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Impact of London Toxicity Charge and Ultra Low Emission Zone on NO_2

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1. Introduction

As a consequence of the increasing importance of agglomeration economies, the concentration of the population in large cities is an ongoing phenomenon. This is not without problems, including high housing prices, pressure on the provision of public goods, higher transportation costs, traffic congestion, pollution and other environmental issues (Glaeser, 2010). Of the latter, poor air quality shortens many lives each year. For instance, about two million people, including 400,000 children, live in London areas that exceed legal limits of air pollution, causing thousands of premature deaths each year (Greater London Authority, 2020a).

In response to growing concerns about air pollution and its consequences on human health and the environment, low emission zones (LEZ) are turning out to be a common strategy in many large and medium-sized cities. However, the initial rationale for adopting traffic restriction measures was more oriented toward combating high levels of traffic congestion in large cities, reducing travel times and increasing traffic speed. This was the case for congestion charges, that is, compulsory payments that impose an almost universal levy on vehicles entering a particular area, during high-demand periods, without discrimination against vehicles based on their exhaust emissions. The first congestion charge was the Singapore Area Licensing Scheme (ALS), implemented in 1975 (Khan, 2001). Many cities around the world have gradually followed and introduced pricing schemes with different characteristics, such as Stockholm (Hensher and Li, 2013) or Gothenburg (Börjesson and Kristofersson, 2015), in Sweden or Durham (Blythe, 2004), in UK. It was not until 2003 that London introduced a congestion charge for driving in the central area (Green et al., 2020). Although different pricing schemes seem to have been effective in changing drivers' behaviour, other specific effects vary depending on the design of the scheme (Ubbels and De Jong, 2009).

However, the persistence of high levels of pollution in many cities has led to the development of policies more focused on environmental problems related to urban traffic (Font et al., 2019). This usually involves taking vehicle emission levels into account when setting the entrance fee or driving rights, generating an incentive to prevent polluting cars from entering the city center, but also to replace older vehicles for more environmentally friendly ones (Peters et al., 2021).

In the European case, the EU has passed binding legislation[1] aimed at achieving air quality levels that limit negative impacts on human health and the environment. These directives still affect the UK as they were transposed into UK legislation via the Air Quality Standards Regulations 2010. The effects of these traffic policies have been analysed not only by economists but also by environmental engineers, meteorologists and medical professionals, finding significant reductions of pollution concentrations associated to LEZ implementations in Berlin (Wolff, 2014), Amsterdam (Panteliadis et al., 2014), London (Carslaw et al., 2016), Paris (Poulhès and Proulhac, 2021), Oslo (Sousa Santos et al., 2020) or Madrid (Salas et al., 2021). An analysis of several German cities by Gehrsitz (2017) concludes that the size of reductions in pollutant concentrations is substantially larger in the more restrictive LEZs. Therefore, the design of the LEZ has been shown to largely determine its effectiveness in reducing pollution.

Although the quality-of-life benefits associated with reducing emissions are clear, they are achieved at a cost. These costs are related to the means by which the reduction of pollution is pursued. In the case of a restrictive traffic policy, we may face undesired fleet turnover or negative economic impacts on small- and medium-sized businesses in the city centre.

The aim of this paper is to analyse the case of London, where local authorities have adopted, in recent years, two consecutive traffic policies with the aim of reducing air pollution levels: (1) the Toxicity Charge that was adopted on October 23, 2017; and (2) the Ultra Low Emission Zone (ULEZ) implemented on April 8, 2019. These restrictions were imposed in addition to the existing 2003 London Congestion

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[1] Directive 2008/50/EC on ambient air quality and cleaner air for Europe and Directive 2004/107/EC relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air.

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Charge and the 2008 Low Emission Zone. Moreover, since the ULEZ extended the payment scheme to weekends, we also analyse the differential impact of these two policies during weekdays, Saturdays and Sundays. Finally, the large number of air quality stations in our dataset allows us to check whether the impact of these two policies was different at roadside and background stations.

Net revenues of these policies were intended to fund London's public transport system, managed by the local government body Transport for London (TfL). Complicating the situation, the COVID-19 pandemic prevented people from using public buses and subway, prompting a drop in fares and advertisement revenues that led to two UK government bailouts of TfL, at a cost of £3.3 billion. Since October 2021, the ULEZ was extended to cover the area bounded by the South Circular Road (A205) and the North Circular Road (A406). Currently, the Mayor of London is planning to expand the ULEZ London-wide in 2023. This ongoing debate makes it particularly relevant to assess the effectiveness of traffic policies currently in force, as this can provide guidance on whether these policies should be continued, modified, or eliminated.

The paper is structured as follows. In Section 2, we review London's recent traffic restrictive policies. The data are described in Section 3. Section 4 presents the empirical specification, and, in Section 5, the results are discussed. Finally, in Section 6, some policy implications of the analysis are drawn.

2. London traffic policies through time

London's first traffic restrictive policy, the Congestion Charge, was introduced in 2003. It was a £5 daily charge to enter the Congestion Charge Zone (CCZ), in Central London, from 7:00 a.m. to 6:30 p.m. (on February 19, 2007 was shortened to 6:00 p.m.), Monday to Friday. It affected commercial and private vehicles entering the CCZ during the charging hours with the exemption of motorcycles, bicycles, buses and taxis. London's Congestion Charge has been in operation with minor changes to the area of application, although the daily fee increased to £8 in 2005, £10 in 2011 and £11.50 in 2014. After the suspension of all road-user charges due to the COVID-19 outbreak, in June 2020, the level of the charge was set at £15 and it applies between 7:00 a.m. to 10:00 p.m., seven days a week, except Christmas Day.[2] Following the introduction of the charge, the overall traffic volume decreased, while bus travel and taxi flows increased by more than 20 percent (Santos, 2008). Moreover, safety increased up to 1.5 km off the CCZ zone (Ding et al., 2021) and a positive effect on adoption of hybrid electric vehicles (HEV) was observed (Morton et al., 2017).

Although it was not specifically oriented towards reducing pollution, emissions were likely reduced by lowering traffic flows. However, assessments of the potential impact of the London's Congestion Charge on air quality were inconclusive. Considering the only roadside station within the charging zone, Atkinson et al. (2009) did not find any significant effect of the introduction of the Congestion Charge on pollutants. When focusing on background stations, they found some evidence of reductions in several pollutants but increases in NO_2. In a more recent study, Green et al. (2020) found that the Congestion Charge led to less congestion and significant reductions in several pollutants. However, NO_2 emissions increased due to higher demand for buses and taxis, which were mainly diesel-based. This highlights the importance of setting payment schedules based on emission levels to achieve air quality improvements through traffic policies, which most of the first congestion charges did not consider. A timeline of the traffic policies implemented in London during the period of analysis is shown in Fig. 1.

In view of the continuing high levels of pollution in London, and to meet EU and UK standards for air quality in urban areas, a Low Emission Zone was introduced in phases from February 2008 (Transport for London, 2017). This LEZ covered Greater London and operated 24 h a day, every day of the year, including weekends and public holidays, but only affected heavy diesel vehicles and large vans, buses and coaches. These large vehicles needed to meet emission standards or pay a daily charge to enter the area.

