Analysis of the 2013 vehicle emission remote sensing campaigns data

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version: final report February 2015

Summary key points

General points

1. This report summarises the main findings from a 6-week vehicle emission remote sensing campaign conducted in the summer of 2013. The analysis follows earlier work in 2012 using the University of Denver vehicle emission remote sensing detector (RSD, also called the Fuel Efficiency Automobile Test, FEAT). The main aims of this study were:

   a) To measure contemporary vehicle emission technologies for vehicles under actual conditions of use. A specific aim was to provide (if possible) the first measurements of NO_x and NO_2 emissions from Euro 6 diesel cars.

   b) To make measurements of the Transport for London (TfL) retrofitted buses using an Eminox SCRT system that combines a CRT (Continuously Regenerating Trap) to reduce particle emissions and SCR (Selective Catalytic Reduction) to reduce NO_x emissions under actual operating conditions in London and under controlled test track conditions.

   c) To make repeat measurements of different vehicle technologies under controlled conditions where a range of speeds and accelerations could be assessed.

   d) In addition, there was an opportunity for a vehicle emission RSD instrument inter-comparison where the research instrument from the University of Denver was compared with a commercial AccuScan 4600, measuring NO owned by the University of Leeds.

2. In an extension to previous work, detailed estimates have been made of CO_2 in g km^{-1} for each vehicle sampled based on its type and speed using the COPERT 4 model (developed and coordinated by the European Commission's Joint Research Centre and the European Environment Agency and is designed for compiling national emission inventories). These calculations provide a means of estimating absolute emission rates in g km^{-1} rather than as ratios to CO_2 and are therefore consistent with other emissions factor information.

3. On-road measurements were made at two locations in the City of Oxford where the focus was the measurement of the local bus fleet. The Oxford High Street site was located about 300 m from the Oxford Roadside AURN site, on the same road. There have been exceedances of the hourly and annual mean NO_2 Limit Values at the AURN site in recent years. The vehicle emission measurements were made at this location to help better understand the origins of the exceedances. The principal aim was to provide a detailed breakdown of the NO_x and NO_2 emissions by different vehicle (in particular bus) types.

4. On-road measurements were also made on Putney Hill in Wandsworth, London. The RSD was located about 900 m from the Putney High Street kerbside and building facade sites on Putney Hill. Due to the close proximity of fixed monitoring sites, additional information can be obtained to compare the remote sensing observations with ambient air concentrations.

Euro 6 diesel car emissions

5. On-road measurements of both NO and NO_2 have been made of Euro 6 diesel cars. The measurements show that compared with Euro 5 cars, Euro 6 diesel cars emit on

average 40% less NO_x. EU emissions legislation suggests a reduction of 56% NO_x in going from Euro 5 to Euro 6 for diesel cars (when tested over the Type Approval Test Cycle). The number of measurements is relatively small (85) and they are dominated by one manufacturer. However, they do provide an indication of the reduction in NO_x expected for vehicles using Euro 6 vehicle technology. The proportion of NO_2 emitted was 34±9%, somewhat higher (but note uncertainties) than Euro 5 diesel cars at 26±1%.

TfL retrofit emissions performance

6. In total there were three different sets of measurements of buses retrofitted with the SCRT system, as used on the TfL retrofit buses in London. An earlier version of the system was measured on Euro III retrofitted buses in Oxford, a 'low NO_2' version was measured in London and also through comprehensive single vehicle controlled tests made at a test track.

7. In Wandsworth, over 700 on-road measurements were made of the low NO_2 SCRT system on TfL Euro III retrofitted buses. On average, a reduction in NO_x of 45% compared with similar (bus type, Euro classification and engine) non-SCRT buses was observed. The corresponding reduction in NO_2 emissions was 61%. The NO_x reduction is not as great as the reduction seen during the controlled testing discussed below. A close examination of the results shows that individual bus emissions can vary widely suggesting the system does not always work at full efficiency for these conditions. A reduction in direct emissions of NO_2 of 61% is substantial.

   The on-road reductions in NO_x and (particularly) NO_2 from buses fitted with the SCRT system are considerable and would make an important contribution to London-wide NO_x and NO_2 emissions reduction.

8. The mean test track emissions of NO_x for the bus without after-treatment was very similar to that measured on-road in London for the same bus type. Additionally, the distribution of the NO_x emissions was also very similar showing that the test track measurements could replicate the emissions observed on-road.

9. At the vehicle test track the SCRT system was shown to effectively reduce emissions of NO_x by 77% on average compared with the base bus with no after-treatment according to the RSD measurements. Reductions in NO_x of 90% were shown for the SCR-only system. Emissions of NO_x and NO_2 were shown to increase as the system cooled.

10. At the vehicle test track, an instrumented bus with NO_x sensors measuring engine-out and tailpipe emissions at 1 Hz produced changes in emissions over time consistent with that for the individual plume samples made using the RSD at the test track.

11. The test track measurements showed that the RSD was able to track transient emission changes from different bus configurations e.g. as NO_x emissions decreased as the SCRT system warmed up. The RSD also followed the pattern of emissions change recorded by on-vehicle engine-out and tailpipe NO_x sensors. These results show that *single* RSD measurements clearly respond to changes in emissions.

12. An analysis of ambient NO_x and NO_2 concentrations on Putney High Street does indicate that NO_x and NO_2 concentrations decreased when the TfL retrofit (SCRT) buses were introduced by about 21% — over the period of the bus retrofitting. This evidence

derives from the application of sophisticated statistical models that aim to remove the variation in concentrations due to meteorology, leaving a signal more clearly influenced by changes in emissions. However, NO_x and NO_2 concentrations are seen to increase again after the retrofitting. The reasons for the increase in concentrations are currently unknown. There is more evidence of a sustained reduction in NO_2 concentrations of 12 to 14% than NO_x (3 to 8%). A longer time series of post-retrofit bus introduction will help show the extent to which any decreases in NO_x and NO_2 are sustained into the future.

13. A comparison of the changes in ambient NO_x and NO_2 at Putney High Street with 15 other roadside sites in London shows that the Putney High Street site had among the largest percentage decreases in NO_x and NO_2 (taking account of meteorology), when comparing consistent before and after periods. These results lend support to the view that retrofitting buses has led to decreased concentrations of NO_x and NO_2 that are not seen at the vast majority of other sites.

14. At Putney High Street ambient monitoring site modelling was used to show that primary NO_2 emissions from vehicles using that road contribute between 57 and 62% of the total annual mean NO_2 concentration based on data from 2010 to 2013. These results highlight the importance of vehicular primary NO_2 emissions in terms of their contribution to roadside ambient NO_2 concentrations.

Variation in emissions with bus technology in Oxford

15. The measurements on Oxford High Street in the City of Oxford provided a good opportunity to investigate bus emissions in considerable detail because the road is closed to most other vehicle types. In addition, individual bus vehicle technologies and after-treatment technologies were identified based on data from two of the major bus companies serving the City of Oxford.

16. There is a wide range of potential factors that can explain the differences in the emissions performance of buses e.g. Euro class, after-treatment used, bus type, engine size, vehicle speed and acceleration and even the bus operating company. However, for emissions of NO_x and NO_2 it was found of the different explanatory variables available to us that the engine manufacturer explained most of the differences between buses with after-treatment and Euro Class being less important. Note that more specific information on individual vehicles would be needed to understand the underlying reasons for the differences observed.

17. The SCRT (on retrofitted Euro III buses) produced the lowest overall emissions of NO_x compared with a wide range of bus technologies (after-treatment and Euro classes) tested. The emissions were slightly lower than the lowest Euro V OEM (original equipment manufacturer) SCR bus results, but were more typically about a factor of three better than most other bus emission technologies. The SCRT system in Oxford was however among the higher emitters of NO_2 across all bus technologies measured, with 40% of the NO_x emitted as NO_2.

18. It is clear that bus emissions of NO_x and NO_2 can vary widely even for vehicles nominally using the same after-treatment and identical Euro class. Emissions of NO_x expressed in g km^{-1} vary by a factor of 7 between different classes of vehicles and a factor of 50 for NO_2. The large range in NO_2 emissions observed likely related to the use or otherwise of diesel oxidation catalysts.

19. Even accounting for a ca. 30% improvement in the fuel economy of hybrid buses compared with non-hybrid buses shows that some hybrid bus technologies are among the highest emitters of NO_x in absolute terms across the different bus types measured in Oxford (after-treatment technology and Euro class). However, there is a wide range in emissions within the hybrid bus category. For example, one bus type from one manufacturer is shown to emit 2.25 times the NO_x compared with another manufacturer for similar Euro V vehicles.

20. There is a consistent difference between the two bus companies (Oxford Bus Company and Stagecoach) operating the same Euro V SCR hybrid vehicle, with buses from Oxford Bus Company emitting 29% less NO_x than buses operated by Stagecoach.

21. There were sufficient samples of individual buses (with sample sizes between 10 and 28) to show that multiple measurements of emissions of an individual bus for a particular technology type can represent the larger population of buses of the same type. However, one exception is for a particular bus engine type (Euro V SCR hybrid) where there is a wide variation in emissions (covering a factor of 3). It is clear that some individual buses can perform consistently well in terms of NO_x emissions.

22. One Compressed Natural Gas (CNG) bus was tested at the Blyton Park Test track. The emissions of NO_x were found to be around half that of average bus emissions in London based on the 2012 survey. The NO_x emissions performance was found to be similar to that for the on-road TfL retrofit buses in Wandsworth.

Effect on ambient measurements and NO_2 exceedances at the Oxford High Street AURN site

23. The RSD measurements made on Oxford High Street were made ≈300 m from the Oxford Centre roadside AURN site and immediately adjacent to the Oxford High Street (non-AURN) site, allowing a comparison to be made with ambient measurement trends.

24. The analysis of the AURN data shows that concentrations of NO_x have remained almost constant over the period 2008 to 2013. However, concentrations and exceedances of the hourly NO_2 Limit Value have varied considerably over this time from zero exceedances in 2009 to 55 in 2012.

25. Using modelling it can be shown that the variation in NO_2 concentrations (and exceedances) is controlled by emissions of primary NO_2. In particular, the results clearly show that the recent increases in NO_2 exceedances have been driven by changes in primary NO_2 and not total NO_x. Furthermore, these exceedances are driven by changes in the bus fleet emissions because the road is closed to most other vehicle types and about 95% of the emissions of NO_x and NO_2 derive from buses. Similarly, recent decreases in 2013 are also linked to changes in primary NO_2. These results show very clearly that roadside concentrations can be strongly controlled by the level of primary NO_2 emission from vehicles.

26. There is evidence from the Oxford High Street site that the variation in primary NO_2 emissions has increased. This evidence derives from the analysis of NO_x-NO_2 relationships. In particular the measurements show that some hourly concentrations of NO_x are associated with comparatively low concentrations of NO_2— which would not be expected if primary NO_2 emissions were high at all times. The RSD results

show that some buses are associated with very low NO_2 emissions. It is possible therefore that these buses can influence some hours more than others, resulting in more variable behaviour in NO_2 concentrations.

27. The performance of the bus fleet with respect to direct NO_2 emissions is therefore of key importance at this location, and most likely many other locations across UK urban areas. Changes to the bus fleet not affecting total emissions of NO_x but reducing NO_2 could have an important effect on NO_2 exceedances. The choice of bus emissions control technology can therefore have a key influence on exceedances of NO_2.

Comparison of commercial and research remote sensing instruments

28. A comparison was made under controlled conditions using multiple vehicles and multiple samples of the AccuScan-4600 and the University of Denver research instrument. The AccuScan does not measure NO_2 and hence comparisons were made using nitric oxide (NO). A range of vehicles from small cars to double deck buses over a range of speeds and accelerations were considered.

29. Overall the instantaneous NO/CO_2 measurements agreed very well with a correlation coefficient of 0.93 and a normalised mean bias of 0.105, with the AccuScan tending to produce slightly higher results. Given that these instruments were not co-located precisely (ca. 1 m apart), have completely independent and different calibration procedures and that instantaneous emissions were measured, this agreement can be considered as very good.

30. These results provide confidence that vehicle emission remote sensing is able to provide consistent and reproducible vehicle emission estimates.

Contents

1 Introduction

1.1 Background

Road vehicles make an important contribution to emissions of NO_x and NO_2, particularly in urban areas. Almost all air quality management areas in the UK for NO_2 are dominated by exceedances due to road vehicle emissions of NO_x. In recent years it has also become clear that the NO_2 component of NO_x (called primary or direct NO_2) has increased and can contribute significantly to exceedances of both the annual and hourly mean EU Limit Values. The first increases in primary NO_2 were observed in the atmosphere over 10 years ago and have since been studied in detail (Carslaw 2005; Carslaw and Beevers 2004; Carslaw, Beevers and Bell 2007).

While these changes have been observed in the atmosphere it is essential to understand the contributions made by different types of road vehicle — both for total NO_x and NO_2.

1.2 Vehicle emission remote sensing

The University of Denver RSD system was hired for a period of six weeks over the summer of 2013. A detailed description of the instrument and its configuration is given in Carslaw and Rhys-Tyler (2013) and is not repeated here. There are also extensive descriptions of the system by Bishop, Peddle et al. (2010), Bishop and Stedman (2008), D. A. Burgard et al. (2006), D. Burgard et al. (2006), Popp et al. (1999), Zhang, Stedman, Bishop, Beaton et al. (1996), Zhang, Stedman, Bishop, Guenther et al. (1995) and Bishop, Starkey et al. (1989). The International Council on Clean Transportation (ICCT) has also produced a good overview of the vehicle emission remote sensing technique outlining its advantages and disadvantages.[1]

Briefly, the remote sensing technique has two important advantages over lab-based emission measurements. First, it is possible to measure the emissions from 1000s of vehicles a day. Second, the measurements are made of vehicles under actual ('real world') driving conditions. The first advantage is important because there are a very wide range of vehicle types, ages and technologies in use that can have very different emissions performances. The second advantage is important because observing vehicles driven under actual urban driving conditions by 'real' drivers is essential to build an accurate picture of vehicles emissions.

Arguably the biggest disadvantage of remote sensing is that it does not provide a direct estimate of absolute emissions in the same units as emission inventories i.e. $g\,km^{-1}$. Instead it provides ratios of pollutants to CO_2 from which *fuel-based* emission factors i.e. the amount of pollutant in g per kg of fuel burnt can be derived, or alternatively NO_x/CO_2 ratios. Previous work highlighted in the references above show that fuel-based emission factors are very useful and have resulted in many new insights. However, if the aim is to develop $g\,km^{-1}$ estimates then assumptions must be made about the amount of fuel (or CO_2) that vehicles emit. It should be noted however that the differences observed in NO_x/CO_2 or NO_2/CO_2 between different buses is sufficiently large (e.g. for the Oxford measurements) that these differences will dominate over any uncertainties in the relative fuel consumption/CO_2 emissions differences between vehicles. In London, the main comparison is between two nominally identical bus types i.e. one with the low-NO_2 SCRT system, the other without, driving under essentially identical conditions where fuel consumption/CO_2 emissions can be expected to be very similar.

[1] The report is titled *On-road vehicle emissions remote sensing* and is authored by Dr Jens Borken-Kleefeld from IIASA, see http://www.theicct.org/road-vehicle-emissions-remote-sensing.

There are other limitations associated with measuring 1000s of vehicles that are not to do with the technique itself but associated information. Even though it is possible to find out a considerable amount of information about each vehicle (e.g. fuel type, engine size) there are limitations to the information that is available. For example, it is not known what type of particle filters are fitted to diesel vehicles or how different engines may have been calibrated, the injection rates of urea for SCR-equipped vehicles at the time of the measurement etc. For lab-based work or measurements using a PEMS (Portable Emission Monitoring System) where a few vehicles can be tested it is possible to find out more about individual vehicles. The different techniques can be seen as complementary. However, we would argue that there is such little information in Europe concerning the in-use emissions of a wide range of vehicles that remote sensing provides invaluable new evidence concerning vehicle emissions.

As noted by Cornwell et al. (2013) in a report for the Low Carbon Vehicle Partnership (LowCVP) a basic rule of engine operation is, if a technology results in lower fuel burn rate (and CO_2 emissions), the air quality emissions on a g km^{-1} basis *should* reduce proportionately. However, Cornwell et al. (2013) also notes there are exceptions to this general rule including the use of SCR and hybrid technologies. In the case of SCR the efficiency depends on many factors including whether the inlet temperature is sufficiently high for urea dosing (generally over 200°C), the initial calibration of the dosing system to match operating conditions, the ratio of NO_2/NO_x (the reactions with ammonia proceed most efficiently with a roughly equal amount of NO and NO_2) and the effect of ammonia storage where ammonia generated earlier can be stored and used later to reduce NO_x. Clearly the above discussion indicates that there are numerous factors that can affect the exhaust emissions of NO_x from vehicles and it is important these issues are appreciated when considering the remote sensing results. It is also the case that different manufacturers will adopt different strategies in their use of technologies such as SCR and SCRT e.g. combined in different ways with particle filters and the use of different calibrations. This is another reason remote sensing is useful because a very wide range of system combinations can be sampled — even if information on the precise configuration of different systems is unavailable.

