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The Effect of a Congestion Charge on Traffic

The Case of London

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The Effect of a Congestion Charge on Traffic: The Case of London

Chu Wang and Jintao Xu*

Abstract

Based on very detailed monitoring data, we examine the effectiveness of the City of London's congestion charge on traffic. Through multiple Regression Discontinuity Design estimations, we found that the introduction of the congestion charge had an immediate effect and brought significant social welfare, but the effect was diminished as time went on, which explains the need for periodic charge rate adjustments. Moreover, when the charges expanded to new zones, there was a spillover effect to the old zones. At the same time, the charge also affected drivers' choice of when to drive.

Keywords: effectiveness of congestion charge, regression discontinuity design, London

JEL Codes: Q58, R41, R48

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1. Introduction

Traffic congestion is a worldwide phenomenon in large cities. As economies grow, cities invariably experience rapid increases in population, concentration of business activities, and traffic. The growing size of the car fleet causes two types of intertwining externalities, namely the delay in time and decline in air quality (Vickrey, 1969; Künzli et al., 2000). The delay in time associated with drivers and cars stuck in traffic is a source of reduced economic efficiency and frustration, as well as increased emissions due to reduced fuel combustion efficiency (Sharp, 1966; Arnott & Small, 1994; Zhang, Batterman, & Dion, 2011). Air quality deterioration has become a major health problem (Brunekreef & Holgate, 2002; Finkelstein, Jerrett, & Sears, 2004). A recent study by Liu et al. (2016) indicates that air pollution is responsible for 1.37 million premature deaths annually in China, which are closely linked to urban traffic congestion.

Cities worldwide have tried various methods to control traffic congestion and the ensuing air pollution. A number of large cities, such as Mexico City (Eskeland & Feyzioglu, 1997; Davis, 2008), Santiago (Mahendra, 2008; de Grange and Troncoso, 2011), Beijing (Wang, Xu, & Qin, 2014; Sun, Zheng, & Wang, 2014), and New Delhi (Kreindler, 2016; Mohan et al., 2017), adopted driving restrictions. Other cities, such as Singapore (Seik, 2000; Olszewski & Xie, 2005), London (Leape, 2006), Stockholm (Bonilla Londoño, 2013), and Gothenburg (West & Börjesson, 2018), embarked on charging a price for entry into an inner city zone. This paper will examine the effectiveness of the traffic congestion charge adopted in London based on direct evidence of how this policy affected traffic volume.

Rigorous examination of the effectiveness of the various measures will shed light on policy improvement for cities that are searching for effective, low-cost, and long-lasting solutions to control traffic congestion. Mexico City was the first to adopt a driving restriction and its experience attracted major interest (Eskeland & Feyzioglu, 1997; Goddard, 1997; Davis, 2008). Davis' comprehensive study demonstrates that the "Hoy No Circula" adopted in Mexico City in 1989 has neither reduced traffic congestion nor led to improvement in air quality.[1] Studies on Santiago by de Grange and Troncoso (2011) also showed that restrictions based on license plate number pushed drivers to get a second vehicle for use on restriction days or to set out earlier to avoid the restriction period, with the result that the driving restriction policy was not effective. Beijing's driving restriction policy also has not been shown to relieve traffic significantly, as rule-breaking behavior is constant and low-cost (Wang, Xu, & Qin, 2014).

While evidence has shown that driving restrictions are not effective, a price signal, in the form of a congestion charge, seems to be effective from some cities' experience.[2] Since Singapore adopted a congestion charge in 1975, as the first trial of road pricing in the world, a few papers have examined the effectiveness of this line of policies. The Electronic Road Pricing (ERP) system of Singapore was shown to be able to allocate traffic volume with given road capacity in a more efficient way, although it requires a relatively high initial investment (Seik, 2000; Olszewski & Xie, 2005). For Stockholm, Eliasson (2009) calculates changes in overall travel time and cost and identifies significant social surplus.

A number of papers have studied the effect of a congestion charge on air pollution[3], with discussion on the costs and benefits of the policy[4]. However, studies accurately testing the direct effect of a congestion charge on traffic volume are still lacking. Our work tries to fill this gap.

[1] One recent study on New Delhi (Mohan et al., 2017) found that driving restrictions do not effectively reduce air pollution because citizens in turn use more motorized transportation. Earlier work by Eskeland and Feyzioglu (1997) showed basically the same results.
[2] Bonilla Londoño (2013) directly compared the effect on air pollution from road pricing in Stockholm and driving restrictions in Bogota, coming to the conclusion that prices are more effective than restrictions.
[3] Many researchers have tested the effect of a congestion charge from the viewpoint of automobile emissions and found the charge policy did help to control air pollution in the charging zone (Percoco, 2013). However, spillover effects happen in the uncharged zones and uncharged time (Beevers & Carslaw, 2005; Gibson & Carnovale, 2015).
4 Prud'homme and Bocarejo (2005) found that the London congestion charge's economic benefits are much less than the scheme's resource costs. Conversely, Leape (2006) thinks annual benefits of London's congestion charge are more than annual cost by £67 million, which means the congestion charge policy brings positive net benefits. Gothenburg's congestion charges could generate considerable net social surplus per year (West & Börjesson, 2018), suggesting that congestion charges could contribute more benefits than costs.

This paper examines the effectiveness of a traffic congestion charge adopted in London. London began to put a price on entry into the inner city circle in 2003. After that, it raised the rate several times in a ten-year span. It also added another zone under the charge system, but this additional zone was later dropped. We think London's dynamic experience provides an excellent case for rigorous analysis. We will be able to accurately identify the direct effects on drivers' choice of driving frequency and driving time. Moreover, some additional information will be generated, such as spillover effects, information delay, and long-term reduction in effectiveness of the policy.

Our preliminary findings include that the introduction of a congestion charge did reduce congestion. At the same time, the charge affected drivers' choice of driving times, in that drivers may actively avoid the charge by driving before and after the charging period, which can be viewed as a negative spillover effect to the uncharged time. Moreover, when the charge expands to new zones, we find that traffic volume from new zones spills over to the initial charging zones. Once the charging zone shrunk, the rebounds of congestion can be observed in both the cancelled zone and the preserved zone. When checking the robustness, we find it interesting that the effect of the congestion charge required a short time to show up, which may be due to information delay, and the effect was diminished as time passed.

This paper is structured as follows. We provide a historical review of London's congestion charge regulation in Section 2. Section 3 elaborates our methodology and describes the data; Section 4 is devoted to discussion of results. Section 5 checks the robustness. Section 6 concludes with further deliberation and policy implications.

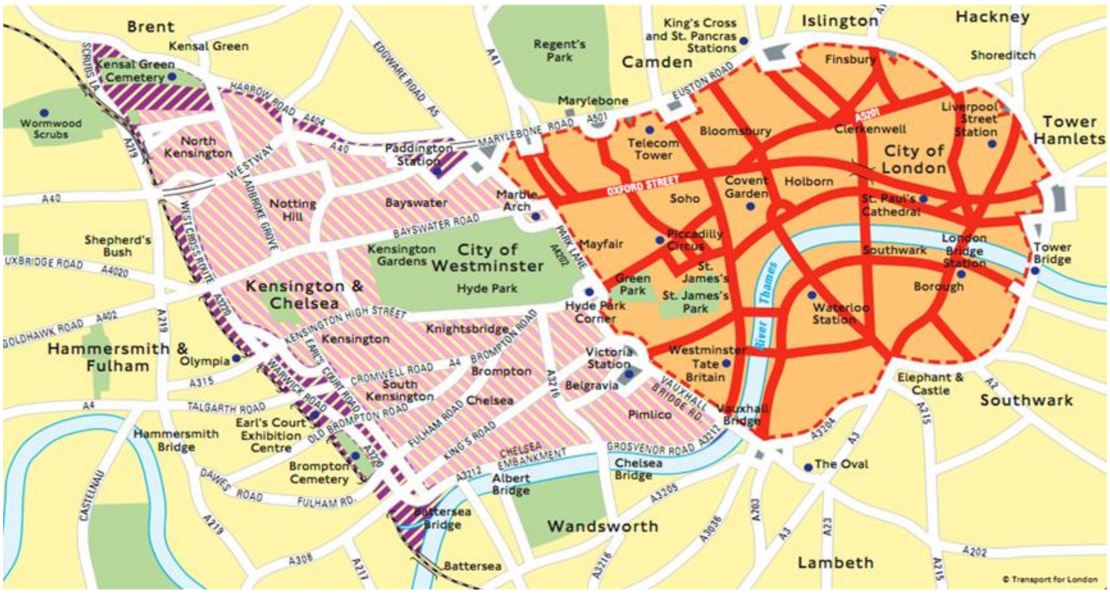
2. London's Congestion Charge: An Overview

Since the mid-20th century, London has been confronted with relatively serious congestion. In 1964, the Smeed Report released by the British government first assessed the feasibility of road charges and suggested that road users should pay for the costs they imposed on others (that is, the negative externality). Based on the recommendation of this report, the London Authority applied to the London Council several times for the approval of a congestion charge. However, the plan for such a charge was repeatedly vetoed by the Council. In 1995, the London Congestion Research Program concluded that the city's economy would benefit from a congestion charge scheme and pushed the introduction of the Road Traffic Reduction Act 1997. This Act then led to the Greater London Authority Act (1999) that gave London mayors the power to introduce “Road User Charging”. Hence, in 2000, when new London mayor Ken Livingstone took office, he proposed to the London Council to introduce a congestion charge and the proposal was finally approved.

Starting on February 17, 2003, London began to charge congestion fees in the approximate area of the London Inner Ring Road from 7:00 a.m. to 6:30 p.m. on weekdays. During the charging time, almost all cars[5] entering into or exiting from the charging zone paid a fee of £5 per day, which means once a vehicle was driving in this zone, it would be charged. On July 4, 2005, Transport for London raised the charging standard from £5 per day to £8 per day. On February 19, 2007, the London Authority decided to expand the charging zone westward (Western Extension Zone) and shorten the charging time to between 7:00 a.m. and 6:00 p.m., but the standard amount charged remained unchanged. On January 4, 2011, the Western Extension Zone was removed. Thus, only the Central London Charging Zone remained. In the meantime, Transport for London decided to raise the rate of the congestion charge to £10 per day. On June 16, 2014, the rate was raised again to £11.5 per day.

[5] Some cars were released from paying full fees; for example, people living within the congestion zone receive a 90% discount on the charge, although they must be a registered resident to qualify.

Figure 1: London Congestion Charge's Central Charging Zone (in orange) and Western Extension Zone (in pink)



3. Empirical Strategy

3.1 Model

We use a Regression Discontinuity Design (RDD) to identify the effect of a congestion charge on traffic volume. RDD is a quasi-random test, whose identification validity requires that a treatment or shock is exogenous (Imbens & Lemieux, 2008; Lee & Lemieux, 2009). The running variable corresponds to the treatment, which is the new policy's implementation (Bajari & Hong, 2011).

We set the time when the London congestion charge policy was introduced as the point of discontinuity and identify whether significant changes in traffic volume happened after that time. Under the assumptions of RDD, all other controlling factors are continuous. If there is a sudden change in traffic volume at the point of the introduction of the congestion charge, then it is the congestion charge that caused this jump.

Regression Discontinuity Design can be conducted both in parametric estimation and nonparametric estimation. Nonparametric estimation uses a kernel function and chooses bandwidth to identify the jump τ_{RD} before and after the discontinuity.

$$\tau_{RD} = \lim_{\text{Time}\downarrow\text{Cutoff}} E[\ln(\text{Volume})_0|\text{Time}] - \lim_{\text{Time}\uparrow\text{Cutoff}} E[\ln(\text{Volume})_1|\text{Time}] \quad \text{(I)}$$

$$(\text{Cutoff-h} \le \text{Time} \le \text{Cutoff+h})$$

Cutoff represents the discontinuity in Model I and h represents bandwidth. The nonparametric method is a local strategy which estimates the best bandwidth according to the given kernel function (Imbens & Kalyanaraman, 2011), so the estimation is very sensitive to the choice of kernel function and bandwidth. Generally speaking, the narrower the bandwidth is, the more accurate the result is. Compared with the nonparametric method which represents the local strategy, the parametric method is the representation of a global strategy which would conduct the regression with the whole sample if there were no constraint. In other words, parametric estimation can be deemed to be a nonparametric estimation with broader bandwidth. So, nonparametric model I can be expressed in the form of parametric model II.