Again, the effectiveness of the London LEZ on pollutant concentrations was inconclusive. Ellison et al. (2013) did not find significant changes in NOx concentrations, whereas Carslaw et al. (2016) concluded that NO_2 concentrations fell, but only after 2010. Font et al. (2019) also found a decrease of around 5 percent per year from 2010, but only after a period of increase in roadside NO_2 levels between 2005 and 2009. Additionally, Mudway et al. (2019) identified reductions in NO_2 and NOx concentrations at background and roadside stations associated with the London LEZ, but the effect on other pollutants was ambiguous. These mixed results may be due to the different methodologies applied. Also, a plausible explanation for the low effect of the LEZ on pollutant concentrations may be the fact that, although the policy discriminated by emission levels, the number of vehicles affected was limited, since it targeted large commercial vehicles (and not private cars and motorcycles).

While air quality has improved across the UK, and London currently complies with the legal limits set by the national Air Quality Regulations for most pollutants, large areas of London city, as well as many areas across UK (Defra, 2020), continue to exceed legal limits for NO_2 levels (Transport for London, 2017). The London Environment Strategy launched by the Mayor of London in 2017 introduced a variety of measures to lower emissions from road traffic, reducing the number of vehicles and cleaning up the fleet (Greater London Authority, 2020a, 2020b).

In October 2017, the Toxicity Charge was launched in addition to the Congestion Charge. Cars and vans driving in the CCZ between 7:00 a.m. and 6:00 p.m. on weekdays that do not meet Euro 4 standards[3] must pay an extra daily charge £10 in addition to the Congestion Charge, bumping up the cost to £21.50 for those affected. Private Hire Vehicles (PHVs) exemptions applied.

This charge was replaced by the ULEZ on April 8, 2019. According to the reports by Transport for London (2017) most vehicles (cars, motorcycles, vans, minibuses, buses, coaches and HGVs) have to satisfy tighter emission standards (Euro 6 standards were required for diesel cars and vans) or pay a daily charge when entering Central London. The ULEZ covers the same area as the Congestion Charge Zone and operates 24 h a day, all days, including weekends and public holidays.[4] ULEZ's daily charge is in addition to any applicable Low Emission Zone charges or Congestion Charge, with fees of £12.50 per day for non-compliant cars, vans and motorcycles, and £100 per day for non-compliant lorries and buses. PHVs exemptions were removed.[5]

Despite the relevance of the Toxicity Charge and the ULEZ, as far as we are aware there is no empirical evidence on their effectiveness in terms of air quality. The objective of this paper is to assess the effectiveness of these policies in reducing NO_2 levels in London. This is an especially relevant research question as NO_2 levels remain the most important factor affecting air quality in London (Transport for London, 2017). Moreover, given that the ULEZ tightened the conditions for access to the city centre in comparison to the Toxicity Charge, this analysis makes it possible to assess the differential impact of these two policies.

[2] Both the Toxicity Charge and the ULEZ did not revoke the Congestion Charge, that was in effect for the entire analysis period. Therefore, the Congestion Charge is a benchmark of our analysis.

[3] Plus Euro IV for lorries and buses and Euro 3 for motorcycles.

[4] Because the ULEZ scheme covers the same zone, we use the CCZ acronym throughout the document to denote the geographic zone instead of using ULEZ in order to differentiate it from the ULEZ policy.

[5] Moreover, from January 1, 2020, all (petrol or diesel) PHVs must comply with the Euro 6 standards.

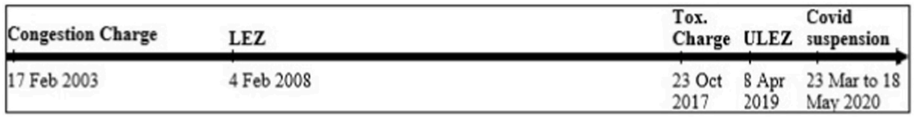

Fig. 1. Summary of main regulatory changes.

3. Data

To carry out the analysis, we use daily NO_2 levels data collected from the London Air Quality Network (LAQN) and from the Automatic Urban and Rural Network (AURN) belonging to the Air Quality England Network. The period of analysis goes from January 1, 2015 to February 29, 2020, and is therefore long enough to also cover the pre-policy period.

We decide to end the sampling period at the end of February 2020 so as not to use data affected by COVID-19 that may bias the results, overestimating the real impact of the ULEZ (Betancourt-Odio et al., 2021). According to the Google (2020) COVID-19 Community Mobility Report, the pandemic had a large impact on economic activity and mobility since the beginning of March in London, and especially so after the national lockdown in Britain that started on March 23. Moreover, all road charging schemes, including the ULEZ and Congestion Charge, were suspended from March 23 to May 18, 2020. Stations with data that start less than one year before the implementation of the Congestion Tax or with less than two-thirds of observations in at least one of the three subperiods (pre–Toxicity Charge, Toxicity Charge application period and ULEZ period) were discarded from the sample.

Fig. 2 shows a map of Greater London with the area covered by the CCZ and the area within the South and North Circular Roads. The central area is the CCZ, which is about 21 square kilometres, with an estimated population of around 209,000 people and five times as many people employed in this area. The figure also shows the monitoring stations considered, the weather reference grid points (drawn as square symbols) and the boroughs' boundaries.[6]

The core stations of our analysis are those within the CCZ or on the boundary. They include five roadside monitoring stations: Beech Street (CT4), Walbrook Wharf (CT6), Strand (NB1), Hackney-Old Street (HK6) and Euston Road (CD9); and four background stations: Camden–-Bloomsbury at Russell Square (BL0), Sir John Cass School (CT3), Horseferry Road (WM0) and Elephant and Castle (SK6). Additionally, we consider three consecutive station "belts". Stations in the area between the South and North Circular Roads outside the CCZ are divided into two groups. The first belt (Belt 1) includes the monitoring stations within 3.5 km of the CCZ boundary, while the second belt (Belt 2) comprises stations that are further away but within or on the circular roads. The third belt (Belt 3) includes stations outside the North and South Circular Roads but less than 3.5 km away from these roads. The remaining 16 stations are located outside the Circular Roads but within Greater London. These stations, located in the outer boroughs of Hillingdon, Harrow, Enfield, Havering, Bexley, Croydon and Kingston upon Thames are far enough away from the CCZ so they should not be influenced by the policy and constitute our reference control group (hereafter Control Stations).

Fig. 3 displays the evolution of the yearly moving average of NO_2 concentrations for the air quality monitoring stations within the CCZ and the three groups of stations farthest away (Belt 2, Belt 3 and Control Stations). Average daily levels are computed for those stations reporting at least 18 h NO_2 levels a day. When computing annual moving averages, we control for seasonal variations as each point in Fig. 3 includes the information for a whole year. The vertical lines indicate the dates when the Toxicity Charge, first, and then the ULEZ entered into force.

The average levels of concentrations are higher as we move closer to the centre, with a sharp increase for the CCZ stations, whose levels are consistently above the legal thresholds. Although there are some between-group differences with respect to the trend of NO_2 concentrations, it seems that they followed a parallel evolution until the Toxicity Charge was implemented. However, the application of the Toxicity Charge led to a departure of NO_2 levels from the trend in the case of stations within the CCZ. Control Stations present the lowest NO_2 emission levels (although these levels are very close to those of the Belt 3 stations throughout the period), with no apparent changes after the application of the Toxicity Charge or the ULEZ. Therefore, we believe that stations outside the South and North Circular Roads can be included in the empirical specification as control stations.

