charge from £10 to £11.50 from the 16th of June 2014 ($CCZ2014$). The sample windows for these events are defined by 2 years before and after the respective event dates. This is except for $CCZ2014$, which is limited to sales 1 year before and after the hike to minimize overlapping with $CCZ2011$. Refer to Figure A.9 for more details.

Table A.7
Estimates of the effects of the other Congestion Charge events on Traffic & House Prices.

	(1) 5km	(2) 4km	(3) 3km	(4) 2km	(5) 1km	(6) 5km	(7) 4km	(8) 3km	(9) 2km	(10) 1km
	Panel A: First Stage (Log Traffic)					*Panel B: Reduced Form (Log House Price)*				
CCZ2005	-0.0089	-0.0104	-0.0112	-0.0109	-0.0293**	-0.0092	-0.0086	-0.0098	-0.0050	-0.0088
	(0.0123)	(0.0121)	(0.0116)	(0.0116)	(0.0127)	(0.0124)	(0.0126)	(0.0130)	(0.0139)	(0.0169)
Mean Dep Variable	17,851	17,851	17,851	17,851	18,083	591,168	591,168	591,168	591,168	589,823
CCZ2011	0.0010	-0.0027	-0.0030	0.0002	0.0145	-0.0110	-0.0101	-0.0103	-0.0090	0.0210
	(0.0134)	(0.0134)	(0.0134)	(0.0129)	(0.0151)	(0.0188)	(0.0188)	(0.0189)	(0.0192)	(0.0176)
Mean Dep Variable	15,782	15,782	15,782	15,778	15,223	745,257	745,257	745,257	744,583	703,105
RemWEZ	0.0120	0.0076	0.0084	0.0257**	-0.0002	0.0378*	0.0365*	0.0333	0.0411*	0.0417
	(0.0115)	(0.0118)	(0.0129)	(0.0130)	(0.0147)	(0.0211)	(0.0219)	(0.0226)	(0.0233)	(0.0264)
Mean Dep Variable	19,851	19,851	19,851	19,851	19,881	1,367,704	1,367,704	1,367,704	1,367,704	1,347,740
CCZ2014	-0.0046	-0.0035	-0.0013	-0.0015	-0.0040	-0.0459	-0.0416	-0.0324	-0.0360	-0.0514
	(0.0033)	(0.0032)	(0.0029)	(0.0035)	(0.0030)	(0.0319)	(0.0323)	(0.0330)	(0.0354)	(0.0439)
Mean Dep Variable	15,822	15,822	15,822	15,822	15,497	1,020,630	1,020,630	1,020,630	1,020,630	976,149

Each coefficient (γ) is from a different first stage estimation of Eq. 2. Sample is constrained to properties within 5 km from the CCZ/WEZ boundary. Panel A reports the first stage regressions with the natural logarithm of annual average traffic volume as the dependent variable. Panel B summarizes reduced form regressions with the natural logarithm of house prices. Four other events are examined: (1) the increase in the charge from £5 to £8 in 2005 ($CCZ2005$), (2) the increase in the charge from £8 to £10 in 2011 ($CCZ2011$) (3) the removal of the WEZ in 2010 ($RemWEZ$) and (4) the increase in the charge from £10 to £11.50 in 2014 ($CCZ2014$). All regressions are estimated with postcode and year-quarter fixed effects. Other control variables include housing characteristics (leasehold, newbuild and terrace dummies), neighbourhood characteristics by-year (% of residents with no education qualifications, % of residents with minority races, unemployment rate and % of lone parent households) and location characteristics by-year (River Thames view dummy, counts of heritage buildings within 200m, distance of the property from nearest park, and distance from the LCC boundary and its second polynomial). For more information on the variables, refer to Table A.1 in Data Appendix. Robust standard errors clustered at Output Area (OA) are reported in parenthesis.*p<0.10, ** p<0.05, *** p<0.01.