The emission measurements do not account for any additional CO_2 from urea injection from SCR-equipped vehicles. Urea, $CO(NH_2)_2$ at 32.5% is mixed with 67.5% deionized water. With typical injection rates of 2 to 6% of fuel used the CO_2 emission from vehicles would increase by 0.2 to 0.6%. Consequently, NO_x emissions expressed per kg fuel burnt could be underestimated by between 0 to 0.6%. Note that there will be occasions when urea is not injected at all e.g. when the exhaust temperature is too low and hence the range is from zero percent.

In total, six weeks of emission measurements were undertaken from 10th June to the 19th July 2013. The experiments were split into three parts (i) two weeks of measurements in the centre of Oxford at two locations, (ii) two weeks of measurements on Putney Hill, Wandsworth in London and (iii) two weeks testing under controlled conditions in Leeds and at the Blyton Park Race Circuit. Each of these periods was associated with specific aims. In Oxford the principal aim was to understand the origins of exceedances in NO_2 concentrations (hourly mean and annual mean Limit Values), which have been observed at the Oxford roadside AURN site. In Wandsworth the location on Putney Hill was chosen because it was located on a road used by TfL retrofit buses. These buses were not measured during the 2012 work (Carslaw and Rhys-Tyler 2013) but use aftertreatment technologies that specifically aim to substantially reduce emissions of NO_x. The first two locations were focussed on on-road measurements of vehicles. The third series of measurements were focussed on testing individual vehicles under controlled conditions where repeat measurements were made of the same vehicle under different operating conditions. An additional aim of the third phase was to undertake an instrument intercomparison involving two remote sensing instruments.

The on-road measurements were made on public roads with single carriageways. No disruption to the normal flow of traffic was caused by the measurements. The in-service vehicles measured were assumed to be legal with respect to type approval emission standards and other motor vehicle regulations. In total there were 41,370 valid measurements of NO_x and NO_2. Note that the total number of measurements exceeded this number but the final number is lower due mostly to the availability of a clear photograph of the vehicle registration plate. It should also be noted that while there were only a few locations used for the measurements (similar to the 2012 surveys) a very wide range of vehicle operating conditions were sampled.

2 Updated results for diesel cars

Similar to the 2012 experiments (Carslaw and Rhys-Tyler 2013), the results are mostly presented as ratios of a pollutant to CO_2. The measurements provide information on the ratio of a pollutant (e.g. NO_x) to CO_2 in the measured exhaust plume. Expressing emissions as ratios to CO_2 is a very effective method for highlighting trends in emissions and differences between vehicles. Note therefore that improvements in the CO_2 (fuel efficiency) performance of vehicles in recent years would reduce absolute emissions in a proportionate way e.g. when expressed in g km^{-1}. For the results shown for Oxford (Section 5), detailed estimates have been made of the CO_2 emission in g km^{-1} allowing for the emissions of NO_x and NO_2 to also be expressed in g km^{-1}.

Figure 1a shows the results for NO_x emissions. Of most interest are the first measurements of Euro 6 diesel passenger car emissions made in the UK. In total, 85 measurements were made of Euro 6 diesel cars with almost all measurements (79) being made in London. **The first measurements of Euro 6 diesel cars show that NO_x is reduced by 40% compared with Euro 5 diesel cars**. It should be noted that 83% of the Euro 6 measurements were from one manufacturer and more variation might be expected as other manufacturers introduce their Euro 6 vehicles. The 40% reduction can be compared with the EU emission standards for Euro 5 to 6 diesel cars which indicate a reduction of 56% i.e. from 0.18 to 0.08 g km^{-1}, when tested over the Type Approval Test Cycle. Note that no Euro 6 petrol vehicles were measured.

There is good consistency between the measurements made in 2012 and 2013. For example, the 2012 survey (Carslaw and Rhys-Tyler 2013) measured 4,577 Euro 5 diesel cars (the Euro category with the highest number of measurements made) with a mean NO_x/CO_2 ratio of 0.0050. The 2013 survey measured 4,608 Euro 5 diesel cars (at different locations) and also measured a NO_x/CO_2 ratio of 0.0050, showing good consistency between the two survey years.

The ratio of NO_2/NO_x for Euro 6 diesel cars is 34±9%, somewhat higher (but note uncertainties) than Euro 5 diesel cars at 26±1%. The NO_2 results are shown in Figure 1b.

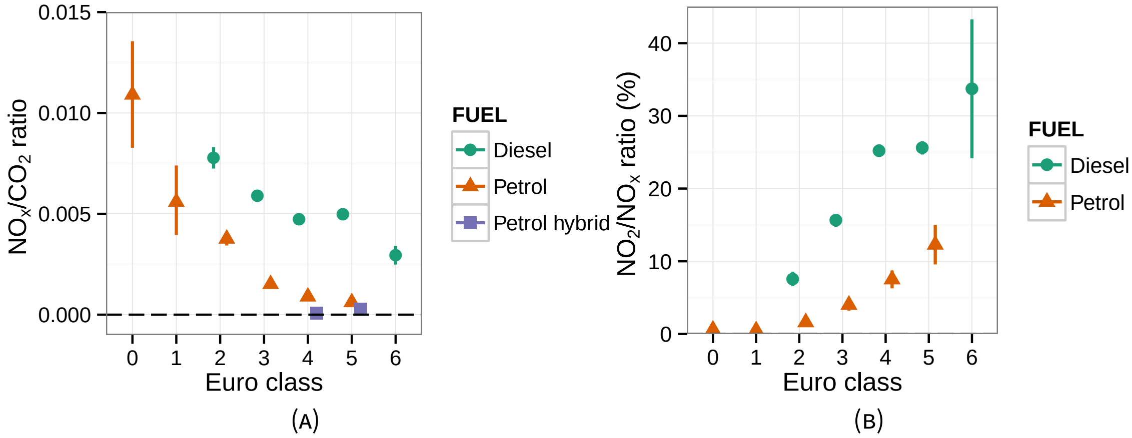


FIGURE 1: A) Emissions of NO_x/CO_2 from passenger cars split by Euro class, B) NO_2/NO_x ratio. The points show the calculated mean emissions and the uncertainties are the 95% confidence intervals in the mean.

3 TfL retrofitted bus emissions

3.1 Results from remote sensing

One of the principal aims of the 2013 experiments was to quantify the emissions from TfL buses fitted with an optimised SCR system. The TfL retrofit buses use a SCRT system manufactured by Eminox. The system came into operation in London in late 2012 and was therefore not measured during the 2012 surveys. Comprehensive measurements of these systems were made during 2013. The principal measurements were made at a location on Putney Hill in Wandsworth where on-road measurements were made. Measurements were also made under controlled conditions at a test track in North Lincolnshire (see Section 4.2). In addition, an earlier version of the SCRT system was also measured on the bus fleet in Oxford.

The Putney Hill site was located 900 m north on the uphill side of the road of the Wandsworth kerbside ambient monitoring site on Putney High Street. The gradient of the road on Putney Hill is estimated to be +1.91°. This location was on a steeper road section than the locations used in the 2012 surveys (−0.5, +0.93, +1.19 and +0.94°). It would be expected therefore that vehicles would be under higher engine loads than at these other locations due to the steeper road gradient. Under these conditions it might also be expected that NO_x emissions could be somewhat higher than a road with zero gradient for example. Given the primary interest was the TfL retrofit buses, higher engine loads would be expected to result in improved performance of the SCRT system due to the higher engine-out temperatures. However, these effects would not be expected to have instantaneous effects on emissions due to thermal lag. These effects are considered in more detail in Section 4.2. Additionally, the RSD results could also be influenced by the recent driving history of each bus e.g. a bus leaving the Putney Bus Garage with a cold engine may not reach full operational temperature by the time it reaches the Putney Hill measurement location.

In total 2,136 measurements of TfL buses were made at the Putney Hill location. Of these, 737 were fitted with the SCRT retrofit system. The retrofit buses were identified based on their registration plate and information from TfL regarding when buses were converted. A summary of the TfL buses sampled on Putney Hill is given in Table 1. All of these buses are double deck and have similar engines sizes except the Dart Pointer vehicles that are single deck and have notably smaller engines (3.9 litres vs. 6.7 to 9.4 litres). Note that the table splits the buses by the bus model listed in the information provided by TfL even if some of the buses are ostensibly the same e.g. the ADL Enviros, which differ only in body type. This approach helps to confirm whether from an emissions perspective similar bus models have the same characteristics.

Buses fitted with the SCRT system were carefully matched with information provided by TfL concerning which vehicles had been retrofitted to use the SCRT system. One advantage of the sampling on Putney Hill was that a relatively large sample of essentially the same bus type as the SCRT retrofits but fitted only with a DPF (Volvo B7 President). These non-SCRT buses act as a very useful comparator because they have the same engine and Euro class and were operated under the same conditions as the measurements of the retrofitted buses. No measurements of hybrid buses were made at the Putney Hill location, although measurements from hybrid buses in London were made during the 2012 surveys.

The SCR catalysts used in the low-NO_2 SCRT are three times larger by volume than those used in the standard SCRT system (as used in Oxford). The systems in the low-NO_2 SCRT are close-coupled and thermally managed so that catalyst activity is maximised whilst still meeting vehicle operating requirements. The system design was developed using empirical measurements and computational fluid dynamics which ensures a highly uniform distribution of NH_3 across the catalyst face so that high conversion levels can be achieved. The calibration used increases the injection of urea where conditions allow, to maximise reduction of NO_x and NO_2 whilst minimising secondary emissions (N_2O and NH_3).

TABLE 1: Summary of TfL bus types sampled on Putney Hill.

Bus model	number	Engine	Euro.class	Technology
ADL Enviro 400	298	Cummins 6.7 litre	IV	SCR
ADL Enviro 400 Elancs	251	Cummins 6.7 litre	IV	SCR
Dart Pointer - slf	576	Cummins 3.9 litre	III	DPF
SCRT retrofit	737	Volvo 7.3 litre	III	SCRT
Volvo B7TL President	240	Volvo 7.3 litre	III	DPF
Volvo B9TL Enviro 400	34	Volvo 9.4 litre	V	DPF

A summary of the NO_x/CO_2 and NO_2/CO_2 emissions is shown in Figure 2. **On average the SCRT vehicles emit 45% less NO_x and 61% less NO_2 compared with the same vehicle type fitted only with a DPF**. This level of reduction in NO_x is less than that reported elsewhere (e.g. the 88% figure quoted here `http://www.tfl.gov.uk/corporate/media/newscentre/archive/22791.aspx`) and the controlled experiments where a 77% reduction in NO_x emissions was observed compared with the same bus without the SCRT system based on RSD measurements (see Section 4.2). The NO_x/CO_2 ratio for SCRT buses (0.0047) is in better agreement with the value of 0.0039 observed for SCRT buses in Oxford. Nevertheless the NO_x/CO_2 ratio for the SCRT buses is the lowest of the buses sampled at this location and lower than the buses tested during the 2012 London surveys where the NO_x/CO_2 ratio varied from about 0.0075 to 0.015. The emissions are similar to the ADL Enviro bus (which has a very different engine) and the Euro V Volvo B9. The ADL Enviro and the Volvo B7 President have similar emissions (around 0.008), also similar to the emissions from TfL buses found during the 2012 campaign. The reduction in direct NO_2 emissions of 61% is considerable and would significantly help towards reducing overall London road vehicle emissions of NO_2.

Similar to the 2012 measurements, the NO_2 emissions are seen to vary widely across the different bus types (Figure 2b). The ADL Enviro and Volvo B9 have very low emissions of NO_2 (almost all the exhaust is in the form of NO). However, comparing the SCRT and

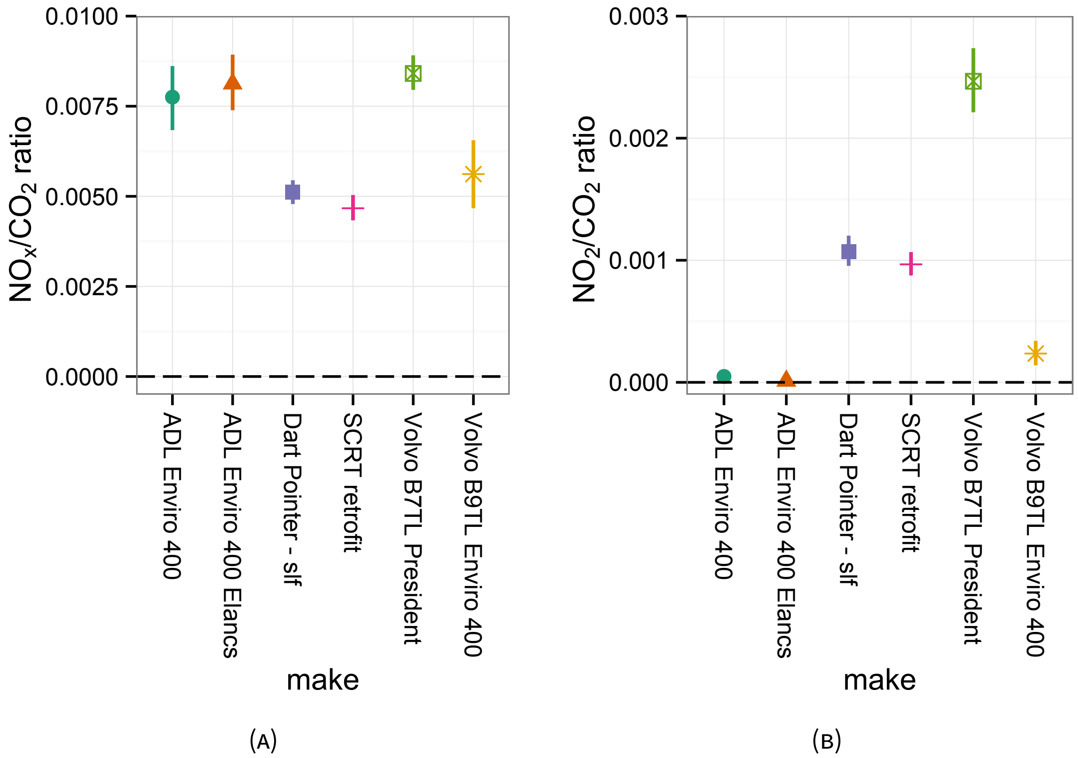


FIGURE 2: Summary of NO_x/CO_2 and NO_2/CO_2 emissions for TfL buses sampled on Putney Hill.

non SCRT (Volvo B7 President) shows that the SCRT system does reduce NO_2 emissions by about 60%. In other words there is no 'NO_2 penalty' for the low-NO_2 SCRT system.

The distribution of NO_x/CO_2 emissions from the six TfL bus models measured on Putney Hill is shown in Figure 3. An interesting aspect of this plot is that the distribution for the TfL retrofitted buses is clearly bi-modal. There is a peak at very low values of NO_x/CO_2 and another around 0.008. There are two possible explanations for the double peak. First, the SCRT system could be operating very well on some buses but is ineffective on others and second, the system could be effective on individual buses some of the time. The effectiveness of the system could also depend on other factors such as route pre-history.

An examination of the TfL retrofit buses in more detail reveals that the higher NO_x/CO_2 peak overlaps that for the same bus type but not fitted with the SCRT system. This can be seen in Figure 4a. In this Figure there is a clear overlap of emissions between the SCRT and non-SCRT vehicles around 0.0075. The lower peak in NO_x emissions is also very apparent for the SCRT-equipped vehicles. These results show that SCRT-equipped buses sometimes emit NO_x similar to non-SCRT buses and that there is no NO_x reduction. The question remains however, whether this behaviour is caused by buses that are always ineffective at reducing NO_x or buses that are sometimes ineffective at reducing NO_x.

Figure 4b shows the distribution of NO_x/CO_2 emissions for *individual* buses i.e. buses with the same number plate, fitted with the SCRT system. The distribution does not show any obvious population of individual buses that are very low emitters of NO_x. Therefore, these results imply that the SCRT system works for some of the time on individual buses and when it does not, the buses emit similar amounts of NO_x to non-SCRT buses of the same type.

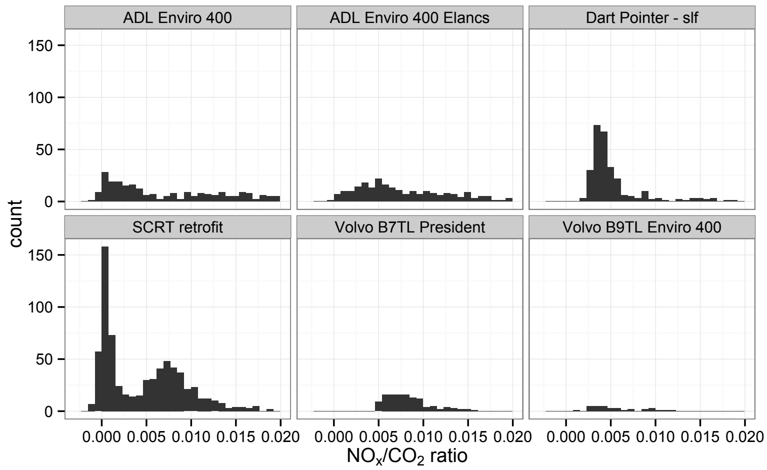


FIGURE 3: Histogram of emissions from different models of TfL buses measured at the Putney Hill location.

