Remote sensing of NO_2 exhaust emissions from road vehicles

A report to the City of London Corporation and London Borough of Ealing

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Glossary of Terms

Term	Meaning
DPF	Diesel Particulate Filter
EEV	Enhanced Environmentally friendly Vehicle). The EEV vehicle is equivalent to a Euro standard somewhere between Euro V and Euro VI i.e. it has the same NO_x limit as the Euro V emission standard, but with a lower PM_{10} limit
EGR	Exhaust Gas Recirculation
f-NO_2	the ratio of NO_2 / NO_x in exhaust emissions on a volume basis expressed as a %
NH_3	Ammonia
NO_2	Nitrogen dioxide
NOx	Oxides of nitrogen (sum of NO and NO_2)
OEM	Original Equipment Manufacturer
RSD	Remote Sensing Detector
SCR	Selective catalytic reduction

Executive summary

- This report summarises key findings from a series of measurement campaigns carried out during the summer of 2012 to measure vehicle emissions using a University of Denver remote sensing detector (RSD). Measurements were made of nitric oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), hydrocarbons (HC), ammonia (NH_3), sulphur dioxide (SO_2) and a measure of particulates based on infrared opacity. This report focuses on the nitrogen containing compounds, NO_x, NO_2 and NH_3. It considers the other pollutants in less detail.

- A key development in this work is the direct measure of NO_2, which has not been possible previously using other RSD equipment available in the UK. While total emissions of NO_x (NO + NO_2) are very important to consider, the speciation of NO and NO_2 is of fundamental importance. Directly emitted NO_2 from vehicles behaves like a primary pollutant close to roads and can make a significant contribution to near-road NO_2 exceedances of both the annual and hourly mean EU Limit Values. In addition, it is known that many modern vehicle technologies result in high emissions of directly emitted NO_2, which this report aims to characterise and quantify.

- Measurements were made in central urban and suburban locations in London. The data are therefore representative of urban traffic operating conditions in general, and the London fleet mix in particular (especially with regard to the taxi and bus fleets). Results, particularly for the wider passenger car population, should be transferable to other urban locations. A total of approximately 93,000 observations were made during the surveys, resulting in a usable sample of approximately 68,000 data records, with combined valid vehicle identification and emission measurements. The in-service vehicles monitored were assumed to be legal with respect to type approval emission standards and other motor vehicle regulations.

- The measurements provide information on the *ratio* of a pollutant (e.g. NO_x) to CO_2 in the observed 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.

Emissions of NO_x

- The results for total NO_x highlight some important findings.

  a The results for NO_x in general highlight that the clearest reductions over the past 20 or so years have been due to petrol vehicles including petrol hybrids, where substantial reductions have been observed with each new Euro class introduction.

  b Broadly speaking, emissions from diesel vehicles of all types have not shown significant reductions in NO_x over the past two decades, although the relative proportions of primary NO and NO_2 do vary over time.

  c For passenger cars, emissions of NO_x for Euro 5 diesel cars are at an equivalent level to pre-Euro vehicles (i.e. pre 1992 vehicles). Emissions peaked for Euro 2/3 cars but are only about 25% less for Euro 5 cars.

  d The survey results presented in this report include TfL buses fitted with Selective Catalytic Reduction (SCR) systems which are ***all*** OEM (Original Equipment Manufacturer) systems. OEM SCR systems have been designed to pass Euro emission standards rather than being optimised for urban-type (i.e. low speed and low engine temperature) conditions. There is little evidence that OEM SCR fitted to buses, including hybrid buses, appreciably reduces total NO_x during urban driving. TfL has a programme of retrofitting SCR systems and purchasing new buses where the SCR systems will be optimised for urban NO_x reduction and where substantial reduction in NO_x (up to 88%) is expected. No TfL buses with retrofit SCR were assessed in this report.

  e Over 15,000 measurements were made of London taxis and the emissions from these vehicles have been presented in a comprehensive way. In general, taxis manufactured before year 2000 emit twice the NO_x per unit of fuel consumed compared with taxis manufactured after 2000. The latter group of vehicles emit NO_x/CO_2 in a similar way to diesel cars of the same age. Efforts to reduce emissions from taxis have so far focused on particulate matter, where taxis are a significant source in central London. However, these vehicles also make an important contribution to total NO_x emissions in central and inner London and there is scope to reduce the emissions from these vehicles. The Mayor's proposals for a new taxi capable of zero emission (at tailpipe) operation is the most effective way of delivering comprehensive reductions in all taxi emissions.

f Diesel light goods vehicles (LGVs), less than or equal to 3.5 tonnes at Euro IV and Euro V, were observed to emit between 4% and 9% more total NO_x than the equivalent diesel passenger cars. They emit similar proportions of primary NO_2.

g The results for heavy goods vehicles (HGVs) show that total NO_x emissions decreased by 20% since Euro II but then remained stable from Euro III to Euro V. Note that the RSD deployment was better suited to emissions measurements from light vehicles, and was less well suited to HGV's (in particular articulated vehicles), of which there are relatively few in central London.

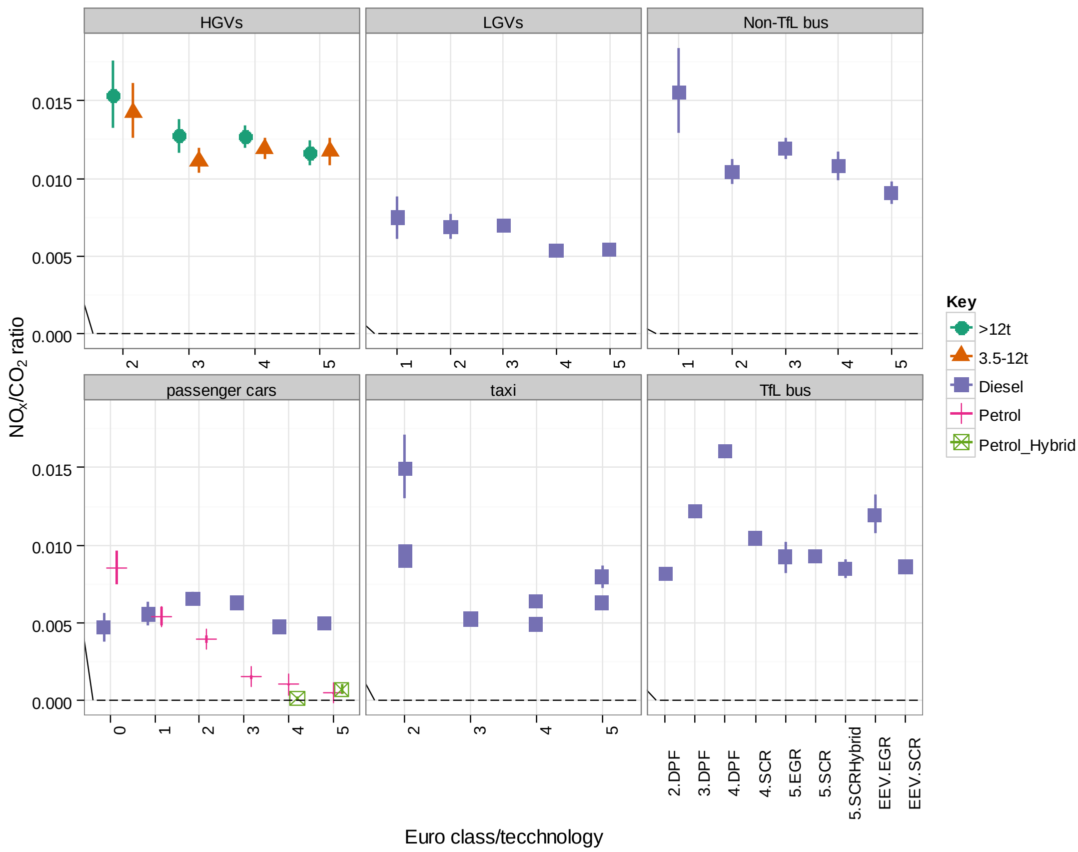

Figure 1 Summary of NO_x/CO_2 emissions ratio by major vehicle type and technology.

Emissions of NO_2

- In terms of the fraction of NO_2 (f-NO_2) in the exhaust of vehicles (expressed by volume as a percentage of total NO_x), there have been important changes through the Euro classes.

a Petrol vehicles emit a very low amount of their NO_x in the form of NO_2 (typically only a few percent); confirming findings in previous studies.

b NO_2 from diesel cars has increased from around 10-15% for Euro 3 and older technologies up to an average of almost 30% for Euro 4/5 technologies. Furthermore, it is found that diesel cars emit increased emissions of NO_x with increasing vehicle specific power (VSP, a measure of engine load) for Euro 3 to Euro 5. It is also found that larger engine capacity (>2.0 litres) diesel cars emit more of their NO_x in the form of NO_2; typically between 40% (Euro 3) and 60% (Euro 4/5) more. Note that diesel cars >2.0l accounted for 36% of total diesel passenger cars measured.

c It is also found that there are consistent differences in the f-NO_2 values of Euro 4 and Euro 5 diesel cars by manufacturer. It is clear that some manufacturers adopt emission control approaches that result in a considerably lower NO_2/NO_x fraction than others. These results indicate there would be scope for significant reductions in NO_2 emissions if the lower emitting technologies were more widely adopted. This may also explain the observed differences by engine capacity, because some manufacturers dominate the larger engine capacity market segment. Further investigation is necessary to understand the effect of specific manufacturer emission control technologies.

d TfL buses have a NO_2/NO_x ratio that is dependent on the emission control technology used – and bus manufacturer. Those fitted with diesel particulate filters (DPF) typically have ratios of 15-20%, which is lower than previously reported results (30-40%). SCR technology shows a very wide variation in NO_2 responses from almost zero for Euro IV to >30% for Enhanced Environmental Vehicles (EEV). These differences *might* be related to different platinum contents of catalysts used as part of modern SCR systems. Similarly, lower NO_2 emissions (but not total NO_x) are also observed for Euro IV non-TfL buses.

e The results for HGVs show that f-NO_2 was about 15-20% for Euro II/III vehicles but decreased to 5-10% for Euro IV/V. No information was available on which of the vehicles sampled used SCR but it is possible that reduced NO_2 fractions in Euro IV/V HGVs has the same cause as observed in TfL buses. Further testing of known technologies would confirm this behaviour.

f London taxis behave in a similar way to diesel cars, with a substantially increased proportion of their NO_x emitted as NO_2 for recent vehicle technologies.

g The reduced NO_2/NO_x ratio found for some vehicle types (Euro IV SCR-equipped TfL buses, non-TfL buses and Euro IV/V HGVs) is likely to have had an influence on recent NO_2 ambient trends at roadside sites in London. A consideration of f-NO_2 ratios based on the analysis ambient measurements clearly shows a mean reduction from around 22% in 2010 to 18% in 2012, which is consistent with recent changes to vehicle technology in buses and HGVs mentioned above. This reduction in directly emitted NO_2 could make an important contribution to reducing ambient NO_2 concentrations at many locations.

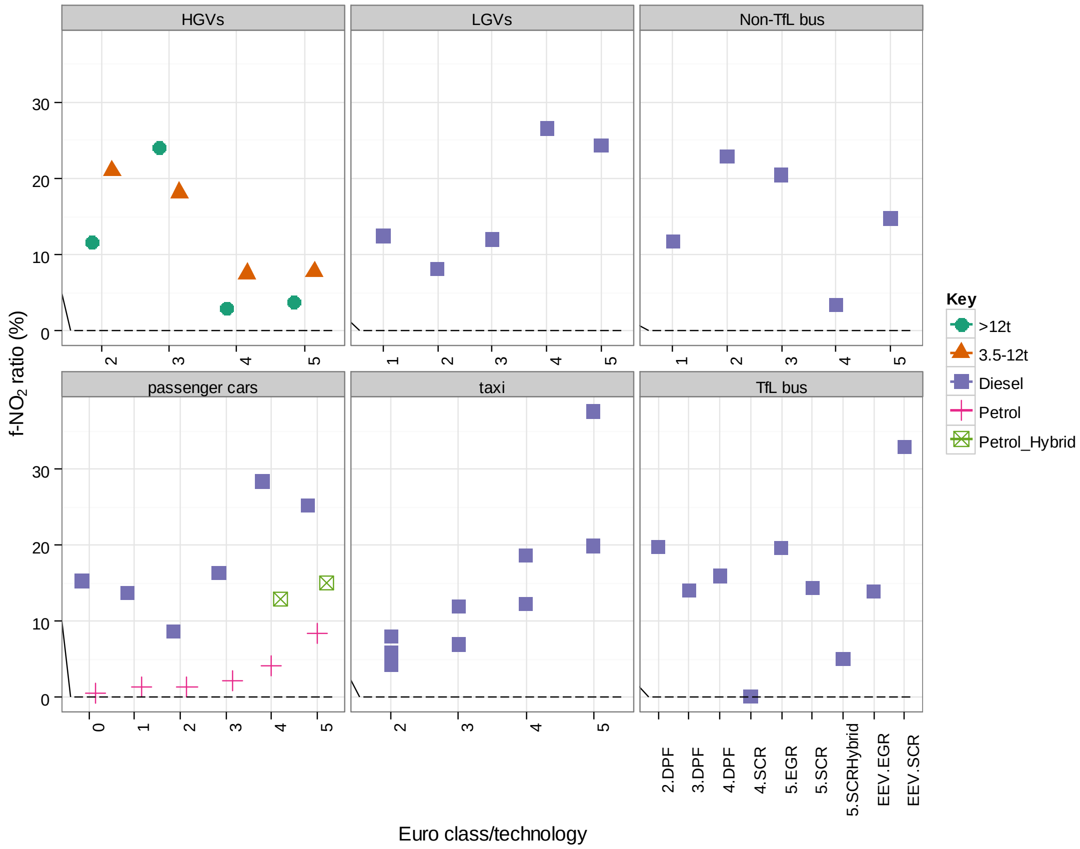

Figure 2 Summary of NO_2/NO_x (f-NO_2) emissions by major vehicle type and technology.

Emissions of NH_3

- The RSD also provides information on NH_3 emissions. There are two vehicle types identified as emitting NH_3: catalyst-equipped petrol vehicles and SCR-equipped TfL buses. Note that other vehicle types such as

HGVs are also likely to use SCR, but data was unavailable to uniquely identify these.

a In the case of petrol vehicles, NH_3 emissions peaked for early generation catalyst vehicles (Euro 1/2) and have progressively decreased to Euro 5.

b For TfL buses the NH_3 has a different origin from the use of SCR where it is deliberately used to help reduce NO and NO_2 to N_2. It is found that older generation buses fitted with OEM SCR (Euro IV) emit higher quantities of ammonia compared with newer generation vehicles (Euro V/EEV).

c In terms of a contribution to UK emissions of NH_3, these results suggest road transport is a very minor source.

Overall findings

- It is clear that emissions control technology is increasing in complexity both in terms of configurations used and specific optimisations applied for particular drive cycles. Broad descriptions by Euro classification used by most emission inventories will not capture this complexity. It will become increasingly important to express emissions in terms of combinations of specific technologies used because these different technologies and combinations of technologies can lead to very different emissions performance for many key species. For example, the results for diesel cars and TfL buses show a very clear and important effect of manufacturer on emissions of NO_2.

- These results have many implications for air quality policy that aims to control concentrations of NO_2. For diesel cars it has been shown that total NO_x emissions, whilst peaking for vehicles manufactured around year 2000, have changed little overall over the past 20 years and in that time new after-treatment technologies have increased the proportion of NO_x that is NO_2. Careful consideration would therefore need to be given to policies that aim to reduce NO_x and NO_2 emissions. However, any potential reductions in NO_x or NO_2 would need to be balanced against potential impacts on other species such as particulate matter.

- A brief analysis of ambient trends of NO_x and NO_2 at 23 roadside and kerbside sites in London over the past 10 years shows that NO_x and NO_2 concentrations have only decreased by about 1 and 0.5% on average per year, respectively. These trends are similar to those previously reported between 2004-2009 by Carslaw et al. (2011), suggesting that NO_x and NO_2 concentration trends remain weakly downward at a rate less than emission inventory estimates. However, there is some indication of a reduction in roadside NO_2 concentrations over the past 2-3 years. These results are broadly consistent with the RSD measurements in that they show little change in NO_x for new technology vehicles entering the fleet during the last few years but some recent indication of reductions in NO_2. A detailed analysis at specific monitoring sites would help link the RSD and ambient measurements in a more robust way.

- Tables have been presented to allow others to adopt and test the emission results in atmospheric emissions inventories. These tables present the gas volume emission ratio of a species to CO_2, together with the 95% confidence interval in the estimate of the mean. These factors could, for example, be applied to existing emissions of CO_2 (in g/km) to derive g/km emission estimates for different pollutants. Note that the reported emissions factors apply under urban-type driving conditions. Note also, that some care in usage is required for certain vehicle types e.g. buses, where the emission characteristics may only reflect an optimised London fleet.

Comparison with previous work

- The current work can be compared with the analysis of previous RSD analysis in the UK reported by Carslaw et al. (2011) (for Defra) and Rhys-Tyler et al. (2011) that used an RSD instrument that could only measure NO and not NO_2. Broadly speaking the results are consistent in that the main findings are that petrol NO_x emissions have decreased considerably over the past 20 years but diesel NO_x emissions have not. However, there are some important differences.

  a For diesel cars the mean f-NO_2 values for Euro 4/5 vehicles are lower than was previously *assumed* (25-30% vs. 55%). Nevertheless, the conclusion that total NO_x emissions from diesel cars has changed little over 20 years still holds. The data indicates an increase in f-NO emissions from diesel cars and vans manufactured since 2008, following a period of reduction since year 2000. The finding that larger engine capacity diesel cars emit a higher fraction of their NO_x as NO_2 is also a new and potentially important finding; this may be related to emissions control technology adopted rather than engine capacity per se.

  b The current results provide a very comprehensive understanding of emissions from London taxis. Over 15,000 measurements were made of London taxis and the emissions from these vehicles have been disaggregated in a comprehensive way.

c The principal difference with the current work is the detail that is provided by the Denver RSD for speciating NO_x and providing emissions information on NH_3. For TfL buses in particular where the emissions from individual vehicles can be robustly matched to specific technologies, it is clear there are important differences between the technologies in terms of NO_2 emissions.

d The results are consistent with previous RSD survey data collected in London in 2008, where only the NO component of total NO_x was measured (Rhys-Tyler et al., 2011). Both the 2008 and 2012 data sets indicate a peak in NO emissions from diesel passenger cars for vehicles manufactured in year 2000, followed by a decline, to a minimum, for diesel cars manufactured in year 2007. However, the 2012 data indicates that from year 2008, this decline in NO emissions has been reversed; the measured mean level of NO emissions from diesel cars manufactured in 2011/2012 is around 17% higher than from diesel cars manufactured in 2007.

e The 2008 and 2012 data sets are also consistent with regard to emissions of NO from London taxis; both data sets indicate a halving (or more) of NO emissions from London taxis in the transition from Euro 2 (LTI TX1) to Euro 3 (LTI TXII). Both data sets also indicate a significant peak in the emissions of particulate matter (based on opacity measurements) from London taxis at Euro 3 (LTI TXII). It should be noted that the 2012 data set has a much larger taxi sample size (circa 15,000) than the 2008 data set (circa 700).

- It is clear that the use of the University of Denver RSD provides important and detailed emissions information that would not be possible to obtain using an instrument that measures only NO. *Indeed, it is now apparent that only measuring NO and making assumptions about the level of NO_2 for modern vehicle technologies could be unreliable and potentially misleading*. Another key benefit is the direct measurement of NH_3, which will remain important to consider in future years due to the increased use of SCR - and aging SCR systems.

Recommendations

1 The RSD approach to measuring vehicle emissions has proved to be extremely valuable. One of the key advantages is the number of vehicles sampled and the opportunities for linking individual vehicle data with comprehensive vehicle information databases. Another key advantage is the speed with which new or emerging vehicle technologies can be tested. For that reason, regular (e.g. annual) RSD surveys would provide

information on the real-world emissions performance of vehicles as soon as they enter the fleet e.g. Euro 6/VI. Such measurements would provide the earliest possible information on the likely future impacts of these vehicles on UK air pollution.

2 The results from these measurements should be compared in detail with emissions factors used in inventories such as the NAEI and LAEI to understand the implications of these new measurements on emissions inventory NO_x, NO_2 and NH_3 estimates for road vehicles.

3 In case of the OEM SCR systems used to ensure TfL buses meet the relevant Euro standard, the limited reduction in total emissions of NO_x and the wide (but consistent) variation in emissions of NO_2 needs to be better understood given the important future impact these technologies could have on emissions from vehicles more generally. However, the systems tested were not optimised for urban NO_x reduction. Recent initiatives by TfL such as the development of an optimised SCR system for retrofitting 900 buses will be important to evaluate under in-use conditions. For example, the analysis of the impact the targeted used of these vehicles at locations such as Putney High Street (Wandsworth) would help confirm the emission characteristics of these vehicles.

4 While considerable progress has been made in understanding the emissions performance of different vehicle technologies, it is clear that the range and configuration of these technologies in modern vehicles is highly complex. There is an increasing need for more detailed individual vehicle technology information. For example, knowing the type (e.g. even the platinum content) and configuration of catalysts, particle filters and SCR systems. Such information would serve two main purposes: the identification of the most effective emissions control technologies to reduce NO_x, and the information needed for emission inventories to calculate robust emission estimates.

Contents

1 Introduction

1.1 Project scope and objectives

Research in recent years has indicated that the proportion of nitrogen dioxide (NO_2) in total oxides of nitrogen (NO_x) produced by the latest generation of road vehicle diesel engines has increased (Carslaw, 2005). However, these findings have been generally based on measurements from a relatively small number of vehicles (perhaps a few hundred at most), carried out either in the laboratory (chassis dynamometer / engine test bed), or measured from instrumented vehicles operating on-road. In addition, emissions of NO_x from light duty vehicles have been observed to stabilise in recent years. A key limitation of vehicle emissions research to date has been the absence of robust data on directly emitted NO_2. In part the reason is due to vehicle emissions type approval legislation itself, which does not differentiate between NO and NO_2 – and hence most measurements report total NO_x. The second important issue is that while remote sensing of road vehicle emissions using commercially available instrumentation has been shown to be very effective at providing detailed and relevant fleet emissions data, to date these measurements only considered nitric oxide (NO) and not NO_2. This project aimed to overcome some of these limitations by measuring NO_2 and NO in road vehicle exhaust directly using appropriate remote sensing instrumentation.

The aims of this project are:

1. To quantify emissions of NO_2 and NO_x in road vehicle exhaust gases in an urban area;
2. To quantify the variation in NO_2 and NO_x emissions across the urban road vehicle fleet by vehicle type (e.g. car, LGV, HGV, bus, taxi), fuel type, Euro standard, engine size and vehicle age;
3. Where practicable, characterise the emissions by driving conditions;
4. To determine the NO/NO_2 ratio in vehicle exhaust gases (by vehicle category) from direct measurement, and;
5. Develop emission factor information that can be used in the NAEI and other inventories, which will directly help to validate them.

1.2 Brief summary of previous work

In a previous comprehensive study for Defra, RSD data were used from surveys around the UK (including London) using a commercial instrument (AccuScan 4600) that only measured NO (Carslaw et al, 2011a, b). That work did however present new and important information concerning the failure of Euro standards in reducing real-world emissions of NO_x. That study also considered trends in ambient NO_x and NO_2 concentrations across the UK in considerable detail – and showed that there was only weak evidence of downward trends from around 2004/4 to 2009. A potentially important limitation of the Carslaw et al.

(2011a) work was that assumptions were used concerning the proportion of NO_2 in vehicles exhaust based on values in the literature. It was known at that time that these assumptions could be erroneous and it was recommended that Defra hire the University of Denver remote sensing instrument that has an NO_2 (and NH_3) capability. The current work contained in this report largely follows on from the recommendations in the Defra 2011 report.

Separately, analysis of the commercial RSD results in London only was undertaken. Results from this work are reported in Rhys-Tyler et al. (2011) and Rhys-Tyler and Bell (2012). The instrument also measured smoke, reported in units of grams of diesel particulate per 100 grams fuel, based on opacity measurements made at ultraviolet wavelengths. The surveys were carried out at 8 sites in Ealing in March/April 2008, and 5 sites in Southwark in June/July/August 2008, over a total of 29 survey days, resulting in over 119 000 observations. Overall, 54,599 observations had both valid emissions measurements and vehicle identification.

Emissions from petrol cars of each pollutant were all observed to display a statistically significant reduction with the introduction of each successive Euro emissions standard from Euro 1 onwards. However, Euro 2 diesel cars were observed to emit statistically higher rates of NO than either Euro 1 or Euro 3 standard diesel cars. The study also confirmed the continuing ‘dieselisation’ of the UK passenger car fleet. Mean NO emissions from Euro 4 diesel cars were found to be 6 times higher than Euro 4 petrol cars.

Smoke emissions from LTI TXII (Euro 3) London taxis were found to be statistically higher than either earlier LTI TX1 (Euro 2) or later LTI TX4 (Euro 4) model variants. This finding has possibly significant implications for local air quality policy interventions such as maximum age limits for taxis in London. The study also went on to investigate the relationships between vehicle specific power (VSP), a proxy for variation in engine load, and emission rates. It was observed that there was a clear relationship between positive VSP values and NO emissions from diesel and petrol cars, especially at Euro 3 and Euro 4. Similar relationships were also observed for particulate matter (smoke) from diesel cars.

1.3 Overview of recent NO_x and NO_2 trends in London

It is useful to first consider recent trends in ambient concentrations of NO_x and NO_2 to update the previous work carried out for Defra (Carslaw et al., 2011a, b). The following Figures provide trend estimates of NO_x and NO_2 at 23 roadside and kerbside sites in London from 2003 to 2012.[1] Data from these sites will tend to reflect recent trends in emissions from road vehicles. These data have been

[1] Note that some of the 2012 data are not yet ratified.

aggregated in a simple way to monthly means and then de-seasonalised. Figure 3 shows that there has been a statistically significant decrease in NO_x concentrations at the 95% confidence level, but the downward trend has only been -1.07% [-1.52, -0.55] a year. This decrease is similar to that found between 2004 and 2009 (-1.6%/yr in Outer London and -0.6%/yr in inner London) and more recent evidence therefore does not indicate any substantial change in NO_x trends i.e. they remain weakly downward and substantially less than expected from emission inventory estimates.

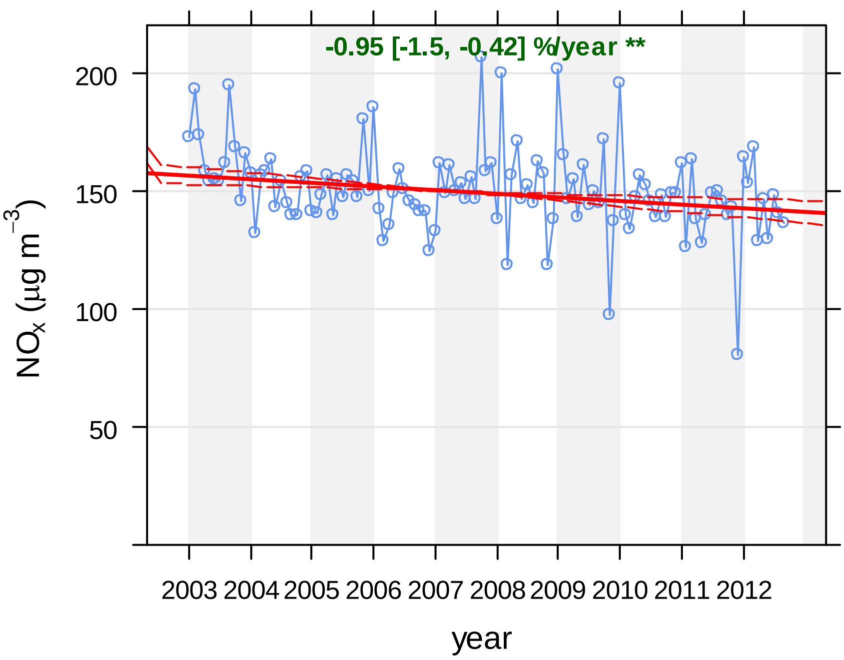

Figure 3 Trend in aggregate de-seasonalised NO_x concentration averaged across 23 London roadside and kerbside sites. The text gives the trend estimate and its 95% confidence interval.

The trends in NO_2 are half those for NO_x over the same ten year period as shown in Figure 4 (-0.59%/yr [-1.01, -0.14]). A smaller reduction in NO_2 would be expected but these decreases clearly have not been large. There is some indication that over the past 3 years or so that NO_2 concentrations have decreased at a greater rate.