(II)

$$\ln(\text{Volume}) = \alpha + \beta*\text{Charge} + \gamma*(\text{Time-Cutoff})^n + \delta*\text{Charge}*(\text{Time-Cutoff})^n + \zeta*D$$

Our research uses model II as the basic regression model and reports the results to identify the changes in traffic volume caused by the congestion charge. We take 30 days as the sample size of the parametric model. Moreover, we add a constraint to limit the size of the sample to compare with the result in Model I (Cutoff-h ≤ Time ≤ Cutoff+h）. In model II, Charge is a dummy variable representing whether the observation is during the charging period. The cutoff is the point when the congestion charge policy is implemented or changed. The discontinuity is the difference between the variable Time, a continuous variable of date, and the variable Cutoff. The discontinuity represents the date the policy came into effect, and regulates the time “distance” from the policy’s introduction or change, which is similar to the bandwidth in the nonparametric method. The cross-term of Charge and (Time-Cutoff) is used to identify the changes of intercept on the discontinuity by controlling the time effect. The variable D stands for weekday dummy, to control for weekends’ and holidays’ fixed effects when the congestion charge is not imposed.

3.2 Data

This research uses high-frequency measures from Transport for London's monitoring stations from June 2002 to March 2012. The network reports measures of traffic flow on the main roads in the central area every fifteen minutes. Transport for London categorizes vehicles into light, medium, and heavy cars and counts them respectively. The summary is shown in Table 1.

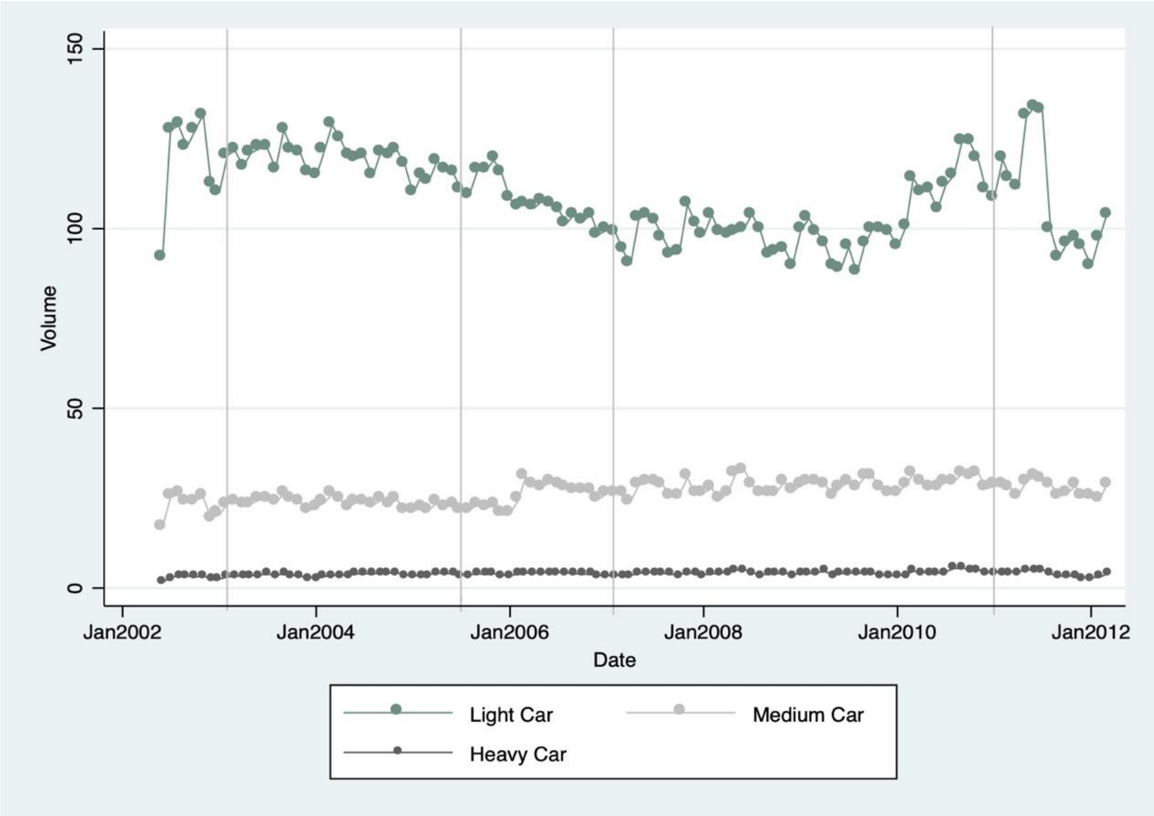
Table 1: Summary of Observations of Vehicle Categories in Charging Zone

Vehicle Categories	Observations	Mean	Standard Error	Min.	Max.
Light Cars	32991350	109.7	97.28	0	24419
Medium Cars	32991350	27.39	29.28	0	3753
Heavy Cars	32991350	4.244	6.112	0	972

Note: The unit of Mean, Min., and Max statistics Is how many cars run on one road during a 15-minute period.

Traffic flow varies from one type to another. Figure 2 indicates that the variation trend of light vehicles is greater than that for medium and heavy vehicles. Compared with light vehicles, the change ranges for medium and heavy vehicles are much slighter. The change in medium vehicles can be divided into two phases: the first one is from 2002 to 2006, at a relatively stable level; and the second phase is after 2006, during which the traffic flow of medium vehicles suddenly rose to a higher level and started to have small and more frequent fluctuations. The traffic flow of heavy vehicles has been capped at a low average without notable change. Therefore, this paper mainly talks about light vehicles, which have a remarkable change trend. The vertical gray lines in Figure 2 indicate when the congestion charge began to be implemented on February 17, 2003, was adjusted for the first time on July 4, 2005, was introduced in the Western Extension Zone on February 19, 2007, and was cancelled in the Western Extension on January 4, 2011.

Figure 2: Traffic Volume Trend of Three Kinds of Vehicles in the Central Charging Zone



From the change trend of traffic flow over time, we could find that, from 2002, light vehicles went up in the short term and then began to drop. During 2002 to 2005, they were at a plateau with small and frequent fluctuations. There was an apparent decreasing trend after 2006 and substantial short-term fluctuations in 2007 and 2008. From 2009, the traffic flow began a two-year period of increasing until 2011, and then it dropped dramatically. It seems that the implementation of the congestion charge is unable to reduce the traffic flow significantly.

Table 2: Summary of Light Cars' Volume in all Regions

Region		Obs.	Road	Start Time	End Time	Mean	Std. Error	Min.	Max.
Central Charging Zone	Internal	5133692	38	200206	201010	70.38	67.39	0	3696
	Gate-way	7879614	48	200206	201107	93.14	71.11	0	1567
	Bound-ary	7668566	45	200206	201107	181.14	116.71	0	17251
	Bridge	1947071	11	200206	201107	105.21	70.90	0	17817
Western Extension Zone	Internal	2421983	15	200601	201010	52.99	45.17	0	1149
	Gate-way	4620255	61	200601	201107	69.77	58.71	0	3140
	Bound-ary	2624009	35	200601	201010	161.62	123.62	0	24419
	Bridge	696160	15	200601	201010	76.87	47.62	0	488

Note: The unit of Mean, Min., and Max statistics Is how many cars run on one road during a 15-minute period. The Road variable represents how many roads are in that region.

Furthermore, the monitoring data from Transport for London not only distinguishes between the Central Charging Zone and the Western Extension Zone, but also includes information on the location of roads, namely the inner part, the gateway, the boundary, and the internal bridges. Table 2 gives the descriptive statistics of the traffic flows in different areas within the charging zone with the number of roads and the time periods. It can be seen that the average and maximum levels of the traffic flow on boundary roads are much larger than the traffic flow within the charging zone and at the gateway. The congestion charge reduces the traffic flow at the gateway and within the charging zone, encouraging cars to bypass on the boundary roads in the meantime. Additionally, the traffic flows everywhere within the Central Charging Zone are greater than those in the Western Extension Zone, because the Central Charging Zone is the city center of London, with more urban life and economic activities and, therefore, greater traffic needs. That also explains why the congestion charge was implemented in the Central Charging Zone first in 2003 and then expanded to the Western Extension Zone in 2007.

Because the monitoring data for the Central Charging Zone started in June 2002 and ended in July 2011, we can use the measures to examine the effects of the initial implementation of the congestion charge in 2003, the first adjustment of the charge in 2005, the charging zone expansion in 2007, and the cancellation of the expanded congestion charging zone together with the second adjustment of the charging rate. However, the monitoring of internal roads in the Central Charging Zone stopped in October 2010, so we are unable to examine the effects of removing the Western Extension Zone and raising the charging rate on the traffic flow of internal roads. The monitoring data of areas in the Western Extension Zone started in 2006, but most of them also ended in October 2010, so we are only able to examine the effects of the congestion charge adoption in the Western Extension Zone, but not the effects of the congestion charge removal. Nevertheless, the measures of the traffic flow at the gateway of the Western Extension Zone continued until July 2011, so we can research the effects of the cancellation of the congestion charge on the traffic situation within the area and compare with the empirical results of the effects of removing the congestion charge in the Western Extension Zone on the traffic flow entering the Central Charging Zone. This will allow us to evaluate different influences of the contraction of the charging zone on both the remaining charging zone and the non-charging zone.

It is noteworthy that there is no charge for vehicles on the boundary roads of the charging zone, only for vehicles entering and driving in the charging zone during the charging time. As a result, we can examine the effects on people's driving behavior through the comparison of traffic flows on boundary roads before and after the congestion charge.

4. Results[6]

Here, we show the effects of congestion charges, charge rate adjustments, and adding and removing a new zone on traffic flow on the internal roads, boundary roads, gateway roads, and bridges.

4.1 The Effects of Changes in the Congestion Charge Price

4.1.a The Effects of Initial Implementation of the Congestion Charge

Our RD regression results on the effects of the charge are shown in Table 3. The traffic flow at the gateway decreased dramatically by 29.9%, and the traffic flow on the roads surrounding the charging zone (labelled "boundary" in the tables) went down by 4.1%. The traffic flow inside the charging zone (labelled "internal" in the tables) fell by 8.8%, while the traffic flow on bridges changed the most, decreasing by 31.1%.