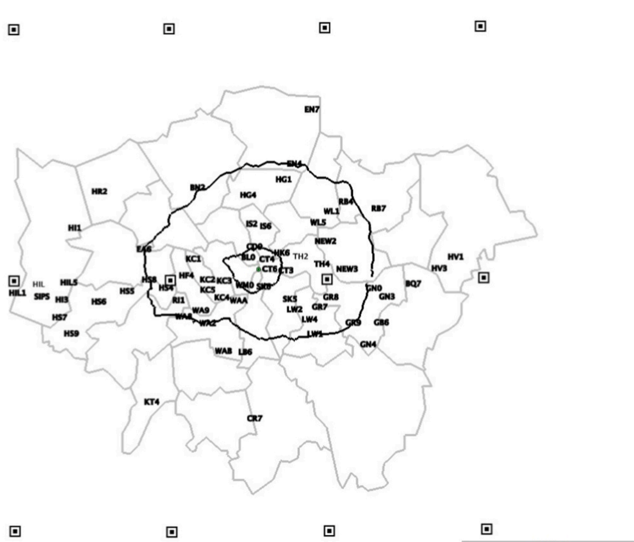

Fig. 2. Greater London.
Note: The squares in Fig. 2 represent London nodes of ERA5 gridded dataset.

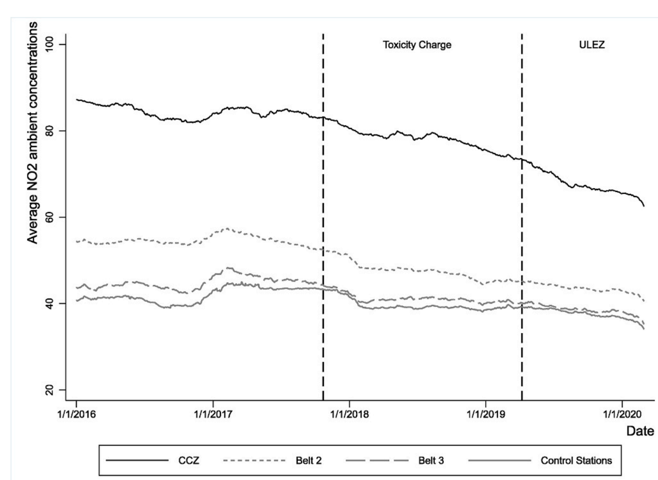

Fig. 3. Moving average of daily NO_2 concentrations by groups of stations.

[6] The stations included in Fig. 2 are listed in Table A2 in the Appendix.

A first insight of the magnitude of the effect of these policies on NO_2 levels in Central London can be observed in Table 1, which reports the average NO_2 before and after the implementation of the Toxicity Charge and the ULEZ by London areas. It also includes the change after the Toxicity Charge (Column 2) and the ULEZ (Column 5) relative to the period prior to the implementation of both policies (Column 1). Finally, by deducting the variation in the Control Stations, we obtain an assessment of the Diff-in-Diff estimator of these traffic policies. In doing so, it is assumed that variations in Control Stations are not linked to either of these two policies and would have been observed in all stations if the policies had not been implemented.

A larger drop in NO_2 levels associated with both policies can be observed as we approach Central London. Additionally, the more restrictive the policies, the larger the subsequent drop, especially as we get closer to the CCZ. These figures can be considered as a first approximation of the real impact on NO_2 levels of the Toxicity Charge and the ULEZ. However, they do not account for other external factors, such as meteorology, that might impact vehicle usage during this period. In what follows, we will include these controls into the analysis.

4. Methods

We estimate Diff-in-Diff models to compare the variation in NO_2 levels within the London CCZ (treatment group) relative to the change in NO_2 levels elsewhere, after the implementation of the Toxicity Charge, first, and ULEZ afterwards.

As discussed above, prior to the implementation of the Toxicity Charge, the monitoring stations within CCZ followed a similar trend to the Belt 3 and Control Stations. However, both traffic policies led to a deviation of the CCZ sites from the pattern of the Belt 3 and Control Stations. Therefore, the parallel trend assumption, which is key to identify the policy effect in Diff-and-Diff models, seems to be satisfied. The empirical model can be written as[7]:

$$NO_{2st} = \alpha + \beta\, CCZ_s + \gamma\, POST\ TC_t + \delta(CCZ * POST\ TC)_{st} + \zeta POST\ ULEZ_t + \lambda(CCZ * POST\ ULEZ)_{st} + \varphi MET_{st} + \varepsilon_{st} \tag{1}$$

where NO_{2st} stands for the daily NO_2 values measured by the air quality station *s* at time *t*; CCZ is a dummy variable which distinguishes stations located in this area; POST TC is a dummy variable which identifies observations during the implementation of the Toxicity Charge; the coefficient on the interaction term between London CCZ and POST TC, δ, is the estimate of the effect of the introduction of the Toxicity Charge on NO_2 levels at the monitoring stations within the London CCZ. Similarly, POST ULEZ is a dummy variable denoting observations during the application period of the ULEZ, and λ, the interaction coefficient between CCZ and POST ULEZ, is the Diff-in-Diff estimator of the effect of the introduction of the ULEZ on NO_2 levels in the stations within the CCZ. If the standard assumptions of the Diff-in-Diff estimators are satisfied, δ and λ can be seen as the causal effects of these policies on the NO_2 levels in the CCZ area, compared to the period previous to the implementation of any of these two policies, i.e., while only the Congestion Charge was in place.

Since weather conditions have been found to be relevant for estimating NO_2 levels (e.g., Salas et al., 2021), we include MET_{st}, which is a vector of daily air-quality-station-variant weather variables. It includes daily temperature, daily wind conditions, geopotential height, precipitation and relative humidity. To assign station specific values to the weather variables, a weight equal to the inverse of the square distance from each air quality station to the ERA5 dataset gridded nodes in London area was used. The ERA5 dataset is produced by the ECMWF (Hersbach et al., 2020) and provides hourly estimates of several meteorological variables, including the ones used in our analysis. They were drawn on an hourly basis for the 2015–2020 period, on a gridded 0.25° × 0.25° spatial resolution, for an area spanning London. The closest ERA5 nodes to London are represented by the square symbols in Fig. 2. Since weather variables vary among stations, this helps to avoid the irrelevance of covariates problem.

As commonly done (see, for instance, Borge et al. 2019), to capture non-linearities of pressure, precipitation and humidity data, we use a quadratic functional form of these variables. Finally, the main components of the daily wind were included together with the intensity of the wind.

Additionally, we introduce a set of dummy variables to indicate whether a given day is a non-labour day, like a Saturday, Sunday or a holiday or Christmas. In order to capture any long-run trend that may influence NO_2 levels, such as an increased use of more efficient vehicles, we include year and month fixed effects, as in Foster et al. (2009). Finally, ε_{st} is the error term assumed to have zero mean, conditional on the air quality station and time period.