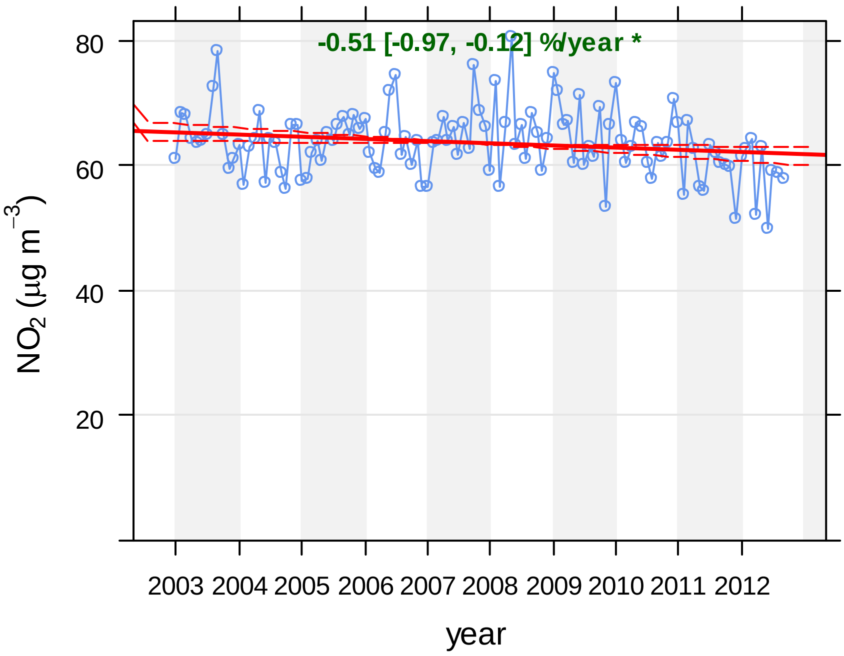

Figure 4 Trend in aggregate de-seasonalised NO_2 concentration averaged across 23 London roadside and kerbside sites. The text gives the trend estimate and its 95% confidence interval.

The difficulty in interpreting Figure 4 is that ambient data can be "noisy" and will be influenced by meteorological variation – both short term and long term variation. However, it is possible to analyse the ambient data to derive an estimate of the mean f-NO_2 value for each road adjacent to each roadside monitoring site. This is valuable for several reasons. First, it provides an independent estimate of the f-NO_2 value for vehicles. Second, it removed meteorological variation to reveal the underlying f-NO_2 from vehicles. Third – and importantly – it allows a comparison between the remote sensing emission results to help understand the connection between the two.

The estimate of the mean f-NO_2 emissions ratio of the roadside increment was made using the technique of Carslaw and Beevers (2005). The technique uses a simple chemistry model to describe how exhaust plumes from vehicles mix into ambient background air. The approach assumes that the NO_2 from such a process consists of two principal sources: that directly emitted by vehicles and that formed through the reaction between NO and O_3. In essence the technique is one of optimisation in that the solution finds the optimum balance between the NO + O_3 reaction and directly emitted NO_2 to best explain the hourly variation of ambient NO_2 concentrations. The output from the analysis is a monthly site dependent estimate of the mean f-NO_2 emissions ratio for the road adjacent to the monitoring site.

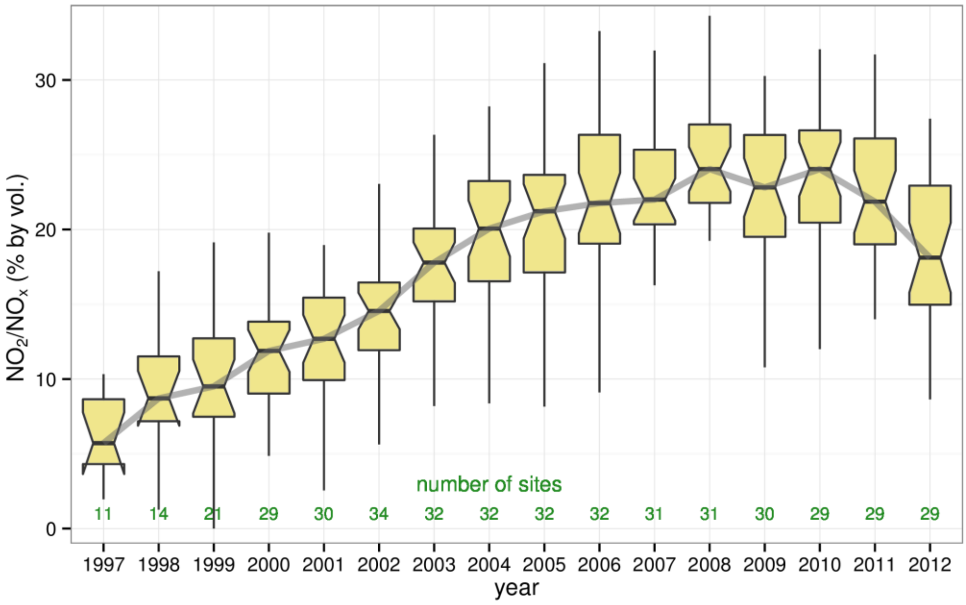

Figure 5 Trend in f-NO_2 calculated from the analysis of ambient measurements at roadside sites in London based on the approach of Carslaw and Beevers (2005).

Figure 5 shows the results from the analysis of roadside data from 1997 to 2012. What is most apparent from Figure 5 is the progressive increase in f-NO_2 ratio from about 5% by vol. in 1997 peaking at about 25% in 2008 to 2010. The increase in the f-NO_2 ratio over the past 15 years or so has been substantial i.e. a factor of five. *It is also clear from Figure 5 that over the last two years (2011 and 2012) there has been a clear reduction in estimated f-NO_2 ratio at roadside sites; decreasing from a maximum of 25% to about 18%.* This decrease in the f-NO_2 ratio is consistent with the RSD results discussed in the following sections. In particular, the recent reductions in the f-NO_2 ratio seen for Euro IV SCR TfL buses and Euro IV HGVs are consistent with the downward trend seen in Figure 5.

1.4 Instrumentation

The project measured emissions of NO_2 and NO (in addition to NH_3, SO_2, CO, HC, and smoke) in road vehicle exhaust gases using roadside remote sensing instrumentation developed at the University of Denver (Bishop and Stedman, 1996; Popp et al., 1999). This instrumentation has been deployed successfully in the USA and Sweden in recent years, but this was the first deployment in the UK.

"The instrument consists of a non-dispersive infrared (NDIR) component for detecting CO, CO_2, and HC, and a dispersive ultraviolet (UV) spectrometer for measuring oxides of nitrogen (NO and NO_2), SO_2 and NH_3. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Co-linear beams of infrared (IR) and UV light are passed across the roadway into the IR detection unit, and are then focused onto a dichroic

beam splitter, which serves to separate the beams into their IR and UV components. The IR light is then passed onto a spinning polygon mirror, which spreads the light across the four infrared detectors: CO, CO_2*, HC and reference.*

The UV light is reflected off of the surface of the dichroic mirror and is focused onto the end of a quartz fibre bundle that is mounted on the coaxial connector on the side of the detector unit. The quartz fibre bundle is split in order to carry the UV signal to two separate spectrometers. The first spectrometer was adapted to expand its UV range down to 200nm to measure the peaks from SO_2 *and* NH_3 *and still measure the 227nm peak from NO. The absorbance from each respective UV spectrum of SO2,* NH_3*, and NO is compared to a calibration spectrum in the same region to obtain the vehicle emissions. The second spectrometer measures only* NO_2 *by measuring an absorbance band at 438nm in the UV spectrum and by comparing it to a calibration spectrum in the same region (Burgard et al., 2006).”*

Source: Bishop et al 2010.

Figure 6 Instrument deployment at Aldersgate Street, London. (Photograph: Glyn Rhys-Tyler)

In addition to measurements of exhaust emissions, a pair of light gates is used to collect vehicle speed and acceleration data. These data can be used to investigate the relationship between vehicle emissions, speed, acceleration, and the power required to propel the vehicle, also taking highway gradient and estimates of relevant vehicle parameters into account (mass, drag coefficient, and rolling resistance). A photograph of each observed vehicle is stored so that licence plate information can be extracted to determine relevant vehicle parameters such as fuel type.

The instrument also measures opacity (percent light extinction) in the infrared at a wavelength of 4 micrometres. This provides an indication of levels of smoke /

particulate matter in the exhaust plume. Previous studies in the United States indicate that multiplication of the percentage infrared opacity by a factor of between 2 and 4 provides an estimate of grams of particulate matter (black soot) per kg of fuel burnt (Schuchmann et al., 2010).

The developers of the instrumentation acknowledge that measurement of light extinction at this infrared wavelength to measure opacity “suffers from the problem that particles have no strong spectral features, and are not strong scatterers in the IR wavelengths” (Stedman and Bishop, 2002). Recent commercial developments of roadside remote sensing devices, such as the instrument deployed in London in 2008, utilise both infrared and ultraviolet wavelengths to measure opacity to address this issue (Rhys-Tyler et al., 2011).

It should be noted that the RSD technique has both advantages and disadvantages compared with techniques such as those that use rolling roads or engine test beds. A key difference is that the RSD measures emissions as ‘snapshots’ in time, and not over full legislative test cycles such as those used for European emissions type approval testing. For this reason it is not easy to directly compare the RSD results with limits set for Type Approval. On the other hand, by making hundreds or thousands of measurements of vehicles operating under ‘real’ driving conditions, the RSD provides comprehensive in-service emissions measurements for a significant proportion of the fleet that rolling road or test bed measurements cannot realistically provide. Finally, the results from the RSD are valid over the conditions under which the measurements were made i.e. urban-type driving conditions, and did not provide information on emissions under other conditions e.g. motorway driving.

2 Emission measurement campaigns

2.1 Survey site selection

Survey sites were selected in the local authority partner areas based on four main criteria; (a) site safety and logistics; (b) traffic composition; (c) a repeat of a subset of 2008 sites to identify trends in fleet composition and emissions; and (d) site characteristics including likely vehicle speeds and accelerations. It became apparent during survey planning that it would be more efficient to implement a smaller number of good quality survey sites. Following a desk top review, site visits were carried out at eleven potential survey sites. Four survey sites were finally selected.

a) A1 Aldersgate Street, City of London (southbound). Lat 51°31'8.21"N, Long 0° 5'49.44"W
b) Queen Victoria Street, City of London (eastbound). Lat 51°30'42.87"N, Long 0° 5'49.14"W
c) A4127 Greenford Road, Ealing (southbound). Lat 51°31'11.03"N, Long 0°21'16.75"W
d) A40 Target Roundabout, Ealing (westbound on-slip). Lat 51°32'39.56"N, Long 0°22'56.48"W

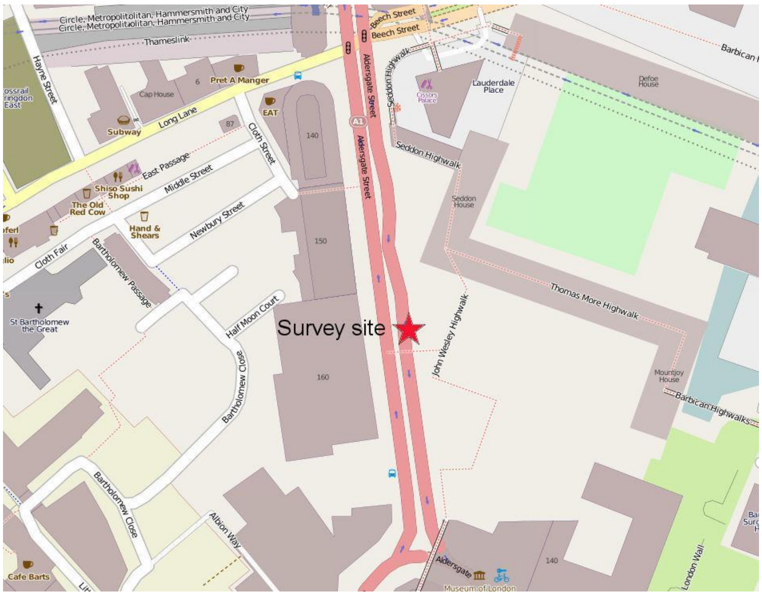

Figure 7 Aldersgate Street survey location (© OpenStreetMap contributors)

Figure 8 Queen Victoria Street survey location (© OpenStreetMap contributors)

Figure 9 Greenford Road survey location (© OpenStreetMap contributors)

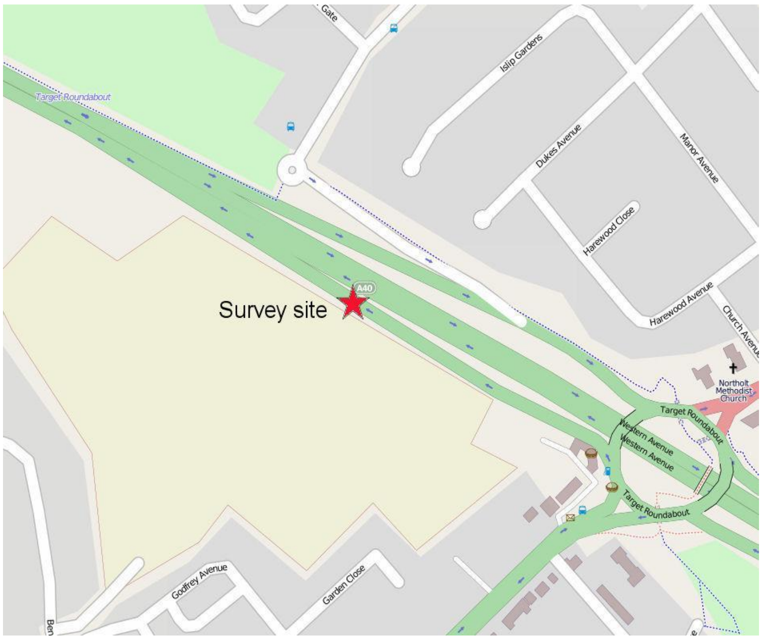

Figure 10 A40 slip road survey location (© OpenStreetMap contributors)

2.2 Remote sensing survey implementation

The remote sensing surveys were implemented during the period May 21st to July 2nd 2012 inclusive. Data were collected on weekdays during daylight hours, generally during the period 0800 – 1800 hours, weather permitting. The remote sensing instrumentation is not weather proof, so surveys were suspended during periods of rain.

Table 1 Summary of remote sensing sample size.

Location	Date	Observations	Valid NO_2 measurements	%
Aldersgate St.	May 21st 2012	2532	1995	78.8
	May 22nd 2012	4704	3696	78.6
	May 23rd 2012	4715	3729	79.1
	May 24th 2012	5219	3977	76.2
	Sub total	*17170*	*13397*	*78.0*
Queen Victoria St.	May 25th 2012	3804	3325	87.4
	May 28th 2012	4004	3620	90.4
	May 29th 2012	5286	4607	87.2
	May 30th 2012	4970	4409	88.7
	May 31st 2012	5056	4492	88.8
	June 1st 2012	3300	2899	87.8
	June 6th 2012	3301	2864	86.8
	June 7th 2012	1576	1297	82.3
	Sub total	*31297*	*27513*	*87.9*
Greenford Rd.	June 12th 2012	4118	3348	81.3
	June 13th 2012	4636	3640	78.5
	June 14th 2012	5552	4197	75.6
	June 15th 2012	1725	1282	74.3
	June 18th 2012	4192	3137	74.8
	June 19th 2012	5660	4381	77.4
	June 20th 2012	4961	3831	77.2
	June 21st 2012	1438	1154	80.3
	Sub total	*32282*	*24970*	*77.3*
A40 slip road	June 25th 2012	408	347	85.0
	June 26th 2012	3285	2648	80.6
	June 27th 2012	1813	1464	80.8
	June 28th 2012	3718	3058	82.2
	June 29th 2012	3120	2570	82.4
	July 2nd 2012	244	213	87.3
	Sub total	*12588*	*10300*	*81.8*
Total		93337	76180	81.6

Table 1 presents a summary of the sample size obtained across the four survey sites. ‘Observations’ indicates the number of survey records obtained at the survey site. The number of ‘valid’ gas measurements is determined by instrumentation data logic checks which, for example, reject a measurement if the exhaust plume is too small, or if there is excessive variability or error in the measurements for a particular observation (circa 50 measurements are taken within a measurement period of half a second, for each observed vehicle exhaust plume).

3 Data processing

3.1 Processing of vehicle images and licence plate matching

Each survey record has, in principle, an associated image (either of the front or rear of the vehicle) from which a licence plate can be transcribed. It was found in practice that around 15% of observations failed to capture a photograph of the vehicle, Further, where an image was obtained successfully, complete licence plates could not always be determined, either because the licence plate was partially or completely obscured or out of view, or because the licence plate was unreadable for other reasons. A two stage process was adopted to process the vehicle images. Firstly, the image files were interpreted using commercially available automatic number plate recognition (ANPR) software. Secondly, the image files were manually processed by visual inspection. Table 2 summarises the results.

Table 2 Summary of licence plate transcription from vehicle images

Location	**Date**	**Image files**	**Licence plates**	**%**
Aldersgate St.	May 21st 2012	2047	1692	82.7
	May 22nd 2012	3771	3142	83.3
	May 23rd 2012	3817	3133	82.1
	May 24th 2012	4089	3413	83.5
	Sub total	*13724*	*11380*	*82.9*
Queen Victoria St.	May 25th 2012	3346	2807	83.9
	May 28th 2012	3647	3413	93.6
	May 29th 2012	4665	4475	95.9
	May 30th 2012	4450	4144	93.1
	May 31st 2012	4510	4262	94.5
	June 1st 2012	2923	2786	95.3
	June 6th 2012	2967	2798	94.3
	June 7th 2012	1361	1301	95.6
	Sub total	*27869*	*25986*	*93.2*
Greenford Rd.	June 12th 2012	3521	3315	94.1
	June 13th 2012	3846	3732	97.0
	June 14th 2012	4491	4340	96.6
	June 15th 2012	1351	1260	93.3
	June 18th 2012	3423	3207	93.7
	June 19th 2012	4681	4393	93.8
	June 20th 2012	4146	3936	94.9
	June 21st 2012	1181	1109	93.9
	Sub total	*26640*	*25292*	*94.9*
A40 slip road	June 25th 2012	350	290	82.9
	June 26th 2012	2735	2591	94.7
	June 27th 2012	1491	1428	95.8
	June 28th 2012	3212	3056	95.1
	June 29th 2012	2677	2479	92.6
	July 2nd 2012	217	210	96.8
	Sub total	*10682*	*10054*	*94.1*
Total		78915	72712	92.1

A commercial supplier was used to match the 72,712 extracted licence plates against available vehicle records from the Driver and Vehicle Licensing Agency (DVLA) database, and the Society of Motor Manufacturers and Traders (SMMT) Motor Vehicle Registration Information System (MVRIS). The DVLA and SMMT data provided a reasonably comprehensive description of relevant vehicle parameters for passenger cars such as vehicle type, fuel type, vehicle age, and engine capacity. In addition, the datasets contained partial data (44%) on emissions 'Euro' classification for passenger cars, particularly for newer vehicles.

Where Euro classification for passenger cars was missing in the DVLA/SMMT datasets, reference was made to light vehicle data published by the Vehicle Certification Agency (VCA). The VCA publish data since year 2000 relating to passenger cars as they are type approved for use in the UK. These data include relevant technical parameters for the vehicles such as manufacturer, year of manufacture, fuel type, engine capacity, CO_2 emissions, and emissions Euro standard. By matching these VCA parameters with the available data from DVLA/SMMT for the survey observations, the majority (88%) of Euro classifications for observed passenger cars could be determined. Missing Euro classifications for the remaining passenger cars (12%) manufactured prior to year 2000, mainly vehicles manufactured in the period 1993 to 1999 (9%), were estimated from the year of manufacture.

Euro emission classes for vehicle types other than passenger cars were determined as follows. Taxis (black cabs) were processed based on model, engine type, and year of manufacture. Data were obtained from Transport for London regarding the Euro classification of the bus fleet, together with data on bus emissions control technology. Where Euro classification data were missing for light and heavy goods vehicles, and powered two-wheelers, these were estimated based on year of manufacture.

Of the 72,712 licence plates submitted, 70,529 (97%) were matched successfully to vehicles in the DVLA or SMMT databases. When the remote sensing emissions data was recombined with the vehicle data, there were approximately 68,073 (94%) records which had both a valid NO_2 measurement, and valid vehicle identification. This dataset essentially forms the basis for the analysis.

Table 3 Summary of observed vehicles by fuel type

Vehicle type	Fuel Type					
	Diesel	**Petrol**	**Petrol / Gas**	**Petrol / Hybrid**	**Electric**	**Total**
Car (M1)	13582	20030	127	769	2	34510
Minibus (M2)	142	4	0	0	0	146
Bus (M3)	2583	0	0	0	0	2583
Van (N1)	12631	471	325	0	2	13429
HGV (N2)	791	0	0	0	1	792
HGV (N3)	568	0	0	0	0	568
Moped (L1)	0	66	0	0	0	66
Motorcycle (L3)	0	848	0	0	0	848
Three wheeler (L5)	0	5	0	0	0	5
Plant	12	0	0	0	0	12
Taxi (M1)						
LTI FX4	877	0	0	0	0	877
LTI TX1	4132	0	0	0	0	4132
LTI TXII	4050	0	0	0	0	4050
LTI TX4	4904	0	0	0	0	4904
Carbodies Metrocab	228	0	0	0	0	228
Mercedes Vito 111	594	0	0	0	0	594
Mercedes Vito 113	329	0	0	0	0	329
Total	45423	21424	452	769	5	68073

The emissions data themselves (with the exception of opacity) are generally presented in this report in terms of ratios to CO_2 by mole, which are constant for a given exhaust plume. The pollutant / CO_2 ratios by moles are abbreviated as Q. The remote sensing instrumentation utilised in this study does not measure absolute levels of pollutant, but ratios of pollutant to CO_2. Moles are also directly proportional to volumes at constant temperature and pressure. Therefore, emissions percentages derived from these ratios are by volume (Stedman and Bishop, 1991).

4 Results

Note that where uncertainty intervals are given these relate to the *95% confidence interval (CI) in the mean*. These uncertainties were derived using a bootstrap resampling technique.

4.1 Passenger cars

The results for passenger cars, which constitute the most numerous vehicle type, are shown by year of manufacture in Figure 11 for NO_x. The first issue to note is that the data show a consistent pattern of change over the period 1985-2012 i.e. wide, “noisy” variations in emissions are absent. This behaviour is indicative of results that represent consistent differences between vehicle types and technologies. In other words the RSD captured sufficient samples of different vehicle types and ages to clearly differentiate their emission characteristics.

As shown by the uncertainty intervals in Figure 11, there is more uncertainty in the mean level of emission for the earlier years. This behaviour is due to sample size issues because there are very few old technology vehicles. Nevertheless, it is very clear from Figure 11 that emissions of NO_x decreased markedly from 1991 to 1992 for petrol cars; coinciding with the introduction of three-way catalysts. From 2005 onwards, emissions from petrol cars (including hybrid vehicles) are very low.

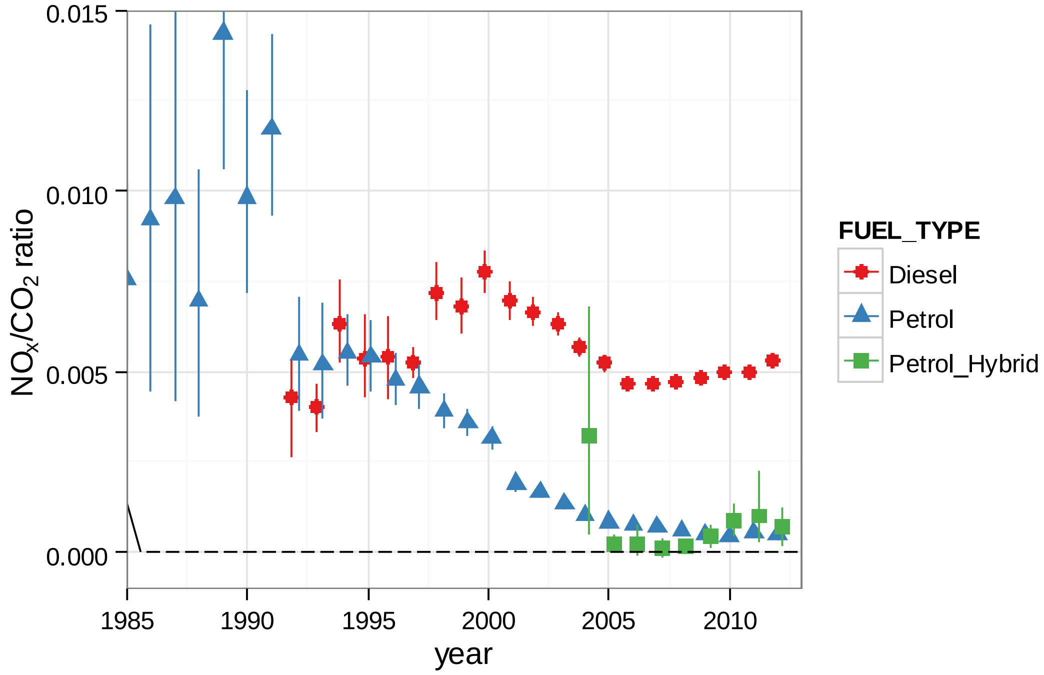

Figure 11 Trends in NO_x/CO_2 emission ratios for passenger cars by year of manufacture.

By contrast, the emissions of NO_x from diesel cars are shown to peak in 2000, decrease by about a third to 2005, but then gradually increase to 2012. Emissions of NO_x from 2012 diesel cars are similar to levels found in vehicles manufactured in the early 1990s.

An important new addition to this study has been the first direct measurement of NO_2 from vehicle exhausts in the UK using the RSD technique. Figure 12 shows the absolute measurements of NO_2/CO_2 for passenger cars. It is clear that petrol vehicles (including hybrids) emit negligible amounts of NO_2 for all years from 1985 to 2012. By contrast, diesel car emissions of NO_2 have increased considerably over the same time frame. Several clear jumps in NO_2 emission are apparent in 1999/2000 (introduction of Euro 3 vehicles) and 2005 (introduction of Euro 4 vehicles). However, emissions of NO_2 from diesel cars in 2012 were higher than for any previous year.

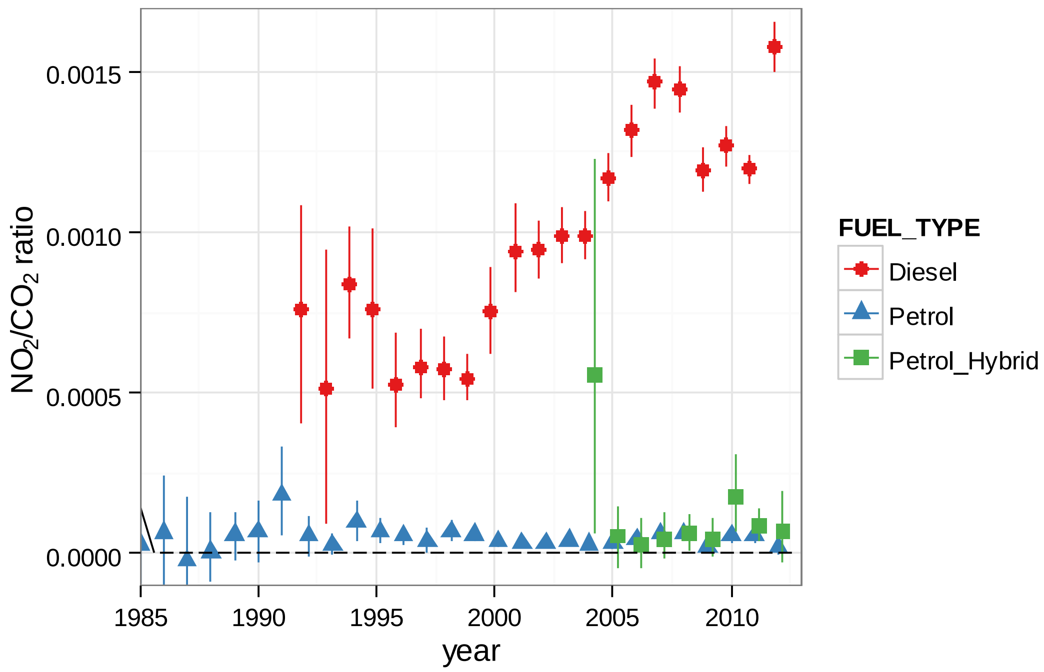

Figure 12 Trends in NO_2/CO_2 emission ratios for passenger cars by year of manufacture.

In terms of the NO_2 expressed as a proportion of NO_x, Figure 13 shows that pre-2000 diesel cars typically emitted around 10% of their NO_x as NO_2, with more recent generation vehicles emitting between 25-30% of their NO_x as NO_2. Note that the results for petrol vehicles are more uncertain for vehicles from the past 5 years or so because total emissions of NO_x are so low.