Table 3: Congestion Charge's Effects on Traffic when Implemented in 2003, %

CCZ-2003	Internal	Gateway	Boundary	Bridge
Charge	-0.0876***	-0.2994***	-0.0413***	-0.3106***
	(-3.40)	(-23.68)	(-2.80)	(-11.77)
Fixed Effect	Yes	Yes	Yes	Yes
Constant	4.2818***	4.7142***	5.2073***	4.9718***
	(189.09)	(440.07)	(406.51)	(218.98)
Observations	51803	66467	62692	15364
R-squared	0.009	0.029	0.006	0.025

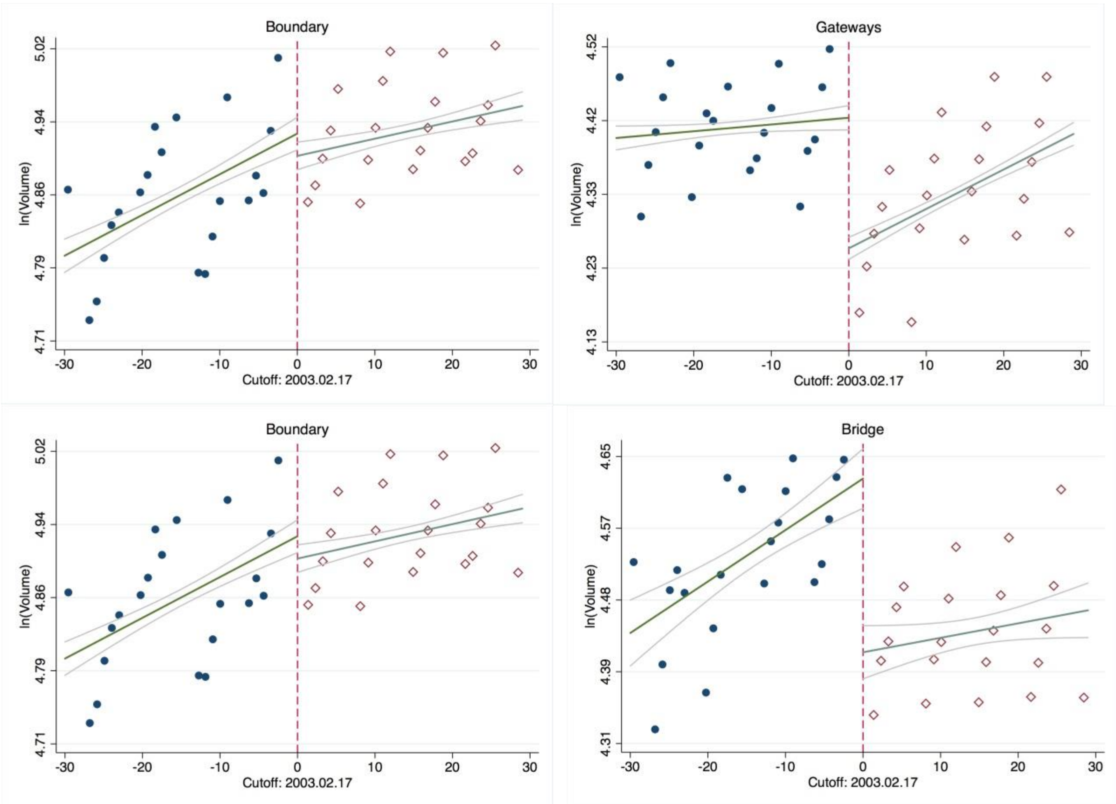
t-statistics in parentheses; ***p<0.01, **p<0.05, *p<0.1

Comparing the marginal change of the traffic flow of different parts in the charging zone, we can find that the marginal change on the boundary roads is smaller

[6] Since several similar policies' effects are studied in this part, we summarize the findings in Appendix A for readers to compare and read easily.

than that on the gateway roads. This phenomenon shows that drivers' behavior was affected by the congestion charge. Some drivers who could head directly to their destination across the charging zone before the congestion charge policy chose to bypass the charging zone by using the uncharged boundary roads after the policy's implementation, which caused an increase of the traffic flow on the boundary ways; therefore, the marginal change of the traffic flow on the boundary roads was limited.

Figure 3: Leap in Discontinuity of Volume when Congestion Charge Introduced in 2003



There is a huge gap between the marginal change of the traffic flow on the internal roads and that at the gateway. The actual marginal change of the traffic flow on internal roads is much smaller. One explanation is that vehicles that have entered the charging zone have already paid a fixed charge. The benefit of driving once one is already inside the charging zone is that it can only dilute the fixed cost. Secondly, fewer cars inside the zone implies that driving becomes more pleasant for those who still drive there. Therefore, we see a small effect of congestion reduction inside the charging zone.

4.1.b The Effects of Adjustments of the Congestion Charge

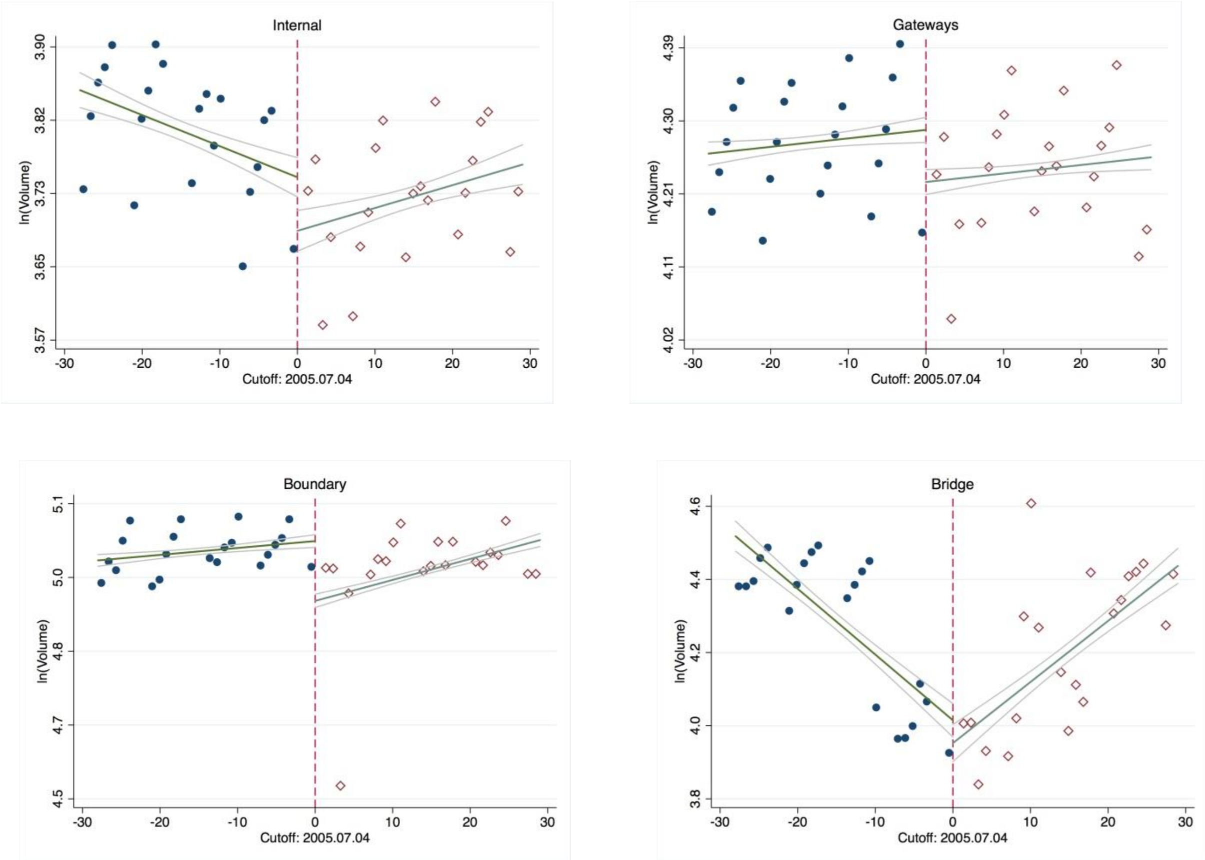
Transport for London raised the congestion charge for the first time on July 4, 2005, increasing the charge level from £5 to £8 per day. We examined the effects of incremental adjustment on traffic conditions, and the regression result is shown in Table 4. We found that the traffic flow at the gateway of the Central Charging Zone dropped about 11% and the traffic flow on the internal roads dropped 8.4%. Meanwhile, the traffic flow on the boundary roads decreased 17.7% and the traffic flow on bridges went down by 16.4%. Compared with the initial launch of the congestion charge in 2003, the marginal change of the traffic flow on internal roads and the marginal change of the traffic flow at the gateway were smaller, while the marginal effect on the boundary roads was larger.

Table 4: Congestion Charge's Effects on Traffic when Fee Raised in 2005, %

CCZ-2005	Internal	Gateway	Boundary	Bridge
Charge	-0.0841***	-0.1101***	-0.1772***	-0.1636***
	(-3.55)	(-7.66)	(-14.77)	(-3.66)
Fixed Effect	Yes	Yes	Yes	Yes
Constant	3.9881***	4.5101***	5.2972***	4.1162***
	(198.65)	(367.34)	(517.31)	(108.96)
Observations	54602	68349	68849	14898
R-squared	0.003	0.002	0.009	0.053

t-statistics in parentheses; ***p<0.01, **p<0.05, *p<0.1

Figure 4: Leap of Discontinuity of Volume when Congestion Charge Raised in 2005



When the price keeps going up, fewer drivers are expected to change their behavior – only those with lower demand elasticity, who attach more attention to commuting comfort than to cost. Considering the factors of income growth and inflation, as well as the smaller increment in the charge, the decreasing marginal effect is not a surprise.

In addition, the gap between the marginal change of the traffic flow at the gateway and on the internal roads shrank; the gap is now tiny compared with the gap in 2003. This shows that fewer drivers decided to drive more once they were inside the internal zone and had already paid the fixed cost. It also suggests that some drivers who might have driven more to dilute their fixed cost after entering the inner zone have now chosen to leave their cars home. It seems the second time around observes the birth of an effective gate price for driving, which affords an efficient allocation of road resources to drivers with higher willingness to pay.

The marginal change of the traffic flow on the boundary roads decreased after the increase in the congestion charge in 2005, which suggests that traffic mode choices also were changed by the increased congestion charge. More people abandoned driving and presumably chose public transportation, making traffic on the boundary roads decrease.

It is worth noting that terrorist explosions occurred on July 7, 2005, three days after the new policy went into effect. The attack targeted the subway and other public transportation, and all targets were within the charging zone. This, perhaps, severely compromised the effectiveness of the congestion charge and also our measure of the net effect. Despite this unfortunate complication, our estimate still reveals a statistically significant drop in driving after the charging increase. We would imagine that the traffic flow would have increased substantially without the congestion charge policy.

4.2 The Effects of Changes in the Charging Zone's Area

4.2.a The Effects of the Congestion Charge in the New Area

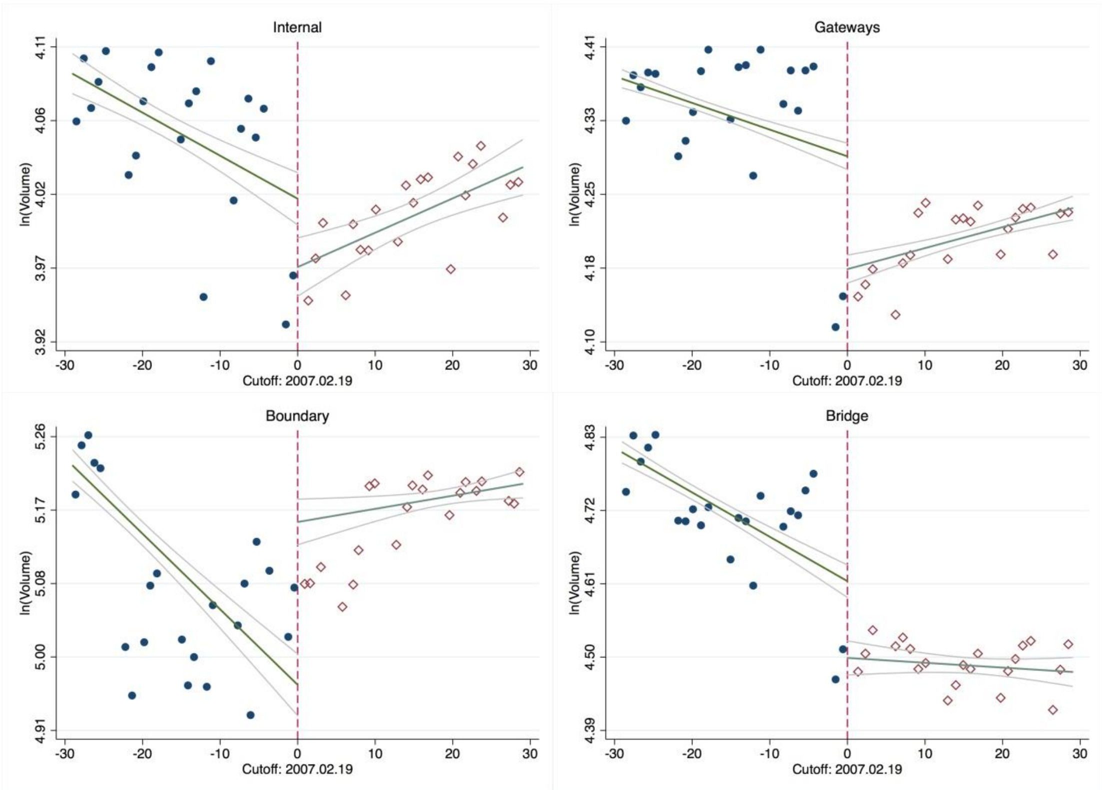
London extended the charging zone in 2007 to include the Western Extension Zone, which doubled the total area under the policy. We examined the effects of the expansion on traffic conditions of the Western Extension Zone; the regression result is shown in Table 5. The traffic flow dropped by 22.8% at the gateway, went down by 9.2% in the new charging zone, and fell by 17.3% on the bridges. However, the volume on the boundary roads increased by 11.5%.

