Environmental Research Group

Impacts of the bus retrofit programme on NO_2 concentrations along Putney High Street

King's College London Environmental Research Group

Prepared for the London Borough of Wandsworth

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Title	Impacts of the SCR bus retrofit programme on NO_2 concentrations along Putney High Street

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Summary

This study's primary aim was to assess the impact on ambient NO_X and NO_2 concentrations of the retrofitting of exhaust emission control units to a proportion of the Transport for London buses passing along Putney High Street. These buses were fitted with Selective Catalytic Reduction (SCR) emission control units specially adapted for urban driving conditions, with the aim of reducing NO_X gases in the exhaust stream. These units are manufactured by Eminox under the trade name 'SCRT'. In test track conditions these modified retrofit units have demonstrated significant improvements over standard factory fitted SCR systems.

The study was carried out on Putney High Street (PHS); at this point a single lane carriageway with shops and flats forming a continuous façade on both sides. Continuous NO_2 monitoring was carried out at the kerbside and adjacent façade of the northbound carriageway. Automatic Number Plate Recognition (ANPR) cameras captured registration details of vehicles passing by the monitoring point in both directions, allowing concentrations to be related to vehicle numbers, classes and emissions characteristics. Analysis was carried out on measurements taken between October 2012 and October 2013.

The analysis made use of a meteorological normalisation statistical model. The technique uses a regression trees approach to obtain a site-specific relationship between pollution concentrations and meteorological conditions. The model derived is then used to reveal trends in concentrations that would have been recorded had the weather remained constant throughout the period. This normalised output has far less noise than measured concentrations and more closely reflects changes in local emissions.

Over the full monitoring period, 2.6 million paired (i.e., north bound and south bound) ANPR captures were made. In total, 450,000 unique registration plates were captured. Buses and coaches comprised 14% of the total vehicle fleet, a figure that was consistent throughout the 12 month period. Approximately 40 plant/construction vehicles passed along PHS per day. This figure did not increase significantly over the period. The proportion of heavy goods vehicles (HGVs) also remained constant at 0.9%.

93 buses from the Putney bus garage were retrofitted with the modified SCR systems between January and May 2013, however, a fault was identified soon after fitting and the units were temporarily deactivated. Fully operational units were reintroduced into the bus fleet between the end of April and the end of July 2013. ANPR camera data revealed that of the 93 buses retrofitted, only 89 were in regular use along PHS. From August 2013 onwards, approximately half of all bus and coach movements along PHS were TfL retrofitted buses. The remainder were either hybrid (5%), or buses with factory fitted emissions control technology. No hydrogen buses passed along PHS during the study.

When the effects of meteorology had been removed, a clear decrease in NO_X and NO_2 concentrations at the kerb and façade monitoring sites became evident between late April and June 2013. The timing of the change was co-incidental with the introduction of operational retrofitted units. Additional analyses established that this change was not recorded at other LAQN monitoring sites and not evident in the same timescale in PM_{10} concentrations measured on PHS. Therefore, it is reasonable to assume that this decrease, amounting to approximately 23% at the kerb and 20% at the façade, was due to reduced bus emissions driven by the 'SCRT' retrofit units.

However, an unexpected increase in normalised concentrations occurred soon after the full fleet of 89 retrofitted buses had been introduced. NO_X concentrations at the kerb increased to within 6% of their pre-retrofit concentrations. Despite this increase, NO_2 concentrations remained 12% and 16% below pre-retrofit concentrations at the end of the study at the kerb and façade respectively. The cause of this increase could not be established, however, a number of

possibilities were ruled out, including increased local construction traffic, removal of significant numbers of retrofit buses from PHS routes and analyser malfunction. TfL's contractors were unable to identify any technical reason why the performance of the modified SCR units could have lost performance around this date. This question requires further investigation to establish the cause.

Despite the degradation in performance, a sustained decrease in ambient NO_2 concentrations of 16% (during normalised meteorological conditions) at the façade is an encouraging result. It should be noted that that less than 50% of the bus journeys passing along PHS after full deployment were retrofitted buses.

The results of the analysis over the period of the introduction of retrofitted buses are consistent with those independently derived in a remote sensing study carried out on Putney Hill during June 2013. The remote sensing study used direct measurements of vehicle exhaust emissions to compare buses retrofitted with modified SCR units against those buses with either factory fitted or no SCR emissions control. Due to the timing of the remote sensing campaign, it was not possible to directly compare the two sets of results following the unexpected increase in the post-retrofit period.

Due to the nature of the reduction in NO_2 the fall in the number of hourly exceedences of the 200 $\mu g\ m^{-3}$ EU Limit threshold per month was more marked than the reduction in mean concentrations. There were 42% and 71% fewer exceedences recorded at the kerb and façade of PHS respectively in the second half of 2013 when compared to the second half of 2010 to 2012.

While buses are known to be a major emissions source of NO_2 on PHS, this result indicates that even if all buses passing along PHS were retrofitted with modified SCR systems, annual mean NO_2 concentrations are likely to remain above the annual mean EU Limit Value of 40 $\mu g\ m^{-3}$. Further action will be required to achieve the EU objectives.

In conclusion, there is reasonably strong evidence that the introduction of modified SCR systems to buses passing along Putney High Street has led to a decrease in NO_2 and NO_X concentrations measured at the kerb and façade. This intervention appears to have been particularly effective in reducing the number of exceedences of the short term EU Limit Value threshold. However, further measures are required to meet both EU Limit Values for NO_2.

The sustained performance of the SCRT units requires further investigation. It should also be noted that the congested stop-start traffic conditions present along PHS are particularly difficult for this type of emission control technology to work at full efficiency and better reductions may be achieved in more free flowing locations.

Acronyms

ATC	Automatic Traffic Counter
AQS	UK Air Quality Strategy
AURN	Automatic Urban Network
ANPR	Automatic Number Plate Recognition [camera]
Defra/DEFRA	Department for the Environment, Rood and Rural Affairs
DfT	Department for Transport
DPF	Diesel Particulate Filter
ERG	Environmental Research Group
EU	European Union
FDMS	Filter Dynamic Measurement System
GAM	Generalised Additive Model
HGV	Heavy Goods Vehicle
KCL	King's College London
LAQN	London Air Quality Network
LEZ	Low Emission Zone
LGV	Light Goods Vehicle
MCC	Manual Classified [traffic] Count
MGV	Medium Goods Vehicle
MTLB	Millbrook London Transport Bus Drive Cycle
NB	Northbound (traffic)
NO_2	Nitrogen Dioxide
NO_X	Oxides of Nitrogen
PHS	Putney High Street
PM	Particulate Matter
PM_{10}	Particulate Matter with an approximate diameter of 10 µm
QA/QC	Quality Assurance / Quality Control
SB	Southbound (traffic)
SCR	Selective Catalytic Reduction
SCRT	'*Selective Catalytic Reduction Technology'* – an Eminox trade name for modified SCR units optimised for urban driving conditions
SMMT	Society of Motor Manufacturers and Traders
TEOM	Tapered Element Oscillating Microbalance
TfL	Transport for London
VCM	Volatile Correction Model

Contents

1. Introduction

The London of Borough of Wandsworth has continuously monitored PM_{10} and nitrogen dioxide (NO_2) concentrations at the kerb of Putney High Street (PHS) since July 2009. This monitoring revealed that, although PM_{10} concentrations were within EU Limit Values, NO_2 concentrations were amongst the highest recorded in London and far exceed the short and long term EU Limit Values. A report by the Transport Research Laboratory (TRL) in 2011 concluded that buses contributed over two-thirds of NO_X emissions in Putney High Street despite making up only ten percent of vehicle flow (Savage and Turpin, 2011).