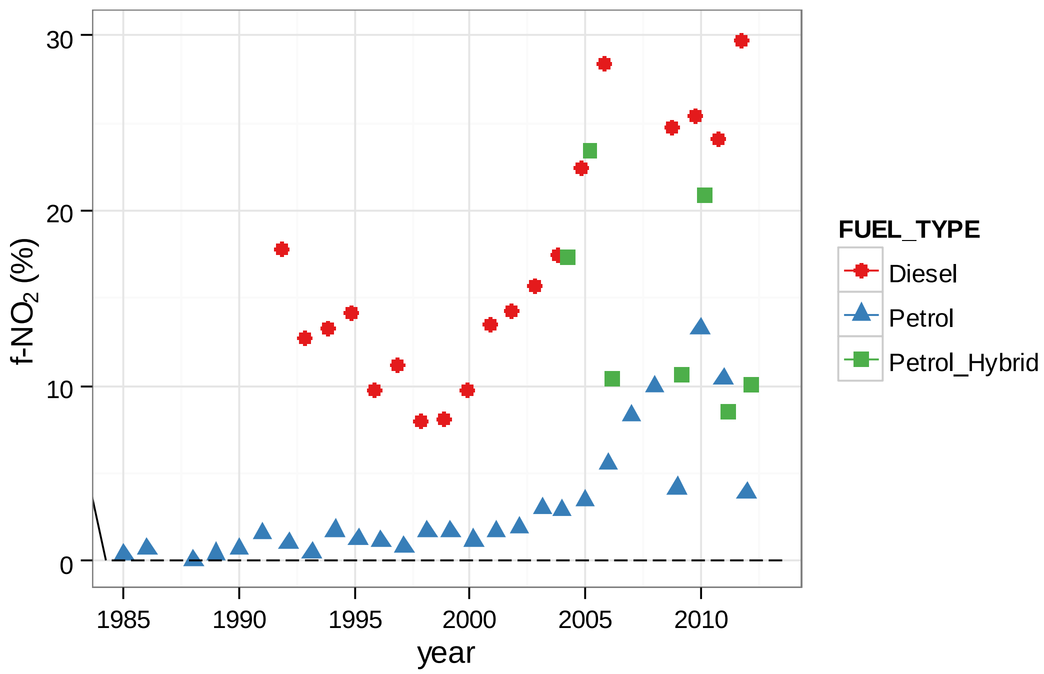

Figure 13 Trends in NO_2/NO_x emission ratios for passenger cars by year of manufacture.

An important contribution made by the RSD is the measurement of ammonia (NH_3). Ammonia emissions are dominated by those from the agricultural sector, but there have been questions over the years concerning the contribution made by road vehicles e.g. Bishop et al. (2010b). Ammonia is important due to its involvement in the formation of secondary inorganic aerosol. From a road vehicle perspective there are two known primary potential sources of ammonia: from catalyst-equipped petrol vehicles and from SCR systems where ammonia is used to reduce emissions of NO_x. The latter is considered in more detail in section 4.2.1 on TfL buses.

Emissions of ammonia from passenger cars are shown in Figure 14. This Figure clearly shows that petrol cars (conventional and hybrid vehicles) emit levels of ammonia that can easily be detected. Emissions peaked around 1992-2000 i.e. early catalyst-equipped vehicles and were very low before 1992 (i.e. for vehicles without 3-way catalytic converters) and have steadily decreased such that emissions for new vehicles (2012) are as low as those for pre-catalyst vehicles. The emissions trend shown in Figure 14 implies that passenger car emissions of NH_3 will continue to decline in future years as older vehicles are removed from the vehicle fleet. It is also clear that emissions from diesel cars are effectively zero, as expected. Taken together, these results are highly consistent in terms of trend and what is known about vehicular sources of NH_3. These emission estimates should be of use to those developing emission inventories where current emission estimates may be highly uncertain.

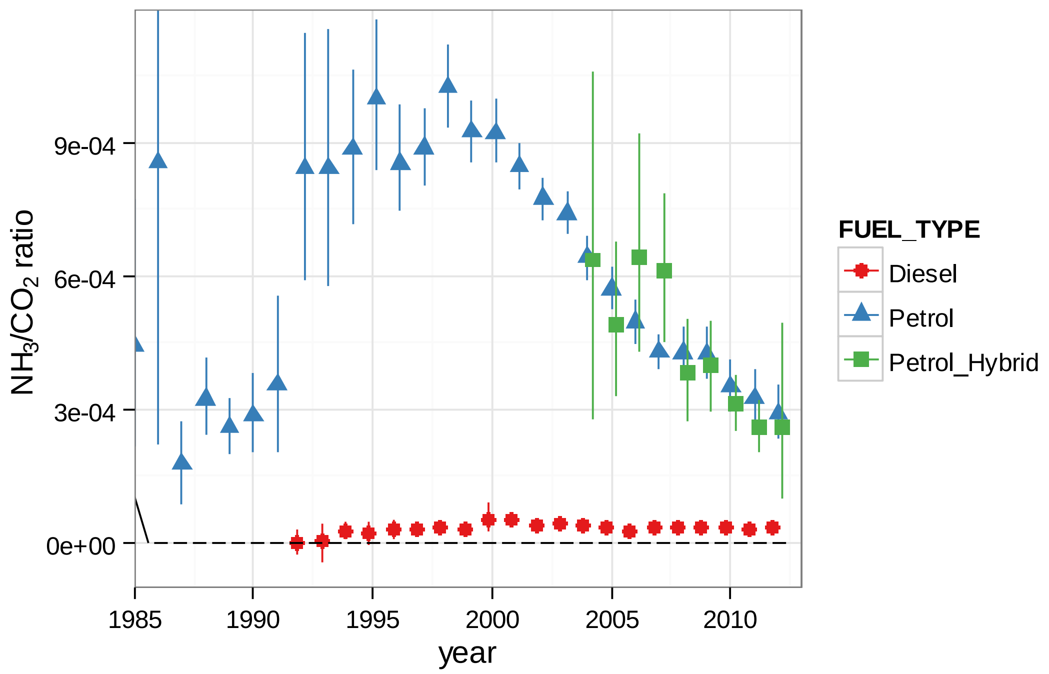

Figure 14 NH_3/CO_2 emissions for passenger cars by year of manufacture.

The results can also be usefully summarised in terms of Euro classification, as shown in Figure 15. Now it is possible to see for example that NO_x emissions from petrol vehicles have decreased considerably through the Euro classes and that those for diesel vehicles peaked for Euro 2/3 vehicles - but Euro 5 NO_x emissions are the same as pre-Euro cars i.e. equivalent to pre-1992 vehicles.

Figure 15 also shows that ammonia emissions are much more important for petrol cars, but have steadily decreased from Euro 1 (first generation catalyst vehicles) to Euro 5.

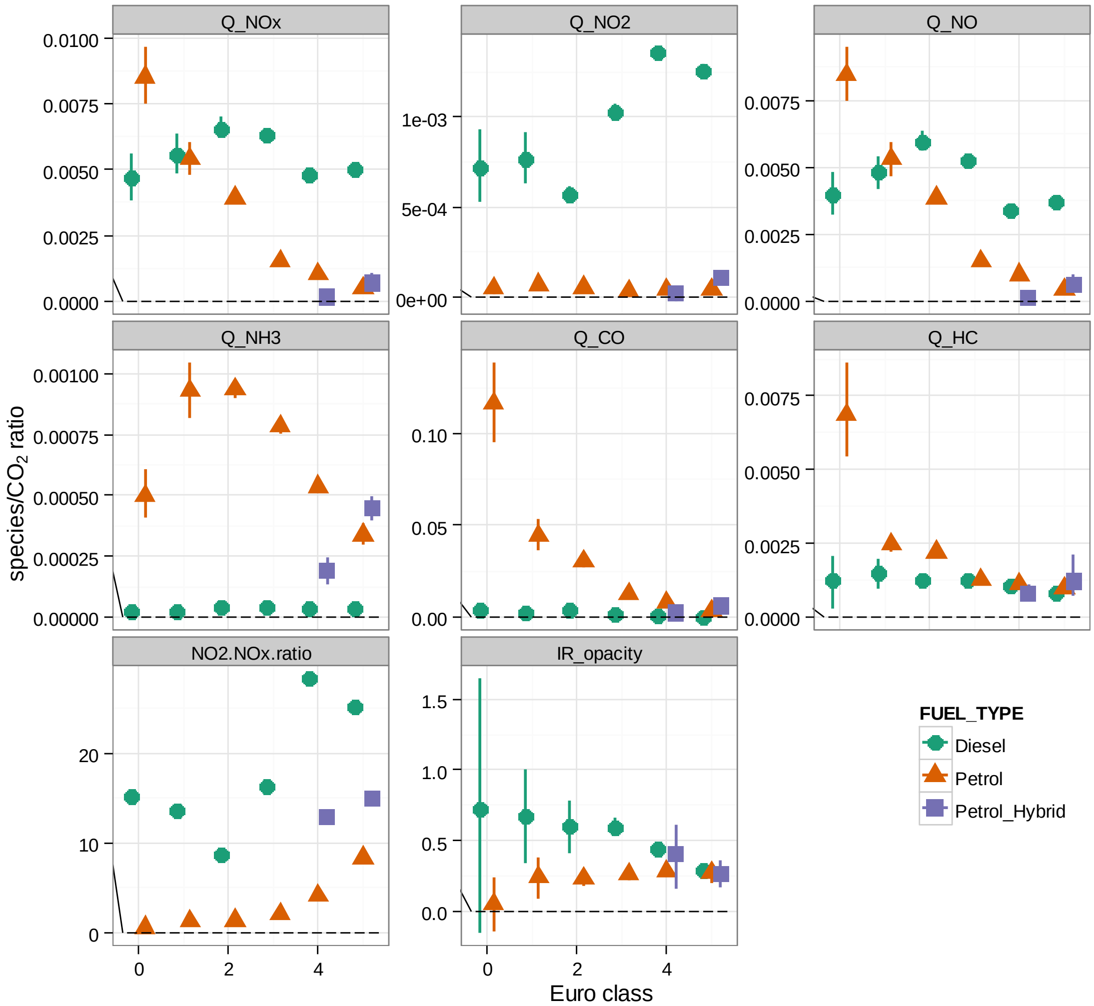

Figure 15 Summary of passenger car emissions by Euro class.

4.1.1 Effect of engine load on diesel car NO_x and f-NO_2 emissions

The concept of Vehicle Specific Power (VSP) has been used widely in recent years to describe the relationship between engine load and exhaust emission rates. (Jimenez-Palacios 1998; Rhys-Tyler and Bell 2012; Carslaw et al 2013). VSP uses measured vehicle speed, acceleration, and road gradient, together with assumed values for vehicle mass and aerodynamic drag, to estimate the power being utilised at the point in time the emissions measurement is taken, usually defined in units of kW/t. Figure 16 illustrates the relationships between VSP and total NO_x emissions for diesel passenger cars, by Euro class, whilst Figure 17 presents the ratio of NO_2 to total NO_x. The figures also illustrate the difference in emissions performance for smaller diesel engines (below 2 litres capacity), and larger diesel engines (greater than 2 litres capacity).

Some interesting observations on the relationships between vehicle dynamics and exhaust emissions of NO_x, NO_2, and NO can be made. Firstly, there appears to be a relatively clear positive relationship between NO_x emissions and positive engine load, over the range of values measured, for Euro 3, 4, and

5 diesel cars. The relationship between NO_2/NO_x ratio and engine load, over the range of values observed, is less distinct. There is a clear positive relationship between the rate of emissions of NO and VSP for Euro 3, 4, and 5 diesel cars, when VSP is positive, over the range of operating conditions surveyed.

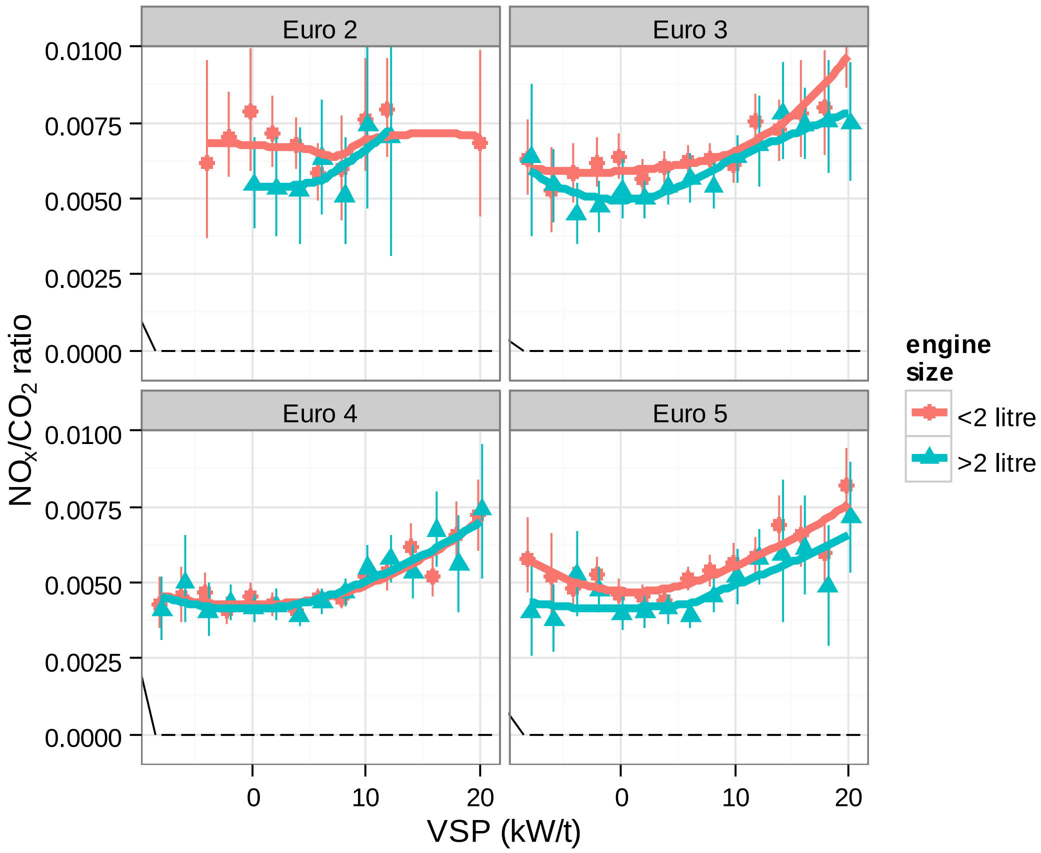

Figure 16 Relationship between vehicle specific power and emissions of NO_x split by Euro class and engine size for diesel cars.

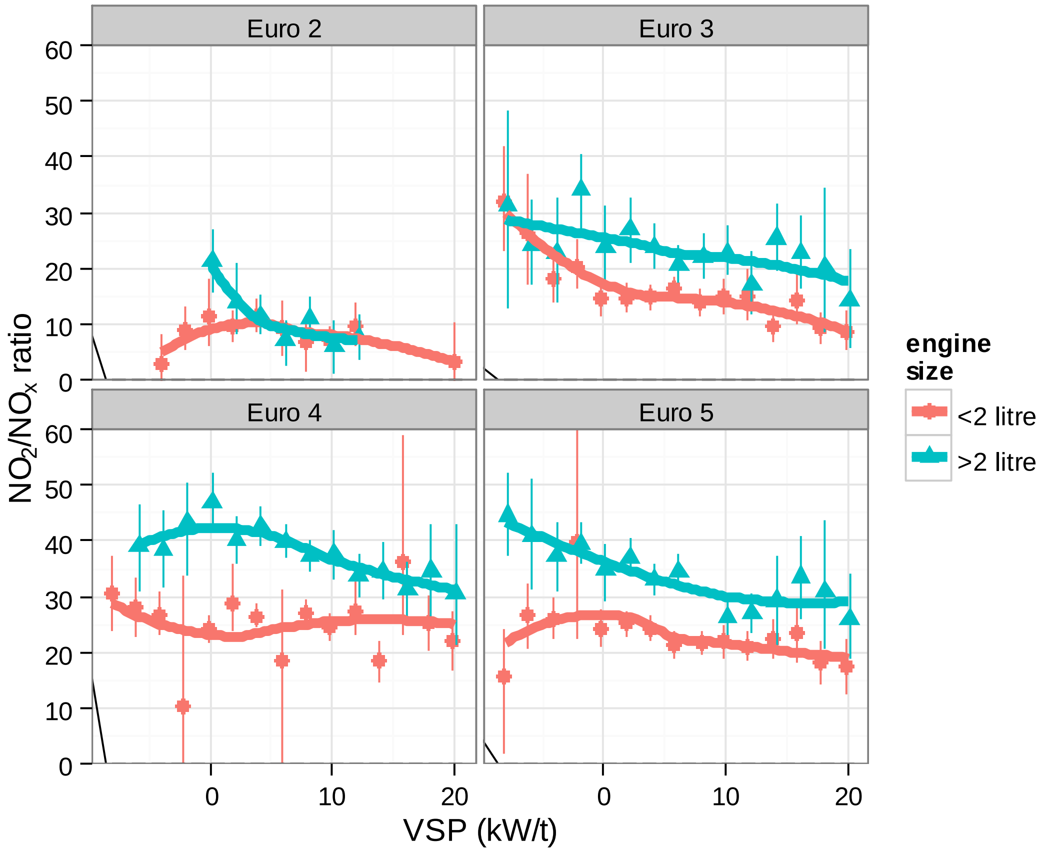

Figure 17 Relationship between vehicle specific power and emissions of NO_2 split by Euro class and engine size for diesel cars.

Secondly, across Euro 3, 4, and 5 diesel cars, absolute levels of NO_2 emissions are higher for larger engine capacities (above 2 litres) relative to NO_2 emissions from smaller engine capacities (less than 2 litres). For NO emissions, the reverse is true, with smaller engine capacities generating higher levels of NO emissions. This is discussed further in the following section addressing variation by manufacturer.

4.1.2 Effect of vehicle manufacturer on diesel NO_x and f-NO_2 emissions

The detailed vehicle information data available enables the results to be categorised by vehicle manufacturer. For Euro 4 vehicles there is generally *very* little variation in the NO_x/CO_2 emission ratio as shown in Figure 18. Note that in this Figure and Figure 19 that manufacturers are only listed if there were at least 30 observations in the data set. Some of the differences may be due to sample sizes as indicated by the error bars. On the whole though there is good consistency for emissions of NO_x.

Figure 19 shows the f-NO_2 values by manufacturer split by Euro classification and engine size for diesel passenger cars. It is apparent from this Figure that there are clear differences by manufacturer, which likely relate to the emissions control equipment used. Indeed, there is much more variation in f-NO_2

emissions than for NO_x, which likely indicates different approaches used for emissions reduction i.e. some result in more oxidation of NO to NO_2. The results are important because they illustrate the range in f-NO_2 values that exist and highlight the potential for reduction in f-NO_2.

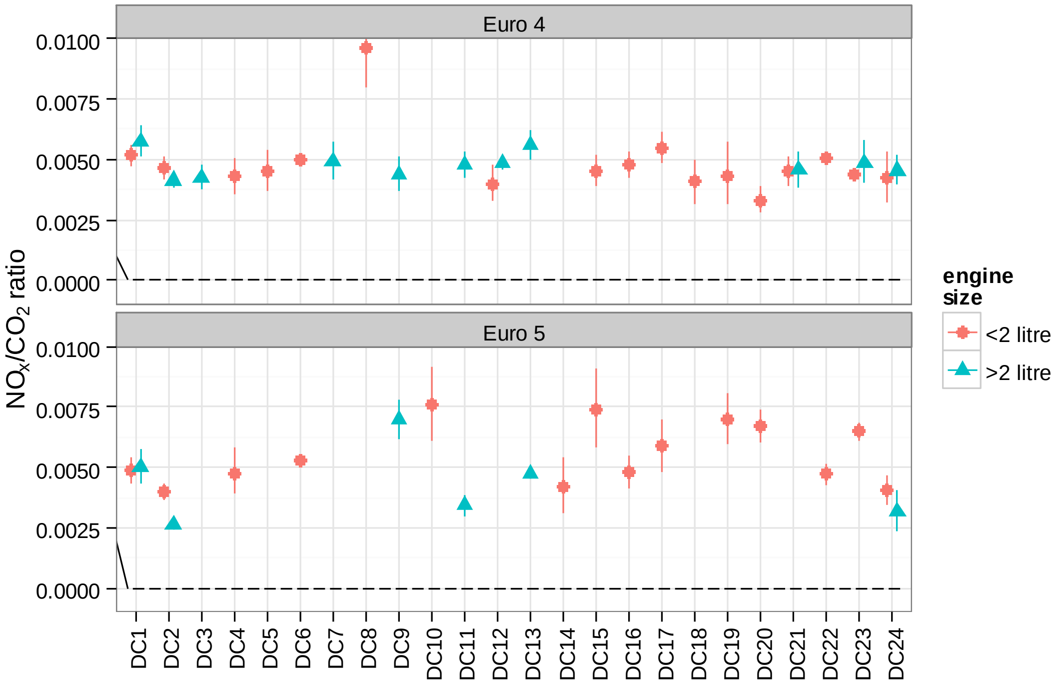

Figure 18 NO_x/CO_2 emissions for diesel cars split by manufacturer, Euro class and engine size.

An important aspect of these results is that they show that certain technologies clearly result in higher (or lower) NO_2 emissions, suggesting there is scope for considerable NO_2 reduction if low f-NO_2 technologies were more widely adopted. The vehicle information data available does not allow for the identification of the specific technologies used by different manufacturers. However, further work to identify the different emission reduction approaches adopted would be recommended.

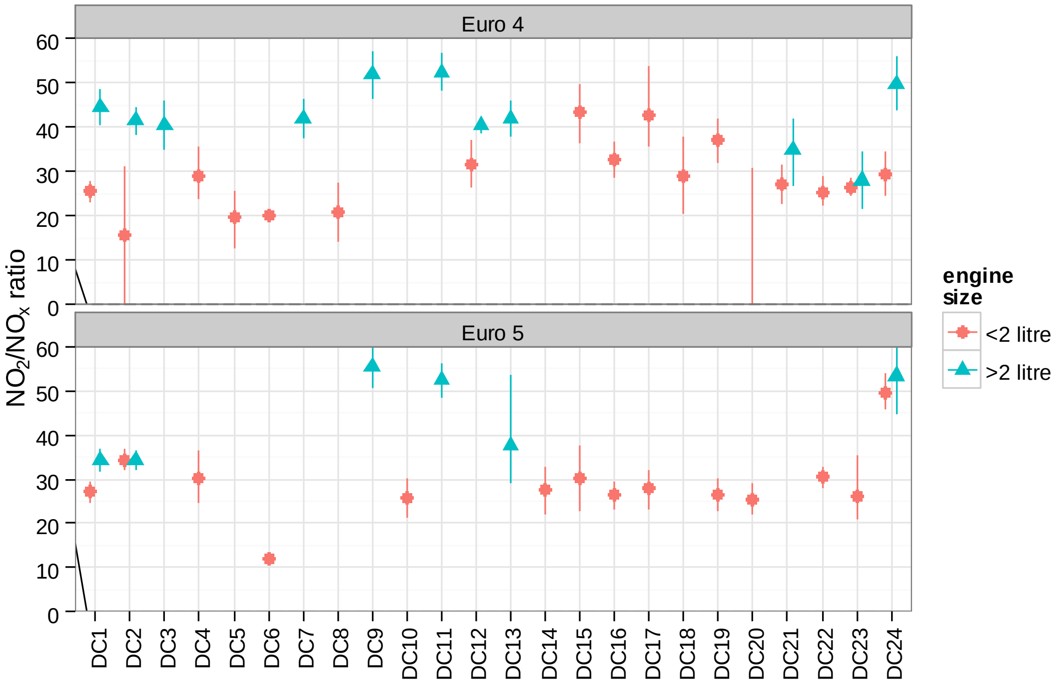

Figure 19 NO_2/NO_x emissions for diesel cars split by manufacturer, Euro class and engine size.

4.2 Buses

4.2.1 TfL Buses

For the bus emissions analysis, detailed data from TfL were used to enhance the analysis of TfL buses (Finn Coyle, Environment Manager, Transport Emissions, personal communication). A key aspect of the data provided was information on the vehicle registration number of over 8,000 vehicles which could be linked directly to the RSD data. Importantly, the data also provided information on the Euro class of the vehicle and the technology used, including whether a bus had a DPF (diesel particulate filter), used EGR (exhaust gas recirculation) or SCR (selective catalytic reduction) and whether hybrid technology was used. In total 1805 TfL buses were measured, of which 371 were unique i.e. a relatively large proportion were sampled multiple times.

It is important to note that the survey results presented in this report for TfL buses fitted with SCR system are ***all*** OEM (Original Equipment Manufacturer) systems. OEM SCR systems have been designed to pass Euro emission standards rather than being optimised for urban-type (i.e. low speed and low engine temperature) conditions. There is evidence elsewhere that such OEM SCR systems are not effective at reducing NO_x under slow speed, urban-type driving (e.g. Velders et al. 2011, Fu et al., 2013). TfL have in recent years developed their own programme of work to optimise SCR systems for use in London. In particular, the introduction of optimised retrofits and new (Euro VI) buses since the time of the surveys considered in this report would be expected to reduce NO_x emissions substantially. No optimised or new buses were measured in this report.

Figure 20 shows the summary emissions by Euro or technology class for all species split by the type of emissions control used (DPF, SCR, EGR and whether a bus has hybrid technology). In terms of NO_x, emissions are shown to peak for Euro IV vehicles with DPF. However, from Euro II to Euro V and EEV[2] vehicles the emissions span a relatively narrow range. In particular, there is little evidence of significant reductions in total NO_x for the newer technology vehicles. Nevertheless, within a particular Euro class, SCR-equipped bus emissions of total NO_x tend to be lower. For example, for Euro IV vehicles, SCR-equipped buses emit a third less NO_x compared with a DPF (non-SCR) equipped bus. Similarly, for the EEV vehicles, those equipped with SCR emit 28% less NO_x compared with the equivalent EGR vehicle. In addition, although the NO_x/CO_2 ratio for hybrids is similar to other technologies, the expected reduction in overall fuel use (CO_2) through using hybrids would result in a commensurate reduction in *absolute* emissions of NO_x expressed in g/km for example.

It should be noted that the emissions of CO and HC from diesel vehicles in general are very low and may often be below the detection limit of the RSD.

[2] Enhanced environmentally friendly vehicle or EEV is a term used in the European emission standards for the definition of a "clean vehicle" > 3.5 tonne in the category M2 and M3. The standard lies between the levels of Euro V and Euro VI.

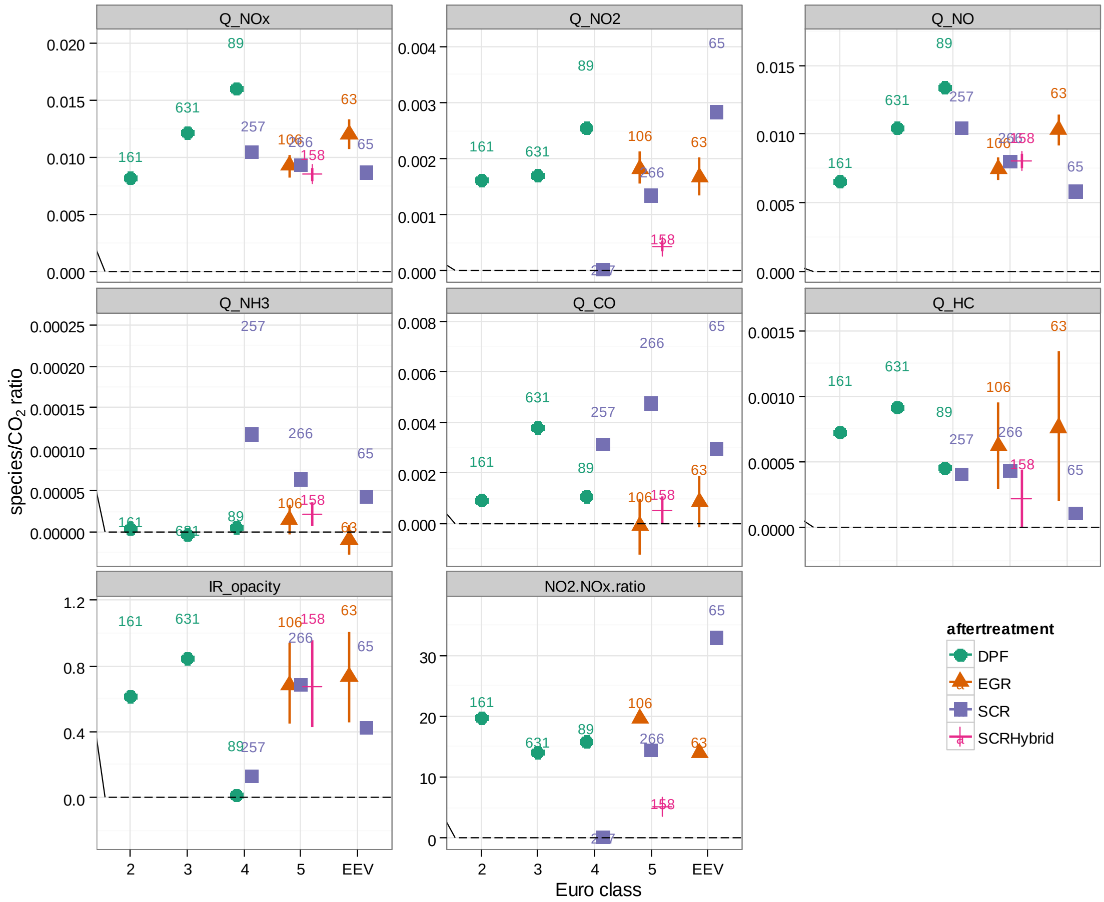

Figure 20 Summary emission results for TfL buses expressed at the volume ratio of emission/CO_2.

