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Affected Area and Residual Period of London Congestion Charging Scheme on Road Safety

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ABSTRACT

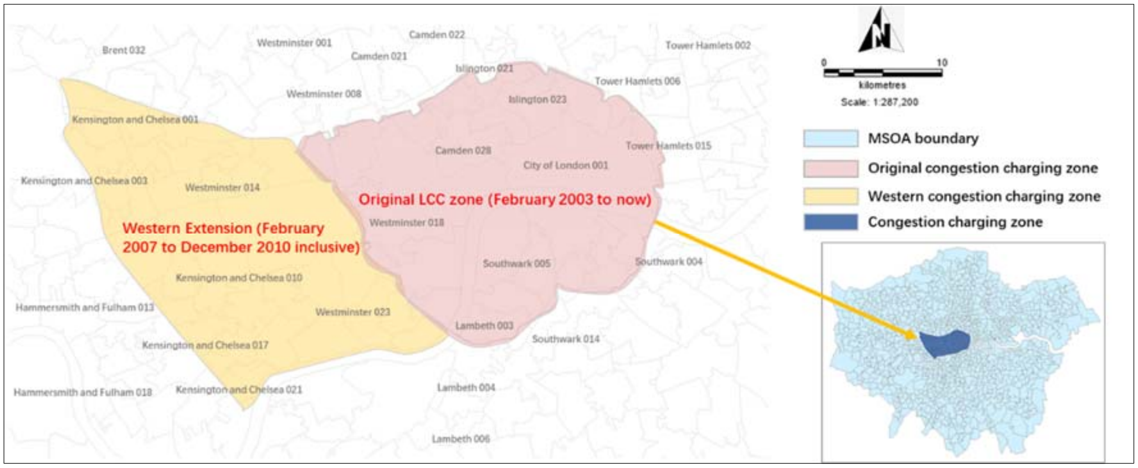
The London congestion charging (LCC) scheme was first introduced in 2003. It did not only help alleviate traffic congestion and reduce vehicle emissions, but also had favorable safety effect. Western Extension of LCC was applied in 2007, but then removed in 2011. It was suggested that adjacent areas of the congestion charging zone could also be benefited. As well, the benefits would not disappear immediately after the removal of congestion charging scheme, which is known as residual effect. This paper attempts to examine the affected area and residual period of the safety benefits by the LCC scheme using the traffic and crash data from 352 Middle Super Output Areas (MSOAs) of London, with which the original LCC scheme was imposed in 24 MSOAs ('treatment' units for Analysis I), the Western Extension scheme was imposed in 27 MSOAs ('treatment' units for Analysis II), and no congestion charging was implemented at all in 301 MSOAs ('control' units for both Analysis I and II). Factors including traffic flow, land use, built environment and population demographics are considered. To eliminate the bias by the selection of treatment and control groups, Propensity Score matching (PSM) method is applied. Results indicate that favorable effect on safety is prevalent in the 1.5 km buffer area of LCC zone. On the other hand, for the residual effect, considerable crash reduction could be found in the first year after the removal of Western Extension of LCC. However, no evidence could be established for significant crash reduction in the second and third years after the removal. Findings should be indicative to the transport management policy that could improve the road safety in the Greater London in the long run.

Keywords: Traffic safety, London congestion charging (LCC) scheme, affected area, residual effect

1. IINTRODUCTION

Congestion charging is a transport management policy initiative aiming to tackle the traffic congestion problem by regulating excess demand for the scarce road space. Many cities, such as Singapore, Stockholm, Milan and London, have implemented congestion charging in the urban areas since 1990s. The congestion charging schemes implemented can be classified into several types, such as cordon scheme (e.g. Singapore and Stockholm), zone scheme (e.g. Florence) and area scheme (e.g. London) (Hong Kong Transport Department, 2009). Congestion charging scheme was found to be effective in reducing traffic volume, lowering vehicle emission and improving traffic speed (Percoco, 2015; Tang, 2016). For example, traffic entering the city center was reduced by 18%, average traffic speed was increased by 30% and traffic-related emission of CO_2 and NO_x was reduced by 20% and 12% respectively, after the implementation of London Congestion Charging (LCC) scheme (Transport for London, 2003; Beevers and Carslaw, 2005a; Noland et al., 2008). However, there were also barriers to the pursuit of the implementation of congestion charging. The public could be skeptical about the policy because of perceived effectiveness and awareness of environment and car-dependent problem (Sugiartoa et al., 2017, 2020).