In December 2011 TfL and the Department for Transport announced a fund of £10 million for the retrofit of around 900 Euro III buses in London with NO_X emission control technology. TfL undertook a staged methodology for selecting which bus routes should be prioritised when deploying retrofitted buses (TfL, 2012). Putney High Street was identified as a focus area and funds were allocated to apply the retrofit technology to all Euro III buses operating out of Putney bus garage. The L.B. Wandsworth commissioned King's College London to analyse the impact of this NO_X reduction technology on NO_2 and NO_X concentrations along Putney High Street. The study was funded through a Defra's Air Quality Grant scheme.

2. Methods

The study combined high frequency NO_2 and NO_X measurements with detailed vehicle fleet profiling from October 2012 to October 2013. The analysis methods described were primarily designed to quantify the impact of the new bus emissions reduction technology on ambient NO_2 concentrations, independent of confounding factors such as meteorology and changes in emissions from the remainder of the vehicle fleet.

2.1 Study site

The study was carried out on Putney High Street (A219); at this point a single lane carriageway with shops and flats forming a continuous façade on both sides. Annual average daily traffic (AADT) flows are approximately 20,000 vehicles with an average speed of around 20 km/h. Putney High Streets acts as a busy through route for vehicles travelling from the South Circular to central London, and a popular shopping destination. A combination of pedestrian crossings, frequent bus stops and loading bays leads to frequent congestion throughout the day.

Continuous NO_2 monitoring was carried out at the kerbside and adjacent façade of the northbound carriageway. As can be seen in Figure 1, a pedestrian crossing was located just to the south of the monitoring point. An Automatic Number Plate Recognition (ANPR) camera was installed on the lamp post next to the kerbside monitoring point recording northbound traffic. A second camera was installed on the nearest lamp post on the southbound carriageway to record southbound traffic.

Figure 1: Photograph showing the study location with pollution and traffic monitoring points indicated (Google Streetview looking north).

2.2 Source data and QA/QC

The primary data source for this study was the continuous NO_2 and traffic monitoring described above, however, a number of other key datasets were used in some analyses, details of which are shown in Table 1

Site Name	Species	Latitude	Longitude
North Kensington	NO_2, PM_{10}	51.5211	-0.2135
PHS Kerb	NO_2, PM_{10}	51.4634	-0.2158
PHS Facade	NO_2	51.4634	-0.2158
PHS ANPR NB	Detailed traffic	51.4634	-0.2158
PHS ANPR SB	Detailed traffic	51.4636	-0.2156
London mean met.	Meteorology	-	-

Table 1: Details of datasets used in the study.

Measurements from all pollution analysers were subject to strict QA/QC procedures as specified in TG(09) (Defra 2011). All measurements were fully ratified. Data capture rates for all pollution analysers were consistently high over the analysis period. The presence of two closely located NO_X analysers meant that measurements could be cross checked against each other; due to their close proximity, the two datasets should track each other to some degree.

LB Wandsworth operates a background monitoring site in Putney close to the study area. It was anticipated that this monitoring site would be used to represent pollution concentrations largely independent of pollution emissions on Putney High Street itself. Unfortunately, a breakdown in the NO_2 analyser at a key period and a mismatch in PM_{10} monitoring method (FDMS) meant that North Kensington was substituted as the background control when required. Both North Kensington and the kerb monitoring site on PHS used TEOM PM_{10} monitors. All PM_{10} measurements used in the study were converted to reference equivalence using the King's Volatile Correction Model (VCM) as described in Green *et al.* (2009).

'London mean' meteorological data were additionally used for some analyses. These data comprise of a subset of meteorological measurement sites across London in open locations with robust reliable sensors. Measurements from these sites are aggregated to form a 'London mean' dataset, which represents weather conditions across the city not unduly influenced by local factors such as trees, tall buildings or shadow effects.

ANPR cameras were loaned to King's College by Transport for London for the study. Each camera recorded the registration plate of vehicles passing beneath them. These plates were stored as individual text files, which were then transferred to the King's central server. Text files were parsed into a relational database, which stored the direction of travel (Northbound [NB] or Southbound [SB]), time of capture, registration plate and percentage reliability. The reliability estimate was automatically assigned by the camera to give an indication of the confidence in the accuracy of the registration plate, i.e., a perfectly clear plate would be given a reliability estimate of 100%, whereas a plate partially obscured by obstacles, dirt etc., might only be given a reliability estimate of 50%. Only captures with a reliability estimate of 90% or above were used in the subsequent analyses.

Unique registration plates were passed to CDL Vehicle Information Services Limited for decoding. The CDL database includes combined vehicle details from the Driver and Vehicle Licensing Agency (DVLA) and Society of Motor Manufacturers and Traders (SMMT). The decoded records returned included anonymised vehicle registration details for each plate, including vehicle classification, make, fuel, weight, age and registered Euro emission class. The decoded plates were linked to the table of time stamped captures to create a detailed fleet breakdown for each minute of each day.

The ANPR cameras were operating between 25th September 2012 and 26th September 2013. Over this period each camera suffered more than one period of failure, resulting in interruptions in data capture. The most significant periods were during March, June and July 2013. Only 'paired' periods were used in subsequent analyses, i.e., where both cameras were in operation and therefore able to capture the full vehicle fleet.

Automatic Traffic Count (ATC) data were obtained from LB Wandsworth from a counter adjacent to the study location over the period May 2010 to February 2011, the most up-to-date data available.

2.3 Introduction of 'ultra-low emission' buses

Selective Catalytic Reduction (SCR) is a method by which urea is injected into exhaust gas, which hydrolyses to ammonia (NH_3) then reacts with NO_X to form nitrogen, water and CO_2. SCR systems can be fitted to diesel vehicles with particulate filters (DPF) in order to reduce total NO_X and primary NO_2 emissions. However, factory fitted SCR systems have been shown to produce little beneficial effect in real world urban driving conditions (Carslaw and Rhys-Tyler 2013). Recognising this failing, TfL worked with SCR unit manufacturers Eminox to produce a modified unit optimised for urban driving conditions. This modified SCR was tested against a test cycle generated using real time speed data collected from a London Bus working on Route 159 from Streatham to Baker Street ('Millbrook London Transport Bus (MTLB) Drive Cycle'), rather than the standard European test cycle. Over the full MTLB drive cycle, the modified unit was found to reduce NO_X concentrations by up to 90% compared to a bus fitted with no exhaust emissions control (Carslaw et al., 2014)

TfL funded the retrofit of the modified SCR units (given the trade name 'SCRT' by the manufacturers) to 93 double decker buses operating out of the Putney Bus garage that were capable of receiving the technology. The remaining 127 buses were technically unsuitable. In the majority of cases, this is because the vehicles were emissions class Euro IV or Euro V and therefore had factory fitted SCR units.

The vehicles were removed from service for a number of days while the necessary modifications were carried out, and then returned to service fully operational. These retrofits were carried out between January and May 2013. Upon returning to service, it was found that a setting within the engine management system was causing the buses to become inoperable during certain driving conditions, and SCRT unit operation was disabled. Buses were returned for a correction to the wiring loom and reactivation during April, May, June and July 2013. This technical issue meant that emissions management on the retrofitted buses was not fully operational until this re-activation.

In the impacts analysis, we therefore took the pre-intervention period to be up to 29th April 2013, when the first re-activation occurred.