The results for NO_2 are more diverse than those for NO_x. The newer SCR-equipped buses (EEV) have the highest NO_2 emission and emit in a similar way to Euro IV vehicles fitted with a DPF. However, the most striking characteristic of the NO_2 results is the wide range of NO_2 emissions for SCR-equipped buses. The older SCR-equipped buses (Euro IV) emit *very* little NO_2 - in fact almost all the emission is in the form of NO. Such low amounts of NO_2 for a diesel vehicle are surprising as they are also much lower than typical engine-out emissions for vehicles without oxy-cats or particle filter (typically around 10-15%). In some respects the results reflect what might be expected from ‘mild reduction’ where NO_2 is reduced to NO but does not go as far as full reduction to N_2.

Euro V vehicles are between these two extremes. One potential cause of the very low NO_2 emissions is the lack of platinum in the catalysts of these vehicles (Finn Coyle, personal communication). Platinum in exhaust catalysts is known to be an important factor in the production of NO_2 in exhaust systems and is used for that reason. In SCR systems NO and NO_2 react with ammonia or urea in the presence of a (non-platinum) catalyst, forming nitrogen and water. Because the SCR reaction is fastest and therefore most efficient when there are equal amounts of the NO and NO_2 a catalyst (commonly using platinum) is needed to form NO_2 in the first place. The higher NO_2 emissions for EEV vehicles are likely related to this issue.

More information can be gained by considering the effects of vehicle manufacturer in the results. Manufacturers can adopt different approaches to emissions control e.g. focussing on reducing engine-out emissions versus post-combustion after-treatment. Indeed, relying only on Euro classification could be misleading because there can be enormous (but consistent) variation in emissions within a particular Euro class. The effect of manufacturer on NO_x emissions is shown in Figure 21, which reveals some important differences between different types of vehicle.

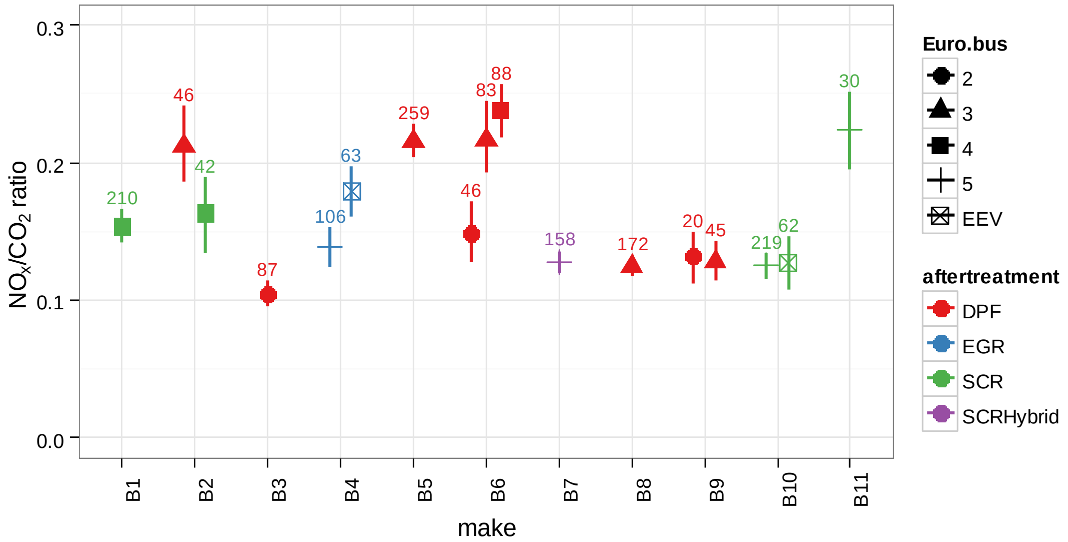

Figure 21 Effect of manufacturer on emissions of NO_x by Euro class and after-treatment.

The effect of manufacturer is however more important for emissions of NO_2, where after-treatment and other effects are more important in controlling emissions. Now it is possible to see some very important differences in the level of NO_2 emission by manufacture as shown in Figure 22.

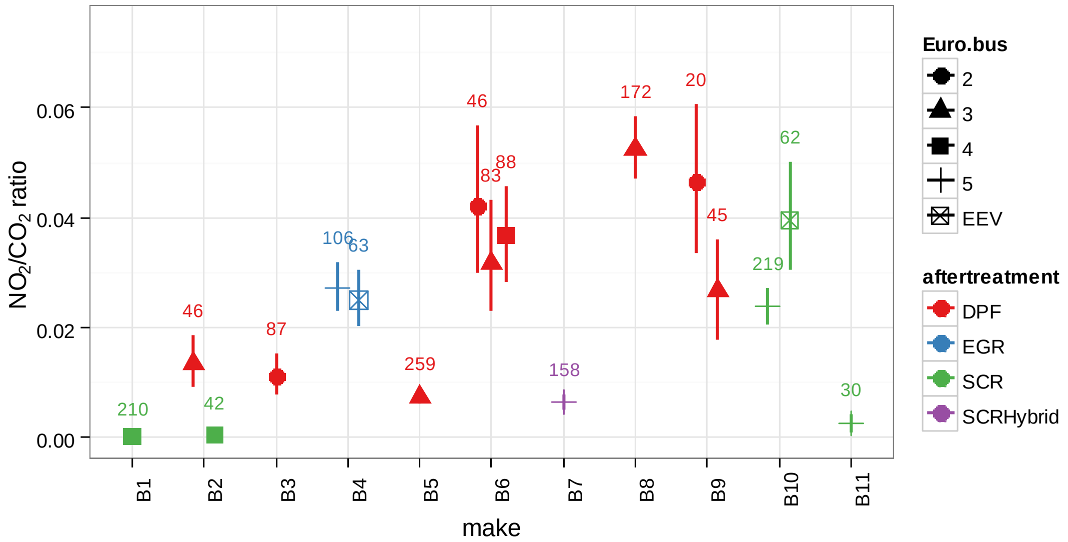

Figure 22 Effect of manufacturer on emissions of NO_2 by Euro class and after-treatment.

One potentially important effect on emissions from SCR vehicles is engine temperature. While engine temperatures were not available, it might be expected that larger-engined buses would have lower temperatures for the same engine load – which could have an effect on the after-treatment efficiency. As shown in Figure 23, there is little effect of engine size on NO_x emissions. However, emissions of NO_2 for the largest buses are considerably higher. It seems therefore that for SCR-equipped large buses there is clear conversion of NO to NO_2 but the conversion does not follow through to much of a reduction in total NO_x. The higher NO_2 for EEV vehicles is likely due to the increases aggressiveness of oxidation of NO to NO_2 to help reduce emissions of CO, HC and PM.

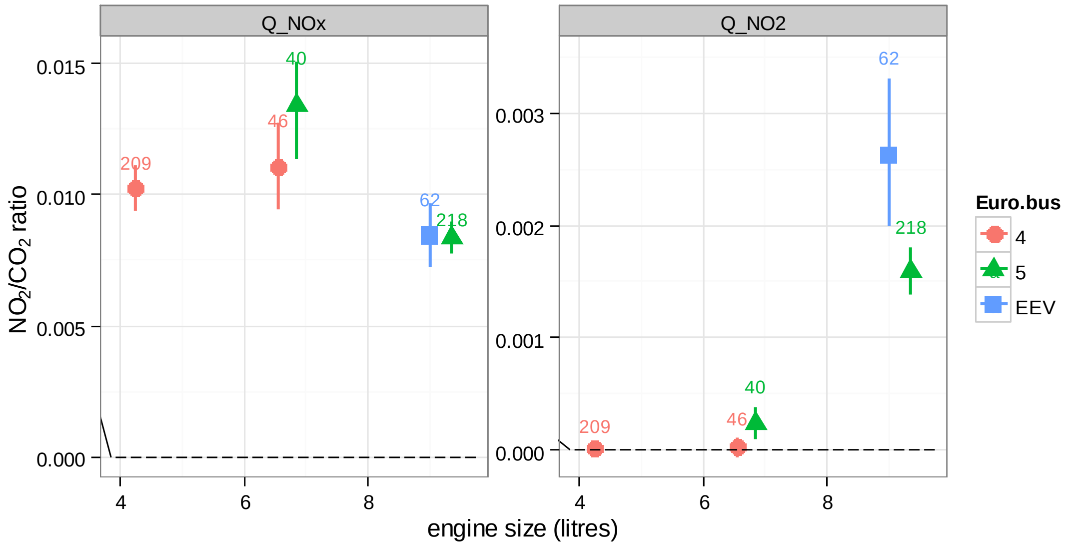

Figure 23 Emissions of NO_x and NO_2 from SCR-equipped TfL buses vs. engine size split by Euro classification.

It should also be stressed that the emission characteristics of vehicles with complex SCR systems are not straightforward to understand and the measurement and analysis of on-road emission characteristics largely absent. These systems are relatively new and have not been well-characterised under urban-type driving conditions. The emissions will be dependent both on the technologies themselves but also how they have been implemented (e.g. how they are combined with other catalysts and particulate filters) and optimised (e.g. whether there has been an attempt to optimise the emissions performance to match the duty cycle of the vehicle). As noted by Heeb et al. (2012), the reactive nitrogen products of such systems can be very dependent on how well controlled the system is and the extent to which the drive cycles is matched to the operation of the SCR system.

Such complexities will become increasingly important for other vehicle types too - it is the availability of RSD data and detailed vehicle information data from TfL that is able to reveal these characteristics for buses, but these issues have wider importance. It is clear that characterising emissions from modern vehicles in general will be an increasingly difficult task. However, describing vehicle emissions in terms of Euro classification alone is inadequate for modern vehicles. Increasingly it will be important to express the emissions in terms of the specific technologies used. However, it can be very difficult to know which technologies a vehicle uses let alone the emission characteristics in sufficient detail and this will pose a significant challenge to those involved with emission inventory development.

4.2.2 Non-TfL buses

In total 782 non-TfL buses were sampled, which indicates that TfL buses made up the majority of all buses sampled (70%). The overall results by Euro class for non-TfL buses are shown in Figure 24. Similar to the TfL buses there is only limited evidence that NO_x emissions have decreased by much from Euro I/II to Euro V. However, it is clear that emissions of NO_2 are much lower for Euro IV and V vehicles compared with older generation vehicles. Indeed, for Euro IV vehicles the proportion of NO_2 in the exhaust is very low and is similar to the older generation SCR-equipped TfL buses. There is some evidence that NH_3 emissions are higher for these vehicles, although the uncertainty is high. However, the results for Euro IV vehicles (TfL and non-TfL) are strikingly similar in that the NO_2 fraction is appreciably lower than other Euro classes – which suggest a common cause. Furthermore, lower NO_2/NO_x ratios are also seen for Euro IV/V HGVs as discussed in section 4.5.

Overall, emissions of NO_x from TfL and non TfL buses are similar at around 0.01 NO_x/CO_2 ratio.

Given that TfL and non-TfL buses will use non-optimised SCR systems, the similarity between the two sets of results is not surprising.

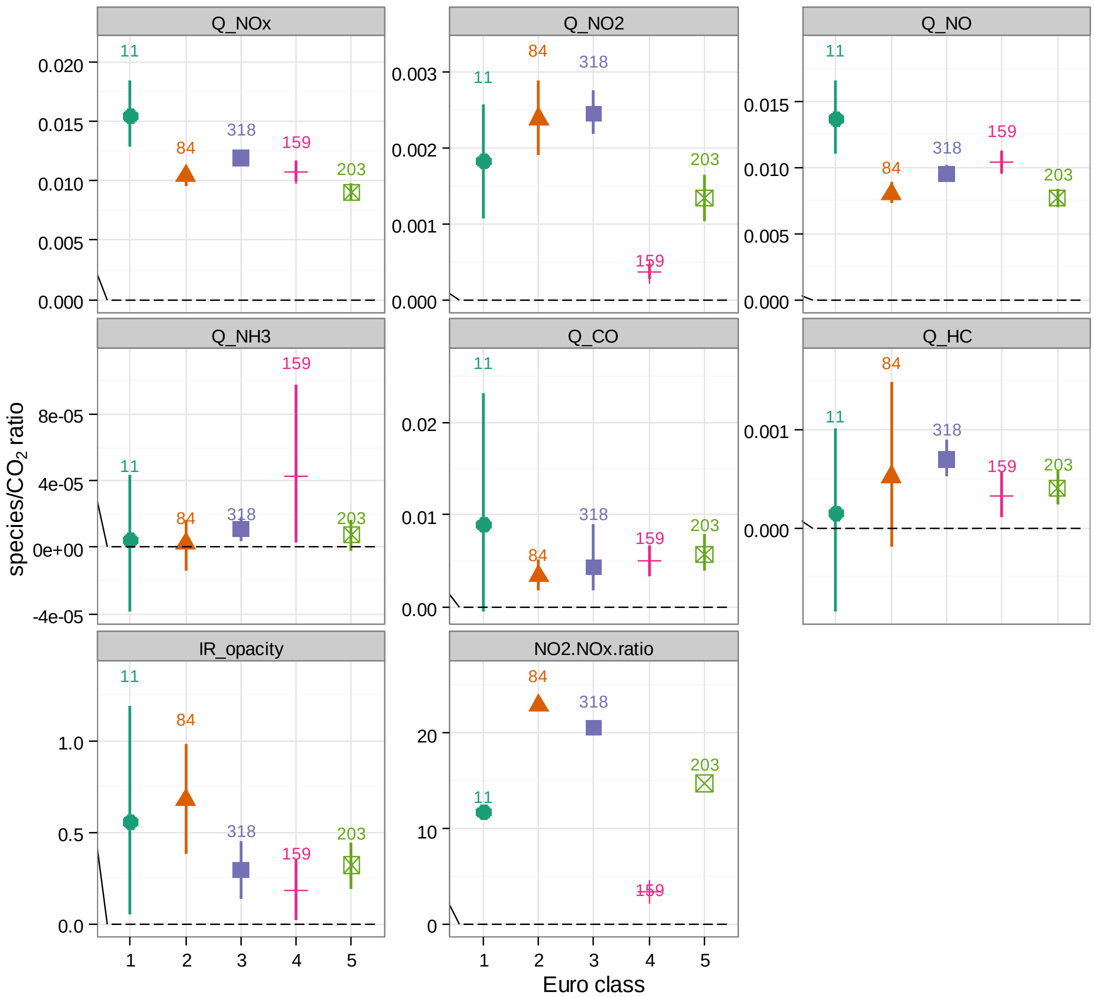

Figure 24 Emissions summary for non-TfL buses.

4.3 London taxis

The locations of the central London survey sites at Aldersgate Street and Queen Victoria Street resulted in a large number of taxis (black cabs) being surveyed. Over 15,000 observations of taxis were made, the majority being LTI TX1, TXII, and TX4 models. As a result of the relatively large sample size, the emissions from taxis can be disaggregated in more detail than most other vehicle types.

Current TfL regulations stipulate that annual licences are only issued to taxis that are under 15 years old and meet Euro 3 emissions standards. This is achieved either by (a) operating a vehicle originally manufactured to Euro 3 standards (or later); (b) retro-fitting approved emissions reduction equipment; or (c) using an LPG conversion. The Mayor has also set out proposals to have a taxi capable of zero emission operation in regular use by 2020. Such a taxi would effectively address all taxi-related local emissions. LTI TX1 models (Nissan engines) were originally manufactured to Euro 2 emissions standards, whereas later LTI TXII models with Ford engines (introduced around 2002) were manufactured to Euro 3 emissions standards. LTI TX4 models with VM Motori engines (introduced around 2006) were originally built to Euro 4 standards, with a Euro 5 compliant version introduced in 2012. Other observed taxi types with much smaller sample sizes include the LTI FX, the Carbodies Metrocab, the Mercedes Vito 111 (Euro 4), and the Mercedes Vito 113 (Euro 5).

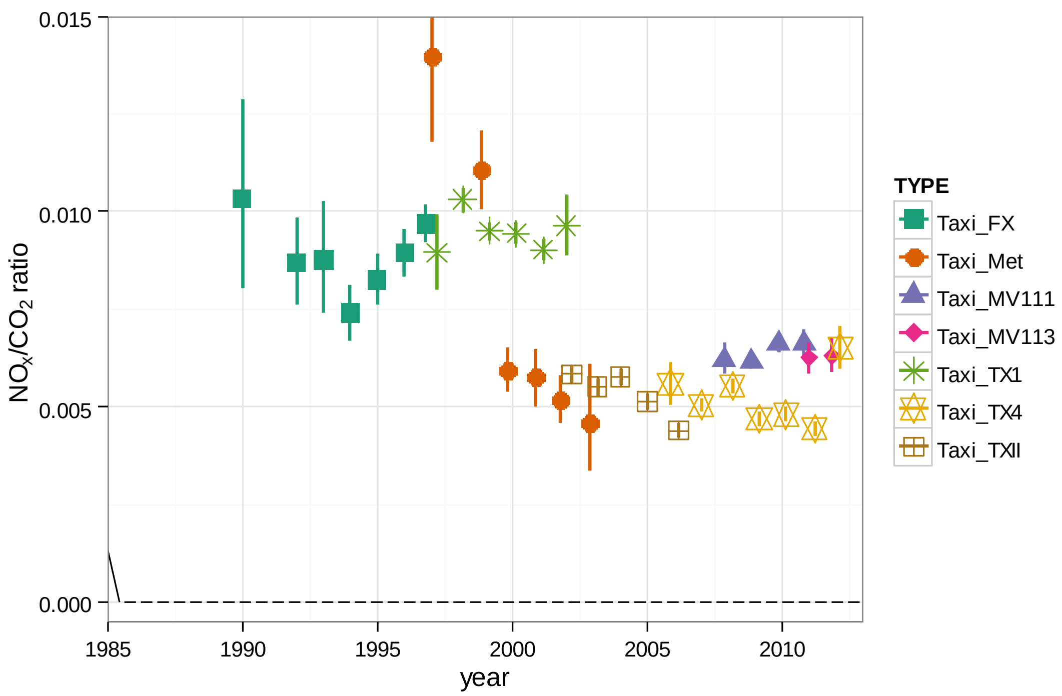

Figure 25 NO_x/CO_2 emissions from London taxis by year.

Previous research based on remote sensing surveys implemented in London in 2008 (Rhys-Tyler et al., 2011) had identified statistically significant changes in both nitric oxide emissions and smoke emissions with the introduction of the LTI TXII and LTI TX4 taxi models. In the transition from the LTI TX1 model to the LTI TXII, it was observed that nitric oxide emissions reduced by more than half; however, at the same time, smoke (particle) emissions (as measured using ultraviolet opacity techniques) were observed to increase around threefold. With the introduction of the LTI TX4 model around 2006, smoke (particle) emissions reduced below the levels of the earlier TX1 model, whilst nitric oxide emissions remained at statistically similar rates to the TXII model.

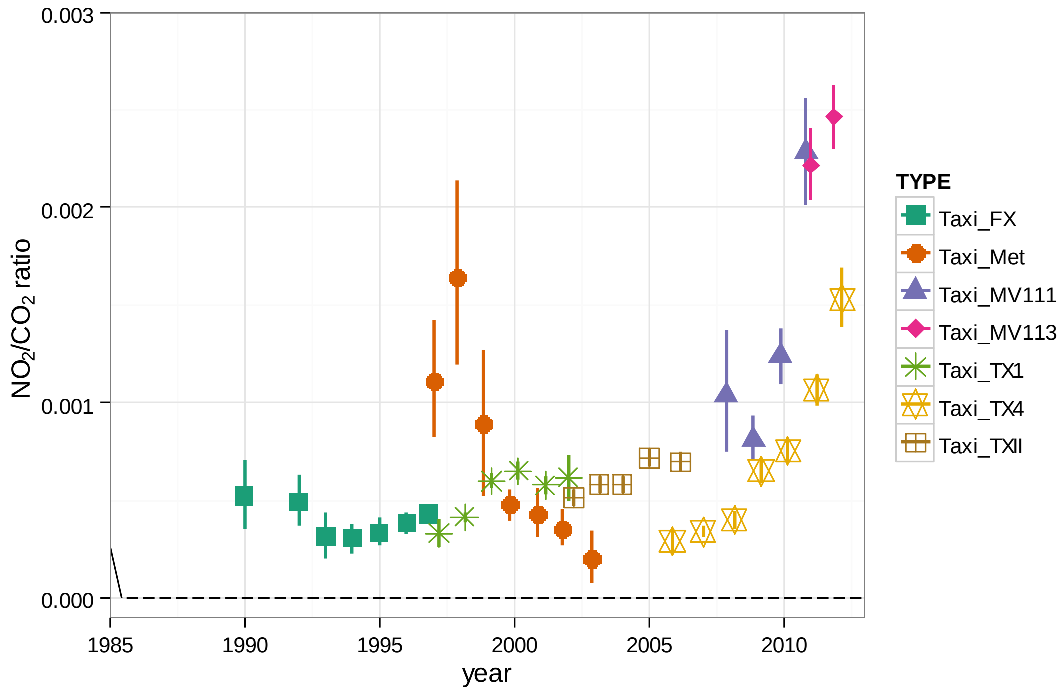

Figure 26 NO_2/CO_2 emissions from London taxis by year.

The patterns observed in the earlier research based on 2008 data are replicated in the 2012 data set, although we now have the advantage of both NO and NO_2 measurements, and a much larger sample size. The plots of NO_x vs. year of manufacture shows clear groupings of vehicles, which broadly split into two categories of higher and lower emissions of NO_x. In terms of significant numbers of taxis, the largest reduction in total NO_x occurred with the transition from the LTI TX1 model (4132 observations), to the LTI TXII model (4050 observations). However, the infrared opacity measurements confirm that smoke (particle) emissions from the LTI TXII model continue to be much higher than from other taxi types, both newer and older.

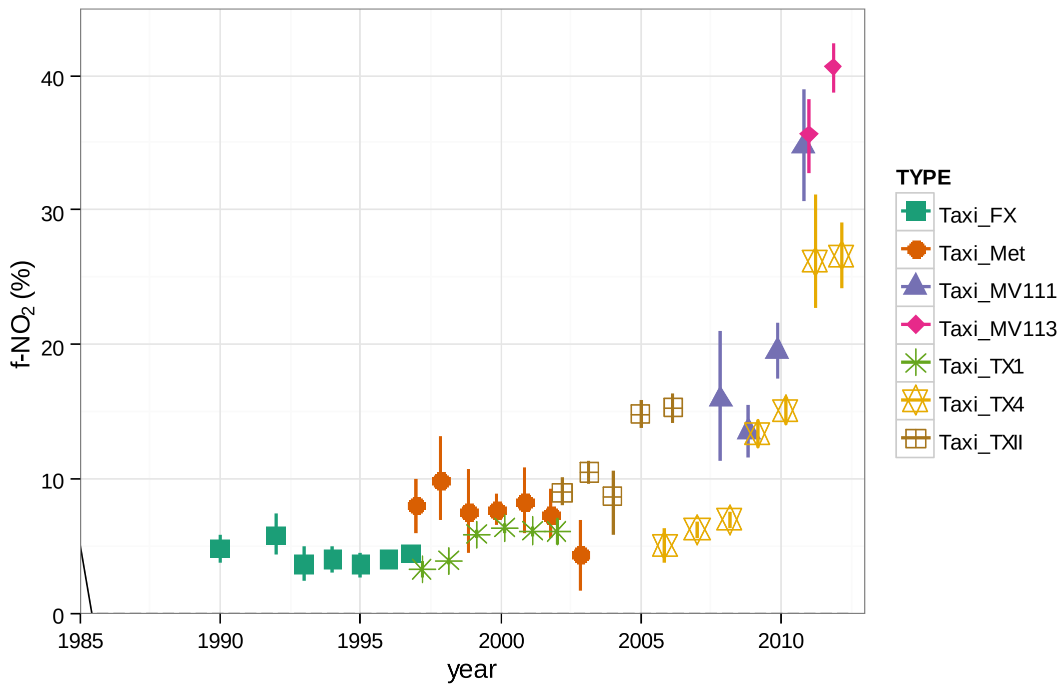

Figure 27 NO_2/NO_x emissions from London taxis by year.

There is a clear indication that absolute levels of NO_2 emissions from taxis manufactured since around 2008 have been increasing. This is true for the LTI TX4, and the Mercedes Vito models. The newest versions of the Mercedes Vito taxis (manufactured in 2011 and 2012) are observed to have the highest absolute emissions of primary NO_2. The fraction of primary NO_2 in total NO_x (f-NO_2) from the taxi fleet is observed to increase significantly for taxis manufactured since around 2009, with substantial variation between manufacturers. Whilst f-NO_2 was typically below 10-12% prior to 2005, LTI TX4 models manufactured in 2011 and 2012 have f-NO_2 values of around 27%, whilst the Mercedes Vito models manufactured in 2011 and 2012 have f-NO_2 values of around 35-40%.

Given the intensity of taxi operations in the centre of London, the increase in levels of NO_2 emissions from the newer taxi fleet is a matter of concern for local air quality management in general, and NO_2 limit values in particular. The high levels of smoke (particle) emissions from LTI TXII taxis also warrants further investigation. Both of these issues should be taken into consideration when developing future policy for taxi emissions. The technologies adopted by manufacturers require further investigation to gain a full understanding of the generation processes for total NO_x, f-NO_2, and particulate matter, with a view to minimising the pollutants of concern in future vehicles.

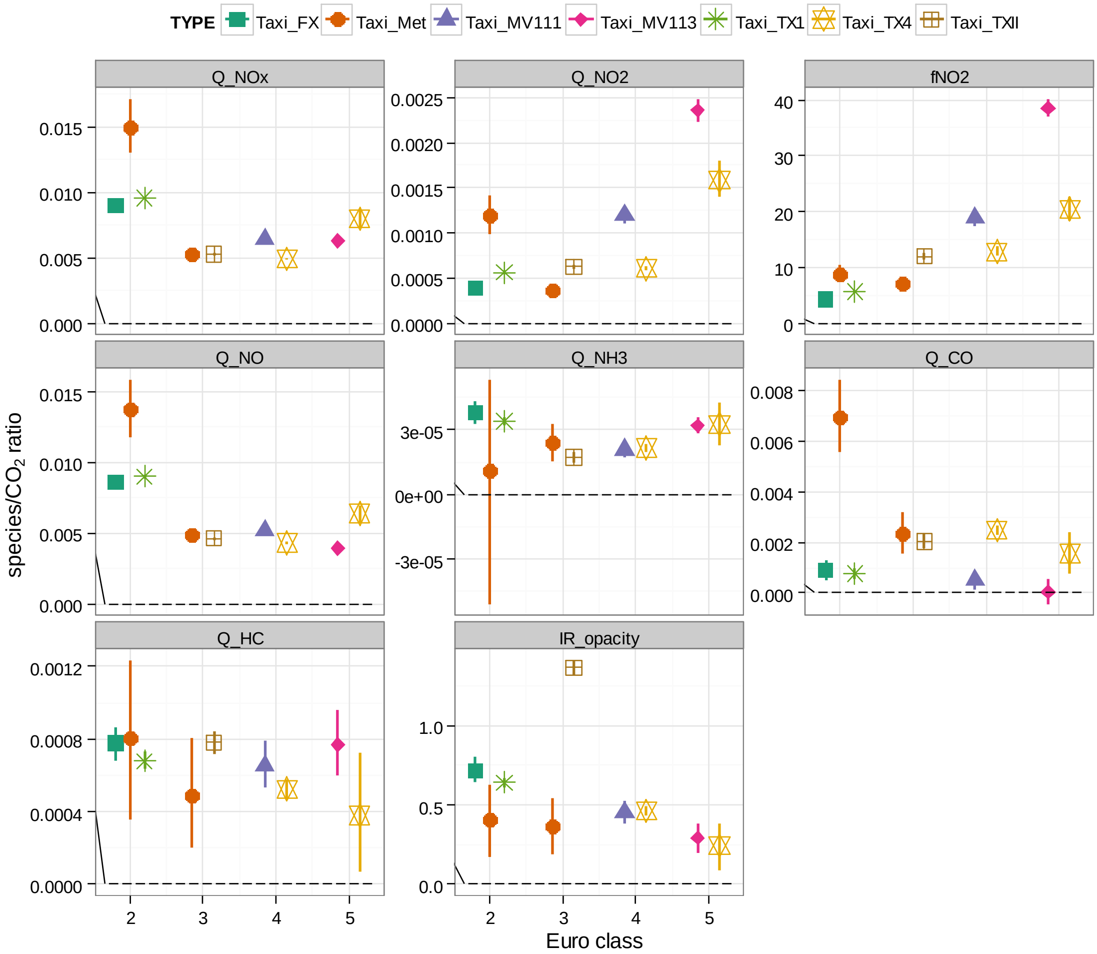

Figure 28 Summary emissions from London taxis by Euro class.