Congestion charging scheme was first introduced in London in February 2003. The LCC zone initially covered the area within the London Inner Ring Road. Land area was 21 km^2 (accounting for 1.3% of total land area of the Greater London), and there were 140,000 residents (1.5% of total Greater London population). The Western Extension (of LCC) was applied in February 2007, but then removed in January 2011 considering the strong views from the residents, businesses and other stakeholders (Li et al, 2018; Noland et al., 2008). According to a survey in October 2010, 62% of respondents opposed against the implementation of the Western Extension. There were also serious barriers to the pursuit of congestion charging policy in Edinburgh and Manchester (Saunders., 2005; May et al., 2010). **Figure 1** illustrates the boundaries of the original LCC zone and the Western Extension. Under the LCC scheme, vehicles operating in the concerned area between 7:00 am and 6:00 pm on the weekdays are charged. Public transport vehicles including buses and taxis, emergency vehicles and motorcycles are exempted. The charge was £5 per day in 2003, and then increased to £11.5 per day in 2014. Residents of LCC zone can enjoy a 90% discount (Santos and Bhakar, 2006).



(Source: https://data.london.gov.uk/dataset/statistical-gis-boundary-files-london)

Figure 1. Boundary of London congestion charging zone

In addition to the favorable effects on traffic congestion, vehicle emission, and speed, congestion charging can also result in safety improvement (Transport for London, 2005). Study indicated that the number of kill and severe injury (KSI) crash in LCC zone was reduced by 14% after the implementation of congestion charging (Li et al, 2012). However, the affected area of congestion charging is rarely investigated. For instance, the traffic congestion and road crashes in adjacent areas ('dilemma' area) of LCC zone can also decrease. It is worth investigating the characteristics of the affected area (i.e. trend of effect size with respect to buffer distance) of congestion charging. Additionally, the favorable effects of congestion charging may persist even after the scheme was removed since the private car users may have switched to other transport modes like public transport, walking and cycling (Allcott and Rogers., 2012). This implies that there is possible spillover effect over time, even after the abolishment of an intervention (Lagarde et al, 2011; Wang et al., 2018; Ramiah et al., 2017, Preecha and Wianwiwat., 2017). Hence, the residual period of the safety effect after the removal of the Western Extension would be investigated. This paper contributes to the literature by estimating the affected area of safety benefits by the LCC and the residual period at which the impact would sustain after the abolishment of LCC, using crash data in the Greater London in the period from 2005 to 2013. Additionally, to measure the effects of an intervention on an entity, it is crucial to account for the effects of possible factors other than the intervention itself. Therefore, the propensity score matching (PSM) method is applied to establish the control group for the comparison, with which the possible confounding factors are accounted.

The paper is organized as follows. Section 2 presents the literature review on the relationship between congestion charging and road safety. Then, method of analysis and data collection are described in section 3 and section 4. Section 5 and section 6 discuss the results and policy implications. Finally, a concluding remark is provided in section 7.

2. LITERATURE REVIEW

2.1 Previous research

Many studies have evaluated the effects of congestion charging on the attributes including public perception (Santos, 2004; Eliasson and Jonsson, 2011; Li et al., 2012; Zheng et al., 2014; Sugiarto et al., 2015; Börjesson et al., 2015; Grisolía et al., 2015; Börjesson et al., 2012), traffic congestion (Li et al., 2012; Beevers and Carslaw, 2005b; Santos and Bhakar, 2006; Hensher and Puckett, 2007; Xie and Olszewski, 2011; Tang, 2016), vehicle emissions (Beevers et al., 2005a; Atkinson et al., 2009; Percoco., 2015) and economy (Santos, 2004; Eliasson et al., 2009; Levinson, 2010; Givoni, 2012; Quddus et al., 2007; Prud'homme and Bocarejo, 2005). Not only the favorable effects on traffic flow characteristics (i.e. traffic volume and vehicle speed), vehicle emissions and economy, but also the safety benefits of introducing congestion charging could be revealed (Transport for London, 2005). Indeed, congestion charging can alleviate traffic congestions by reducing the traffic level, travel time and increasing vehicle speed. Both traffic volume and speed can, in turn, affect road safety (Lord et al., 2005). Studies indicated that both crash frequency and crash rate reduced remarkably after the introduction of congestion charging (Leape, 2006; Quddus, 2008a, b; Noland et al., 2008; Green et al., 2016). Despite that, study indicated that crashes involving two-wheeled vehicles could increase after the implementation of congestion charging (Li et al., 2012). However, previous studies are limited in investigating the effect of congestion charging on the crash distribution with respect to the attributes including vehicle class and road user type. Sensitivities of traffic characteristics like traffic volume, travel time and vehicle speed are often ignored.

On the other hand, researchers have been paying more attention to the residual effect (i.e. spillover effect over time) on social well-being after the abolishment of a public policy, such as financial subsidization scheme, transport demand management and healthcare system reform (Lagarde et al, 2011; Wang et al., 2018). Results indicated that residual effects of the abolished policies could persist for 15 to 23 months. As well, the residual periods (i.e. durations that the spillover effects persist) could vary across different geographical locations (Allcott and Rogers., 2012; Ramiah et al., 2017, Preecha and Wianwiwat., 2017). Hence, it is hypothesized that the LCC (the abolished Western Extension) can also have residual effects on travel behavior, and therefore road safety level. As such, the residual period of congestion charging should be investigated.