2.4 Traffic characterisation

Prior to their use in other analysis outputs, a validation exercise was carried out in order to verify whether the ANPR cameras were capturing the number plates of all vehicles passing along PHS in both directions. This was done by comparing the mean hourly count of all vehicles in each direction as recorded by ATC counters and ANPR cameras. Note that a true comparison was not possible as the ATC and ANPR capture periods did not overlap.

ANPR captures were then used to characterise the fleet passing along PHS in terms of vehicle class and number. TfL provided a list of all London Transport (LT) buses in operation across the capital during March 2013, including their route and emissions class. This allowed the separation of LT buses from other buses and coaches. A second list gave individual registration numbers of the retrofitted buses, and the date on which they became fully operational (i.e., following wiring loom repair). In combination with the ANPR captures, this allowed a precise calculation of the number of retrofitted and non-retrofitted bus passes along PHS on each day. Note that counts were based on bus passes, not number of buses, as most buses passed along PHS multiple times in one day.

2.5 Meteorological normalisation

King's has developed an advanced statistical technique designed to remove the effects of meteorology on pollution concentrations. This allows trends in pollution concentrations to be assessed independent of the influence of weather conditions.

The technique uses a regression trees approach to obtain a site-specific relationship between pollution concentrations and meteorological conditions (Carslaw and Taylor 2009). The model derived is then used to produce a 'normalised' dataset, i.e., trends in concentrations that would have been recorded had the weather remained constant (average over all conditions) throughout the period. This normalised output has far less noise than measured concentrations and more closely reflects changes in local emissions. Note that not all local emissions will be from vehicles. This is particularly true in the case of PM_{10}, which has diverse urban sources.

The normalisation technique was applied to hourly mean NO_X and NO_2 concentrations at the PHS kerb and façade sites using the 'London mean meteorology' dataset (as described in Section 2.2). The technique was also applied to PM_{10} concentrations recorded by the kerbside site. Due to the strong influence of regional particulate sources, hourly mean TEOM PM_{10} concentrations from an urban background site in North Kensington (LAQN site code 'KC1') were used as an additional explanatory variable in the statistical model. In each case, meteorological conditions were fixed at their median. The resulting time series showed an estimate of concentrations at noon each day arising from local emissions, primarily from the adjacent road, under fixed meteorological conditions.

3. Results

3.1 Putney High Street fleet characterisation

3.1.1. Assessment of ANPR capture rates

Over the full monitoring period, 2,655,999 paired ANPR captures were made. Of these, 405,136 paired captures (15%) were discarded because they had a reliability estimate of < 90%, or could not be matched on the CDL database. In total, 449,394 unique registration plates were captured.

Figure 2 shows the results of the ANPR camera capture rate validation exercise. It is clear that the number of vehicles captured on each hour by the ANPR camera was very similar to the ATC on the southbound carriageway; the mean difference was 1% over the period 06:00 to 20:00. However, the mean difference on the northbound carriageway was 20% over the same period. Therefore, the NB camera was not capturing 20% of the fleet during peak flow hours. This under read would not have affected the pollution impact analysis, but should be borne in mind when interpreting the fleet characterisation in the following section.

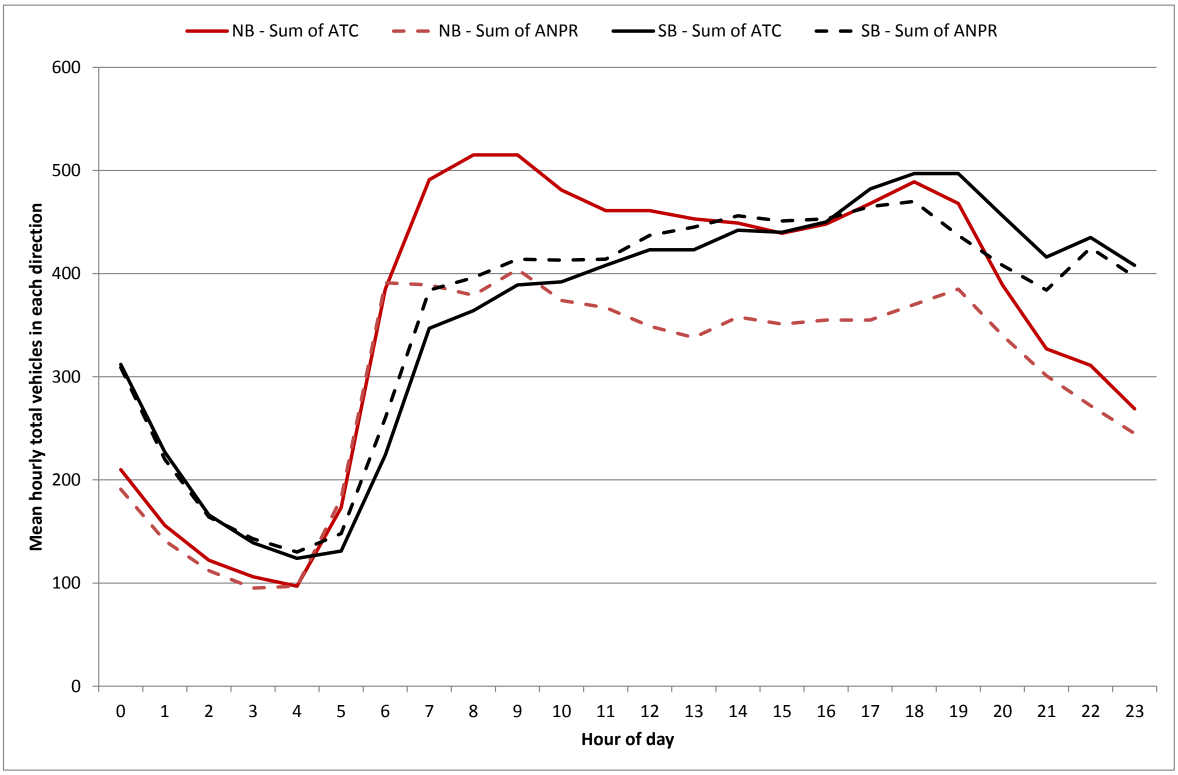

Figure 2: Comparison of mean vehicle counts northbound (NB) and southbound (SB) by ATC and ANPR cameras.

3.1.2. Fleet composition

Figure 3 shows the composition of the vehicle fleet passing along PHS over the analysis period (SB only). As expected, the majority of the fleet was passenger cars, then buses and coaches, then light vans. Buses and coaches comprised 14% of the total vehicle fleet, a figure that was consistent throughout the 12 month period. Approximately 40 plant/construction vehicles passed along PHS per day. This figure did not increase significantly over the period, despite the commencement of building works to the Putney Exchange shopping centre. The proportion of heavy goods vehicles (HGVs) also remained constant at 0.9%, although the absolute numbers varied from month to month. Fleet composition on PHS is examined in more detail in TRL's previous ANPR study (Savage and Turpin, 2011).