Table 5: Congestion Charge's Effects on Western Extension Zone When Introduced in 2007, %

WEZ-2007	Internal	Gateway	Boundary	Bridge
Charge	-0.0921***	-0.2276***	0.1154***	0.1725***
	(-6.13)	(-18.82)	(3.38)	(-7.64)
Fixed Effect	Yes	Yes	Yes	Yes
Constant	3.9819***	4.3168***	4.9564***	4.6416***
	(328.76)	(447.01)	(166.54)	(259.68)
Observations	56936	120467	32904	18239
R-squared	0.006	0.015	0.004	0.092

t-statistics in parentheses; ***p<0.01, **p<0.05, *p<0.1

Figure 5: Discontinuity of Volume when Congestion Charge Introduced in 2007



Comparing the reduction of the traffic flow at the gateway and on the internal roads, the latter is much smaller, which indicates that vehicles within the charging zone are still “overused”. It is the same phenomenon that was shown in 2003 when the congestion charge policy was first introduced in the Central Charging Zone. With the expansion of the charging zone, vehicles that paid in the Western Extension Zone could drive in the Central Charging Zone without any more fees. For some drivers inside the charging zone, because of the enlarged areas, the driving benefit increased. We are facing a bigger common pool resource issue now. Our estimate is that the actual charge per mile dropped by about 50%. This demonstrates that, as the previous “effective price” (which can constrain the overuse of cars within the charging zone) disappeared, more vehicles chose to enter the charging zone. The drivers can drive more miles to subsidize the congestion fee they paid.

After the congestion charge had been implemented in the Western Extension Zone, the traffic flow on its boundary roads increased dramatically. This shows that the congestion charge deeply influenced traffic behavior in this area and that different groups of people with various price elasticities chose different commuting methods. The increasing traffic flow on boundary roads could be caused by diverting vehicles to somewhere outside the charging zone or by drivers aiming toward a certain point before transferring to public transportation into the charging zone.

4.2.b The Effects of Expanding the Charging Zone on the Initial Zone

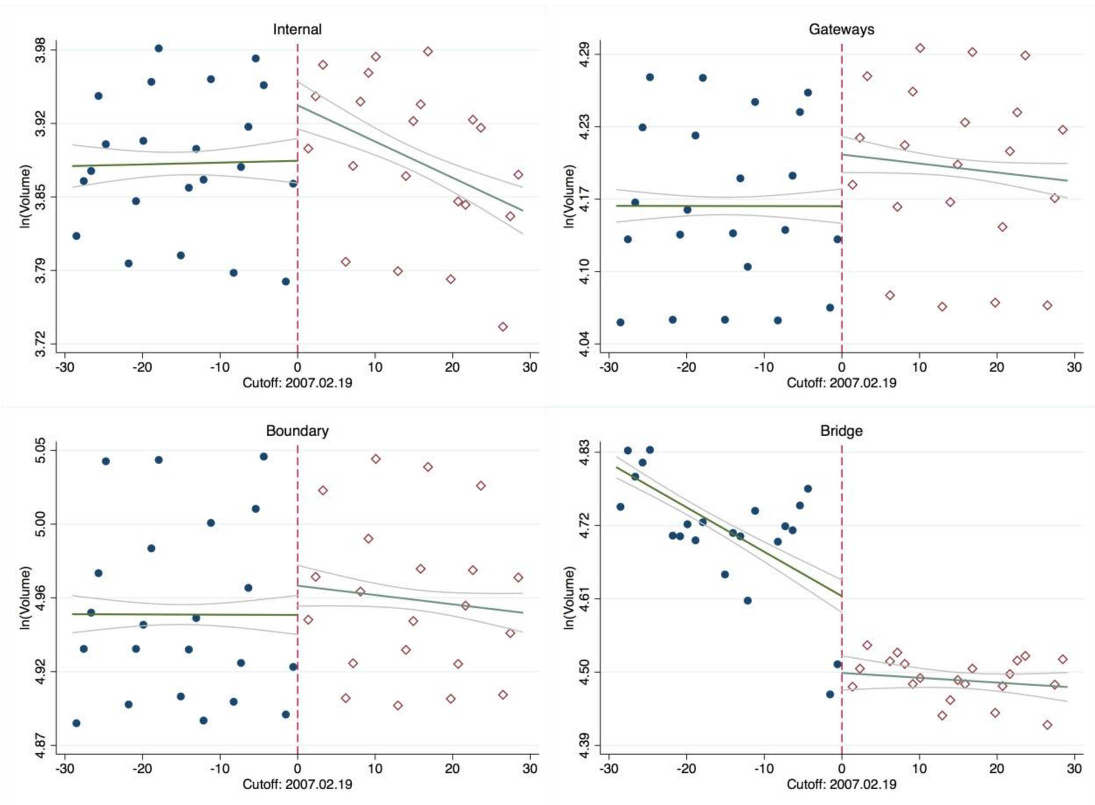
The effects of adding the Western Extension Zone to the congestion charge system on the Central Charging Zone are shown in Table 6. After the policy adjustment, the traffic flows at the gateways increased and the volume on the boundary decreased a bit, which is quite different from previous policy changes.

Table 6: Congestion Area Extension Effects on Central Charging Zone in 2007,%

CCZ-2007	Internal	Gateway	Boundary	Bridge
Charge	0.0134	0.0404***	-0.0189*	0.0049
	(0.60)	(2.89)	(-1.73)	(0.19)
Fixed Effect	Yes	Yes	Yes	Yes
Constant	4.0979***	4.3345***	5.2402***	4.5334***
	(220.16)	(369.40)	(570.31)	(216.80)
Observations	60827	64798	78296	17580
R-squared	0.001	0.002	0.001	0.003

t-statistics in parentheses; ***p<0.01, **p<0.05, *p<0.1

Figure 6: Discontinuity of Volume in Central Charging Zone when Congestion Zone Extended in 2007



The traffic flow at the gateway was increased significantly. The coefficient of the traffic flow on the boundary roads is negative, implying that more cars choose to enter the charging zone rather than bypass the charging zone. This is probably a reflection of a relative marginal cost reduction of entering the central zone now. Moreover, the charging zone has been expanded with the charging fee remaining the same, which means the actual charge per mile for cars inside the charging zone has dropped, inducing more cars to enter and more driving inside.

4.2.c The Effects of Narrowing the Charging Zone

Perhaps as a response to the unsatisfactory outcome of the charging zone expansion, on January 4, 2011, Transport for London decided to cancel the congestion charge at the Western Extension Zone and, in the meantime, to raise the standard congestion charge to £10 per day at the Central Charging Zone. We examined the combined effects of the charging zone contraction and the higher congestion charge in 2011. The regression result is shown in Table 7.

We found that the traffic flow at the gateway of the Central Charging Zone decreased by 6.9%, while the traffic flow at the gateway of the Western Extension Zone, where the congestion charge had been removed, rose 4.1%. Moreover, Table 29 shows that once the cancellation was implemented, there was a huge leap of 77.9% volume increasing at the gateway of the Central Charging Zone, but this leap eased as time went on. This means that some vehicles are “squeezed out” to the cancelled charging zone after the contraction of the charging zone, and the spillover effect of removing the charge in the remaining zone is so severe that it compromised the effects of raising the charge level at first.

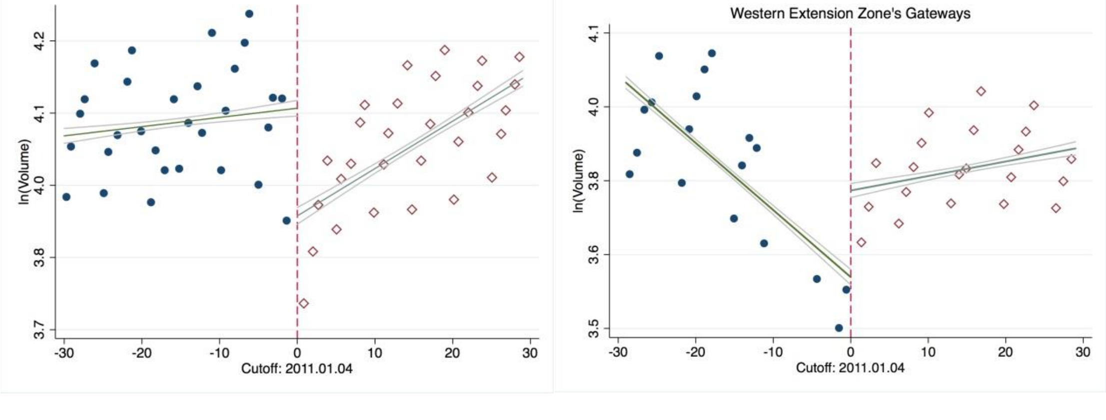
For the Central Charging Zone’s gateway, the new higher fee did prevent more cars entering into the Central Zone. However, on the other side, the increased margin of the traffic flow at the gateway of the Central Charging Zone may consist of those vehicles coming from the Western Extension Zone to the Central Charging Zone that have to enter the Central Charging Zone because of commuting needs. Hence, the traffic flows at the gateway increase proportionally in the beginning. As time goes on, some commuters may feel the cost of the increasing charge is unaffordable and then change their transport modes, so the effect of raising fees showed. From another perspective, the marginal difference between the traffic flows at the gateway of the two areas indicates that a congestion charge can control the traffic flow and at a remarkable level. It can be deduced that expanding a charging zone may not ease traffic pressure in the original zone; on the contrary, the congestion in the newly set zone will spill over to the original zone. However, the contraction of a charging zone will cause a spillover effect and increase congestion in both the remaining and cancelled charging zones.

Table 7: Effect of Charge Raised and Western Extension Zone Cancelled on Traffic, %

2011	Central Charging Zone Gateways	Western Extension Zone Gateways
Charge	-0.0687***	0.0490***
	(-4.47)	(5.34)
Fixed Effect	Yes	Yes
Constant	4.1952***	4.1832***
	(320.75)	(616.09)
Observations	61152	103334
R-squared	0.003	0.003

t-statistics in parentheses; ***p<0.01, **p<0.05, *p<0.1

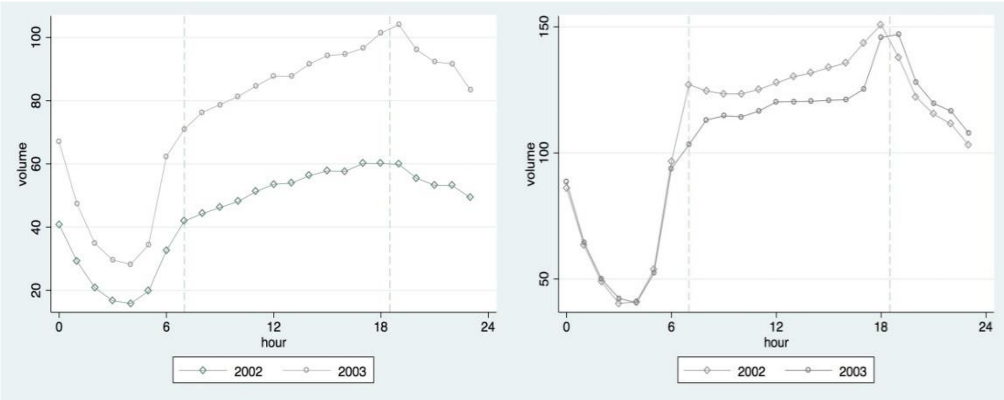
Figure 7: Congestion Charge Policy Adjustment Effect on Central Charging Zone



4.3 The Effects of the Congestion Charge on Travel Time

This part examines the effects of the congestion charge on the choice of travel time and compares the traffic flows at the gateway of the charging zone and within the charging zone in the days before and after the charging time. The area within the dotted line in Figure 8 is the daily charging time.