2.2 The current paper

This study aims to investigate the affected area and residual period of LCC scheme for road safety improvement. Previous studies indicated that congestion charging could have favorable effects on overall safety levels. However, the influence areas were limited to the LCC zone only. Indeed, traffic characteristics in the areas adjacent to the LCC zone could be similar. Therefore, the safety benefits could have been underestimated. Additionally, to the best of our knowledge, the residual effects of LCC on road safety have not yet been attempted. Indeed, the influences of a policy intervention would not be vanished immediately after the abolishment. There is possible spillover effect over time because of the persistence of social norms (Allcott and Rogers, 2012). Therefore, to better estimate the safety influence of the removal of LCC, it is crucial to estimate the residual period of an abolished congestion management policy. Moreover, to solve the fundamental questions of how to account for the non-randomized intervention and possible confounding factors in the empirical studies, the PSM approach is applied to estimate the difference between treatment and control group. Findings of this study can facilitate the decision making of transport planners and engineers, particularly the optimum transport policy that can maximize the overall safety benefits.

3. METHOD

For the effectiveness evaluation of an intervention, it is essential to assess the performance of the same entity if the intervention had not been implemented (Guo et al., 2020). This is known as 'control'. In the experimental study, it is possible to select the control group using randomized control trial. Then, possible selection and allocation bias can be eliminated. However, for the empirical studies on transport demand management and road safety intervention, it may not be practical and ethical to apply the randomized control trial approach for selecting the treatment and control (not treated) groups (Wood et al., 2015a; Li et al., 2018; Guo et al., 2018a; Li et al., 2019).

Similar to other causal analysis (Sasidharan and Donnell, 2013; Wood et al., 2017; Wood et al., 2015b), the PSM method is applied to evaluate the safety effects of LCC scheme (treatment), while the bias by possible confounding factors that predict the entities receiving the treatment are accounted for (Rosenbaum and Rubin, 1983). Compared to other matching approaches, PSM method applies one single index - propensity score - to create a counterfactual control group, based on more than one matching covariate. It is an efficient matching tool for the empirical settings with which the number of units in the control group is relatively less.

3.1 Notations

Let $y_i\ (D)$ denote the outcome of unit i, where i = 1,2, …and N, and N is the total number of units (i.e. zone). Set the treatment indicator D_i = 1 if unit i receives the treatment, and D_i = 0 otherwise. The treatment effect for unit i can be specified as,

$$\delta_i = y_i\ (1) - y_i\ (0)$$

Then, the parameter of interest is Average Treatment Effect (*ATT*) for the treated unit. It can be specified as,

$$\delta_{ATT} = E(\delta|T=1) = E(Y(1)|T=1) - E(Y(0)|T=1)$$

3.2 Key assumptions

There are three key assumptions to guarantee the validity and accuracy of the results of PSM (Rosenbaum and Rubin, 1983).

(1) Assumption 1: Stable Unit Treatment Value Assumption (SUTVA)

SUTVA requires that no intervention (congestion charging scheme) is imposed for any unit (untreated) other than the treatment units

(2) Assumption 2: Conditional Independence Assumption (CIA)

CIA assumes that probability of the outcomes is independent of the treatment status, with which all observed factors are controlled for. CIA can be described as,

$$(Y(1), Y(0)) \perp T|X.$$

(3) Assumption 3: Common Support Condition (CSC)

CSC is known as overlap assumption. It ascertains that control group can be identified for each treatment group. Also, there is enough overlap for the characteristics of treatment and control units for the matching. CSC can be described as,

$$0 < P(T=1|X) < 1 \text{ (Overlap)}$$

3.3 Implementation of PSM

There are three steps for the implementation of PSM method as follows.

(1) Step 1: Calculate the propensity score

Propensity score can be calculated by discrete choice model family (Smith, 1977; Guo et al., 2018b). In this study, a logit model specified as follow is applied,

$$P(T=1|X) = \frac{EXP(\alpha + \boldsymbol{\beta}'\boldsymbol{X})}{1 + EXP(\alpha + \boldsymbol{\beta}'\boldsymbol{X})}$$

where α is the intercept and $\boldsymbol{\beta}'$ is the vector of parameters for covariate $\boldsymbol{X}$.

(2) Step 2: Select the matching algorithm

Reliability of PSM outcome depends on the matching algorithm. Four common matching algorithms, including K-nearest neighbors matching, caliper and radius matching, kernel and local linear matching, stratification and interval matching, can be applied (Heinrich et al., 2010). In this study, all the above four matching algorithms are considered for comparison.

(3) Step 3: Estimate the treatment effect

Treatment (e.g. LCC) effect is estimated by assessing the treatment and corresponding control units. In this study, the Psmatch2 in STATA package is applied to estimate the treatment effect (Leuven and Sianesi, 2003).

To investigate the affected area and residual period of LCC on safety, the control group is set out and the safety effects is assessed using the procedures as follows in this study.