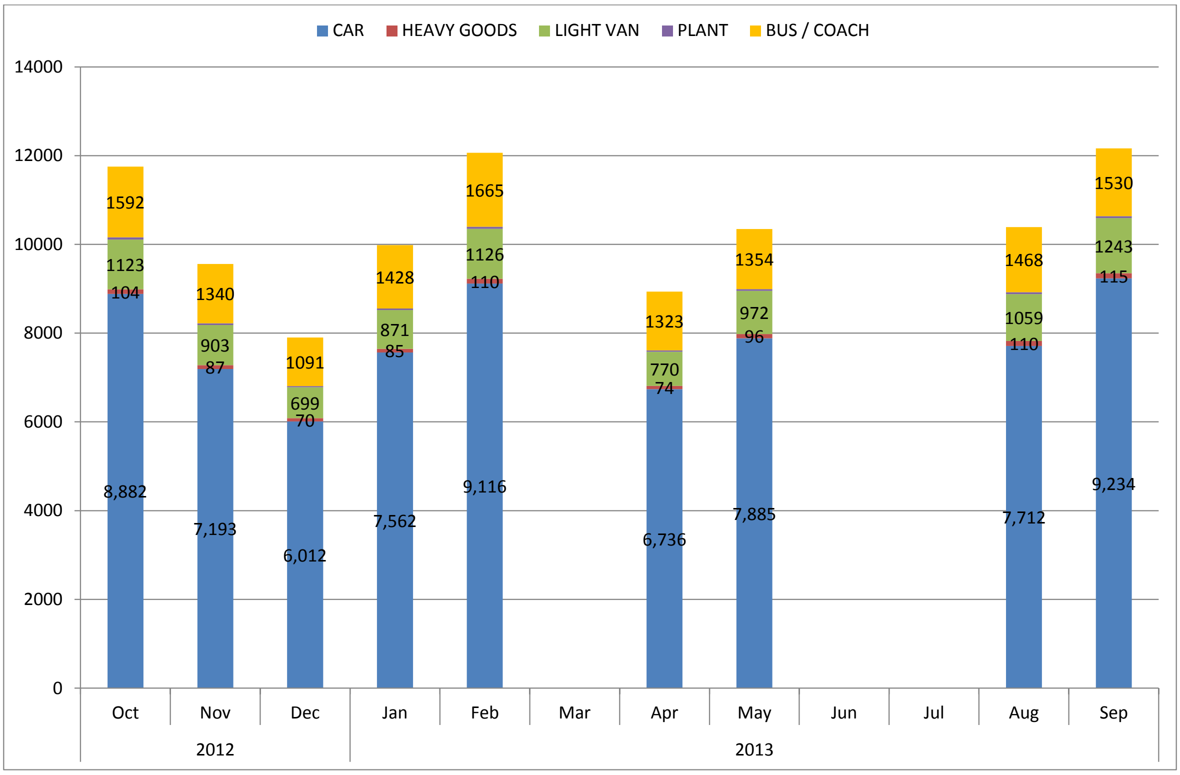

Figure 3: Classified monthly average daily total vehicle flows as recorded by the SB ANPR camera October 2012 to September 2013.

3.2 Introduction of retrofitted buses

93 out of 220 buses operating out of the Putney bus garage were retrofitted with the modified SCR systems between January and May 2013, however, due to a fault identified soon after fitting, they did not all become fully operational until July 2013. As Figure 4 illustrates, the majority of the vehicles were operational on PHS during June 2013. As the units were disabled soon after their initial fitting, the 'SCR Fitted' dates are largely irrelevant to impacts on air quality.

Of the 93 buses fitted, only 89 were in regular use along PHS, according to the ANPR camera data. Four buses – registration plates LF52ZTU, LG02KNX, LX05EBD and LX53BEK – were not captured passing the cameras at any point during the 12 month period.

The ANPR dataset enabled analysis of the proportion of retrofitted buses passing along PHS at the monitoring point per month. The percentage of captures associated with retrofitted buses rose from <1% in April, to 49% in August, dropping back slightly to 46% in September (approximately 17,000 retrofit bus captures per month out of a total of 37,000 bus captures). These figures mean that any detectable impact on air quality arising from the retrofit programme will have occurred from May 2013 onwards. It should also be noted that more than half of the buses passing the monitoring point were not retrofitted (as explained in Section 2.3).

TfL introduced other 'ultra-low emission' buses to the PHS fleet during the study period; ANPR captures showed that ten hybrid buses were introduced into the fleet during September to November 2012. Hybrid buses consistently accounted for approximately 5% of all bus captures during the study (c. 2,000 captures per month). As this number did not change over the analysis period, the presence of hybrid buses will not have affected the retrofit air quality analysis. No hydrogen buses passed along PHS during the study.

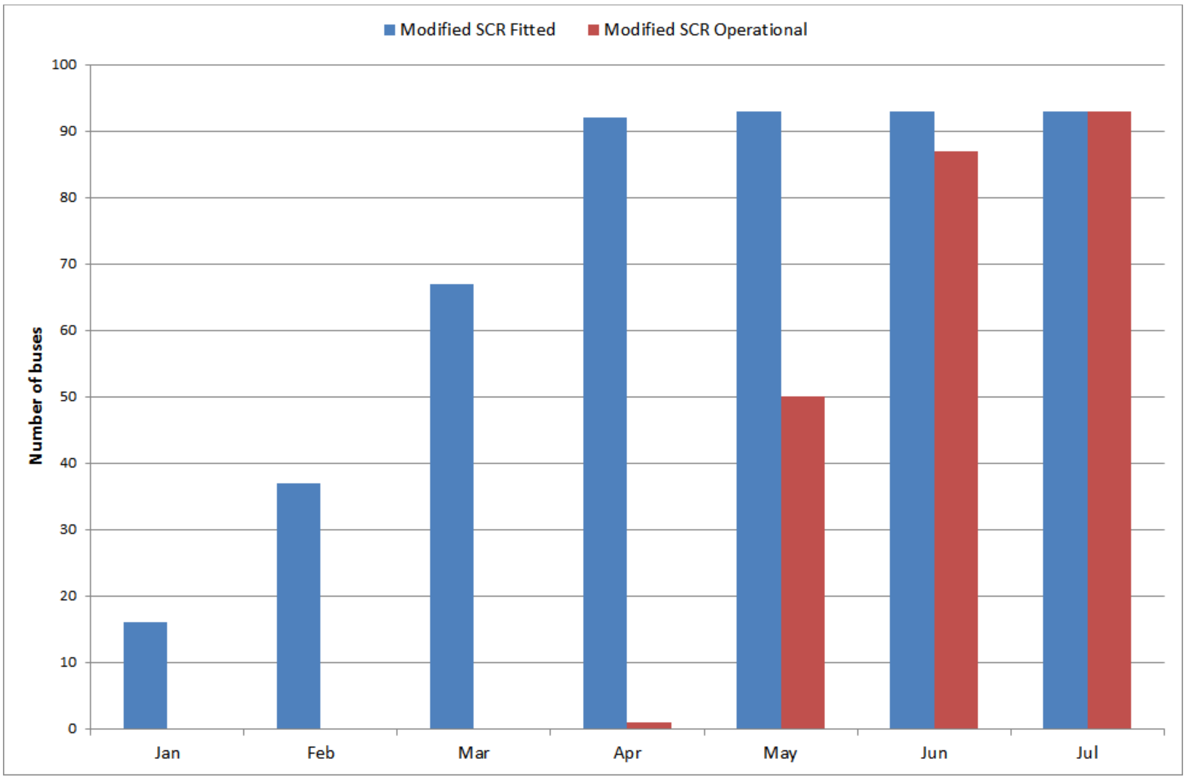

Figure 4: Number of buses operating on PHS between January and July 2013, showing when modified SCR units were fitted and operational.

3.3 Impact on pollutant concentrations

The meteorological normalisation method was applied to NO_X concentrations recorded by the kerbside site. This analysis removed the influence of meteorology on pollution levels, allowing an assessment of the impact of changes in emissions (Figure 5).

The measured data, shown in red in Figure 5, show considerable day to day variation, driven by meteorological conditions, primarily wind speed and direction. When the effects of meteorology are removed, the data become far less variable (black line). A good example of the performance of the normalisation method is seen in March and April 2013. While the measured concentrations appear to halve during this period, from around 400 µg m^{-3} to around 200 µg m^{-3}, the normalised trace shows no change. This indicates that the large drop was due to beneficial weather conditions, not a change in vehicle emissions. Conversely, a sharp drop in the normalised trace at the end of December and beginning of January highlights the impact of the Christmas holiday on vehicle emissions.