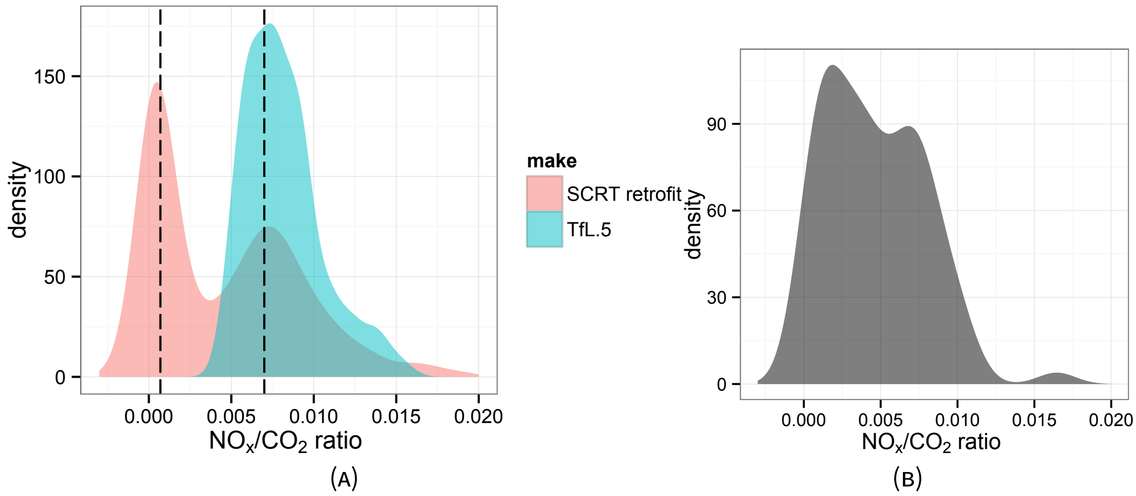


FIGURE 4: Density plots showing the distribution of NO_x emissions from TfL retrofit buses A) Comparison of with-without retrofit emission distributions, b) distribution of NO_x emissions from single retrofit buses.

For NO_2, the NO_2/NO_x ratio for SCRT vehicles is relatively low at 21% for the Wandsworth data. This ratio is lower than the non-SCRT Volvo B7 President buses (29%), suggesting the new SCRT system does indeed reduce emissions of NO_2. The figure of 21% can be compared with a value of 27% for the controlled tests discussed in Section 4.2 where the NO_x reduction was greater. Furthermore, the SCRT buses in Oxford, which have not been optimised to reduce NO_2, the ratio is much higher at 41%. These results show that the low NO_2 SCRT system used on the TfL retrofits is effective at reducing the NO_2 emissions over the first generation of the system used in Oxford.

One explanation of the bimodal distribution of NO_x for the SCRT equipped buses is that at lower speeds the system cools down and the NO_x conversion efficiency drops. The measured speed of the vehicle itself does not have an influence on the level of NO_x emission as shown in Figure 5. However, it is likely more important that the recent driving history of the bus has more of an influence on emissions. For example, a bus caught in highly congested traffic along Putney High Street where the system cools may not be fully efficient in reducing NO_x by the time it reached the measurement site on Putney Hill.

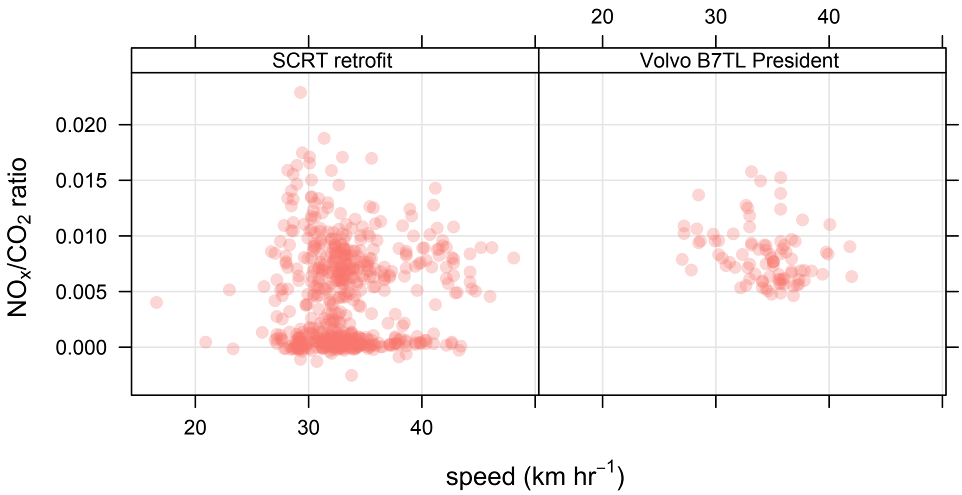


FIGURE 5: NO_x/CO_2 ratio vs. vehicle speed at the Putney Hill site for Euro III Volvo buses. Those fitted with the SCRT system are shown on the left.

3.2 Analysis of ambient measurements on Putney High Street

Measurements of NO_x and NO_2 have been made at Putney High Street since July 2009 at both the kerbside and building facade. The results considered here relate to concentrations at the kerbside unless stated otherwise. The concentrations of NO_x and NO_2 measured at the Putney High Street site have been the highest or among the highest of any recorded across the LAQN. Putney High Street has a high flow of TfL buses and for this reason it was among the locations chosen by TfL to retrofit Euro III buses to the SCRT system. These measurements are discussed in more detail by Barratt and Carslaw (2014) but aspects of the analysis are discussed here. The Putney High Street measurement site experiences higher numbers of retrofit buses compared with the location of the RSD further up Putney Hill. Putney High Street is often congested and more congested than the RSD location on Putney Hill.

One of the challenges in analysing ambient data to detect changes in concentrations due to some intervention is that meteorology can easily falsely mask or emphasise trends, making it difficult or impossible to determine the true effect. However, sophisticated statistical models can be developed to account or remove the effect of meteorology (Carslaw, Beevers and Tate 2007; Carslaw and Taylor 2009). The method of Carslaw and Taylor (2009) has been applied to the Putney High Street NO_x and NO_2 data. Briefly, models were developed based on hourly NO_x or NO_2 together with meteorological input data from the London Heathrow site. In essence, these models aim to explain concentrations in terms of potentially complex interactions between variables such as wind speed, direction and temperature, as well as other variables e.g. representing the trend. Once a model is developed, a new time series is produced by running the model hundreds or thousands of times by randomly sampling the meteorological data as input. This process yields a single new time series representing a trend that would be expected if average meteorological conditions occurred every day. With 'fixed' meteorological conditions, the remaining trend represents a trend that is much more strongly affected by changes in emissions.

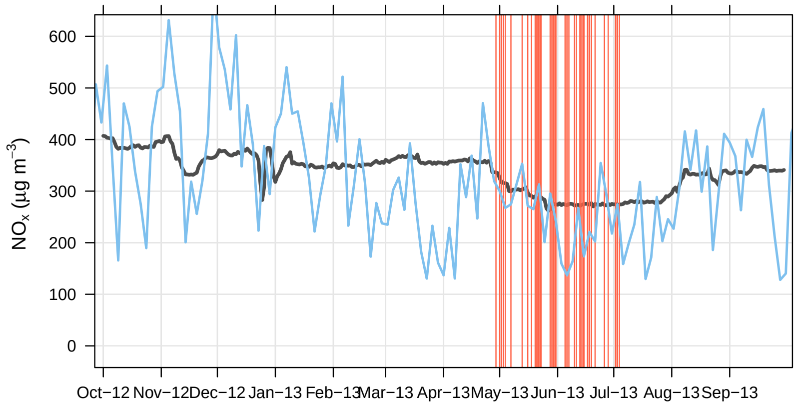


FIGURE 6: Ambient concentrations of NO_x at the Putney High Street LAQN site. The blue line shows the 3-day mean of the raw NO_x data. The black line shows the meteorologically normalised NO_x concentrations. The vertical lines show the dates when the SCRT system was fixed on individual buses.

Figure 6 shows the effects of applying the model to the Putney NO_x data. The blue line shows a 3-day average of the raw NO_x data. Considering the raw data alone it would be very difficult to discern any obvious change in NO_x concentration over this period. The black line shows the effect of applying the model, which produces a line which is much less noisy. The vertical lines show when SCRT buses were introduced. It should be noted that the buses (all Euro III) were actually converted about a month before that shown in Figure 6. However, due to a problem with the system, the SCRT was not operational until the problem had been fixed (Finn Coyle, TfL, personal communication). The dates for the vertical lines shown in Figure 6 therefore correspond to when the SCRT was operational. It should be noted that in these types of analysis various changes in concentration can be observed that are not always possible to explain. This situation is not surprising because there is usually only a limited amount of meta data available that can help identify different changes e.g. information on roadworks, local changes that might affect traffic flow or fleet composition, instrument problems not identified in the QA-QC procedures.

The changes in NO_x concentration are better shown in Figure 7. In this Figure there is a very clear reduction in NO_x corresponding to the time the SCRT buses were introduced from about 350 to 275 µg m^{-3} (21%). Given the close correspondence between the reduction in NO_x and the introduction of the SCRT buses it would appear very unlikely that other causes could explain the reduction in NO_x. However, NO_x concentrations are seen to *increase* towards the end of July, almost returning to their pre-SCRT introduction values.

Reductions in the concentration of NO_2 were also seen at the time the SCRT buses were introduced — shown in Figure 8. Concentrations decreased from about 140 µg m^{-3} to as low as 110 µg m^{-3} (21% reduction), before increasing to 120 µg m^{-3}. There is more evidence to suggest that NO_2 decreased following the introduction of the SCRT system than total NO_x. This behaviour might be expected from what is known of the emissions changes for NO_2 at least from the RSD measurements i.e. the low NO_2 SCRT does result in lower NO_2 emissions than the base vehicle fitted with a CRT.

Interestingly, there is more evidence of a reduction in NO_2 concentrations for the instrument located at the building facade rather than the one at kerbside, as shown in Figure 9. In this Figure there is a sustained decrease in NO_2 concentrations over the period when the retrofit buses were introduced from ≈120 to 95 µg m^{-3} i.e. also about 21%. The results shown in Figure 9 are the most compelling of all the results analysed in terms of evidence linking bus conversions to reductions in NO_2 concentrations because the start of the decrease in NO_2 concentration is timed very well with the introduction of the retrofit buses

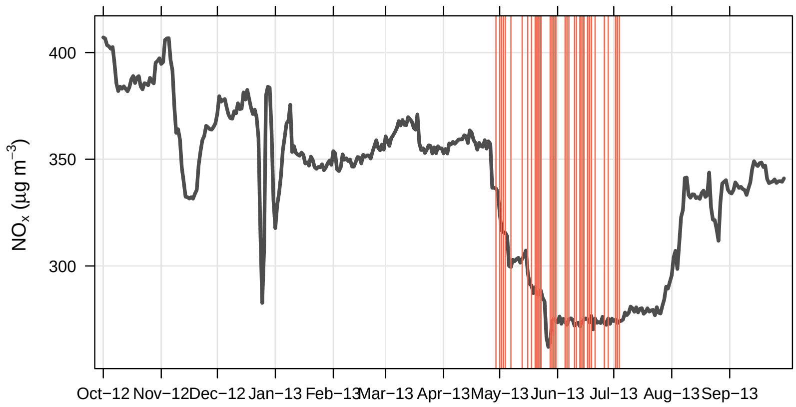


FIGURE 7: Ambient concentrations of NO_x at the Putney High Street LAQN site. The black line shows the meteorologically normalised NO_x concentrations. The vertical lines show the dates when the SCRT system was fixed on individual buses.

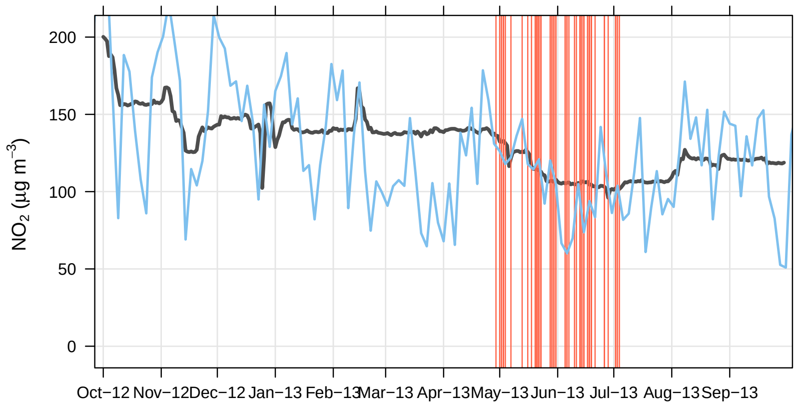


FIGURE 8: Ambient concentrations of NO_2 at the Putney High Street LAQN site. The blue line shows the 3-day mean of the raw NO_2 data. The black line shows the meteorologically normalised NO_2 concentrations. The vertical lines show the dates when the SCRT system was fixed on individual buses.

and the end period of the decrease is timed with when the last buses were converted.

The clearer changes in NO_2 compared with NO_x are difficult to understand at the Putney ambient monitoring sites but on balance the nature of the changes observed do seem to be related to known changes in bus conversions. Taking the 'before' period as January 2012 to April 2013 and after from July 2013 to January 2014 (inclusive), the following can be said about the changes in concentrations of NO_x and NO_2. NO_2 concentrations have reduced between 12 and 15% and NO_x by 3 to 8% based on the kerbside and facade measurements. It is not clear why the concentrations of NO_x and to a lesser extent NO_2 increase again shortly after the introduction of SCRT buses — albeit not to the levels observed before their introduction.

Some care is needed with the interpretation of these data. The 12 to 15 and 3 to 8% changes for NO_2 and NO_x are for simple before-after comparisons. If the increase in concentration of NO_x and NO_2 post-July 2013 has nothing to do with bus retrofits (and there is no reason to believe it has) and has some other cause then these reductions would be considered pessimistic concerning the performance of the SCRT system. If that were the case then the data would suggest a 21% reduction in NO_x and NO_2 due to the introduction of the SCRT system.

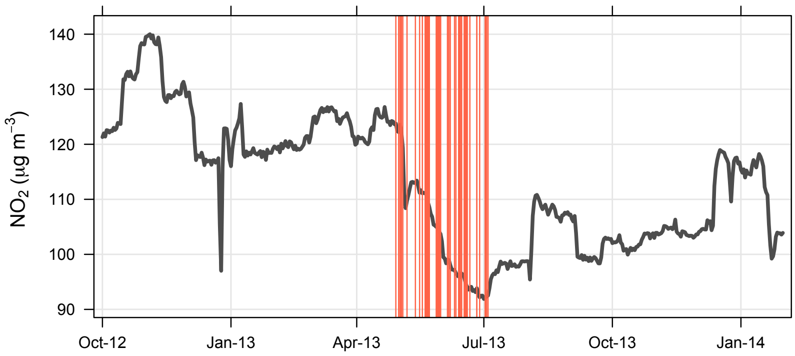


FIGURE 9: Ambient concentrations of NO_2 at the Putney High Street facade site. The black line shows the meteorologically normalised NO_2 concentrations. The vertical lines show the dates when the SCRT system was fixed on individual buses.

The models described above have also been applied to 15 other LAQN roadside sites from January 2012 to the end of January 2014 to understand whether the changes in NO_x and NO_2 seen at the Putney High Street site are different compared with other roadside sites in London. Figure 10 shows the percentage change in NO_x and NO_2 for 16 LAQN roadside sites using the same before and after period used for the Wandsworth kerbside site described above. These results show that the Wandsworth site was among the sites with the largest percentage change in NO_x and NO_2 concentration. Only Marylebone Road (MY1) and the Kensington and Chelsea Knightsbridge (KC3) sites showed greater changes in NO_2. These results lend support to the idea that there were much greater reductions in NO_2 concentrations at Putney High Street than most other roadside sites in London.

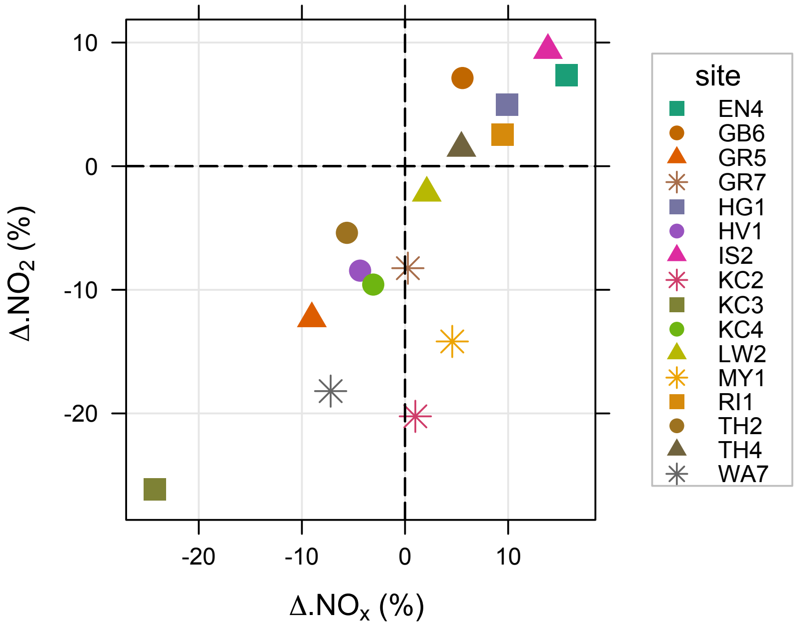


FIGURE 10: Percentage changes in NO_x and NO_2 predicted at roadside sites in London. The plot compares 'before' and 'after' concentrations for periods pre-April 2013 and post July 2014. The analysis is based on the use of statistical models to remove the effect of meteorological change. The Putney High Street site is shown as 'WA7'.