(1) Information on crash frequency, built environment, traffic flow and population demographic profile of all units (both treated and untreated zones) are collected.
(2) Covariates to propensity score are identified using logit model.
(3) Overlap assumption of covariates (between treatment and control group) is assessed.
(4) Construction of control group (for each treatment group) using multiple matching algorithms.
(5) Similarity check for treatment and control groups.
(6) Estimation of affected area and residual period of safety effects.

3.4 Treatment and control group

In this study, land use, built environment, traffic flow, crash and population demographic related data for each Middle Super Output Area (MSOA) in Greater London are available. The average population of an MSOA was 8,300. **Figure 2** presents the distributions of respective MSOAs by the congestion charging scheme and time period. As shown in **Figure 2**, the Original LCC scheme (number of MSOA = 24) was introduced in February 2003 and the Western Extension (number of MSOA = 27) was in force during the period from February 2007 to December 2010. Additionally, 301 MSOAs with which no congestion charging has ever been introduced are also considered. To evaluate the affected area of LCC on safety (Analysis I as shown in **Figure 2**), data related to the implementation of original LCC scheme of 325 MSOAs (24 for 'treated' and 301 for 'untreated' respectively) in year 2005 and 2006 are used. Also, six buffer distances (i.e. 0 km, 0.5 km, 1 km, 1.5 km, 2 km and 4 km, etc.) are considered. On the other hand, to estimate the residual period of LCC on safety (Analysis II), data related to the implementation of the Western Extension of 328 MSOAs (27for 'treated' and 301 for 'untreated' respectively) in year 2011 and 2013 are used. As mentioned in Section 3.2, the overlap assumption is essential for the validity of proposed PSM analysis. To ensure enough overlap, number of 'untreated' units should be high. Therefore, 301 MSOAs with no congestion charging imposed at all are considered. Lastly, for the estimation of affected area, ratio of treatment group to control group remains constant when the buffer distance changes.

MSOA	**Time period**		
	February 2003 to January 2007	February 2007 to December 2010	January 2011 to now
	Analysis I		**Analysis II**
Original charging zone (24)	**Treatment**		
Western extension (27)			**Treatment**
No congestion charging (301)	**Control**		**Control**

Legend: ⟷ *Implementation of LCC scheme*

Figure 2. Study design of proposed PSM analysis

4. DATA

When too many covariates are included, there could be insufficient overlap of the propensity score distributions. However, when there are too few covariates, the unconfoundedness assumption would be violated. A mathematical simulation approach was proposed to eliminate the bias and minimize the mean square error (MSE) of effect estimates, even many covariates were considered in the PSM (Brookhart et al, 2006). Bias and mean square error (MSE) can be specified as,

$$Bias = \frac{1}{S}\sum_{s=1}^{S}(\hat{y}(s) - \alpha_4)$$

$$MSE = \frac{1}{S}\sum_{s=1}^{S}(\hat{y}(s) - \alpha_4)^2$$

where $\hat{y}(s)$ is the estimated effect of exposure in the s^{th} simulated dataset applied, and S is the total number of simulations.

Outcome variable of the proposed PSM of this study is the number of crashes per MSOA occurred in the period from 7:00 am to 6:00 pm on Monday to Friday, during which LCC scheme is in force. For instance, data are extracted from the DfT's crash database, with which information on crash location, casualty age and gender, vehicle class are available.

It is well recognized that crash occurrence is correlated to population demographic and socioeconomic characteristics, such as age, gender and household income (Li and Hensher, 2012; Lee et al., 2015; Wang et al., 2017; Guo et al., 2018c; Sze et al., 2019). In this study, information on median household income of every MSOA are extracted from the Greater London Authority (GLA) database, and information on age and gender of every MSOA are extracted from the Office for National Statics (ONS) database respectively.

Additionally, safety effects of built environment, land use and transport characteristics are considered (Wei and Lovegrove,2013; Hamann and Peek-Asa, 2013; Chen, 2015; Li et al., 2012, 2019). In this study, land use (i.e. residential, commercial, green area and transport infrastructure) data are extracted from the GLA database. Also, road density (i.e. Class A Road, Class B Road and Minor Road), speed limit, traffic flow (AADT) and bicycle flow data are extracted from DfT dataset and the locations of bus stop and bicycle hiring station are extracted from TfL database respectively. The above data are mapped into corresponding MSOA using the ArcGIS and MapInfo software. **Table 1** summarize the data of the 352 MSOAs considered in the study.