The effect of traffic policies is likely to go beyond their target areas. Citizens may change their transportation habits, cutting pollution levels also in the LEZ surrounding areas (Salas et al., 2021) and may improve the health of those people living outside the implementation area but that move to the city centre for work, shopping or leisure (Poulhès and Proulhac, 2021). Alternatively, limiting the access of polluting vehicles to the city centre may result in the diversion of these vehicles to other zones, increasing air pollution there. For instance, de Bok et al. (2020) found that, for the Netherlands, kilometres travelled by delivery vehicles outside traffic restricted areas would increase. In either case, the "stable unit treatment value" assumption will not be satisfied (Clarke, 2017) since the implementation of the Toxicity Charge and the ULEZ might have generated externalities in the areas close to the CCZ.

To evaluate these potential *spillover* effects, we allow for different "treatment" units in the analysis. Thus, in the estimated model, we explicitly include four dummies to identify different areas: stations within the CCZ and three consecutive "belts" of monitoring stations. The area between the CCZ and the South and North Circular Roads includes Belt 1 (stations closer to the CCZ limit) and Belt 2 (stations further away but within or on the circular roads). Belt 3 includes stations outside the North and South Circular Roads but less than 3.5 km away from these roads. The remaining "control" stations are located off the South and North Circular roads and far enough from the CCZ to be affected by the Toxicity Charge or the ULEZ. Area dummies are interacted with the POST TC and POST ULEZ variables.

5. Results

Given the different underlying natures of the monitoring stations, and in line with the report by the Greater London Authority (2020b), all the empirical analysis was run separately for roadside and background stations. First, we estimate the overall effects of the Toxicity Charge and the ULEZ. Since the ULEZ extended the restrictions of Toxicity Charge beyond working days, we also analyse the differential effects by type of day.

5.1. Estimated effects of the Toxicity Charge and the ULEZ

As described by the Greater London Authority (2018), roadside stations are located within 1–5 m of a busy road and background sites are at least 50 m away from any large single pollution source, and more than 30 m from busy roads. Therefore, these two types of monitoring stations are designed to capture different degrees of public exposure to traffic pollutants. In fact, our data show that NO_2 levels are always higher for roadside sites, regardless of the area where they are located, but the relative difference decreases as we move away from the CCZ.

To interpret the results, it should be recalled that the Toxicity Charge

[7] In Table A1 in the Appendix, definitions and summary statistics of the variables are shown.

Table 1
Average NO_2 levels in μg/m^3.

	(1) Before 23rd Oct17	(2) Toxicity Charge	(3) DIF TC (2)–(1)	(4) DID TC	(5) ULEZ	(6) DIF ULEZ (5)–(1)	(7) DID ULEZ
CCZ	70.917	60.690	−10.227	−10.183	49.006	−21.911	−16.118
Belt 1	53.855	47.698	−6.157	−6.112	37.206	−16.649	−10.856
Belt 2	49.045	43.287	−5.758	−5.713	36.879	−12.166	−6.374
Belt 3	43.185	41.971	−1.214	−1.170	35.237	−7.948	−2.155
Control	39.183	39.139	−0.045	–	33.390	−5.793	–

and the ULEZ cover the same area (the CCZ), but that the ULEZ policy intensified the requirements adopted with the implementation of the Toxicity Charge: the fee for non-compliant vehicles was increased; operation hours were extended, weekends were included; emission standards were tightened and PHVs exemptions were removed. Table 2 displays the results separately for roadside and background monitor stations.

The way the model is specified, the coefficients of the implementation of the ULEZ do not assess the effect of the greater intensity of this policy in relation to the Toxicity Charge, rather the change relative to the period prior to both policies. Columns (1) and (3) exhibit the roadside and background OLS estimators, while columns (2) and (4) present the fixed effects estimations, again, for roadside and background stations, respectively. As expected, the inclusion of station fixed effects, capturing all time-invariant characteristics of the monitoring sites, considerably increases the explanatory power of the models. In any case, the inclusion of station fixed effects does not affect the coefficients of interest, namely those capturing the effects of the traffic policies.

With respect to weather variables, relative humidity is inversely related to NO_2 levels, though the quadratic term is not significant. This estimated parabolic effect is more pronounced in background stations, signalling a strong negative link between relative humidity and NO_2. Precipitation shows a nonlinear effect. During rainy days we tend to observe lower levels of emissions, but there is a certain degree of saturation of this effect, especially for very rainy days (as in Zhao et al., 2019). Regarding geopotential height, the estimated coefficients show that the lower the pressure levels, the higher the expected levels of NO_2, though at a decreasing rate. As expected, all components of wind intensity exhibit a significant negative impact on NO_2 levels (Zhang et al., 2015; Zhao et al., 2019). As in Salas et al. (2021), once temperature at 1000 hPa is controlled for, we estimate a negative effect of temperature on NO_2 levels, but as temperature at 1000 hPa increases, so do the expected levels of NO_2. Not surprisingly, Christmas, bank holidays and weekends, especially Sundays, are associated to lower levels of NO_2, being these measured effects smaller at background stations.

Finally, and most importantly, the estimated effects of the traffic policies show that both the Toxicity Charge and the ULEZ have had a positive and significant effect on reducing NO_2 levels within the CCZ. Furthermore, since background stations are located at least 30 m from busy roads, we find smaller reductions in their measurements of NO_2 levels. On the one hand, the Toxicity Charge is responsible for an 8.2 μg/m^3 reduction of NO_2 concentrations in the roadside stations within the CCZ, according to column (2). This drop represents a 10.5 percent reduction from the initial average NO_2 levels at roadside CCZ stations. On the other hand, ULEZ's policy has had a larger effect on pollution, with an estimated reduction of 14.9 μg/m^3 (19 percent) compared to the pre-Toxicity Charge situation, which is almost twice the reduction caused by the Toxicity Charge. These are our Diff-In-Diff estimators, which represent the evolution in NO_2 had the policy not been implemented. These estimations are somewhat lower than the equivalent ones stated by the Greater London Authority (2020b, page 16), which reports 20 μg/m^3 drops or higher for central London roadside sites following the implementation of the ULEZ.

Additionally, our results are consistent with the existence of positive *spillover* effects, since roadside stations that are outside but close to the CCZ experienced significant drops in NO_2 levels after the entering into force of these two policies. However, these reductions were of lesser magnitude than those inside the CCZ. In particular, the Toxicity Charge led to a reduction of 5.76 μg/m^3 (10.4 percent) at Belt 1 stations and of 4.78 μg/m^3 (9.7 percent) at Belt 2 stations, though it had no significant effects on Belt 3. The ULEZ, as expected, had a greater impact, with estimated reductions of 10.9 μg/m^3 (19.8 percent) at Belt 1 stations and of 5.54 μg/m^3 (11.2 percent) at Belt 2 stations. As with the Toxicity Charge, there was no significant effect at Belt 3 stations. Compared to the figures from the Greater London Authority report (2020b, page 16), our estimates of the *spillover* effects are larger for the inner London roadside sites, that is, within North and South Circular Roads (or our first and second belts). Discrepancies between Greater London Authority's results and ours stress the importance of controlling for other variables that may affect NO_2 levels in order not to obtain biased estimates.

