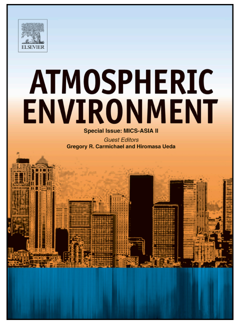
Accepted Manuscript



Title: The impact of the Congestion Charging Scheme on ambient air pollution concentrations in London

Authors: R.W. Atkinson, B. Barratt, B. Armstrong, H.R. Anderson, S.D. Beevers, I.S. Mudway, D. Green, R.G. Derwent, P. Wilkinson, C. Tonne, F.J. Kelly

PII: S1352-2310(09)00626-8

DOI: 10.1016/j.atmosenv.2009.07.023

Reference: AEA 9188

To appear in: *Atmospheric Environment*

Received Date: 23 May 2008

Revised Date: 11 July 2009

Accepted Date: 14 July 2009

Please cite this article as: Atkinson, R.W., Barratt, B., Armstrong, B., Anderson, H.R., Beevers, S.D., Mudway, I.S., Green, D., Derwent, R.G., Wilkinson, P., Tonne, C., Kelly, F.J. The impact of the Congestion Charging Scheme on ambient air pollution concentrations in London, Atmospheric Environment (2009), doi: 10.1016/j.atmosenv.2009.07.023

The impact of the Congestion Charging Scheme on ambient air pollution concentrations in London

Atkinson RW[1], Barratt B[2], Armstrong B[3], Anderson HR[5], Beevers SD[2], Mudway IS[2], Green D[2], Derwent RG[4], Wilkinson P[3], Tonne C[3], Kelly FJ[2]

1. Division of Community Health Sciences, St. George's, University of London, Cranmer Terrace, London, SW17 0RE.
2. Environmental Research Group, MRC-HPA Centre for Environment and Health, King's College London
3. London School of Hygiene and Tropical Medicine
4. rdscientific, Newbury, UK
5. MRC-HPA Centre for Environment and Health, St George's, University of London and King's College London

Address for correspondence
Dr R W Atkinson
Division of Community Health Sciences
St. George's, University of London
Cranmer Terrace
London
SW17 0RE

Tel: +44 (0)20 8725 5174
Fax: +44 (0)20 8725 3584
Email: atkinson@sgul.ac.uk

Introduction

On 17th February 2003, a congestion charging scheme (CCS) was introduced in London with the aim of reducing traffic congestion in the centre of the city - an area covering approximately 22 km^2 or 1.4% of the Greater London Area. The scheme operates via a punitive charge on four-wheeled vehicles entering the charging zone during the charging period (Monday-Friday, 07:00-18:00). The CCS was one component of a package of changes in traffic management and in the public vehicle fleet (e.g. new buses, particle traps, bus lanes) implemented in London at the same time (TfL 2004).

The main objective of the CCS was met: in the first year traffic volumes entering the zone fell by 18% and congestion (defined by the time taken to travel 1 km) in the zone was reduced by 30% compared to pre-charging levels (TfL 2004). This mirrors the effectiveness of similar schemes in Singapore, Stockholm and Norway (Chin 1996; Tuan Seik 2000; Victoria Policy Transport Institute 2007).

We investigated the potential impact of the introduction of the CCS on measured pollutant concentrations in London. Pollutants studied were: oxides of nitrogen (NO_X), nitric oxide (NO), nitrogen dioxide (NO_2), particles with a median diameter less than 10 microns (PM_{10}), carbon monoxide (CO) and ozone (O_3) measured at roadside and background monitoring sites across Greater London. We were unable to investigate $PM_{2.5}$ due to insufficient data available for analysis. Although similar intervention studies have examined temporary changes in pollution sources (Pope et al. 1992, Friedman et al. 2001, Yuval et al. 2007) this is the first evaluation of the effects of a permanent traffic management scheme on pollution levels in a major city. With road pricing schemes being considered in the UK and elsewhere in the world this study provides valuable information to policy makers and the general public.

Methods

Study Design

The aim of our study was to assess the effects of the CCS on pollution concentrations in London. We approached this task in three ways. Our first, and principal, objective was to study the potential impact of the CCS on pollutant concentrations within the congestion charging zone (CCZ) itself. Secondly, we investigated the possible impact of the scheme upon pollution concentrations on the area surrounding the charging zone and finally we assessed the possibility that the CCS may have had an impact upon pollutant concentrations at weekends (when the CCS does not operate).

Pollution concentrations in London are influenced by local factors and by London-wide and regional (including trans-boundary) sources and determinants of pollution (e.g. trends in vehicle numbers in London, vehicle technology, meteorological conditions and long-range transport of pollutants). To identify the impact of the CCS on pollution levels within the CCZ therefore we compared temporal changes in pollutant concentrations at sites within the zone with those located in a control area where temporal changes in pollutant concentrations were assumed to indicate London-wide and regional temporal patterns in pollution only. The control area was defined as the area 8 km or more from the CCZ centre but within Greater London.

To assess the possible impact of the scheme upon pollution concentrations on the area surrounding the charging zone, termed the boundary zone, we plotted the temporal changes in pollutants at all available monitors within Greater London (subject to data availability) ordered by distance from the centre of the CCZ. This analysis was then repeated using data for congestion charging hours (07:00-18:00) during weekends, when the scheme was not in operation to provide an assessment of the impact of the CCS on non working days.

Data

Hourly average pollutant concentrations recorded at monitoring sites across Greater London were extracted from the London Air Quality Network (LAQN) database (LAQN 2005). NO_X, NO and NO_2 were monitored at 102 sites, PM_{10} at 87 sites, CO at 32 sites and O_3 at 29 sites. Daily average concentrations for the hours the CCS was in operation (Monday to Friday, 07:00 to 18:00) were calculated for a 4-year period, 2 years before and 2 years after the implementation of the scheme in February 2003. Completeness criteria applied to the calculation of the daily average values (75% of hourly observations available) and to the selection of sites for analysis (daily average values available for at least 75% of days in the four year period). Data from both roadside (sample inlets between 1m and 5 m from the kerbside of a road) and urban background (sample inlets sites at least 10 m from any major local sources and broadly representative of city-wide background concentrations) monitoring stations were selected for analysis. Rural concentrations of ozone in the south east of England (7 monitoring sites) were also extracted from the LAQN database. Figure 1 illustrates these zones together with the location of the individual monitoring stations selected for this study.

Statistical Analysis

Daily pollutant concentrations for the two year period before and the two year period after the scheme's introduction on the 17th February 2003 were summarised using geometric means. Changes in pollutant geometric mean concentrations pre and post CCS implementation were expressed as percentage changes.