Table 1. Summary statistics of traffic, land use and population profile

Variable	Attribute	Mean	S.D.	Min.	Max.
Number of observation (MSOA = 352)					
Bicycle crash frequency		37.5	23.6	1	388
Population density	Population per km^2	41.4	32.5	1.41	241.9
Gender	Proportion of male population	0.49	0.02	0.44	0.56
	Proportion of female population	0.51	0.02	0.44	0.55
Age	Proportion of age above 64	0.17	0.10	0.04	0.48
	Proportion of age below 16	0.21	0.05	0.08	0.36
Income	Annual average household income (€)	55,510	19,082	26,390	14,6210
Land use	Proportion of residential area	0.17	0.06	0.04	0.36
	Proportion of business and office area	0.16	0.11	0.00	0.50
	Proportion of green area	0.37	0.14	0.05	0.79
	Proportion of road, railway and footpath area	0.30	0.08	0.13	0.77
Road density	Class A road (km per km^2)	11.95	11.28	0.90	57.5
	Class B road (km per km^2)	2.72	4.47	0	35.1
	Minor road (km per km^2)	3.22	4.45	0	27.7
Traffic flow	Annual average daily traffic (AADT)	22,320	14,525	25	12,0073
Bicycle flow	Annual average daily bicycle flow	806	973	3	8,713
Density of bus stop	Bus stop per km^2	0.08	0.07	0	0.52
Density of bicycle hiring station	Bicycle hiring station per km^2	0.01	0.02	0	0.09

5. RESULTS

5.1 Validity of PSM method

In this study, PSM method is applied to evaluate the affected area and residual period of LCC on road safety, using the integrated crash, land use, population and traffic characteristics data from the Greater London. Prior to the effect estimation, it is necessary to construct a control group (MSOAs with no LCC imposed that share similar characteristics as the treated unit) for each treated unit (i.e. MSOA with LCC imposed). Suitability of control group can be assessed using the Balancing Test and Propensity Score Distribution described as follows (Li et al., 2018).

(1) Balancing test

Table 2 presents the results of Balancing Test. This test is to assess the independence between the treatment and control groups with respect to the variables considered. A significant *t*-statistic indicates the possible imbalances between the treatment and control groups for a particular attribute. As shown in Table 2, proportion of male population, proportion of residential area and Class A road density area are found contributing to the imbalances, at the 5% level, before matching (U). However, as also shown in Table 2, no evidence can be established for any possible imbalance after matching (M). This justifies that the possible bias can be eliminated since the characteristics between the treatment and control groups are balanced after matching.

(2) Propensity Score Distribution

Figure 3 illustrates the results of overlap test with respect to the Propensity Score. Overlap area can indicate the common support. Units falling into the common support region are considered as ‘on support’, and ‘off-support’ otherwise. ‘Off-support’ units should not be considered in further analysis. As shown in **Figure 3**, overlaps between treatment and control groups are sufficient and all fall into the common support regions. This again justifies the plausible and reliable matching.

Table 2. Results of Balancing test for treatment and control group

Variable attribute	Unmatched (U)/ Matched (M)	Mean		% reduction		t-test	
		Treatment	Control	% bias	bias	t	p-level
Income	U	46523	49324	-15.0	20.5	-1.22	0.222
	M	46523	44297	11.9		0.89	0.375
Population density	U	48.77	43.61	14.7	71.2	1.19	0.233
	M	48.77	50.25	-4.2		-0.27	0.788
Male	U	0.502	0.492	53.1	48.4	4.36	0.000*
	M	0.502	0.506	-27.4		-1.82	0.071
Age above 64	U	0.094	0.090	17.3	-22.4	1.40	0.161
	M	0.094	0.089	21.2		1.48	0.141
Residential area	U	0.129	0.166	-56.9	84.8	-4.46	0.000*
	M	0.129	0.135	-8.7		-0.63	0.528

Class A road	U	12.65	9.804	29.2	59.6	2.38	0.018*
	M	12.65	13.806	-11.8		-0.71	0.478
Class B road	U	2.786	2.417	10.2	-5.9	0.77	0.439
	M	2.786	2.392	10.8		0.73	0.468
Minor road	U	3.521	2.821	16.3	-9.4	1.38	0.169
	M	3.521	2.755	17.9		1.19	0.236
AADT	U	25849	25854	-0.0	-22928	-0.00	0.998
	M	25849	27015	-8.3		-0.56	0.576
Bicycle flow	U	1206	1039	20.4	54.4	1.60	0.111
	M	1206	1282	-9.3		-0.61	0.542