If the modified SCR units drove a decrease in NO_X and NO_2 concentrations, we would expect this decrease to coincide with the dates on which the retrofit buses became operational. This relationship is illustrated in Figure 6 and Figure 7, where the number of operational retrofit buses is overlaid onto normalised NO_X and NO_2 concentrations respectively recorded at the kerb (WA7) and façade (WA8).

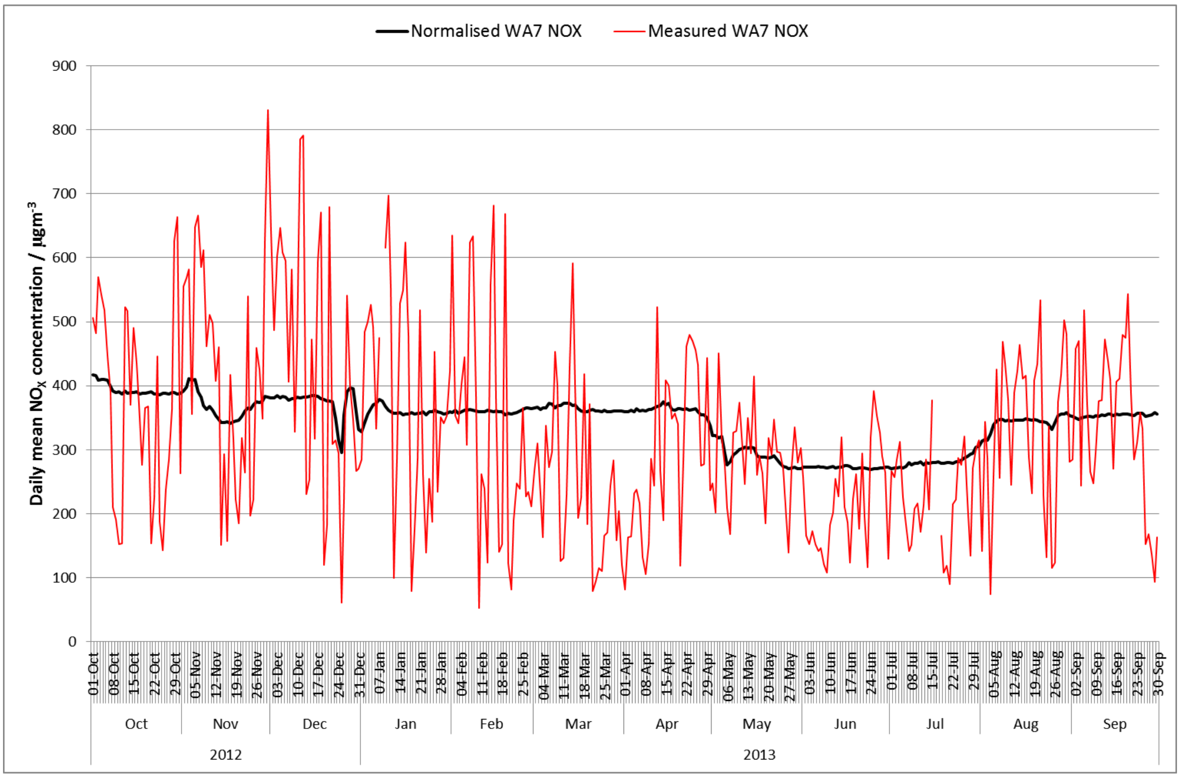

Figure 5: Measured (red) and normalised (black) daily mean NO_X concentrations recorded by the PHS kerbside site.

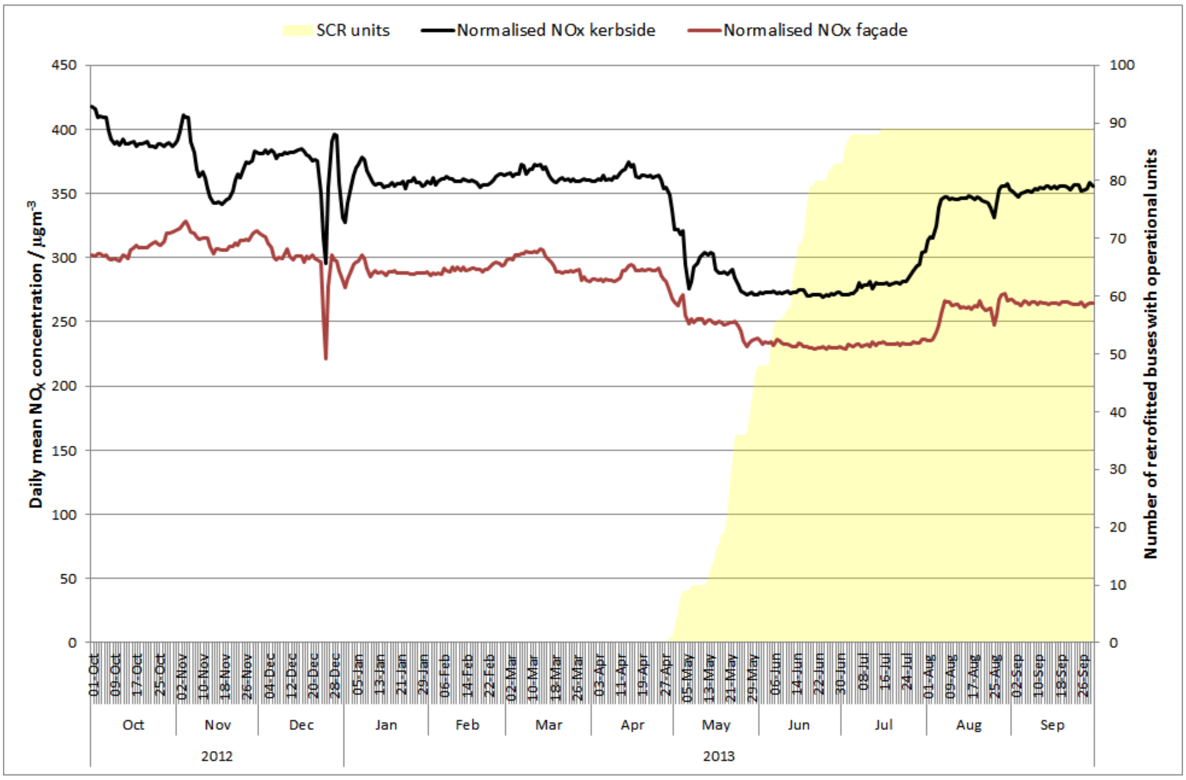

Figure 6: Normalised NO_X concentrations at the kerb and facade of PHS, with the introduction of retrofitted buses overlaid in yellow.