Using the methods of Carslaw and Beevers (2005) it is possible to estimate the different origins of NO_2 concentrations at the Putney High Street ambient monitoring site. Figure 11 shows how the total annual mean NO_2 concentration is broken down by three main source origins: background, primary (directly emitted by vehicles) and secondary (local NO_2 production from the NO + O_3 reaction). What is clear from Figure 11 is the large contribution from directly emitted NO_2 at this site. The contribution from directly emitted NO_2 varies from 57 to 62% of the total annual mean NO_2 at this location — highlighting the importance of vehicular primary NO_2 emissions. The primary NO_2/NO_x ratio component varies from 31% in 2011 to 26% in 2013. It is the reduction in primary NO_2 emissions in 2013 that drives the overall reduction in annual mean concentrations seen in Figure 11.

4 Controlled emission tests

4.1 Instrument comparison between the FEAT and AccuScan 4600

During the 2013 measurement campaign there was an opportunity to compare the performance of the FEAT with that of a commercial instrument (AccuScan 4600) that is owned by the University of Leeds. The AccuScan only measures the NO component of total NO_x and therefore comparisons were made between the two instruments for NO/CO_2.

Figure 13 compares the FEAT with the AccuScan 4600. Figure 13a shows all the individual emission measurements of NO/CO_2 where both the FEAT and AccuScan recorded a valid measurement. The Figure shows individual measurements of the exhaust plumes. Considering the nature of these results the overall agreement between the two systems is very good. The correlation coefficient (R) is 0.93 and the normalised mean bias of the AccuScan compared with the FEAT is 0.105 i.e. on average the AccuScan recorded emissions of NO that were 1.105 that of the FEAT. Figure 13b show the results averaged by vehicle, which also shows that the two instruments compare well across a wide range of NO_x emissions.

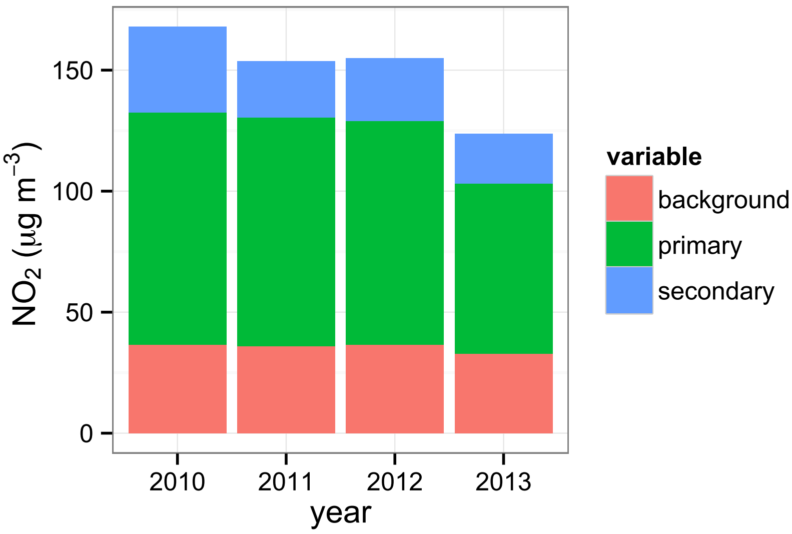


FIGURE 11: Source apportionment of NO_2 concentrations at the Putney High Street kerbside site. The plot shows the estimated breakdown of annual mean NO_2 concentrations by background, primary (directly emitted by vehicles) and secondary (local NO_2 production from the NO + O_3 reaction).

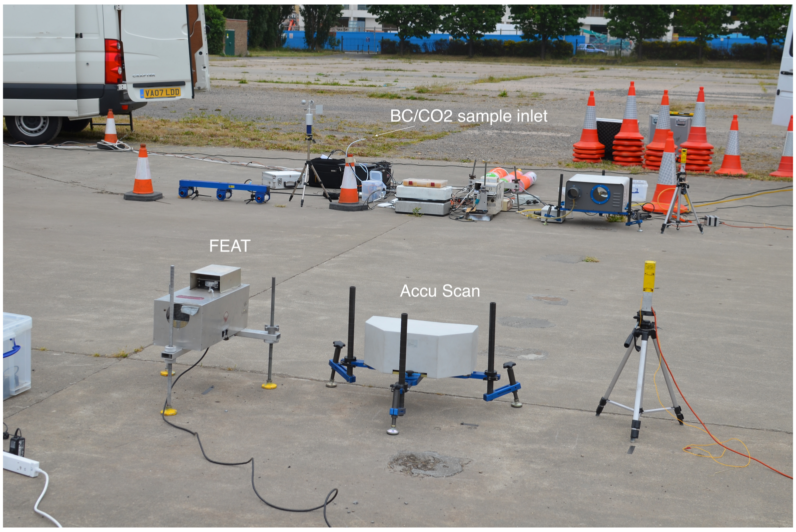


FIGURE 12: Layout of the FEAT, AccuScan and Aethalometer for the vehicle emission controlled testing at Leeds.

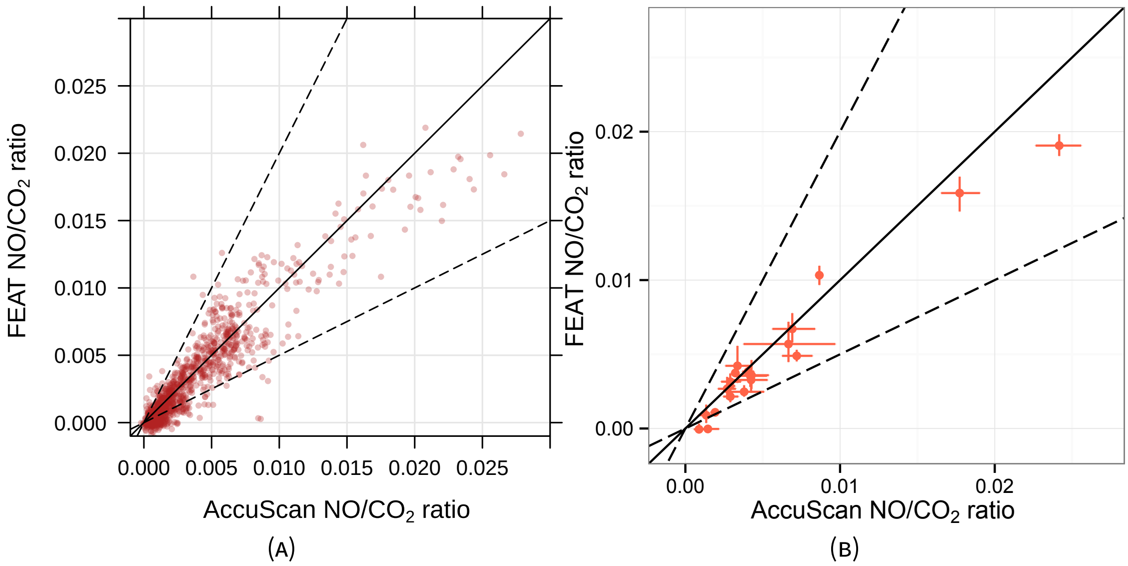


FIGURE 13: A) Comparison between the Denver FEAT and AccuScan remote sensing measurements for NO/CO_2 for individual, instantaneous vehicle exhaust measurements, B) comparison averaged by individual vehicle, with the error bars showing the 95% confidence interval in the mean. The dashed lines show the factor of two envelope.

4.2 Bus Tests at Bylton Park Race Circuit

A series of bus emissions tests were made at the Blyton Park Race Circuit in North Lincolnshire. The principal interest was understanding the emissions performance of the Eminox system under controlled conditions for different configurations of the system: a bus with no aftertreatment, with SCR and with SCRT. The bus used at Blyton was a Volvo B7 Euro III fitted with a Low NO_2 SCRT system. This bus is of the same type as those retrofitted by TfL in London and measured on-road in Wandsworth — but was not measured in Wandsworth during the on-road campaign. The CRT (DOC + DPF) was removed and the SCR catalyst retained i.e. an SCR only configuration. In addition, the bus was tested without any aftertreatment (but with the silencer). In total therefore a series of three tests were performed. These are referred to as Base, SCR and SCRT. The measurements were made at 0° gradient with the bus making repeat passes of the beam, in both directions. In addition to providing a more detailed understanding of the Eminox system, these tests are also valuable in terms of understanding how well the RSD system performs. For example, the tests help understand the extent to which 'snapshots' of emissions from the RSD can characterise the emissions from a vehicle during on-road operation.

In addition to the Volvo B7, measurements were also made of one CNG (compressed natural gas) bus operating from Nottingham. The bus was a Euro V Scania single deck with 9.3 litre engine. Photographs of the buses are shown in Figure 14. No measurements were made of hybrid buses.

The vehicles were tested over a series of accelerations and speeds similar to the conditions experienced during the on-road measurements in Putney and Oxford. A summary of the emissions and number of tests for each bus is given in Table 2. Taking the base bus i.e. the Volvo B7 without any aftertreatment the mean NO_x/CO_2 emission was 0.0087. This emission level compares very well with the on-road emissions measured during the 2012 campaign for a range of TfL buses (Carslaw and Rhys-Tyler 2013). In this respect the measurements represent a good baseline that is very similar to typical emissions for in-use buses in London.

(A) (B)

FIGURE 14: Photographs of the Volvo B7 (A) and Scania CNG buses (B).

The testing at Blyton Park brought together a range of technologies to help better understand the emissions:

- Each bus or bus configuration was instrumented with a VBOX GPS sensor to accurately measure the bus location at 10 Hz. The main use of the sensor was to derive the instantaneous vehicle speed and acceleration.
- The Volvo bus in its SCR and SCRT configuration was instrumented by Eminox/Johnson Matthey to measure a range of engine and exhaust variables at 1 Hz. These variables included engine rpm, the mass flow, the CRT and SCR inlet temperatures and the engine-out and tailpipe NO_x emission (using a NO_x sensor).

The two sets of measurements described above essentially provided continuous measurements while a bus was being tested. By contrast, the RSD provided only an instantaneous emissions measurement when the vehicle passed the beam. This is the first time that all of these technologies have been brought together to provide a comprehensive understanding of the vehicle emissions.

TABLE 2: Summary of vehicle emissions for the Volvo B7 and CNG buses together with the vehicle speed and acceleration details. The NO_x/CO_2 and NO_2/CO_2 have been multiplied by 10,000 to make it easier to compare the results.

vehicle	samples	NO_x/CO_2	NO_2/CO_2	NO_2/NO_x (%)	speed (range) ($km\ h^{-1}$)	accel. (range) ($m\ s^{-2}$)
Base	89	86.9	3.7	4.3	22.9 (10.2 to 29.2)	0.72 (−0.07 to + 1.48)
SCR	119	8.9	1.1	12.7	24.7 (15.2 to 36.7)	0.57 (−1.16 to + 1.12)
SCRT	170	20.3	5.5	27.3	25.5 (11.0 to 44.9)	0.54 (−0.34 to + 1.30)
CNG	90	43.6	7.7	17.6	18.4 (4.7 to 42.5)	0.64 (−1.44 to + 1.53)

The base bus NO_x/CO_2 averaged over all test track conditions was 0.0087, as shown in Table 2. This figure can usefully be compared with the mean on-road value for the same model bus in Wandsworth i.e. a Volvo B7 Euro III that has not been retrofitted. The mean NO_x/CO_2 ratio for this bus type in Wandsworth was 0.0085, which is in very good agreement with the test track results. Moreover, the distribution of emissions is *very* similar in each case. Figure 15 shows the distribution of NO_x/CO_2 for the bus on the test track (81 measurements) and the non-SCRT bus in Wandsworth (240 measurements). The striking aspect of Figure 15 is excellent agreement in the emission distributions. Not only is the mode of the emissions nearly identical (ratio = 0.075), the distribution is also very similar. These results provide some confidence that the measurements made on the test track are representative of the measurements made on road in London.

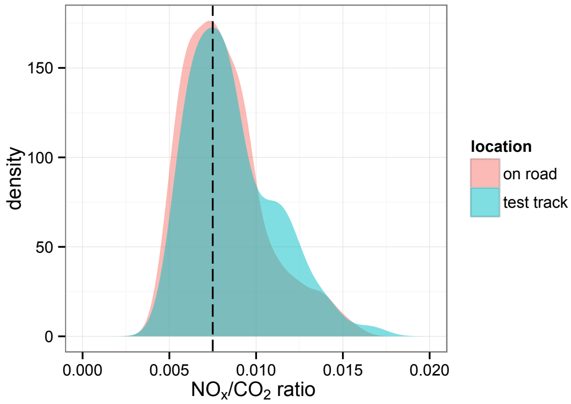


FIGURE 15: Distribution of NO_x/CO_2 emissions for the Volvo bus on the test track and on-road in Wandsworth.

For NO_x, the SCRT system reduces emissions by 77% compared with the base bus. The SCR on its own shows a greater reduction of 90%. The on-bus NO_x sensor gave reductions of 92% and 94% respectively i.e. the reduction calculated by comparing engine-out with tailpipe NO_x. The tests made on the SCR only mode of operation had a higher SCR inlet temperature on average compared with the SCRT (306 vs. 264°C). The difference in temperature likely reflects the additional cooling that occurs in the exhaust stream when going through the CRT before reaching the SCR. It should be stressed that the emissions of NO_x from all of these bus technologies (with the exception of the base bus) are much lower than that found for buses in London in 2012 (Carslaw and Rhys-Tyler 2013). The emissions of NO_2 are more variable.

The results for the CNG bus (NO_x/CO_2 = 0.0044) can be compared with both the 2012 surveys for TfL and non-TfL buses (Carslaw and Rhys-Tyler 2013) and the bus fleet in Oxford (discussed Section 5). Typically the Euro V buses in London and Oxford emit around 0.01 NO_x/CO_2 ratio, which shows that the CNG bus emits considerably less NO_x than other buses with the same Euro standard. As noted previously, the 'base' Volvo bus emits very similar emissions of NO_x under test track conditions compared with the on-road RSD measurements, suggesting the mean of the RSD measurements is reasonably representative of actual in-use driving conditions.

In terms of the NO_2/CO_2 ratio, the CNG bus is the highest emitter of the buses tested, followed by the SCRT, base bus and then the SCR. The reason for the change in order of emissions for NO_2 compared with NO_x is that these different technologies emit very different proportions of NO_2 from 4.3% of total NO_x (base bus) to 27.3% for the SCRT bus.

The summary results in Table 2 disguise some important emission characteristics of the different buses. Figure 16 shows the time series of emissions where the vehicles made many traverses of the beam over a period of a few hours. For the base bus the emissions of NO_x are largely invariant over time, except for a period around 11:30 to 12:00 where the emissions are higher. This period coincides with tests undertaken at *constant* speed. In fact, this period is better seen in Figure 17 where there are two distinct groups of data. For positive accelerations it can be seen the emission of NO_x is lower (seen by the colour of each data point). For constant speeds i.e. acceleration at (or close to) zero, the emission of NO_x/CO_2 is higher.

For the SCR and SCRT results the emissions start high (similar to the base bus) but as time

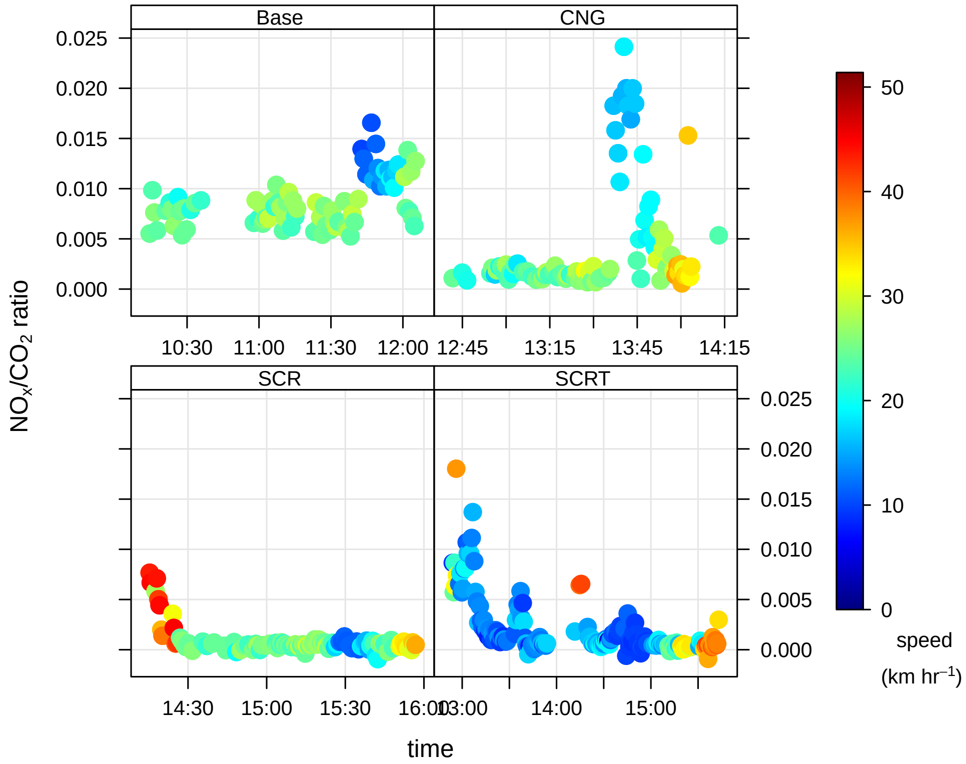


FIGURE 16: Summary of NO_x/CO_2 emissions for different buses and aftertreatment technologies against time. The colour shows the bus speed in km h^{-1}.