**Significant imbalance at the 5% level*

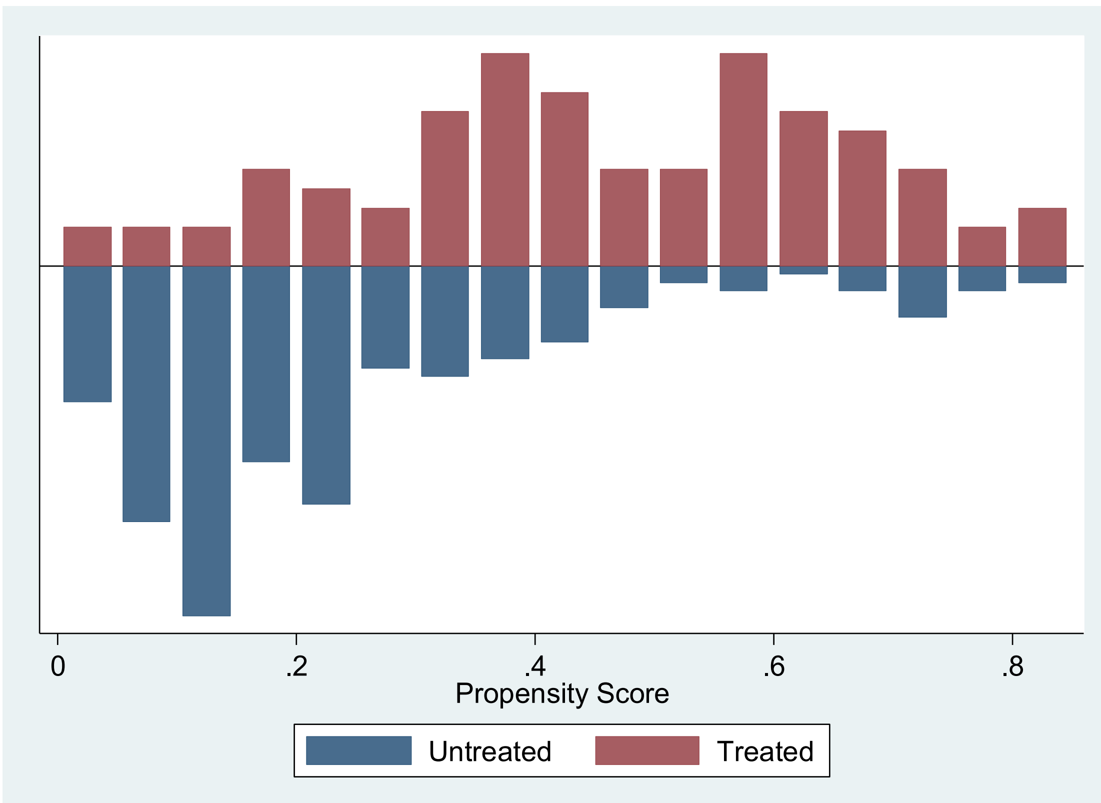


Figure 3. Results of overlap test with respect to propensity score

5.2 Analysis I: Affected area of LCC on safety

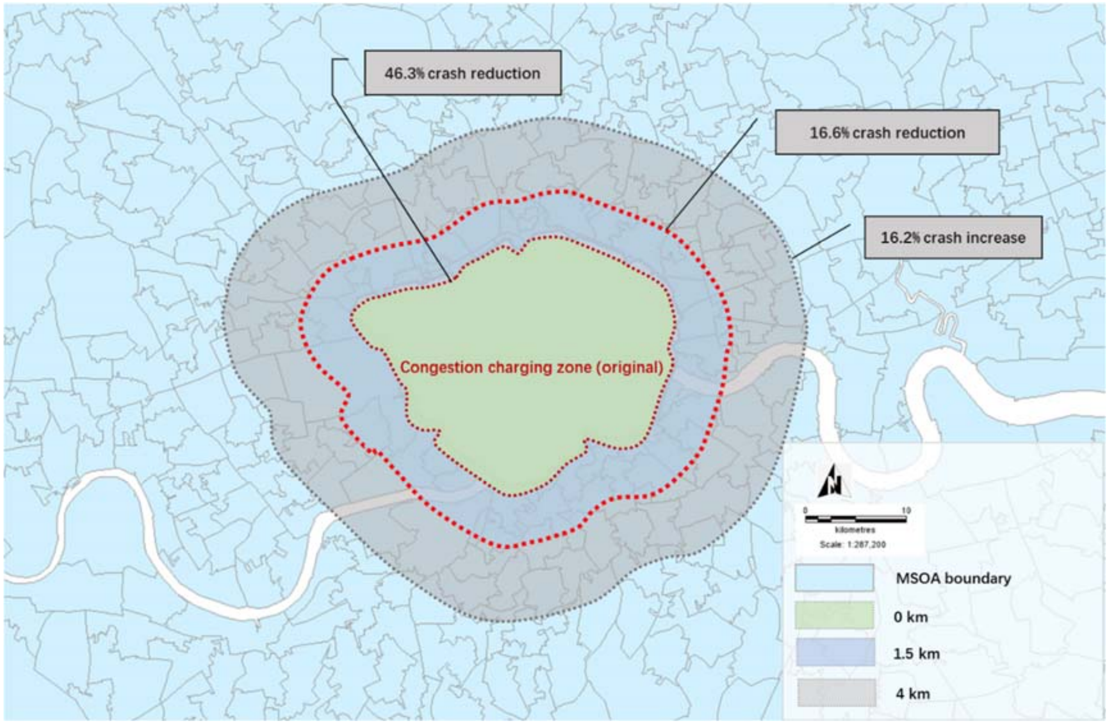
In this part of the study, affected area of LCC was examined. For instance, six buffer distances (i.e. 0 km, 0.5 km, 1 km, 1.5 km, 2 km and 4 km) are considered. **Table 3** shows the estimation results of affected area. Results indicated that the crash reduction (46.3%) in the original LCC zone (i.e. buffer = 0 km) was significant at the 1% level, after accounting for the confounding factors. Also, there could be possible safety benefits in the adjacent zones. For instance, crash reduction was significant when the buffer distance was 0.5 km (26.6%), 1.0 km (18.2%) and 1.5 km (16.6%), at the 5% level. No evidence could be established for remarkable crash reduction when the buffer distance was greater than 1.5 km. As shown in **Figure 4**, the favorable safety effects of LCC gradually declined from 46.3% when there was no buffer (i.e. original LCC zone) to 16.6% when the buffer distance was 1.5 km.