Regional and trans-boundary sources of all pollutants excluding ozone did not change significantly over the 2 year pre- and post-intervention periods (data not shown). They therefore had no impact upon the calculation of the relative changes in pollution. However, rural concentrations of ozone increased by 1.7 ppb between the pre and post CCS periods. The calculation of the percentage changes in ozone concentrations after the implementation of the CCS were therefore adjusted for this absolute increase across the south east of England.

The software package SPLUS was used for all analyses.

Results

Geometric mean concentrations of NO_X, NO, NO_2, PM_{10}, CO and O_3 measured during charging hours within the CCZ, the boundary zone and the control zone, two years before and after the introduction of the scheme, are shown in Tables 1 (roadside sites) and 2 (background sites). These tables also give the percentage change at each location together with the average percentage changes for monitoring stations in the control zone.

Assessing the potential impact of the CCS on pollution concentrations within the CCZ

Pre and post CCS concentrations of NO_X, NO, NO_2, PM_{10} and CO and O_3 (background only) measured at roadside and background monitoring stations within the CCZ and the control zone are compared in Figures 2a and 2b.

Roadside stations

Concentrations of NO_X and NO at the single within CCZ roadside site (CD3) fell by 5% and 9.5% respectively compared to average changes of -4.4% and -9.4% measured at the 16 roadside locations in the control zone. Concentrations of NO_2 and PM_{10} rose by 3.7% and

2.5% respectively at CD3 and these compare with similar changes at monitoring stations in the control area.

Background stations

Background concentrations of NO_X and NO (3 sites), PM_{10} (single site) and CO (2 sites) within the CCZ all fell whilst NO_2 and O_3 concentrations rose at the three sites within the zone. These figures contrast with small average increases in NO_X, NO and NO_2 monitored at seven locations in the control area (0.6%, 1.1% and 0.2% respectively) and small average decreases in PM_{10} (-0.8%) and O_3 (-6.8%) measured at 5 and 3 monitoring stations respectively.

Assessing the potential impact of the CCS on background pollution concentrations across London

Figure 3 shows the percentage changes in mean background pollutant concentrations in the two years after the scheme was introduced compared to the two years before plotted against the monitoring stations distance from the centre of the charging zone. For NO_X, Figure 3 shows that the largest percentage changes (decreases) occurred at two of the three monitoring stations within the zone and at three of seven monitoring stations in the boundary zone. Changes in NO_X at the remaining monitoring stations in the boundary and control zones tended to be smaller and variable in direction. By comparison, concentrations in NO tended to fall both within the charging and boundary zones whereas changes in concentrations in the control zone tended to smaller and more variable in direction. For NO_2 there seemed to be no consistent pattern in the direction and size of the percentage changes measured at stations in the boundary and control zones. This contrasts with increases in concentrations recorded at the three within zone monitoring stations. Concentrations of CO measured at two locations within the zone decreased compared to smaller changes at other more distant sites whereas O_3 increased at two of three monitoring stations within the zone and tended to decrease in other locations (with one notable exception). There was little evidence to suggest a pattern in temporal changes in concentrations of PM_{10}, in relation to distance from the CCZ.

Assessing the potential impact of the CCS on background pollution concentrations at weekends

Geometric mean background concentrations of NO_X, NO, NO_2, PM_{10}, CO and O_3 measured during charging hours at weekends within the CCZ, the boundary zone and the control zone, two years before and after the introduction of the scheme, are shown in Table 3. The changes, expressed as percentages, are illustrated graphically in Figure 4. These figures suggest that the pattern of temporal changes in weekend pollution concentrations measured within the charging zone and in the control area were similar to those observed on days when the CCS was in operation.

Discussion

Temporal changes in pollution concentrations within the congestion charging zone were compared to changes, over the same time period, at monitors unlikely to be affected by the CCS (the control area) and in the boundary zone between the two. Similar analyses were done for CCS hours during weekends (when the Scheme was not operating). The pollutants investigated were NO_X, NO, NO_2, PM_{10}, CO and O_3 and the analysis focused on the hours during which the scheme was in operation.

Based on the single roadside monitor with the CCS Zone, it was not possible to identify any relative changes in pollution concentrations associated with introduction of the scheme. However, using background monitors, there was good evidence for a decrease in NO and increases in NO_2 and O_3. There was little change in background concentrations of NO_X. There was also evidence of relative reductions in PM_{10} and CO. When all background monitors were considered, these changes appeared to vary with distance from the centre of the charging zone. Similar changes were observed during the same hours in weekends when the scheme was not operating.

To evaluate temporal trends in air pollution within a relatively small area in the centre of London it was essential to adjust for temporal trends in pollution concentrations across London as a whole. This control was achieved by adopting a temporal-spatial design in which changes within the CCS zone were compared with those in areas unlikely to be directly affected by it (the control zone, >8km from CCS zone). A further refinement was to relate changes to the distance of monitors from the centre of the zone.

Our *a priori* hypothesis was that a vehicle-related intervention such as the CCS would have the greatest relative impact on pollution concentrations measured at the roadside. However, it was not possible to evaluate this hypothesis stringently since the analysis was limited by having only a single roadside site within the CCS zone. A more convincing analysis of NO_X data recorded at background monitoring stations was possible however since data were available from 3 monitoring stations within the zone and 7 in the control area. Furthermore, temporal changes in NO_X, NO and NO_2 concentrations within the control area were comparable in terms of size and direction and thus provided a stable baseline against which to evaluate temporal changes within the zone.

The congestion charging scheme was implemented overnight on 17th February 2003 rather than as a phased approach. It led to an immediate and sustained reduction in traffic volumes entering the charging zone (TfL 2007). We chose therefore to compare air pollution levels 2 years following the scheme's introduction with the prior 2-year period since this approach has a number of advantages over comparisons using shorter time periods. First, the impact of short-term temporal factors (e.g. school holidays) on any comparison is minimised. Second, by using complete years either side of the implementation date seasonal factors are balanced out. The year the scheme was implemented was characterised by unusual meteorological conditions but by using four years of data we minimised any potential bias arising from these unusual conditions that may not have already been accounted by our temporal-spatial study design

The question of whether the observed reduction in background concentrations of NO, PM_{10} and CO and the increases in background NO_2 and O_3 observed within the zone are attributable to the implementation of the CCS is problematic. The congestion charging scheme was one specific action within a general programme of measures to reduce traffic congestion and air pollution across London as a whole. These measures included the implementation of bus lanes, the use of larger 'bendy' buses, the fitting of particle traps to diesel buses, increased bus frequency and changes to traffic light phases. Whilst these were not confined to the charging zone it is possible that, because of the concentration of traffic in the centre, these other measures may have had a greater relative impact in central London than outer London, thus explaining the observed temporal patterns in pollution observed in this analysis.