Regarding background stations, as shown in Columns (3) and (4), the implementation of the Toxicity Charge is associated with a 5.68 μg/m^3 reduction of NO_2 concentrations within the CCZ. That represents a 15.6 percent reduction with respect to the previous period. In turn, the ULEZ policy is responsible for a reduction of 7.03 μg/m^3 (19.3 percent). Therefore, application of the ULEZ resulted in a mere estimated additional drop of 1.35 μg/m^3 in the NO_2 levels of the background stations, while it led to a reduction for roadside stations that doubled that of the Toxicity Charge. Finally, *spillover effects* are also observed in background stations, but only in the sites closest to the CCZ. The Toxicity Charge led to a reduction, at the 10 percent level of significance, of 2.91 μg/m^3 (9.7 percent) at Belt 1 stations but had no significant effect at the other belts stations. Similarly, the ULEZ had significant effects only at Belt 1 stations, with an estimated reduction of 4.2 μg/m^3 (14 percent).

5.2. Differential effects by day type

As the implementation of the ULEZ implied not only higher rates charged to vehicles that enter the CCZ area but also its extension to Saturdays and Sundays, we analyse the differential effect of the Toxicity Charge and the ULEZ on weekdays, Saturdays and Sundays. Table 3 reports average NO_2 levels by type of day. Average NO_2 levels, both for roadside and background stations, are highest on weekdays in all areas considered. On the whole, the Toxicity Charge had a lower impact on NO_2 levels than the ULEZ for inner London roadside and background stations regardless of the day. This is the expected result as the ULEZ intensified the conditions of the Toxicity Charge.

Given that roadside sites measure the direct impact of traffic on emissions and the fact that there was no change in the incentives to adjust transport habits on weekends due to the Toxicity Charge, we would expect a lower impact on Saturday and Sunday NO_2 levels associated to this policy. In fact, the NO_2 reduction on Saturdays and Sundays was less than 40 percent of the reduction during the weekdays at CCZ roadside stations. However, the Toxicity Charge had different effects at background stations. The drop observed at the CCZ background stations in NO_2 levels on Saturdays is similar to that on weekdays. Since the background sites are not designed to assess emissions directly related to any pollutant source, including traffic, it is plausible that reductions in (polluting) traffic flows during the preceding weekdays might reduce

Table 2
Diff-in-Diff models.

	(1) OLS-Roadside	(2) FE-Roadside	(3) OLS-Background	(4) FE-Background
CCZ Stations	42.62***	–	4.701	–
	[5.94]	–	[1.26]	–
Belt 1	19.26**	–	−3.364	–
	[3.37]	–	[-0.92]	–
Belt 2	12.02*	–	0.585	–
	[2.41]	–	[0.13]	–
Belt 3	2.443	–	−5.521	–
	[0.66]	–	[-1.40]	–
Post TC*CCZ	−7.912***	−8.191***	−5.282**	−5.683**
	[-3.76]	[-3.61]	[-3.01]	[-3.49]
Post TC*Belt 1	−5.935**	−5.756**	−2.427	−2.908
	[-3.21]	[-3.33]	[-1.40]	[-1.81]
Post TC*Belt 2	−5.445*	−4.781*	−3.931	−4.138
	[-2.31]	[-2.14]	[-1.42]	[-1.67]
Post TC*Belt 3	−1.332	−1.300	1.631	1.105
	[-0.85]	[-0.84]	[0.82]	[0.60]
Post ULEZ*CCZ	−14.53***	−14.94***	−6.941**	−7.025**
	[-4.81]	[-4.74]	[-3.60]	[-3.70]
Post ULEZ*Belt 1	−12.54***	−10.91**	−4.077*	−4.225*
	[-3.81]	[-3.51]	[-2.27]	[-2.38]
Post ULEZ*Belt 2	−5.532*	−5.536*	−4.130	−4.348
	[-2.34]	[-2.32]	[-1.35]	[-1.46]
Post ULEZ*Belt 3	−1.184	−1.074	0.866	0.745
	[-0.57]	[-0.52]	[0.43]	[0.39]
Precipitation	−0.217***	−0.150**	−0.282***	−0.286***
	[-4.00]	[-3.48]	[-4.77]	[-5.74]
Precipitation^2	0.009***	0.008***	0.0113***	0.0126***
	[4.72]	[4.84]	[4.06]	[5.46]
Geopot. height	0.002***	0.002***	0.00176***	0.00184***
	[9.51]	[9.36]	[9.73]	[10.39]
Geopot. height^2	-4e-08***	-3e-08***	−3.78e-08***	−3.8e-08***
	[-10.18]	[-10.46]	[-9.07]	[-9.62]
Humidity	−0.250***	−0.162*	−0.439***	−0.401***
	[-4.20]	[-2.66]	[-5.90]	[-6.03]
Humidity^2	0.0002	−0.001	0.00220***	0.00188***
	[0.40]	[-1.34]	[4.20]	[4.16]
Temp at 2 m	−6.053***	−5.489***	−5.918***	−5.748***
	[-20.19]	[-28.63]	[-25.50]	[-32.22]
Temp 1000 hPa	6.113***	5.574***	5.724***	5.550***
	[20.44]	[27.63]	[25.26]	[31.61]
Northeast wind	−5.189***	−5.459***	−4.266***	−4.341***
	[-11.59]	[-11.59]	[-12.70]	[-13.38]
Southeast wind	−5.117***	−5.332***	−3.613***	−3.630***
	[-17.04]	[-16.26]	[-12.90]	[-12.85]
Southwest wind	−5.506***	−5.697***	−4.372***	−4.409***
	[-25.44]	[-26.04]	[-28.58]	[-27.74]
Northwest wind	−5.706***	−6.012***	−4.741***	−4.810***
	[-16.95]	[-19.15]	[-14.75]	[-15.51]
Sunday	−12.65***	−12.62***	−7.879***	−7.865***
	[-15.02]	[-15.03]	[-26.91]	[-26.78]
Saturday	−5.824***	−5.815***	−3.789***	−3.796***
	[-10.91]	[-10.94]	[-18.81]	[-18.80]
Bank holiday	−13.15***	−13.17***	−7.942***	−7.852***
	[-12.50]	[-12.45]	[-21.63]	[-22.76]
Christmas	−8.366***	−8.307***	−5.226***	−5.080***
	[-6.48]	[-6.56]	[-6.74]	[-6.85]
Year-month fixed effects	YES	YES	YES	YES
Station fixed effects	YES	YES	YES	YES
N	74027	74027	46232	46232
R^2	0.514	0.723	0.521	0.679
adj. R^2	0.513	0.722	0.520	0.678
AIC	637392.2	595745.3	359648.6	341136.8
BIC	637769.9	596123.0	359867.1	341355.3

Standard errors in parentheses. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.
Reference category: Air quality stations outside and not close to the North and South Circular Roads.

the levels monitored on Saturdays at these stations. Moreover, the observed reductions on Sundays are about half the size of those on Saturdays, as if this translation effect were attenuated over time.

By introducing traffic restrictions on Saturdays and Sundays, the ULEZ effects were more uniform on weekdays and weekends, as we would expect, and were associated with reductions of around 20 percent compared to the previous NO_2 levels for roadside and background stations within the CCZ.

To extend the analysis, Table 4 reports the Diff-in-Diff estimators of the Toxicity Charge and the ULEZ by day type, including station -fixed effects and time and weather controls. In order not to impose the same functional form for the control variables, separate regressions were

Table 3
Average NO_2 levels in μg/m^3 by day and station types.