4.4 Vans (N1 diesel only)

Vans (N1 goods vehicles with a gross mass of up to 3.5 tonnes) comprise a large proportion of the UK vehicle fleet and vehicle kilometres driven. At the four survey locations, the proportion of vans was between 15% and 22% of total traffic flow. Of these, between 94% and 99% were diesel powered, with a small proportion of petrol fuelled vehicles. Diesel vans (N1) at Euro IV and Euro V were observed to emit between 4% and 9% more total NO_x than the equivalent diesel passenger cars, with similar observed proportions of primary NO_2.

A reduction in total emissions of NO_x is observed in the transition from Euro III to Euro IV which is similar to that observed for diesel passenger cars. However, this reduction is driven by a reduction in the NO component of total NO_x (reduced by 36%); the NO_2 component is observed to actually increase by 69%. This results in a step change in the fraction of primary NO_2 (f-NO_2) in total NO_x from 12% to 27%, as illustrated in Figure 29.

The observed reduction in the NO component of total NO_x in the transition from Euro III to Euro IV (36%) in the 2012 surveys is consistent with the reduction observed previously in the 2008 surveys (42%).

Based on the infrared opacity measurements, smoke emissions from diesel vans are observed to decline with each successive Euro class from Euro II onwards (observed Euro I vehicles were limited by a very small sample, and may not be representative).

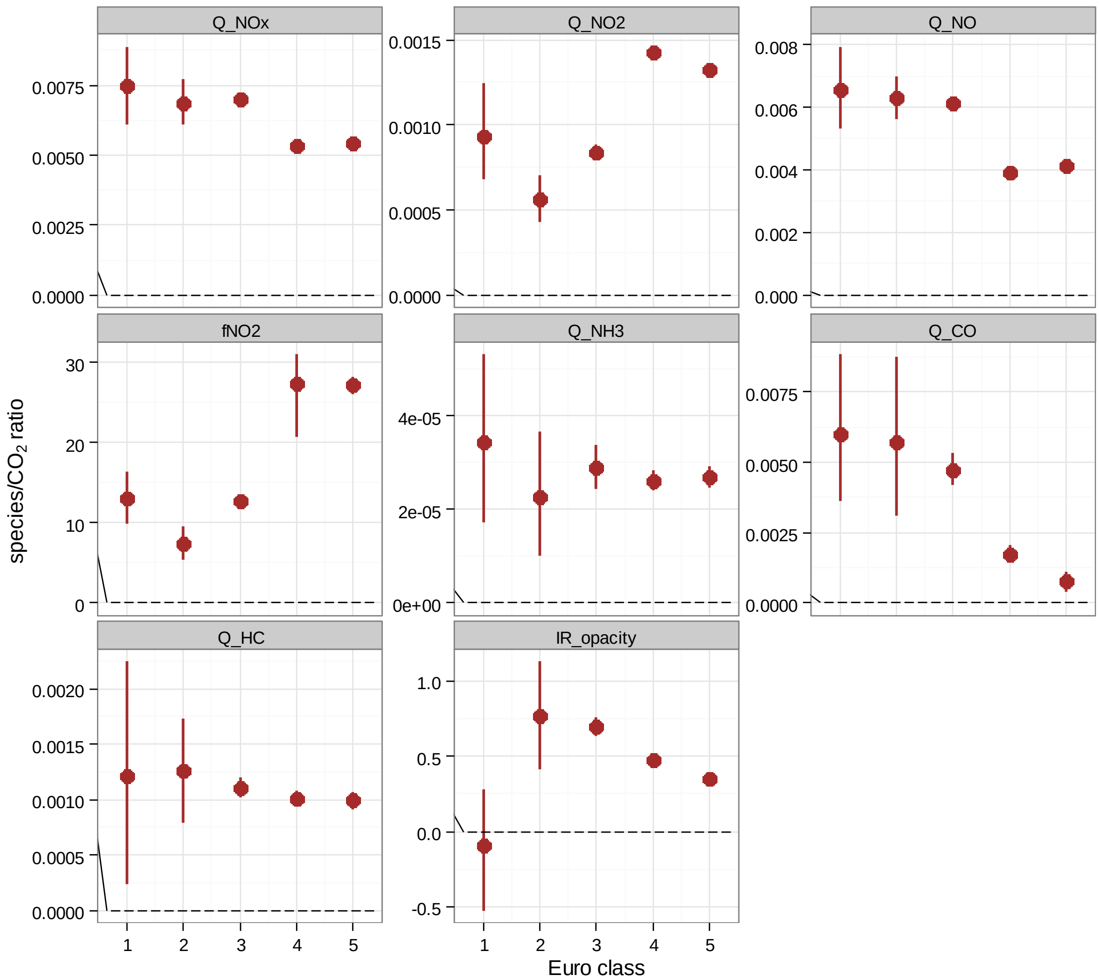

Figure 29 Summary emissions from diesel vans (N1) by Euro class.

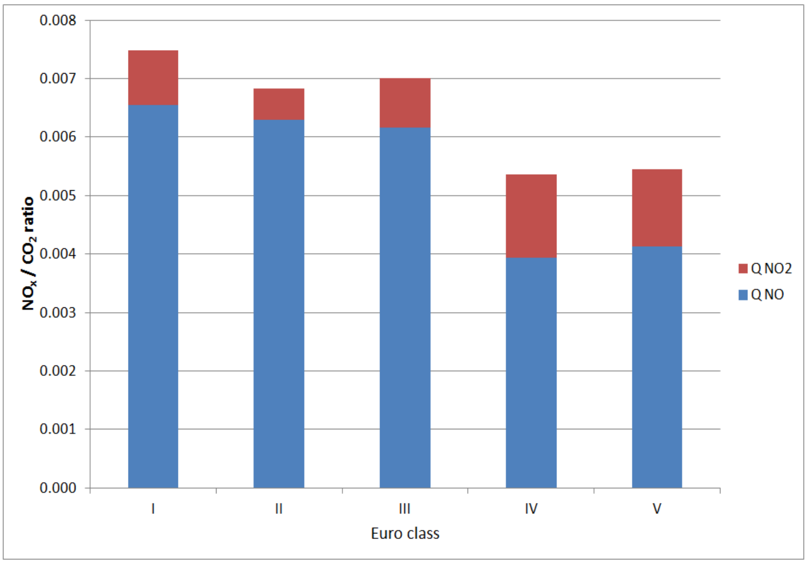

Figure 30 Ratio of total NO_x to CO_2 for diesel vans (N1) by Euro class

4.5 Medium and Heavy Goods Vehicles (N2 + N3)

The HGV vehicle class has been split into two main categories: N2 (HGVs from 3.5 to 12t) and N3 (HGVs >12t). In total 791 N2 vehicles were sampled and 568 N3. The results in this section are shown separately for each vehicle class.

The main emission results for HGVs are shown in Figure 31 by Euro class and Figure 32 by year of manufacture. Overall, we observe very little change in NO_x emissions from Euro II to Euro V. However, there does appear to be a step change reduction in the emission of NO_2 for Euro IV/V vehicles, dropping from around 15-20% NO_2/NO_x to 5 to 10%. This change is difficult to explain because the details of the emissions systems used on these vehicles are not available. However, there are similarities with the TfL bus results for SCR-equipped vehicles where almost all the NO_x was in the form of NO; particularly for the larger HGVs (N3). It is possible that there is a similar effect for HGVs where there is a mix of SCR and non-SCR equipped vehicles and the overall effect is to reduce the proportion of the NO_x that is NO_2 but which does not affect overall emissions of NO_x appreciably. However, there is no obvious effect on emissions of NH_3 which might be expected if SCR was important. It is also worth noting that the smaller HGVs (N2) tend to be associated with higher levels of NO_2.

There appears to be a similar effect for both Medium Goods Vehicles (N2) between 3.5 and 12 tonnes, and for Heavy Goods Vehicles (N3) greater than 12 tonnes. In both cases, the f-NO_2 is observed to reduce at Euro IV and Euro V. Total NO_x emissions are generally consistent from Euro III to Euro V, with the NO component increasing.

The sample size achieved in the remote sensing surveys for Medium and Heavy Goods Vehicles is substantially smaller than most of the other observed vehicle types. It should also be recognised that the vehicle fleet operating in London will be influenced by the presence of the Low Emission Zone.

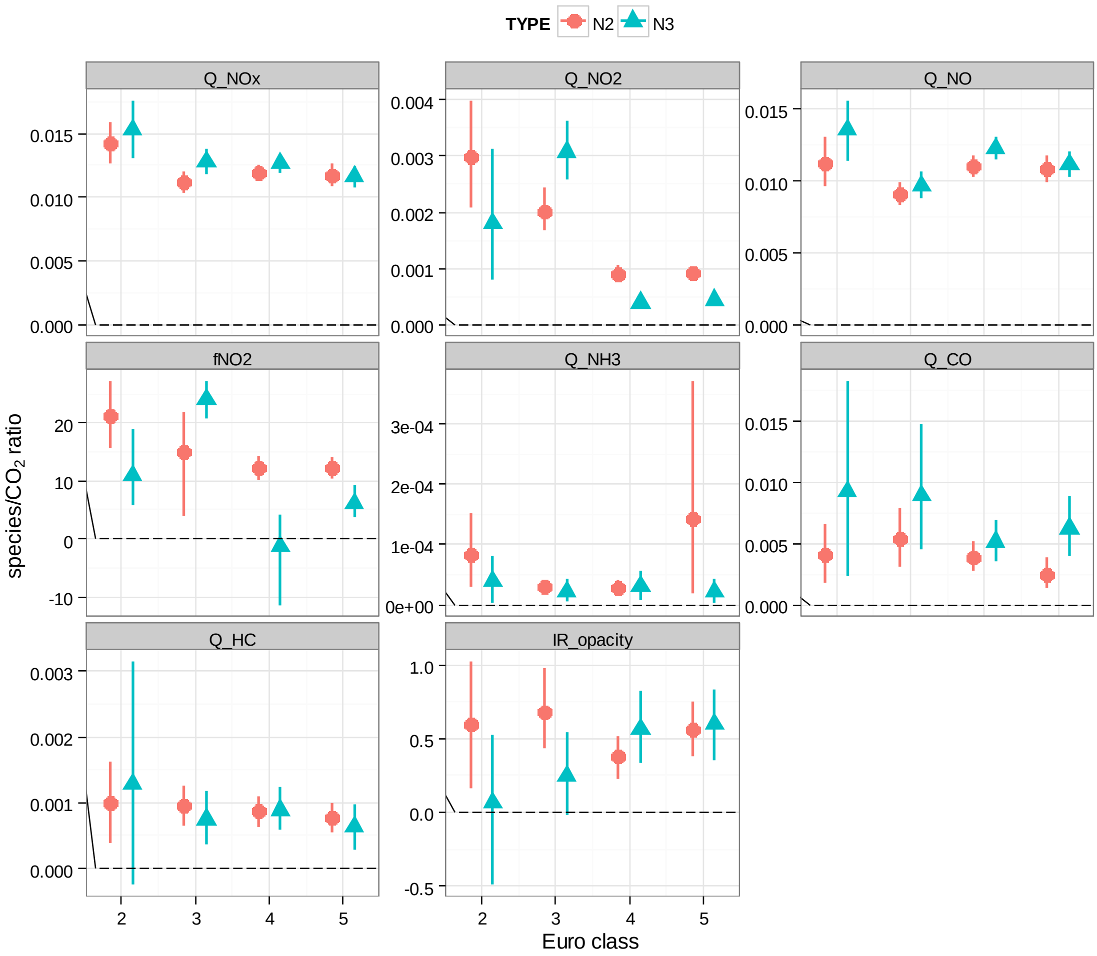

Figure 31 Summary emissions from HGVs (N2 and N3) split by Euro class.

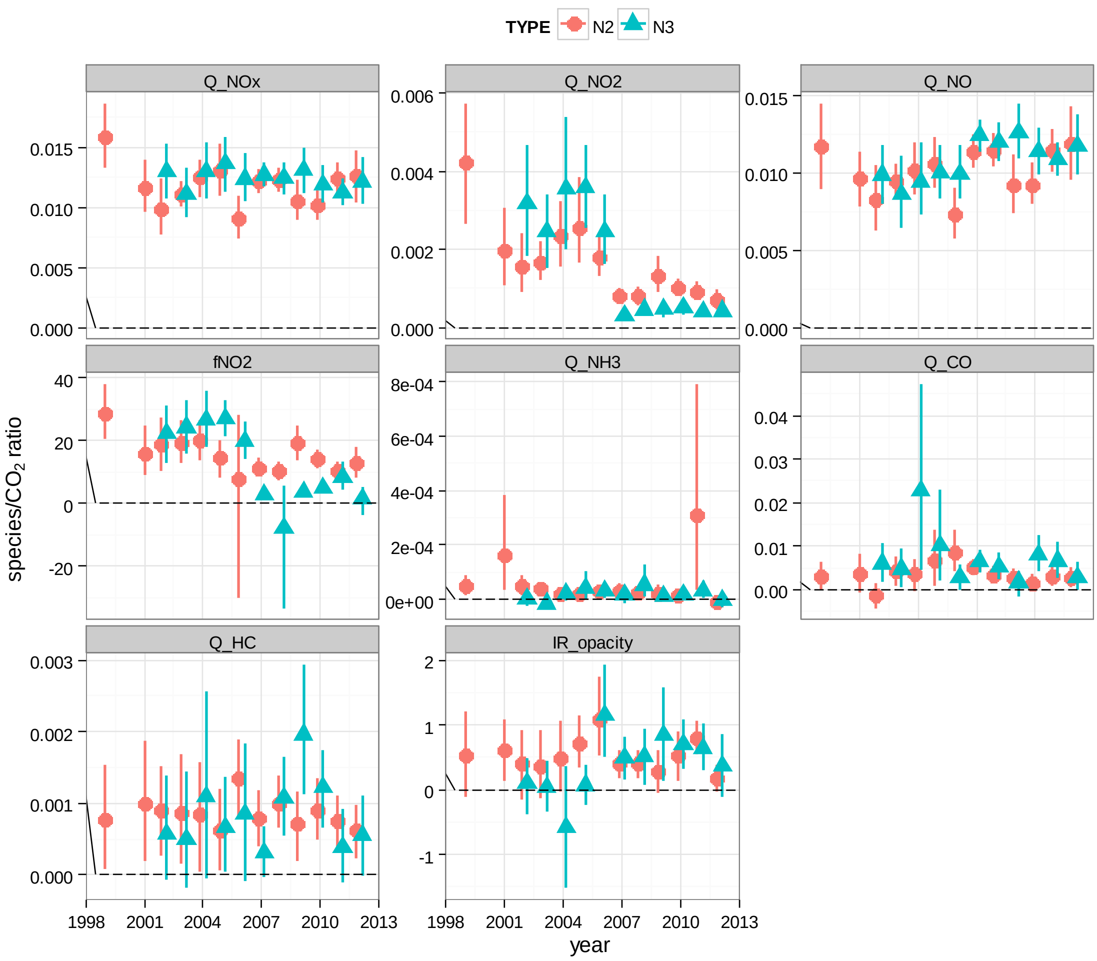

Figure 32 Summary emissions from HGVs (N2 and N3) split by year of manufacture.

4.6 Motorcycles

The results for motorcycles (L3 type only) are shown by year in Figure 33. In total 848 motorcycles were sampled. There is some limited evidence that NO_x emissions have decreased from these motorcycles over the past 10 years or so. The level of emissions of NO_x when expressed as a ratio to CO_2 is similar to diesel cars. However, the clearest evidence for reductions in emissions is for CO and HC where emissions reduced from 2005 to 2006 based on the year of manufacture. Interestingly, there has been a gradual increase in NH_3 emissions from motorcycles over the past decade. This is probably due to the catalytic converters designed to reduce regulated emissions from motorcycles that produce ammonia emissions as a by-product of catalytic conversion.

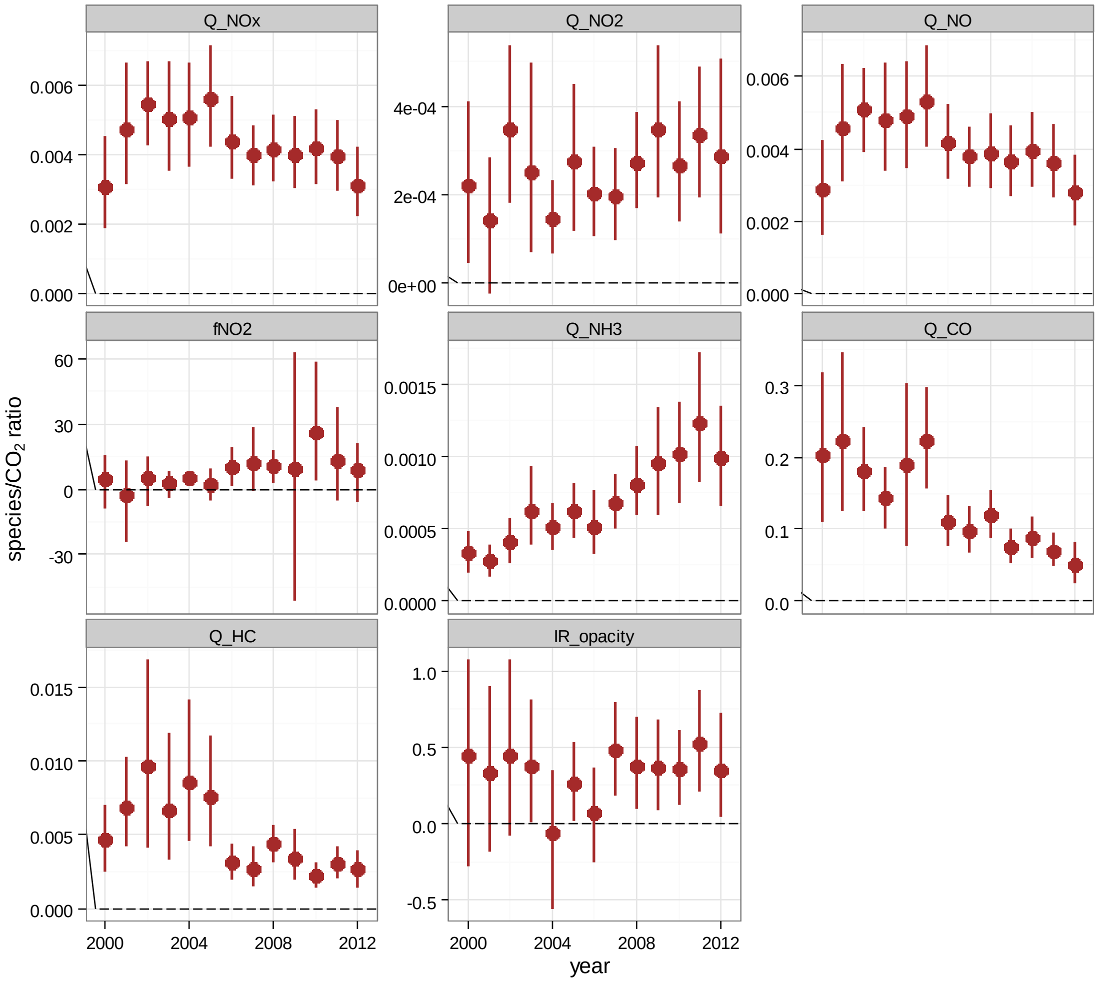

Figure 33 Summary emissions from motorcycles (L3) by year of manufacture.

4.7 Comparison of vehicle emissions across survey sites

As discussed earlier, the survey sites were selected in the local authority partner areas based on four main criteria; (a) site safety and logistics; (b) traffic composition; (c) a repeat of a subset of 2008 sites to identify trends in fleet composition and emissions; and (d) site characteristics including likely vehicle speeds and accelerations. The four survey sites selected were:

a) A1 Aldersgate Street, City of London (southbound).
b) Queen Victoria Street, City of London (eastbound).
c) A4127 Greenford Road, Ealing (southbound).
d) A40 Target Roundabout, Ealing (westbound on-slip).

Aldersgate Street and Queen Victoria Street are central area locations in the City of London where large numbers of taxis and buses operate, where traffic density and congestion is high, and where vehicle speeds are expected to be low. A 30mph speed limit applies, but traffic congestion and spacing between junctions mean that observed speeds are generally lower. The estimated road gradient at the Aldersgate Street survey site was -0.50 degrees, whereas the estimated road gradient at Queen Victoria Street was +0.93 degrees.

Greenford Road in Ealing has a more suburban character, still with a 30mph speed limit, but with greater distances between junctions, and lower traffic densities. The fleet mix will differ compared to the City of London survey locations, with far lower volumes of taxis (black cabs) in particular. Greenford Road was also one of the locations surveyed using remote sensing in 2008. The estimated road gradient at the Greenford Road survey site was +1.19 degrees.

The A40 Target Roundabout slip road was chosen primarily for its higher speeds. The speed limit is 50mph. Vehicles are generally accelerating (uphill) to join the A40 westbound. The estimated road gradient at the A40 Target Roundabout slip road survey site was +0.94 degrees.

Table 4 presents a summary of the observed mean vehicle speeds and accelerations at each survey location.

Table 4 Summary of observed mean vehicle speeds and acceleration by survey location

Location	**Number of speed measurements**	**Mean speed mph (Std. Dev.)**	**Mean speed m/s (Std. Dev.)**	**Number of acceleration measurements**	**Mean acceleration m/s^2 (Std. Dev.)**
Aldersgate St.	6445	17.6 (3.4)	7.85 (1.5)	6445	+0.30 (0.71)
Queen Victoria St.	16292	18.1 (3.6)	8.09 (1.63)	16292	+0.17 (0.69)
Greenford Rd.	17692	25.3 (5.4)	11.33 (2.42)	17692	-0.15 (0.77)
A40 slip road	8590	37.4 (6.0)	16.72 (2.67)	5653	+0.24 (0.43)

As expected, mean vehicle speeds at Aldersgate Street and Queen Victoria Street were broadly comparable at around 18mph. Acceleration rates at Aldersgate Street were marginally higher.

Mean vehicle speed at Greenford Road was 25mph, but mean acceleration was marginally negative (with a relatively wide standard deviation). This may have been due to the proximity of upstream junctions at Windmill Lane and King's Avenue.

Mean vehicle speed at the A40 slip road survey location was 37mph with a positive mean acceleration. The relatively small standard deviation associated with the acceleration value is due to the reduced scope for high positive acceleration values as speed increases, together with the lack of congestion related interactions with other vehicles to generate deceleration events.

The frequency distributions of vehicle speeds across the four survey sites are presented in Figure 34 below in the form of a box plot. It can be seen that there is no overlap in the interquartile ranges of the two central area sites (Aldersgate Street and Queen Victoria Street), and the two other sites at Greenford Road and the A40 slip road.

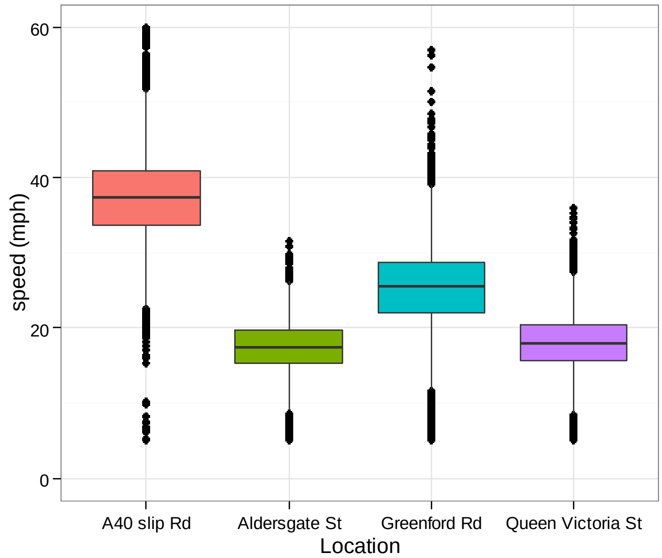

Figure 34 Box plot of observed vehicle speed by survey site.

The consequence of variability in speed and acceleration by survey site is that the calculated vehicle specific power (VSP kW/t) also varies by location. Figure 35 below presents the variation in VSP across survey sites in terms of percentiles. As is to be expected, the VSP values calculated at the A40 slip road are significantly higher than the other sites because of the higher speeds encountered. It is notable that the lower (indeed negative) acceleration values measured at Greenford Road have skewed the distribution of VSP at this site.

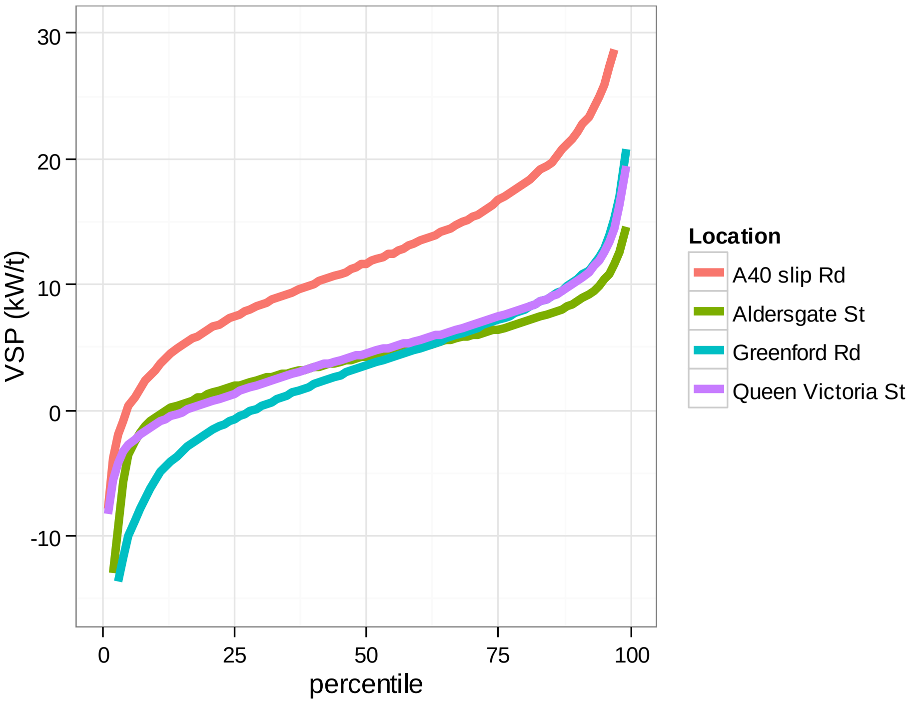

Figure 35 Frequency distribution (percentiles) of VSP by survey site

Figure 36 illustrates the relationship between VSP and total emissions of NO_x for Euro 4 and Euro 5 diesel passenger cars, across the four survey locations. Generally speaking, the 95% confidence intervals for most VSP bins for each survey site overlap, indicating that a diesel car engine under a particular load will emit similar levels of NO_x emissions, independent of location. However, such conclusions should be treated with caution, since a particular value of VSP can be generated by various combinations of factors influencing engine load (including speed, acceleration, gradient, mass etc.). It would be desirable in future surveys to collect data across wider ranges of variables (especially higher speeds) to investigate such issues more thoroughly. In addition, other site / survey specific factors may influence the results (such as instrument calibration, ambient atmospheric conditions, ambient temperature influencing engine operation and use of vehicle ancillaries etc.)

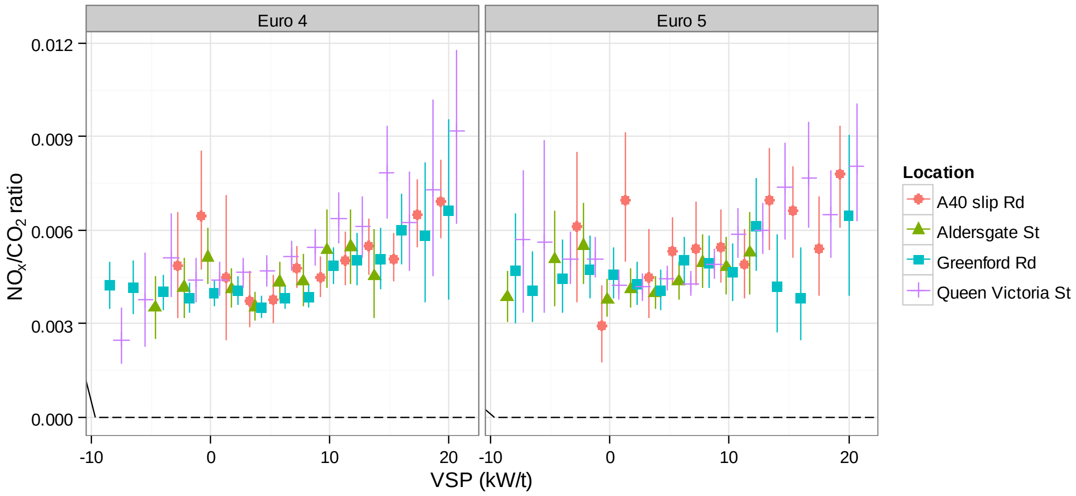

Figure 36 Variation in NO_x/CO_2 emissions with VSP by location and Euro class for diesel cars.