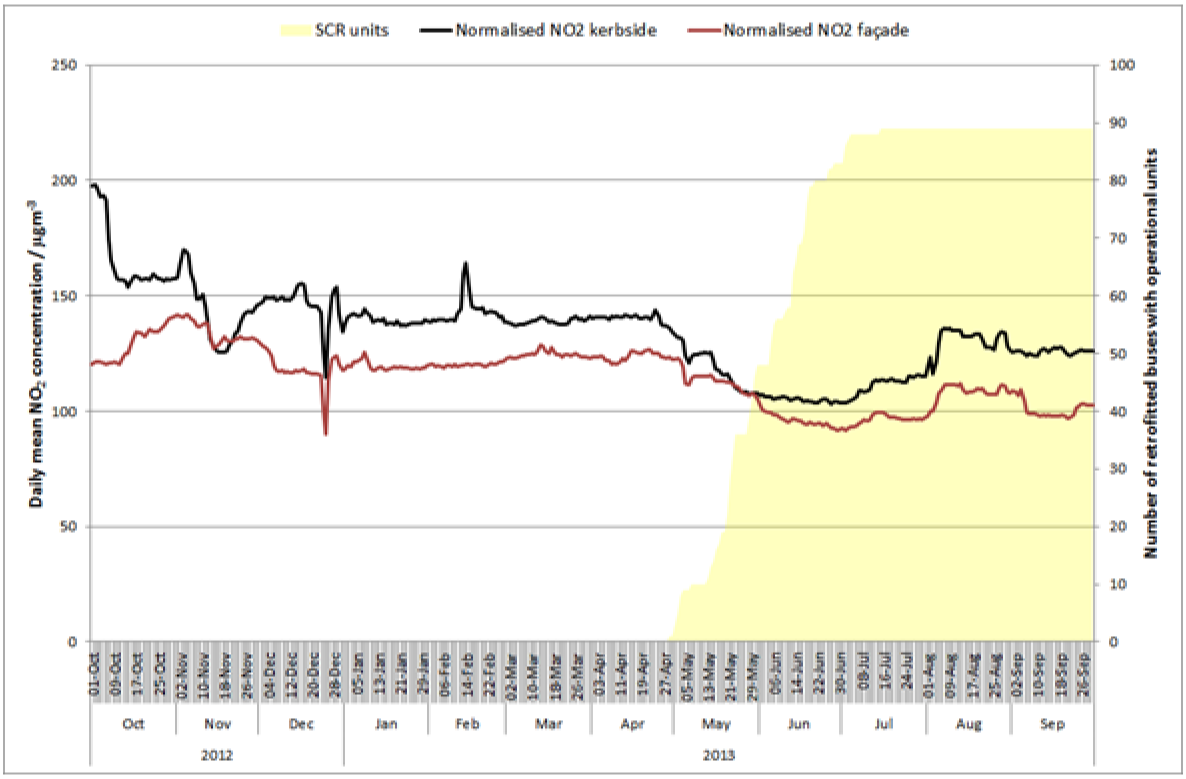

Figure 7: Normalised NO_2 concentrations at the kerb and facade of PHS, with the introduction of retrofitted buses overlaid in yellow.

First considering NO_X trends (Figure 6), concentrations at the kerb and façade dropped rapidly coinciding with the start of the retrofitted buses being introduced back into the fleet at the end of April. Concentrations continued to decrease until the end of May, when they stabilized. At this point about 50 of the 89 retrofitted buses are operational on PHS. Despite the introduction of a further 39 retrofitted buses, no further decreases were evident in the normalised data. This lower level was maintained until the end of July, when NO_X concentrations rose rapidly, cancelling out much of the previous decrease.

The pattern in normalised NO_2 was similar (Figure 7), but with two notable differences. First, the decrease in NO_2 was more gradual and sustained throughout the introduction of all 89 buses. Second, the increase in August was less strong, resulting in a more defined decrease overall. This was especially evident at the façade side.

Changes in normalised NO_X and NO_2 concentrations are summarised in Table 2. The study was divided into three periods; 'Pre-retrofit' was defined as 1st October 2012 to 28th April 2013, i.e., up to the day before the first retrofitted bus with an operational unit was introduced into the fleet, 'Transition' was defined as 29th April to 31st July 2013 covering the introduction of all 89 retrofitted buses into service, 'Post-retrofit' was defined as 1st August to 30th September 2013 (the end of the study period) representing the period when the normalised results showed a sudden increase in NO_X concentrations, despite all 89 retrofitted buses being in service.

The results showed that in all cases, normalised NO_X concentrations were lower following full introduction of the retrofitted buses, but not as low as during the transition period, while buses were still being introduced. In the case of the kerbside site, NO_X concentrations in the post-retrofit period were 6% lower of those in the pre-retrofit period, i.e., little change overall. The greatest sustained change was recorded in NO_2 at the façade; a change of 20 µg m^{-3} between pre and post-retrofit represents a 20% decrease in concentrations of ambient NO_2. This is a substantial decrease most likely resulting from the retrofitting of emissions control technology to a relatively small number of vehicles.

Period	Dates	NO_X / µg m^{-3}		NO_2 / µg m^{-3}	
		Kerb	Façade	Kerb	Façade
Pre-retrofit	1-oct-2012 to 28-apr-2013	370	298	146	125
Transition	29-apr-2013 to 31-jul-2013	283 (-24%)	239 (-20%)	112 (-23%)	102 (-18%)
Post- retrofit	01-aug-2013 to 30-sep-2013	348 (-6%)	262 (-12%)	128 (-12%)	105 (-16%)

Table 2: Summary of changes to NO_X and NO_2 concentrations prior to, during and following introduction of retrofitted buses. Percentage change in comparison with the pre- retrofit period is shown in parentheses.

3.4 Additional analyses to establish the cause of the post-retrofit increase in NO_X

While the sustained decrease in NO_2 was encouraging, questions remained as to why the greater decrease seen during the transition period was not sustained. Given that the normalisation method removes the impact of meteorology on concentrations, the increase in normalised concentrations recorded in early August must have been due to one or more of the following:

1. Inaccuracies in the NO_X monitoring results,
2. A sudden local or London-wide increase in NO_X concentrations independent of meteorology,
3. An abrupt change in the vehicle fleet passing along PHS at this time,
4. A proportion of the retrofitted buses being taken out of service or reassigned to different routes not passing along PHS,
5. Failure or partial failure of the modified SCR system.

A number of additional analyses were carried out to investigate which of these scenarios was most likely to be the cause.

The study benefitted from two completely independent NO_X monitoring systems in close proximity. The fact that the patterns in NO_X and NO_2 concentrations recorded by these two monitors followed each other closely makes it extremely unlikely that inaccuracies in the monitoring results were the cause. To increase confidence in the results, the analysers were given an additional independent equipment audit by the National Physical Laboratory in January 2014 and both passed with no faults. The calibration gas was also recertified and found to have no significant drift.

The normalisation method was applied to two additional datasets to establish whether other pollutants and locations followed the same pattern as NO_X at PHS.

A nearby roadside site in Castelnau, Richmond-upon-Thames was used to compare normalised NO_X concentrations independent of the retrofit programme. The pattern of normalised trends showed no distinct change in NO_X during the transition period. There was an increase in the post-retrofit period, leading to an overall increase, but this was not abrupt and commenced a month later than that recorded on PHS. NO_2 concentrations at the Richmond roadside site during the transition and post-retrofit periods were within +/-2% of the pre-retrofit period. Further work is planned to establish changes in NO_2 at other locations across London in order to establish the London-wide impact of the retrofit programme.

As the kerbside site on PHS also recorded PM_{10} over the study period, it was possible to compare normalised NO_X trends against normalised PM_{10} trends. The modified SCR units would not be expected to have an impact on PM_{10} concentrations as all buses already had particulate filters. Therefore, any relationship between trends in NO_X and PM_{10} over the analysis period would suggest an alternative cause. The chart of normalised PM_{10} at the kerb is shown in Figure 8, overlaid with NO_X for comparison. The normalised PM_{10} trace is more variable than that of NO_X, reflecting the influence of a mix of particulate sources independent of vehicle emissions from the adjacent road, such as construction or demolition activity. This activity need not be local to the site. While there is some relationship between the variation in PM_{10} and NO_X at the kerb, the timescales do not match, with a more gradual decease, then increase in PM_{10}, rather than an abrupt change. It is therefore unlikely that this change was driven by the same factors as the change noted in NO_X.