Figure 8: The Difference of Distribution of Volume in Central Charging Zone Over a Day Affected by Congestion Charge Introduced in 2003 (Left: Internal Zone; Right: Gateways)



From Figure 8, it can be seen that the traffic flow within the charging zone increases compared with that from before the charging went into effect; the flow at the gateway of the charging zone decreases sharply during the charging period. It also seems that people drive more after the charging period of the day, compared with the days before the policy was introduced. Thus, the policy has reduced the driving within the charging zone during the charging time, but had an adverse impact beyond the charging time. It means that the congestion charge also has a certain degree of "spillover effect" over hours of the day on workdays.

We further examine the effects of the congestion charge on the choice of travel time on a workday. We divide 24 hours in a day into seven intervals. The first interval is between 00:00 a.m. and 6:00 a.m., the night time; the second is between 6:00 a.m. and 7:00 a.m., the hour before charging begins, which is often viewed as the AM shoulder; the third is between 7:00 a.m. and 10:00 a.m., the time when people commute to work, known as the AM peak; the fourth is between 10:00 a.m. and 4:00

p.m., the main work time; the fifth is between 4:00 p.m. and 6:00 p.m., from the time when people get off work to the time when the charging period ends, also called the PM peak (before the policy adjustment in 2007, the charging time was between 4:00 p.m. and 6:30 p.m.); the sixth is between 6:00 p.m. and 8:00 p.m., the two hours after the charging ends (the corresponding section before 2007 was 6:30 p.m. to 8:30 p.m.), known as the PM shoulder; the last is the remaining time in a day until 12:00 a.m..

Tables 8 through Table 13 in Appendix B, respectively, show the daily distribution of the traffic flow at the gateway of the Central Charging Zone since 2003 when the congestion charge was introduced, daily distribution of the traffic flow on roads within the Central Charging Zone since 2003, daily distribution at the gateway of the Central Charging Zone since the charge was raised in 2005, daily distribution in the Western Extension Zone since the charge was introduced in this area in 2007, and daily distribution in the Central Charging Zone since 2011 when the charge was removed in the Western Extension Zone.

It can be seen that since 2003, when the charge was introduced in the Central Charging Zone, the traffic flow within the area during the AM peak dropped remarkably, by a margin of 17.5% greater than any other time intervals. During the main work time, the traffic flow also went down. Though the margin is less than that in the AM peak, it still indicates that the charge has effectively controlled the traffic flow on the roads within the charging zone. However, before and after the charging time, during the AM shoulder and PM shoulder, the traffic flow trends upwards significantly, which indicates that the charges altered people’s driving patterns across time of day.

We also examine the changes in the traffic flow at the gateway of the charging zone. In the AM peak, the traffic flow entering and exiting the charging area falls remarkably by 32.5%. During the main work time, the flow entering and exiting also drop significantly by 25.9%. In the PM peak, however, the flow drops by 36.4%. This means that the charge prevents a large number of cars from entering or leaving the charging area. This marginal change is similar to the marginal change of the flow during the morning peak, which demonstrates that travelers going to work are markedly affected by the charge. In the period of the PM shoulder, the traffic flow entering and exiting the charging zone increases a bit, indicating a certain “rebound effect”. Generally speaking, during each interval, the traffic flow at the gateway of the charging zone shows the downward trend. Disregard the upward trend in the AM shoulder and the PM shoulder; this change may be regarded as being caused by two effects. First, after implementing the congestion charge, the total traffic flow entering the charging zone decreased. Second, to avoid charging, cars enter the charging zone ahead of the charging time. Part of the traffic during the AM peak, therefore, is transferred to the time before and after charging. This is the spillover effect on time choice caused by charging.

In 2005, the increase in the amount charged had less effect on time intervals compared with 2003. Traffic flow was reduced by 5.8%. The lesser effect is certainly in line with the diminishing marginal effect rule, maybe compounded by income and inflation factors. On the other hand, we cannot rule out the impact of the 2005 terrorist attacks on the London public transport system. The incentive to adopt public transportation was certainly compromised, at least temporarily.

The traffic flow during regular working hours registers a fall of 12.6%. It means the increase of marginal cost evidently cannot reduce the use of cars in the morning, but can effectively reduce the flow entering and exiting the charging zone during the main work time. Most commuters entering or exiting the charging zone during times other than peak hours are more flexible on time and more sensitive to prices. The charge spike, therefore, directed a larger part of this price-sensitive group to public transport. During the PM peak, there is also a drop of traffic flow by 13.5%. In the PM shoulder, there is a drop of 9.6%. Comparing 2005 to 2003, the spillover effect from the charging period to the later evening hours disappears.

After 2007 when the congestion charge was expanded to the Western Extension Zone, the flow on the gateways of the Western Extension Zone changed significantly in time distribution. During the AM peak, traffic drops by 22.4%; during work hours, 16.0%; and in the PM peak, 24.0%. However, the volume increased in the AM shoulder and PM shoulder. This spillover effect on time choice was caused by the policy change, exactly the same as the congestion charge policy introduced in 2003.

In 2011, affected by the removal of charging in the Western Extension Zone and the increase in the charging rate in the Central Charging Zone, the traffic entering and exiting the Western Extension Zone increased remarkably in almost all intervals apart from the PM peak This proves that the charging has had a huge effect on vehicle use. Because the charge was canceled, commuters did not have to choose the time before dawn to travel to avoid the charge and opted to travel during the main AM peak instead.

The traffic flow entering and exiting the Central Charge Zone has also dramatically increased during the AM peak in the morning by 7.2%, which we can only attribute to the spillover effect (the dramatic traffic increase in the Western Expansion Zone). Traffic flow increased by 11.2% in the AM shoulder, which means that many cars choose to travel ahead of time to avoid payment of a heightened congestion charge.

4.4 Effective Pricing

We consider the new charge rate in 2005 an "effective price" because it caused very similar reductions in traffic flow both at the gateway and inside the Central Charging Zone (it actually led to a similar rate of reduction at all four critical spots, i.e., internal roads, gateways, boundary and bridges). In 2003, when the first charge was introduced, traffic going through the gateway was dramatically reduced (down by 29.9%), while the decrease in traffic inside the Central Zone was much less dramatic (down by 8.8%). This indicates that in 2003, when a low charge rate was in place, a number of drivers could make up the marginal cost of charging by driving more inside the Central Zone. By further raising the charge rate in 2005, this portion of drivers found diminished benefit of doing so and might have opted to leave their cars home.

5. Robustness Check

The validity of the Regression Discontinuity Design method hinges upon the continuity of other variables at the time interval we chose. The choice of the time interval (the "bandwidth"), therefore, has an important impact because the longer the bandwidth, the more likely the other unobservable variables would change and we would get a less precise estimate of the effect of the policy variable. The wider the bandwidth, the more likely people's driving behavior would be affected by other changing factors in addition to the congestion charge. We can use the bandwidth test to identify the effective period of the congestion charge.

Tables 14 through 40 in Appendix C show the bandwidth test for each introduction of policy and the results of the tests when the bandwidth is shortened and extended. The results are listed by zones and time. In the beginning of the part for each zone, tables showing the tests of shortened bandwidth have an incremental alternative of three days, ranging from the 3rd day, 6th day, 9th day … until the 30th day after the introduction of a new policy. After the part about the shortened tests, there are tables displaying the tests of extended bandwidth that have an incremental alternative of 15 days, ranging from the 45th day, 60th day, 75th day … until the 120th day after the introduction of a new policy.

Only Table 14 shows that the congestion charge in the Central Charging Zone had significant effects on the traffic flow on roads within the charging zone at the time when this charge was newly introduced, but the effects on other areas are significant only after the charge had been in place for some time. For instance, in Table 15, the traffic flow only steadily and substantially decreases after 24 days of implementation, which strongly supports the idea that the effect of the congestion charge has "information delay" to some extent. When the bandwidth is within the range of 3 to 30 days, the net effect of the congestion charge steadily and gradually decreases in most bandwidth test results.

The "information delay" of the congestion charge is different under different policies. We compare the effect of the charge in the same area in 2003 and 2005 and find that the delay was longer in 2005. This may be caused by the fact that the marginal cost of driving increased by £5 when the charge began to be implemented in 2003. However, when the charge was raised in 2005, the marginal cost increased by only £3. If the income effect is considered, the charge increase has a less significant effect on marginal costs than the first introduction of the charge. Thus, in the initial introduction, residents were extremely sensitive to changes in prices and costs. When the prices were raised, because the change was smaller, the drivers were less responsive. However, after some time, the impacts of driving cost kicked in, leading more people to give up driving. Thus, when the price was raised, there was an adapting period.

With the process of expanding the bandwidth from 45 days to 120 days, we find that almost all coefficients become insignificant or positive. Over time, the effects were offset by other factors, which led to increased use of vehicles.

6. Benefit and Cost Comparison

The congestion charge policy created both positive and negative externalities to the society, as it creates much social welfare by saving commuting time, at the cost of utility given up by those who switched from driving to public transport.

The social welfare is mainly from improved traffic conditions, which allows higher speed and reliability. As a result, more commuting time is saved for work or leisure. In addition, faster driving not only saved time but also reduced the fuel consumption and emission of toxic pollutants like NOx and CO. According to the TfL annual report, traffic-related NOx and PM10 emissions were reduced by 12% respectively, amounting to a GBP 3 million welfare gain to the society every year.

As shown in Tables 41 and 42 in the Appendix, the first introduction of the congestion charge created annualized welfare of GBP 228 million with a GBP 190 million charging revenue. The first introduction’s benefits are much higher than the added benefits contributed by the later changes in 2005 and 2007. In contrast, the cancellation of the WEZ in 2011 caused a GBP 76 million loss due to the worsened driving conditions, which could have been more severe if the traffic volume in the central zone had not been restrained by the rising fees.

The cost of this policy is relatively fixed, including a lump sum infrastructure cost of GBP 25 million, operating cost of GBP 90 million, negative externalities of GBP 40 million and other minor costs. The negative externality is the inconvenience caused to commuters, who transferred to public transportation from driving. So, the annual cost of this policy is estimated to be GBP 130 million, much lower than the revenue generated from the charges. The surplus is used to improve public transportation, perhaps bringing about additional social well-being.

7. Conclusion

This research has proven the effectiveness of the congestion charge. It finds that the congestion charge is effective in the short term, but the effect becomes more significant as time goes on. This means that the introduction of this charge has some “information delay”, and people need time to adapt. In the long term, its net effects are offset as a series of factors, such as more car ownership and increasing income, take effect. Hence, the charge rate needs to be raised from time to time.

This paper has examined the influence of expanding the charging zone and found the expansion cannot divert the traffic pressure in the original charging zone and that the congestion will spill over to the initial zone. In the meantime, if the charging zone contracts, strong spillover effects will emerge and the congestion will be more serious. However, due to the lack of data from the peripheral non-charging zone, it is impossible to empirically test whether charging will have spillover effects on peripheral non-charging roads. Apart from examining the spillover effects from the perspective of location, this research has also examined such effects from the perspective of time and found that the congestion charge may significantly reduce the traffic flow during the morning and evening peak. However, the reduced traffic flow will partly transfer to the hours before and after the charging period. Finally, we find that this policy contributes net social welfare, but that the net social benefits were reduced when the Western Extension Zone was cancelled.