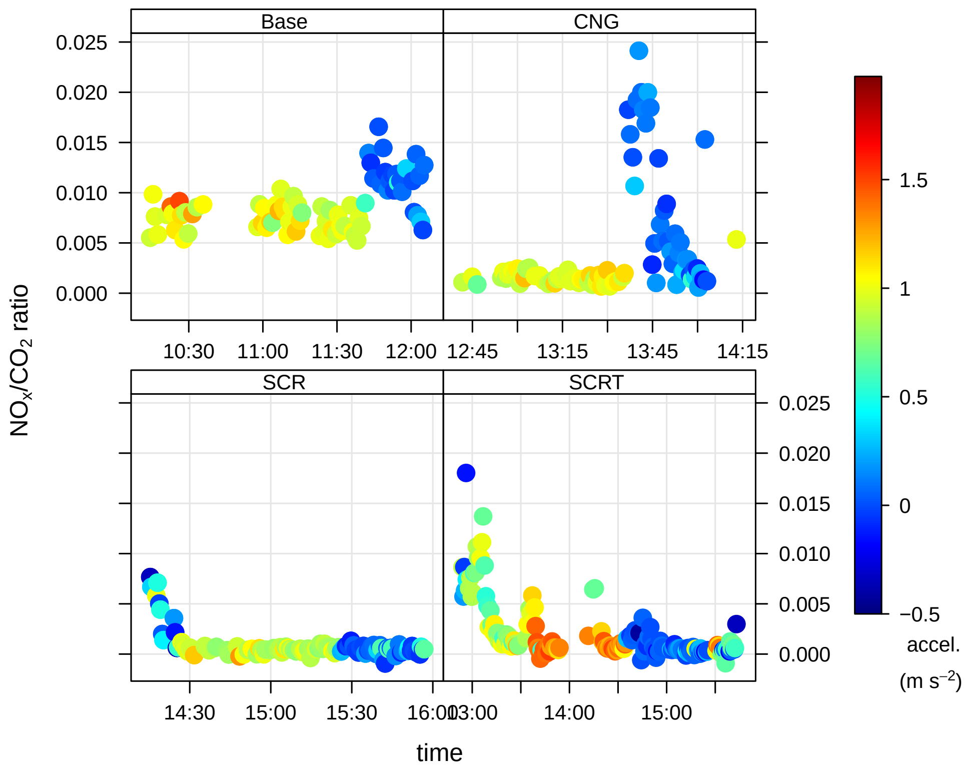


FIGURE 17: Summary of NO_x/CO_2 emissions for different buses and aftertreatment technologies against time. The colour shows the bus acceleration in m s^{-2}.

progresses they decrease considerably. The initial high emissions are due to cooler engine temperatures and a less efficient SCR system, as shown in the example plot in Figure 18 for the initial tests on the SCRT system. The SCR inlet temperature was logged on the vehicle itself together with other variables. It is only when the temperature reaches about 200°C is urea injected. It is clear that the RSD is able to detect the higher NO_x emissions when the system is 'cool' — even to the extent that individual measurements show this behaviour. The tests started with a warm engine and after-treatment. The plots show that it takes ≈15–20 minutes for the system to reach full efficiency. Once full efficiency is reached the emissions of NO_x are very low. For example, the *median* emission of NO_x/CO_2 for the base, SCR and SCRT configurations are 0.0081, 0.0005 and 0.0008, respectively. In other words, the data in Table 2 are skewed by the warm-up periods. Nevertheless, it appears that the SCRT system has more difficulty maintaining full NO_x reduction efficiency compared with the SCR-only system because the SCRT is further down the exhaust and takes longer to warm-up, and the upstream DPF absorbs heat.

The relationship between the RSD NO_x emissions and the SCR inlet temperature is better seen in Figure 19. This plot confirms that temperatures around 200 °C tend to be associated with higher emissions of NO_x. However, above these temperatures the RSD confirms that the NO_x emissions generally remain very low. These results confirm that the RSD is well capable of detecting when the SCR is ineffective during its warm-up phase.

The Euro III Volvo was also instrumented with a NO_x sensor that measured engine-out and tailpipe NO_x concentrations. Sensors of the type used are not capable of measuring concentrations with high accuracy but do provide a good indication of the level of emission. The 1 Hz data tends to be noisy. However, as seen later the data can be modelled to show more general variations with vehicle speed and acceleration. While the SCRT system warmed up and NO_x concentrations decreased it was possible to compare the tailpipe NO_x concentration with the instantaneous plume measurement from the RSD over a range of NO_x emissions. Figure 20 shows the tailpipe NO_x concentration in ppm together with the NO_x/CO_2 ratio for the first hour of measurements. Note that the two variables have different units and cannot be compared on exactly the same basis. However, it is clear from Figure 20 that the general pattern of NO_x emission is in agreement between the two measurements. The results clearly show that capturing an instantaneous plume measurement using the RSD is able to provide a consistent measure of how NO_x emissions change over time. The NO_x sensor started recording after the RSD and hence there is an absence of NO_x sensor measurements at the beginning of the time series. Sensors of the type described above have also been used by Eminox on test vehicles in London to examine the performance of the SCRT system in use.

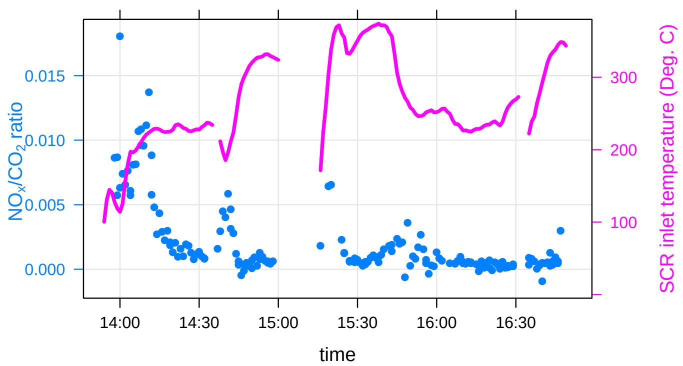


FIGURE 18: Plot showing the instantaneous NO_x/CO_2 ratio from the University of Denver instrument and the SCR inlet temperature (°C).

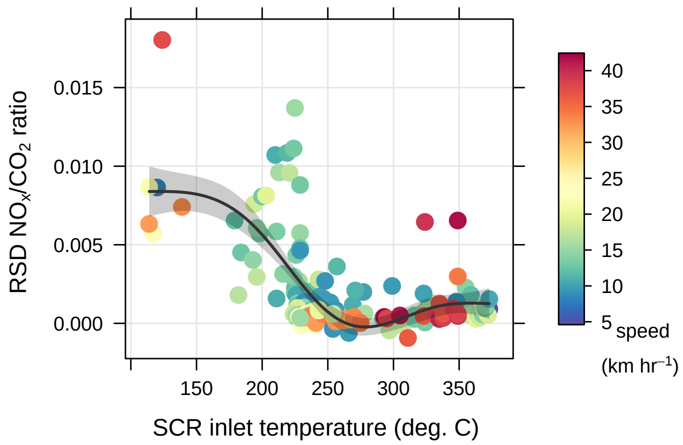


FIGURE 19: Plot of SCR inlet temperature vs. the NO_x/CO_2 ratio from the RSD for the SCRT bus. The colour represents the speed of the bus.

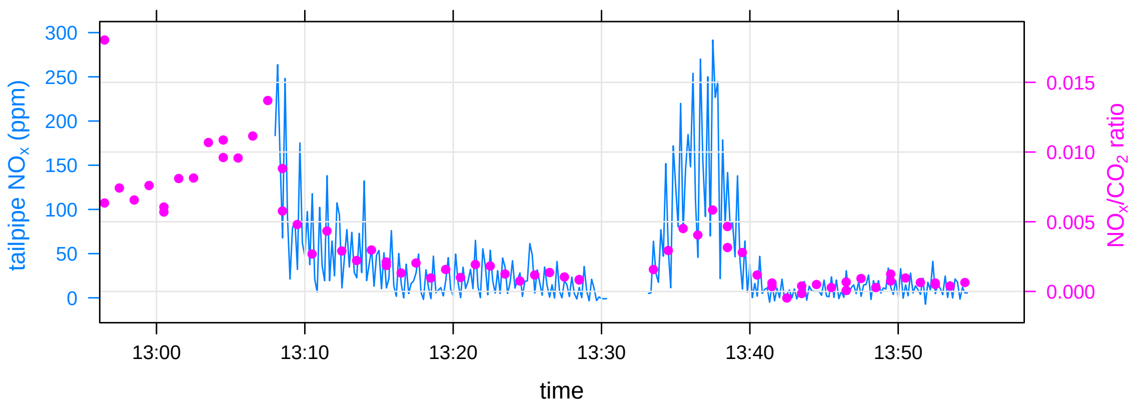
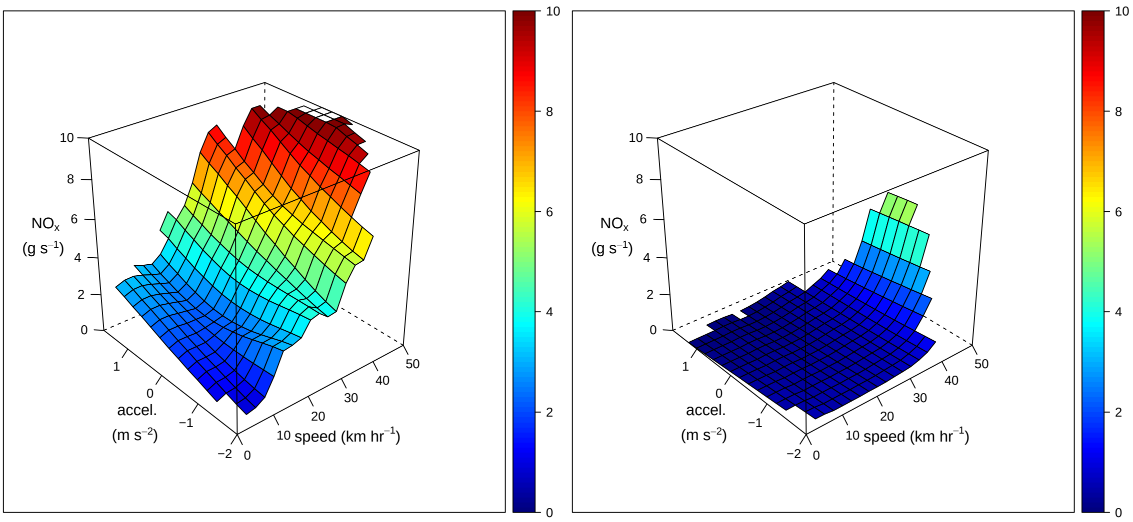


FIGURE 20: Bus on-board sensor tailpipe NO_x concentration (ppm) and the RSD NO_x/CO_2.

A more comprehensive plot is shown of the SCRT bus speed, engine parameters and the RSD NO_x/CO_2 ratio in Figure 21. In Figure 21 the continuous variables (vehicle speed and engine parameters) are plotted together with the discrete measurements of NO_x/CO_2 from the RSD. The speed trace (top panel) shows the series of different speed-acceleration conditions used. The SCR inlet temperature (2nd panel) is much more smoothly varying than the other variables due to the heat storage inertia of the system. The gaps in the time series are periods where the bus engine was turned off between tests. After each engine off period it can be seen the SCR temperature takes time to increase again. The engine-out NO_x emissions are very variable but higher emissions in g min^{-1} can be seen to correspond to higher vehicle speeds. The tailpipe NO_x emissions show very clear periods of elevated emissions corresponding to when the SCR inlet temperature is below (or close to 200°C). The tailpipe NO_x emissions are shown to increase when the SCR temperature is just above 200°C between 14:30 and 15:00 — also corresponding to a period when the vehicle speeds were lower. Finally, the discrete RSD NO_x/CO_2 measurements (bottom panel) tend to track the on-board NO_x sensor well.

The sensors fitted to the bus (GPS and engine/exhaust) enable the analysis of the vehicle emissions of NO_x to be understood in terms of the vehicle dynamics (speed and acceleration). Figure 22 shows a modelled surface plot of speed vs. acceleration and NO_x emission for engine-out (A) and tailpipe NO_x emissions (B). This Figure shows very clearly how engine-out NO_x emissions tend to increase with vehicle speed and acceleration. Similarly, Figure 22 also shows the effectiveness of the SCRT system in reducing emissions of NO_x, especially under conditions of high engine load. These plots also show that while the NO_x sensor tends to be noisy on a 1-Hz time scale there are clear variations in NO_x with vehicle speed and acceleration.



(A) (B)

FIGURE 22: A) Plot of vehicle speed vs. acceleration for the SCRT bus with the colour scale showing the level of engine-out NO_x emission in g min^{-1} and B) for tailpipe NO_x.

4.3 Controlled testing of other vehicles

The majority of the controlled emission tests were carried out on a disused car park next to Elland Road football ground. Of particular interest were a range of vehicles supplied by Leeds City Council. These vehicles included school buses, a hybrid diesel van, a CNG van and a road sweeper. Many of these vehicle types have not been measured before

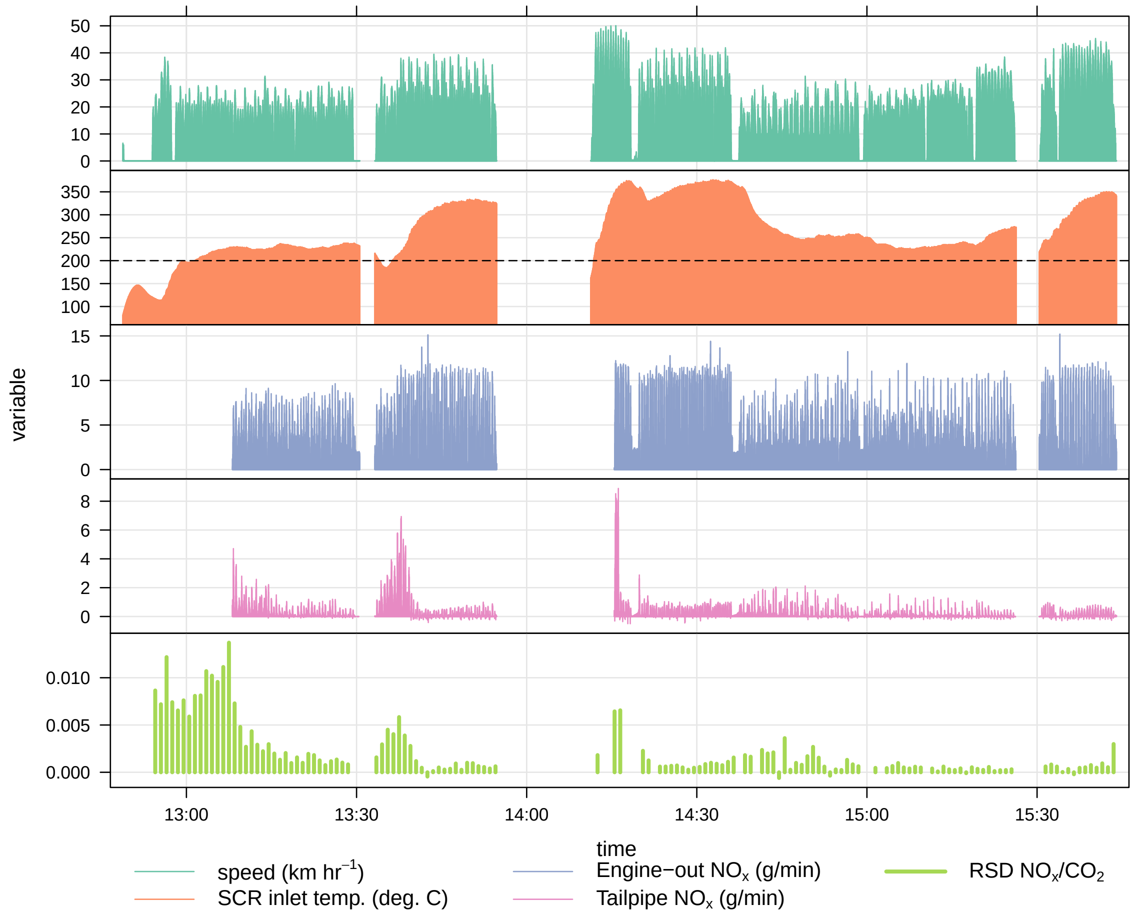


FIGURE 21: Plot showing multiple variables for the SCRT tests at Blyton Park. From the top to bottom the following is shown: GPS speed (km h^{-1}), SCRT inlet temperature (°C), engine-out NO_x (g/min), tailpipe NO_x (g/min) and the RSD NO_x/CO_2 ratio. The dashed line on the SCR inlet temperature plot shows the 200°C temperature.

and hence there was interest in their emissions performance. These tests were generally carried out at relatively slow speeds because the re-suspension of dust caused problems with the measurement. The mean speed for all tests was 22 km h^{-1} (range 7 to 42 km h^{-1}). These conditions tend to reflect fairly slow moving traffic in urban areas and this should be remembered when considering the results. All measurements were made with vehicles with warm engines i.e. they had driven several km to the test site and were tested immediately after arrival.