	ROADSIDE					BACKGROUND				
	Before Oct 23, 2017	Toxicity Charge	ULEZ	DID TC	DID ULEZ	Before 23th Oct 2017	Toxicity Charge	ULEZ	DID TC	DID ULEZ
Weekdays										
CCZ	90.15	79.51	66.03	−9.34	−15.97	42.01	37.00	30.99	−6.34	−7.68
Belt 1	64.03	56.15	42.66	−6.58	−13.24	33.76	31.63	25.06	−3.45	−5.36
Belt 2	56.48	49.38	42.31	−5.79	−6.02	37.66	34.42	29.35	−4.57	−4.97
Belt 3	46.93	43.65	37.03	−1.98	−1.76	31.90	33.79	28.51	0.57	−0.05
Control st.	43.96	42.65	35.82	–	–	34.88	36.21	31.54	–	–
Saturdays										
CCZ	73.97	71.99	54.80	−3.69	−12.27	34.78	34.09	26.07	−5.39	−7.28
Belt 1	55.53	52.12	37.15	−5.12	−11.49	27.32	29.83	20.98	−2.19	−4.91
Belt 2	49.38	45.00	36.36	−6.10	−6.12	32.14	31.35	25.03	−5.49	−5.68
Belt 3	38.97	39.99	31.47	−0.69	−0.60	25.47	30.75	23.00	0.58	−1.04
Control st.	36.79	38.49	29.89	–	–	28.71	33.41	27.28	–	–
Sundays										
CCZ	64.85	60.54	47.73	−3.62	−11.36	30.89	30.16	23.41	−2.56	−5.60
Belt 1	48.61	45.32	33.70	−2.60	−9.16	25.56	24.59	19.67	−2.80	−4.01
Belt 2	43.50	39.09	33.36	−3.73	−4.39	28.60	26.75	22.92	−3.69	−3.80
Belt 3	34.69	34.55	28.17	0.55	−0.77	23.59	26.20	21.58	0.77	−0.14
Control st.	32.65	31.97	26.90	–	–	26.98	28.82	25.10	–	–

Table 4
Diff-in-Diff models by day type.

	ROADSIDE			BACKGROUND		
	WEEKDAYS	SATURDAY	SUNDAY	WEEKDAYS	SATURDAY	SUNDAY
Post TC*CCZ	−9.874***	−4.183*	−4.029**	−6.291***	−5.675***	−2.670
	[-3.64]	[-2.50]	[-2.94]	[-3.77]	[-4.15]	[-1.48]
Post TC*Belt 1	−6.537***	−4.990**	−2.660	−3.215	−1.974	−2.459
	[-3.66]	[-2.88]	[-1.49]	[-1.97]	[-1.44]	[-1.38]
Post TC*Belt 2	−5.033*	−5.169*	−3.117	−4.210	−4.796*	−3.156
	[-2.16]	[-2.18]	[-1.67]	[-1.65]	[-2.07]	[-1.28]
Post TC*Belt 3	−1.908	−0.355	0.785	1.234	0.583	1.053
	[-1.15]	[-0.24]	[0.56]	[0.65]	[0.40]	[0.53]
Post ULEZ*CCZ	−16.27***	−12.38***	−11.42***	−7.318***	−7.175***	−5.475*
	[-4.48]	[-5.26]	[-4.98]	[-3.91]	[-3.79]	[-2.48]
Post ULEZ*Belt 1	−11.72**	−9.842**	−8.080**	−4.459*	−4.142*	−3.325
	[-3.50]	[-3.44]	[-3.31]	[-2.48]	[-2.43]	[-1.73]
Post ULEZ*Belt 2	−5.793*	−5.708*	−4.091*	−4.445	−4.938	−3.238
	[-2.30]	[-2.26]	[-2.30]	[-1.44]	[-1.68]	[-1.22]
Post ULEZ*Belt 3	−1.481	0.213	−0.265	0.965	−0.205	0.585
	[-0.65]	[0.12]	[-0.16]	[0.50]	[-0.11]	[0.29]
Bank holiday	−13.71***	–	–	−8.477***	–	–
	[-12.95]	–	–	[-23.31]	–	–
Christmas	−7.507***	–	−19.44***	−5.216***	–	−13.58***
	[-5.73]	–	[-10.46]	[-7.62]	–	[-9.46]
Meteorological controls	Yes	Yes	Yes	Yes	Yes	Yes
Year-month fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Stations fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N	52762	10662	10603	32909	6676	6647
R^2	0.727	0.723	0.731	0.690	0.662	0.678
adj. R^2	0.726	0.72	0.728	0.689	0.656	0.673
AIC	426713.4	83958.7	80664.2	242818.8	48458.6	47245.3
BIC	427077.2	84257	80962.2	243028.8	48628.7	47415.3

Standard errors in parentheses. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.
Reference category: Air monitoring stations outside and not close to the Great Circular Road.

estimated for weekdays, Saturdays and Sundays. Additionally, and in line with the previous analysis, roadside and background stations were considered separately. First, the sum of the sample sizes per day type for both roadside and background stations equals the sample size of the aggregate models presented in Table 2.

Second, it is worth noting that the R^2 is very stable within station types and very similar to the values obtained for columns (2) and (4) in Table 2. Third, and as expected, the estimated effects of the Toxicity Charge and the ULEZ on NO_2 levels by areas in Table 2 are averages of those reported by days in Table 4, and are closer in all cases to the weekdays model. Fourth, once controls are taken into account, the estimated coefficients are similar to the descriptive figures in Table 3.

Regarding roadside sites, both the Toxicity Charge and the ULEZ have had a positive impact on reducing NO_2 emissions within the CCZ, but this effect is always more significant for weekdays. Additionally, the ULEZ estimated effects on pollution are much larger than those associated with the Toxicity Charge, as discussed above. Due to the extension of the ULEZ to Saturdays and Sundays, this differential impact is especially pronounced at weekends, with estimated ULEZ effects for CCZ roadside sites that almost triples those of the Toxicity Charge on those days. In any case, the weekend cuts on NO_2 levels linked to the implementation of the Toxicity Charge, though not very large, are still significant. These reductions may be associated with the renewal of the bus fleet just before and during the Toxicity Charge period or the ban on new licenses for diesel taxis from January 1, 2018. They may also be due to the translation from weekdays to weekends of new transport habits induced by the Toxicity Charge. Turning to the ULEZ, which applies 24/7, the roadside site emissions reductions for weekends associated with this policy converge, in relative terms, to those for weekdays. Nevertheless, since average NO_2 levels are lower during the weekends, the estimated reductions in levels are somewhat larger for weekdays.

When the sample is split by days, the positive *spillover* effects at roadside stations associated with the implementation of the Toxicity Charge disappear on Sundays but remain significant for weekdays and Saturdays at inner London sites. Moreover, although the direct Saturday effect on CCZ sites is apparently smaller than the *spillover* effects, the estimated coefficients are not significantly different. In the case of the ULEZ, *spillover* effects are significant within the North and South Circular Roads during the whole week and are larger than those associated with the Toxicity Charge.