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Appendices

Appendix A: Summary of Results

Aspect		Policy	Result
Effects on Driving or not	Charging Fee Change	2003 Initiation £0→£5	• All zones' congestion was significantly and dramatically relieved. • Charging policy led to more cars bypassing on boundary roads and induced paid cars to drive more in the inner zone.
		2005 Adjustment £5→£8	• Increasing fees not only decreased the traffic volume on roads, but also induced cars to drive more while they were in the zone. • There may be an effective price that limits induction by rising cost to rule out drivers with higher demand elasticity.
	Charging Area Change	2007 Expansion	• Paid cars' over-driving phenomenon in inner zone and bypassing on boundaries show again in new charging zone. • More cars directly entering into the original charging zone and fewer bypassing around the former boundaries.
		2011 Cancellation	• Significant increase of traffic showed on the area where the Western Extension Zone (WEZ) was after WEZ's congestion charge cancellation. • The spillover effect of removing the charge to the remaining zone is severe.
Effects on Driving time's Choice			• There is spillover effect on time choice that commuters may drive before and after the charging period in a day to avoid being charged.

Appendix B

Table 8: Traffic Volume on Internal Roads in 24h After Charged in 2003 in Central Charging Zone

ln(Volume)	0:00 -6:00	6:00 -7:00	7:00 -10:00	10:00 -16:00	16:00 -18:30	18:30 -20:30	20:30 -24:00
Charge	0.0260	0.0997	-0.1754***	-0.0545	-0.0615	0.1326**	0.0662
	(0.68)	(1.01)	(-3.50)	(-1.55)	(-1.07)	(2.12)	(1.36)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	2.8790***	3.9949***	4.2934***	4.2577***	4.3252***	4.2649***	4.0610***
	(85.51)	(46.08)	(97.60)	(137.96)	(85.50)	(77.87)	(95.09)
Observations	25531	4445	13551	26951	11301	8992	15545
R-squared	0.052	0.025	0.011	0.010	0.007	0.018	0.035

t-statistics in parentheses; ***p<0.01, **p<0.05, *p<0.1

Table 9: Traffic Volume on Gateway Roads in 24h After Charged in 2003 in Central Charging Zone

ln(Volume)	0:00 -6:00	6:00 -7:00	7:00 -10:00	10:00 -16:00	16:00 -18:30	18:30 -20:30	20:30 -24:00
Charge	-0.0451*	0.0075	-0.3255***	-0.2594***	-0.3639***	0.0065	-0.0362
	(-1.74)	(0.12)	(-11.49)	(-15.62)	(-14.62)	(0.22)	(-1.60)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	3.2601***	4.4108***	4.7554***	4.6611***	4.7922***	4.7652***	4.4265***
	(148.67)	(82.35)	(198.07)	(331.11)	(227.22)	(192.26)	(230.40)
Observations	34609	5772	17337	34680	14450	11557	20225
R-squared	0.044	0.006	0.025	0.024	0.057	0.017	0.040

t-statistics in parentheses; ***p<0.01, **p<0.05, *p<0.1

Table 10: Traffic Volume on Gateway Roads in 24h After Charge Raised in 2005 in Central Charging Zone

ln(Volume)	0:00 -6:00	6:00 -7:00	7:00 -10:00	10:00 -16:00	16:00 -18:30	18:30 -20:30	20:30 -24:00
Charge	-0.1294***	0.0227	-0.0580*	-0.1258***	-0.1351***	-0.0958***	-0.1047***
	(-4.62)	(0.35)	(-1.89)	(-6.47)	(-4.68)	(-2.84)	(-3.87)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	3.3166***	4.3247***	4.5347***	4.4846***	4.5418***	4.7505***	4.4174***
	(138.68)	(79.16)	(173.16)	(269.87)	(184.16)	(164.98)	(191.13)
Observations	35599	5943	17828	35659	14862	11884	20800
R-squared	0.031	0.001	0.001	0.003	0.005	0.005	0.014

t-statistics in parentheses; ***p<0.01, **p<0.05, *p<0.1

Table 11: Traffic Volume on Gateway Roads in 24h After Charged in 2007 in Western Extension Zone

ln(Volume)	0:00 -6:00	6:00 -7:00	7:00 -10:00	10:00 -16:00	16:00 -18:00	18:00 -20:00	20:00 -24:00
Charge	-0.0419**	0.0918**	-0.2244***	-0.1601***	-0.2395***	0.0142	-0.0041
	(-2.16)	(2.25)	(-12.32)	(-14.01)	(-13.04)	(0.76)	(-0.26)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	2.5401***	3.6618***	4.3190***	4.2788***	4.4389***	4.4699***	4.0133***
	(155.18)	(106.52)	(281.17)	(444.06)	(299.88)	(283.39)	(289.52)
Observations	60906	10667	32026	64047	24394	21350	39536
R-squared	0.042	0.003	0.016	0.011	0.023	0.009	0.025

t-statistics in parentheses; ***p<0.01, **p<0.05, *p<0.1

Table 12: Traffic Volume on Gateway Roads in 24h After Cancellation in 2011 in Western Extension Zone

ln(Volume)	0:00 -6:00	6:00 -7:00	7:00 -10:00	10:00 -16:00	16:00 -18:00	18:00 -20:00	20:00 -24:00
Charge	-0.5260***	0.0859**	0.2058***	-0.0229*	0.0296	0.0078	-0.1283***
	(-22.89)	(1.96)	(9.45)	(-1.69)	(1.29)	(0.35)	(-7.22)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	2.6581***	3.4066***	3.8814***	4.2157***	4.2389***	4.3434***	3.7974***
	(136.03)	(91.35)	(209.28)	(364.61)	(217.13)	(229.05)	(251.14)
Observations	54138	9395	28186	56357	18791	18792	37581
R-squared	0.059	0.011	0.016	0.002	0.005	0.005	0.045

t-statistics in parentheses; ***p<0.01, **p<0.05, *p<0.1

Table 13: Traffic Volume in Gateway Roads on 24h After Cancellation in 2011 in Central Charging Zone

ln(Volume)	0:00 -6:00	6:00 -7:00	7:00 -10:00	10:00 -16:00	16:00 -18:00	18:00 -20:00	20:00 -24:00
Charge	-0.5853***	0.1118*	0.0723**	-0.1328***	-0.0877**	-0.0265	-0.1654***
	(-20.53)	(1.71)	(2.29)	(-6.53)	(-2.57)	(-0.78)	(-6.47)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	3.1779***	3.9099***	4.0763***	4.2482***	4.2146***	4.4109***	4.0632***
	(130.91)	(70.36)	(151.72)	(245.23)	(145.07)	(152.23)	(186.55)
Observations	33254	5560	16680	33353	11119	11116	22239
R-squared	0.062	0.007	0.007	0.003	0.004	0.007	0.024

t-statistics in parentheses; ***p<0.01, **p<0.05, *p<0.1

Appendix C

Table 14: Bandwidth Check of Congestion Charge Effect on Internal Roads in Central Charging Zone in 2003

Bandwidth	3	6	9	12	15	18	21	24	27	30
/days	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)
Charge	-0.3799*	-0.2684*	-0.3004***	-0.3065***	-0.3135***	-0.2925***	-0.2336***	-0.2020***	-0.1361***	-0.0876***
	(-1.91)	(-1.81)	(-5.11)	(-6.26)	(-8.00)	(-8.21)	(-7.29)	(-6.88)	(-4.93)	(-3.40)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.4548***	4.3781***	4.4472***	4.4561***	4.4773***	4.4612***	4.4094***	4.3815***	4.3271***	4.2818***
	(40.21)	(39.58)	(85.58)	(107.00)	(129.55)	(141.76)	(158.05)	(167.38)	(179.06)	(189.09)
N	5813	11253	16460	21170	25933	31397	36738	42070	47037	51803
R^2	0.007	0.006	0.005	0.006	0.006	0.005	0.005	0.005	0.006	0.009

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 15: Bandwidth Check of Congestion Charge Effect on Internal Roads in Central Charging Zone in 2005

Bandwidth	3	6	9	12	15	18	21	24	27	30
/days	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)
Charge	-0.0038	0.2335*	0.0523	-0.0243	-0.0322	-0.0366	-0.0479	-0.0606**	-0.0908***	-0.0841***
	(-0.02)	(1.67)	(0.96)	(-0.54)	(-0.91)	(-1.13)	(-1.63)	(-2.24)	(-3.57)	(-3.55)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	3.9964***	3.8474***	4.0059***	4.0172***	3.9830***	3.9844***	3.9753***	3.9749***	3.9847***	3.9881***
	(38.63)	(36.44)	(84.35)	(107.79)	(132.75)	(143.23)	(161.17)	(170.14)	(182.14)	(198.65)
N	5240	10392	15635	21148	26753	32273	37787	43297	48812	54602
R^2	0.001	0.006	0.005	0.004	0.004	0.004	0.003	0.003	0.003	0.003

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 16: Bandwidth Check of Congestion Charge Effect on Internal Roads in Central Charging Zone in 2007

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	0.1420	0.0381	-0.0351	-0.0453	-0.0255	-0.0340	-0.0316	-0.0123	-0.0034	0.0134
	(0.82)	(0.30)	(-0.71)	(-1.10)	(-0.77)	(-1.13)	(-1.15)	(-0.49)	(-0.14)	(0.60)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.0441***	4.0810***	4.1248***	4.1325***	4.1137***	4.1192***	4.1292***	4.1221***	4.1151***	4.0979***
	(41.89)	(42.24)	(95.90)	(121.06)	(148.00)	(160.09)	(180.28)	(190.04)	(205.74)	(220.16)
N	6208	12416	18623	24832	31034	37065	43011	48938	54881	60827
R^2	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 17: Bandwidth Check of Congestion Charge Effect on Internal Roads in Central Charging Zone in 2003, 2005, and 2007

Band width /days	2003				2005				2007			
	45 ln(Volume)	60 ln(Volume)	90 ln(Volume)	120 ln(Volume)	45 ln(Volume)	60 ln(Volume)	90 ln(Volume)	120 ln(Volume)	45 ln(Volume)	60 ln(Volume)	90 ln(Volume)	120 ln(Volume)
Charge	-0.1690***	-0.1370***	-0.0057	0.0149	-0.0839***	-0.0949***	-0.0496***	-0.0394***	-0.0077	-0.0128	-0.0049	-0.0475***
	(-7.92)	(-7.40)	(-0.37)	(1.10)	(-4.42)	(-5.84)	(-3.77)	(-3.47)	(-0.43)	(-0.84)	(-0.39)	(-6.65)
FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.3203***	4.3770***	4.2036***	4.1641***	4.0033***	4.0272***	3.9930***	3.9831***	4.1455***	4.1608***	4.1143***	4.1334***
	(228.84)	(258.58)	(293.18)	(325.64)	(247.61)	(295.99)	(362.05)	(415.47)	(276.78)	(324.47)	(393.32)	(934.88)
N	73835	92586	127248	163182	83019	111249	167049	218245	90528	120753	180707	1100374
R^2	0.018	0.013	0.010	0.014	0.003	0.004	0.005	0.005	0.001	0.001	0.001	0.001

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 18: Bandwidth Check of Congestion Charge Effect on Boundary Roads in Central Charging Zone in 2003

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	-0.0814	-0.2056**	-0.0688**	-0.1168***	-0.1125***	-0.0642***	-0.0578***	-0.0789***	-0.0582***	-0.0413***
	(-0.69)	(-2.41)	(-2.05)	(-4.14)	(-4.98)	(-3.14)	(-3.14)	(-4.68)	(-3.68)	(-2.80)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	5.2275***	5.2767***	5.1958***	5.2335***	5.2278***	5.1934***	5.1973***	5.2251***	5.2189***	5.2073***
	(80.14)	(83.24)	(174.83)	(218.39)	(266.04)	(289.26)	(326.39)	(349.48)	(379.78)	(406.51)
N	6808	13078	19149	25250	31321	37577	43741	49996	56344	62692
R^2	0.003	0.002	0.004	0.004	0.003	0.004	0.005	0.005	0.005	0.006