ANPR data were also interrogated to establish whether any large changes in the vehicle fleet occurred during the transition or post- retrofit periods. As noted in Section 3.1.2, the proportion of retrofitted bus captures decreased slightly between the end of the transition period (49%) to the start of the post- retrofit period (46%). This small change was not considered sufficient to cause the increase in NO_X. No increase in plant/construction vehicles was captured over this period, further supporting the conclusion that the construction works on the Putney Exchange building did not have a major influence on recorded NO_X concentrations. Finally, the ANPR data did not indicate any large increase in vehicle numbers and the timing of the change did not coincide with any school holiday periods.

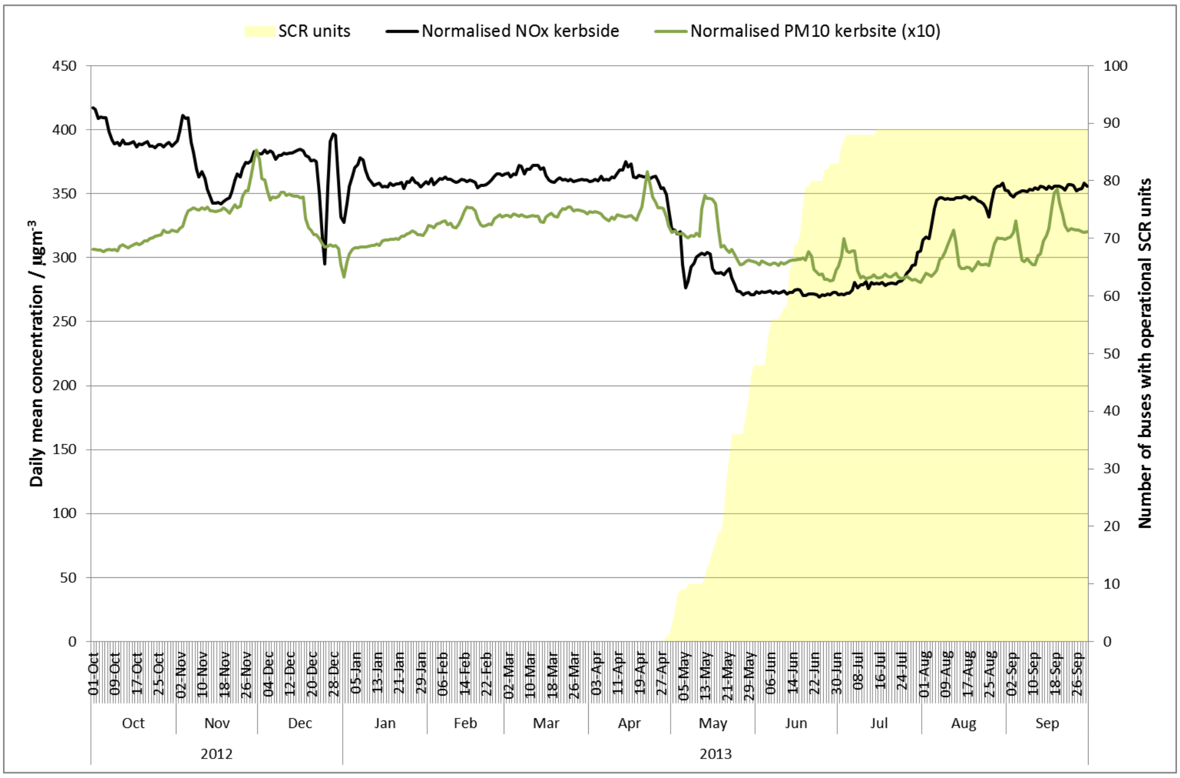

Figure 8: Normalised NO_X and PM_{10} concentrations at the kerb of PHS, with the introduction of retrofitted buses overlaid in yellow. Note that PM_{10} has been scaled x10 to aid interpretation.

4. Discussion

Isolating and quantifying cause and effect of air quality management initiatives in real world settings is notoriously difficult due to the wide range of influences on ambient pollution concentrations. This study benefited from an unusually rich dataset of high resolution NO_2, NO_X measurements and vehicle emissions data in an ideal study location, allowing a greater confidence in the study's results and conclusions.

The study's primary aim was to assess the impact on ambient NO_X and NO_2 concentrations of the retrofitting of NO_X exhaust emission control units to a proportion of the London Transport buses passing along Putney High Street. The modified SCR emission control units used in the retrofit programme were designed to reduce NO_X gases in the exhaust stream of diesel vehicles in urban driving conditions typical of a London Bus. Pollution measurements were taken at the kerb and adjacent façade on the west side of PHS. ANPR cameras captured registration details of vehicles passing by the monitoring point in both directions, allowing concentrations to be related to vehicle numbers, classes and emissions characteristics.

Prior to this analysis, officers at LB Wandsworth noted a decrease in the number of hourly exceedences of the short term NO_2 EU Limit Value during early 2013, carrying through to the middle of the year. The results of this analysis indicate that this decrease is likely to be a combination of favourable weather conditions and a decrease in vehicle fleet NO_2 emissions accelerated by the introduction of retrofitted buses.

When the effects of meteorology had been removed, a clear decrease in NO_X and NO_2 concentrations at the kerb and façade monitoring sites became evident between late April and June 2013. The timing of the change was co-incidental with the introduction of retrofitted buses with operational SCRT units. Additional analyses established that this change was not recorded at other LAQN monitoring sites and not evident within the same timescale in PM_{10} concentrations measured on PHS. Therefore, it is reasonable to assume that this decrease, amounting to approximately 23% at the kerb and 20% at the façade, was due to reduced bus emissions driven by the retrofitted units.

However, an unexpected increase in normalised concentrations occurred soon after the full fleet of 89 retrofitted buses had been introduced. NO_X concentrations at the kerb increased to within 6% of their pre-retrofit concentrations. Despite this increase, NO_2 concentrations remained 12% and 16% below pre- retrofit concentrations overall at the kerb and façade respectively. The cause of this increase could not be established, however, a number of possibilities were ruled out, including increased local construction traffic, removal of significant numbers of retrofitted buses from PHS routes and analyser malfunction. TfL's contractors were unable to identify any technical reason why the performance of the SCRT units could have lost performance around this date. This question requires further investigation to establish the cause, but is beyond the remit of this report.

Despite the degradation in performance, a sustained decrease in ambient NO_2 concentrations of 16% (during normalised meteorological conditions) at the façade is an encouraging result. It should be noted that that less than 50% of the bus journeys passing along PHS after full deployment were retrofitted.

This result can be compared with that derived in the associated remote sensing study carried out in Putney during 2013 (Carslaw *et al.*, 2014). This study used a vehicle emission remote sensing detector (RSD) to quantify emissions from a range of vehicle emission technologies under actual conditions of use (on-road emissions), in this case on Putney Hill, L.B. Wandsworth. Due to the timing and location, the study was able to quantify emissions specifically from SCR buses passing along PHS (737 individual RSD measurements). The RSD analysis found that, on average, the SCR buses emitted 45% less NO_X compared with the same vehicle type fitted only with a Diesel Particulate Filter. The RSD measurements were carried out during the 'transition' period, i.e., during the period of greatest reduction in normalised NO_X and NO_2, therefore this 45% reduction in NO_X emissions compares well with the 24% reduction in ambient concentrations recorded by 50% of the bus fleet. Due to the timing of the remote sensing campaign, it was not possible to directly compare the two sets of results following the unexpected increase in the post-retrofit period.