The boundary of the CCZ is formed by an Inner Ring Road and is the most obvious alternative route for through traffic wishing to avoid the zone. TfL reported an initial increase in total vehicle-kilometres of 4% on the boundary road together with a decrease in congestion resulting from the implementation of effective traffic management on this key route (TfL 2007). They also reported that measurements taken during 2004 and 2005 suggested that traffic on the Inner Ring Road during weekday charging hours declined very slightly overall compared to 2003 and that flows in 2005 were comparable with pre-charging conditions in 2002. The observed temporal changes in background pollutant concentrations within the CCZ reported in this study were also reflected, to some degree, at monitoring stations just outside the charging zone. There are two potential explanations for this observation: 1) these changes were not attributable to the CCS but to the other traffic management actions that acted beyond the CCZ or 2) the CCS and other traffic management changes within the zone led to temporal changes in background pollutant concentrations that extended beyond the CCZ boundary.

The purpose of the weekend analyses was to provide a further 'control' for the main analyses by investigating days when the CCS was not operating, but which were subject to the same temporal and seasonal confounders present in the main analyses. Monitoring of total daily traffic volumes at 14 automatic traffic count sites in the charging zone six weeks before and after the start of the CCS show that weekend traffic volumes were unaffected by the implementation of the charging scheme (personal communication - S Beevers). These data are supported by the conclusion from TfL that there were no obvious direct effects from congestion charging on weekend traffic levels (TfL 2006). The temporal-spatial changes in weekend pollution concentrations made at weekends were found to be broadly comparable to those observed in the weekday analyses. This result suggests that the implementation of the CCS alone was not responsible for the temporal changes we observed during congestion charging hours but that other factors specific to the sites analysed or the impact of general traffic management schemes in central London may have been responsible.

This study is the first evaluation of the effects on air pollution of the overnight introduction of a long-term traffic management scheme. There have been a small number of studies of the impact of short-term, reversible traffic management schemes on air pollution. During the 1996 Olympic Games in Atlanta, GA, a range of measures were implemented to reduce traffic congestion and minimise the impact of a large number of visitors on air quality violations for O_3 pollution. The Games lasted 17 days and during that period substantial reductions in O_3, CO and PM_{10} pollution levels were observed relative to the baseline period (Friedman et al. 2001). It appears however that the reduction in ozone was part of a regional pattern which weakens the argument that the intervention was responsible and illustrates the need for spatial controls in this type of evaluation. A second study evaluated pollution concentrations in Haifa, Israel, during a military conflict lasting several weeks during the summer of 2006. The conflict led to a reduction in traffic volumes of 40% and the investigators found a reduction in NO_2, hydrocarbons and PM compared to control periods either side of the conflict (Yuval et al. 2007). The unusual circumstances surrounding these two examples make it difficult to draw any meaningful comparisons with the present study other than that both reported falls in measured pollution concentrations during the periods of reduced traffic volumes.

In conclusion, our study suggests that the introduction of the CCS in 2003 was associated with small temporal changes in air pollution concentrations in central London relative to outer areas. However, the causal attribution of these changes to the CCS per se is not appropriate since the scheme was introduced concurrently with other traffic and emissions interventions which might have had a more concentrated effect in central London. Many other cities are contemplating or implementing such schemes and these results give some indication of the possible effects on air quality. This study also provides important pointers for study design and data requirements for those who wish to evaluate their schemes in terms of air quality. It also shows that results may be unexpected (the increase in NO_2) and that the overall effect on toxicity may not be entirely favourable (increase in O_3).

Acknowledgements:

Supported by the Health Effects Institute through research agreement RFA04-1/04. We also wish to thank the reviewers for their thoughtful and constructive comments.

References

Chin ATH. 1996. Containing air pollution and traffic congestion: transport policy and the environment in Singapore. Atmospheric Environment 30, 787-801.

Friedman MS, Powell KE, Hutwagner L, Graham LM, Teague WG. 2001. Impact of changes in transportation and commuting behaviors during the 1996 Summer Olympic Games in Atlanta on air quality and childhood asthma. Journal of the American Medical Association 285, 897-905

London Air Quality Network. 2005. Air quality in London 2003. Fuller G. (ed) Environmental Research Group, King's College London, Report no.11.

Pope AC, Schwartz J, Ransom MR. 1992. Daily mortality and PM_{10} pollution in the Utah valley. Archives of Environmental Health 47, 211-217

Transport for London. 2004. Central London Congestion Charging. Impacts Monitoring. Second Annual Report. The Mayor of London, Greater London Authority, London.

Transport for London. 2006. Central London Congestion Charging. Impacts Monitoring. Fourth Annual Report. The Mayor of London, Greater London Authority, London.

Transport for London. 2007. Central London Congestion Charging. Impacts Monitoring. Fifth Annual Report. The Mayor of London, Greater London Authority, London.

Tuan Seik F 2000. An advanced demand management instrument in urban transport: electronic road pricing in Singapore. Cities 17, 33-45.

Victoria Transport Policy Institute. 2007. Online Transport Demand Management Encyclopaedia (last updated May 2007). *www.vtpi.org/tdm.* Accessed 03/07/07.

Yuval FB, Broday DM. 2008. The impact of a forced reduction in traffic volumes on urban air pollution. Atmospheric Environment, 42 428-440

Table 1 Geometric mean concentrations of pollutants at roadside monitoring sites two years before and two years after the introduction of the CCS