Regarding background stations, the Toxicity Charge has no statistically significant effects on Sundays. As background stations are located away from main roads, it seems that any pollution reductions during the previous weekdays associated with the Toxicity Charge do not carry over to Sunday at these sites. In contrast, the drop in NO_2 levels observed at CCZ background stations due to the Toxicity Charge on Saturdays is similar to that of weekdays. This suggests that traffic-related pollution is present at background monitoring stations with a certain delay (WHO Regional Office for Europe, 2013). Finally, in keeping with the result for roadside stations, the ULEZ has a significant impact on the NO_2 levels at CCZ background sites during the whole week, being lower on Sundays. The estimated *spillover* effects associated with the ULEZ are only significant for the closest sites to the CCZ background sites (Belt 1), except for Sundays.

In sum, the weaker *spillover* effects associated with the Toxicity Charge could be considered as empirical evidence in favour of traffic policies applied on a 24/7 basis, as these policies could generate permanent *spillover* effects in nearby areas. These *spillover* effects are lower than the effects on the area where traffic restrictions apply, though they are of the same order of magnitude.

6. Discussion and policy implications

Economies of agglomeration have encouraged the settlement of ever-larger proportions of the population in large cities such as London. However, congestion costs, pollution, mostly linked to traffic, and high transportation costs are also associated with this process. Over recent years, the growing concern about air pollution and traffic congestion has led to the establishment of policies designed to provide incentives against the use of private means of transport, especially polluting ones, by imposing driving restrictions and payment charges in order to be able to drive within certain areas. Sometimes, as in the case of London, these charges were intended to fund public transport and contribute to its improvement. In particular, London local authorities adopted two consecutive traffic policies in the last years of this decade: the Toxicity Charge, introduced on October 23, 2017, and the Ultra Low Emission Zone (ULEZ), introduced on April 8, 2019. They were defined as environmental policies whose main aim was to reduce air pollution rather than alleviate traffic congestion. As such, they discriminate among vehicles according to their exhaust emissions. Both traffic policies were imposed in addition to the existing London Congestion Charge dating from 2003, which imposed a near universal tax on vehicles entering Central London during periods of high demand when traffic was very dense.

Given the way the Toxicity Charge and the ULEZ were implemented, we perform a Diff-in-Diff analysis to evaluate the effectiveness of these initiatives in reducing NO_2 levels. The estimated effects show that both the Toxicity Charge and the ULEZ have had a significant impact on reducing NO_2 emissions, as measured by roadside and background stations within the CCZ. Moreover, our results are robust to differentiating by type of day.

On the one hand, the Toxicity Charge is responsible for an 8.2 $\mu g/m^3$ reduction, which is a 10.5 percent drop relative to the initial average NO_2 levels at roadside CCZ stations. The ULEZ policy amplified this effect on pollution, with an estimated reduction of 14.9 $\mu g/m^3$ (19 percent). However, this drop is not large enough to meet the legal limit for NO_2 levels, set at an annual average of 40 $\mu g/m^3$, in large areas of central London. It appears that the London authorities are on the right track, but further efforts are still needed to bring NO_2 levels below harmful limits.

On the other hand, given that background stations are located far from roads with heavy traffic, we estimate smaller declines in NO_2 levels after the implementation of the two policies: 5.68 $\mu g/m^3$ after the Toxicity Charge implementation and 7.03 $\mu g/m^3$ after the ULEZ. However, given the lower average NO_2 levels at background stations, these figures represent, in relative terms, reductions of around 16–19 percent, which are larger than those estimated for roadside stations. Compared to the Toxicity Charge, the ULEZ seems to have been more relevant for roadside stations, as its effects almost doubled the reductions associated with the Toxicity Charge at Central London roadside sites. However, increased ULEZ restrictions only led to a small additional estimated drop in NO_2 levels, but enough to ensure that all background stations in central London are well below the legal limits.

We also find positive *spillover* effects within North and South Circular Roads, with these being larger for the ULEZ than for the Toxicity Charge. These were larger and spread further away when measured at roadside stations than when they were estimated at background sites. These results highlight the potential efficacy of traffic policies in reducing pollution in large cities. Moreover, our evidence of a positive externality due to the implementation of the Toxicity Charge and the ULEZ seems to imply that these policies have already prompted adjustments in transportation habits, improvements in the vehicles emission levels, drops in the use of private cars and increments in the use of the public transport network. As González et al. (2021) have shown the deterioration of public transport (in their case due to strikes), increases the private use of cars and rises pollution. Therefore, it is very likely that the enhancement of public transport, associated to the resources obtained from the net revenue of these traffic policies, will generate the desired effects.

Furthermore, since the implementation of the ULEZ implied charging vehicles that enter the ULEZ area on weekends, we analyse the effect of these two policies by differentiating between weekdays, Saturdays and Sundays. The effects of the Toxicity Charge and the ULEZ on NO_2 levels are more important during weekdays. However, by introducing traffic restrictions on Saturdays and Sundays, the ULEZ effects were more uniform during the whole week, as would be expected, while the Toxicity Charge weekend effects were much lower. These reductions, which are not directly linked to the application of new traffic restrictions during the weekend, can be associated with the renewal of the bus fleet or the ban on new licenses for diesel taxis that took place on January 1, 2018. It is also possible that new transport habits induced by the Toxicity Charge during weekdays were also applied on weekends. Thus, if people get used to using public transportation or bicycles to commute to work, they might also use these to get around on the weekends instead of using private cars. Alternatively, families switching to a cleaner car would use it whenever they needed, including weekends.

As far as background stations are concerned, the reduction of NO_2 levels observed at CCZ stations on Saturdays due to the Toxicity Charge is similar to that of weekdays. However, this policy has no statistically significant effects on Sundays. This suggests that traffic-related pollution is present at background monitoring stations with some delay. Traffic pollution changes associated with the Toxicity Charge on weekdays carry over to Saturdays but not to Sundays.

Finally, the weaker *spillover* effects associated with the Toxicity Charge at all types of stations on weekends, which even disappear on

Sunday, could be considered as empirical evidence in favour of traffic policies applied on a 24/7 basis. No persistent *spillover* effects were estimated when the policy was applied only during peak hours. However, when traffic restrictions are permanent, the estimated *spillover* effects were, in fact, lower but of the same order of magnitude than the effects on the area of application.

In conclusion, as Sousa Santos et al. (2020) have verified, compared to other traffic measures to reduce NO_2 levels, implementation of LEZs is the most effective. Moreover, we observe important differences in the effectiveness of the LEZ policies depending on the strictness of the rules applied, which may also result in positive *spillover* effects in nearby areas.

Hence, the results presented highlight the importance of tightening LEZ initiatives and moving towards zero emission zones (ZEZ) to combat the concentration of pollutants in urban areas, particularly in megacities like London. Regarding urban goods transport, we must be aware that the application of ZEZ could reduce emissions; however, the kilometres travelled by each non-compliant delivery vehicle outside the ZEZ would increase although, at the same time, ZEZ could incentivise improvements in the logistics efficiency (de Bok et al., 2020).

Our results in terms of NO_2 reductions are consistent with changes in urban mobility, which may improve all Londoners' health. Since the introduction of restrictive measures is increasingly widespread, this type of analysis can be helpful to guide and evaluate new policies in other cities.

CRediT author statement

Juan Prieto-Rodríguez: Conceptualization, Data curation, Formal analysis and Writing. María Jose Pérez-Villadóniga: Conceptualization, Visualization, Investigation and Writing. Rafa Salas: Conceptualization, Visualization, Data curation and Writing. Anna Ruso: Data curation and Writing- Reviewing and Editing.