However, the most significant difference between the survey locations which influences aggregate traffic related emissions, including NO_x and NO_2, is fleet composition. The wide variation in fleet composition across the four survey locations, in terms of vehicle type, fuel type, and Euro emissions class, will have a significant influence on the nature of the aggregate exhaust pollution emitted locally. A fundamental difference relates to the split between diesel fuelled vehicles and petrol fuelled vehicles. At Aldersgate Street and Queen Victoria Street, between 86% and 88% of observed motorised vehicles were diesel powered. In contrast, at Greenford Road, 42% of vehicles were diesel powered. At the A40 slip road, 51% of vehicles were diesel powered. Given that diesel engines are the primary source of NO_x and NO_2 (particularly relative to the much lower emission rates from petrol engines), such significant differences in the proportion of diesel engine vehicles on the local highway network will result in significant differences in the aggregate traffic related emissions of total NO_x and NO_2, for a given level of traffic flow.

Appendix C presents the absolute and relative percentages of vehicles for each survey location, by vehicle type, fuel type, and Euro class.

At Aldersgate Street and Queen Victoria Street, between 39% and 44% of total observed motorised traffic flow were taxis; at Greenford Road and the A40 slip road, taxis (black cabs) comprised less than 0.5% of motorised traffic.

At Aldersgate Street and Queen Victoria Street, around 8% of total traffic flow were petrol cars; at Greenford Road and the A40 slip road, petrol cars made up between 47% and 56% of motorised traffic.

The overall consequence of this variation in fleet mix, speed, and acceleration is that the mean emission rate per average vehicle passing through each of these survey locations varies significantly, the total emissions being the product of the mean emission rate and the number of vehicles passing through the site. Figure 37 presents the mean NO_x emission rate per vehicle by survey location, whilst Figure 38 presents the mean opacity measurements (indicative of the emission rates for particulate matter).

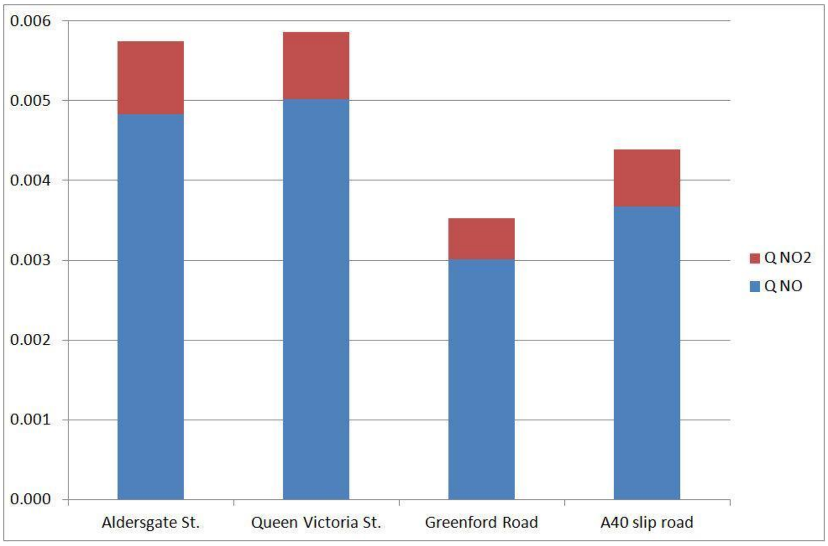

Figure 37 Mean NO_x emission rate per vehicle by survey site.

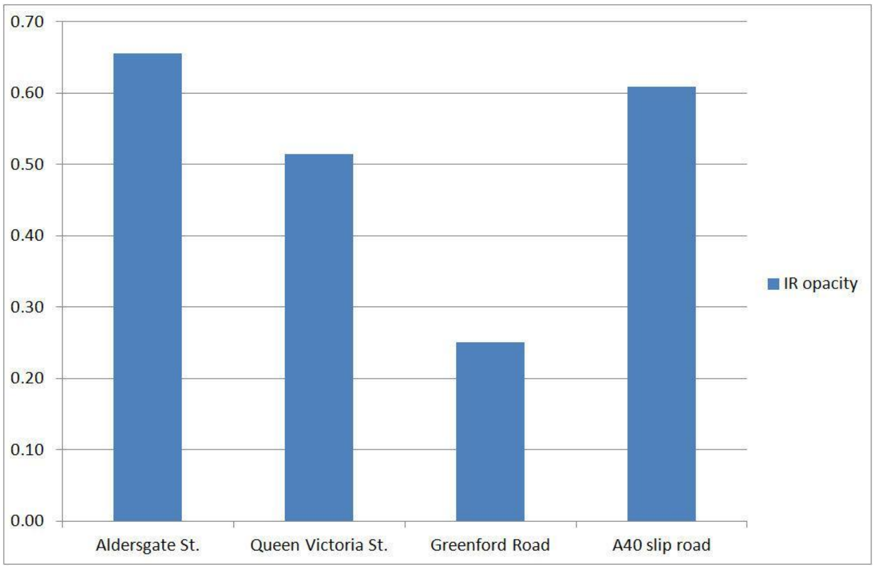

Figure 38 Mean infrared opacity (particulate matter) per vehicle by survey site.

4.8 Trends in fuel consumption and implications for NO_2 emissions in urban areas

Exhaust emissions in the current study have been generally reported in terms of ratios of pollutant to CO_2 observed in the exhaust plume, which can be converted into units of grams of pollutant per unit of fuel consumed. However, if we wish to calculate the absolute amount of pollutant being emitted into the atmosphere, we need to consider the amount of fuel being burnt.

Taking diesel passenger cars as an example, we can estimate the urban fuel consumption by year of manufacture from the observed 2012 fleet by utilising the published urban fuel consumption figures (derived from VCA data). The average urban fuel consumption for diesel cars by year of manufacture, as observed in the 2012 surveys, is presented in Figure 39.

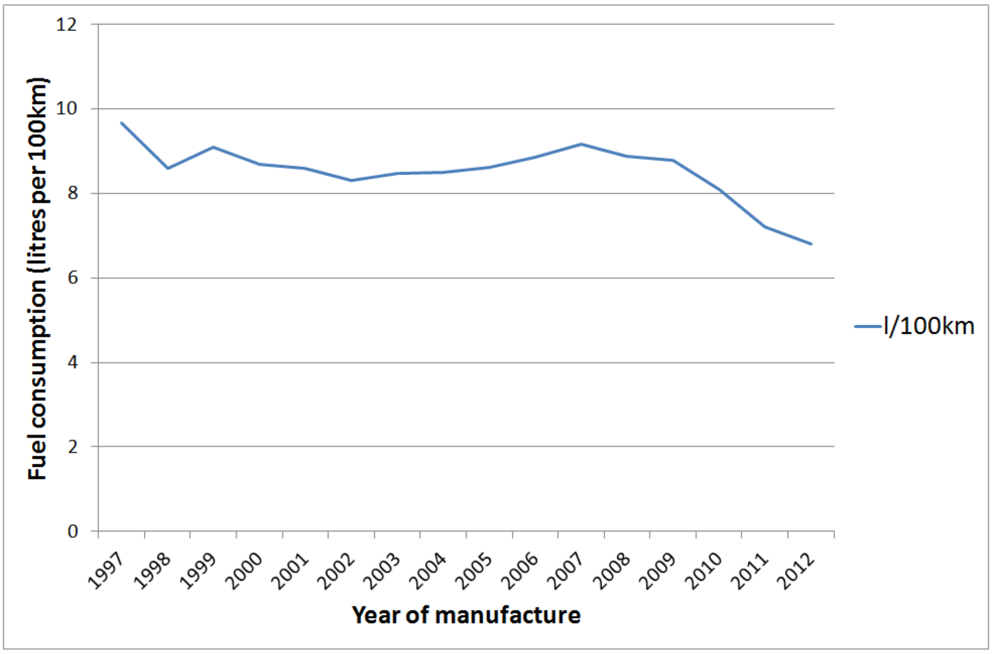

Figure 39 Average urban fuel consumption (litres per 100km) for observed diesel cars by year of manufacture

It can be seen that urban fuel consumption (based on published type approval figures) was relatively stable for vehicles manufactured in the period 1997 to 2009, but since 2010 fuel consumption has reduced. We can use this data to estimate the amount of pollutant emitted per unit distance travelled.

Figure 40 presents the rate of NO_2 emitted per kg of fuel consumed, and the rate of NO_2 emitted per 100km travelled (urban). This assumes that a litre of diesel weighs a nominal 0.835kg (broadly correct at 15°C). Figure 41 and Figure 42 present similar comparisons for NO and total NO_x respectively.

As expected, it can be seen that the improvement in average fuel consumption from 2010 onwards serves to mitigate to some extent the absolute levels of pollutant emissions from diesel cars manufactured in these years.

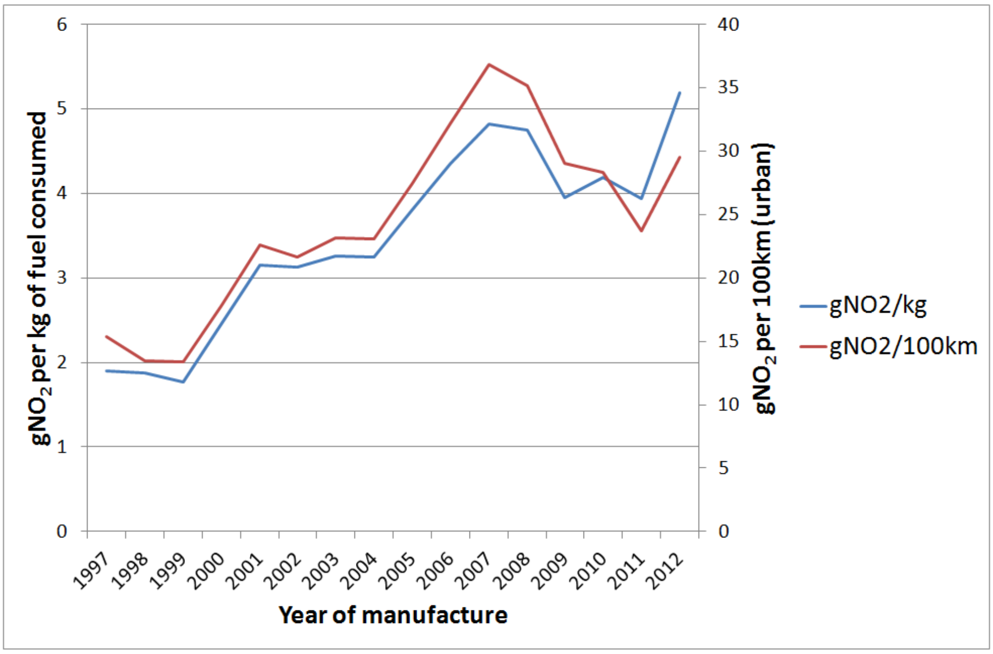

Figure 40 Comparison between mean NO_2 emissions per kg of fuel, and mean NO_2 emissions per 100km for observed diesel cars

With reference to Figure 40, the increase in mean NO_2 emissions from vehicles manufactured in 2012 is reduced slightly when we take improvements in average fuel consumption into account, but there is still an absolute increase in mean NO_2 from these vehicles, compared to vehicles manufactured in 2009, 2010 or 2011.

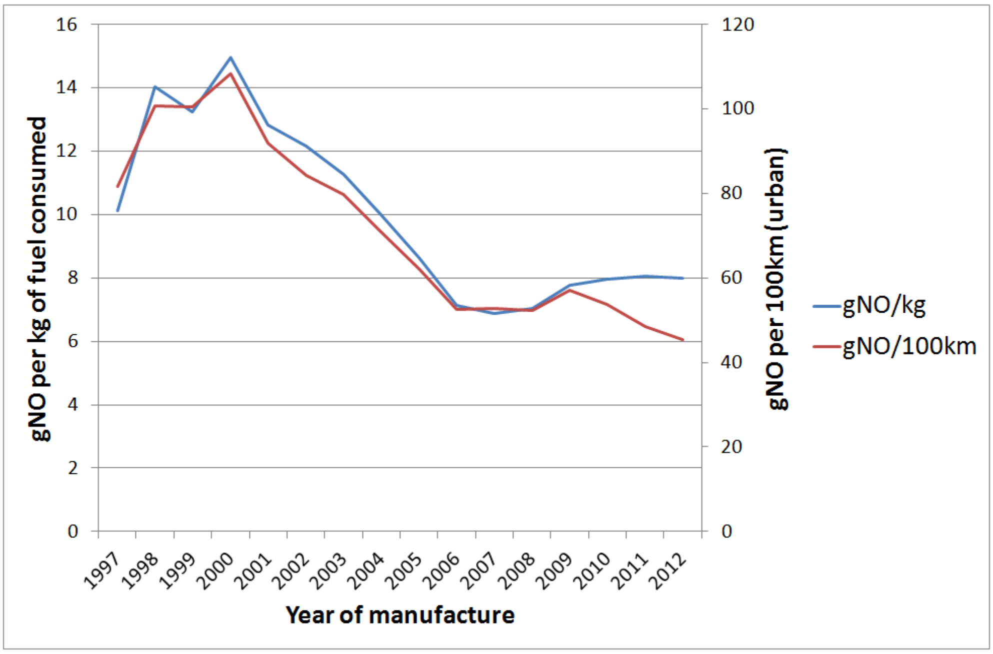

Figure 41 Comparison between mean NO emissions per kg of fuel, and mean NO emissions per 100km for observed diesel cars

With reference to Figure 41, mean emissions of nitric oxide per kilometre are seen to reduce from vehicles manufactured in the period 2010 to 2012.

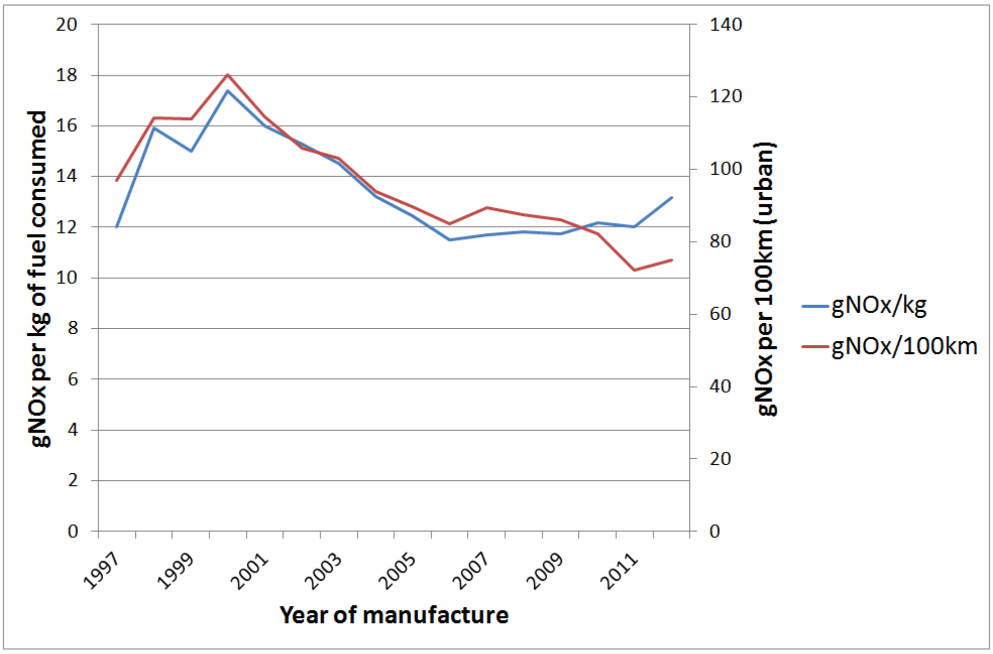

Figure 42 Comparison between mean NO_x emissions per kg of fuel, and mean NO_x emissions per 100km for observed diesel cars

Overall, total mean NO_x (Figure 42) were at a minimum for vehicles manufactured in 2011 (based on grams per unit distance), but increased for vehicles manufactured in 2012 due to the increase in the NO_2 emissions component.

It is important to remember that these figures are not presenting time trend information. They are only presenting a ‘snap shot’ of the observed diesel car fleet as at 2012 (i.e. they are not telling us what the fleet emission rates were in 2011 or 2010).

It should also be noted that ‘real world’ urban fuel consumption may not be consistent with published fuel consumption rates measured over the European type approval driving cycle. Recent research carried out on behalf of the European Commission (Kadijk et al., 2012; Smokers et al., 2012) suggests that a proportion of the reported improvements in passenger car CO_2 emission levels in recent years could be attributed to the increased utilisation of flexibilities in the test procedure. Other researchers have suggested that the gap between type-approval and “real-world” fuel consumption / CO_2 values increased from about 8% in 2001 to 21% in 2011, with a particularly strong increase since 2007 (Mock et al., 2012). Emission inventories would need to take these factors into account to avoid under estimating fleet emission rates.

5 Inter survey comparisons: 2008 and 2012

One of the criteria for selecting the Greenford Road survey location in Ealing for the 2012 remote sensing surveys was that this location had been surveyed previously in 2008. A comparison of the two data sets will, in principle, facilitate the identification and analysis of time trends in the fleet emissions characteristics. However, key differences between the 2008 and 2012 surveys were:

- Survey instrumentation: The 2008 remote sensing surveys utilised a commercial AccuScan 4600 remote sensing device which measured CO, HC, and NO (in addition to an ultra violet and infra red measurement of smoke). The 2012 surveys utilised the University of Denver remote sensing device which measured CO, HC, NO, SO_2, NH_3, and NO_2 (in addition to an infra red measurement of smoke).

- Survey direction: The 2008 survey collected data in both northbound and southbound directions. The 2012 survey surveyed in a southbound direction only.

- Sample size: The 2008 survey collected approximately 5,100 usable (valid emissions measurements combined with positive vehicle identification) observations over 3 survey days. The 2012 survey collected approximately 22,900 usable observations over 8 survey days.

Although the surveys were implemented on the same road, differences in survey layout may have had an influence on vehicle operation through the survey sites. Table 5 presents a summary of mean vehicle speed, acceleration, and VSP for the two data sets.

Table 5 Summary of observed vehicle dynamics at Greenford Road.

Survey year	Mean speed kph (Std. Dev.)	Mean acceleration m/s^2 (Std. Dev.)	Mean VSP kW/t (Std. Dev.)
2008	35.4 kph (9.4)	+0.20 m/s^2 (0.49)	4.63 kW/t (4.60)
2012	40.8 kph (8.7)	-0.15 m/s^2 (0.77)	2.91 kW/t (7.51)

Figure 43 (a-c) presents a comparison of the frequency distribution of observed speed, acceleration, and VSP for the 2008 and 2012 surveys at Greenford Road in terms of percentiles. It can be seen that mean observed speed in 2012 was consistently higher than 2008 (by approximately 5 kph), whereas mean observed acceleration in 2012 was consistently lower than 2008 (indeed negative up to the 60th percentile). The net result is that the calculated VSP values for the 2008 data set are consistently higher than the 2012 data set, up to around the 70th percentile, above which the 2012 values are marginally higher. This is potentially significant for the interpretation of any comparison of emissions data because of the relationships between engine load and emissions rates noted earlier.

Due to the limited sample size achieved in the 2008 RSD surveys, the comparison with the 2012 data will be limited to three groups of vehicles: diesel passenger cars (M1); petrol passenger cars (M1); and diesel light goods vehicles (N1). The focus will be on emissions of oxides of nitrogen.

Table 6 Summary of sample size by vehicle type at Greenford Road.

Survey year	Diesel passenger cars (M1)	Petrol passenger cars (M1)	Diesel light goods vehicles (N1)
2008	784	3060	795
2012	5052	12841	3470

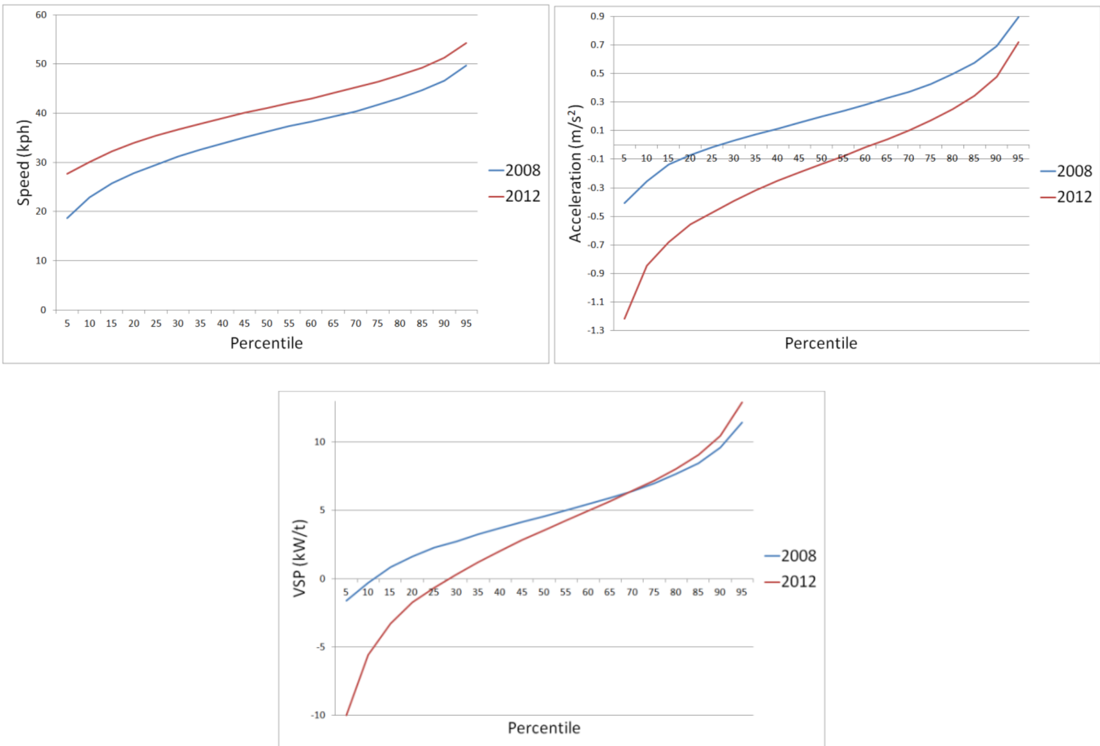

Figure 43 Comparison of the frequency distribution of observed (a) speed, (b) acceleration, and (c) calculated VSP for the 2008 and 2012 surveys at Greenford Road.

Table 7 presents a summary of the mean NO/CO_2 and NO_2/CO_2 ratios (‘Q’ values) by vehicle type and survey year. The mean NO emission rate per unit of fuel consumed from diesel passenger cars observed in 2012 is 26% higher than the value observed in 2008. The mean NO emission rate per unit of fuel consumed from diesel light goods vehicles (N1) observed in 2012 is 19% higher than the value observed in 2008. Finally, the mean NO emission rate per unit of fuel consumed from petrol passenger cars observed in 2012 is 5% higher than the value observed in 2008. The reasons for these differences are explored further in the following sections.

Table 7 Mean NO/CO_2 and NO_2/CO_2 ratio by vehicle type at Greenford Road.

Survey year	Diesel passenger cars (M1)		Petrol passenger cars (M1)		Diesel light goods vehicles (N1)	
	NO/CO_2	NO_2/CO_2	NO/CO_2	NO_2/CO_2	NO/CO_2	NO_2/CO_2
2008	0.002995	-	0.001552	-	0.003804	-
2012	0.003777	0.001109	0.001631	0.000033	0.004524	0.001196

5.1 Petrol passenger cars

Figure 44 presents the number of survey observations of petrol passenger cars, by year of manufacture, and by year of survey. The figure highlights the significant difference in sample size for the two survey years, and also illustrates the frequency distribution of the fleet composition by age of vehicle. The mode for the 2008 survey data is at year of manufacture 2000, whereas the mode for the 2012 survey data is at year of manufacture 2003.

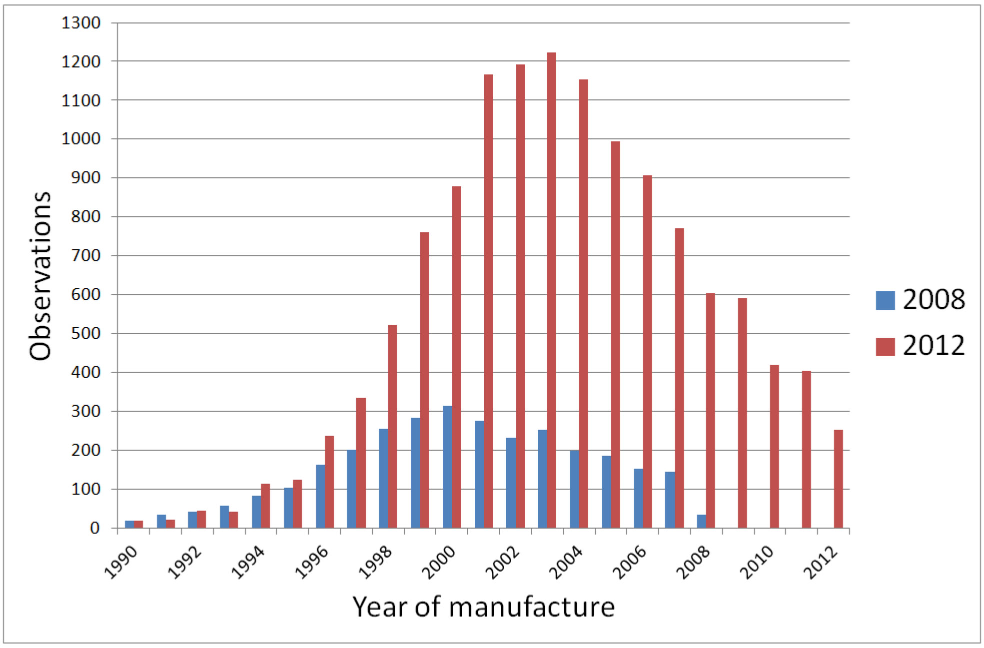

Figure 44 Observed petrol passenger cars at Greenford Road by year of manufacture and survey year.

Figure 45 presents the observed mean rate of NO emissions from petrol passenger cars at Greenford Road by year of manufacture and survey year. It can again be seen that the rate of NO emissions measured in 2012 is generally higher than in 2008, although the 95% confidence intervals about the mean values from the two surveys for years of manufacture 2007 and 2008 overlap. This may again be suggestive of an age or mileage related deterioration in NO emissions, although other factors may be significant.

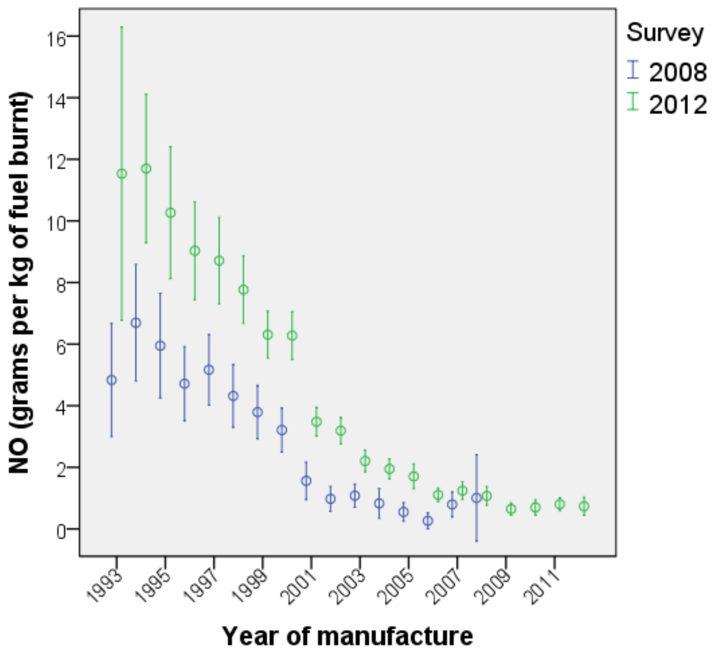

Figure 45 Observed mean NO emissions from petrol passenger cars at Greenford Road by year of manufacture and survey year.

Figure 46 highlights the possible age / mileage related deterioration in nitric oxide emissions from petrol passenger cars by presenting the difference between the 2012 and 2008 survey results.