Monitoring Station		**NO_X (ppb)**			**NO (ppb)**			**NO_2 (ppb)**			**PM_{10} (μgm^{-1})**		
	Dist	**Pre**	**Post**	%	**Pre**	**Post**	%	**Pre**	**Post**	%	**Pre**	**Post**	%
Congestion charging zone													
CD3	1.0	107.6	102.2	-5.0	63.9	57.8	-9.5	42.1	43.0	2.1	41.0	43.3	5.6
Boundary zone													
MY1	3.0	187.3	193.9	3.5	133.4	123.1	-7.7	50.0	68.0	36.0	51.9	52.9	2.0
KC3	3.5	155.5	157.3	1.2	98.8	96.6	-2.2	54.8	58.8	7.4			
KC4	4.3	156.2	157.4	0.7	103.5	97.6	-5.7	50.8	58.1	14.3			
KC2	4.6	129.3	125.4	-3.0	82.5	76.0	-7.8	45.4	48.2	6.0	43.5	41.9	-3.6
SK2	4.8	96.3	82.2	-14.7	58.5	50.2	-14.2	36.3	37.0	1.8			
TH2	5.4	118.7	94.5	-20.4	78.7	57.7	-26.7	37.7	35.2	-6.6			
CD1	5.7										36.5	41.3	12.9
WA4	7.9	61.6	56.1	-8.9	32.3	26.8	-17.0	27.5	27.8	0.9	28.8	31.7	10.2
Control zone													
GR5	8.6	76.2	61.2	-19.7	42.5	32.4	-23.6	32.4	27.7	-14.6	29.5	29.1	-1.6
RI1	9.0	47.9	45.7	-4.6	23.6	21.7	-7.9	23.3	23.1	-0.9	26.4	27.9	6.0
CY1	9.9	78.5	69.1	-11.9	45.4	38.4	-15.3	28.0	27.5	-1.6	32.8	29.2	-10.8
HS4	10.0	99.1	115.7	16.8	64.7	66.0	2.0	33.5	48.4	44.3	35.7	35.4	-0.8
EA2	10.5	88.6	90.4	2.1	55.8	54.3	-2.8	30.7	33.6	9.5	31.9	33.2	4.1
HG1	10.5	57.5	53.6	-6.7	31.3	27.4	-12.3	24.8	24.9	0.5	28.1	27.7	-1.3
EN4	12.6	74.5	73.2	-1.7	42.0	40.2	-4.4	30.7	31.4	2.3	39.0	40.6	4.0
RB4	12.7	57.5	60.8	5.6	29.1	30.2	3.7	25.5	27.7	8.7	28.7	31.1	8.5
CR4	15.0	73.8	67.7	-8.3	41.4	35.4	-14.5	31.2	31.5	0.9	32.6	32.2	-1.2
GB6	15.2	87.1	72.2	-17.1	57.5	44.5	-22.7	27.3	25.5	-6.4	30.0	31.6	5.2
EN2	16.1	46.3	44.5	-3.8	21.6	20.0	-7.3	23.5	23.1	-1.7	28.3	28.9	2.0
CR2	16.3	104.9	91.3	-13.0	72.2	58.9	-18.5	29.0	29.9	3.0			
A30	19.1	105.5	118.5	12.3	70.3	71.7	1.9	34.4	42.6	23.7	29.4	33.6	14.5
HI1	20.5	76.3	74.3	-2.6	51.2	47.1	-8.0	24.4	26.3	8.0	28.9	31.5	9.0
HV3	21.7	60.7	56.7	-6.6	36.2	32.6	-10.1	23.1	22.9	-0.9	27.7	27.9	0.7
HV1	22.6	56.4	53.6	-5.0	29.9	28.3	-5.4	24.7	23.5	-4.5			
Average				-4.4			-9.4			3.7			2.5

Notes: Pre – 2 year period prior to implementation of the CCS; Post -2 year period after the implementation of the CCS; % - percentage change in pollution concentration pre to post CCS implementation; Boundary zone – CCZ to 8km; Control zone - 8km+

Table 2 Geometric mean concentrations of pollutants at background monitoring sites two years before and two years after the introduction of the CCS

Monitoring Station		**NO_X (ppb)**			**NO (ppb)**			**NO_2 (ppb)**			**PM_{10} (μgm^{-1})**			**CO (ppm)**			**O_3 (ppb)**			
	Dist	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**Pre**	**Post**	**%**	**%†**
Congestion charging zone																				
BL0	1.5	60.2	58.3	-3.2	32.6	23.4	-28.2	29.0	32.7	12.8	35.6	30.1	-15.4	0.42	0.33	-22.4	8.1	9.7	20.0	-1.2
CT1	1.5	62.7	56.3	-10.2	30.4	24.0	-21.1	30.5	30.8	1.0							9.4	12.4	32.3	13.8
WM0	1.9	49.1	43.3	-11.8	21.9	18.7	-14.6	25.1	26.9	7.2				0.48	0.35	-25.5	9.5	12.4	31.1	12.6
Boundary zone																				
SK1	2.5	56.9	52.4	-7.9	27.7	23.6	-14.7	27.7	27.6	-0.2				0.42	0.38	-10.2	12.5	13.4	6.7	-6.4
IS1	3.6	40.2	40.6	1.1	14.0	14.0	0.1	24.3	24.8	2.0	27.3	30.1	10.2							
TH3	4.8	40.8	36.4	-10.9	14.1	11.0	-22.1	24.5	23.2	-5.4										
WE0	6.0	48.3	49.7	2.8	20.3	19.4	-4.5	26.8	29.0	8.4				0.24	0.36	49.6				
TH1	6.7	35.7	31.0	-13.3	11.3	9.7	-13.8	22.7	19.8	-13.1	25.9	28.6	10.4				12.3	15.9	29.5	15.4
KC1	6.9	32.5	32.6	0.5	11.0	10.5	-4.7	20.1	20.7	2.8	25.5	26.4	3.6	0.35	0.39	11.6	13.9	15.2	9.6	-2.9
HK4	7.0	52.6	52.2	-0.7	24.8	23.5	-5.5	25.7	26.7	3.6				0.44	0.41	-6.7	11.7	12.7	8.2	-6.0
WA2	7.8	67.7	66.8	-1.3	35.3	31.6	-10.4	29.4	33.0	12.2				0.84	0.96	14.4	8.8	10.1	15.5	-4.5
Control zone																				
WL1	9.7	30.6	30.5	-0.3	9.8	10.4	6.4	19.8	18.8	-5.0	24.5	24.3	-0.6							
LW1	9.8	56.8	57.9	1.9	24.6	27.8	12.9	28.8	28.2	-2.1										
BN2	11.1	28.1	28.7	2.1	9.1	9.3	2.4	18.0	18.0	0.3	23.1	24.0	3.6							
EA1	13.4	35.8	37.1	3.8	14.4	13.9	-3.5	19.7	21.6	9.8							11.2	13.2	18.7	2.7
EN3	15.1	26.2	25.2	-3.9	8.4	8.1	-3.6	16.7	15.8	-5.0	23.4	21.4	-8.3	0.36	0.35	-2.4	17.7	16.8	-4.9	-14.7
RB1	15.3	33.9	33.3	-1.9	13.0	12.1	-6.7	19.8	20.0	1.0	25.0	26.2	5.0				15.2	15.9	4.3	-6.6
HR1	17.3	13.1	13.5	3.2	6.3	6.5	2.5	13.1	13.5	3.2	21.7	20.8	-4.0							
Average				0.6			1.1			0.2			-0.8						5.2	-6.8

Notes: Pre – 2 year period prior to implementation of the CCS; Post -2 year period after the implementation of the CCS; % - percentage change in pollution concentration pre to post CCS implementation; Dist – distance in km from centre of the congestion charging zone. † Adjusted for 1.7 ppb increase in rural ozone concentrations; Boundary zone – CCZ to 8km; Control zone - 8km+

Table 3 Geometric mean concentrations of pollutants at background monitoring sites during CCS hours at weekends two years before and two years after the introduction of the CCS