Declaration of competing interest

Authors do not have any potential conflict of interest.

Data availability

Data will be made available on request.

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Appendix

Table A1
Definitions and descriptive statistics.

Variable name	Mean	St. Dev.	Definition
NO_2	44.186	24.241	Average daily level of NO_2 in µg/m^3
CCZ	0.131	0.338	Dummy: 1 if air station at the CCZ and 0 otherwise
Belt 1	0.147	0.354	Dummy: 1 if monitoring station within 3.5 km of the CCZ and 0 otherwise
Belt 2	0.325	0.469	Dummy: 1 if monitoring station further than 3.5 km of the CCZ but within or on the North and South Circular Roads and 0 otherwise
Belt 3	0.146	0.353	Dummy: 1 if monitoring station outside the North and South Circular Roads but less than 3.5 km away from them and 0 otherwise
Post TC	0.287	0.453	Dummy: 1 if observation is between the date of implementation of the Toxicity Charge (October 23, 2017) and the implementation of the ULEZ (April 8, 2019) and 0 otherwise
Post ULEZ	0.180	0.384	Dummy: 1 if observation is after the date of implementation of the ULEZ (April 8, 2019) and 0 otherwise
Precipitation	1.915	3.373	Daily precipitation in mm
Geopot. height	155.69	1041.4	Geopotential Height at 1000 hPa in meters
Humidity	78.397	10.087	Daily mean relative humidity in %
Temp at 2 m	10.995	5.329	Daily average temperature at 2 m in Celsius
Temp 1000 hPa	10.802	5.162	Daily mean temperature at 1000 hPa in Celsius
Northeast wind	0.639	1.503	Northeast wind speed in m/s
Southeast wind	0.459	1.229	Southeast wind speed in m/s
Southwest wind	2.309	2.692	Northwest wind speed in m/s
Northwest wind	0.720	1.559	Southeast wind speed in m/s
Bank holiday	0.022	0.146	Dummy: 1 if bank holiday and 0 otherwise
Saturday	0.144	0.351	Dummy: 1 if Saturday and 0 otherwise
Sunday	0.143	0.351	Dummy: 1 if Sunday and 0 otherwise
Christmas	0.003	0.052	Dummy: 1 if Christmas Day and 0 otherwise
Roadside	0.616	0.486	Dummy: 1 if air station is classified as roadside and 0 otherwise
Background	0.384	0.486	Dummy: 1 if air station is classified as background and 0 otherwise

Table A2
List of monitoring stations.

Name	Code	Type	Area
Camden - Bloomsbury at Russell Square	blo	Background	CCZ
City of London - Sir John Cass School	ct3	Background	CCZ
Southwark - Elephant and Castle	sk6	Background	CCZ
Westminster - Horseferry Road	wm0	Background	CCZ
Camden - Euston Road	cd9	Roadside	CCZ
City of London - Beech Street	ct4	Roadside	CCZ

(*continued on next page*)

Table A2 (*continued*)

Name	Code	Type	Area
City of London - Walbrook Wharf	ct6	Roadside	CCZ
Hackney - Old Street	hk6	Roadside	CCZ
Westminster - Strand (Northbank BID)	nb1	Roadside	CCZ
Islington - Arsenal	is6	Background	Belt 1
Kensington and Chelsea - North Ken	kc1	Background	Belt 1
Islington - Holloway Road	is2	Roadside	Belt 1
Kensington and Chelsea - Cromwell Road	kc2	Roadside	Belt 1
Kensington and Chelsea - Knightsbridge	kc3	Roadside	Belt 1
Kensington and Chelsea - Chelsea	kc4	Roadside	Belt 1
Kensington and Chelsea - Earls Court Road	kc5	Roadside	Belt 1
Southwark - A2 Old Kent Road	sk5	Roadside	Belt 1
Tower Hamlets - Mile End Road	th2	Roadside	Belt 1
Wandsworth - Battersea	waa	Roadside	Belt 1
Haringey - Priory Park South	hg4	Background	Belt 2
Hounslow - Chiswick	hs4	Background	Belt 2
Lewisham - Catford	lw1	Background	Belt 2
Newham Wren Close Road	new3	Background	Belt 2
Wandsworth - Wandsworth Town Hall	wa2	Background	Belt 2
Wandsworth - Putney	wa9	Background	Belt 2
Waltham Forest Dawlish Rd	wl1	Background	Belt 2
Waltham Forest Leyton	wl5	Background	Belt 2
Ealing - Hanger Lane Gyratory	ea6	Roadside	Belt 2
Greenwich - Blackheath	gr7	Roadside	Belt 2
Greenwich - Woolwich Flyover	gr8	Roadside	Belt 2
Greenwich - Westhorne Avenue	gr9	Roadside	Belt 2
Hammersmith and Fulham - Shepherd's Bush	hf4	Roadside	Belt 2
Haringey Town Hall	hg1	Roadside	Belt 2
Hounslow - Gunnersbury	hs8	Roadside	Belt 2
Lewisham - New Cross	lw2	Roadside	Belt 2
Lewisham - Loampit Vale	lw4	Roadside	Belt 2
Newham Cam Road	new2	Roadside	Belt 2
Redbridge - Gardner Close	rb4	Roadside	Belt 2
Richmond - Castelnau	ri1	Roadside	Belt 2
Tower Hamlets - Blackwall	th4	Roadside	Belt 2
Wandsworth - Putney High Street Facade	wa8	Roadside	Belt 2
Barnet - Chalgrove School	bn2	Background	Belt 3
Lambeth - Streatham Green	lb6	Background	Belt 3
Redbridge - Ley Street	rb7	Background	Belt 3
Enfield - Derby Road	en4	Roadside	Belt 3
Greenwich - Falconwood	gb6	Roadside	Belt 3
Greenwich - A206 Burrage Grove	gn0	Roadside	Belt 3
Greenwich - Plumstead High Street	gn3	Roadside	Belt 3
Greenwich - Fiveways Sidcup Rd A20	gn4	Roadside	Belt 3
Hounslow - Brentford	hs5	Roadside	Belt 3
Wandsworth - Tooting High Street	wab	Roadside	Belt 3
Bexley - Belvedere West	bq7	Background	Control
Enfield - Prince of Wales School	en7	Background	Control
Hillingdon - Keats Way	hi0	Background	Control
Hillingdon - Oxford Avenue	hi3	Background	Control
London Hillingdon	hil	Background	Control
Hillingdon - Harmondsworth	hil1	Background	Control
Hounslow - Hatton Cross	hs7	Background	Control
Hounslow - Feltham	hs9	Background	Control
Hillingdon - Sipson	sips	Background	Control
Croydon - Purley Way A23	cr7	Roadside	Control
Hillingdon - South Ruislip	hi1	Roadside	Control
Hillingdon - Hayes	hil5	Roadside	Control
Harrow - Pinner Road	hr2	Roadside	Control
Hounslow - Heston	hs6	Roadside	Control
Havering - Rainham	hv1	Roadside	Control
Havering - Romford	hv3	Roadside	Control
Kingston - Tolworth Broadway	kt4	Roadside	Control

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