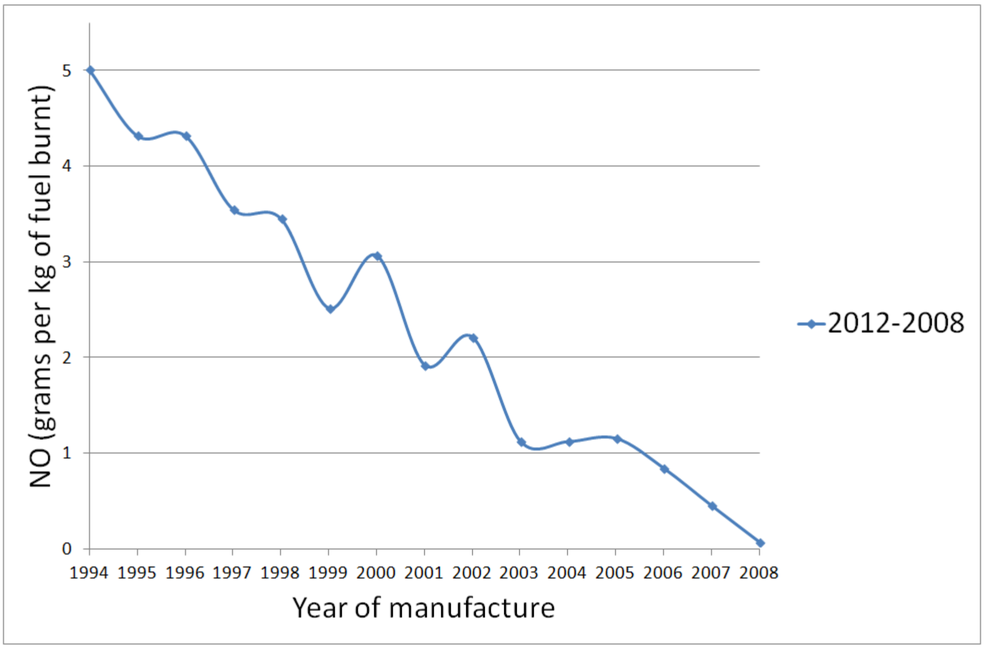

Figure 46 Difference between observed mean NO emissions from petrol passenger cars at Greenford Road by year of manufacture (2012 survey results minus 2008 survey results).

This demonstrates quite a clear linear deterioration in NO emissions for vehicles manufactured over the period 1994 to 2008. The two data sets are seen to converge for vehicles manufactured in 2008, suggesting relatively little deterioration for vehicles less than four years old.

5.2 Diesel passenger cars

Figure 47 presents the number of survey observations of diesel passenger cars, by year of manufacture, and by year of survey. Again, the figure highlights the significant difference in sample size for the two survey years, and the difference in the frequency distribution of the fleet composition by age of vehicle. The frequency distribution for diesel cars tends to be skewed because of the increasing rate of acquisition of diesel cars in recent years, relative to petrol cars.

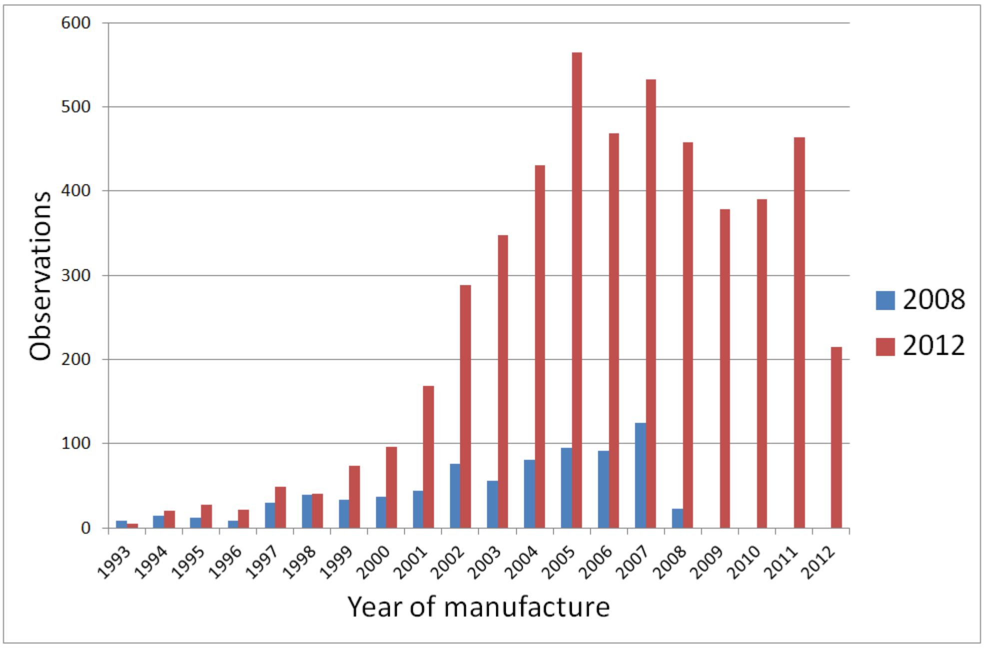

Figure 47 Observed diesel passenger cars at Greenford Road by year of manufacture and survey year.

Figure 48 presents the observed mean rate of NO emissions from diesel passenger cars at Greenford Road by year of manufacture and survey year. It can be seen that the rate of NO emissions measured in 2012 is generally higher than in 2008, although the 95% confidence intervals about the mean values for years of manufacture 2004, 2006, 2007, and 2008 overlap. The increase in NO emissions from years of manufacture 2007 to 2012 is notable in the 2012 survey data. There is a clear divergence in the NO emissions from the two surveys, between year of manufacture 1997 and 2003, which may be suggestive of an age or mileage related deterioration in NO emissions.

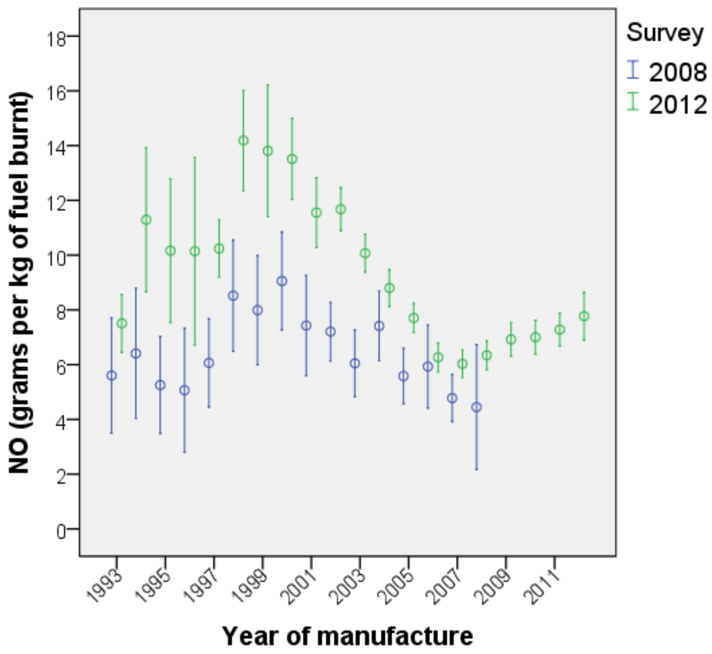

Figure 48 Observed mean NO emissions from diesel passenger cars at Greenford Road by year of manufacture and survey year.

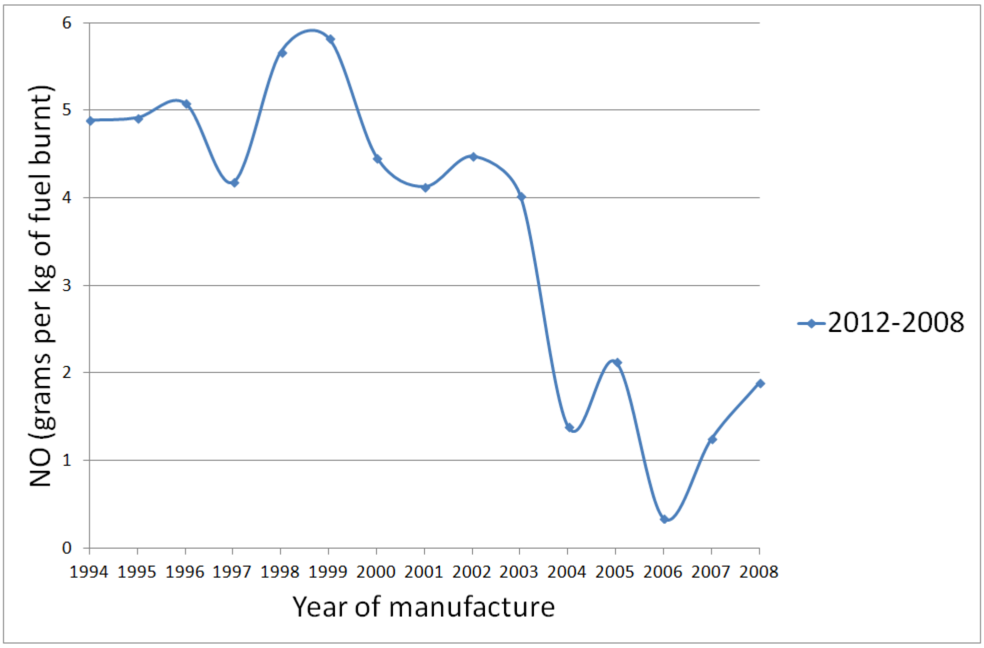

Figure 49 Difference between observed mean NO emissions from diesel passenger cars at Greenford Road by year of manufacture (2012 survey results minus 2008 survey results).

Figure 49 highlights this possible age / mileage related deterioration in nitric oxide emissions by presenting the difference between the 2012 and 2008 survey results. This demonstrates that the difference in emissions observed in the two surveys is relatively small for diesel passenger cars manufactured in the period 2004 to 2008, but that there is a much larger difference in emissions observed in the two surveys for diesel passenger cars manufactured in the period 1994 to 2003.

5.3 Diesel light goods vehicles (N1)

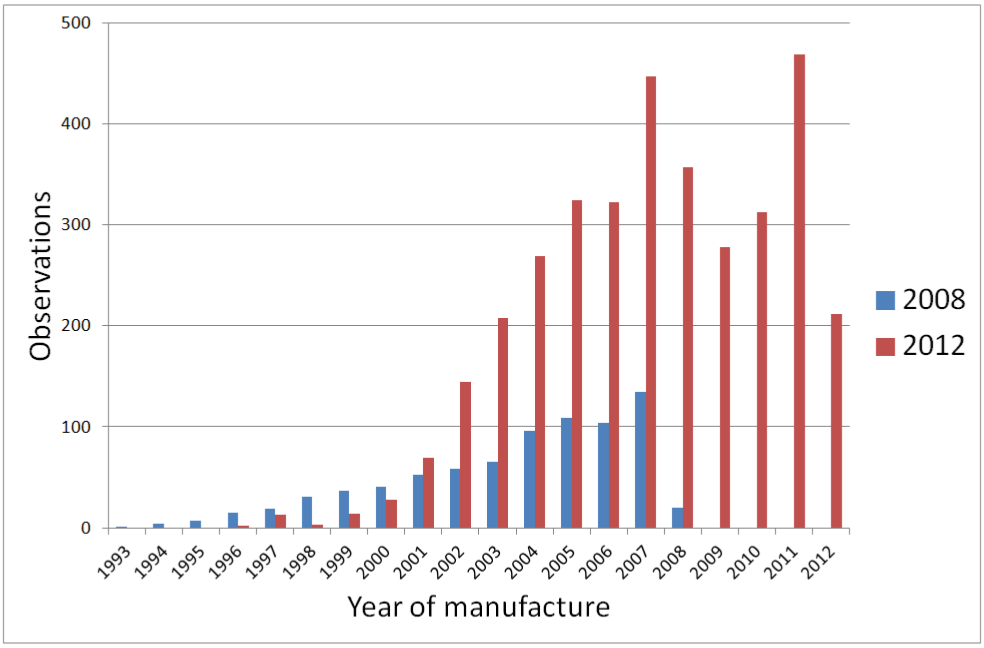

Figure 50 Observed diesel light goods vehicles (N1) at Greenford Road by year of manufacture and survey year.

Figure 51 presents the observed mean rate of NO emissions from diesel light goods (N1) vehicles at Greenford Road by year of manufacture and survey year. Again, the rate of NO emissions measured in 2012 is generally higher than in 2008, although the 95% confidence intervals about the mean values from the two surveys tend to converge for the older vehicles manufactured before 2002. Observed NO emissions from vehicles manufactured since 2002 are consistently higher in the 2012 survey data. In this respect, the results for diesel light goods vehicles differ from the observed diesel passenger cars.

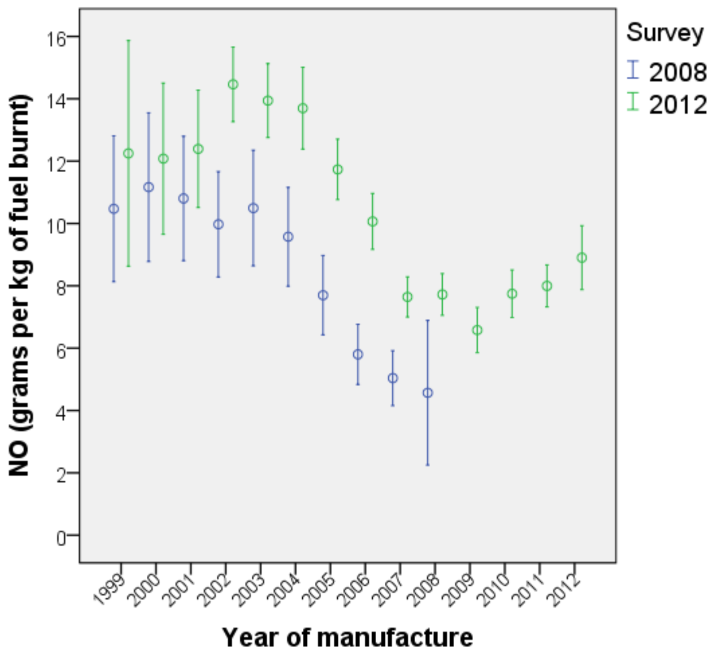

Figure 51 Observed mean NO emissions from diesel light goods vehicles (N1) at Greenford Road by year of manufacture and survey year.

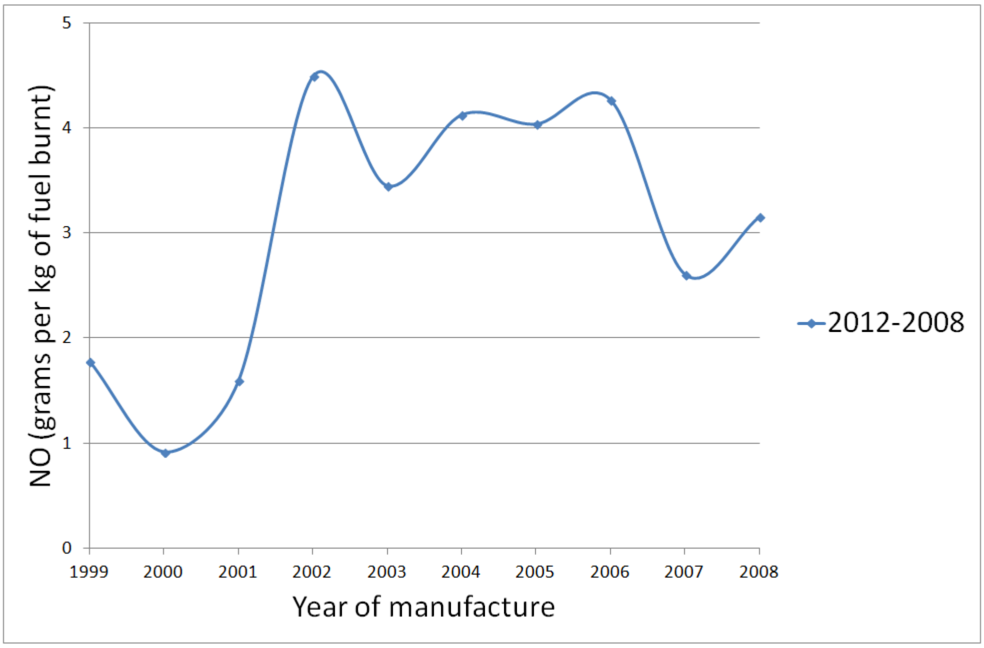

Figure 52 Difference between observed mean NO emissions from diesel light goods vehicles (N1) at Greenford Road by year of manufacture (2012 survey results minus 2008 survey results).

5.4 Summary

The comparison between the two data sets is encouraging from a methodological point of view. Emissions of nitric oxide measured in the two surveys are observed to converge in newer petrol and diesel passenger cars suggesting (a) that the measurements carried out in the two surveys with differing instrumentation are nonetheless consistent, and (b) that age and / or mileage related deterioration is observed, with different deterioration relationships by vehicle type and fuel type. Petrol fuelled passenger cars in particular appear to demonstrate a linear deterioration with respect to age / mileage, whereas the relationships for diesel fuelled vehicles are more complex.

Guidance published by the European Environment Agency (EEA) suggests a linear mileage correction factor for urban NO_x emissions up to a maximum of 2.2 for Euro 1 and Euro 2 petrol cars (from 45 000 km up to 120 000 km). At Euro 3 and Euro 4, the EEA suggest no urban NO_x degradation for petrol cars with engine capacities ≤1.4 litres, but a linear mileage correction factor up to a maximum of 1.57 (assumed average mileage of 17 000 km up to a maximum of 160 000 km) for engine capacities greater than 1.4 litres. The EEA assume no additional mileage related emissions degradation for diesel cars beyond that assumed in baseline emission factors corresponding to fleet average mileage (30 000−60 000 km) (EMEP/EEA, 2012).

Direct comparison with the EEA mileage correction factors is not straightforward at this time because of the lack of NO_2 measurements in the 2008 data set. However, this problem can be overcome by future data collection. Regular future remote sensing surveys in the UK (including both NO and NO_2) at fixed census locations with consistent instrumentation and methodologies will help to provide a more definitive description of the evolution of fleet emissions over time, particularly with respect to vehicle age. At the present time, there is no definitive and comprehensive source of vehicle mileage data for the UK road fleet, although this might be available from MoT test data (e.g. for passenger cars which are three years old or more).

6 Enhanced analysis of remote sensing data

In this work package the RSD data are analysed in more detail to better understand the potential effect on emissions that different drivers have.

Specifically, the analysis in this section aims to do the following:

1. Develop emission models based on the RSD data that link the emission of NO_x and NO_2 to driving conditions based on vehicle specific power, VSP.
2. Use a very large and comprehensive database of actual driving conditions based on 20 instrumented cars and 80 drivers where vehicle speed and acceleration, together with other variables, were measured at 1 Hz.
3. To apply the emission models to the driving behaviour database to understand the likely impact that these driving conditions (and individual drivers) have on emissions.
4. To consider these impacts both in terms of vehicle technology and fuel type.

6.1 Detailed driver behaviour data

To highlight the potential implications in terms of NO_x and NO_2 emissions control.
The driver behaviour data used in the current study is derived from a large European project led by the Institute for Transport Studies (ITS) at the University of Leeds. ITS led a vehicle safety project that involved measuring vehicle usage using on-board instrumentation to record vehicle speed, acceleration, GPS position and a host of other variables at 10 Hz. The experiments were concerned about safety and were primarily focused on the effects of intelligent speed adaptation (ISA) – where the vehicle can limit vehicle speeds depending on the road being driven on. A vast amount of data was collected using 20 instrumented vehicles and 80 drivers of a range of ages and backgrounds. There were four trials covering two distinctive geographic areas and different types of driver. Trials 1 and 2 took place in the Leeds area consisting mainly of city environment but also some outlying rural areas and villages. Trials 3 and 4 took place in the Leicestershire area, which were mainly rural single carriageways and small towns.

The important characteristics of the ITS data for the current work is that a wide range of drivers were assessed (and hence driving styles) together with comprehensive data on vehicle dynamics. A subset of the full database has been used consisting of “baseline” driving and limited to roads with speed limits of 20, 30 or 40 mph i.e. similar to those where the remote sensing was carried out. In total there were **113,000 km driven for 79 drivers** consistent with over 12 million speed-acceleration measurements.

6.2 Emission model development

From the speed and acceleration measurements, vehicle specific power was calculated to enable the emissions models to be developed from the data (Carslaw et al., 2013; Jimenez-Palacios, 1998). The next step was to develop emissions models that relate vehicle technology (describe by Euro classification and year of vehicle manufacture) and driving conditions, encapsulated by VSP. Because the RSD data are noisy, an approach based on Generalized Additive Models (GAMs) was chosen to fit an optimum smooth surface to the data relating vehicle age to VSP. The results of the modelling are shown in Figure 53 to Figure 55.

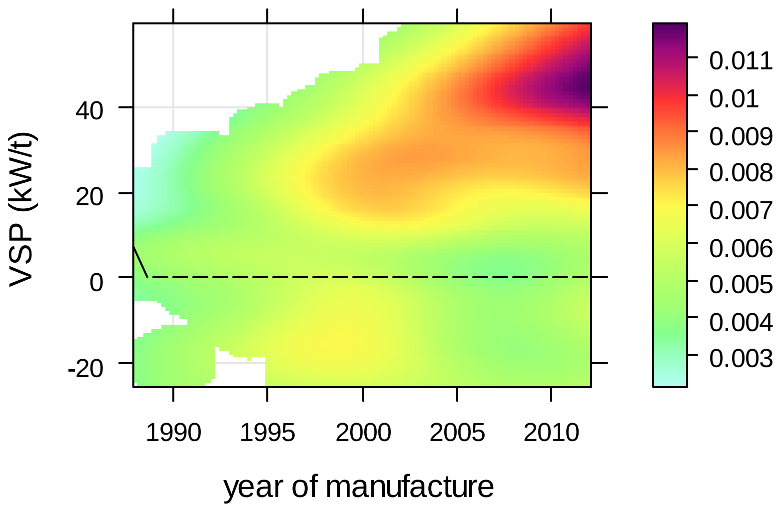

Figure 53 Modelled surface NO_x/CO_2 ratio for diesel cars relating vehicle year of manufacture and VSP.

Figure 53 shows the model results for diesel car NO_x emissions. It is apparent from this Figure that NO_x emissions tend to increase for recent model years and in particular from 2005 (Euro 4) onwards. However, the increase in NO_x/CO_2 ratio is most significant at higher values of VSP i.e. when the engine is under load. This behaviour has been previously noted (Carslaw et al., 2011, 2013).

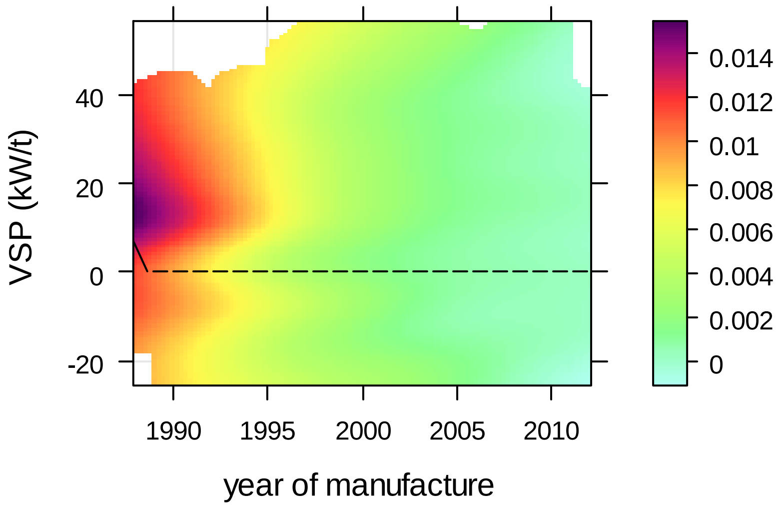

Figure 54 Modelled surface NO_x/CO_2 ratio for petrol cars relating vehicle year of manufacture and VSP.

By contrast the results for petrol cars are markedly different to diesel cars, as shown in Figure 2. In this case the highest emissions of NO_x are associated with years < 1993 i.e. before catalysts were fitted. However, it is also apparent that Euro 1 and 2 cars are also associated with higher emissions of NO_x.

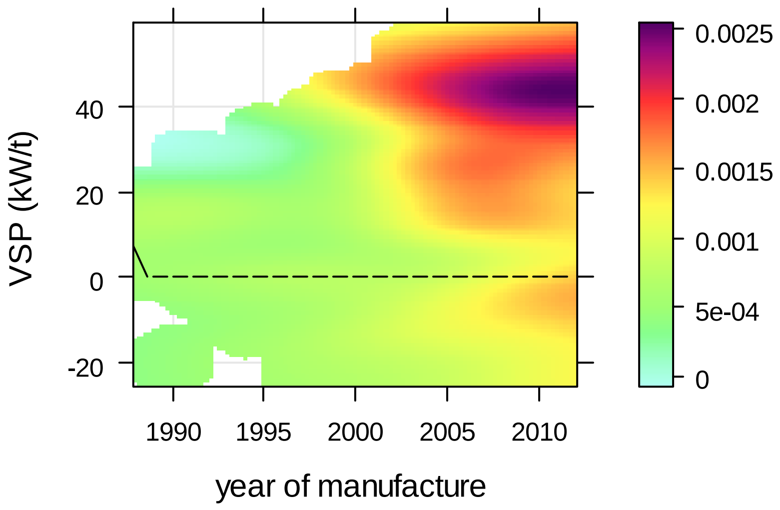

Figure 55 Modelled surface NO_2/CO_2 ratio for diesel cars relating vehicle year of manufacture and VSP.

The results for NO_2 (Figure 55) for diesel cars follow similar patterns to NO_x (Figure 53) e.g. they show a more prominent increase for the newest vehicles (Euro 4/5) also at higher VSP. Note that models for NO_2 from petrol vehicles were not developed due to their very low (negligible) emission of NO_2.

6.3 Model results

Having developed emission models to relate vehicle age (and Euro classification) to driving behaviour through VSP, it is now possible to apply them to the individual driver behaviour data previously described. This was achieved by using the 1 Hz driving data for each driver and applying each model in turn to calculate 1-Hz emissions. Due to the size of the data sets involved, a simplified analysis was undertaken to help summarise the main issues. In particular, we have considered two percentile levels of VSP: 50 and 95% The 50% percentile will represent the most common driving patterns used by each driver and the 95% will give an indication of the higher levels of VSP.

Figure 56 shows how levels of VSP vary at their 50th and 95th percentile values for speed limits less than or equal to 40 mph. Taking a typical urban speed of 30 mph Figure 56 shows there is a narrow range in driver behaviours at this speed at the 50th percentile level. This observation is consistent with all drivers spending most of their time at a constant cruise speed and not associated with large accelerations or decelerations. However, at the 95% percentile level, not only is the VSP considerably higher on average (about 15 kW/t at 30 mph for the 95th percentile cf. 5 W/t for the 50th percentile), there is much more variation between different drivers. The ITS driver data show that for roads with the same speed limit and for the *same average speed*, there is a relatively large variation in the strength of the accelerations and decelerations of drivers. The behaviour of drivers varies from what could be called ‘mild’ to ‘aggressive’ driving.

These different driving behaviours are likely to have an effect on vehicle emissions. It has been shown that at higher engine loads (VSPs) emissions of NO_x and NO_2 can increase considerably (Carslaw et al., 2013). Moreover, these increases depend on both the fuel type (petrol or diesel) and the technology of the vehicle itself (pre Euro to Euro 5). It is of interest to know the extent to which actual driving behaviour affects emissions and the extent to which the emissions are affected by the vehicle technology used.

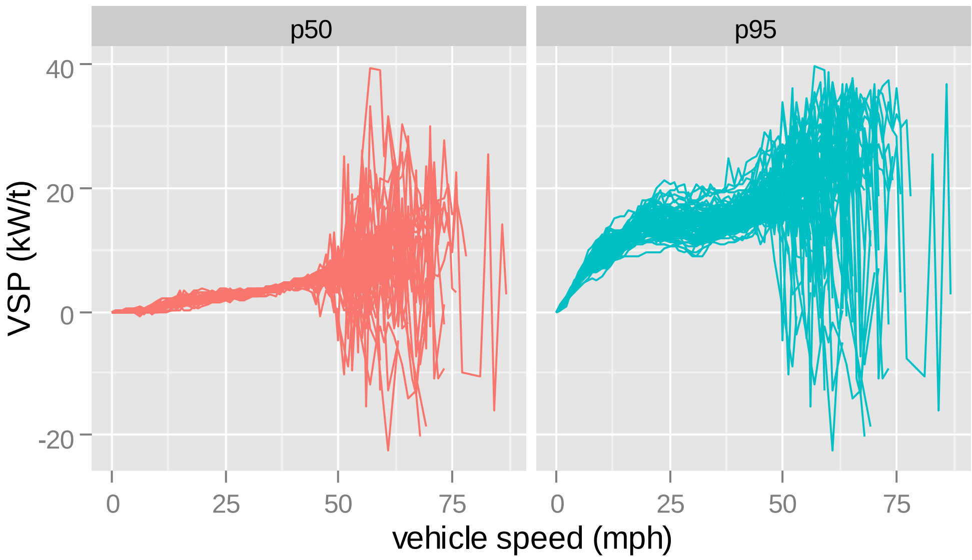

Figure 56 Levels of VSP by driver for the 50th and 95th percentile values.

The main results for NO_x are shown in Figure 57 plotted by fuel type and percentile level. These results highlight some important differences between petrol and diesel vehicles. First, the changes in emissions of NO_x through the Euro classes reflect the general pattern seen for the overall RSD results. For example, it is clear that NO_x emissions from petrol vehicles have decreased substantially from pre-Euro 1 to Euro 5. There is also an important difference between emissions at the 50th percentile of VSP compared with the 95th percentile. The principal difference is that the spread in emissions between different drivers is very narrow in both the cases of petrol and diesel. This narrow range is due to the 50th percentile VSP being dominated by steady, cruise driving rather than driving with lots of accelerations and decelerations.