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 19: Bandwidth Check of Congestion Charge Effect on Boundary Roads in Central Charging Zone in 2005

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	0.0179	0.3810***	0.0387	-0.2014***	-0.1728***	-0.1917***	-0.1808***	-0.1758***	-0.1871***	-0.1772***
	(0.20)	(4.55)	(1.27)	(-8.21)	(-8.95)	(-11.07)	(-11.73)	(-12.57)	(-14.40)	(-14.77)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	5.2672***	5.2455***	5.3882***	5.4005***	5.3205***	5.3185***	5.2969***	5.2990***	5.3045***	5.2972***
	(107.22)	(82.99)	(201.51)	(263.62)	(324.89)	(357.46)	(407.46)	(437.10)	(472.15)	(517.31)
N	6900	13749	20649	27549	34355	41255	48149	55049	61949	68849
R^2	0.000	0.071	0.045	0.024	0.018	0.014	0.012	0.011	0.010	0.009

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 20: Bandwidth Check of Congestion Charge Effect on Boundary Roads in Central Charging Zone in 2007

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	-0.1168	-0.0510	-0.0777***	-0.0892***	-0.0544***	-0.0407***	-0.0276**	-0.0159	-0.0172	-0.0189*
	(-1.36)	(-0.80)	(-3.14)	(-4.34)	(-3.28)	(-2.68)	(-2.01)	(-1.26)	(-1.46)	(-1.73)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	5.3174***	5.2870***	5.3035***	5.3034***	5.2655***	5.2606***	5.2562***	5.2473***	5.2405***	5.2402***
	(111.56)	(110.22)	(246.52)	(311.18)	(377.48)	(405.95)	(458.39)	(484.56)	(527.04)	(570.31)
N	7826	15656	23486	31316	39146	46976	54806	62636	70466	78296
R^2	0.002	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 21: Bandwidth Check of Congestion Charge Effect on Boundary Roads in Central Charging Zone in 2003, 2005, and 2007

Band width /days	2003				2005				2007			
	45 ln(Volume)	60 ln(Volume)	90 ln(Volume)	120 ln(Volume)	45 ln(Volume)	60 ln(Volume)	90 ln(Volume)	120 ln(Volume)	45 ln(Volume)	60 ln(Volume)	90 ln(Volume)	120 ln(Volume)
Charge	-0.0548***	-0.0471***	0.0615***	0.1337***	-0.1273***	-0.0995***	-0.0751***	-0.0492***	-0.0258***	-0.0255***	-0.0281***	0.0059*
	(-4.53)	(-4.57)	(7.51)	(19.12)	(-13.51)	(-12.44)	(-11.67)	(-8.93)	(-2.93)	(-3.36)	(-4.56)	(1.77)
FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	5.2106***	5.2622***	5.1802***	5.1048***	5.2722***	5.2685***	5.2540***	5.2530***	5.2407***	5.2487***	5.2496***	5.2326***
	(492.55)	(579.56)	(711.71)	(813.90)	(650.19)	(777.10)	(958.73)	(1117.58)	(712.26)	(825.87)	(1013.80)	(2554.13)
N	93324	121931	175961	229457	102795	137295	205741	274602	117445	155710	233736	1440712
R^2	0.014	0.011	0.018	0.013	0.005	0.003	0.003	0.002	0.001	0.001	0.001	0.001

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 22: Bandwidth Check of Congestion Charge Effect on Bridges in Central Charging Zone in 2003

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	-0.4365**	-0.4278***	-0.3010***	-0.2921***	-0.2674***	-0.2803***	-0.3011***	-0.2908***	-0.3005***	-0.3106***
	(-2.17)	(-2.88)	(-5.23)	(-6.08)	(-6.82)	(-7.76)	(-9.14)	(-9.62)	(-10.58)	(-11.77)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	5.0448***	5.0559***	4.9592***	4.9517***	4.9266***	4.9377***	4.9532***	4.9544***	4.9620***	4.9718***
	(45.11)	(45.16)	(98.46)	(123.41)	(146.28)	(157.56)	(175.41)	(186.26)	(202.49)	(218.98)
N	1656	3312	4968	6624	8004	9384	10810	12328	13846	15364
R^2	0.066	0.054	0.051	0.048	0.041	0.037	0.034	0.030	0.027	0.025

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 23: Bandwidth Check of Congestion Charge Effect on Bridges in Central Charging Zone in 2005

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	0.2356	0.1757	0.1825	0.0371	0.0973	0.1294*	0.0322	-0.0341	-0.1013**	-0.1636***
	(0.42)	(0.41)	(1.22)	(0.32)	(1.08)	(1.69)	(0.49)	(-0.61)	(-2.02)	(-3.66)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.0674***	4.1243***	4.2013***	3.9918***	3.9069***	3.9356***	3.9826***	4.0234***	4.0622***	4.1162***
	(12.99)	(12.91)	(32.35)	(40.49)	(51.18)	(59.67)	(72.78)	(82.45)	(93.91)	(108.96)
N	1379	2748	4059	5396	6756	8136	9608	11310	13104	14898
R^2	0.000	0.002	0.030	0.028	0.031	0.038	0.042	0.048	0.051	0.053

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 24: Bandwidth Check of Congestion Charge Effect on Bridges in Central Charging Zone in 2007

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	-0.0464	-0.0508	-0.0430	-0.0446	-0.0185	-0.0392	-0.0321	-0.0160	-0.0070	0.0049
	(-0.22)	(-0.32)	(-0.70)	(-0.88)	(-0.44)	(-1.04)	(-0.96)	(-0.53)	(-0.25)	(0.19)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.5914***	4.5781***	4.6043***	4.5843***	4.5539***	4.5704***	4.5736***	4.5707***	4.5528***	4.5334***
	(39.77)	(37.74)	(87.76)	(111.51)	(133.76)	(146.28)	(167.88)	(180.83)	(199.28)	(216.80)
N	1758	3516	5274	7032	8790	10548	12306	14064	15822	17580
R^2	0.001	0.001	0.001	0.001	0.003	0.002	0.002	0.003	0.003	0.003

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 25: Bandwidth Check of Congestion Charge Effect on Bridges in Central Charging Zone in 2003, 2005, and 2007

Band	2003				2005				2007			
width	45	60	90	120	45	60	90	120	45	60	90	120
/days	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)
Charge	-0.3494***	-0.2362***	-0.1786***	-0.1763***	-0.1984***	-0.1680***	-0.2197***	-0.1897***	0.0104	0.0455***	0.0399***	-0.0067
	(-16.74)	(-13.33)	(-12.57)	(-14.50)	(-6.28)	(-6.67)	(-11.83)	(-12.59)	(0.51)	(2.61)	(2.86)	(-0.87)
FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.9891***	4.9413***	4.8883***	4.8670***	4.2004***	4.2776***	4.4123***	4.4827***	4.5489***	4.5374***	4.5228***	4.5806***
	(281.42)	(327.20)	(402.37)	(460.84)	(156.96)	(203.76)	(283.68)	(353.86)	(274.33)	(317.56)	(392.02)	(969.31)
N	23552	31832	48392	62468	23040	31319	47879	64255	25818	33458	48278	327994
R^2	0.031	0.030	0.033	0.030	0.053	0.049	0.038	0.030	0.003	0.003	0.005	0.019

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 26: Bandwidth Check of Congestion Charge Effect on Gateway Roads in Central Charging Zone in 2003

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	-0.3796***	-0.4392***	-0.3045***	-0.3311***	-0.3335***	-0.3377***	-0.3309***	-0.3212***	-0.3132***	-0.2994***
	(-3.74)	(-5.92)	(-10.50)	(-13.73)	(-17.34)	(-19.29)	(-20.99)	(-22.16)	(-23.06)	(-23.68)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.7946***	4.8156***	4.7305***	4.7407***	4.7357***	4.7297***	4.7251***	4.7178***	4.7195***	4.7142***
	(85.07)	(86.14)	(186.37)	(235.14)	(290.05)	(314.32)	(355.07)	(375.06)	(408.71)	(440.07)
N	6624	13248	20010	26723	33347	39971	46595	53219	59843	66467
R2	0.066	0.061	0.052	0.045	0.041	0.039	0.037	0.034	0.032	0.029

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 27: Bandwidth Check of Congestion Charge Effect on Gateway Roads in Central Charging Zone in 2005

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	0.0360	0.0940	-0.0450	-0.1503***	-0.1391***	-0.1352***	-0.1284***	-0.1114***	-0.1226***	-0.1101***
	(0.32)	(1.06)	(-1.34)	(-5.46)	(-6.29)	(-6.74)	(-7.12)	(-6.73)	(-7.93)	(-7.66)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.4770***	4.5472***	4.5585***	4.5717***	4.5360***	4.5407***	4.5246***	4.5074***	4.5096***	4.5101***
	(70.97)	(67.54)	(155.39)	(198.80)	(241.64)	(263.44)	(297.03)	(314.22)	(336.87)	(367.34)
N	6900	13754	20652	27552	34449	41349	48201	54917	61587	68349
R2	0.004	0.014	0.008	0.005	0.004	0.003	0.003	0.002	0.003	0.002

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 28: Bandwidth Check of Congestion Charge Effect on Gateway Roads in Central Charging Zone in 2007

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	0.0434	0.0060	-0.0106	-0.0298	-0.0069	0.0027	0.0190	0.0340**	0.0363**	0.0404***
	(0.40)	(0.07)	(-0.34)	(-1.14)	(-0.33)	(0.14)	(1.10)	(2.14)	(2.42)	(2.89)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.3626***	4.3989***	4.3998***	4.3937***	4.3682***	4.3639***	4.3562***	4.3498***	4.3412***	4.3345***
	(72.68)	(72.22)	(160.99)	(203.02)	(248.06)	(268.42)	(302.33)	(317.59)	(343.77)	(369.40)
N	6480	12958	19438	25918	32398	38878	45358	51838	58318	64798
R2	0.001	0.001	0.002	0.002	0.002	0.001	0.001	0.002	0.002	0.002

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 29: Bandwidth Check of Congestion Charge Effect on Gateways Roads in Central Charging Zone in 2011

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	0.7785***	0.0537	-0.0655**	-0.0382	-0.0814***	-0.0564***	-0.0814***	-0.0754***	-0.0721***	-0.0687***
	(4.36)	(0.36)	(-2.01)	(-1.34)	(-3.48)	(-2.70)	(-4.26)	(-4.31)	(-4.38)	(-4.47)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	3.6785***	3.9135***	4.0146***	4.0395***	4.1285***	4.1287***	4.1852***	4.1926***	4.1924***	4.1952***
	(39.05)	(47.49)	(118.89)	(160.37)	(206.76)	(219.69)	(253.57)	(267.06)	(293.46)	(320.75)
N	6072	12144	18215	24287	30359	36431	42547	48744	54948	61152
R2	0.015	0.011	0.010	0.007	0.005	0.005	0.004	0.004	0.003	0.003

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 30: Bandwidth Check of Congestion Charge Effect on Gateways Roads in Central Charging Zone in 2003 and 2005

Bandwidth /days	2003				2005			
	45	60	90	120	45	60	90	120
	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)
Charge	-0.3379***	-0.2355***	-0.2051***	-0.1874***	-0.0757***	-0.0476***	-0.0521***	-0.0190***
	(-32.89)	(-26.45)	(-28.04)	(-29.64)	(-6.58)	(-4.83)	(-6.49)	(-2.74)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.7708***	4.7446***	4.7305***	4.7000***	4.5228***	4.5057***	4.4832***	4.4579***
	(544.86)	(614.57)	(735.96)	(839.67)	(455.98)	(536.32)	(653.75)	(752.18)
N	97650	121615	169589	217887	101051	132009	192360	250228
R2	0.032	0.029	0.030	0.028	0.003	0.004	0.006	0.008