It is also important to consider how a 20% reduction in normalised NO_2 concentrations impacts on the short and long term EU Limit Values for NO_2 (40 µg m^{-3} as an annual mean and 200 µg m^{-3} as an hourly mean, not to be exceeded more than 18 times per year). Historically, NO_2 concentrations recorded at both the kerb and façade on PHS have been well above these limit values. Even though buses were estimated to be a major emissions source, TfL have not claimed that the introduction of SCR buses onto PHS would bring the location into compliance by itself.

The consistent level of reduction in NO_X and NO_2 identified in this study is considerably less than that achieved during test track trials, where a 77% reduction in NO_X emissions was observed compared with the same bus without the any SCR system (Carslaw *et al.*, 2014). The reasons for this difference require further investigation, but are likely to be related to driving conditions specifically on PHS. The congested stop-start traffic conditions present along PHS are particularly difficult for this type of emission control technology to work at full efficiency. This analysis produced a single 'spot check' assessment of performance, rather than over the full drive cycle of the bus and better reductions may be achieved in more free flowing locations.

Figure 9 shows trends in monthly mean NO_2 concentrations as recorded by the kerb and façade sites since June 2010 (when the façade site was commissioned). Even though monthly means are not directly comparable with the annual mean limit value, it is clear that concentrations at both sites are more than twice the 40 µg m^{-3} target. Both sites show a gradual downward trend over the period. More notable is the decrease in the number of hourly exceedences of the 200 µg m^{-3} threshold per month over this period. Up until 2013, the number of exceedences per month was between 130 (summer months) and 320 (winter months). An unusually high frequency of easterly winds led to an usually low number of exceedences during the spring of 2013, but this continued through to the end of the year. This trend demonstrates that a decrease in (meteorologically normalised) *mean* NO_2 concentrations of between 10% and 20% has translated into a far greater reduction in the number of exceedences of the hourly objective threshold recorded at both sites; there were 42% and 71% fewer exceedences at the kerb and façade respectively in the second half of 2013 when compared to the second half of 2010 to 2012.

While the timing of this decrease suggests that the retrofit programme may have been the cause of the decrease, a larger scale London-wide analysis of all bus routes with and without retrofitted vehicles would be required to increase confidence in this causative outcome.

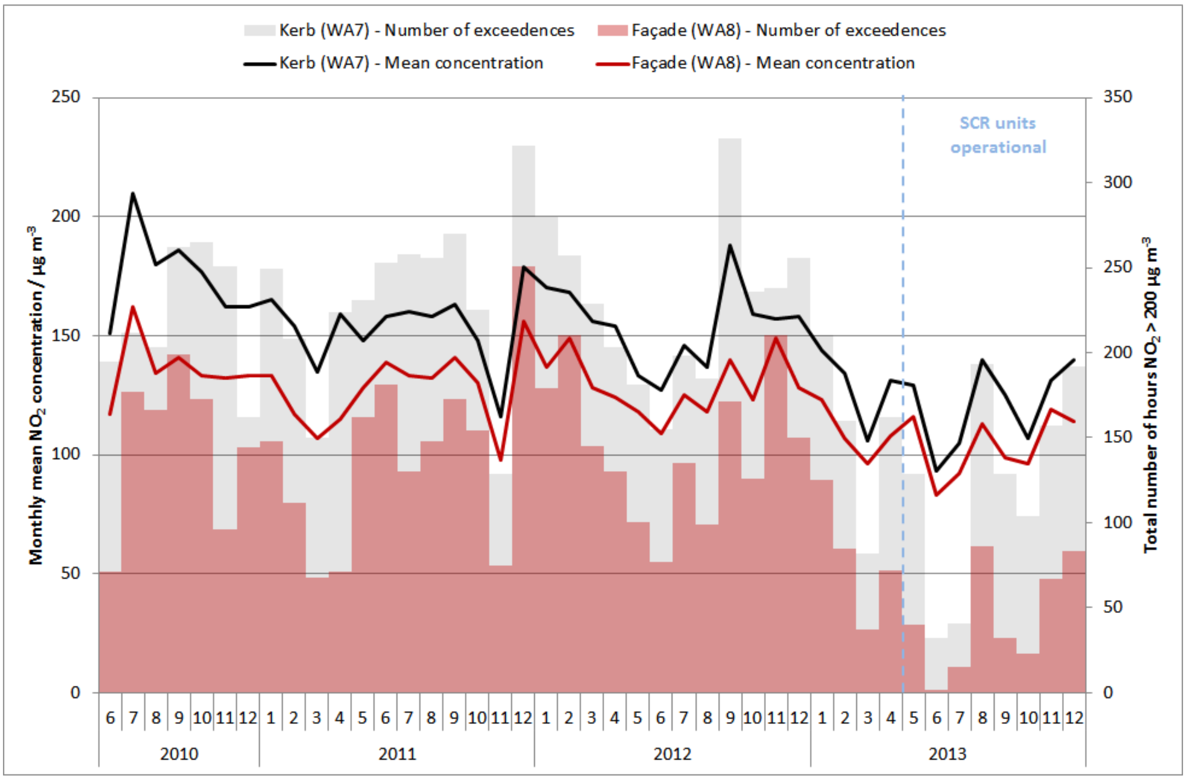

Figure 9: Trends in mean NO_2 concentrations and exceedences of the EU short term limit value per month recorded by both sites on PHS.

5. Conclusions

There is reasonably strong evidence that the introduction of modified SCR systems ('SCRT') to buses passing along Putney High Street led to a decrease in NO_2 and NO_X concentrations measured at the kerb and façade. The sustained decrease in NO_X and NO_2 is estimated as 9% and 14% respectively (average of kerb and façade).

This intervention has been particularly effective in reducing the number of exceedences of the short term EU Limit Value threshold. However, further measures are required to meet both EU Limit Values for NO_2.

The analysis was only able to assess performance of the retrofitted units in congested stop-start driving conditions. It is likely that performance is improved in more free flowing driving conditions, where the system is able to maintain a high temperature. However, it should be recognised that these congested conditions are typical of many locations across London.

The sustained performance of the SCR units requires further investigation.

This study demonstrates the high value of combined high resolution pollution and detailed traffic information in establishing the impact of air quality management measures on vehicle emissions. The long-term use of ANPR cameras in such studies should be considered essential.

6. Recommendations for further work

We recommend that NO_X monitoring at the kerb and façade continue during 2014 in order to assess whether any further non-transient changes occur in the measurements. We also recommend that the ANPR cameras be kept in situ and reactivated if there is any reason to believe that the vehicle fleet on PHS changes during 2014.

These recommendations are particularly important if TfL introduce any further changes to bus emissions control, such as amended maintenance procedures, amended SCRT unit configuration and introduction of more or fewer retrofitted buses running along PHS. These changes should be considered in conjunction with any air quality management initiatives enacted by LB Wandsworth.

This work assessed the impact of only a small part of the London-wide retrofit programme on NO_X and NO_2 concentrations (93 buses out of 900). By extending the study method to other locations across the city, it would be possible to gain a more detailed picture of the programme impacts, including locations with different bus driving conditions and varying retrofitted bus frequencies.

The unique dataset gathered during this study presents a valuable resource for researching relationships between vehicle fleets and ambient pollution concentrations. The analyses presented in this report focus on the impact of the retrofit programme, but a number of further questions could be investigated without recourse to additional monitoring campaigns. The dataset would be further enhanced if combined with remote sensing results carried out during 2013 at a nearby location in Putney (Carslaw *et al.*, 2014).

7. References

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