Overall, as reflected in Panel A of Table A.7, most of the estimates suggest charge increments do not materially improve traffic conditions. This could explain why these hikes have an immaterial effect on house prices, as documented in Panel B. The only exception is during the charge increment in 2005 ($CCZ2005$). Restricting the analysis to areas 1 kilometre in and out the CCZ, I observe significant reductions of traffic flow at around 2.98%. This works out to around 523 less vehicles every day. These effects, however, are too small to induce a perceptible impact on house

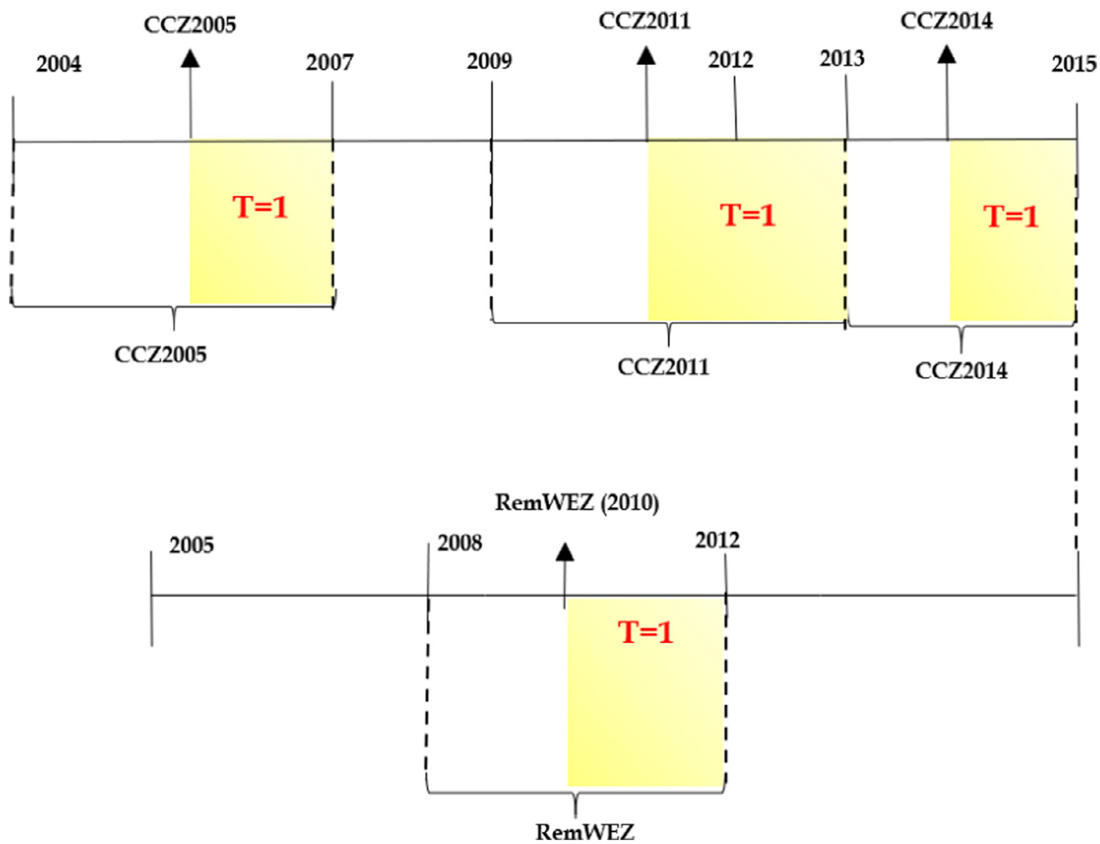

Fig. A1. Sample window for the different CC events (T=1 denotes Treatment Period).

prices. The immaterial effects of the charge increment are consistent with the findings reported by Agarwal et al. (2015) who also show that the increase in the Congestion Charge in Singapore do not affect residential transacted prices.

In other results, I observe that the removal of the WEZ could have affected house prices in the WEZ. Although these estimates suggest that house prices increase by around 3.34% to 4.26% after the WEZ is removed, they are imprecisely estimated and are no longer statistically significant when I constrain the analysis to sales 1km from the charge boundary. The corresponding effects on traffic flow are also too small and imprecisely estimated to be statistically significant at any conventional levels. This is except for properties within 2km from the charge boundary, which experienced a small increase of around 2.60%. Hence, the removal of the WEZ is a weak instrument for changes in traffic flow with none of the F-statistics larger than 10 as observed in Table A.8. Overall, these results do not provide conclusive evidence that the removal of the WEZ led to a rebound in traffic flow, consistent with the findings reported by TfL. The absence of any deterioration in traffic conditions and the removal of the need to pay the congestion charge could explain why home prices escalated after the WEZ is removed.