However, at higher (95 percentile) levels of VSP, there is a broad range in emissions possible from diesel cars, which is caused by the different driver behaviours. The first issue to note is that there is a wider range in emissions for the newer technology vehicles (Euro 3 to 5). Second, the range in emissions from these vehicles is large (about +/-20%). It can be shown that the key factor that differentiates the emissions between different drivers is the VSP - and in particular the strengths of accelerations. The results show that where drivers accelerate more strongly (resulting in a higher VSP) the emissions of NO_x increase substantially. For example, for a Euro 5 diesel car the most aggressive driver is predicted to emit 50% more NO_x than the least aggressive driver.

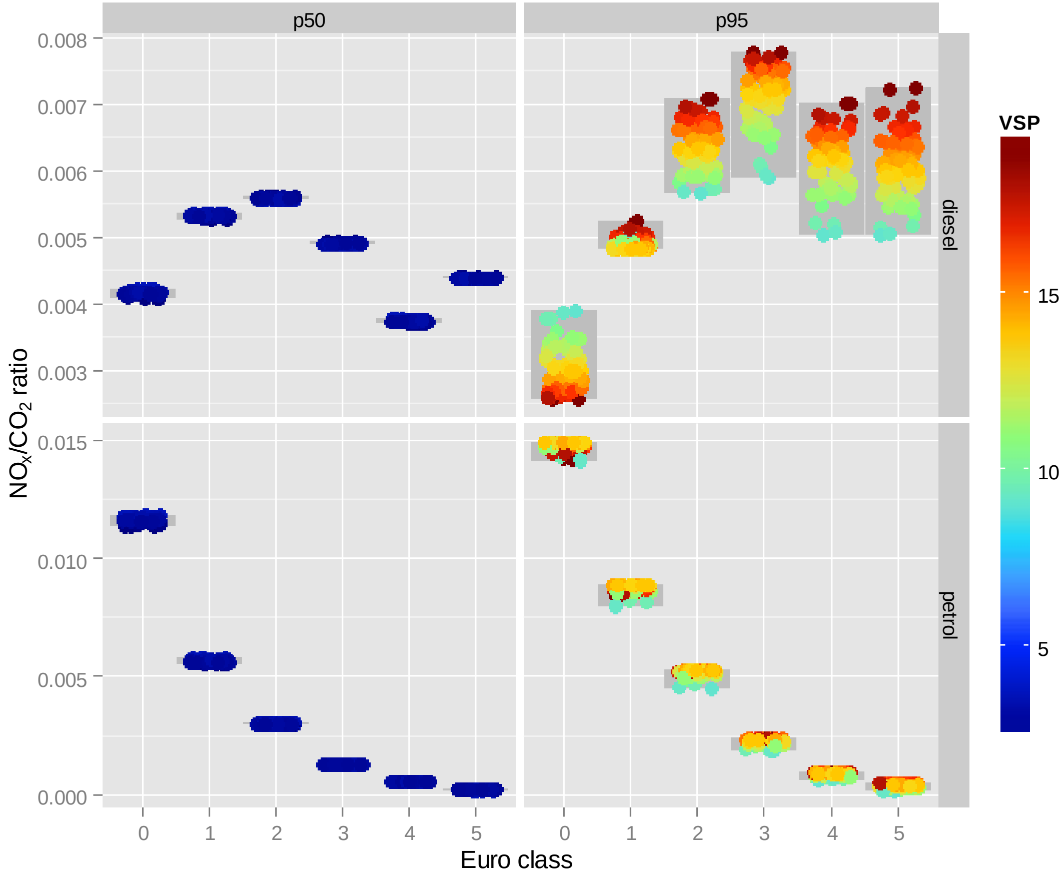

Figure 57 Results showing the NO_x/CO_2 emissions ratio for petrol and diesel cars for the 50th and 95th percentiles. The individual driver emissions are shown coloured by the level of VSP.

The results for NO_2 (diesel only) show the clear increase in NO_2 emissions from Euro 2 to Euro 3, and then a further increase to Euro 4/5. Compared with NO_x however there is less of a range in emission due to driver behaviour - but the range is still greater for Euro 3 to Euro 4 vehicles compared with older generation vehicles.

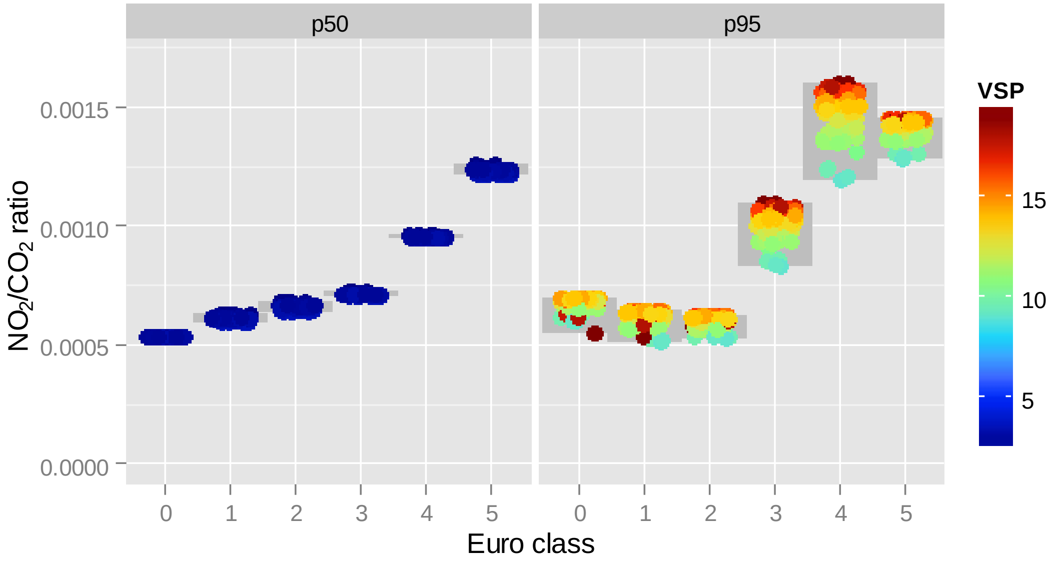

Figure 58 Results showing the NO_2/CO_2 emissions ratio for petrol and diesel cars for the 50th and 95th percentiles. The individual driver emissions are shown coloured by the level of VSP.

Overall these results show that for emissions of NO_x and NO_2, the emissions from modern diesel cars can be strongly influenced by driver behaviour in a way that was absent in earlier model vehicles. This increased sensitivity to driver behaviour is related to the aggressiveness with which vehicles are driven, and specifically the vehicle specific power. It is difficult to know whether powerful, modern diesel cars that are much more powerful than previous generations of vehicles have changed the way they are driven. For example, older vehicles without turbochargers and similar technologies could not be accelerated quickly. A change in driving behaviour brought about by the introduction of more powerful diesel cars could however result in considerably increased emissions of NO_x.

One of the important factors affecting some of the results above is likely related to trends in engine power over the last two decades. As shown in Figure 59 there are clear differences in the trends in rated maximum vehicle power for petrol and diesel cars. These data are based on the vehicle information database for the RSD data and therefore reflect a vehicle-km weighted estimate of trends in vehicle power because they are based on the numbers of vehicles sampled using the RSD. For petrol cars there has been a steady increase in vehicle power over time from about 80 kW in 1990 to about 100 kW in 2012.

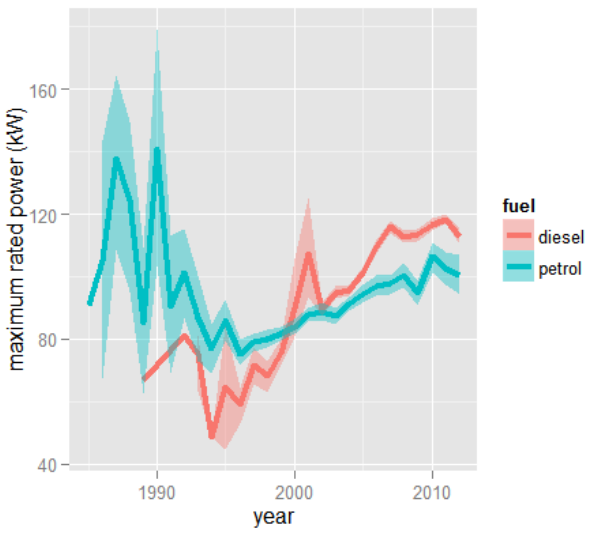

Figure 59 Trends in maximum rated vehicle power (kW) calculated from the RSD data for petrol and diesel cars. The shading shows the 95% confidence interval in the mean. The data are from earlier RSD campaigns.

By contrast, the trends shown in Figure 59 for diesel cars show more substantial increases over time. In 1995 the average maximum rated power for a diesel car was ≈60 kW compared with ≈80 kW for petrol cars. However, since the early 1990s the maximum power of diesel cars has steadily increased such that by 2012 the maximum power rating was about 120 kW on average. The maximum rated power of diesel cars in recent years is therefore substantially higher than that of petrol vehicles.

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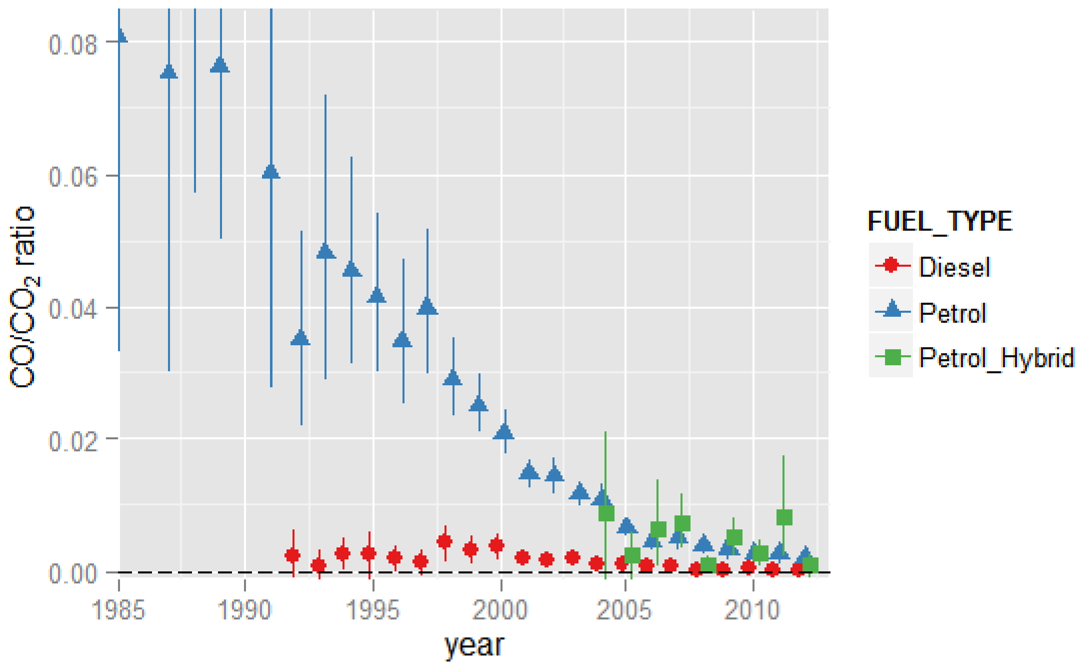
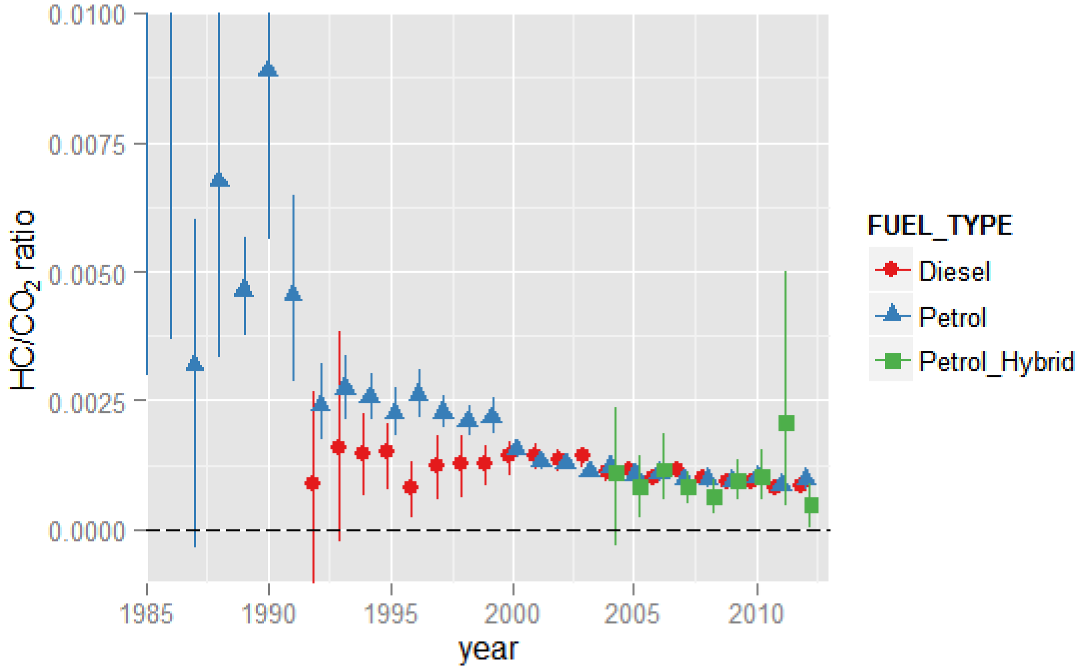
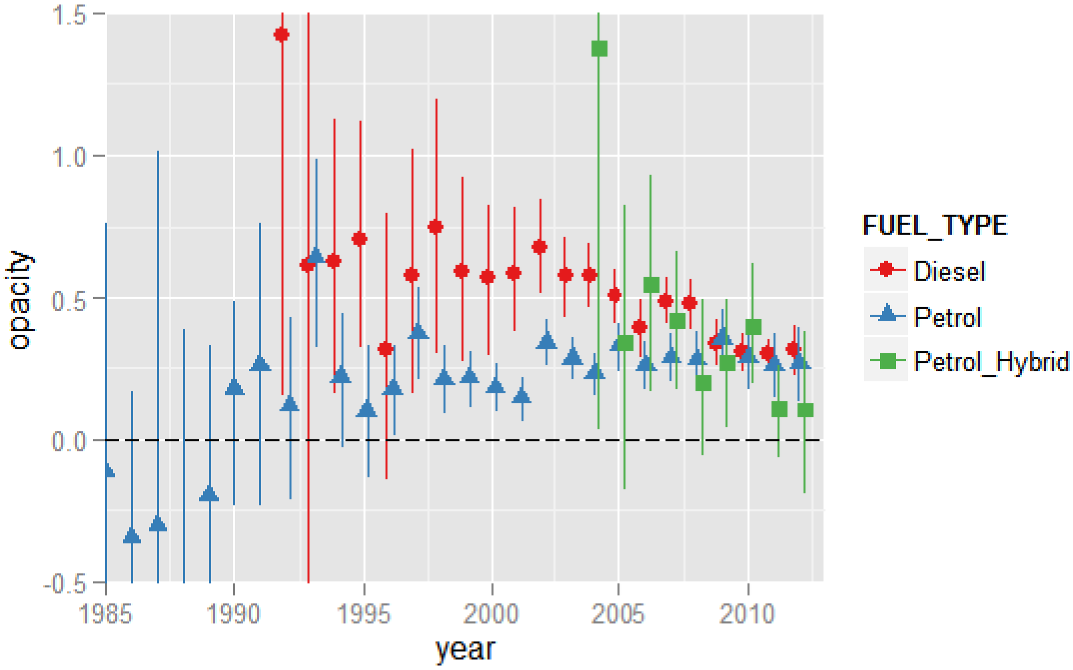
Appendix A - Emission results for other pollutants

Passenger cars







opacity
1.5
1.0
0.5
0.0
-0.5
1985
1990
1995
2000
2005
2010
year
FUEL_TYPE
Diesel
Petrol
Petrol_Hybrid

Appendix B Emission factor tables

This appendix contains the NO_x and NO_2 emission factor tables **expressed in volume units** to the ratio of CO_2. These factors could be used to check the agreement with NAEI/LAEI emission factors. Also given is the 95% confidence interval.

Passenger cars

Table 8 Diesel passenger car emissions for NO_x/CO_2 and f-NO_2 (%).

Euro class	species	mean	ymin	ymax
0	f-NO_2	15.4511	11.7510	19.1237
1	f-NO_2	13.9283	11.5231	16.4369
2	f-NO_2	10.0190	8.9498	11.3301
3	f-NO_2	18.6160	17.7254	19.4747
4	f-NO_2	30.6559	28.6420	32.2785
5	f-NO_2	29.6473	27.1716	33.4927
0	Q_NO_x	0.0047	0.0038	0.0057
1	Q_NO_x	0.0056	0.0049	0.0063
2	Q_NO_x	0.0066	0.0062	0.0069
3	Q_NO_x	0.0063	0.0061	0.0064
4	Q_NO_x	0.0048	0.0047	0.0049
5	Q_NO_x	0.0050	0.0049	0.0051

Table 9 Petrol passenger car emissions for NO_x/CO_2 and f-NO_2 (%).

Type	Euro class	species	mean	ymin	ymax
Petrol	0	f-NO_2	3.0000	3.0000	3.0000
Petrol	1	f-NO_2	3.0000	3.0000	3.0000
Petrol	2	f-NO_2	3.0000	3.0000	3.0000
Petrol	3	f-NO_2	3.0000	3.0000	3.0000
Petrol	4	f-NO_2	3.0000	3.0000	3.0000
Petrol	5	f-NO_2	3.0000	3.0000	3.0000
Petrol	0	Q_NO_x	0.0087	0.0076	0.0098
Petrol	1	Q_NO_x	0.0054	0.0048	0.0060
Petrol	2	Q_NO_x	0.0039	0.0037	0.0041
Petrol	3	Q_NO_x	0.0015	0.0014	0.0016
Petrol	4	Q_NO_x	0.0010	0.0010	0.0011
Petrol	5	Q_NO_x	0.0005	0.0004	0.0006
Petrol_Hybrid	4	f-NO_2	3.0000	3.0000	3.0000
Petrol_Hybrid	5	f-NO_2	3.0000	3.0000	3.0000
Petrol_Hybrid	4	Q_NO_x	0.0002	0.0001	0.0003
Petrol_Hybrid	5	Q_NO_x	0.0007	0.0004	0.0011

London Taxis

Table 10 London taxi emissions for NO_x/CO_2.

Euro Class	TYPE	N	variable	mean	ymin	ymax
2	Taxi_FX	872	Q_NO_x	0.0090	0.0087	0.0093
2	Taxi_Met	80	Q_NO_x	0.0149	0.0131	0.0172
2	Taxi_TX1	3877	Q_NO_x	0.0096	0.0094	0.0097
3	Taxi_Met	148	Q_NO_x	0.0052	0.0049	0.0056
3	Taxi_TXII	4050	Q_NO_x	0.0053	0.0052	0.0054
4	Taxi_MV111	594	Q_NO_x	0.0064	0.0063	0.0065
4	Taxi_TX4	4719	Q_NO_x	0.0049	0.0048	0.0050
5	Taxi_MV113	329	Q_NO_x	0.0063	0.0060	0.0066
5	Taxi_TX4	185	Q_NO_x	0.0080	0.0072	0.0087

Table 11 London taxi emissions for NO_2/NO_X.

Euro Class	TYPE	N	variable	mean	ymin	ymax
2	Taxi_FX	872	f-NO_2	4.2	3.9	4.5
2	Taxi_Met	80	f-NO_2	8.8	7.3	10.4
2	Taxi_TX1	3877	f-NO_2	5.4	5.2	5.5
3	Taxi_Met	148	f-NO_2	7.2	6.4	8.1
3	Taxi_TXII	4050	f-NO_2	12.0	11.3	12.6
4	Taxi_MV111	594	f-NO_2	18.9	17.5	20.4
4	Taxi_TX4	4719	f-NO_2	12.8	12.1	13.7
5	Taxi_MV113	329	f-NO_2	38.6	37.0	40.1
5	Taxi_TX4	185	f-NO_2	20.4	18.3	22.8

TfL buses

Table 12 NO_x/CO_2 (volume ratio) for TfL buses. The table gives the mean and the 95% CI (ymax, ymin).

Euro class	aftertreatment	N	mean	ymax	ymin
2	DPF	161	0.0082	0.0088	0.0076
3	DPF	631	0.0122	0.0127	0.0117
4	DPF	89	0.0160	0.0173	0.0146
4	SCR	257	0.0105	0.0113	0.0097
5	EGR	106	0.0093	0.0102	0.0083
5	SCR	266	0.0093	0.0100	0.0087
5	SCR-Hybrid	158	0.0085	0.0091	0.0080
EEV	EGR	63	0.0120	0.0132	0.0107
EEV	SCR	65	0.0086	0.0099	0.0075

Vans

Table 13 NO_x/CO_2 and f-NO_2 for vans.

Euro Class	n	Variable	mean	ymax	ymin
1	26	Q_NO_x	0.007	0.009	0.006
2	93	Q_NO_x	0.007	0.008	0.006
3	2603	Q_NO_x	0.007	0.007	0.007
4	5347	Q_NO_x	0.005	0.005	0.005
5	4412	Q_NO_x	0.005	0.006	0.005
1	26	f-NO_2	13.1	16.7	9.9
2	93	f-NO_2	7.5	9.4	5.4
3	2603	f-NO_2	12.7	13.4	12.0
4	5347	f-NO_2	27.3	31.0	20.8
5	4412	f-NO_2	27.2	28.2	26.1

HGVs

Table 14 NO_x/CO_2 and f-NO_2 for HGVs.

Euro Class	n	variable	mean	ymin	ymax
II	67	Q_NO_x	0.014	0.013	0.016
III	326	Q_NO_x	0.012	0.011	0.012
IV	530	Q_NO_x	0.012	0.012	0.013
V	421	Q_NO_x	0.012	0.011	0.012
II	67	f-NO_2	18.5	13.7	23.5
III	326	f-NO_2	18.6	12.2	23.1
IV	530	f-NO_2	6.6	1.4	9.6
V	421	f-NO_2	9.4	7.9	11.2

Appendix C: Observed fleet composition by survey location

This appendix presents the observed fleet composition (absolute volumes and percentages).

Aldersgate Street

Number of observations

Aldersgate Street											
		Euro									
		0	1	2	3	4	5	6	EEV	Other	Total
Cars	Diesel		1	20	195	708	822				1746
	Petrol	13	15	75	212	423	158				896
	Petrol hybrid					26	157				183
TfL Buses	Diesel			160	354	51	519		111	152	1347
Taxis	Diesel			1426	1148	1541	131				4246
PTW	Petrol									6	6
Vans	Diesel		5	5	355	987	797				2149
	Petrol	8	4	1	19	86	31				149
MGV	Diesel			3	6	36	29				74
HGV	Diesel				16	17	14				47
Total		21	25	1690	2305	3875	2658	0	111	158	10843

Percentages

Aldersgate Street											
		Euro									
		0	1	2	3	4	5	6	EEV	Other	Total
Cars	Diesel		0.0	0.2	1.8	6.4	7.5				15.9
	Petrol	0.1	0.1	0.7	1.9	3.9	1.4				8.2
	Petrol hybrid					0.2	1.4				1.7
TfL Buses	Diesel			1.5	3.2	0.5	4.7		1.0	1.4	12.3
Taxis	Diesel			13.0	10.5	14.0	1.2				38.7
PTW	Petrol									0.1	0.1
Vans	Diesel		0.0	0.0	3.2	9.0	7.3				19.6
	Petrol	0.1	0.0	0.0	0.2	0.8	0.3				1.4
MGV	Diesel			0.0	0.1	0.3	0.3				0.7
HGV	Diesel				0.1	0.2	0.1				0.4
Total		0.2	0.2	15.4	21.0	35.3	24.2	0.0	1.0	1.4	98.8

Queen Victoria Street

Number of observations

Queen Victoria Street											
		Euro									
		0	1	2	3	4	5	6	EEV	Other	Total
Cars	Diesel	2	1	31	339	1633	2164	1			4171
	Petrol	18	28	142	399	874	446				1907
	Petrol hybrid					64	247				311
TfL Buses	Diesel			1	274	6	5		2	416	704
Taxis	Diesel			3619	3043	3754	380				10796
PTW	Petrol									834	834
Vans	Diesel		3	18	781	2278	2099				5179
	Petrol	1		7	24	130	66				228
MGV	Diesel	1		9	57	121	104				292
HGV	Diesel			7	26	40	25				98
Total		22	32	3834	4943	8900	5536	1	2	1250	24520

Percentages

Queen Victoria Street											
		Euro									
		0	1	2	3	4	5	6	EEV	Other	Total
Cars	Diesel	0.0	0.0	0.1	1.4	6.6	8.7	0.0			16.8
	Petrol	0.1	0.1	0.6	1.6	3.5	1.8				7.7
	Petrol hybrid					0.3	1.0				1.3
TfL Buses	Diesel			0.0	1.1	0.0	0.0		0.0	1.7	2.8
Taxis	Diesel			14.6	12.3	15.1	1.5				43.5
PTW	Petrol									3.4	3.4
Vans	Diesel		0.0	0.1	3.2	9.2	8.5				20.9
	Petrol	0.0		0.0	0.1	0.5	0.3				0.9
MGV	Diesel	0.0		0.0	0.2	0.5	0.4				1.2
HGV	Diesel			0.0	0.1	0.2	0.1				0.4
Total		0.1	0.1	15.5	19.9	35.9	22.3	0.0	0.0	5.0	98.9

Greenford Road

Number of observations

Greenford Road											
		Euro									
		0	1	2	3	4	5	6	EEV	Other	Total
Cars	Diesel	12	52	234	1466	2377	910	1			5052
	Petrol	150	281	2071	3817	5582	940				12841
	Petrol hybrid					39	144				183
TfL Buses	Diesel					298	6		13	175	492
Taxis	Diesel			48	9	10					67
PTW	Petrol									59	59
Vans	Diesel		15	45	1014	1404	992				3470
	Petrol	5	4	7	25	27	4				72
MGV	Diesel		1	33	105	118	67				324
HGV	Diesel		1	9	48	79	67				204
Total		167	354	2447	6484	9934	3130	1	13	234	22764

Percentages

Greenford Road											
		Euro									
		0	1	2	3	4	5	6	EEV	Other	Total
Cars	Diesel	0.1	0.2	1.0	6.4	10.4	4.0	0.0			22.0
	Petrol	0.7	1.2	9.0	16.6	24.3	4.1				56.0
	Petrol hybrid					0.2	0.6				0.8
TfL Buses	Diesel					1.3	0.0		0.1	0.8	2.1
Taxis	Diesel			0.2	0.0	0.0					0.3
PTW	Petrol									0.3	0.3
Vans	Diesel		0.1	0.2	4.4	6.1	4.3				15.1
	Petrol	0.0	0.0	0.0	0.1	0.1	0.0				0.3
MGV	Diesel		0.0	0.1	0.5	0.5	0.3				1.4
HGV	Diesel		0.0	0.0	0.2	0.3	0.3				0.9
Total		0.7	1.5	10.7	28.3	43.3	13.7	0.0	0.1	1.0	99.3

A40 Slip Road

Number of observations

A40 slip road											
		Euro									
		0	1	2	3	4	5	6	EEV	Other	Total
Cars	Diesel	1	8	79	635	1180	709	1			2613
	Petrol	25	70	579	1209	2039	464				4386
	Petrol hybrid					26	66				92
TfL Buses	Diesel								1	39	40
Taxis	Diesel			12	5	9	4				30
PTW	Petrol									20	20
Vans	Diesel	3	3	28	486	734	579				1833
	Petrol	2	1	4	9	6					22
MGV	Diesel		2	5	29	35	30				101
HGV	Diesel			1	41	88	89				219
Total		31	84	708	2414	4117	1941	1	1	59	9356

Percentages

A40 slip road											
		Euro									
		0	1	2	3	4	5	6	EEV	Other	Total
Cars	Diesel	0.0	0.1	0.8	6.7	12.5	7.5	0.0		0.0	27.8
	Petrol	0.3	0.7	6.2	12.8	21.7	4.9				46.6
	Petrol hybrid					0.3	0.7				1.0
TfL Buses	Diesel								0.0	0.4	0.4
Taxis	Diesel			0.1	0.1	0.1	0.0				0.3
PTW	Petrol									0.2	0.2
Vans	Diesel	0.0	0.0	0.3	5.2	7.8	6.2				19.5
	Petrol	0.0	0.0	0.0	0.1	0.1	0.0				0.2
MGV	Diesel		0.0	0.1	0.3	0.4	0.3				1.1
HGV	Diesel			0.0	0.4	0.9	0.9				2.3
Total		0.3	0.9	7.5	25.7	43.8	20.6	0.0	0.0	0.6	99.4