Monitoring Station		NO_X (ppb)			NO (ppb)			NO_2 (ppb)			PM_{10} (μgm^{-1})			CO (ppm)			O_3 (ppb)			
	Dist	Pre	Post	%	Pre	Post	%	Pre	Post	%	Pre	Post	%	Pre	Post	%	Pre	Post	%	%†
Congestion charging zone																				
BL0	1.5	39.3	39.1	-0.4	19.8	13.1	-34.1	21.8	24.5	12.5	26.9	23.3	-13.4	0.32	0.28	-11.6	11.3	14.3	26.6	11.6
CT1	1.5	35.8	30.8	-14.0	13.1	9.4	-28.3	21.3	20.4	-3.9							13.3	18.5	39.4	26.6
WM0	1.9	26.3	25.0	-4.8	6.1	4.2	-30.5	16.2	18.2	12.8				0.40	0.30	-26.2	12.6	17.9	41.2	27.8
Boundary zone																				
SK1	2.5	38.9	33.6	-13.7	16.7	12.7	-23.6	21.0	20.1	-4.4				0.35	0.33	-7.1	15.5	17.8	14.7	3.8
IS1	3.6	26.8	25.1	-6.5	7.5	6.6	-12.2	17.7	17.7	-0.3	20.8	21.0	1.0							
TH3	4.8	26.8	22.1	-17.5	6.8	4.9	-27.6	17.5	16.1	-7.6										
WE0	6.0	31.6	30.5	-3.7	10.1	8.6	-14.5	20.2	20.9	3.2				0.19	0.30	56.6				
TH1	6.7	22.4	18.1	-19.4	5.2	4.2	-18.6	15.9	13.1	-17.8	20.2	21.6	7.0				15.7	0.0	-100.0	-110.8
KC1	6.9	21.6	19.3	-10.9	6.0	4.7	-21.6	14.5	13.8	-4.4	20.4	21.0	2.7	0.27	0.33	22.8	15.6	20.2	29.4	18.5
HK4	7.0	36.5	33.6	-8.0	15.4	12.9	-15.9	19.5	19.4	-0.5				0.35	0.33	-5.9	14.6	17.2	17.8	6.1
WA2	7.8	44.2	38.4	-13.2	19.7	13.8	-29.6	21.6	22.2	2.6				0.72	0.79	8.7	11.0	14.2	29.2	13.7
Control zone																				
WL1	9.7	20.1	18.8	-6.2	4.9	5.3	9.3	13.9	12.8	-8.0	20.1	21.0	4.6							
LW1	9.8	37.4	35.7	-4.6	13.8	14.8	6.8	21.1	19.7	-6.4										
BN2	11.1	17.7	17.7	0.4	4.7	4.6	-2.7	12.2	12.5	2.0	19.1	19.5	2.4							
EA1	13.4	23.9	21.7	-9.0	8.1	6.0	-26.5	14.4	14.8	2.6							14.0	17.6	25.7	13.5
EN3	15.1	17.2	15.6	-9.2	4.7	4.1	-12.9	11.8	11.0	-6.4	20.1	18.2	-9.8	0.32	0.30	-3.8	21.1	21.9	4.0	-4.1
RB1	15.3	21.4	20.4	-4.8	6.8	5.9	-12.9	13.9	13.9	-0.3	22.1	23.3	5.6				18.4	20.8	12.7	3.5
HR1	17.3	13.2	13.0	-1.7	3.8	3.5	-7.5	9.0	9.0	0.4	17.8	17.3	-2.5							

Notes: Pre – 2 year period prior to implementation of the CCS; Post -2 year period after the implementation of the CCS; % - percentage change in pollution concentration pre to post CCS implementation; Dist – distance in km from zone centre. † Adjusted for 1.7 ppb increase in rural ozone concentrations; Boundary zone – CCZ to 8km; Control zone - 8km+

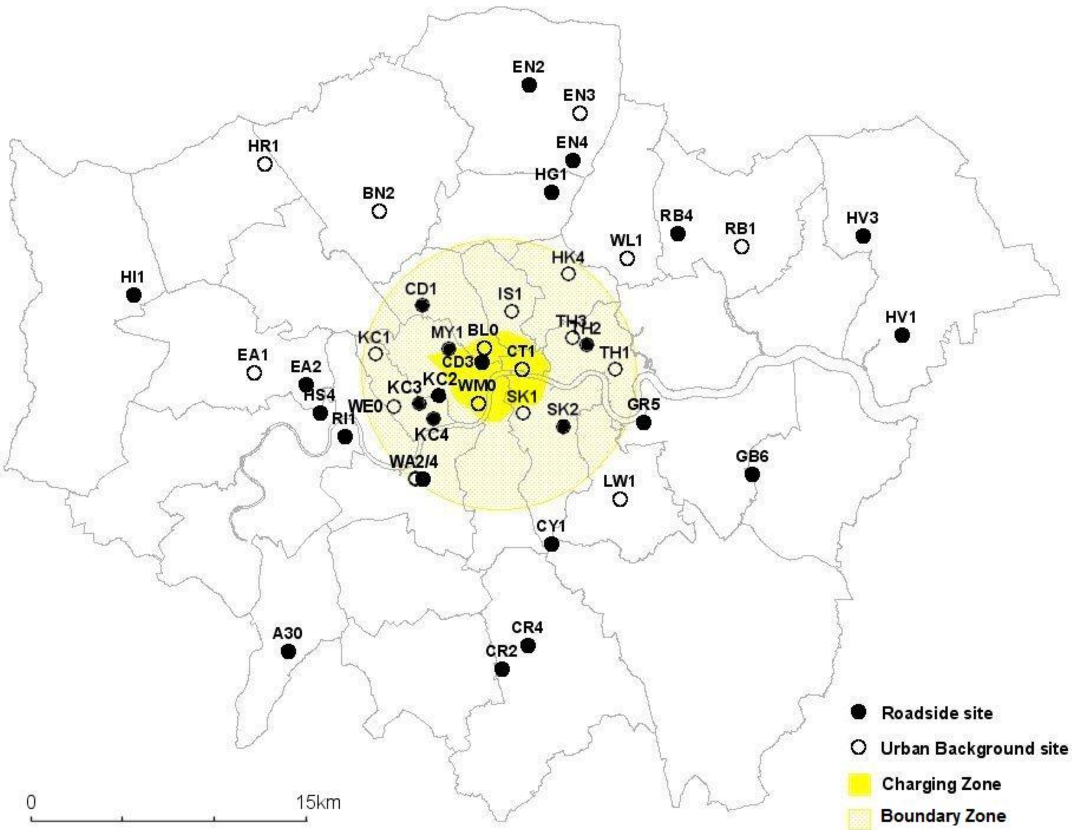
Figure 1 Map of Greater London indicating the location of monitoring stations within the congestion charging zone, the boundary zone and the control zone
Note: Only stations providing sufficent data (see Methods) and included in the analyses are indicated