Table 3. Results of PSM model for the affected area of LCC scheme

Buffer (km)	Sample	Treatment	Control	Difference	S.E.	t-stat	Safety effect
Crash							
0 (LCC zone)	Unmatched	37.5	50.7	-13.2	4.6	-2.9	-46.3%**
	ATT	37.5	69.3	-32.7	10.4	-3.2	
0.5	Unmatched	43.4	55.2	-13.8	2.3	-6.0	-26.6%**
	ATT	43.4	59.7	-16.2	5.0	-3.2	
1.0	Unmatched	42.3	49.1	-6.8	2.5	-2.7	-18.2%*
	ATT	42.3	51.7	-9.4	4.0	-2.4	
1.5	Unmatched	47.8	47.9	-0.2	2.4	-0.1	-16.6%*
	ATT	47.8	57.3	-9.5	3.9	-2.5	
2.0	Unmatched	51.0	47.3	3.6	3.4	2.1	3.6%
	ATT	51.0	49.2	1.8	3.7	0.5	
4.0	Unmatched	51.0	47.3	3.7	5.5	0.7	16.2%
	ATT	48.1	43.9	7.1	4.2	1.0	

** statistical significance at the 5% level*

*** statistical significance at the 1% level*



(Source: https://data.london.gov.uk/dataset/statistical-gis-boundary-files-london)

Figure 4. Relationship between safety effect and buffer of LCC zone

5.3 Analysis II: Residual period of LCC on safety

The residual period of LCC on safety was then estimated based on the data of the Western Extension in the period 2011-2013. **Table 4** shows the estimation results of residual period of LCC scheme. In the first year after the abolishment of Western Extension, crash reduction (15.2%) was remarkable at the 5% level. However, no evidence could be established for significant crash reduction in the second and third year after the abolishment. Therefore, the residual period of the favorable safety effect by LCC was one year. Such finding is consistent with that of previous studies (Lagarde et al., 2011; Allcott and Rogers., 2012).

Table 4. Results of PSM model for the residual period of LCC scheme

Residual period (year)	**Sample**	**Treatment**	**Control**	**Difference**	**S.E.**	**t-stat**	**Safety effect**
Crash							
1	Unmatched	31.7	34.9	-3.3	2.2	-1.5	-15.2%*

	ATT	31.7	37.4	-5.7	3.0	-2.0	
2	Unmatched	29.4	31.4	-2.0	2.4	-0.8	-12.2%
	ATT	29.4	33.5	-4.1	4.2	-1.1	
3	Unmatched	28.7	27.7	1.0	2.6	1.1	4.0%
	ATT	28.7	27.6	1.1	3.3	0.3	

** statistical significance at the 5% level*

6. DISCUSSIONS

In this study, we attempt to examine the safety effect of LCC using the PSM approach, with which the bias by selection of control group is accounted for. Firstly, the affected area of LCC on safety was estimated. Six buffer distances, i.e. 0 km, 0.5 km, 1 km, 1.5 km, 2 km and 4 km, etc., are considered. Results indicated that favorable safety effect could be revealed in the 1.5 km buffer area of LCC. Indeed, congestion charging can affect the traffic characteristics, i.e. traffic volume and vehicle speed (Lord et al., 2005). They could then in turn affect the road safety. To this end, changes in traffic volume and vehicle speed by LCC were also estimated (as shown in Table 5(a) and Table 5(b)). Average speeds of roads were estimated based on the respective speed limits (Greibe, 2003). As shown in Table 5(a), traffic volume of the treatment group was significantly lower than (17.3%) that of the control group at the 5% level, in the 1.5 km buffer area of LCC zone. As shown in Table 5(b), the average speed of the treatment group was significantly lower than (1.2%) that of the control group at the 5% level, again in the 1.5 km buffer area of LCC zone. Such findings were consistent with that of previous studies (Beevers and Carslaw., 2005b; Li et al., 2012, Tang, 2016). Results of affected area of safety were similar to that of traffic volume and speed. It was because crash frequency was indeed positively correlated to traffic flow (i.e. exposure) and vehicular speed (Greibe., 2003; Elvik et al., 2004). Yet, current study is limited to the traffic and speed data. Average speeds of roads were estimated based on the speed limits. It is worth exploring the relationship between congestion charging, speed and its distribution, and potential crash risk when more comprehensive traffic count data is available in the extended study.