A summary of the results for NO_x is shown in Figure 23 split by vehicle type, Euro class and fuel. The school buses (BMC buses) can be considered as high emitters of NO_x compared with on-road measurements made in London and Oxford with emissions of NO_x/CO_2 of 0.016 (Euro IV) to 0.020 (Euro III). Both of the school buses had low levels of NO_2 as shown in Figure 24 and Figure 25.

The LPG and CNG vans (based on petrol vehicles) were shown to be very low emitters of NO_x and NO_2 and behaved similar to or better than modern petrol vehicles in this respect e.g. compared with the results from the 2012 campaign. The low emissions are likely due to the efficiency of the three-way catalysts on these vehicles. Provided there is a fuel economy advantage for this vehicle type over the base vehicle (non-hybrid), its emissions would be lower in absolute terms e.g. in g km^{-1}. The road sweeper emitted low levels of NO_x, which in part could be due to its low speed/load duty cycle.

The range of diesel and petrol cars tested behaved in a very similar way to vehicles tested for on-road.

Note that the other buses (Volvo B7 and the CNG Scania) have been considered in more detail in Section 4.2.

Taken as a whole the emission tests confirm that the alternative fuels (CNG/LPG) result in very low emissions of NO_x when used in spark ignition engines. The school bus emissions are however at the high end of emissions measured previously in London or Oxford. All of the other vehicles tested had NO_x and NO_2 emissions similar to those derived from on-road measurements.

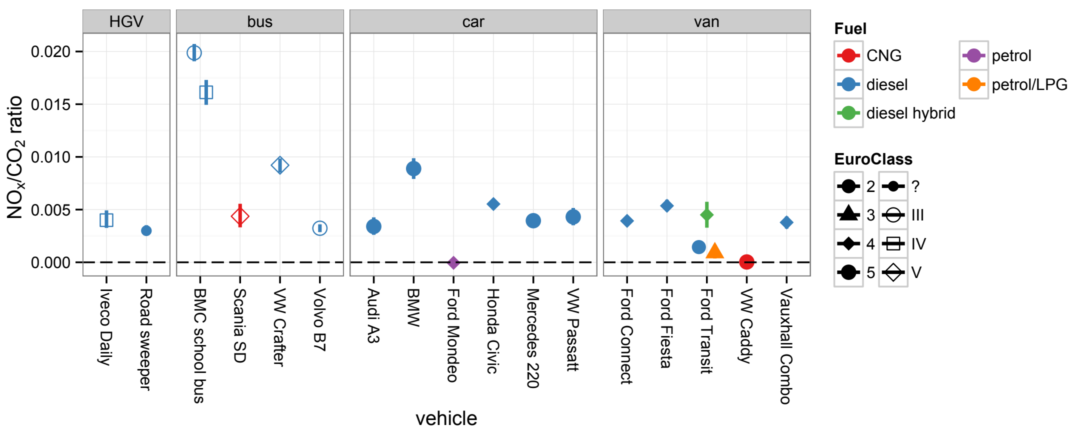


FIGURE 23: Emissions of NO_x/CO_2 for the range of vehicles tested under controlled conditions split by type, Euro class and fuel type.

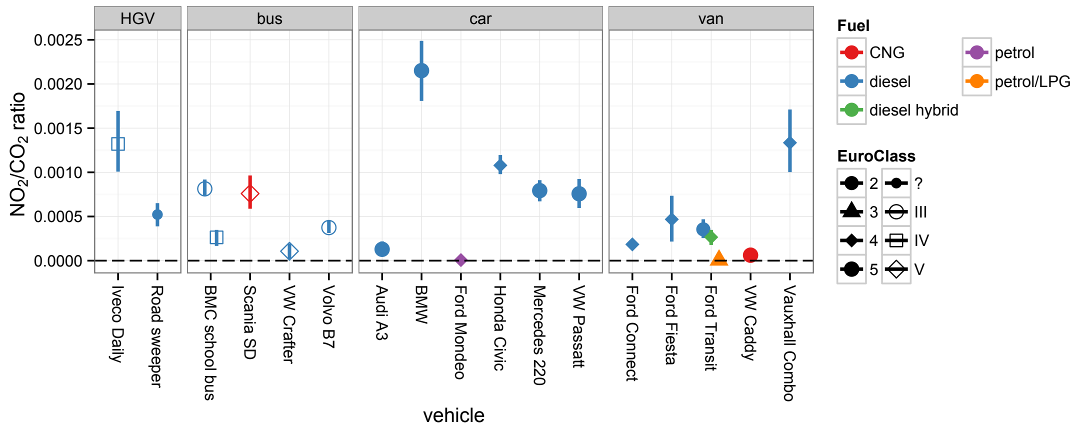


FIGURE 24: Emissions of NO_2/CO_2 for the range of vehicles tested under controlled conditions split by type, Euro class and fuel type.

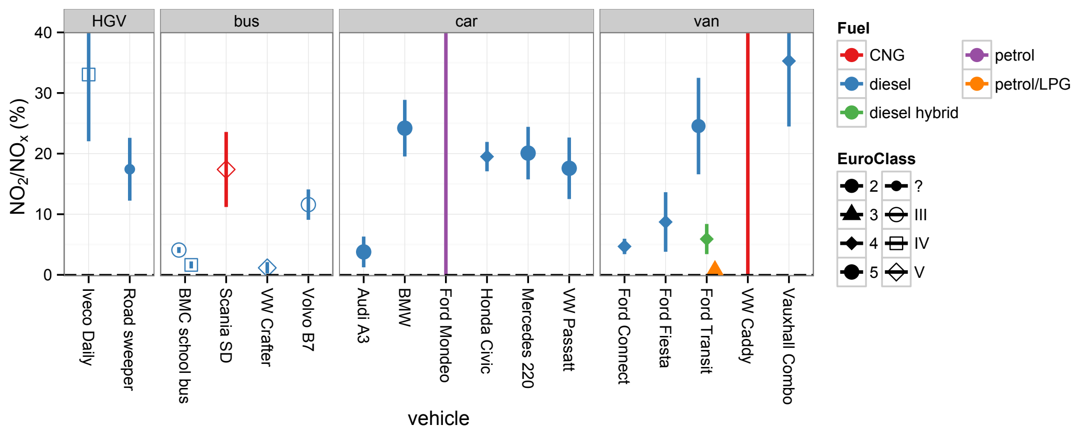


FIGURE 25: Ratio of NO_2/NO_x for the range of vehicles tested under controlled conditions split by type, Euro class and fuel type.

5 Measurements in Oxford

5.1 Introduction

Remote sensing measurements were made in Oxford over a period of two weeks and at two locations. The principal interest in measurements in Oxford was to develop a better understanding of increased exceedances in the hourly NO_2 Limit Value at the Oxford Centre Roadside site. The ambient measurements at this site are discussed in more detail in Section 5.5. This part of the High Street operates a 'bus gate' where only buses and taxis are allowed to travel along this part of the High Street from 07:30 to 18:30 (see Figure 26). The High Street site for remote sensing is therefore well-suited to investigate the emissions from different bus technologies.

Measurements were also made along Oxpens Road, which has characteristics that are more typical of an urban road e.g. there are no special restrictions on certain vehicle types in place.

The buses travelling along this section of the High Street include those from two main bus operators. Both companies provided details on the individual buses in operation including

(A) (B)

FIGURE 26: A) Map showing the location of the RSD measurements on the High Street, B) the experimental set up.

details on the bus number plate, engine manufacturer, vehicle technology (e.g. hybrid) and after-treatment system used (e.g. SCR). This information could be linked directly with the photographs taken of individual buses by the RSD system, providing a detailed breakdown in emissions by different bus technologies.

Table 3 gives a breakdown of the buses sampled in Oxford based on the number of RSD measurements. The majority of the buses sampled along Oxford High Street were Euro V (83%). However, within the Euro V category there is a wide range of vehicle technologies and after-treatment types allowing for an in-depth analysis of these Euro V buses. All the SCR systems analysed were OEM (used on most Euro V buses and EEV buses), except for the Euro III retrofit buses that used the SCRT system and the Euro II that used the CRT system. Note that the SCRT system is not identical to that used on TfL buses described earlier and has not been optimised to reduce the NO_2 proportion of the total NO_x. The hybrid technology used for Cummins vehicles is a series configuration, whereas Volvos were parallel. In a parallel hybrid system the bus is driven by the battery *or* directly by the engine; in a series hybrid system there is no direct link between the engine and wheels and the bus can be driven solely by electric power (which can be derived from battery power or from the generator, or from both).

TABLE 3: Breakdown of bus numbers sampled split by bus engine manufacturer, Euro class and technology. Note that these are the primary technologies identified by the two main bus companies operating in the City of Oxford. Some SCR vehicles could also use EGR but this information was not available.

Euro class	technology	engine make	number	percent
II	CRT	Cummins	27	1.4
III	SCRT	Mercedes	158	8.3
IV	EGR	MAN	36	1.0
V	EGR	Scania	282	14.9
V	SCR	Cummins	142	7.5
V	SCR	Scania	93	4.9
V	SCR	Mercedes	97	5.1
V	SCR	Volvo	81	4.3
V	SCR-hybrid	Cummins	542	28.6
V	SCR-hybrid	Volvo	337	17.8
EEV	SCR	Paccar	101	5.3

5.2 A detailed look at Oxford bus emissions by technology

Calculations were made of the absolute NO_x and NO_2 emissions of the different vehicle types in Oxford i.e. emissions expressed in g km^{-1}. These calculations together with information on the flow of vehicles (measured directly by the RSD) provide a means by which the total source contribution by vehicle type can be estimated. To estimate absolute emissions of NO_x and NO_2 it is necessary to first estimate the emission of CO_2 based on the type of vehicle and its speed. The NO_x/CO_2 (or NO_2 CO_2) ratio is then multiplied by the CO_2 estimate to yield g km^{-1} estimates of NO_x and NO_2.

Use has been made of the COPERT 4 v10 emissions model and the adoption of refined assumptions for passenger cars and vans. The refined emission estimates for passenger cars are described in Mellios et al. (2011) and Ntziachristos et al. (2013). The refined approach is based on linear models of the variables mass, engine capacity, rated power, and power to mass ratio of vehicles and its relationships have been provided in Mellios et al. (2011).

Hybrid buses require a different approach because of their reduced fuel use (and hence CO_2 emission). For hybrid buses it has been assumed that they emit 30% less CO_2 than non-hybrid buses. The precise reduction in CO_2 will be route and hybrid bus technology dependent. However, information provided by one of the two bus operators suggests that a 30% reduction in fuel use is reasonable based on in-service measurements of fuel economy. Accordingly, the g km^{-1} estimates from hybrid buses have been reduced by 30%.

In total there were 1896 measurements of buses from the two major bus companies: Oxford Bus Company and Stagecoach. These companies operate different vehicles except for some Euro V SCR hybrid buses, where a comparison can be made between the two companies. There are many different ways of presenting the emission results. Emission inventories tend to focus on the Euro classification and the type of after-treatment used. However, an analysis of the emissions data by many different types of variable e.g. bus type, engine size etc. using a regression tree approach showed that the engine manufacturer was the most important variable explaining emissions of NO_x. Indeed, the relative importance of the three most important variables was engine make = 57, after-treatment = 37 and Euro Class 6. These results are surprising because it would be expected that the after-treatment and Euro class would be most important in explaining emissions of NO_x.

Considering the 2012 measurements in London reported by Carslaw and Rhys-Tyler (2013) for double deck buses also shows that the make of the engine is the most important explanatory variable for emissions of NO_x. In Oxford the Cummins is shown to be related to higher emissions of NO_x for similar vehicles (Euro class and after-treatment) than any other manufacturer. The London 2012 results show the same finding i.e. the same engine manufacturer is consistently higher than other manufacturers for NO_x for similar vehicles, regardless of the after-treatment used. These results provide strong evidence that under urban driving conditions one engine manufacturer in particular is consistently associated with higher NO_x emissions compared with similar engines from other manufacturers. It should be noted that there is not full information available on every vehicle and engine and the engine manufacturer effect is likely a proxy for some other variable.

Figure 27 shows the mean emissions of NO_x by technology and engine type. An important aspect of the results is the large range in NO_x emissions. The full range spans a factor of 7 from the lowest (the SCRT system on the Euro III vehicles) to the highest Euro V SCR bus. Most of the buses measured are new models (Euro V or EEV) and it is clear from Figure 27 that the level of NO_x emission from different Euro V vehicles is very large. Furthermore there is also a very large range in emissions for Euro V vehicles using SCR where the emission of NO_x varies by a factor of six. These results suggest therefore that SCR itself can vary in effectiveness by a very large amount depending on the bus (or bus company) it is used with.

Another important aspect of the results shown in Figure 27 is the performance of hybrid bus technologies. Even assuming a 30% improvement in fuel economy over non-hybrid technologies reveals that some hybrid bus technologies are among the highest emitters of NO_x of the bus results shown in Figure 27. The hybrid vehicles (with similar engine sizes, 4.5 and 4.8 litres and both double deck) are split between two manufacturers with one emitting 2.25 times the amount of NO_x compared with the other.

Furthermore, there is a difference between the two bus operators operating the *same* SCR Euro V hybrid bus type and Euro class. Oxford Bus Company emits 11.0 ± 1.3 g km^{-1} on average compared with 15.5 ± 0.9 g km^{-1} for Stagecoach i.e. Oxford Bus Company emits 29% less NO_x than Stagecoach. For NO_2 both companies emitted similar levels: 1.1 and 1.2 g km^{-1}, respectively. While there are clear differences between different engine manufacturers and technologies used it also seems to be the case the bus company can have an important effect on emissions of NO_x.

Retrofitting a Euro III bus to use SCRT results in emissions of NO_x that are slightly less than the best Euro V bus i.e. a bus with OEM SCR.

Similar to the emissions of NO_x, the calculated emissions of NO_2 from the bus fleet are also highly variable. Indeed, there is a much greater variation in emissions of NO_2 compared with NO_x as shown in Figure 28. There is a factor of *fifty* between the lowest (Euro V OEM SCR) and highest emitting (Euro II CRT retrofit) bus types for NO_2. The lowest emitting buses for NO_2 presumably do not have a DOC that produces higher emissions of NO_2. The highly variable emission of NO_2 (but consistent within each bus technology group) will have important implications for NO_2 concentrations close to roads (this is discussed more in Section 5.5). It is interesting to note that the highest total NO_x emitter (Euro V OEM SCR) is the lowest NO_2 emitter — in fact, for that bus type almost all the exhaust is in the form of NO.

Large variations in the emissions of NO_2 could have multiple origins. For example, as catalysts age they can become less reactive and it might therefore be expected that older buses with particle filters would have lower emissions of NO_2. While catalyst aging may well be an effect (and an issue that should be considered further), there is very wide variation in the emission of NO_2 for relatively new buses of a similar age (e.g. Euro V). It would appear therefore that most of the variation in NO_2 emissions between the vehicles is due to the emissions control system and not catalyst aging.

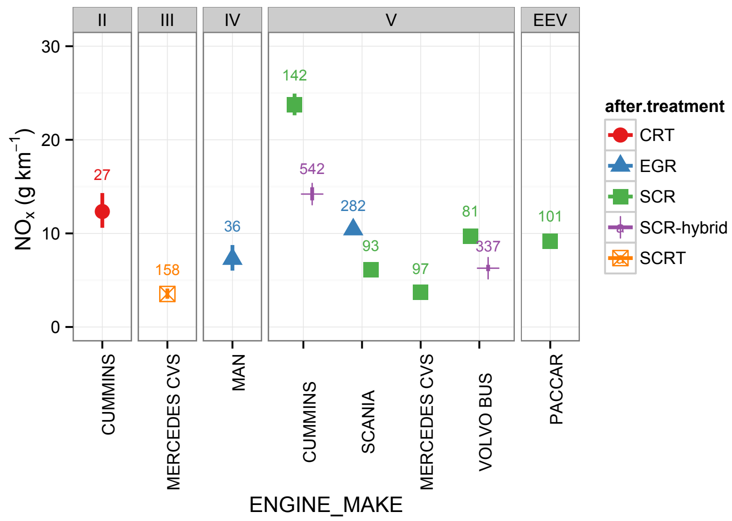


FIGURE 27: NO_x emissions for buses measured along Oxford High Street. The vehicles have been split by Euro class and bus engine type and technology. The number of measurements made of each vehicle type is also shown.