Figure 2a Geometric mean concentrations of pollutants at roadside and background monitoring sites in the CCZ and the control zone measured two years before and two years after the introduction of the CCS
Note: Solid circles indicate monitoring stations inside the congestion charging zone; hollow circles monitoring stations in the control zone

Figure 2b Geometric mean concentrations of pollutants at roadside and background monitoring sites in the CCZ and the control zone measured two years before and two years after the introduction of the CCS
Note: Solid circles indicate monitoring stations inside the congestion charging zone; hollow circles monitoring stations in the control zone

Figure 3 Percentage change in geometric mean pollutant concentrations at background monitoring stations stratified by station location (within zone, boundary and control zones) and distance from CCZ centre
Note: Solid circles indicate stations within CCZ, hollow circles with cross indicate stations surrounding the zone boundary and hollow circles indicate stations in control zone (8 km+ from zone centre). The Y axis shows percent change pre-post CCS implementation and the X-axis shows the distance in km from the centre of the charging zone

Figure 4 Percentage change in geometric mean pollutant concentrations measured during weekends at background monitoring stations stratified by station location (within zone, boundary and control zones) and distance from CCZ centre
Note: Solid circles indicate stations within CCZ, hollow circles with cross indicate stations surrounding the zone boundary and hollow circles indicate stations in control zone (8 km+ from zone centre). The Y axis shows percent change pre-post CCS implementation and the X-axis shows the distance in km from the centre of the charging zone


EN2
EN3
EN4
HG1
HR1
BN2
RB4
RB1
HV3
WL1
HK4
HI1
CD1
IS1
HV1
TH3
TH2
KC1
MY1
BL0
EA1
EA2
CD3
CT1
TH1
KC3
KC2
WM0
HS4
WE0
SK1
SK2
GR5
RI1
KC4
GB6
WA2/4
LW1
CY1
A30
CR4
CR2
Roadside site
Urban Background site
Charging Zone
Boundary Zone
0
15km

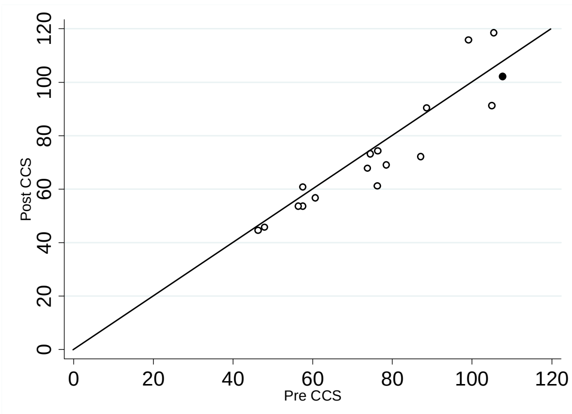
Key to Figure 1:

Site code	***Location***	***Pollutants***	***Site code***	***Location***	***Pollutants***
	Roadside			**Background**	
Congestion Charging Zone			*Congestion Charging Zone*		
CD3	Camden	NO_X, PM_{10}	BL0	Bloomsbury	NO_X, PM_{10}, CO, O_3
			CT1	City of London	NO_X, O_3
			WM0	Westminster	NO_X, CO, O_3
Boundary Zone			*Boundary Zone*		
CD1	Camden	NO_X, PM_{10}	HK4	Hackney	NO_X, CO, O_3
KC2	Kensington & Chelsea	NO_X, PM_{10}	IS1	Islington 1	NO_X, PM_{10}
KC3	Kensington & Chelsea	NO_X	KC1	Kensington & Chelsea	NO_X, PM_{10}, CO, O_3
KC4	Kensington & Chelsea	NO_X	SK1	Southwark	NO_X, CO, O_3
MY1	Marylebone Rd.	NO_X, PM_{10}	TH1	Tower Hamlets	NO_X, PM_{10}, O_3
SK2	Southwark	NO_X	TH3	Tower Hamlets	NO_X
TH2	Tower Hamlets	NO_X	WA2	Wandsworth	NO_X, CO, O_3
WA4	Wandsworth	NO_X, PM_{10}	WE0	West London	NO_X, CO
Control Zone			*Control Zone*		
A30	A3	NO_X, PM_{10}	BN2	Barnet	NO_X, PM_{10}
CR2	Croydon	NO_X	EA1	Ealing	NO_X, O_3
CR4	Croydon	NO_X, PM_{10}	EN3	Enfield	NO_X, PM_{10}, CO, O_3
CY1	Crystal Palace	NO_X, PM_{10}	HR1	Harrow	NO_X, PM_{10}
EA2	Ealing	NO_X, PM_{10}	LW1	Lewisham	NO_X
EN2	Enfield	NO_X, PM_{10}	RB1	Redbridge	NO_X, PM_{10}, O_3
EN4	Enfield	NO_X, PM_{10}	WL1	Waltham Forest	NO_X, PM_{10}
GB6	Greenwich Bexley	NO_X, PM_{10}			
GR5	Greenwich	NO_X, PM_{10}			
HG1	Haringey	NO_X, PM_{10}			
HI1	Hillingdon	NO_X, PM_{10}			
HS4	Hounslow	NO_X, PM_{10}			
HV1	Havering	NO_X			
HV3	Havering	NO_X, PM_{10}			
RB4	Redbridge	NO_X, PM_{10}			
RI1	Richmond	NO_X, PM_{10}			