VIII. Spatial clustering of standard errors

Table A.9 reports the Conley Spatial HAC standard errors (Conley, 1999) that allow for both spatial and serial correlation of standard errors for both first stage (Panel A) and reduced form (Panel B) regressions estimated using *reg2hdfespatial* written by Thiemo Fetzer. I allow spatial correlation of standard errors for transactions within the distance bandwidths denoted in the column headers, and serial correlation of standard errors for transactions taking place within 1 year from one another. I also report robust standard errors clustered at output area in column 2 for comparison. Results indicate that the significance of the estimates from both first stage and reduced form regressions are largely unaffected by the way standard errors are clustered. Conley spatial HAC standard errors appear quite small and stable across different distance cutoffs.[45] If anything, these results suggest that clustering standard errors at output area is less conservative compared to standard errors that allow for spatial and temporal correlation.

[45] As I am limiting the analysis to sales within 1000m from the charge boundary, it is not advisable to go any further than 2000m as there would not be enough clusters.

Table A.8
Instrumental Variable Estimates of the effects of the other charge events on House Prices.

	(1) 5km	(2) 4km	(3) 3km	(4) 2km	(5) 1km
ln(Traffic) - CCZ2005	1.0346	0.8295	0.8717	0.4566	0.3011
	(1.9257)	(1.4882)	(1.4130)	(1.3271)	(0.5769)
Obs	50,626	42,321	33,276	22,750	13,407
No.of Postcodes	12,191	10,518	8533	6128	3679
1st Stage F-Statistics	0.52	0.73	0.93	0.88	5.31
ln(Traffic) - CCZ2011	-10.8123	3.7096	3.4231	-41.0373	1.4461
	(143.7717)	(19.4608)	(16.3366)	(2409.9357)	(1.9357)
Obs	42,792	36,482	29,112	20,606	12,320
No.of Postcodes	12,850	11,263	9254	6849	4127
1st Stage F-Statistics	0.01	0.04	0.05	0.00	0.93
ln(Traffic) - RemWEZ	3.1633	4.8209	3.9652	1.6007	-248.7434
	(3.3987)	(7.8583)	(6.5295)	(1.1732)	(21855.6051)
Obs	33,745	28,663	22,451	15,611	8820
No.of Postcodes	6774	5677	4397	3153	1815
1st Stage F-Statistics	1.09	0.41	0.43	3.90	0.00
ln(Traffic) - CCZ2014	10.0097	11.7437	25.2298	24.8331	12.8195
	(10.3902)	(14.3888)	(65.4794)	(66.4986)	(14.7900)
Obs	18,530	14,694	11,278	7748	4872
No.of Postcodes	8285	6944	5411	3621	2134
1st Stage F-Statistics	1.88	1.24	0.19	0.18	1.78

Each coefficient is the IV estimate (β_{IV}) from a different regression that measures the direct elasticity between traffic volume and house prices using the different CC events as instruments that include 1) the increase in the charge from £5 to £8 in 2005 ($CCZ2005$), (2) the increase in the charge from £8 to £10 in 2011 ($CCZ2011$) (3) the removal of the WEZ in 2010 ($RemWEZ$) and (4) the increase in the charge from £10 to £11.50 in 2014 ($CCZ2014$). Dependent variable is the natural logarithm of transacted house prices. Sample is constrained to properties within 5 kilometres (Column 1) to 1 km (Column 5) from the CCZ/WEZ boundary. All regressions are estimated with postcode and year quarter fixed effects. Other control variables include housing characteristics (leasehold, newbuild and terrace dummies), neighbourhood characteristics by-year (% of residents with no education qualifications, % of residents with minority races, unemployment rate and % of lone parent households) and location characteristics by-year (River Thames view dummy, counts of heritage buildings within 200m, distance of the property from nearest park and from the LCC boundary). For more information on the variables, refer to Table A.1 in Data Appendix. Robust standard errors (in parenthesis) are clustered at Output Area (OA). * p<0.10, ** p<0.05, ***p<0.01.