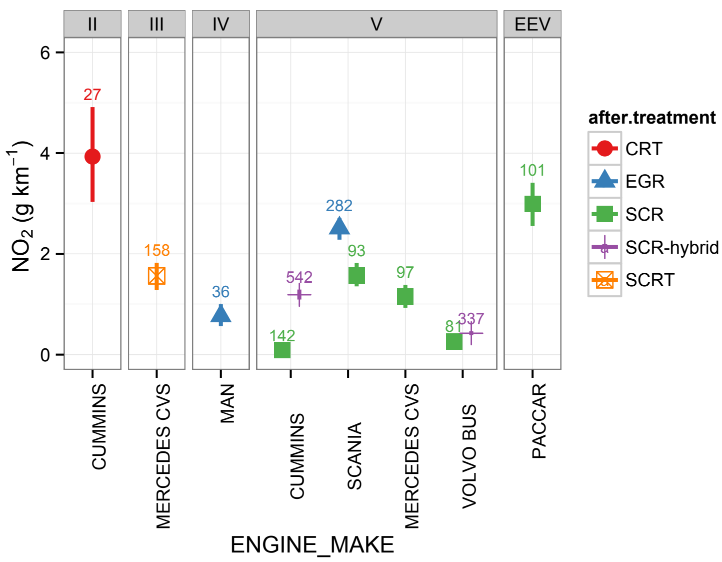


FIGURE 28: NO_2 emissions for buses measured along Oxford High Street. The vehicles have been split by Euro class and bus engine type and technology. The number of measurements made of each vehicle type is also shown.

The wide variation in NO_2 emissions makes it difficult to assess the impact that these technologies have on ambient concentrations. On the one hand high emissions of total NO_x will drive the NO + O_3 reaction in the atmosphere to produce NO_2, but on the other, low direct emissions of NO_2 will lead to a reduction in roadside NO_2 concentrations. As discussed in Section 5.5 it is clear that at the Oxford AURN site at least, the direct emission of NO_2 is the main driver leading to exceedances of the annual and hourly Limit Values for NO_2. Therefore, buses with relatively high emissions of total NO_x (but very low NO_2) are likely to have advantages in terms of NO_2 exceedances over buses that emit much lower emissions of total NO_x but emit a higher proportion of NO_2.

The measurements also show that the SCRT system while producing the lowest emissions of total NO_x has relatively high emissions of NO_2 (the NO_2/NO_x ratio for these vehicles is about 40%, as shown in Figure 29). The absolute emission of NO_2 is however lower than the CRT system on the Euro II buses despite having a slightly higher NO_2/NO_x ratio because the absolute emissions of NO_x from the SCRT system is lower than the CRT. Note that the SCRT system used in Oxford is not the newer 'low NO_2' (optimised) system of the type that is used in the retrofit buses in London, discussed in Section 3. The 40% value is similar to that reported for CRT systems (AQEG 2008).

The measurement location on Oxford High Street was suitable for *repeat measurements of individual buses*. Indeed, there were sufficient numbers of measurements of individual buses to allow a comparison to be made of their emissions across different engine and bus types. This is useful because it helps to show how consistent the emissions are and whether one bus differs from another bus using identical technologies. The mean number of samples of individual buses was 10, but some buses were measured up to 28 times, as shown in Figure 30. The results for NO_x in Figure 30 clearly show that it is possible to distinguish between individual bus emissions — even within a group of bus types that are nominally identical. In general the results show that within a particular bus type, individual bus emissions are similar. These results show for the most part that multiple measurements of emissions of an individual bus for a particular technology type can represent the larger population of buses of the same type.

However, the findings above for repeat measurements from individual buses do not apply to Euro V hybrid SCR buses from one manufacturer (Cummins). For these vehicles there is a wider range in emissions performance from the 'best' to the 'worst' emitters (around a factor of three). The hybrid NO_x emissions from the other major manufacturer are not only lower but are much more consistent with only a factor of two difference between lowest and highest NO_x emitter. The reasons for the much larger variation in emissions from one manufacturer are difficult to identify because all of the measurements were made under similar bus operating conditions. However, the results do indicate that it is possible for emissions to be consistently low on some buses and the underlying reasons should be investigated further e.g. specific information on the hybrid system used.

5.3 Effects of vehicle speed on emissions

In total there were 1621 valid measurements of bus vehicle speed and acceleration. Overall, the speed varied from 10 to 45 km h^{-1}, with the most speeds being between 25 to 30 km h^{-1}. Figure 31 and Figure 32 show how the emissions of NO_x and NO_2 vary by vehicle speed (binned into 5 km h^{-1} intervals), Euro class and after-treatment technology. In the case of NO_x there is little variation in emissions over the range 15 to 40 km h^{-1} for most bus types. However, for the Euro V SCR buses (including hybrids) the emission of NO_x does increase with decreasing vehicle speed. It should be noted that other variations such as engine load may be important in these comparisons. However, the data presented here represent how

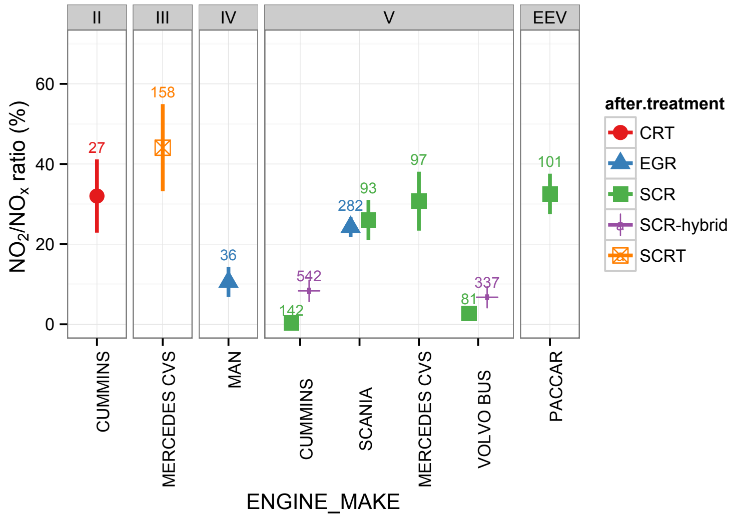


FIGURE 29: NO_2/NO_x ratios for buses measured along Oxford High Street. The vehicles have been split by Euro class and bus engine type and technology. The number of measurements made of each vehicle type is also shown.

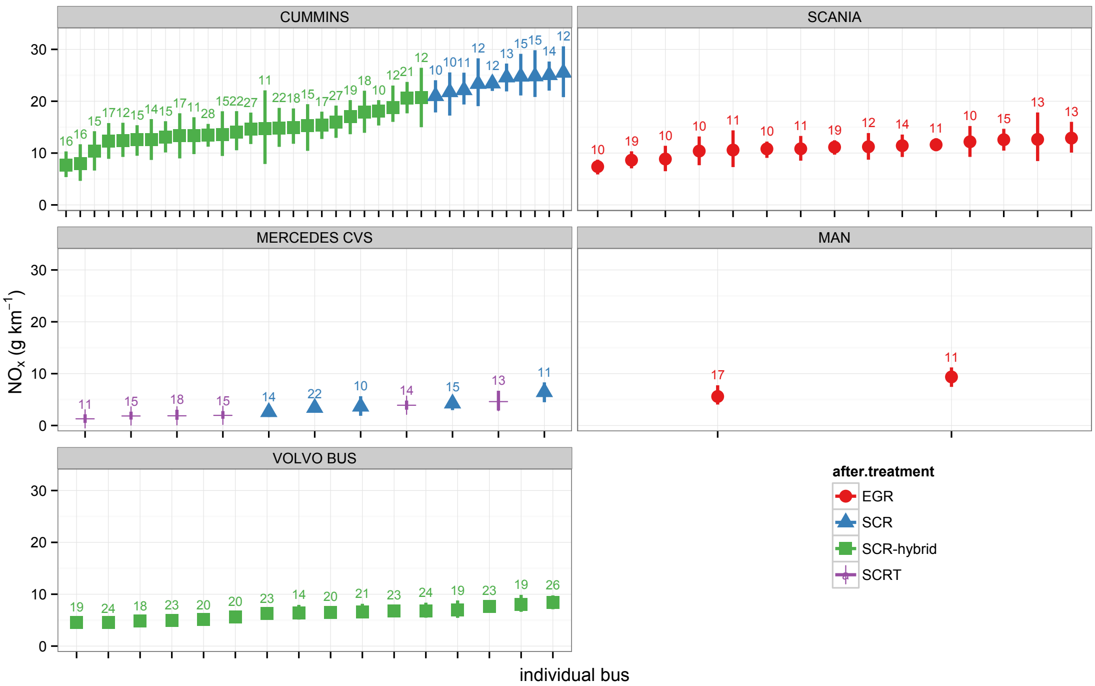


FIGURE 30: NO_x emission from individual buses split by engine make. The emissions have been ordered from low to high for each engine manufacturer.

the different buses operate under actual conditions of use.

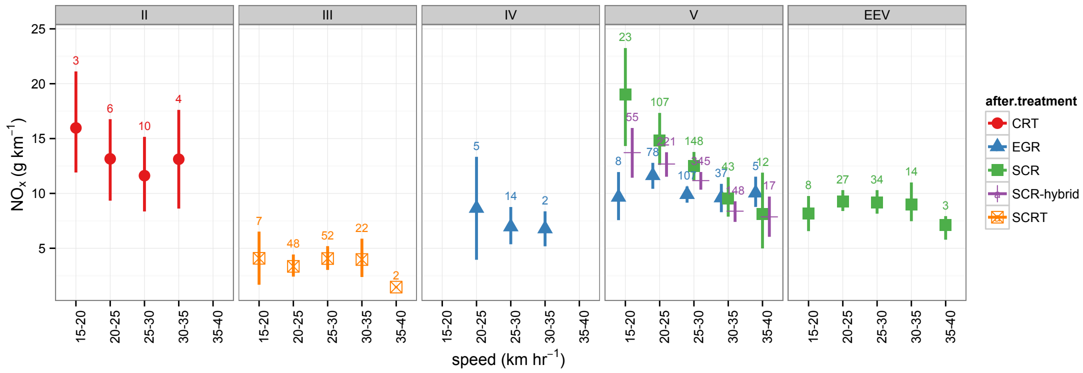


FIGURE 31: Variation in NO_x emissions by vehicle speed, Euro class and after-treatment technology.

The behaviour of NO_2 emissions is rather different to NO_x. Similar to NO_x most buses do not show a strong dependence on vehicle speed. However, for the Euro V vehicles (i.e. that account for 83% of the buses) there is differing behaviour depending on the vehicle technology in question. For the SCR vehicles, the SCR-hybrids tend to have higher NO_2 emissions at lower vehicle speeds (similar to the total NO_x behaviour), whereas the non-hybrid SCR vehicles tend to have lower emissions of NO_2 at lower vehicle speeds. The lower emissions of the SCR vehicles at higher speeds likely reflects an increased number of conditions where there are higher exhaust temperatures (> 200°C) and the SCR reactions are efficient.

Under lower vehicle speed conditions the data shows that Euro V SCR vehicles tend to emit more NO_x and the hybrid-SCR vehicles tend to have higher emissions of NO_2. However, it should also be acknowledged that the remote sensing measurements did not cover very low vehicle speeds below 10 km h^{-1} and idling conditions. These conditions may be important at some locations in Oxford. Based on the variations shown in Figure 32, under more lower speed, congested conditions it might be expected that the SCR hybrid vehicles are proportionately more important emitters of NO_2.

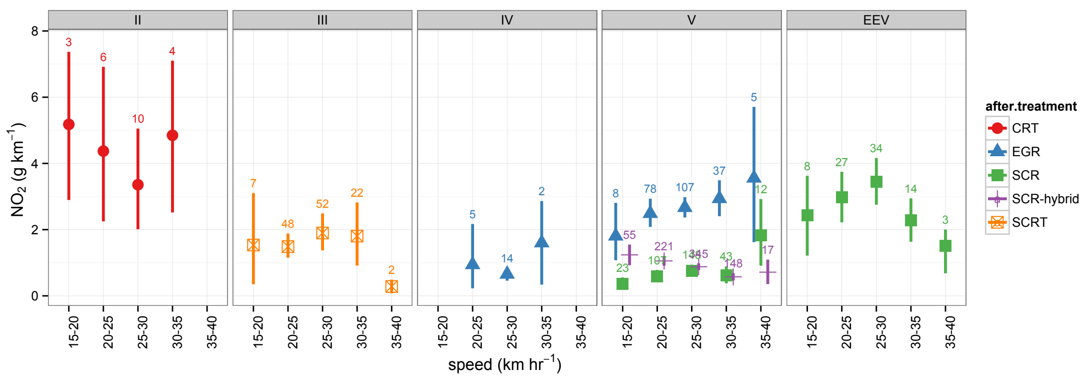
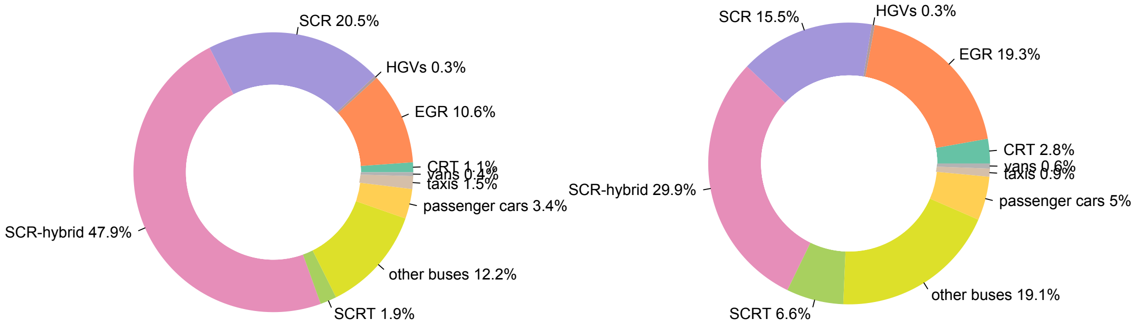


FIGURE 32: Variation in NO_2 emissions by vehicle speed, Euro class and after-treatment technology.

5.4 Source apportionment of NO_x and NO_2 emissions

The emissions by vehicle type expressed in g km^{-1} together with the number of vehicles measured by the RSD allows for an estimate of the total contributions to NO_x and NO_2

emissions on the High Street. It should be noted that these estimates related to typical daytime averages from around 08:00 to 18:00 and do not include weekends. Figure 33 shows the total contribution to NO_x and NO_2 emissions split by vehicle type. As expected, buses dominate the total, accounting for around 95% of the total emissions of NO_x and NO_2. The largest contribution to NO_x emissions is due to buses operated by companies other than the two major ones in Oxford.[2] For NO_x, SCR-equipped buses account for 45.3% of the NO_x (but only 28.5% of the NO_2), with the hybrid SCRs accounting for about a third of total NO_x emissions.

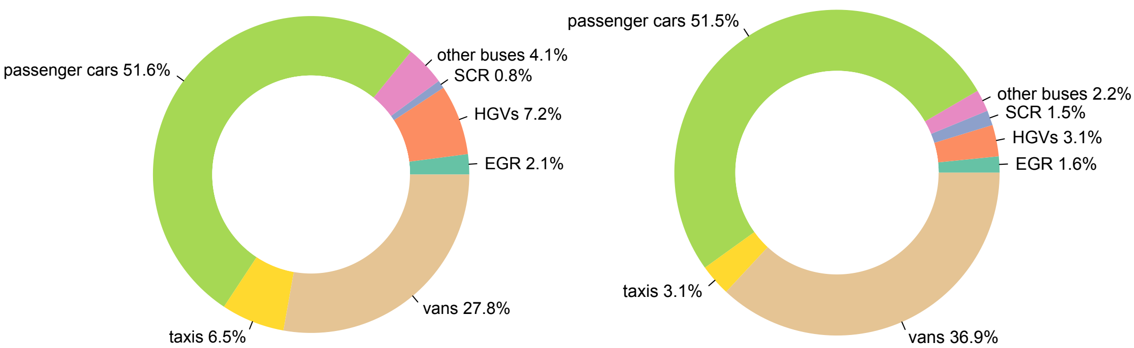


(A) (B)

FIGURE 33: A) Source apportionment of NO_x by vehicle type on Oxford High Street, B) Source apportionment of NO_2 by vehicle type on Oxford High Street.

The source apportionment on Oxpens Road is very different to the High Street because of the lack of buses. The Oxpens Road site is more typical of a urban or sub-urban location dominated by cars and vans. For both NO_x and NO_2 passenger cars account for about half the total emissions, as seen in Figure 34. At this location the contribution of vans is also important with about 28% of the total NO_x emissions coming from vans. For emissions of NO_2, the vans become proportionately more important, accounting for about 37% of the total emissions of NO_2.

The contrast between the High Street and Oxpens Road emphasises the importance of the local fleet composition in controlling the emissions of NO_x and NO_2.



(A) (B)

FIGURE 34: A) Source apportionment of NO_x by vehicle type on Oxpens Road, B) Source apportionment of NO_2 by vehicle type on Oxford Oxpens Road.

[2] This figure is based on bus number plate data provided by the two major bus companies operating in the city of Oxford.

5.5 Analysis and linkage with ambient measurements in Oxford

The RSD measurements on Oxford High Street were made approximately 300 m from the Oxford Centre Roadside AURN site and directly adjacent to the Oxford High Street (non-AURN) site. The close proximity of the sites to the RSD measurements and the similarity of the vehicle fleet affecting both means that the analysis of ambient measurements may useful yield additional information about the sources of NO_x and NO_2 over time. Figure 35a shows the monthly mean variation in concentrations of NO_x from 2008 to 2013. These Figures shows that over the period 2008 to 2013 there has been no statistically significant change in NO_x concentrations, although the slope is positive overall. Over the same period NO_2 concentrations have tended to increase (with a slope of 1.7 $\mu g\ m^{-3}\ yr^{-1}$), but the increase has not been uniform over the period.