On the other hand, the residual period of safety benefits by LCC was also investigated. Results indicated that safety benefits could be revealed in the first year after the abolishment of the Western Extension of LCC. However, such favorable effect vanished in the second and third years after the abolishment. This was consistent with the findings of previous study that behavioral adaptation could be seen 15 months after the abolishment of a public policy (Allcott and Rogers., 2012). Table 5(c) shows the results of the time trend of the changes in traffic flow after the abolishment of the Western Extension. Results indicated that traffic volume of the treatment group was significantly higher than that of the control group, in the second and third year after the abolishment, at the 5% level. Therefore, it could be expected that the safety benefits be vanished.

Table 5. Results of PSM model for traffic flow and speed

(a) Affected area of traffic flow

Buffer (km)	Sample	Treatment	Control	Difference	S.E.	t-stat	Effect
1.5	Unmatched	25,651	25,853	-202	1788	-0.1	-17.3%*
	ATT	25,651	31,213	-5562	2642	-2.1	
2.0	Unmatched	25,670	25,817	-147	-1532	-0.1	-15.2%
	ATT	25,670	30,300	-4630	2983	-1.6	
4.0	Unmatched	25,068	26,142	-1074	2473	-0.1	-8.9%
	ATT	25,068	27,534	-2465	2518	-1.0	

** statistical significance at the 5% level*

(b) Affected area of average speed (km/h)

Buffer (km)	Sample	Treatment	Control	Difference	S.E.	t-stat	Effect
1.5	Unmatched	30.2	30.3	-0.1	0.1	-0.6	-1.2%*
	ATT	30.2	30.6	-0.4	0.2	-2.1	
2.0	Unmatched	30.3	30.2	0.1	0.1	0.8	0.1%
	ATT	30.3	30.3	0.03	0.2	0.2	
4.0	Unmatched	30.2	30.3	-0.1	0.2	-0.5	-0.8%
	ATT	30.2	30.4	-0.2	0.2	-1.3	

** statistical significance at the 5% level*

(c) Time trend of the changes in traffic flow

Residual period (year)	Sample	Treatment	Control	Difference	S.E.	t-stat	Effects
1	Unmatched	22,938	19,392	3,546	2,081	1.5	-11.6%

	ATT	22,938	23,208	-269	3,632	-0.1	
2	Unmatched	21,579	20,663	915	3,535	0.3	43.9%*
	ATT	21,579	15,000	6,588	3,280	2.0	
3	Unmatched	23,935	19,011	4,924	2,297	2.1	43.1%**
	ATT	23,935	16,722	7,213	2,640	2.7	

** statistical significance at the 5% level*

*** Statistical significance at the 1% level*

7. CONCLUSIONS

A series of policies and infrastructures have been implemented to relieve the traffic congestion and promote air quality in London. London Congestion Charging (LCC) scheme is one of the measures to solve these problems in London. In recent years, a lot of government reports and researches are conducted to estimate the relationship between LCC and traffic congestion, vehicle emissions, public responses and economy (Xie and Olszewski., 2011; Beevers and Carslaw., 2005a; Sugiarto et al., 2015; Givoni., 2012). However, it is rare that the safety benefits and the affected area of congestion charging are investigated. For example, traffic characteristics in the adjacent areas of the congestion charging zones could be modified. Additionally, residual effects could persist after the abolishment of a public policy (Lagarde et al., 2011; Ramiah et al., 2017; Preecha and Wianwiwat, 2017 Wang et al., 2018).

In this study, the affected area and residual period of the safety benefits by the LCC scheme are investigated using the PSM method. Attributes including land use, built environment, transport infrastructure and traffic characteristics are considered for the establishment of control groups. Results indicate that remarkable safety benefits can be revealed in the 1.5 km buffer area of the LCC zones. It can be because of the reductions of traffic flow and speed in the area. Additionally, the residual safety effect can be revealed one year after the abolishment of the Western Extension. Such findings could be indicative to the transport demand management and policy. For example, effective area-wide road safety countermeasures (i.e. deployment of traffic signals, road markings, traffic signs, and speed limit, etc.) could be developed to maximize the safety benefits. They are worth investigating when the data from policy discourses are available in the extended study.

Yet, this study is limited to the availability of disaggregated population profile, traffic flow and speed data. Data are aggregated at the zone (MSOA) and year level. It would be worth exploring the number of month and buffer distance that the safety benefits be vanished when more comprehensive data is available in the extended study (Allcott and Rogers., 2012). Moreover, it is valuable to conducted an observational before-after safety (BA) evaluation based on the crash data and compare the results of this study to that of the BA safety results.

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