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 31: Bandwidth Check of Congestion Charge Effect on Gateways Roads in Central Charging Zone in 2007 and 2011

Bandwidth /days	2007				2011			
	45	60	90	120	45	60	90	120
	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)
Charge	0.0137	0.0298***	0.0353***	0.1303***	-0.0521***	-0.0286***	0.0436***	0.0456***
	(1.21)	(3.08)	(4.50)	(30.69)	(-4.17)	(-2.66)	(4.90)	(5.94)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.3747***	4.3694***	4.3536***	4.3026***	4.2074***	4.2186***	4.1555***	4.1946***
	(461.97)	(538.60)	(659.10)	(1654.66)	(397.31)	(466.10)	(551.34)	(649.14)
N	97198	129587	194383	1300988	91974	125634	191564	254966
R2	0.002	0.002	0.001	0.022	0.002	0.005	0.006	0.006

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 32: Bandwidth Check of Congestion Charge Effect on Internal Roads in Western Extension Zone in 2007

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	-0.2358*	-0.0105	-0.1317***	-0.1386***	-0.1012***	-0.1020***	-0.1026***	-0.0950***	-0.0970***	-0.0921***
	(-1.93)	(-0.12)	(-3.71)	(-4.68)	(-4.29)	(-4.82)	(-5.44)	(-5.49)	(-6.00)	(-6.13)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.1072***	3.9678***	4.0424***	4.0546***	4.0123***	4.0070***	4.0084***	4.0012***	3.9922***	3.9819***
	(60.60)	(58.19)	(130.83)	(165.07)	(202.01)	(222.19)	(260.32)	(275.01)	(303.07)	(328.76)
N	4588	9178	13768	18356	22946	29744	36542	43340	50138	56936
R2	0.011	0.009	0.007	0.007	0.006	0.006	0.007	0.007	0.007	0.006

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 33: Bandwidth Check of Congestion Charge Effect on Boundary Roads in Western Extension Zone in 2007

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	0.2427	-0.2171**	-0.0031	-0.0578	-0.0522	-0.0438	0.0509	0.1435***	0.1189***	0.1154***
	(1.55)	(-2.02)	(-0.04)	(-0.80)	(-0.92)	(-0.86)	(1.13)	(3.47)	(3.17)	(3.38)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.9507***	5.1814***	5.0651***	5.0719***	5.0394***	5.0736***	4.9855***	4.8837***	4.9395***	4.9564***
	(56.89)	(63.77)	(77.28)	(90.40)	(104.02)	(119.73)	(135.99)	(140.79)	(154.38)	(166.54)
N	540	1080	2588	6032	9476	14162	18848	23534	28218	32904
R2	0.060	0.028	0.032	0.015	0.014	0.011	0.008	0.005	0.004	0.004

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 34: Bandwidth Check of Congestion Charge Effect on Bridge Roads in Western Extension Zone in 2007

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	-0.3354**	-0.2889**	-0.3236***	-0.3127***	-0.2477***	-0.2256***	-0.1863***	-0.1553***	-0.1749***	-0.1725***
	(-2.08)	(-2.41)	(-6.83)	(-7.85)	(-7.88)	(-7.71)	(-6.88)	(-5.96)	(-7.21)	(-7.64)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.7893***	4.7681***	4.7800***	4.7622***	4.7356***	4.7269***	4.6719***	4.6433***	4.6530***	4.6416***
	(53.58)	(52.74)	(115.42)	(145.40)	(177.69)	(189.53)	(214.68)	(216.00)	(240.02)	(259.68)
N	1080	2160	3328	4672	6016	8464	10912	13343	15791	18239
R2	0.107	0.087	0.073	0.077	0.075	0.102	0.104	0.088	0.093	0.092

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 35: Bandwidth Check of Congestion Charge Effect on Gateway Roads in Western Extension Zone in 2007

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	-0.2402**	-0.2492***	-0.2383***	-0.2635***	-0.2459***	-0.2603***	-0.2531***	-0.2338***	-0.2425***	-0.2276***
	(-2.22)	(-3.10)	(-7.70)	(-10.33)	(-12.57)	(-15.06)	(-16.54)	(-16.72)	(-18.62)	(-18.82)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.3658***	4.3486***	4.3614***	4.3500***	4.3208***	4.3351***	4.3314***	4.3209***	4.3296***	4.3168***
	(72.65)	(71.71)	(161.22)	(207.23)	(264.75)	(297.60)	(350.66)	(373.18)	(412.65)	(447.01)
N	7555	15115	23290	32698	44452	59655	74859	90059	105263	120467
R2	0.031	0.030	0.024	0.022	0.018	0.019	0.018	0.016	0.016	0.015

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 36: Bandwidth Check of Congestion Charge Effect on Bridge Roads in Western Extension Zone in 2007

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	-0.0426	0.4850***	-0.0543	-0.1521***	-0.1506***	-0.1610***	-0.1657***	-0.1674***	-0.1400***	-0.1391***
	(-0.37)	(3.91)	(-1.44)	(-4.92)	(-5.83)	(-6.76)	(-7.48)	(-8.23)	(-7.39)	(-7.67)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.4930***	4.3628***	4.4714***	4.5995***	4.6111***	4.6167***	4.6225***	4.6182***	4.5863***	4.5785***
	(84.52)	(108.15)	(139.52)	(185.32)	(208.91)	(225.66)	(257.73)	(258.63)	(292.96)	(295.22)
N	688	1400	2276	3152	4208	5162	5960	6914	8792	10646
R2	0.002	0.092	0.073	0.058	0.066	0.065	0.071	0.067	0.097	0.100

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 37: Bandwidth Check of Congestion Charge Effect on Bridge Roads in Western Extension Zone in 2007

Bandwidth /days	30 ln(Volume)	60 ln(Volume)	90 ln(Volume)	120 ln(Volume)	150 ln(Volume)	180 ln(Volume)	210 ln(Volume)	240 ln(Volume)	270 ln(Volume)	300 ln(Volume)
Charge	-0.1391***	-0.2616***	-0.3829***	-0.3560***	-0.2943***	-0.2313***	-0.2240***	-0.2154***	-0.2058***	-0.1814***
	(-7.67)	(-18.71)	(-37.72)	(-43.82)	(-41.84)	(-36.24)	(-38.18)	(-39.52)	(-39.05)	(-35.87)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.5785***	4.6856***	4.7902***	4.7745***	4.7203***	4.6912***	4.6781***	4.6539***	4.6350***	4.6187***
	(295.22)	(387.97)	(552.69)	(685.77)	(782.20)	(859.39)	(935.27)	(995.75)	(1033.62)	(1088.75)
N	10646	23685	32353	42103	53178	63996	75354	86700	95456	102256
R2	0.100	0.087	0.080	0.073	0.055	0.056	0.053	0.044	0.042	0.043

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 38: Bandwidth Check of Congestion Charge Effect on Gateway Roads in Western Extension Zone in 2007

Bandwidth /days	3 ln(Volume)	6 ln(Volume)	9 ln(Volume)	12 ln(Volume)	15 ln(Volume)	18 ln(Volume)	21 ln(Volume)	24 ln(Volume)	27 ln(Volume)	30 ln(Volume)
Charge	0.0058	0.4534***	-0.0489**	-0.1639***	-0.1514***	-0.1486***	-0.1764***	-0.1678***	-0.1657***	-0.1569***
	(0.08)	(5.59)	(-1.98)	(-8.26)	(-9.16)	(-9.88)	(-12.84)	(-13.53)	(-14.73)	(-15.10)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.1279***	4.0223***	4.1045***	4.2166***	4.2218***	4.2365***	4.2681***	4.2712***	4.2755***	4.2743***
	(123.99)	(152.66)	(195.26)	(265.04)	(299.42)	(327.99)	(387.08)	(392.65)	(460.53)	(481.77)
N	4811	9795	15927	22059	29451	36129	43245	50687	61943	73659
R2	0.001	0.027	0.024	0.018	0.018	0.017	0.016	0.014	0.016	0.015

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 39: Bandwidth Check of Congestion Charge Effect on Internal and Boundary Roads in Western Extension Zone in 2007

Bandwidth	Internal				Boundary			
/days	45	60	90	120	45	60	90	120
	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)
Charge	-0.0886***	-0.0903***	-0.0944***	-0.0820***	0.1490***	0.1843***	-0.0155	-0.2605***
	(-7.23)	(-8.49)	(-11.02)	(-11.28)	(6.33)	(9.95)	(-1.11)	(-23.26)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.0188***	4.0544***	4.0403***	3.9842***	4.9604***	4.9283***	5.1379***	5.4168***
	(401.02)	(460.43)	(561.94)	(649.87)	(225.22)	(279.59)	(384.96)	(509.39)
N	82966	103887	143478	181984	61900	93834	162012	226558
R2	0.006	0.005	0.006	0.007	0.005	0.005	0.024	0.024

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Table 40: Bandwidth Check of Congestion Charge Effect on Bridge and Gateway Roads in Western Extension Zone in 2007

Bandwidth /days	Bridge				Gateway			
	45	60	90	120	45	60	90	120
	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)	ln(Volume)
Charge	-0.1442***	-0.2225***	-0.4134***	-0.4012***	-0.2163***	-0.2068***	-0.1326***	-0.1353***
	(-7.98)	(-14.89)	(-37.11)	(-44.64)	(-22.52)	(-25.47)	(-20.74)	(-24.61)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	4.5977***	4.6776***	4.8668***	4.8342***	4.3502***	4.3517***	4.3191***	4.3164***
	(309.83)	(372.84)	(516.11)	(640.80)	(554.83)	(647.39)	(805.33)	(923.49)
N	25595	32314	47408	63608	178909	222879	297355	362918
R2	0.099	0.095	0.068	0.066	0.016	0.019	0.023	0.027

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01

Appendix D

Table 41: Cost and Benefit Analysis on Congestion Charge Policy, Based on the Volume Change

Million in GBP(£)	2003	2005	2007	2011
Annualized Benefits (Net Added)	**228**	**70**	**120**	**-76**
Traffic Fee Revenue	**190**	**210**	**268**	**227**
Total Cost	**-135**	**-121**	**-131**	**-121**

Note: Revenue and cost are from annual reports of Transport for London. Benefits are estimated by authors; please find details in the references.

Table 42: Cost and Benefits Analysis: Driven by Changes on Volume

Millions in GBP			**2003**	**2005**	**2007**		**2011**	
#1		**Benefit (per year)**	CCZ	CCZ	CCZ	WEZ	CCZ	WEZ
	a	Time Saved	196.49	36.94	19.87	34.52	-6.71	-30.50
		Directly- Value of travel time saved	170.64	32.06	17.25	29.96	-5.82	-26.47
		Indirectly- Reliability Improved	25.85	4.88	2.62	4.56	-0.89	-4.03
	b	Air Quality Improved	3.00	3.00	3.00	3.00	-3.00	-3.00
		NOx and PM10	2.00	2.00	2.00	2.00	-2.00	-2.00
		CO2	1.00	1.00	1.00	1.00	-1.00	-1.00
	c	Fuel Consumption Reduced	15.00	16.00	16.00	16.00	-3.11	-14.14
	d	Accidents Reduced	14.00	14.00	14.00	14.00	-2.72	-12.37
Total			*228.49*	*69.94*	*52.87*	*67.52*	*-15.54*	*-60.00*
#2		**Cost (per year)**						
	a	Infrastructure	-25.00	0.00	0.00	0.00	0.00	0.00
	b	Operating	-90.00	-90.00	-91.00	0.00	-91.00	0.00
	c	Inconvenience to those switching to public transit	-20.00	-31.00	-40.00	0.00	-30.00	0.00
Total			*-135.00*	*-121.00*		*-131.00*		*-121.00*