In Figure 35c the exceedances of the hourly NO_2 Limit Value show very clearly that the number of hours where NO_2 is >200 $\mu g\ m^{-3}$ increased from 2010 (1 hour) to 2012 (55 hours). Exceedances in 2013 where only a partial year of ratified data has been considered were equal to 10. These plots together reveal important information about trends in vehicle emissions. The first point to note is that while concentrations of NO_x have been stable over 2008–2013, concentrations of NO_2 have not. Importantly, even though NO_x concentrations have been invariant, there have been large changes in hourly NO_2 exceedances at this location. These results highlight that primary NO_2 emissions must have had an important role in governing both the annual mean and hourly exceedances of NO_2 along Oxford High Street.

Indeed, from the Oxford roadside sites and the Oxford St Ebbes urban background site (ideally located ≈800 m upwind of the prevailing wind direction), it is possible to use a simple constrained hourly chemistry model to estimate the average primary NO_2 emissions ratio for the vehicles on the High Street (Carslaw and Beevers 2005). The resulting estimates of the NO_2/NO_x (f-NO_2 ratio) is shown in Figure 35d. In this Figure it is now clear how primary NO_2 emissions have varied over the last few years. The NO_2/NO_x ratio was about 15% in 2008/2009, but increased to about 20% in 2011/2012. This increase is also mirrored by the hourly exceedances shown in Figure 35c i.e. is highest in 2011/2012. The AURN and High Street sites mostly track each other as far as the estimated primary NO_2 trends go — except in 2013 where the High Street is shown to have a much lower level of primary NO_2 of about 10%. The primary NO_2 estimates for the High Street site should be considered as less certain in 2013 compared with other years and also compared with the AURN site. Additionally, based on how the estimates were made, the value of 10% is likely a reasonable estimate of a lower limit. The reasons for this uncertainty are discussed in more detail below.

Also shown on Figure 35d is a black diamond representing the mean NO_2/NO_x ratio based on the results from the remote sensing measurements. This ratio was calculated by summing all the g km^{-1} NO_x and NO_2 emissions. Clearly, the remote sensing measurements represent a short period compared with a whole year (about 1 week), but nevertheless can be compared with the NO_2/NO_x derived from ambient measurements. The ratio from the RSD measurements is between the AURN and High Street values and seems to be in reasonable agreement.

These results clearly show that the recent increases in NO_2 exceedances at the Oxford Centre Roadside site have been driven by changes in primary NO_2 and not total NO_x. The analysis is a good example of how important the primary NO_2 fraction can be in controlling exceedances of NO_2. Any changes in the bus fleet in Oxford (flow or technology used) have not affected concentrations of NO_x. However, changes to technology have affected the emission of primary NO_2 with important impacts on atmospheric concentrations and these changes are of key importance in understanding the situation in Oxford. The importance of primary NO_2 on roadside concentrations is also shown in Figure 11.

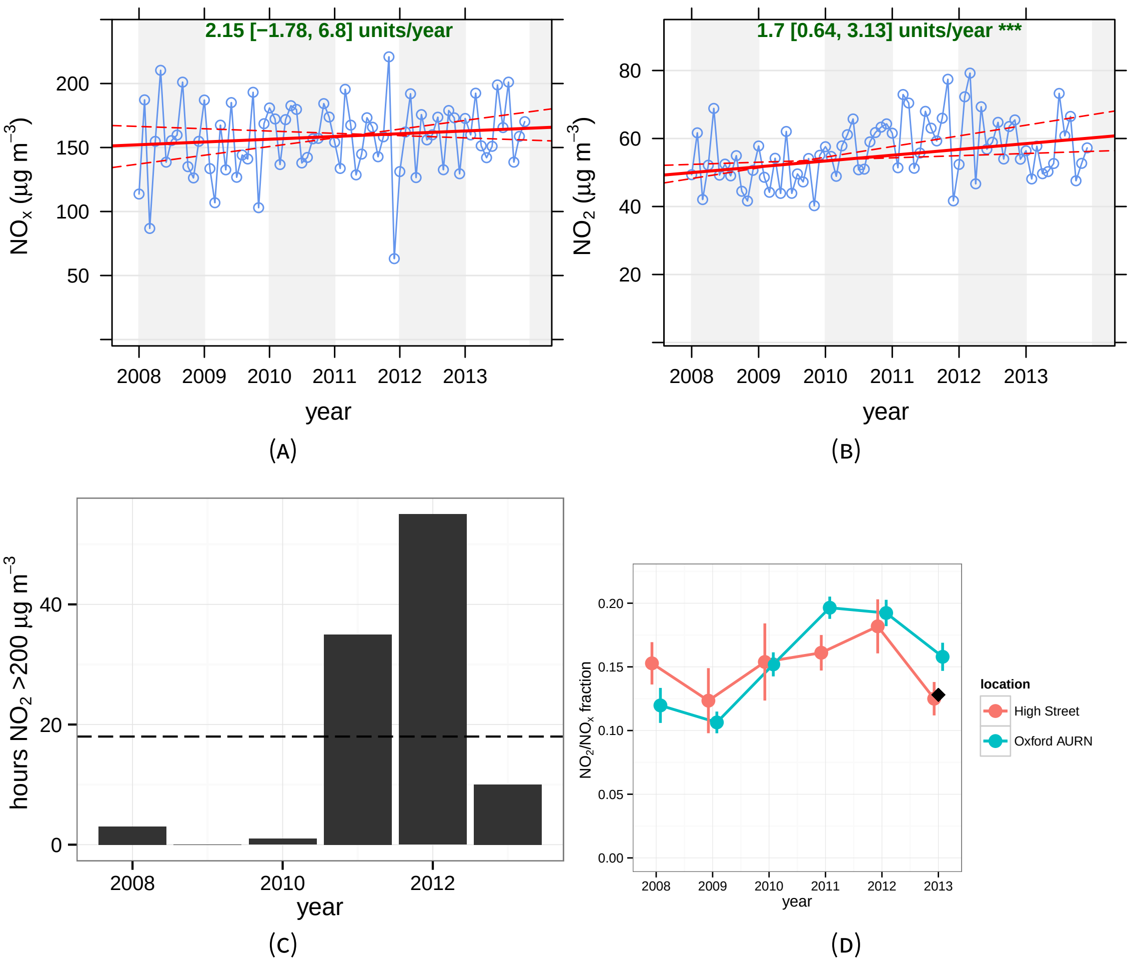


FIGURE 35: Various trends at Oxford Centre Roadside. (a) deseasonalised trend in monthly NO_x concentrations, (b) deseasonalised trend in monthly NO_2 concentrations, (c) hourly exceedances of NO_2, (d) estimated mean primary NO_2 (fraction) based on Carslaw and Beevers (2005) applied to the AURN and High Street sites. Note that data for part of 2013 are provisional.

The sensitivity of the number of exceedances to the level of primary NO_2 in the exhaust of vehicles has been considered by re-modelling the hourly NO_2 concentrations assuming levels of primary NO_2 from 1 to 40%, with constant concentrations of total NO_x. These results are shown in Figure 36. The results show that when the mean level of primary NO_2 reaches about 22 to 23% it can be expected that the number of exceedances will be close to 18 hours. Therefore, for levels of primary NO_2 above this value it can be expected the EU Limit Value will be exceeded. There was found to be little variation in these results by year.

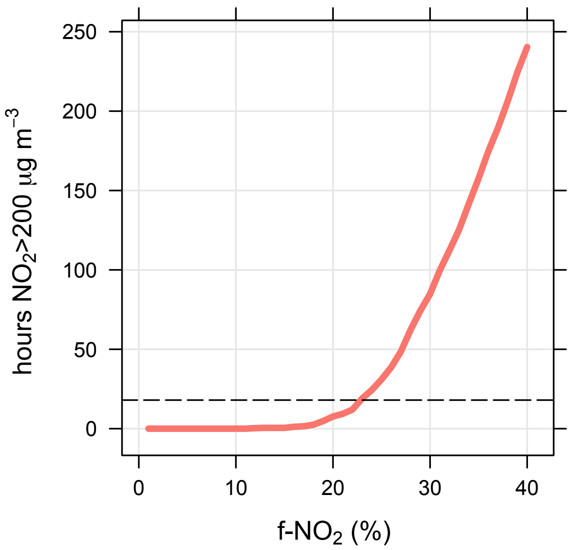


FIGURE 36: Modelled number of hourly exceedances of the NO_2 Limit Value for different mean values of the level of primary NO_2.

Some more insight into the NO_2 concentrations can be gained by plotting NO_x against NO_2. In Figure 37 the NO_x-NO_2 relationship is shown for the High Street site and coloured by the background O_3 concentration from the St. Ebbes background site. These plots very nicely show the influence that background O_3 has on NO_2 concentrations. The NO_2 concentration at a roadside site is comprised of three main (but related) elements: a background contribution, a contribution from the reaction $NO + O_3 \rightarrow NO_2 + O_2$ when vehicle plumes mix with background air and that from directly emitted NO_2 from vehicles using the road. Figure 37 shows that for a particular concentration of NO_x the NO_2 concentration can span a relatively large range. For example, in 2010 for a NO_x concentration of 200 µg m^{-3} the NO_2 concentration varies from about 50 to 120 µg m^{-3}. However, over this range the background O_3 concentration varies from about 20 to 90 µg m^{-3}. Much of the range in NO_2 concentration seen for a particular concentration of NO_x will be due to the influence of background O_3.

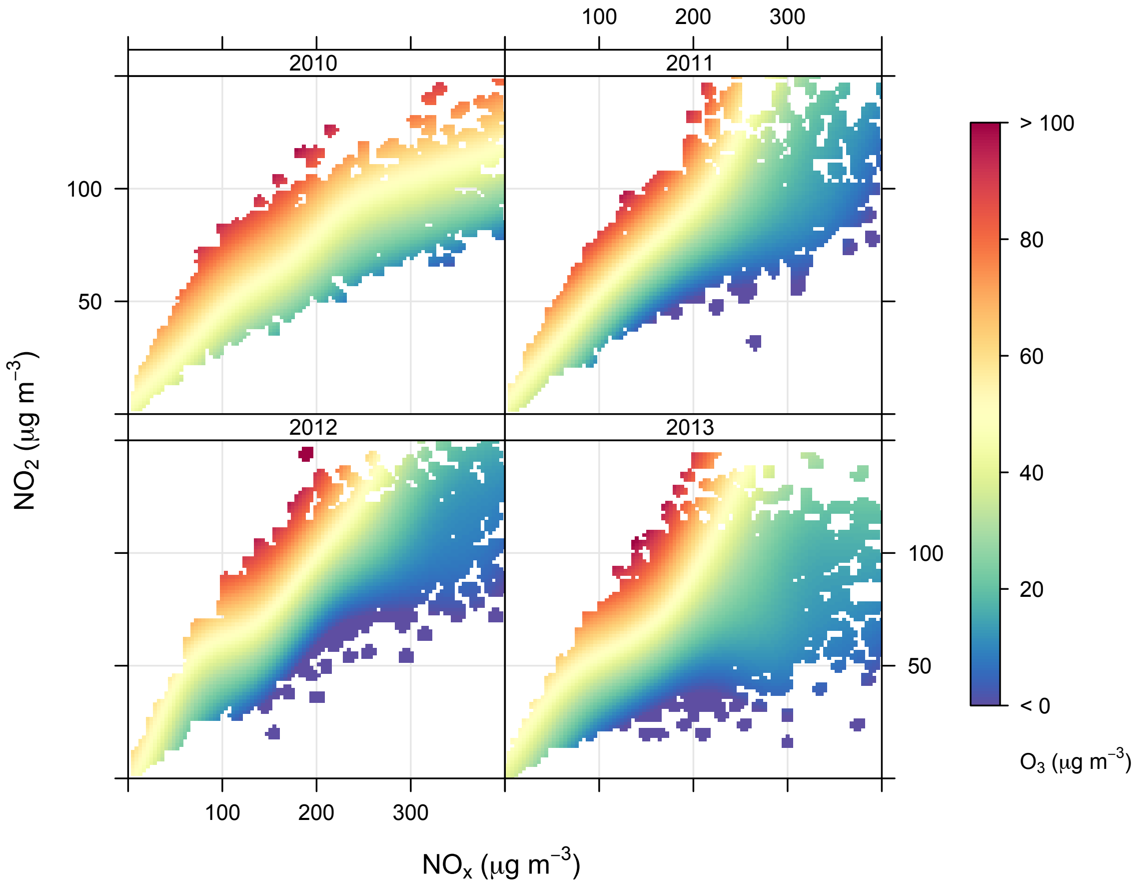


FIGURE 37: The relationship between hourly NO_x and NO_2 concentrations for the High Street ambient measurement site. The colour represents the background O_3 concentration based on data from St. Ebbes background site. The O_3 concentrations have been smoothed to highlight the overall variation.

Figure 37 also shows some other important effects. At high concentrations of NO_x (>300 µg m^{-3}) O_3 concentrations tend to be low. The plots also show that the lowest NO_2 concentrations for a particular concentration of NO_x occur when the background O_3 concentration is very low. It is generally not possible to have high NO_x concentrations and very low NO_2 concentrations. Considering again 2010 when the NO_x concentration is 400 µg m^{-3} the lowest NO_2 concentration is about 75 µg m^{-3}. The concentration of NO_2 does not reach zero in a major part due to directly emitted NO_2 from road vehicles.

What is clear however from Figure 37 is that 2013 looks to be different from other years. For 2013 there is a wider range in NO_2 (extending to lower NO_2 concentrations than other years) concentrations for a particular concentration of NO_x. Given that the High Street NO_x concentrations in 2013 were similar to the other years and the background O_3 concentration also, it is believed that the much broader spread in NO_2 concentration will be largely due to a much more widely varying primary NO_2 emission. These lower values in 2013 have also affected the estimate of the primary NO_2 value for this year i.e. it would have resulted in an underestimate. This behaviour likely reflects a bus fleet with more variability in NO_2 emissions than seen in other years. While it is known from the emission measurements that the primary NO_2 emissions are very variable by vehicle type in 2013 (see Figure 29) there are no measurements of the situation in previous years. At more typical sites with mixed traffic there is much less likelihood of an underestimate in the primary NO_2 fraction — the Oxford site is unusual in being restricted to buses only where individual hours can be affected by particular types of vehicle.

6 Suggestions for further work

While the measurements presented in this report are comprehensive, there are clear areas where further work would be beneficial, as summarised below.

- Vehicle fleets continue to change and it is essential that robust and reliable on-road emissions data continue to be collected. In particular, more measurements are required of Euro 6 diesel cars and vans and Euro VI HGVs and buses.
- Important differences in the emissions of NO_x and NO_2 have been identified in this report including variations by engine type for buses. The actual reasons for these differences are unclear and information on vehicle engineering and engine control could help explain why these differences are observed.
- There is a need to better understand the vehicle pre-history when making measurements using remote sensing of SCR-equipped vehicles. This is because the driving conditions over the period leading up to the measurement could affect the measurement made. For example, periods of very slow/idling conditions could result in the SCR being ineffective. While this does not affect the accuracy of the measurement made it would help better explain some of the differences in emissions observed.
- The performance of hybrid buses should be further investigated. In particular information on the fuel efficiency of these vehicles under actual conditions of use needs to be better quantified together with an improved understanding of the differences that may exist between serial and parallel systems.
- We observed consistent differences in the emissions of NO_x between nominally identical buses in Oxford operated by two different companies. An investigation of the differences in operating procedures used by these two companies may help identify best practice and lead to further reduce emissions.
- The analysis of ambient measurements in Putney would benefit from both a longer time series analysis (to determine whether reductions in NO_x and NO_2 are observed in the longer term), and the analysis at other roadside monitoring sites that could be strongly influenced by the TfL bus retrofit scheme.
- There have now been two measurement campaigns using the University of Denver FEAT system in the UK (in 2012 and 2013). Regular surveys (e.g. annual) would help track the changes in vehicle emissions over time as well as provide early vehicle emissions performance data. In time these surveys would also provide detailed information on vehicle emissions degradation. The latter point is important because there are now numerous vehicle technologies affecting emissions and the way they deteriorate over time is largely unknown.
- The impact that different vehicle technologies have on urban ambient NO_x and NO_2 concentrations needs to be understood through the generation of new emission inventories and detailed dispersion modelling.

Acknowledgements

We appreciate the financial support of Defra for this project. We wish to thank Prof. Donald Stedman and Dr Gary Bishop from the University of Denver for the hire of the FEAT system, Irena Ježek from Aerosol d.o.o (Slovenia, for black carbon emission measurements, to be separately reported), Colin Oates for his work operating the instrument, Enviro Technology Services plc for providing logistical support hiring the FEAT system, Dr James Tate and Christopher Rushton from the University of Leeds for making available the RSD4600 for comparison, Claire Barratt for the photograph number plate translation, Richard Crowther and Dave Cherry from Leeds City Council for organising the availability of vehicles to test, Martin Alan from Scania for organising and providing a CNG bus, Niki Welsh and Steve Rawson from Eminox for organising the availability of the Blyton Park Race Circuit and provision of a Volvo bus for testing, Lynzi Robb from Johnson Matthey for the bus engine data, Ruth Calderwood (City of London), Steve Neville (Westminster Council) and Bill Legassick (Southwark Council), Roy Fox and David Kennett (Wandsworth Council), Roger Pitman (Oxford City Council) for their local support and Finn Coyle (TfL) for information on TfL buses.

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