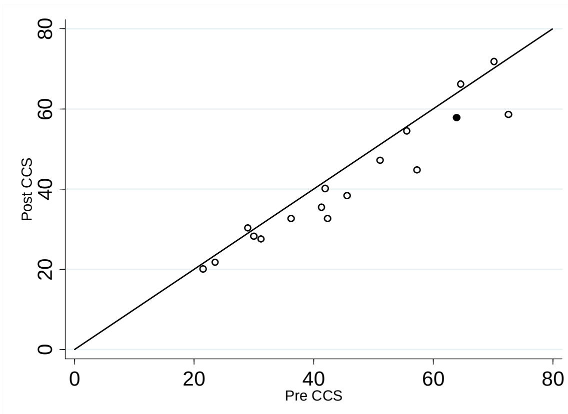
NO_X – NO, NO_2 AND NO_X all measured

Roadside

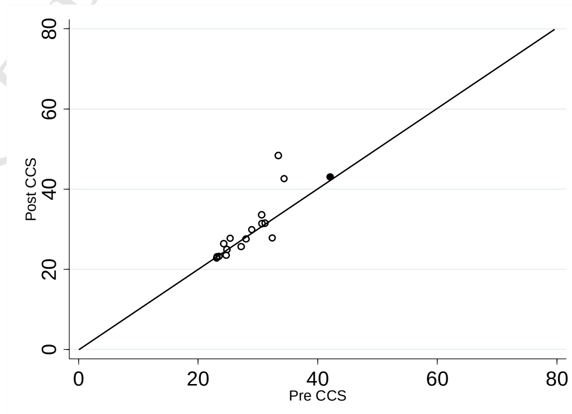
a) NO_X



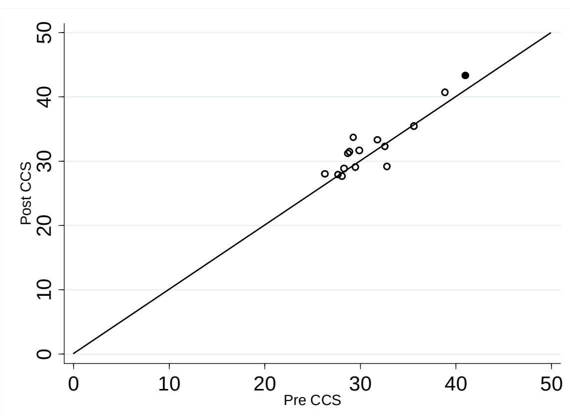
b) NO



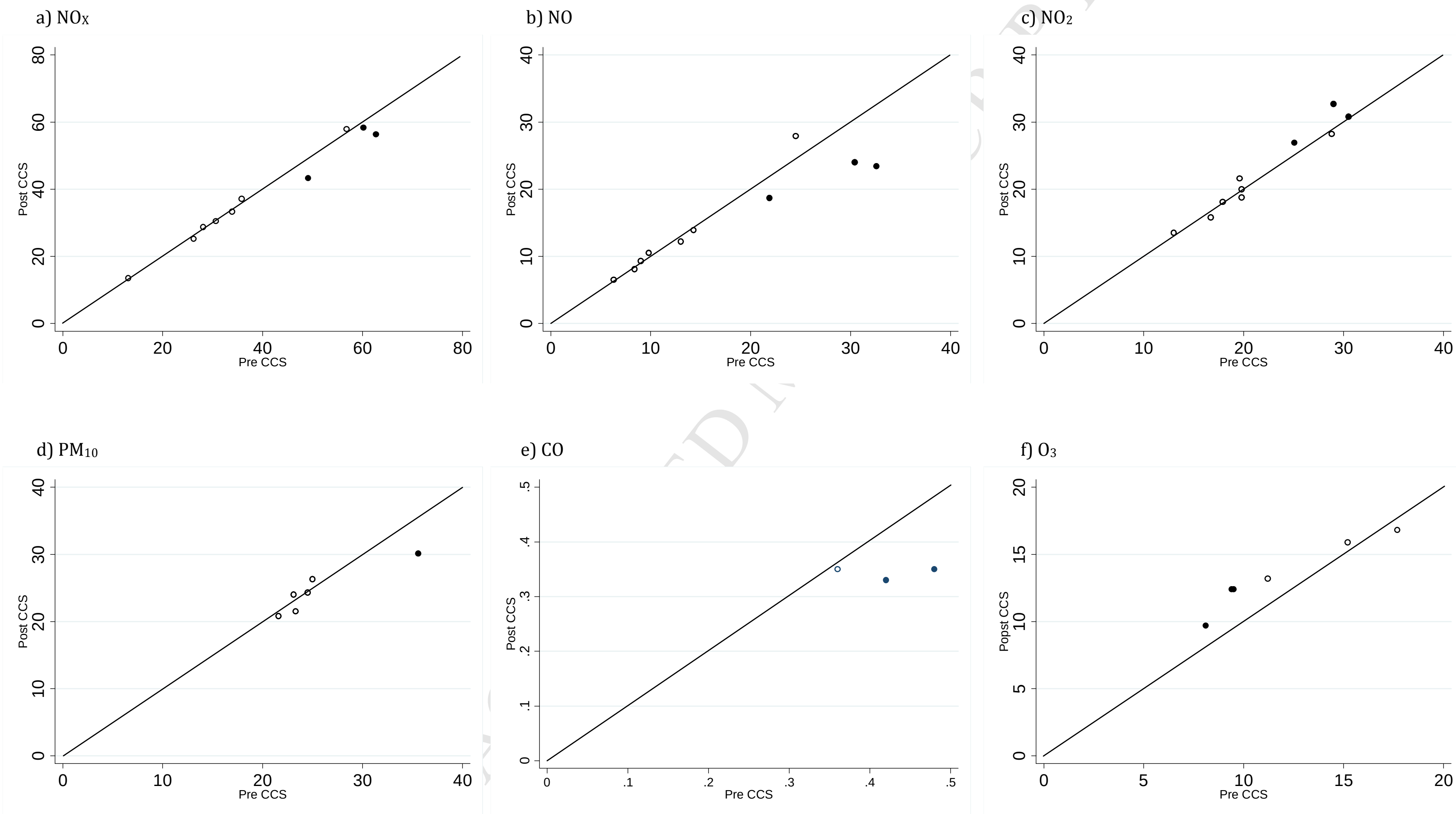
c) NO_2

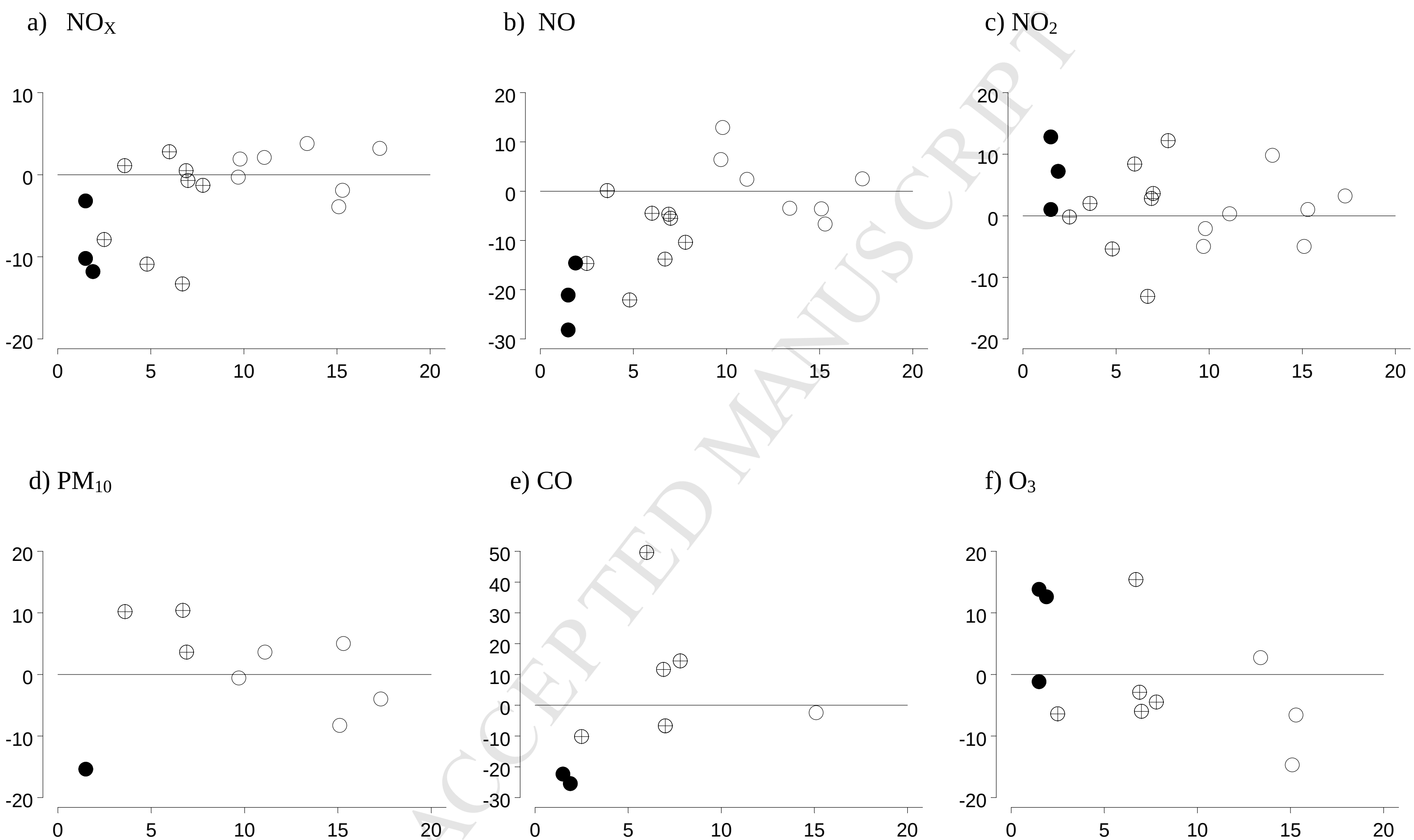


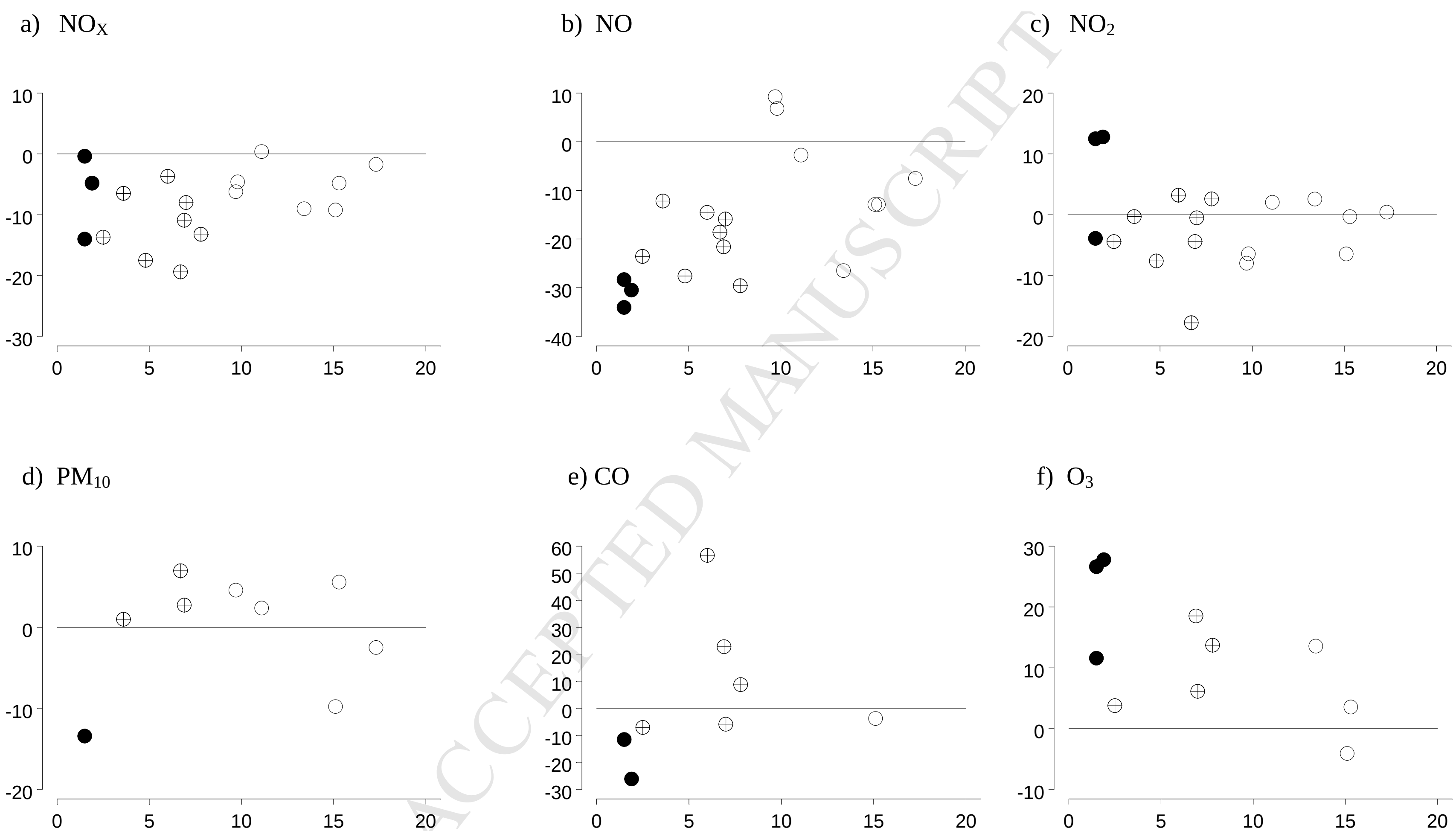
e) PM_{10}



Background


a) NOx
Post CCS
Pre CCS
b) NO
Post CCS
Pre CCS
c) NO2
Post CCS
Pre CCS
d) PM10
Post CCS
Pre CCS
e) CO
Post CCS
Pre CCS
f) O3
Popst CCS
Pre CCS


a) NO_X
10
0
-10
-20
0
5
10
15
20
b) NO
20
10
0
-10
-20
-30
0
5
10
15
20
c) NO_2
20
10
0
-10
-20
0
5
10
15
20
d) PM_{10}
20
10
0
-10
-20
0
5
10
15
20
e) CO
50
40
30
20
10
0
-10
-20
-30
0
5
10
15
20
f) O_3
20
10
0
-10
-20
0
5
10
15
20



a) NOX
b) NO
c) NO2
d) PM10
e) CO
f) O3
10
0
-10
-20
-30
-40
20
30
40
50
60
0
5
10
15
20