Table A.9
Effect of the LCC on house prices & traffic flow within 1000m from the charge boundary with Conley Spatial HAC standard errors reported.

	(1) OA	(2) 100m	(3) 500m	(4) 1000m	(5) 1500m	(6) 2000m
Panel A: First Stage (Log Traffic)						
LCC)	-0.0626***	-0.0626***	-0.0626***	-0.0626***	-0.0626***	-0.0626***
	(0.0183)	(0.0048)	(0.0068)	(0.0080)	(0.0087)	(0.0089)
Obs	0.98	0.01	0.01	0.01	0.01	0.01
Panel B: Reduced Form (Log House Price)						
LCC)	0.0329***	0.0329***	0.0329***	0.0329***	0.0329***	0.0329***
	(0.0107)	(0.0077)	(0.0079)	(0.0079)	(0.0080)	(0.0080)
Obs	53,490	53,490	53,490	53,490	53,490	53,490
R2	0.75	0.09	0.09	0.09	0.09	0.09

Dependent variable is the logarithm of annual average daily traffic volume for vehicles with 4 wheels or more for Panel A and the logarithm of transacted house prices for Panel B. Sample is constrained to properties within 1000m from the LCC boundary. All regressions are estimated with postcode and year quarter fixed effects. Other control variables include housing characteristics (leasehold, newbuild and terrace dummies). For more information on the variables, refer to Table A.1 in Data Appendix. Robust standard errors clustered at Output Area (OA) is reported in column 1. From Column 2 to 6, I report Conley Spatial HAC using different distance bandwidths, from 100m (column 2) to 2000m (column 6). I also allow these standard errors to be serially correlated for sales made within 1 year from one another. * p<0.10, ** p<0.05, *** p<0.01.

Table A.10
Reduced form estimates of the Congestion Charge Effect on House Prices across Major and Minor Roads.

	(1) 1000m	(2) 900m	(3) 800m	(4) 700m	(5) 600m	(6) 500m
LCC(Major Roads)	0.0367**	0.0403**	0.0423**	0.0373*	0.0278	0.0163
	(0.0169)	(0.0178)	(0.0189)	(0.0206)	(0.0215)	(0.0229)
LCC(Minor Roads)	0.0249**	0.0277**	0.0348***	0.0344***	0.0342**	0.0312**
	(0.0109)	(0.0112)	(0.0121)	(0.0128)	(0.0140)	(0.0149)
Obs	53,982	50,102	45,552	41,126	36,074	31,939
R2	0.76	0.75	0.75	0.75	0.75	0.75
Mean HP	654,362	653,841	652,936	651,441	650,224	648,940

Dependent variable is the natural logarithm of the transacted property prices. Each coefficient is from a different regression. Sample is constrained to sales within 1000m (Column 1) to 500m (Column 6). $LCC(MajorRoads)$ is a binary variable equals to one for properties that are inside the CCZ or WEZ after the LCC is introduced and the closest road is a A road. $LCC(MinorRoads)$ is a binary variable equals to one for properties that are inside the CCZ or WEZ after the LCC is introduced and the closest road is a B or unclassified road. All regressions are estimated with postcode and year quarter fixed effects. Other control variables include housing characteristics (leasehold, newbuild and terrace dummies), neighbourhood characteristics by-year (% of residents with no education qualifications, % of residents with minority races, unemployment rate and % of lone parent households) and location characteristics by-year (River Thames view dummy, counts of heritage buildings within 200m, distance of the property from nearest park, and distance from the LCC boundary and its second polynomial). For more information on the variables included, refer to Table A.1 in Data Appendix. Robust standard errors clustered at Output Area (OA) are reported in parenthesis.* $p<0.10$, ** $p<0.05$, *** $p<0.01$.

CRediT authorship contribution statement

Cheng Keat Tang: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Visualization.

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